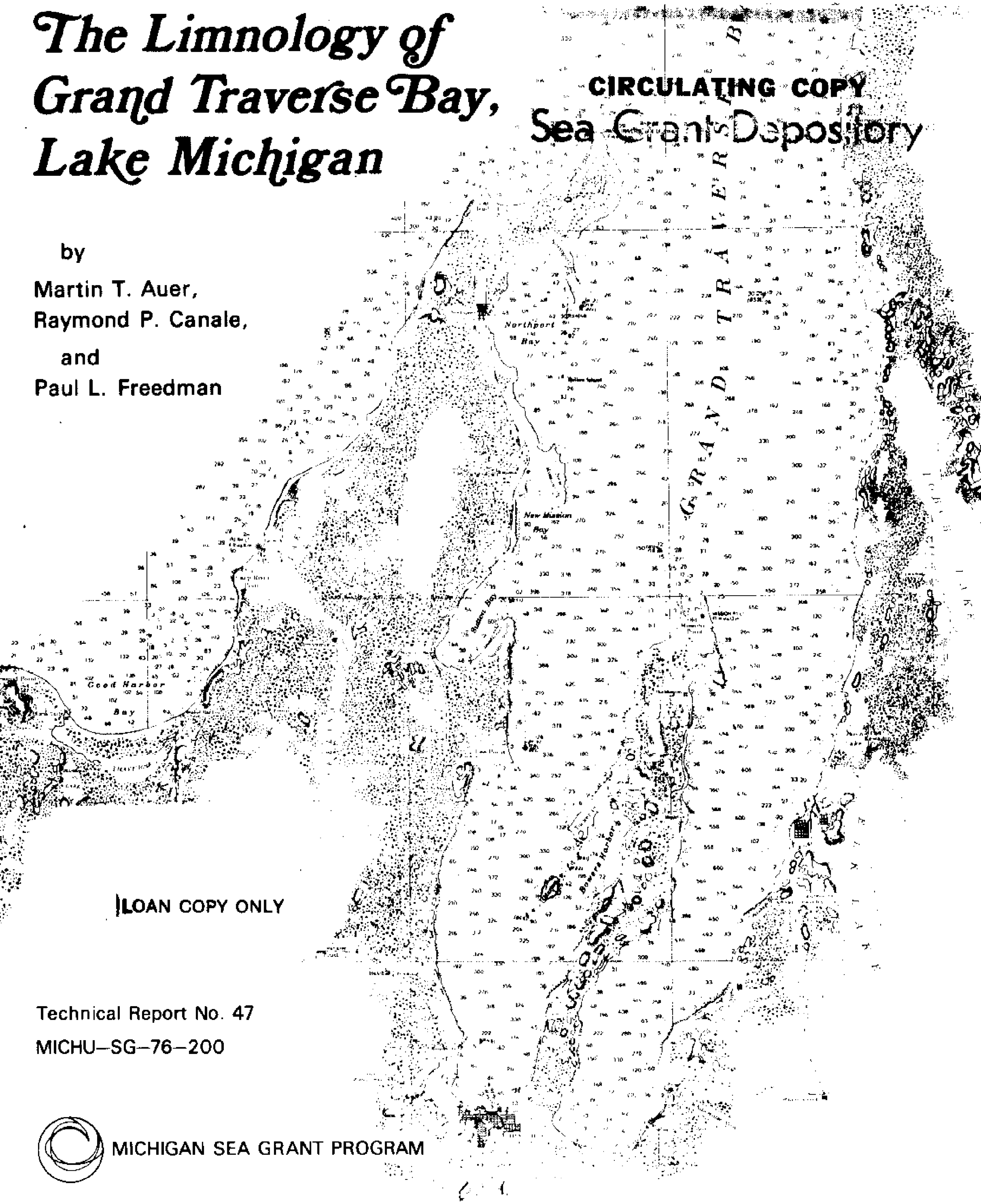
The Limnology of Grand Traverse Bay, Lake Michigan

by

Martin T. Auer,
Raymond P. Canale,
and
Paul L. Freedman



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MICHIGAN SEA GRANT PROGRAM

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PREFACE

The University of Michigan Sea Grant investigation resulting in this report was conducted with four major objectives in mind:

1) To assess the level of water quality in Grand Traverse Bay and identify areas of diminished water quality.
2) To evaluate the relative importance of contaminant sources to the bay.
3) To examine trends in water quality in the bay and identify any potential problems in the future.
4) To establish a limnological baseline for future comparison and to aid in the development of a water quality model for Lake Michigan.

To this end the project report, "The Limnology of Grand Traverse Bay, Lake Michigan," has been prepared. The report contains seventeen chapters divided into three sections, each section with a particular intent. The first section (Chapters I-IX) contains the summary, introduction and chapters dealing with the geologic, morphometric and circulatory characteristics of the bay. The following two chapters present methods of analysis and data management. Finally this section contains a detailed discussion of the hydrology and contaminant sources to the bay. This section is intended for those interested in a thorough understanding of Grand Traverse Bay and the findings of this report.

The second section (Chapter X) is a summary of general water quality in the bay. Results of chemical analyses for trace metals, algal growth nutrients and major ions are presented. A summary of findings regarding phytoplankton, zooplankton, coliform bacteria, benthos, and surficial sediments is provided. This section relates to the applied portion of this research and is intended to stand alone without the support of other chapters.

The third and final section of this report (Chapters XI-XVI) is a collection of individual reports describing in detail findings regarding phytoplankton, zooplankton, benthos and surface sediments. Each chapter is self-standing and serves as an in-depth report of a particular facet of the limnology of Grand Traverse Bay. The literature cited follows this section.

Appendix A presents references used in the compilation of tables of general values, and Appendix B is a bibliography of Michigan Sea Grant reports and papers of Grand Traverse Bay. Sample station coordinates, cruise dates, and the Grand Traverse Bay data files are published separately (Auer et al. 1976).

ACKNOWLEDGEMENTS

This report is the result of five years of sampling and analysis by the University of Michigan Sea Grant Program on Grand Traverse Bay. The work of Dean Arnold, John J. Gannon, Tom Kelly, and Jim Sygo in various phases of the field program was fundamental to the success of this project. Additionally, Messrs. Kelly and Sygo were particularly helpful in providing background material for the report. Thanks are due to the numerous people who participated in the sampling program, including Captain Dunster and the crew of the R/V MYSIS and Captain Thibault and the crews of the R/V INLAND SEAS and the R/V LAURENTIAN. Mary-Lee Sharp was responsible for the bulk of the chemical analysis.

A number of individuals were involved in the data reduction and formative phases of the report. Fred Juengling, John Podriznik and Jim Squire were especially helpful in this regard. Allan Vogel contributed the zooplankton material for the report and prepared supportive information on Great Lakes water quality and Michigan Sea Grant studies in Grand Traverse Bay. The chapter on phytoplankton studies was largely the result of the efforts of Wendy Moore; her careful presentation of data and notes is gratefully acknowledged. Peter Meier analyzed the benthos data and provided a chapter of that phase of the study. The authors wish to thank Diane Rumps and Noreen Waller for their assistance throughout the development of the report. We would like to thank Linda Gacioch, Kristy Grosser and Fran Williams for the final typing of this manuscript. We would also like to thank Nancy Auer for her help in proofreading the draft copies. Steve Schneider's editorial comments are gratefully acknowledged.

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I. SUMMARY

Grand Traverse Bay is a deep, cold portion of Lake Michigan, located in the northwest part of the lower peninsula of Michigan. The only significant population center of the bay is Traverse City (population 23,400; 1974 estimate). The basin is primarily agricultural in nature, although limited food processing and light manufacturing are established in Traverse City. One of the most important assets of the region is its recreational resource, i.e. that available for boating, fishing and swimming. This study has evaluated the aquatic resource in relation to past, present, and future water quality conditions.

The bay is cartographically divided into three zones: the open bay (adjacent to Lake Michigan), and the east and west arms. Traverse City is located at the south end of the west arm. The two major tributaries to Grand Traverse Bay, the Elk and Boardman Rivers, discharge to the east and west arms, respectively. These two rivers provide the largest percentage of both flow and chemical constituents to the bay; the Boardman in terms of ammonia-nitrogen and phosphorus, and the Elk in terms of nitrate-nitrogen and silicon. These two tributaries account for over 80% of the average annual load of these materials to the bay. Trace metal loadings to the bay are generally proportional to the tributary flow. The other tributaries to the bay provide a small percentage of chemical constituents due to their low flow.

Levels of algal growth nutrients in Grand Traverse Bay are very low and indicative of an oligotrophic environment. Phosphorus is the limiting nutrient and is present in almost undetectable quantities during the summer. Ammonia-nitrogen concentrations are also low and extremely variable throughout the year. Nitrate-nitrogen levels are high, but stable, and comparable to those of other oligotrophic environments. Silicon levels are generally sufficient to support a diatom-dominated phytoplankton population, but become depleted in the summer. Algal growth nutrients are most comparable to Lake Huron, while levels of trace metals and other ions match those of Lake Michigan.

The spring and early summer phytoplankton populations of the bay are composed mainly of diatoms, with a switch toward green and blue-green algae occurring in the late summer and fall. Species composition and cell numbers observed are similar to those reported for Lake Michigan. Primary productivity and standing crop (chlorophyll *a*) were higher in the west arm than in the remainder of the bay due to phosphorus input from the Boardman River.

Zooplankton in Grand Traverse Bay are primarily calanoid copepods, cyclopoid copepods and cladocerans. There was little consistent variation observed in either species composition or total numbers which were similar to those found in Lake Michigan. Horizontal variation in spatial composition was noted in the west arm and Elk River Plume as compared with the remainder of the bay.

The benthic organisms in the bay had a density less than that reported for Lake Michigan, although species composition was similar.

Organisms observed (oligochaetes, mollusks, amphipods, etc.) were generally characteristic of an oligotrophic environment. No effects on the benthic fauna were observed to result from the discharge of the Boardman River.

Public health problems have been associated with the drinking water supply and public swimming beaches in the Traverse City area as indicated by elevated levels of total and fecal coliform bacteria. Relocation of the drinking water intake pipe to the east arm and the cessation of direct discharge of cherry wastes to the bay have mitigated this problem. Storm sewers now remain the chief source of coliform to Grand Traverse Bay.

Studies revealed that the distribution and character of surface sediment were principally a result of the physical limnology of the bay. Some elevated concentrations of chemical constituents were noted in the region of the Boardman River plume. In general though, organic and trace metal content of all sediments did not reveal any significant contamination. It was concluded that these sediments do not constitute any environmental or ecological hazard to the bay.

It may be summarized that the pristine conditions existing in Grand Traverse Bay make it a valuable resource in its own right. Although evidence of slight pollution was observed, particularly near the Boardman River, the sources of this contamination are currently being placed under control. The implementation of secondary wastewater treatment, particularly with advanced phosphorus removal, is an important step toward the preservation of the excellent conditions of the bay waters. Water quality conditions in Grand Traverse Bay, particularly in the lower west arm, should improve further in the period following this study because of these efforts.

II. INTRODUCTION

The Michigan Sea Grant Program selected Grand Traverse Bay as the locus of pilot efforts to develop a complete model of a small part of the Great Lakes ecosystem. Grand Traverse Bay provided a microcosm of the problems and processes encountered in Lake Michigan, and ultimately in all the Great Lakes. Its general characteristics, such as morphometry, shoreline, water quality, and land use, are similar to those of the other upper Great Lakes. The bay provides an especially close physical analog of Lake Michigan: bordered by a populated urban area (Traverse City) at its southern extremity, it is an aquatic cul-de-sac fed only by streams and precipitation, not by up-stream parts of the Great Lakes as is, for example, Lake Huron. With the decline in value of traditional products and industries such as timber and salt, the Grand Traverse Bay area has become increasingly dependent on tourism and recreational activity. As a result, high water quality in the bay is one of the most valuable assets of the region, and this trend is expected to continue during the next several decades. Although the bay is not yet dangerously polluted, local planners anticipate considerable industrial and urban development, which will inevitably result in regional conflicts regarding water and land resource utilization. Scientific facts are required to help resolve these issues and to guide the orderly and purposeful growth of the area in the years ahead. The intent of this report is to summarize all available limnological data for Grand Traverse Bay in a form readily available for such use.

III. ECONOMIC AND CULTURAL INFORMATION

The Chippewa Indians were among the earliest inhabitants of the Grand Traverse Bay region. The first European inhabitants were trappers and missionaries. During this period, man had little environmental impact on the water quality of the bay. This changed with further settlement and the onset of the logging era in the late 1840's. By 1883 area mills were producing 190 million board feet of lumber annually (Colby 1971). Much of the hardwood lumber cut was shipped to Chicago to be used as flooring. The Boardman River was used to float the logs to the mills, and this practice, along with the debris and organic input from clear-cutting, had a major impact on the river and plume. Exploitation of the white pine and hardwood forests continued until approximately 1915.

With the demise of the logging industry, agriculture, particularly fruit production, became important. Fruit production now accounts for approximately 60% of the agricultural income of the region. Although apples were initially the most important fruit crop in the area, cherries are now the primary product. Several cherry processing plants operate in the area. The success of the cherry growing industry is in part a result of the modifying effect of the bay on the climate.

Since Traverse City is not a major manufacturing center, waterborne commerce in the region is essentially limited to bulk shipment of petroleum products and coal. Coal shipments are used for power generation at Traverse City.

Early settlers used the bay as a fishery resource. Their catch was sold locally since transportation denied access to large city markets. Commercial fishing was important in Grand Traverse Bay in the period from 1880 through the 1940's. Chubs, lake trout, suckers, lake herring and lake whitefish were the most important species in the commercial catch. Invasion by the sea lamprey, the rise in alewife populations and overfishing are generally blamed for the decline in smelt and chub fishing in the bay in recent years. In 1968 commercial fishing was banned from Grand Traverse Bay.

The sport fishery has grown rapidly in recent years, largely due to the stocking of lake trout and coho and chinook salmon. In 1971 there were 22 charter boat operations on the bay and it is obvious that the sport fishery makes a significant contribution to the region's economy. Additional aquatic recreational forms such as swimming and sailing are also very popular in the bay. These, coupled with camping and tourism, help to underscore the importance of good water quality in Grand Traverse Bay to the economic condition of the region.

IV. MORPHOMETRY

The physical limnology and morphometry of Grand Traverse Bay has been heavily documented by Lauff (1957); the morphometry of the bay will be summarized here. Grand Traverse Bay is an inland extension of northern Lake Michigan. It is located in the northwestern tip of the lower peninsula of Michigan and has an essentially north-south orientation (see Figure IV-1). The southern half of the bay is divided into the east and west arms which are separated by Old Mission Peninsula. The bay is approximately 48 km long and 19 km wide. The two arms are approximately the same length, 29 km, and both vary in width from 5 to 7 km. A sill extends across the mouth of Grand Traverse Bay separating the bay from Lake Michigan proper.

The general conformation of Grand Traverse Bay and the character of its surrounding lands are a result of the actions of Pleistocene glaciation on the Paleozoic bedrock formation. The shore line of the bay is fairly regular due to beach modification in the period of ancient Lake Nipissing. The bay itself is composed of two deep basins occupying the east and west arms. The two basins extend into the open bay and merge. The deep basins are trenchlike and reflect their glacial origin.

The steep bottom slopes of the basins in Grand Traverse Bay result in a fairly rapid depletion of shallow water. Few shallow areas exist in the bay except in harbors, in nearshore regions, and near Marion Island. Figure IV-2 is a bathymetric map of Grand Traverse Bay. A hypsographic curve, shown in Figure IV-3, depicts the distribution of depths in Grand Traverse Bay. The total surface area of the bay is 681.6 km^2 and the respective areas of the east and west arms are 160.6 km^2 and 167.8 km^2 (Lauff 1957). Combined these two arms account for approximately one half of the total bay surface area. The maximum depths in the two deep basins are 122.5 m in the west arm and 186.5 m in the east arm, while the mean depth in the bay is 55 meters. The volume of Grand Traverse Bay is 373.9 X 10^8 m^3.

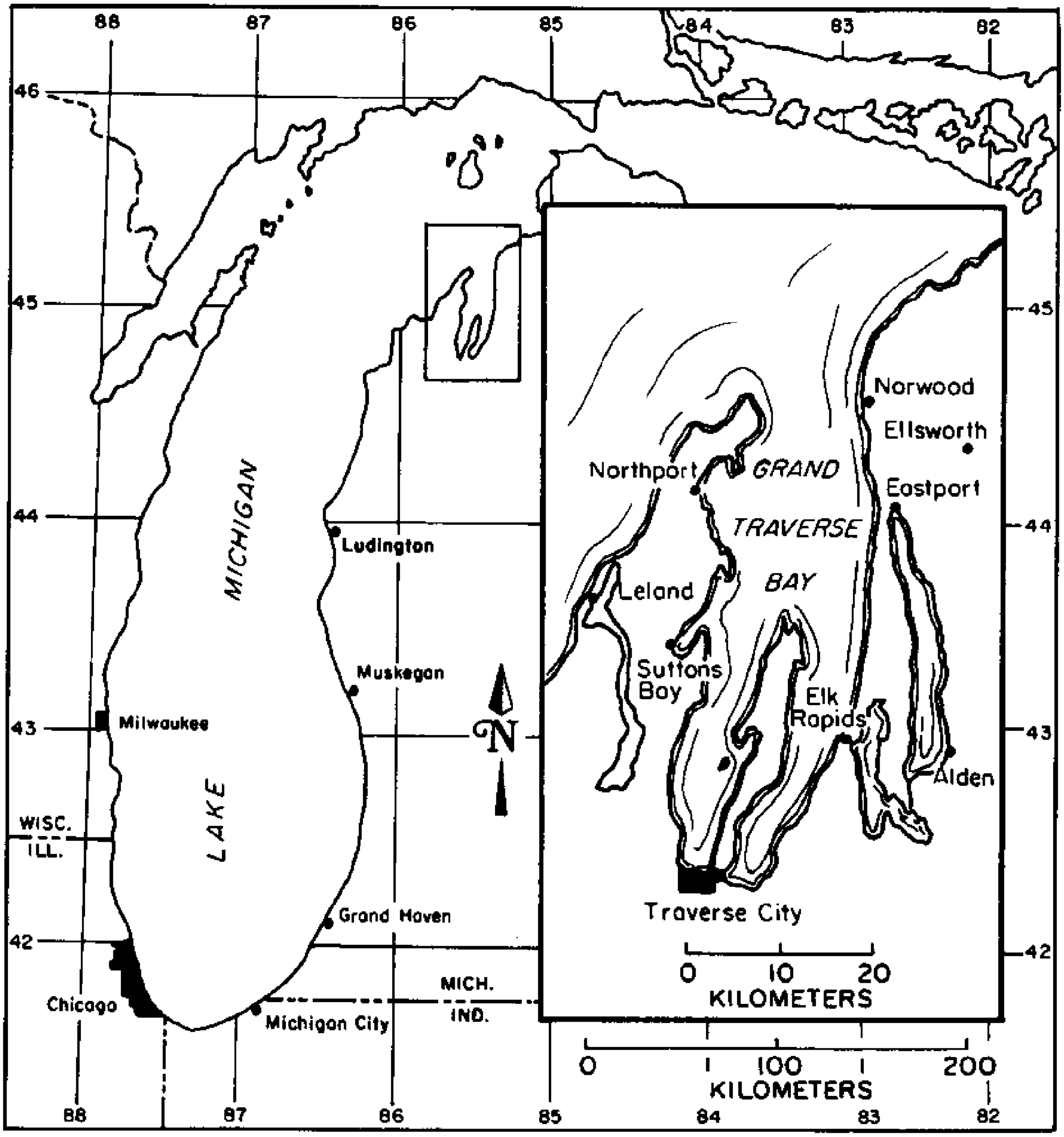


FIGURE IV-1. Location map of Grand Traverse Bay, Lake Michigan.

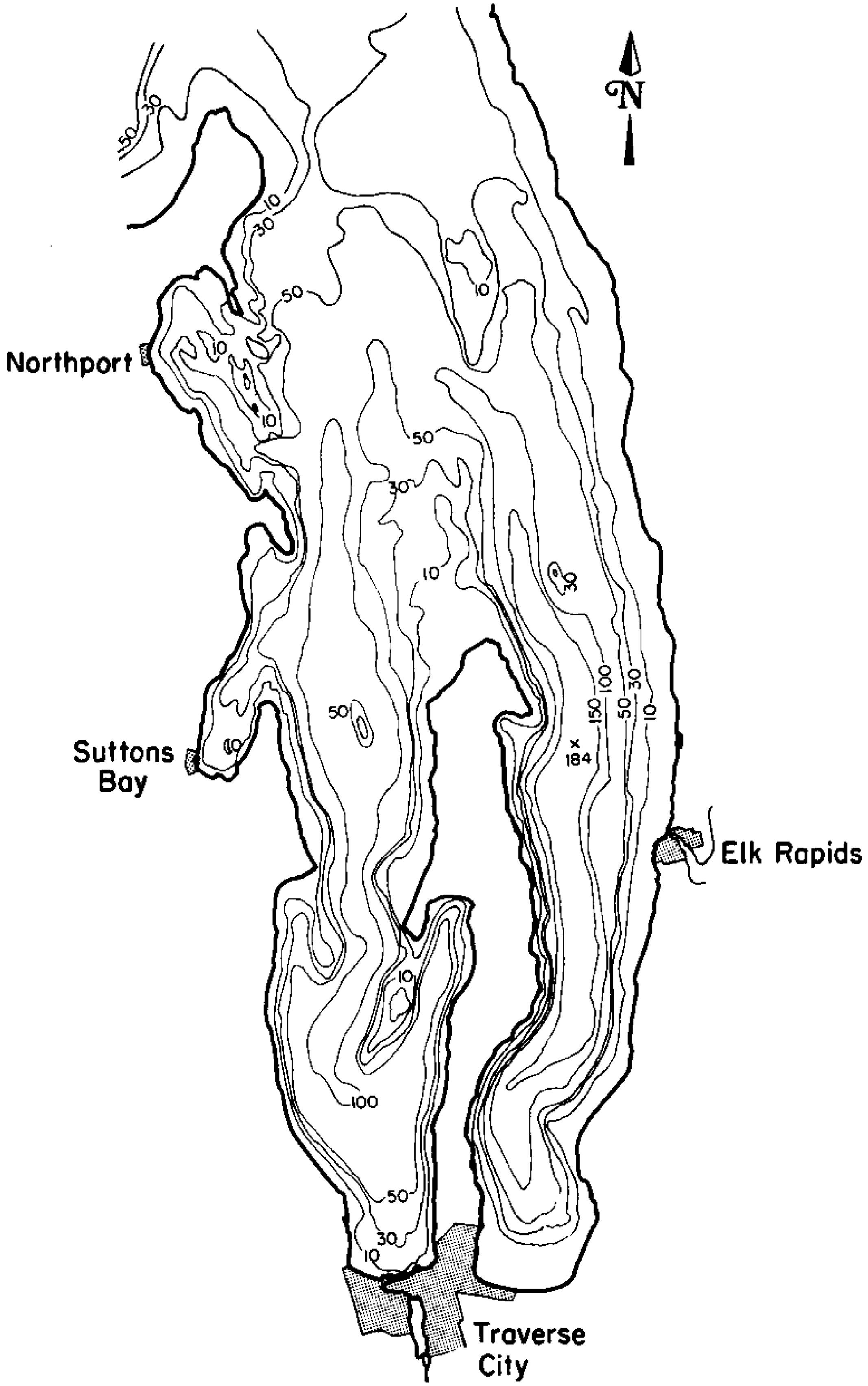


FIGURE IV-2. Bathymetric map of Grand Traverse Bay (depths in meters).

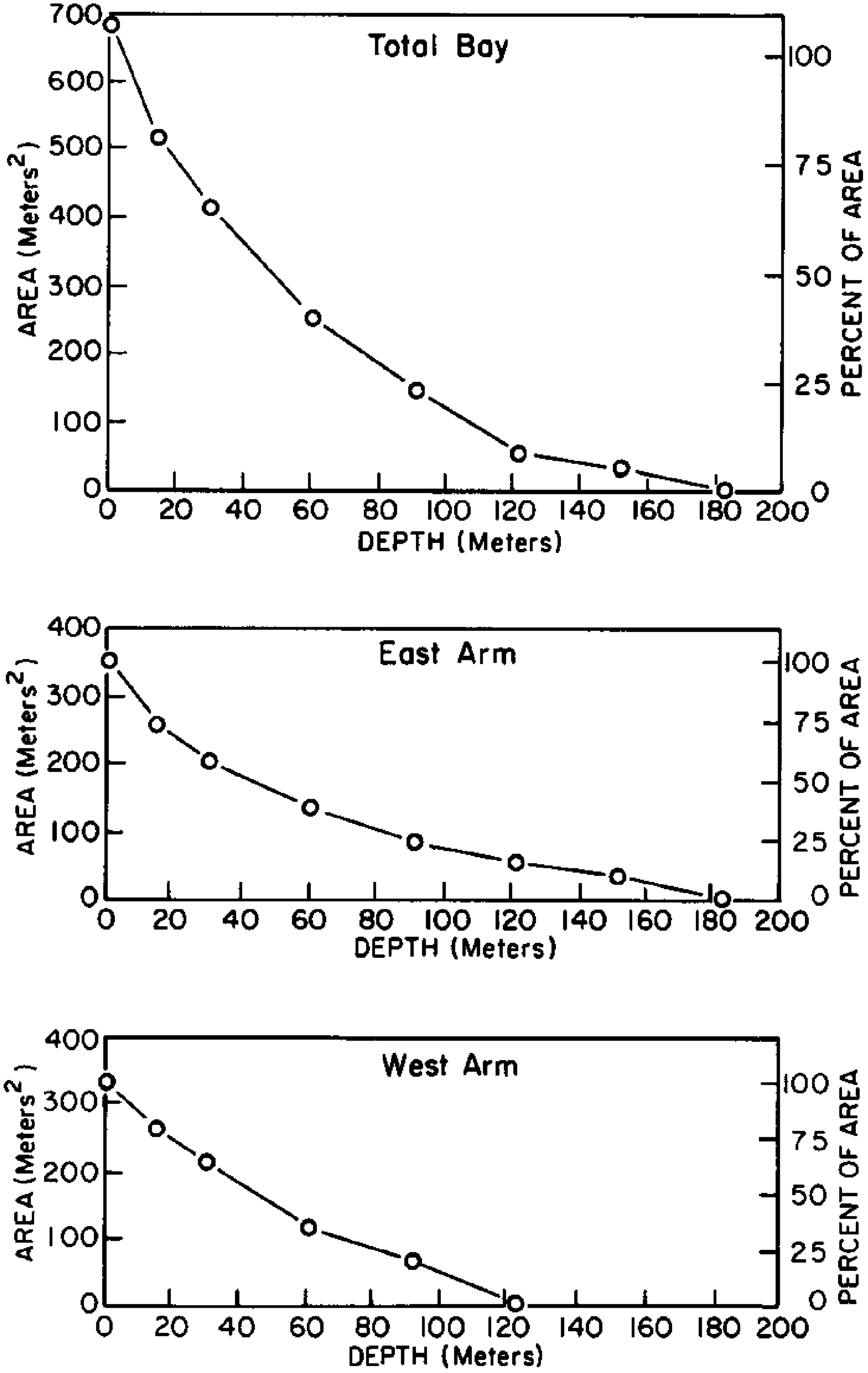


FIGURE IV-3. Hypsographic curves for Grand Traverse Bay. Data from Lauff (1957).

V. GEOLOGY

The geologic development of the Grand Traverse Bay region may be summarized by four major events spanning millions of years. The first event is the laying of bedrock by sedimentation during oceanic intrusion in the Paleozoic period. The next event was glacial erosion and deposition during the Pleistocene period. After the recession of the glacier, the region was further modified through the hydrologic action of ancient lakes. Finally, flora and fauna were reestablished in the area and present drainage patterns began development (Dorr and Eschman 1970, Hough 1958, Martin 1957).

The bedrock in the Grand Traverse Bay region reflects the effects of sedimentation from two of the six major Paleozoic oceanic-encroachments on North America. The basic foundation of the Grand Traverse Bay region was formed during two of these periods, the Devonian and Mississippian. A map of the bedrock formations is shown in Figure V-1. The bedrock underlying the outermost portions of the bay and the extreme northeastern portions of the drainage basin is largely Middle Devonian limestone of the Traverse group. These rocks are the oldest component of the bedrock foundation of the region. Very few outcrops of these rocks exist except along the northeastern shore of the bay, principally in Charlevoix County. These limestone rocks fossilized representatives of the Paleozoic flora and fauna within their layers. These strata are therefore of interest to geologists and rock enthusiasts who yearly comb the shores of Grand Traverse Bay searching for "Petosky stones" and other fossilized organisms.

Black Antrim shales from the late Devonian and early Mississippian periods were the next segment of the bedrock foundation to be formed, partially overlying the limestone from the southeast. These shales underlie a large segment of the open bay and lands to the northeast and southwest. Outcrop exposures of this shale are found between Torch Lake and Grand Traverse Bay.

Overlying the Antrim shale to the southeast are the Ellsworth shales of the early Mississippian period. This bedrock underlies both the east and west arms of Grand Traverse Bay, and much of the southeast and eastern portions of the drainage basin. The most recent of the Mississippian bedrock formations found in the area are the Coldwater shales which overlap the Antrim shales, again from the southeast. These shales underlie an area beginning just southeast of the bay and extend over most of the Boardman River basin. Other, much younger, bedrock shale was deposited in the region but was subsequently eroded to its present southern limits. Very limited amounts of Marshall and Michigan shales are found in the southernmost portions of the Grand Traverse Bay basin.

Following the Paleozoic formation of the bedrock, the surface features were drastically altered by the effects of the continental glacier. Beginning about one million years ago an ice sheet 3 to 5 kilometers thick advanced and retreated across the Great Lakes Region four times. The final advance of this continental glacier into northern Michigan occurred just 11,500 years ago. The Valders advance was relatively short-lived and ended the

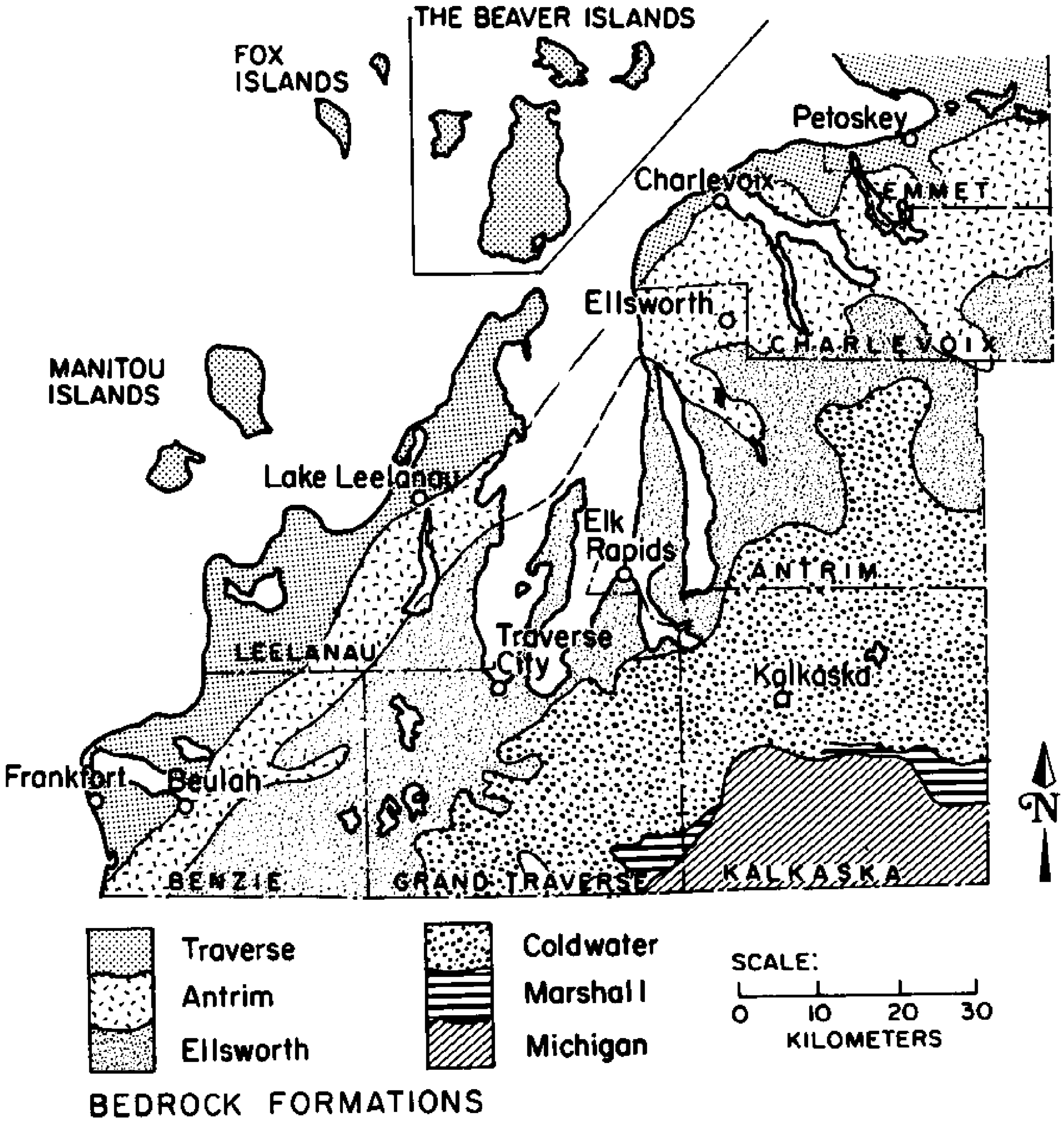


FIGURE V-1. Geological map of the bedrock formations of the Grand Traverse Bay region. After Martin (1957).

last of the four major glacial periods, the Wisconsin. The effects of the Valders advance and, to a lesser extent, those of the earlier substages of the Wisconsin glacier determined the surface geology of the Grand Traverse Bay region. The movements of the glacier, advancing, stagnating, and receding, transported and deposited rocks and soil throughout the region. As a consequence of this action the surface geology of the region is characterized by moraines, glacial outwash, till plains, and drumlins (see Figure V-2). These features, particularly moraines, defined river basins and valleys.

The weight of the glacier depressed the northern part of the continent. Following the retreat of the Valders ice sheet, the Grand Traverse Bay region was part of ancient Lake Algonquin which included the entire Lake Michigan and Lake Huron basins. The lake stage at that time was 184 m above present sea level. The lake then drained southward into the Mississippi River via the Chicago outlet and eastward through the Detroit-St. Clair river system.

As the glacial ice retreated further, the northern outlets to Lake Algonquin were exposed and the lake level dropped drastically to the Chippewa-Stanley stage of 70 m above present sea level. Crustal rebound of glacially depressed regions, however, slowly raised the northern outlets and subsequently elevated the lake stage to the Nipissing stage (184 m above present sea level), which persisted for 3000 years. The powerful rising waters of the lake cut and formed much of the present shoreline of Grand Traverse Bay. Wave and current action carried sediments, eroded and undercut cliffs, and deposited this material creating shoals, bars, and bays. During this period the crustal uplift continued, separating Elk and Torch lakes from the main lake. As the level of Lake Nipissing rose it finally eroded away the St. Clair River channel and the lake dropped to its present level (176.5 m above present sea level).

Minor geologic changes followed the drop in Lake Nipissing. Plant and animal life spread north from the unglaciated southern areas, and rivers slowly developed their modern courses. The Boardman River, formerly a tributary of the Manistee River which empties directly into Lake Michigan, was diverted to its present hydrologic course by streams flowing from the northern slope of the Manistee moraine.

Surface features which dominate the present day landscape include: the Port Huron moraine (which forms the southern boundary of the watershed), the Manistee moraine, and the rolling till plains and drumlins of Antrim and Leelanau counties and Old Mission Peninsula. Soils of the region are generally well-drained, glacially derived sands, loamy sands, or sandy loams. Some poorly drained organic soils are present in low portions of the Boardman River and upper Chain-of-Lakes areas. The major portion of both Leelanau and Old Mission Peninsula are rolling and hilly with elevations several hundred feet above the bay. The land along the east shore of the bay is mixed in character revealing some rolling highlands, some flat areas, and a few steep-sided drumlin ridges. South of the bay the lands are principally of low relief and include outwash and glacier deposits. This geographical character continues south to the Port Huron moraine, the southern boundary of the Grand Traverse Bay basin.

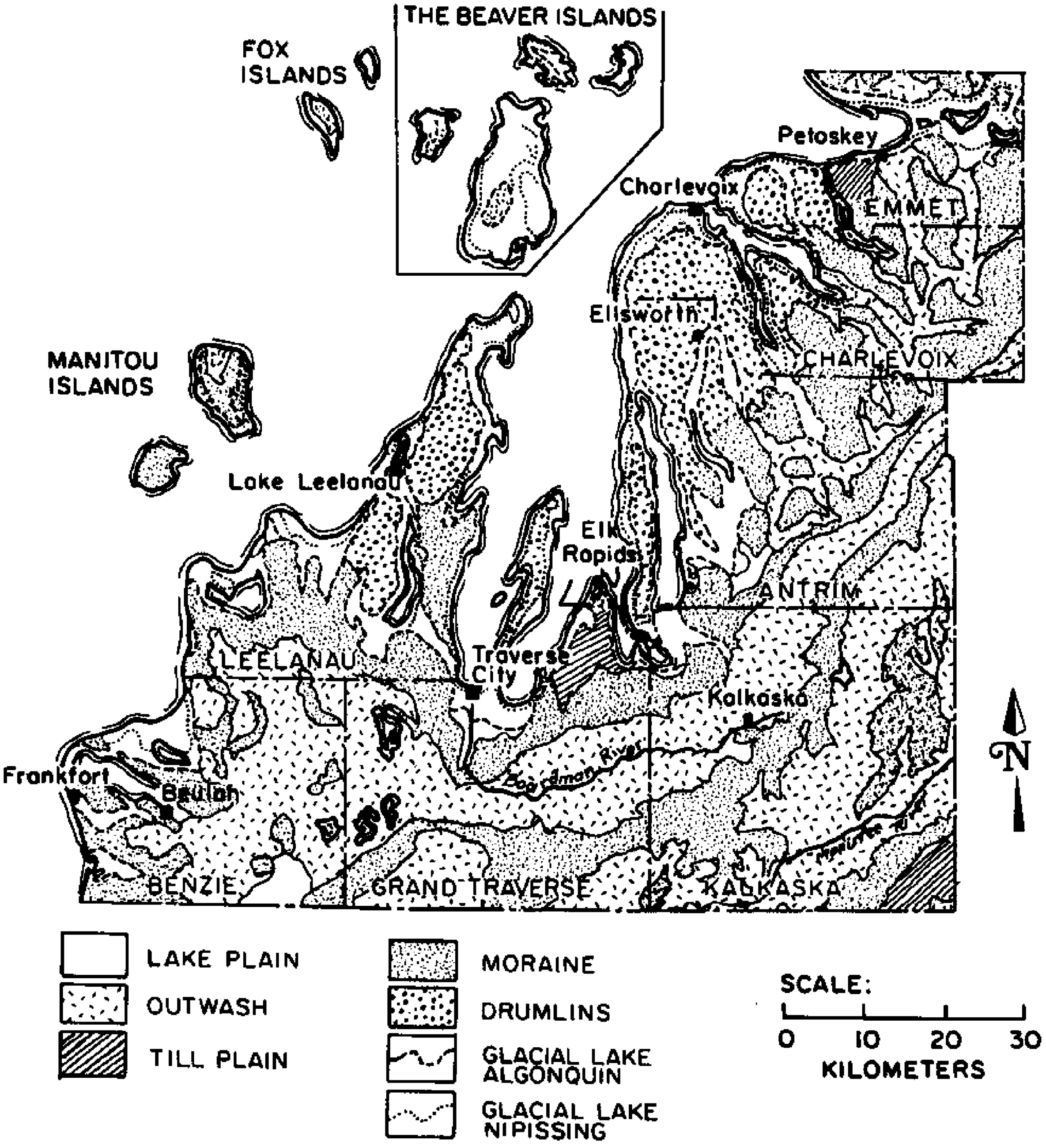


FIGURE V-2. Surface geology of the Grand Traverse region (After Martin 1957).

VI. CIRCULATION

All of the physical, chemical, and biological components of an aquatic community are affected by water movements. Such movements in lakes are induced by forces which act to displace the water from an equilibrium state. Such displacements can be caused by wind, gravity, Coriolis force (earth rotation), energy dissipation from rivers and streams, and thermal or chemical density gradients. Generally, water movements in lakes are either periodic or nonperiodic. Currents caused by winds or density gradients are generally nonperiodic while surface waves, surface seiches and internal seiches are examples of periodic motions.

The flow of water in lakes is generally turbulent. As a consequence, the magnitude of associated eddy diffusivity can be an important factor contributing to transfer and mixing of dissolved substances and plankton. This is especially true in the vicinity of river plumes, bays and other locations where these materials can accumulate to high concentration. During the spring the effectiveness of such transfer processes can be reduced by the formation of thermal bars which act to trap nutrients or plankton in nearshore waters (Nalewajko 1966; Richardson 1976). Other phenomena such as horizontal gyres or upwelling and sinking zones of water can also promote the accumulation of materials which may facilitate the development of regions characterized by high nutrient concentrations, high primary productivity, and low transparency.

Water movements in lakes can also play a significant role in nutrient cycling. Stagnant regions of lakes may promote sedimentation of algae and detrital matter and result in deep deposits of organic bottom muds. During periods of high winds, inorganic nutrients derived from such materials may be mixed from bottom waters into surface waters where they may become available to the lake biota.

Water movements and turbulence in lakes are extremely important to gas transfer processes. The replenishment of oxygen-deficient waters in lakes is directly linked to the rate of renewal of elements of surface water with subsurface depleted waters. The maintenance of stable pH conditions and supply of dissolved carbon dioxide is also dependent on the rate of surface renewal at the lake-air interface. The rate of exchange depends on concentration differences between phases and the degree of turbulence at the lake-air interface. Similarly the transfer of other ecologically important gases such as nitrogen, methane, and hydrogen sulfide as well as heat is a function of mixing and turbulence in lakes.

Some aspects of the physical limnology of Grand Traverse Bay have been studied by Lauff (1957). Circulation patterns in the bay were estimated using a number of techniques including analysis of sediment particle size distribution. The presence of large sediment particles generally indicates strong current and turbulence while smaller silt and clay particles suggest more quiescent conditions. Horizontal and vertical contours of transparency, temperature, magnesium and silica were used to trace the movement of water masses. Lauff (1957) proposed a composite surface current pattern for Grand Traverse Bay using the dynamic height method (Ayers 1956). Results from the above techniques were supplemented with limited drift bottle recoveries released by Harrington (1894). This composite current pattern is reproduced in Figure VI-1.

The Sea Grant Program has conducted further studies on the physical limnology of Grand Traverse Bay to quantify circulation patterns. The studies involved two approaches of current measurement: Lagrangian measurements which employ buoy and drogue techniques, and Eulerian measurements, which utilize subsurface current meters moored at fixed stations. The results of drogue measurements have been reported by Monahan et al. (1973). Figure VI-2 shows the locations of 14 different drogue studies conducted over a two-year period. The drogue studies which were used to follow currents at various depths were typically 6 hours in duration. During the two-year period, drogues were tracked under a variety of wind directions and speeds. Figures VI-3 and VI-4 show the results of drogue studies in the lower west arm of the bay under north and northwest wind conditions. During the period of observation the surface currents appeared to follow the wind or were skewed a few degrees to the right of the wind. For wind speeds of 10 knots, typical surface current speeds ranged from 1.4 to 12.8 cm/sec. The currents shown in Figures VI-3 and VI-4 have a tendency to drive the Boardman River plume shoreward and to the east of the outlet. This pattern is similar to that suggested by Lauff (1957). Because the most common winds in the area have westerly components,it is expected that,over the long term, water quality conditions east of the river mouth would be lower than corresponding locations west of the river outlet. This hypothesis has been confirmed through an analysis of the chemical and biological monitoring data as described in other sections of this report.

Current meter observations have been used to supplement information about drift patterns in the bay. Current meters provide data which define long-term changes in the speed and direction of water movements at a fixed point. In addition, insight into the oscillatory and turbulent nature of the fluid is enhanced by such techniques. The results of observations have been reported for two stations (see Figure VI-2) in Grand Traverse Bay by Johnson and Monahan (1971). The major emphasis of this study was characterization of the exchange flow between the bay and Lake Michigan, and provision of input-forcing functions for numerical circulation models.

A numerical model for wind- and seiche-forced circulation in Grand Traverse Bay has been developed by Smith and Green (1975). This model is based on the simple concepts of mass transport and continuity with terms which account for Coriolis force, gravity, and wind stress. The solutions of these equations are vertically averaged transport patterns. The results of the circulation model have been compared favorably with several prominent observed features of the flow. For example, Monahan et al. (1973) set a network of drogues extending WNW from the tip of Old Mission Peninsula to the west shore and another set perpendicular to the first line. Under northerly wind conditions subsurface drogues moved in a clockwise pattern on the same spatial scale as that predicted by the model, as illustrated in Figure VI-5. It has been concluded from these studies that the model gives a reliable simulation of the barotropic circulation of Grand Traverse Bay. The model for fluid transport has been combined with other models for chemical and biological parameters for the purpose of providing a useful predictive tool for water quality planning and management. These models are described in other Sea Grant reports (Canale and Green 1972, and Canale et al. 1973).

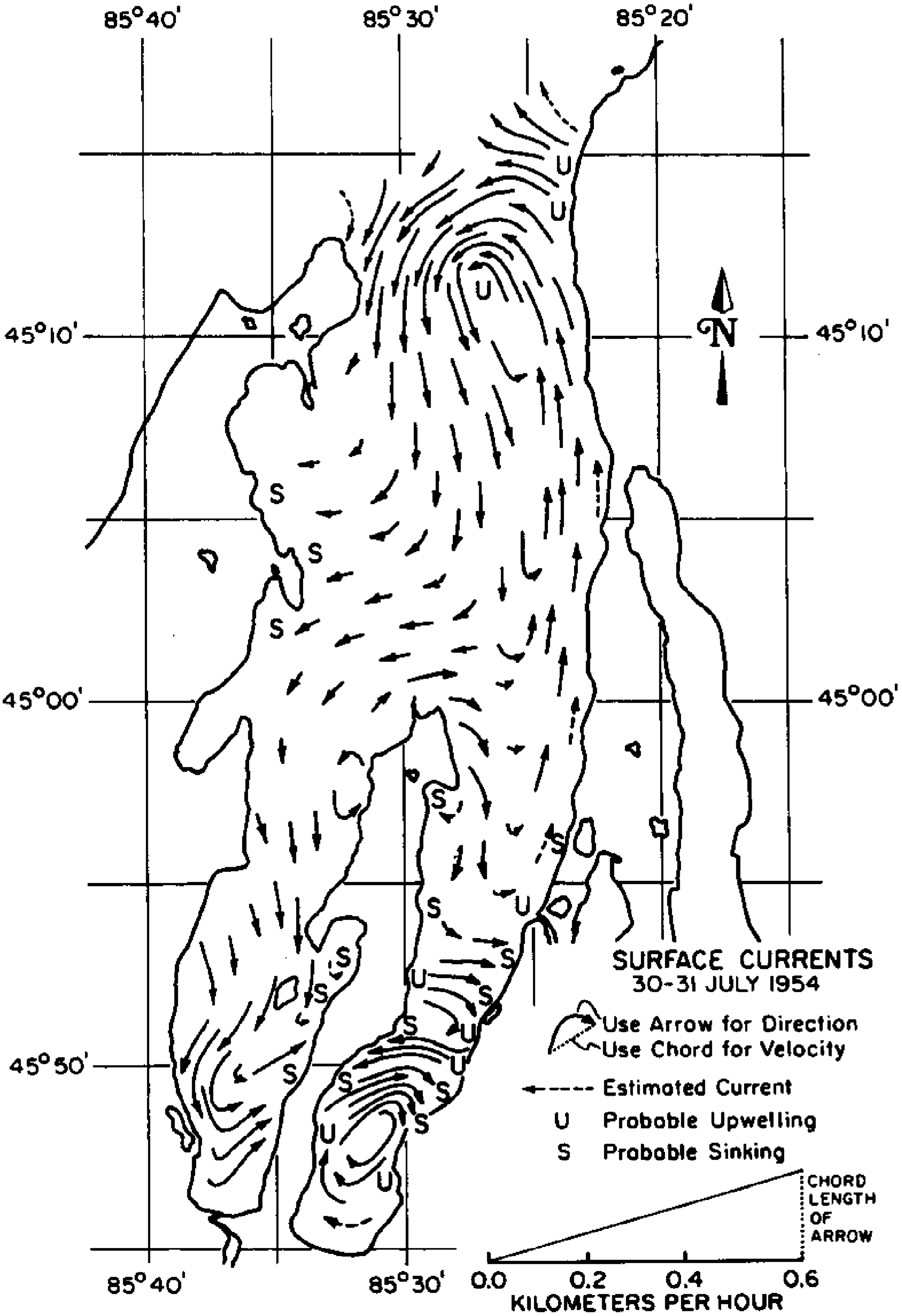


FIGURE VI-1. Surface currents in Grand Traverse Bay, 30-31 July 1954. Modified from Lauff (1957).

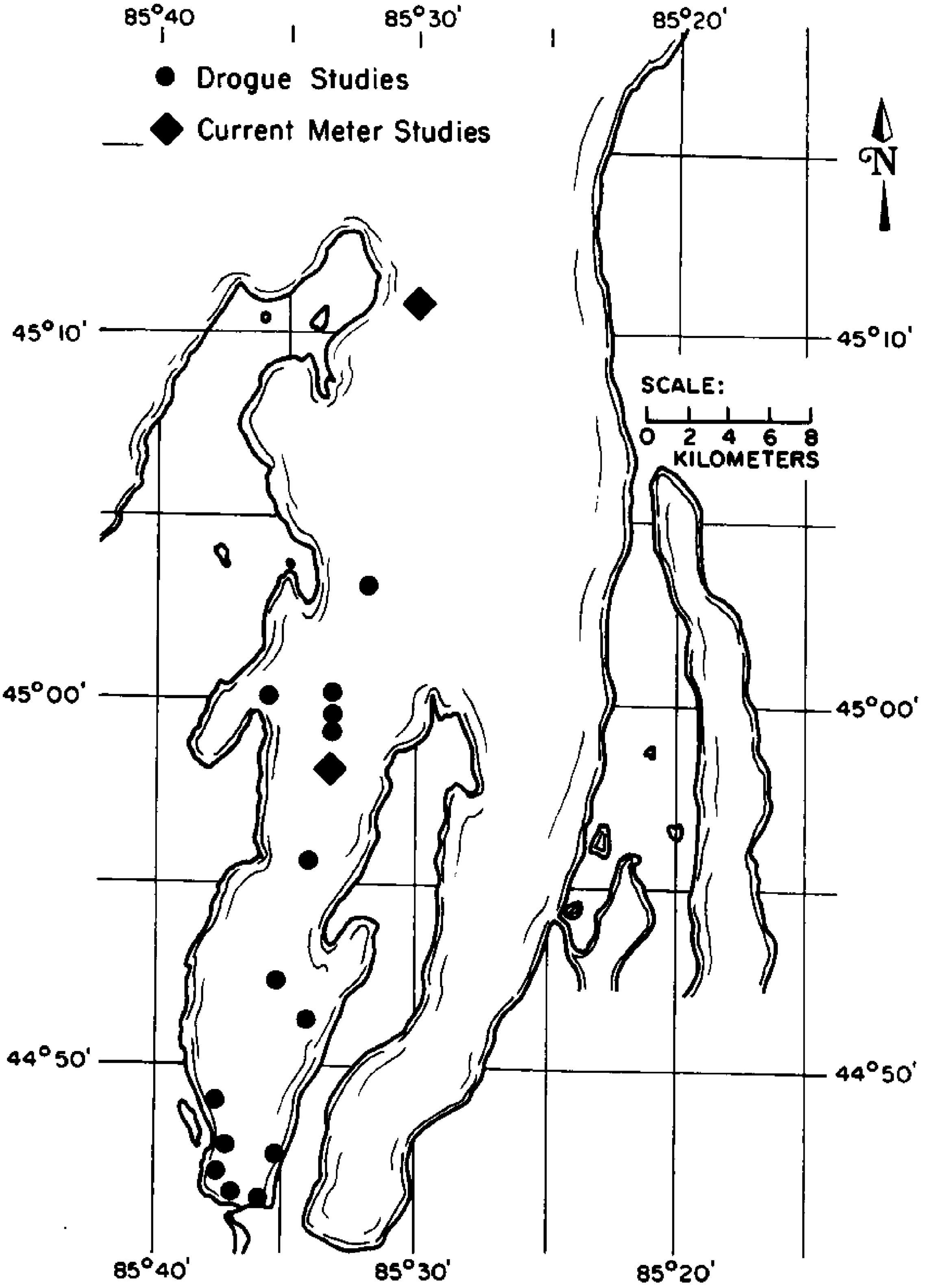


FIGURE VI-2. Drogue and current meter study locations. (After Johnson and Monahan (1971).

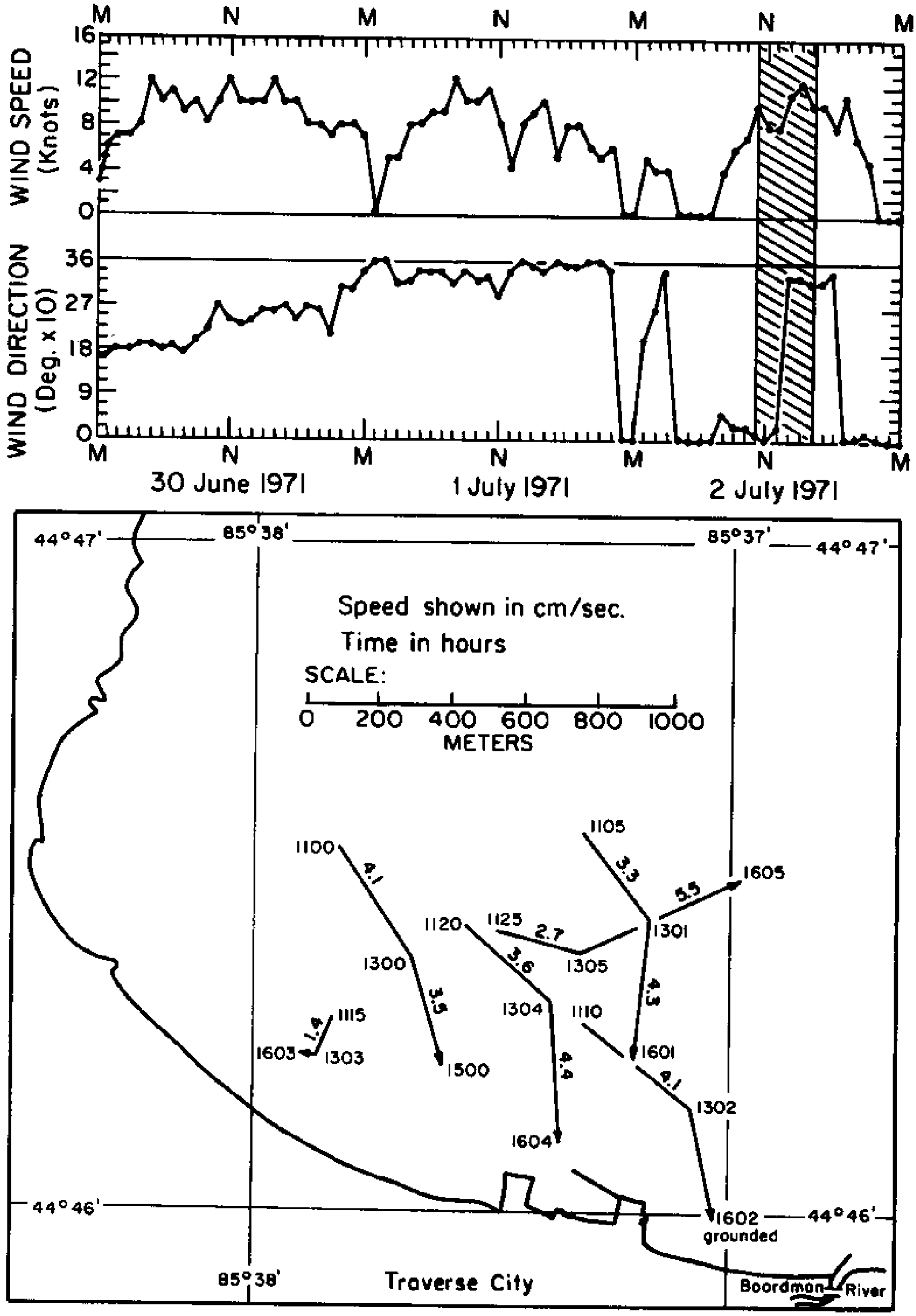


FIGURE VI-3. Drogue studies in Grand Traverse Bay - 11 to 13 May 1971 (after Monahan et al. 1973).

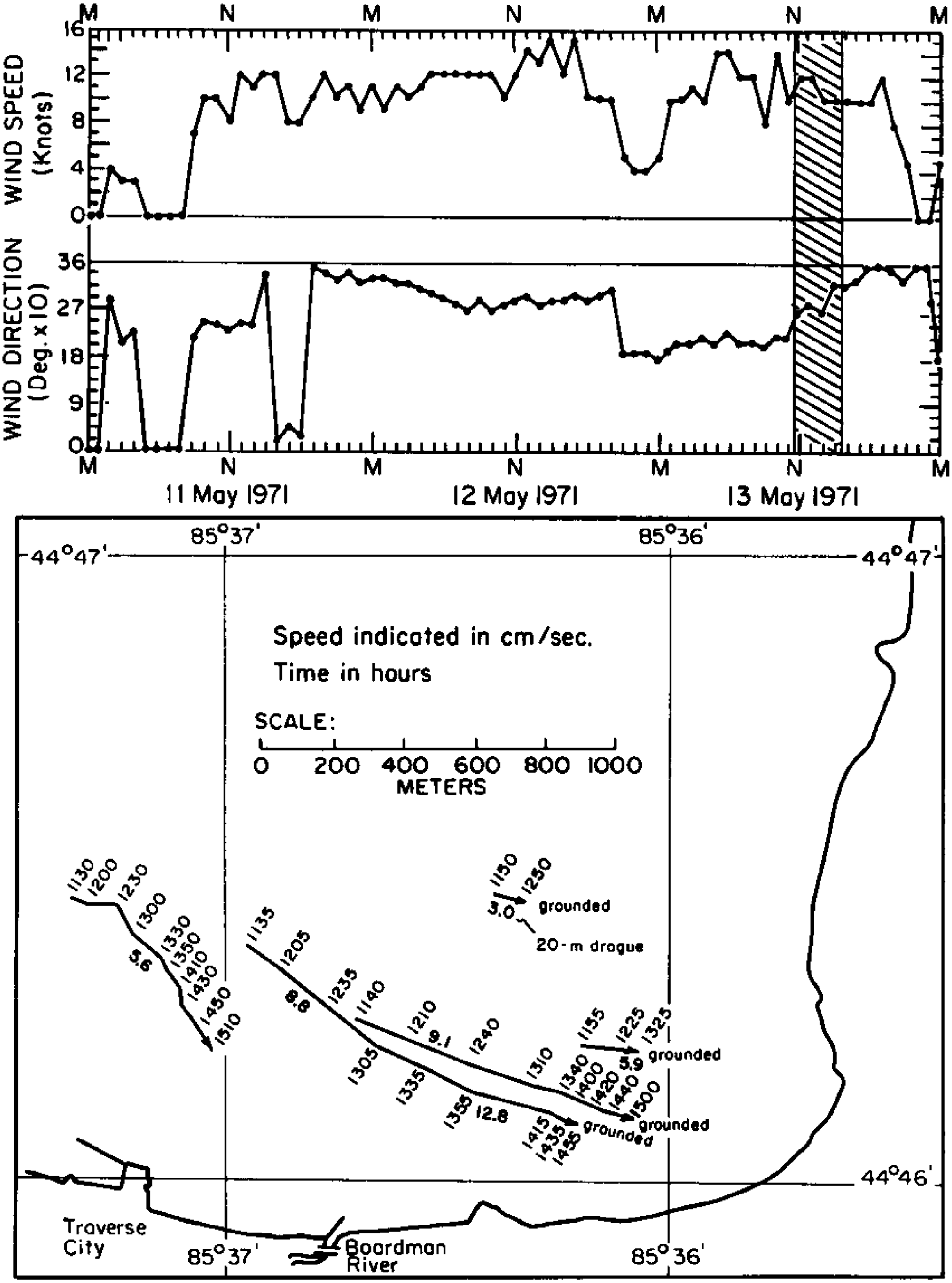


FIGURE VI-4. Drogue studies in Grand Traverse Bay - 30 June to 2 July 1971 (after Monahan et al. 1973).

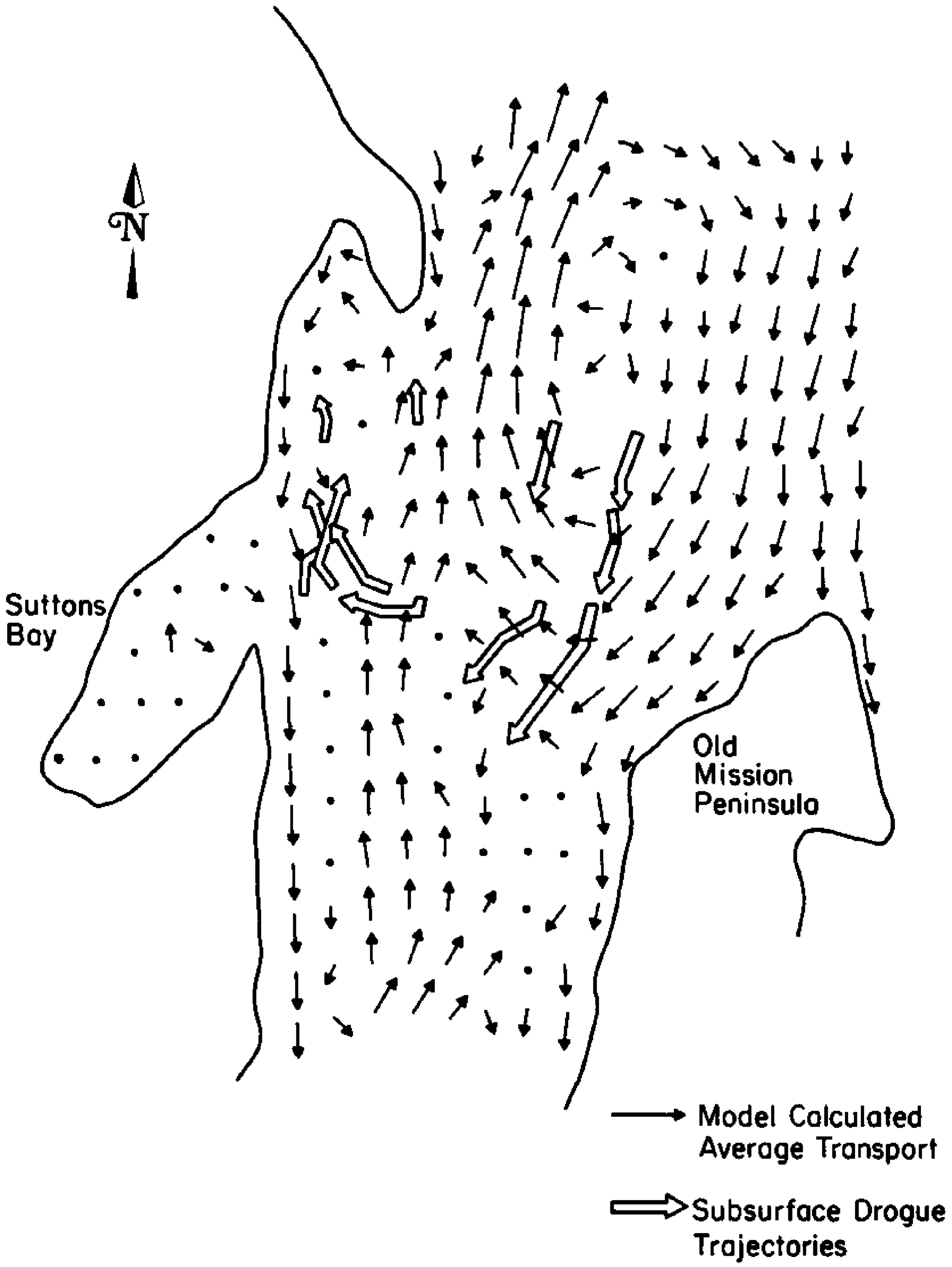


FIGURE VI-5. Calculated mass transport in Grand Traverse Bay (after Smith and Green 1975).

VII. METHODS AND MATERIALS

General

A multidisciplinary study was devised to assess the water quality of Grand Traverse Bay. This program consisted of a comprehensive limnological sampling program which monitored physical, chemical and biological parameters in the bay and its tributaries. Temperature, dissolved oxygen, transparency, major ions (including phytoplankton nutrients), trace metals, coliform bacteria, chlorophyll *a*, phytoplankton, zooplankton and benthos were sampled during the investigation. River and bay sampling began in July of 1970 and continued through 1975. An abbreviated presentation of the bay sampling schedule is given in Table VII-1. The exact date of each cruise is presented in Auer et al. 1976. During the first two years of the study 16 tributaries were monitored for flow, major ions and phytoplankton growth nutrients, trace metals, and coliform bacteria. Results from these efforts were used to quantify sources of pollution to the bay. During this same period fourteen bay stations were monitored at two to four week intervals during the ice-free season. For the period 1875-1975 Grand Traverse Bay was frozen for an average of 42 days each winter. Freeze-up occurred in late January to mid-February with ice-out completed by late March to mid-April. During the period of this study ice cover was observed as follows: 1971, 2/10-4/15 (64 days); 1972, 2/9-4/18 (69 days); 1973, 2/26-3/3/ (5 days); 1974 and 1975, no ice formed beyond skim ice. Three additional stations were located in Lake Michigan proper and sampled on three occasions. These sampling locations (stations #1 through #14 and 31, 144, 145) are shown in Figure VII-1 and geographically identified in Auer et al. 1976.

The bottom sediments of Grand Traverse Bay were sampled on two cruises in 1970. A sampling grid of 67 stations was established in the bay; 29 stations were located in the west arm, 22 in the east arm, and 16 in the outer bay. Surface sediments were sampled by duplicate PONAR grabs at each station. The sediments were analyzed for texture, grain size, Eh, pH, and trace metal and ionic content (Baker-Blocker et al. 1975).

The objectives of the first phase of the Grand Traverse Bay investigation were to 1) assess the relative water quality in the bay, 2) determine its suitability for present and future uses, 3) identify areas having existing or potential water quality problems, and 4) isolate and quantify the contaminant sources influencing the bay.

Information gathered during the first phase of the Grand Traverse Bay investigation was used to design an altered sampling program starting in May of 1972. Because of more dynamic conditions, relatively higher pollution levels and recreational intensity, the focus of the monitoring efforts was shifted to the west arm of the bay with only occasional samplings in the east arm and open bay. River monitoring was curtailed at this time. Tributary samples were taken only from the Boardman River since all other sources were considered to be less significant. Twenty-seven stations were added to the bay monitoring program (see Figure VII-1) with some of these monitored on a biweekly schedule. Additional stations were sampled occasionally to

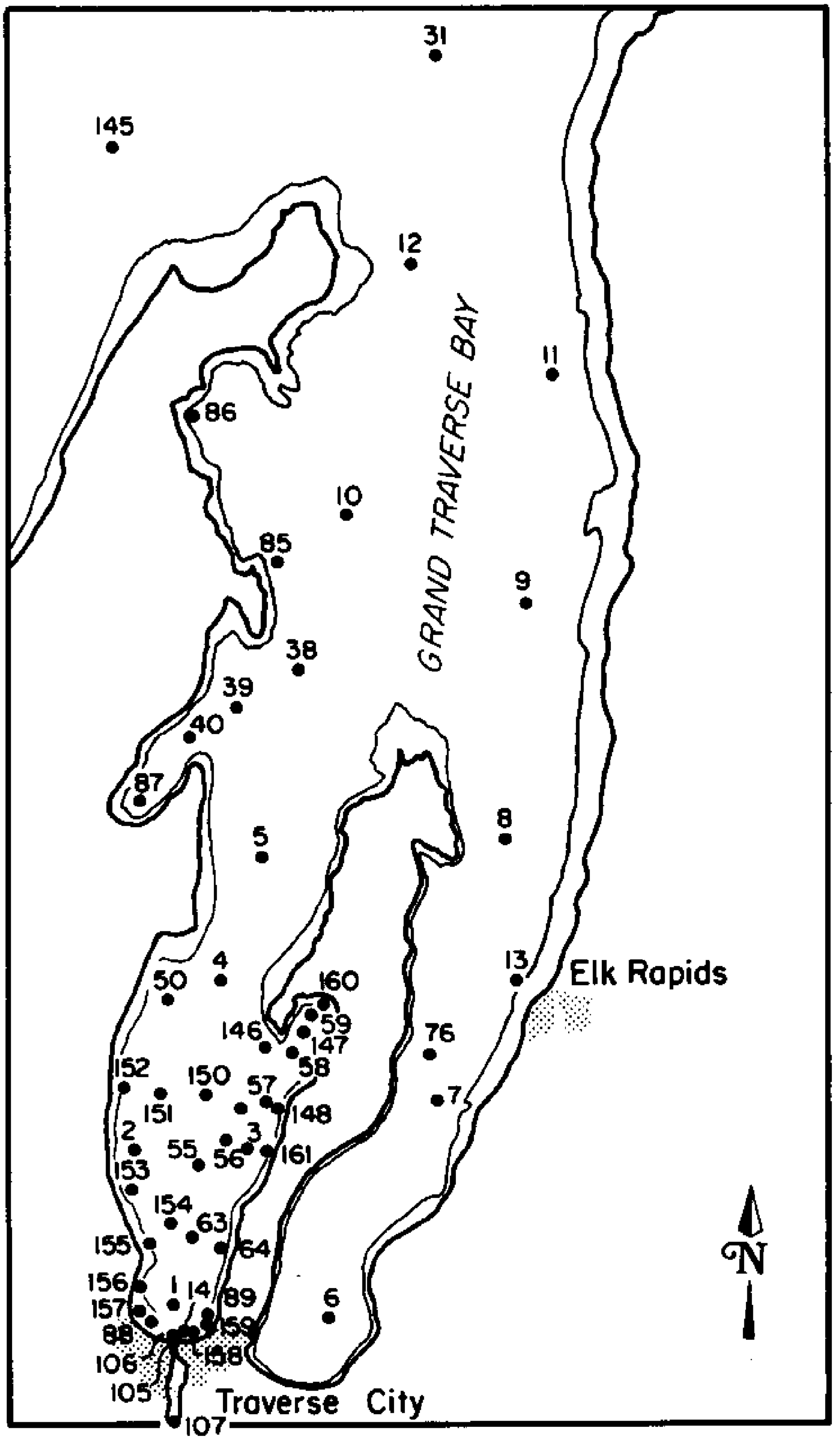


FIGURE VII-1. Sampling station locations in Grand Traverse Bay.

TABLE VII-1. Summary of Grand Traverse Bay sampling schedule.

Thermal Season	Dates	Lake Michigan No. of Cruises	Lake Michigan Total Stations Sampled	Outer Bay No. of Cruises	Outer Bay Total Stations Sampled	East Arm No. of Cruises	East Arm Total Stations Sampled	West Arm No. of Cruises	West Arm Total Stations Sampled	Lower West Arm No. of Cruises	Lower West Arm Total Stations Sampled	Boardman River No. of Cruises	Boardman River Total Stations Sampled
Summer Stratification	27 July 1970- 15 Oct. 1970	-	-	3	8	2	8	4	11	4	7	-	-
Spring Overturn	11 Jan. 1971- 30 Apr. 1971	-	-	1	3	3	11	4	8	3	6	-	-
Summer Stratification	13 June 1971- 30 Oct. 1971	1	3	5	18	4	16	5	26	5	16	-	-
Fall Overturn	15 Nov. 1971- 7 Dec. 1971	1	1	1	4	1	4	2	7	2	5	-	-
Spring Overturn	7 Mar. 1972- 19 May 1972	1	3	1	5	2	6	3	64	3	12	3	4
Summer Stratification	27 June 1972- 6 Oct. 1972	1	1	1	4	1	4	5	125	5	16	5	10
Fall Overturn	27 Oct. 1972- 8 Dec. 1972	1	3	1	4	1	4	2	41	2	8	2	4
Spring Overturn	22 Mar. 1973- 1 June 1973	1	3	1	4	1	4	11	141	11	29	10	22
Summer Stratification	5 June 1973- 31 Oct. 1973	1	2	-	-	-	-	15	96	16	30	15	30
Fall Overturn	7 Nov. 1973- 27 Nov. 1973	-	-	-	-	-	-	3	18	3	6	3	6
Summer Stratification	24 July 1974- 7 Sept. 1974	1	1	2	8	2	7	1	4	1	1	-	-
Spring Overturn	11 May 1975	1	1	1	4	1	4	1	6	1	1	-	-
Summer Stratification	20 July 1975	1	1	1	2	-	-	1	2	-	-	-	-

monitor specific or unique water quality events. The objectives of the second phase were to identify and quantify 1) the water quality problems in the west arm of Grand Traverse Bay, 2) assess these problems relative to the usage required of the bay, and 3) identify the factors responsible for these problems and quantify the extent of influence in the bay.

In 1973, having identified the water quality problems in Grand Traverse Bay and the causative factors, research efforts were directed towards an investigation of the seasonal dynamics of water quality and primary productivity in the lower west arm of the bay. Eight bay stations plus two Boardman River stations were sampled weekly. Occasional samples were taken from the east arm and open bay. Data obtained in this phase permitted a refined analysis of the chemical and biological cycles in the bay and facilitated the development of several water quality models used for water management and quality predictions (Canale 1973, Canale et al. 1973, Canale et al. 1975).

The final phase (1974-1975) of the Sea Grant Grand Traverse Bay water quality investigations involved a reduced sampling program consisting of a limited number of cruises each year. Between nine and fifteen stations were sampled throughout the entire bay. The objectives of this final phase were to continue the monitoring of the bay as begun in 1970, and identify any long-term water quality trends.

Sampling Methods and Schedules

During the five years of the Sea Grant Grand Traverse Bay investigation the numbers of stations and measured parameters varied depending on the specific phase of the study, environmental conditions, and personnel and ship availability. A summary of this yearly distribution is given in Tables VII-2 and VII-3. In general, all waters sampled were analyzed for the following physical and chemical parameters: alkalinity, conductivity, chlorides, temperature, dissolved oxygen, nitrate, nitrite, ammonia, total and dissolved phosphorus, silica, and transparency. Trace metals were measured semi-routinely during the first two years. Stations were sampled routinely for phytoplankton and zooplankton, with periodic samplings of primary productivity and benthic invertebrates. Chlorophyll *a* was measured beginning in May of 1972. Coliform bacteria concentrations were also measured in river waters and in coastal bay waters during the first two years of the study. Details of this work are given in the coliform bacteria section of this report.

All bay water samples were obtained from on board University of Michigan research vessels, while river samples were routinely obtained from on-land sites or bridges. Vessels used in the study included the R/V INLAND SEAS, the R/V MYSIS, and the R/V SEA GRANT I.

Water samples were taken from both river and bay stations using a four-liter polyvinylchloride Van Dorn type sampling bottle. Surface samples were obtained using plastic buckets. At bay stations, samples were taken typically at 2, 10, and 20 meters of depth and at 1 meter off of the bottom. The bottom water samples were taken using a modified, inverted Van Dorn bottle designed to close when a weight suspended one meter below the bottle made contact with the lake bottom.

TABLE VII-2. Sampling frequency for physical/chemical parameters (X) and zooplankton (O) in Grand Traverse Bay

Station

Cruise	1	2	3	4	5	6	7	8	9	10	11	12	13	14	17	22	31	38	39	40	50	55	56	57	58	59	63	64	76	81	85	86	87	88	89	105	106	107	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161
1	X	X	X	X	X	X	X	X	X	X		X	X																																											
5	X		X		X					X																																														
8	X		X																																																					
14	X	X	X	X	X	X	X	X	X	X	X	X	X	X																				X	X																					
19	⊗	⊗	⊗	O										X																				X	X																					
21	⊗		X			⊗	⊗	⊗					X																					O																						
23			X			⊗	⊗	⊗																																																
25	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	O	⊗	⊗																																											
28	X	X	X	X	X	X	X	X	X	X	X	⊗	X	X																				X	X																					
30	O	O			O	O	O	O					O																																											
33	⊗	X	X	X	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	X	O	O														O		O	O																							
34	X	X	X	X	X					X				X				X	X	X				X	X	X					X		X	X	X																					
36	X	X	⊗	⊗	X	X	X	X	X	X	X	X	X	X																				X	X																					
38	⊗	X	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	X																			⊗	O	O																					
39	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	X	⊗	⊗	X			X																	X	X				X	X																
41	⊗	X	O	⊗	⊗		⊗	⊗	⊗	⊗	X	⊗	⊗				X												X				⊗																							
42	⊗	X	X											X																				X	X																					
43	⊗					⊗		⊗													X			X	X	X		X							X		X					X	X	X			X				X	X	X	X	X	X
44	⊗	X	X	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗				X				X	X	X	X	X	X	X	X				⊗			X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
45	⊗	X	X	⊗																	X	X	X	X	X	X	X	X							X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
46	O		O																																																					
47	⊗	X	⊗	⊗																	X	X	X	X	X	X	X	X							X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
48	⊗	X	⊗	⊗																	X	X	X	X	X	X	X	X				O			X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
49	⊗	X	⊗	⊗	⊗	X	⊗	⊗	⊗		⊗		⊗				X				X	X	X	X	X	X	X	X							X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
50	X	X	X	X																	X	X	X	X	X	X	X	X							X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
51	⊗	X	⊗	⊗																	X	X	X	X	X	X	X	X							X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
52	⊗	X	⊗	⊗	X	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗				X				X	X	X	X	X	X	X	X							X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
53	⊗		O										O									X	X	X	X		X	X							X	X	X						X	X				X	X	X	X	X	X	X	X	X
54	⊗	⊗	X	X																	X	X	X	X	X	X	X	X							X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
55	⊗	O	O																			X						X								X		X										X		X		X	X			X
56	X																					X						X								X		X										X		X		X				
57	X																					X						X								X		X										X		X		X	X			X
58	⊗	⊗	X	X																	X	X	X	X	X	X	X	X							X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
59	⊗	O																				X						X								X		X										X		X		X	X			X
60	⊗	⊗	X	X																	X	X	X	X	X	X	X	X							X	X	X	X			X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
61	⊗	O																				X						X								X		X										X		X		X	X			X
62	⊗	O																				X						X								X		X										X		X		X	X			X
63	⊗	O																				X						X								X												X		X		X	X			X
64	⊗	⊗	X	X	X	X	X	X	X	X	X	X	X				X				X	X	X	X	X	X	X	X							X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
65	⊗	O																				X						X								X		X										X		X		X	X			X
66	⊗	O																				X						X								X		X										X		X		X	X			X
67	⊗		O																			X						X								X		X										X		X			X			X
68	⊗	O																				X						X								X		X										X		X		X	X			X
69	⊗	O																				X						X								X		X										X		X		X	X			X
70	⊗																					X						X								X		X										X		X		X	X			X
71	X																					X						X								X		X										X		X		X	X			X
72	X																					X						X								X		X										X		X		X	X			X
73	X																					X						X								X		X										X		X		X	X			X
74	⊗																					X						X								X		X										X		X		X	X			X
75	⊗		O																			X						X								X		X										X		X		X	X			X
76	⊗		O																			X						X																				X		X		X	X			X
77	⊗	X	⊗																																	X		X																		
78																																				X		X															X			
79	⊗		O																			X						X								X		X										X		X		X	X			X
80	⊗		O																			X						X								X		X										X		X		X	X			X
81	X																					X						X								X		X										X		X		X	X			X
82	⊗		O																			X						X								X		X										X		X		X	X			X
83	⊗		O																			X						X								X		X										X		X		X	X			X
85					X	X	X	X	X	X	X	X	X				X																																							
86	X	X	X	X	X	X	X	X	X	X	X	X																																												
87	X	X	X	X	X	X	X	X	X	X	X	X	X				X									X							X																							
88		X	X							X		X					X																																							

Table VII-3. Sampling frequency for chlorophyll *a* (O) and primary productivity (X) in Grand Traverse Bay

	Station																																											
Cruise	1	2	3	4	5	6	7	8	9	10	11	12	13	31	50	55	56	57	58	59	63	64	89	105	106	107	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161
8	O		O																																									
14	O	O	O	O	O	O	O	O	O	O	O	O	O																															
19	O		O																																									
21	O		O					O					O																															
23			O			O	O	O																																				
25	O	O	O	O	O	O	O	O	O	O	O	O	O																															
27	O																																											
28	O	O	O	O	O	O	O	O	O	O	O	O	O																															
30	O					O																																						
33	O	O	O	O	O	O	O	O	O	O	O	O	O																															
34	O	O	O	O																																								
36	O	O	O	O	O	O	O	O	O	O	O	O	O																															
38	O	O	O	O	O	O	O	O	O	O	O	O	O																															
39	O	O	O	O	O	O	O	O	O	O	O	O	O																															
41	O	O	O	O	O	O	O	O	O	O	O	O	O	O																														
42	O	O	O																																									
43																																												
44	O	O	O	O	O	O	O	O	O	O	O	O	O																															
45	⊗	⊗	⊗	⊗											X	X	X	X	X		X	X	X	X					X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
46	⊗	⊗	O	O												X	X	X			X	X	X	X	X					X	X	X	X	X		X	X	X	X	X	X	X		X
47	⊗	⊗	⊗	⊗											X	X	X	X	X	X	X	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
48	⊗	⊗	O	O												X	X	X			X	X	X		X						X	X												
49	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	X	X	X	X	X	X	X		X	X	X		⊗	⊗	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
50	⊗	⊗	⊗	⊗											X	X	X	X	X	X	X	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
51	⊗	⊗	⊗	⊗												X	X	X	X	X		X		X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
52	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	X	X	X	X	X	X	X	X	X	X	X		⊗	⊗	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
53	⊗															X	X	X	X	X	X	X	X	X	X						X	X				X	X	X	X	X	X	X	X	X
54	⊗	⊗	⊗	⊗											X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
55	X															X						X		X		X										X		X		X	X			X
56	X															X						X		X		X										X		X		X	X			X
57	X															X						X		X		X										X		X		X	X			X
58	⊗	⊗	⊗	⊗											X	X	X	X	X	X	X	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
59	X															X						X		X		X										X		X		X	X			X
60	⊗	⊗	⊗	⊗											X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
61	X															X						X		X		X										X		X		X	X			X
62	X															X						X														X		X		X	X			X
63	X															X						X														X		X		X	X			X
64	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
65	X															X						X		X		X										X		X		X	X			X
66	⊗															⊗						X		X		X										X		⊗		X	⊗			X
67	X															X						X		X		X										X		X			X			X
68	⊗															⊗						X		X		X										X		⊗		X	⊗			X
69	⊗															⊗						X		X		X										X		⊗		X	⊗			X
70	⊗															X						X		X		X										X		⊗		X	⊗			X
71	⊗															X						X		X		X										X		⊗		X	⊗			X
72	X															X						X		X		X										X		X		X	X			X
73	X															X						X														X		X		X	X			X
74	X															X						X		X		X										X		X		X	X			X
75	X															X						X		X												X		X		X	X			X
76	X															X						X														X		X		X	X			X
77	⊗	⊗	⊗																					X		X															X			
78																								X		X																		
79	X															X						X		X		X										X		X		X	X			X
80	X															X						X														X		X		X	X			X
81	X															X						X		X		X										X		X		X	X			X
82	X															X						X														X		X		X	X			X
83	X															X						X		X		X										X		X		X	X			X
85	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	X	X								X																						
86	X		X	X	X	X	X	X	X	X	X	X	X	X								X																						
87	X	X	X	X	X	X	X	X	X	X	X	X	X	X							X																							
88		X	X							X		X		X										X		X																		

Water samples were siphoned from the Van Dorn bottles into the necessary containers for sample storage and preservation. Waters intended for nutrient analysis were temporarily stored in refrigerated 1 liter polyethylene bottles. Portions were directly transferred into smaller polyethylene bottles and frozen while other portions were pressure filtered through 0.45 µ Millipore filters and then frozen. Filtering and freezing were routinely carried out on board ship during transit periods between stations. All samples were transported daily from the research ship to a Traverse City laboratory. The samples were then processed and prepared for transport to University of Michigan laboratories at Ann Arbor for analyses. Only very limited analyses were done in Traverse City. Sample storage and preservation techniques for each parameter are discussed in the next subsection with techniques of analysis. The methods of analysis used on water samples along with the detection and confidence limits of the method are summarized in Table VII-4. (The precisions noted reflect the uncertainty at the level of concentrations typically measured in Grand Traverse Bay). Nutrient and chemical analyses were generally performed on either a Technicon AutoAnalyzer (Model I, 1970 through 1972 and Model II 1972 to 1975) or a Perkin Elmer Model 403 atomic absorption spectrophotometer. Any other instruments used are noted specifically in the text.

Quality control was routinely monitored. Periodically throughout each day's analyses standard calibration samples were measured alongside Grand Traverse Bay water samples. The frequency of occurrence was approximately once for each twenty analyses. Spike and recovery experiments were also routinely performed. Studies were initiated to test storage and preservation techniques. Results from these quality control procedures suggest good precision and accuracy. In 1973 the analytical staff participated in a U.S. Environmental Protection Agency interlaboratory nutrient analyses comparison. The results of this study are shown in Table VII-5. These tests indicate high reliability in Sea Grant analysis techniques.

TABLE VII-4. Summary of methods of analysis.

Parameter	Method	Remarks
Alkalinity	acid titration	precision: 0.02 meq/ℓ accuracy: 0.06 meq/ℓ
Ammonia	Auto Analyzer	L_D = 10 µg N/ℓ precision: 15 µgN/ℓ
Benthos	hand counts	
Calcium	atomic absorption	L_D = 0.01 mg/ℓ
Chlorides	Auto Analyzer	L_D = 0.2 mg/ℓ precision: 0.2 mg/ℓ
Chlorophyll α	fluorimetry	L_D = 0.01 µg/ℓ precision: 0.08 µg/ℓ

cont. TABLE VII-4. Summary of methods of analysis.

Parameter	Method	Remarks
Chromium	atomic absorption	L_D = 3 µg/ℓ
Cobalt	atomic absorption	L_D = 10 µg/ℓ
Coliform	membrane filter technique	---
Conductivity	YSI Meter	precision and accuracy 5-7%
Copper	atomic absorption	L_D = 0.1 µg/ℓ
Magnesium	atomic absorption	L_D = 0.03 mg/ℓ
Nickel	atomic absorption	L_D = 2 µg/ℓ
Nitrate & Nitrite	Auto Analyzer diazotization and cadmium reduction	L_D = 10 µg N/ℓ precision: 10 µg N/ℓ
pH	Corning Model 12 Meter	precision and accuracy 0.05 units
Phosphorus	Auto Analyzer ascorbic acid reduction w/digestion for total-P on unfiltered sample.	L_D = 5 µg P/ℓ confidence: 20% @ 10 µg P/ℓ 2% @ 60 µg P/ℓ
Phytoplankton	hand counts	---
Potassium	atomic absorption	L_D = 0.005 mg/ℓ
Primary Productivity	*in situ* C^{14}-bicarbonate uptake	---
Silicon	Auto Analyzer silicomolybdate complex formation	L_D = 0.03 mg Si/ℓ precision: 0.2 mg Si/ℓ
Sodium	atomic absorption	L_D = 0.005 mg/ℓ
Strontium	atomic absorption	L_D = 10 µg/ℓ
Temperature	bathythermograph mercury thermometer	precision = 0.1°C
Transparency	Secchi disc	precision and accuracy variable
Zinc	atomic absorption	L_D = 1.0 µg/ℓ
Zooplankton	hand counts	---

TABLE VII-5. EPA interlaboratory comparison study.

	Sample A		Sample B	
	U of M	EPA	U of M	EPA
Total P μg/ℓ	0.069	0.064	0.043	0.038
Soluble Reactive P μg/ℓ	0.010	0.010	0.008	0.008
NH_3^-N μg/ℓ	0.038	0.041	0.021	0.026
NO_3^-N μg/ℓ	0.268	0.252	0.631	0.610

Physical and Chemical Methods of Analysis

Alkalinity:

Alkalinity samples were stored in completely filled polyethylene bottles, unfrozen. Analyses were done immediately following the cruise using the acidification - pH measurement technique (Strickland and Parsons 1968). The samples were titrated with 0.01 N hydrochloric acid to a pH of below 4. The alkalinity was calculated according to the equation:

$$\text{Alk.(meq/l)} = \frac{\text{Na Va} - \text{Va } (\text{H}^+)}{\text{Vs Va}} \quad \times \quad 1000$$

where Na = normality of the acid
Va = volume of acid used in titration
Vs = volume of sample
H^+ = normality of final hydrogen ion concentration (antilog $|pH|$).

Chlorides:

The filtered, frozen, nutrient water samples were used for the determinations of chloride concentrations. Analyses were done on the Technicon Auto Analyzer. A colorimetric determination was used which depended on the liberation of the thiocyanate ion from mercuric thiocyanate caused by the formation of a unionized but soluble mercuric chloride. In the presence of ferric ions the liberated thiocyanate forms a highly colored compound the color of which is proportional to the original chloride concentration (Technicon Instrument Corp. 1971; O'Brien 1962, Zall et al. 1956). The chloride detection limit was 0.2 mg/ℓ and the precision (uncertainty) was 0.2 mg/ℓ.

Conductivity:

Electrical conductivity was measured on the alkalinity samples prior to titration using a YSI Model 31 conductivity bridge calibrated in μmho units. All measurements were corrected to 25°C. A precision and accuracy of 5 to 7% was expected.

Dissolved Oxygen:

Samples for dissolved oxygen were analyzed using the sodium azide modification of the Winkler titration (APHA 1971). Samples were fixed immediately in the field in standard glass D.O. bottles. The samples were acidified and titrated with thiosulfate aboard ship or at the end of the day in the Traverse City laboratory. The titrant was standardized each day with a biniodate solution. The precision of the test was 0.1 mg/ℓ.

Hydrogen Ion Activity:

The pH of sampled waters was determined using a Corning Model 12 pH meter with temperature correction. A glass pH electrode with an associated calomel reference electrode was used. The meter was calibrated to two different pH buffer solutions each day. The precision and accuracy of the test was 0.05 pH units.

Major Cations and Anions:

The concentrations of the elements sodium, potassium, calcium, and magnesium were each determined using a Perkin Elmer Model 403 atomic absorption spectrophotometer using an air-acetylene flame. Analysis methods were performed as described in <u>Analytical Methods for Atomic Absorption</u> (Perkin Elmer 1966). All of these elements were analyzed using the appropriate hollow cathode lamp as an energy source with the exception of sodium, which was analyzed by flame emission. The respective detection limits were 0.01 mg/ℓ of calcium, 0.03 mg/ℓ of magnesium, 0.005 mg/ℓ of sodium, and 0.005 mg/ℓ of potassium.

Ammonia Nitrogen:

Ammonia concentrations were determined on the Auto Analyzer utilizing the Berthelot reaction. In this technique the formation of a blue compound results when a solution of an ammonium salt is added to sodium phenoxide (Technicon Instrument Corp. 1973b, U.S.E.P.A. 1974). EDTA was used to prevent precipitation of hydroxides of calcium and magnesium. The detection limit was 10 μg N/ℓ. The accuracy of the test at low concentrations, however, was highly dependent on ammonia contamination from laboratory air.

Nitrogen-nitrate,-nitrite:

Nitrate was determined on the Auto Analyzer utilizing a procedure whereby nitrate is reduced to nitrite in a cadmium column and then reacted with sulfanilamide under acid conditions to form a diazo compound. This compound then couples with N-1-napthylethylenediamine dihydrochloride to form a reddish purple azo dye, the color of which is proportional to the nitrate-nitrite concentration (Technicon Instrument Corp. 1972, U.S.E.P.A. 1974). Nitrite could be measured separately by foregoing the reduction. The detection limit and precision of the test were both 10 μg N/ℓ.

Phosphorus:

Total dissolved phosphorus was determined on the filtered nutrient water samples after digesting in an a persulfate solution (Menzel and

Corwin 1965). The resulting released soluble reactive phosphorus was determined on the Auto Analyzer using the Murphy and Riley (1962) ascorbic acid reduction technique (Technicon Instrument Corp. 1973, U.S.E.P.A. 1974). A phosphomolybdenum complex is formed and reduced by ascorbic acid to form a blue compound, the color of which is directly proportional to the phosphorus concentration. Total phosphorus was determined similarly except that the analysis was done on an unfiltered nutrient water sample. The detection limit in both tests was 5 µg P/ℓ with a confidence limit of 20% at low concentrations (10 µg P/ℓ range) improving to 2% at 60 µg P/ℓ.

Relative Irradiance:

A submersible T.S. submarine illuminance meter equipped with two photocells and direct readout was used to measure relative light extinction in Grand Traverse Bay waters. Readings were generally made at 2, 5, 10, 15 and 20 m of depth.

Solar Radiation:

A Weather-Measure solar radiation recorder was used to determine incident solar radiation. The unit was mounted on the laboratory roof in Traverse City.

River Flow:

Tributary discharge flows were measured using a mechanically activated Gurley current meter.

Silicon:

Dissolved silicon concentrations were determined on filtered nutrient water samples using a colorimetric Auto Analyzer technique. This method is based on the formation of a silicomolybdate complex which is reduced by an ascorbic acid solution to form "molybdenum blue." Oxalic acid was used to prevent phosphate interference (Technicon Instrument Corp. 1973, APHA 1971). The detection limit for this test was 0.03 mg Si/ℓ and the precision was 0.2 mg/ℓ.

Trace Metals:

Trace metals analysis was done on filtered and acidified water samples using a Perkin-Elmer Model 403 atomic absorption spectrophotometer. An air-acetylene flame was used for all analyses except strontium which used a nitrous oxide-acetylene flame. The methods are outlined in <u>Analytical Methods for Atomic Absorption Analysis</u> (Perkin Elmer 1966). The detection limits were 0.1 µg/ℓ copper, 1 µg/ℓ zinc, 10 µg/ℓ cobalt, 2 µg/ℓ nickel, 3 µg/ℓ chromium, and 10 µg/ℓ strontium.

Temperature:

On sampling cruises performed off of the R/V's INLAND SEAS and MYSIS, temperature profiles in the water were measured using a bathythermograph lowered and retrieved vertically through the entire water column. Surface water temperatures were checked using a continuously recording thermometer probe suspended several feet away from the side of the ship. In samplings off of the R/V SEA GRANT I (which included the majority of the cruises) temperatures were measured using a mercury thermometer. A precision of 0.1°C was observed.

Sediments:

Sea Grant researchers sampled surface sediment with a PONAR dredge and sectioned off the top 2 cm of sediment for later analysis. Subsequent analyses were, however, carried out with independent financing and are documented elsewhere (Baker-Blocker et al. 1975). These included trace metal analyses on acid-peroxide sediment extracts using atomic absorption techniques and analysis for organic carbon content using combustion and gas chromatographic techniques.

Transparency:

A standard Secci disc (20 cm diameter) was used to measure water transparency. Readings were the average of the levels of disappearance and reappearance of the disc recorded in meters from the surface. The precision and accuracy vary widely depending on environmental conditions and personnel.

Biologic Methods

Benthos:

The benthic invertebrate community was sampled using a 484 cm^2 PONAR benthos dredge and sorted using an elutriation device as described by Powers and Robertson (1965, 1967). The organisms retained were preserved in mason jars in a 4% formalin solution and transported to the Ann Arbor laboratory. The invertebrates were separated from the debris in the laboratory and preserved in 70% ethanol. Identification of the organisms through 1973 was only to class and order categories, whereas the last set of data were expressed to the lowest feasible taxonomic group. However, the Oligochaeta and Nematoda classifications were still utilized. The midges (Chironomidae) were sorted into similar groups under the dissecting microscope and representative members of each group were mounted utilizing polyvinylactophenol for genus and species identification under higher magnification.

Chlorophyll *a*:

Samples intended for chlorophyll *a* analysis were collected and stored in 2-liter amber polybottles containing a 5 ml magnesium carbonate suspension. While still aboard ship (or at the end of the day in the Traverse City laboratory) 100 to 500 ml of the stored samples was filtered through a 0.45 µ Millipore filter. The filters were folded and then frozen in coin envelopes inside a desiccator. All operations were done in complete darkness. The samples were transported to Ann Arbor and then analyzed for chlorophyll *a* as outlined in Strickland and Parsons (1968). A G.K. Turner

Model 110 Fluorimeter was used for the analysis. The unit was periodically calibrated using standard chlorophyll *a* samples and checked against spectrophotometric techniques. The detection limit was 0.01 μg Chl α/ℓ and the precision was 0.08 μg Chl α/ℓ.

Coliform and other bacteria:

Determinations of fecal coliform cell counts were accomplished using the membrane filter techniques as outlined in Standard Methods (APHA 1971). Samples were taken and stored on ice until returned to the Traverse City laboratory. There the waters were filtered through 0.45 μ Millipore membrane filters and incubated for 24 hours at 45°C in petri dishes containing M-FC broth (a solution containing tryptose, peptone, yeast, lactose and bile salts). Sterilization of the filtering apparatus was accomplished using alcohol dosing and flames. Blue colonies were each counted as representative of one fecal coliform count. Countings were aided by use of a 10X binocular microscope. Counts were also occasionally done for total coliform and fecal streptococci following similar procedures to the above but using M-Endo broth and M-Enterococcus agar respectively and with incubation temperatures at 35°C (APHA 1971).

Phytoplankton:

One-liter samples were collected monthly for phytoplankton analysis at two depths, 2 and 20 m. The liter sample was shaken and 50 ml was filtered onto a glass-fiber filter (Stoermer et al. 1972). The filter plus phytoplankton were mounted on a slide in beechwood creosote. In several days the filter became clear and the phytoplankton were counted. Counts were made from 3 transects across the filter which closely approximates the number of cells in 1 ml of the original sample.

Primary Productivity

Grand Traverse Bay primary production was determined using an *in situ* C^{14}-bicarbonate uptake technique. Two clear and one opaque, 250 ml glass stoppered Pyrex reagent bottles were filled with water from specified depths. Each bottle was stored in the dark and then individually inoculated with two microcuries of C^{14} bicarbonate solution (Strickland and Parsons 1968). Transfer of the inoculum from the ampules to the bottles was done with a syringe followed by rinsing. The bottles were then mounted on plexiglass racks, lowered to their respective depths, and anchored to a station located by a separately attached buoy. Following four to six hours of incubation the bottles were retrieved and fixed with a formaldehyde solution. The contents of the bottles were later filtered onto 0.45 μ HA Millipore filters and rinsed with distilled water. The filters and associated suspended solids were then exposed to fuming hydrochloric acid for 10 minutes to remove inorganic carbonate particles which might contain C^{14} (Wetzel 1965). The filters were subsequently placed in 20 ml polyethylene liquid-scintillation vials and covered with a dioxane-based water miscible solution. The radiocarbon was determined using a Unilux I liquid scintillation counter. The carbon uptake was then computed considering the C^{14}, pH and alkalinity measurements (Strickland and Parsons 1968).

Zooplankton:

The zooplankton of Grand Traverse Bay were collected by pulling No. 10 mesh (153μ) conical nylon nets through the water column from 1 meter above the bottom to the surface. A tandem net apparatus was used. The collection efficiency of this net size is estimated to be 85% for the crustacean zooplankton and *Asplanchna* and about 0.5% for the nauplii, other rotifers and the other zooplankton smaller than 150 μ. The samples were fixed with Keachie solution: 5% formalin and 20% saturated sugarwater (Keachie 1967). They were then labelled and stored in mason jars. Preserved samples were divided into subsamples by a plankton splitter and then enumerated for all zooplankton. Identification was routinely done to genus for crustaceans and some rotifers, and order for all others. The preserved samples have been saved for species enumeration at a later date. Edmondson (1959) was used to identify the zooplankton. Counting was done at 12X with a binocular zoom microscope.

VIII. CONSOLIDATION OF DATA

It was obvious from the magnitude of the Grand Traverse Bay sampling program that some form of data consolidation was necessary to aid in the evaluation and interpretation of this information. Four different groupings of data were employed: depth, time, thermal season and cartographic zones. In the segregation of data into these groupings extreme caution was exercised to avoid the suppression of any anomalies in chemical or biological trends.

Data grouped by depth were averaged for a particular increment (i.e., < 2 meter depth, 3-10 meter depth, etc.), while those segregated by time were averaged over a cruise. This procedure allows analysis of any trends associated with depth, such as increased ammonia-nitrogen in bottom waters, or long range variation, such as an increase or decrease in standing crop of phytoplankton in the bay over a period of years. The temporal groupings also provide for correlations of various aquatic phenomena with events in the basin including storms, wastewater treatment plant efficiency and seasonal shifts in population density.

An earlier study (Stoermer et. al. 1972) proposed that, for purposes of analysis, the bay be divided into three sections or zones: the open bay, east arm and west arm. Sea Grant data from various stations were evaluated with the intent to discover any additional regions of aberration within this earlier framework. Table VIII-1 presents examples of the data format used for such evaluations. To aid in a visualization of the following discussion, figures are provided which describe the morphology (Figure VIII-1), and zone divisions (Figures VIII-2 and VIII-3). A map locating sampling stations has been provided as Figure VII-1.

The first zone (Zone I) to be assigned was that comprising the three open Lake Michigan sampling stations. This grouping allows a comparison of Grand Traverse Bay data with Lake Michigan values.

Zone II, the open bay, is one of the designations of Stoermer et. al. (1972) and includes four offshore stations plus one station in Northport Bay. The ammonia-nitrogen and total dissolved phosphorus data for the four offshore stations were averaged over the entire water column for each cruise. The standard deviation for each cruise was also calculated. Variation in ammonia-nitrogen was primarily vertical and the standard deviation approached the sensitivity of the analysis. For total dissolved phosphorus approximately 80% of the standard deviations were less than 2µ gP/ℓ. Station #86 at Northport Bay showed water chemistry consistent with that of the offshore stations. The lack of consistent variation within this zone confirmed the fact that these stations could be treated as a unit.

The stations located in the east arm make up Zone III. The standard deviation within cruises for ammonia-nitrogen and total dissolved phosphorus was again primarily due to vertical rather than horizontal differences. Of the nitrogen standard deviations, 82% were less than 15µ gP/ℓ. An identical percentage was less than 5 µgP/ℓ for total

Table VIII-1. Examples of data format used in zone selection.

Open Bay
(average total dissolved phosphorus)

Cruise	µgP/ℓ	Std. Dev.	N
1	26,709±	4,529	12
5	23,633±	3.557	3
14	40,200±	69,861	14
25	19.580±	3.838	10
28	9,200±		1
33	10.500±	1.707	13
36	10.062±	4.624	8
39	7,290±	1,147	10
41	3,520±	0.536	5
44	65.800±	29,067	22
49	9,565±	4,008	17
52	13,311±	3,007	18
64	24,479±	13,863	19

East Arm
(Average ammonia nitrogen)

Cruise	µgP/ℓ	Std. Dev.	N
1	16.557±	8.917	14
14	13.260±	9,221	10
21	17.786±	6,190	14
23	23.050±	3.958	12
25	5,292±	4,326	13
28	27.393±	12.020	14
33	26.407±	6,684	14
36	23,793±	16,996	14
38	12.314±	7.271	14
39	14,800±		1
43	21,137±	4,768	8
44	2,064±	1.444	14
49	23,643±	11.990	14
52	8,871±	8.250	14
64	17,086±	32,374	14

West Arm (north)
(average total dissolved phosphorus, surface)

Cruise	µgP/ℓ	Std. Dev.	N
1	9,700±	0.566	2
5	8,300±		1
14	13.600±	1,838	2
25	18,100±	4.667	2
33	7.300±		1
41	3.450±	0,071	2
43	3,211±	1.040	9
44	18,723±	4,039	13
45	22.323±	5.234	13
47	11.962±	9.127	13
48	8.538±	7,038	13
49	6,627±	4.580	11
50	8,554±	2,469	13
51	8,377±	2,272	13
52	12.420±	1.705	10
53	19.020±	0,909	5
54	9,185±	2,434	13
58	16.325±	7.486	12
60	8.733±	2.025	12
64	13.817±	16.388	12

West Arm (south)
(average ammonia nitrogen, surface)

Cruise	µgN/ℓ	Std. Dev.	N
1	8.800±		1
5	11,900±		1
8	5.100±		1
14	53.550+	68.600	2
19	20.950±	3.041	2
21	13.400±		1
25	3.900±		1
28	28.500±	5.374	2
33	22,800±	1,697	2
34	26.800±	9,758	2
36	22,000±	12,587	2
38	22,900±	3.536	2
39	14,900±		1
43	25.250±	29,702	8
44	7,886±	6.362	7
45	15.429±	8.272	7
47	6,243±	12,003	7
48	45,543±	38,291	7
49	20.857±	11,443	7
50	20.086±	13,652	7
51	76.029±	142.511	7
52	54.543±	123.982	7
53	59,086±	12,275	7
54	13,429±	3,705	7
55	23.433±	18.548	3
56	27.133±	16,013	3
57	26,733±	2,723	3
58	27.500±	18.586	7
59	32.600±	19.752	3
60	63.843±	113,328	7
61	15.533±	4,856	3
62	11.400±	1,253	3
63	8.433±	1,779	3
64	22,671±	19.166	7
65	8,167±	3,667	3
66	11.667±	3.109	3
67	50,200±	35.355	2
68	66,467±	62,550	3
69	10.900±	2.751	3
70	3,067±	1,498	3
71	12,467±	9,780	3
72	16,600±	4,359	3
73	13,700±	2,883	3
74	13,933±	7,766	3
75	8.533±	7.228	3
76	2.900±	0.954	3
77	6.900±		1
78	1.000±		1
79	3.200±	2.685	3
80	5.333±	2,926	3
81	3.433±	1.210	3
82	6.333±	4.488	3
83	2,133±	2,259	3

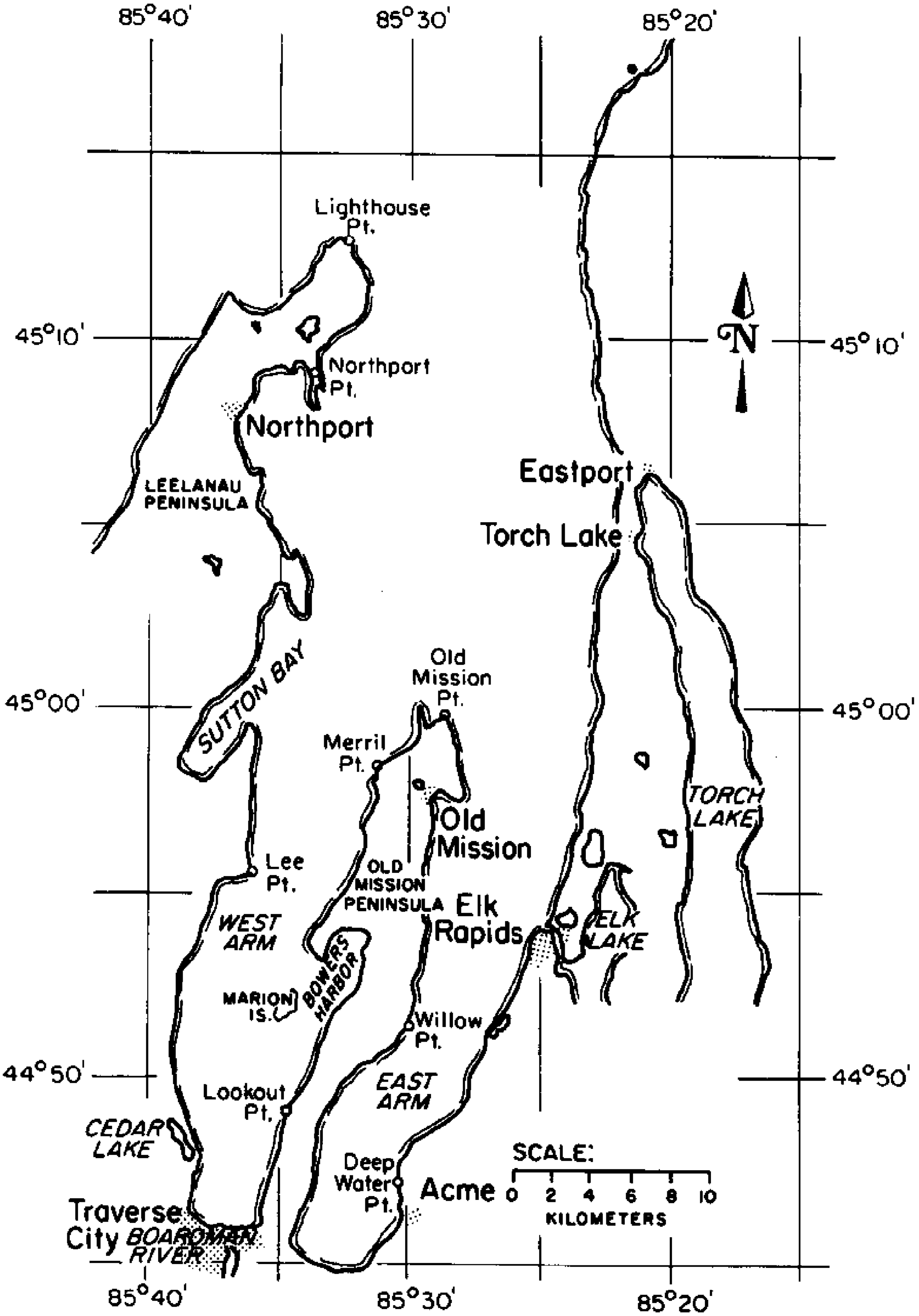


FIGURE VIII-1. Morphologic map of Grand Traverse Bay. Modified from Lauff (1957).

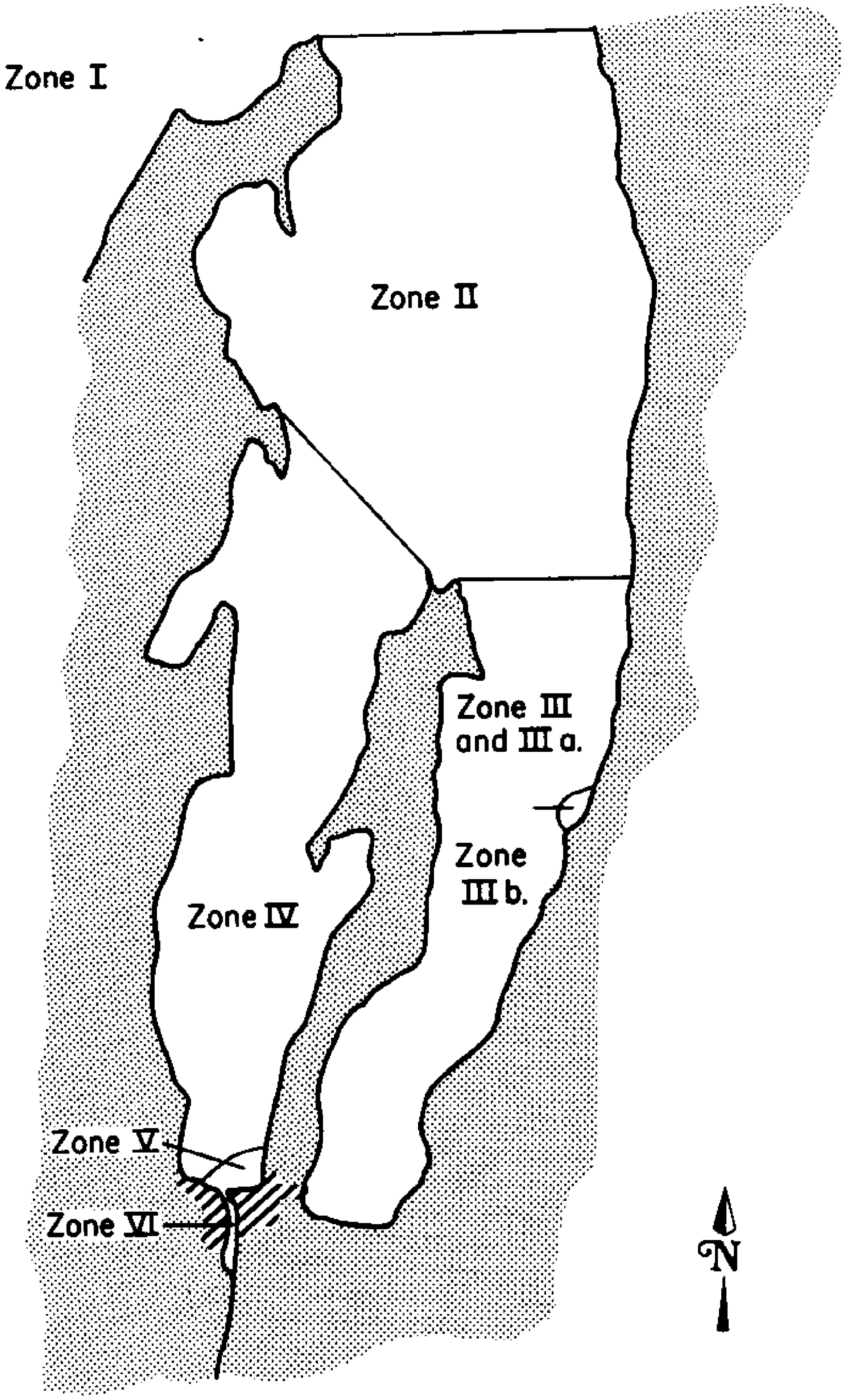


FIGURE VIII-2. Zone divisions in Grand Traverse Bay.

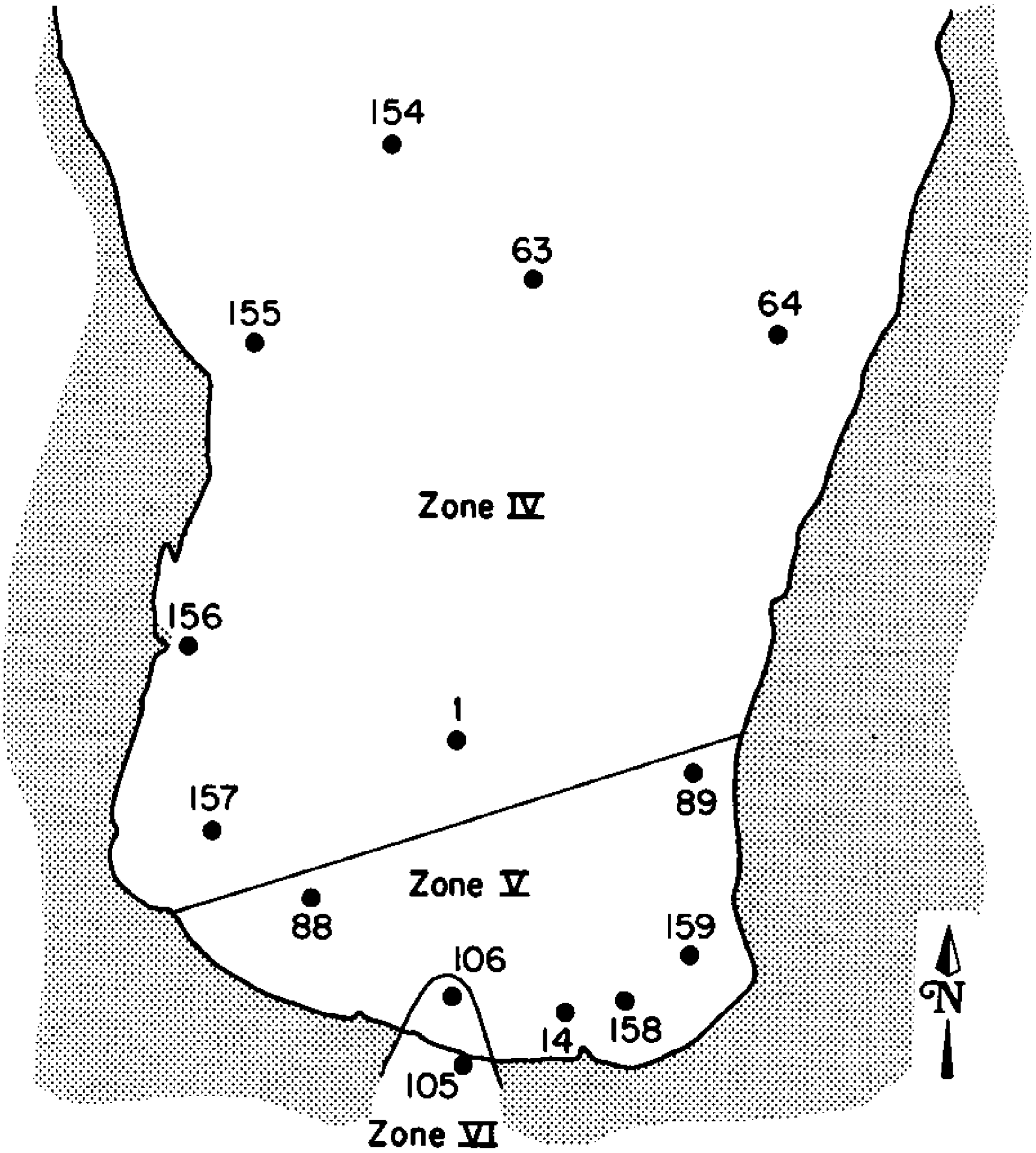


FIGURE VIII-3. Zone divisions and sampling stations in the southern West Arm of Grand Traverse Bay.

dissolved phosphorus. Although water chemistry data for the Elk River plume (station #13) were consistent with the remainder of the east arm stations, this was not the case for zooplankton and primary productivity data. Values for these parameters at the Elk River plume suggest that this station (#13) be treated as a separate entity. For analysis of primary productivity and zooplankton data, two divisions will be considered: Zone IIIa (east arm stations not including #13) and Zone IIIb (station #13).

Perhaps the most complex and dynamic region in Grand Traverse Bay is the west arm. Initially, the west arm was divided into three segments (north, middle, and south). Evaluation of chemistry data, as above, showed that the north and middle segments along with portions of the south segment could be combined into a single west arm region (Zone IV). Nitrogen and phosphorus data for Suttons Bay and Bowers Harbor indicated no irregularities which would lead to their segregation from this zone.

Although interzonal differences in water chemistry and biological indicators were not always obvious, it was decided that such a division would facilitate the comparision of this with earlier studies and serve to best point out trends in water quality. On certain occasions, data for Zones II, III, and IV were grouped as the "outer bay" and compared against Zone V which is then referred to as the "inner bay".

Zone V (lower west arm) is intended to contain the region of influence of the Boardman River. A contour map of total dissolved phosphorus averaged for two depths at each of 11 stations in the southern portion of the west arm helps to delineate this zone of influence (See Figure VIII-4). From examination of this plot the following stations were selected for inclusion in Zone V (lower west arm): #14, #88, #89, #158 and #159. Since primary productivity was not measured at any of these stations, station #1 is included in this zone for the analysis of primary productivity data only.

The final zone, Zone VI (Boardman River), is composed of three stations. Two of the stations, #105 and #107, are located in the Boardman River downstream and upstream of the Traverse City wastewater treatment facility effluent, respectively. Station #106, the Boardman River plume, was included in this group because averaging with the lower west arm would introduce an intolerable bias toward high values. Station #106 is more an indication of river nutrient levels than those in the bay (see Figure VIII-5). *Chemical values for this zone, however, are only from Station #105.* The zone divisions for Grand Traverse Bay are summarized in Table VIII-2.

The grouping of data by thermal season was accomplished by analysis of temperature (averaged over the entire bay) versus depth profiles. From these plots it could be determined whether the bay was thermally stratified or homogenous and mixed during a particular curise. These plots are presented in Figure VIII-6. The thermal breakdown by cruise and data and the physical event which is represented is outlined in Table VIII-3.

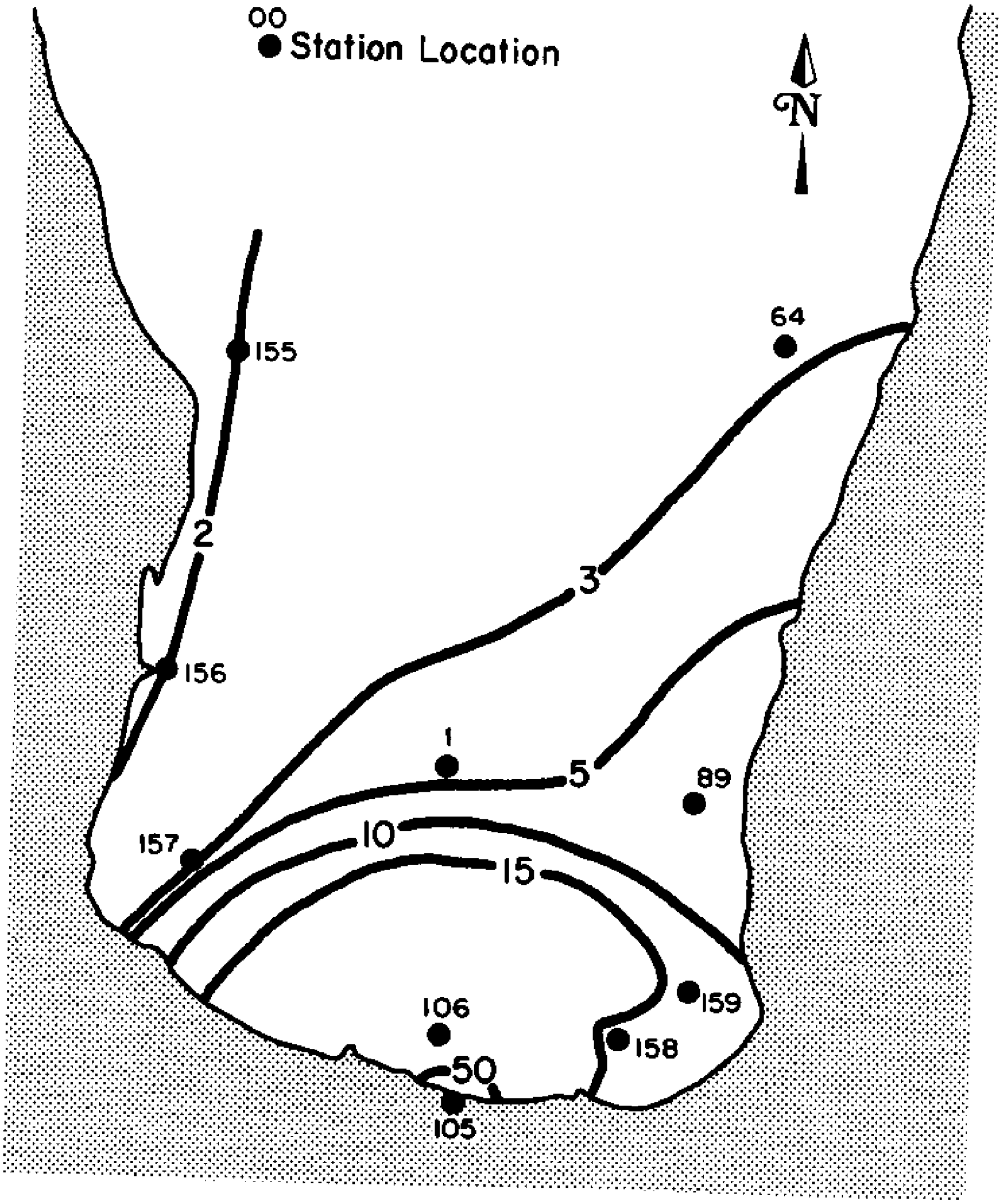


FIGURE VIII-4. Surface total dissolved phosphorus concentrations (μgP/ℓ) in the southern West Arm of Grand Traverse Bay on 11-13 July 1972.

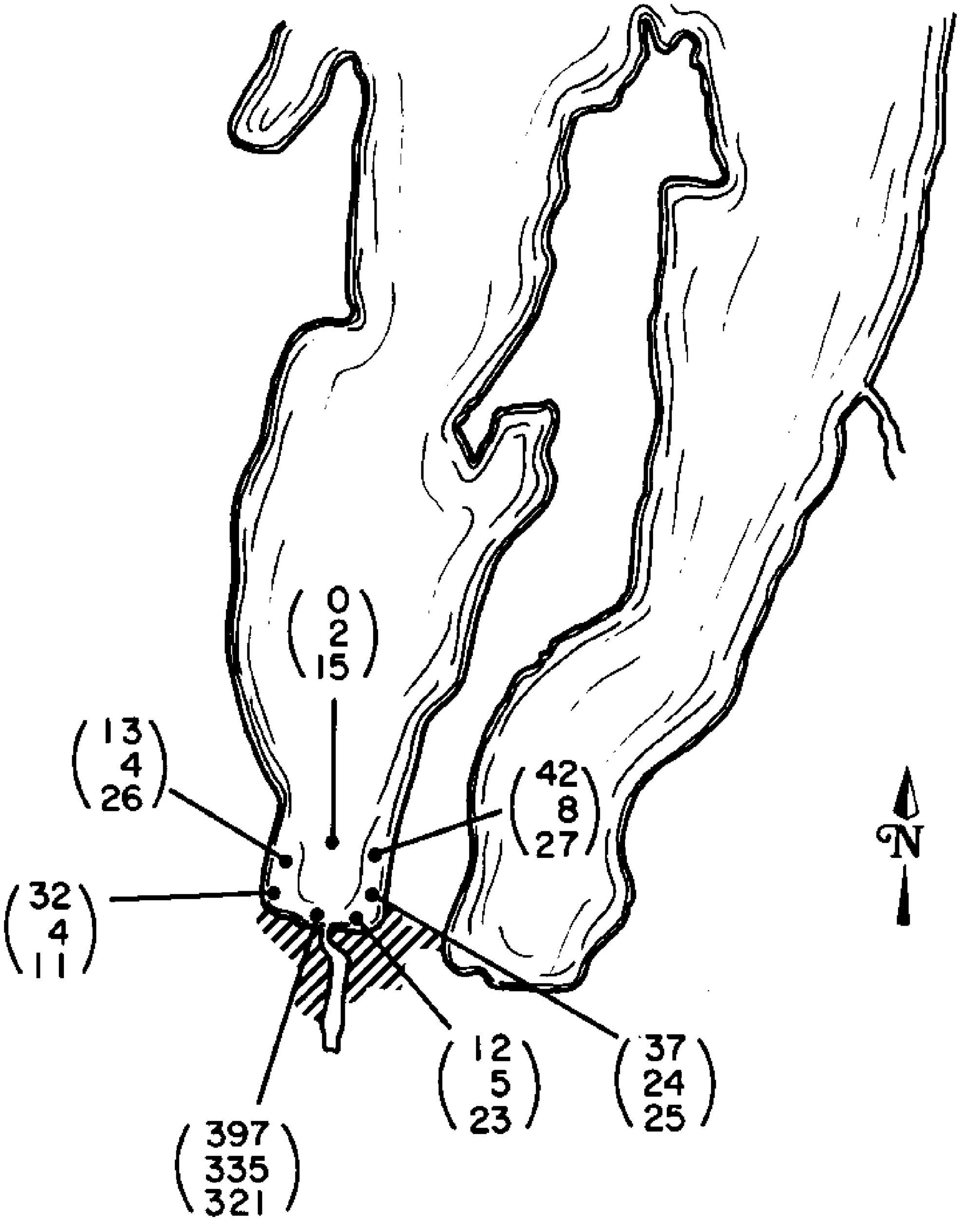


FIGURE VIII-5. Surface ammonia-nitrogen concentrations (μgN/ℓ) at selected lower west arm stations in Grand Traverse Bay on three dates:
(4 October 1972)
(27 October 1972)
(9 May 1973)

TABLE VIII-2. Division of Grand Traverse Bay sampling stations into zones

Zone	Name	Stations Included
I	Open Lake Michigan	31, 144, 145
II	Open Bay	9, 10, 11, 12, 22, 85, 86
III	East Arm	6, 7, 8, 13, 17, 76, 81
*IIIa.	East Arm	6, 7, 8, 17, 76, 81
*IIIb.	Elk River Plume	13
IV	West Arm	1, 2, 3, 4, 5, 38, 39, 40, 50, 55, 57, 58, 59, 63, 64, 87, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 160, 161
V	Lower West Arm	14, 88, 89, 158, 159
VI	Boardman River Plume	105, 106**, 107**

*this division applies only to zooplankton and primary productivity data.

**not included in chemical data

___underlined stations indicate those at which zooplankton samples were collected

"Outer Bay" refers to Zones II, III & IV combined.

"Inner Bay" refers to Zone V.

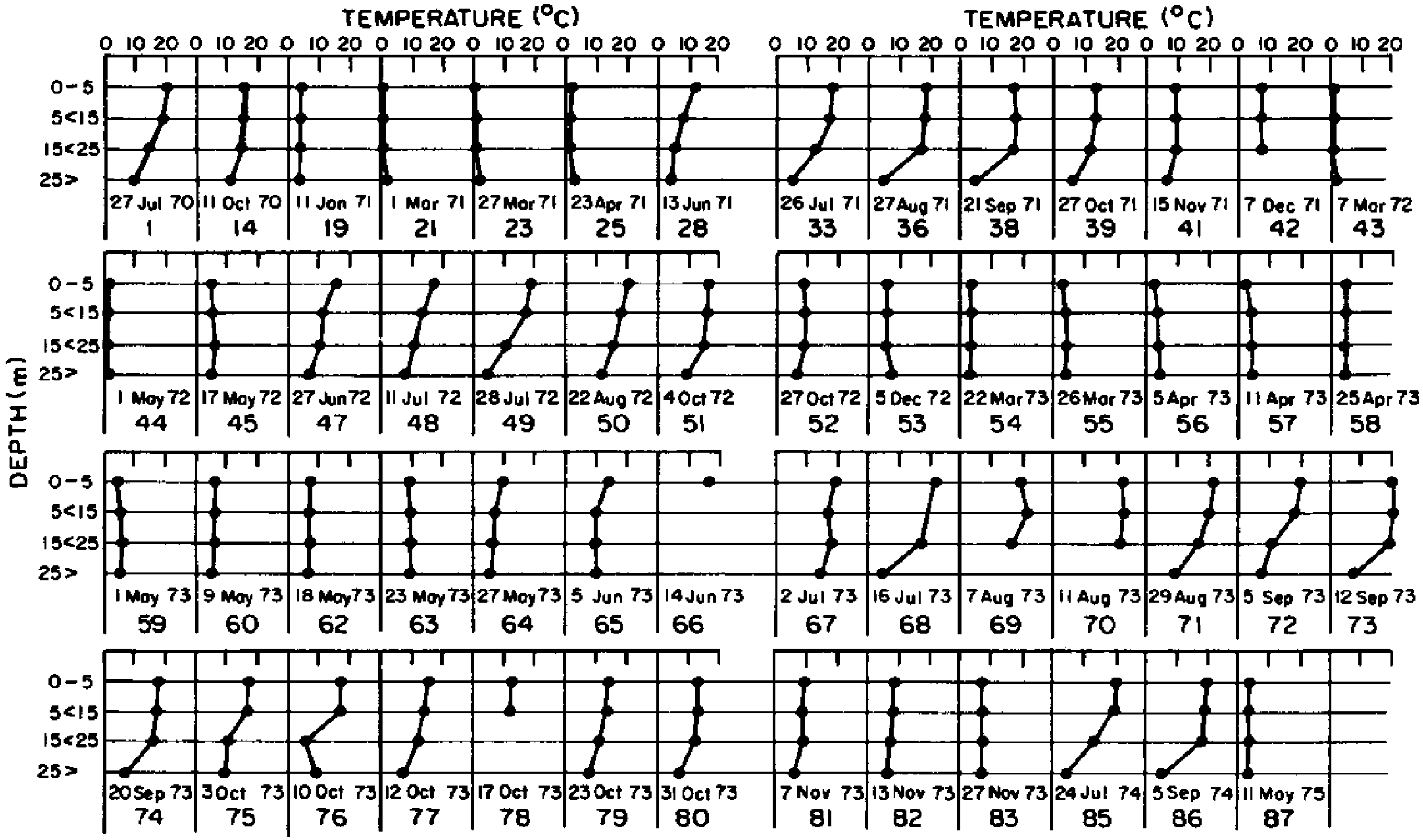


FIGURE VIII-6. Temperature profiles (baywide averages) for Grand Traverse Bay.

TABLE VIII-3. Breakdown of data by thermal season

Cruises	Dates	Condition
1 thru 14 (1, 5, 8, 14)	27 July 1970 thru 15 October 1970	Summer Stratification 1970
19 thru 25 (19, 21, 23, 25)	11 January 1971 thru 30 April 1971	Spring Overturn 1971
28 thru 39 (28, 33, 34, 36, 38, 39)	13 June 1971 thru 30 October 1971	Summer Stratification 1971
41 and 42	15 November 1971 thru 7 December 1971	Fall Overturn 1971
43 thru 45	7 March thru 19 May 1972	Spring Overturn 1972
47 thru 51 (47, 48, 49, 50, 51)	27 June 1972 thru 6 October 1972	Summer Stratification 1972
52 and 53	27 October 1972 thru 8 December 1972	Fall Overturn 1972
54 thru 64 (54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64)	22 March thru 1 June 1973	Spring Overturn 1973
65 thru 80 (65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80)	5 June 1973 thru 31 October 1973	Summer Stratification 1973
81 thru 83 (81, 82, 83)	7 November 1973 thru 27 November 1973	Fall Overturn 1973
85 and 86	24 July 1974 thru 7 September 1974	Summer Stratification 1974
87 and 88	11 May 1975 thru 20 July 1975	Summer Stratification 1975

IX. HYDROLOGY AND CONTAMINANT SOURCES

During the first two years of the Grand Traverse Bay investigation (1970 and 1971) studies were directed toward evaluating all tributary discharges and loadings to the bay. A hydrologic investigation and a routine tributary monitoring program were important components of the first phase of this project. The results from these studies permitted clear identification of the contaminant sources to the bay and their relative significance (Brater 1972, Gannon and Meier 1974). The following sections present a discussion of these findings and the relative significance of various other contaminant sources to the bay.

Hydrology

Grand Traverse Bay drains an area of 3226 km^2 in the northwestern lower peninsula of the state of Michigan. There exist 16 identifiable tributaries to the bay, two discharging to the open bay, four discharging to the east arm and ten discharging to the west arm. A map of these tributaries is presented in Figure IX-1. These tributaries account for 2185 km^2 of the total drainage basin. Of the remaining area 717 km^2 is attributed to the actual surface area of the bay, and 355 km^2 to direct or small intermittent stream discharges. A summary of Grand Traverse Bay hydrologic statistics is given in Table IX-1. This table enumerates the bay tributaries and their associated drainage areas and average (1970-1971) measured flows.

The two principal tributaries in the system are the Boardman and Elk Rivers which drain areas of 722 km^2 and 1270 km^2 respectively (Brater 1972). These rivers collectively account for 81% of the total land drainage and typically over 90% of all the hydrologic inputs to the bay. Waters from the remaining drainage areas are collected by smaller streams, often having drainage areas of no more than a few square kilometers. The third largest tributary, Mitchell Creek, has a drainage area of 36.3 km^2 and discharges an average flow of 28.4 $m/^3$ min. This accounts for less than 2% of the total bay tributary flow.

It has been estimated that over 95% of the tributary flow in the Grand Traverse Bay basin is ground water (Brater 1972). As a result, river flows are relatively stable. The soils of the region have high infiltration rates and capacities and, therefore, prevent any significant amounts of surface runoff. The lack of extensive urbanization also contributed to this effect. The daily hydrograph of the Boardman River demonstrates this stability (Figure IX-2). Although fluctuations do exist resulting from storm events, the hydrograph is relatively stable. The drought characteristics of the Boardman River also demonstrate considerable stability (Table IX-2) when compared with other river systems. Hydrograph and drought data are available only for the Boardman River, which is the only USGS gauged river in the basin.

Morphologically, most of the hydrologic inputs to Grand Traverse Bay discharge into the east or west arms (see Figure IX-1). The open bay accepts only Northport and Ennis Creeks, which have a combined area of less than 15 km^2 and a total average flow of 6.3 m^3/min. In the west arm the

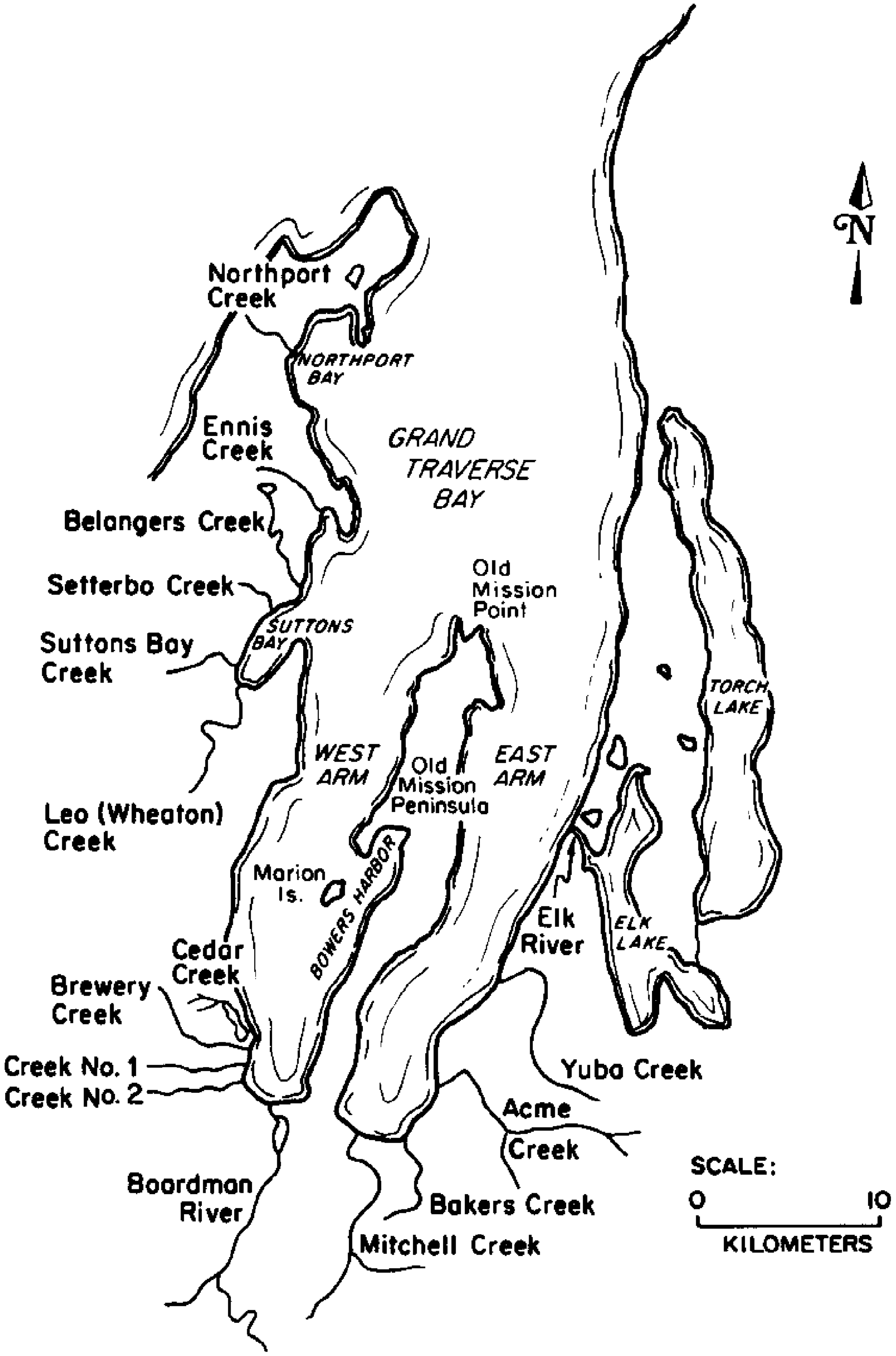


FIGURE IX-1. Grand Traverse Bay region tributary map.

TABLE IX-1. Hydrologic statistics on Grand Traverse Bay tributaries*

Tributary	Drainage Area (km^2)	Average Measured Flow 1970-71 (m^3/min)	% of Total Flow to Specific Region	% of Total Flow to GTB
Open Bay				
Northport Creek	10.3	4.74	75.8	0.29
Ennis Creek	4	1.51	24.2	0.09
Unmonitored	3.5	---		
Subtotals	49.3	6.25		0.38
West Arm				
Bellangers Creek	23.3	14.09	2.57	0.89
Setterbo Creek	2	0.97	0.17	0.061
Suttons Bay Creek	4	2.45	0.45	0.15
Leo (Wheaton) Creek	9.0	6.90	1.26	0.43
Cedar Creek	16.0	15.68	2.87	0.99
Brewery Creek	5.7	3.08	0.56	0.19
Creek #1	---	0.76	0.14	0.05
Creek #2	---	1.24	0.22	0.078
Boardman River	722	501	91.7	31.53
Unmonitored	115	---		
Subtotals	897	546.17		34.37
East Arm				
Mitchell Creek	36.3	28.48	2.75	1.79
Bakers Creek	6.5	3.04	0.29	0.19
Acme Creek	33.7	24.71	2.38	1.55
Yuba Creek	21.2	15.50	1.49	0.97
Elk River	1270	965	93.1	60.7
Unmonitored	205	---		
Subtotals	1562.7	1036.73		65.2
Totals	2509.	1589.15		
Grand Traverse Bay Water Area	717.			
Grand Total	3226			

*Compiled from Brater (1972), Gannon and Meier (1974), and USGS (1971, 1972)

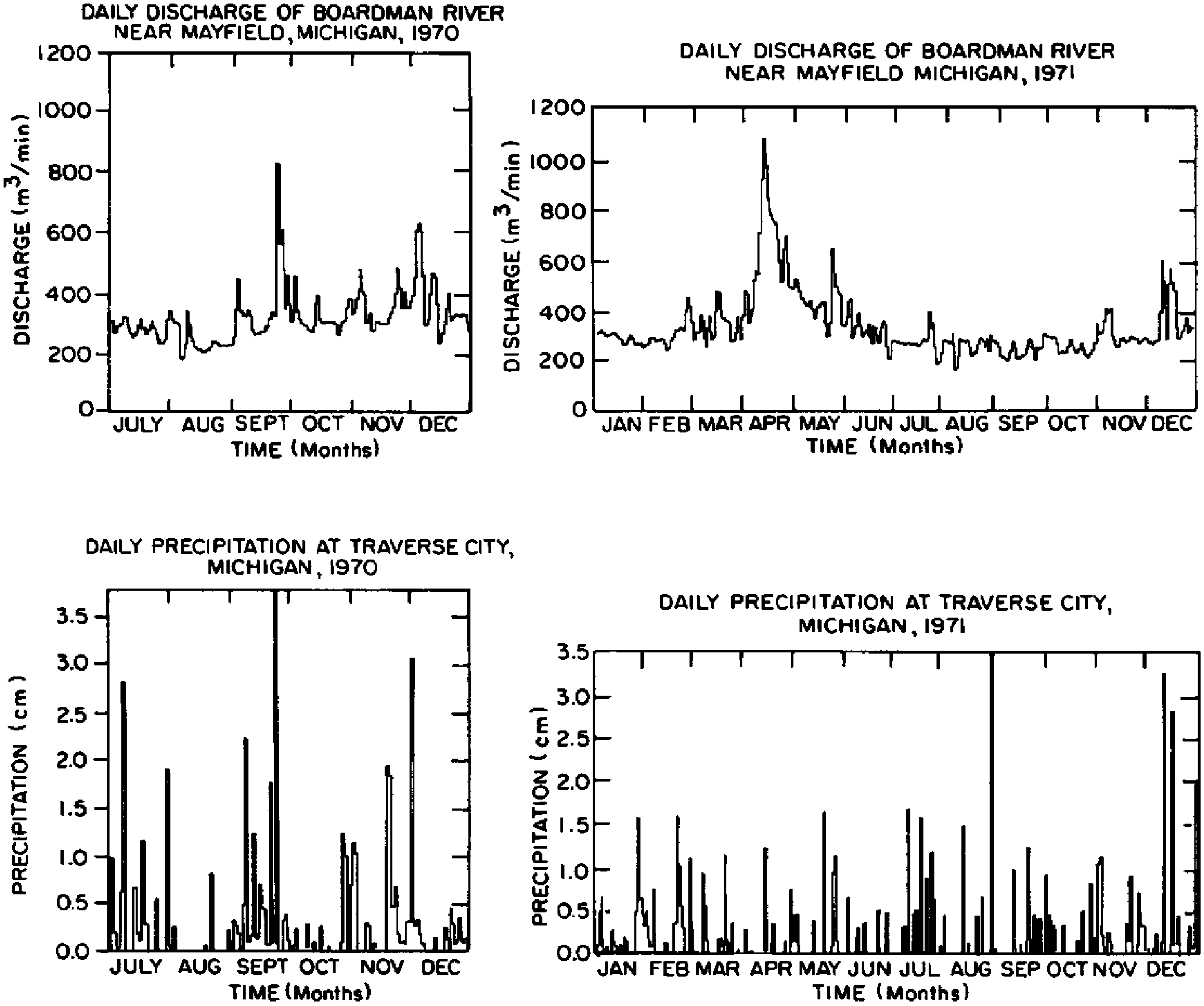


FIGURE IX-2. Hydrologic characteristics of the Grand Traverse Bay region (modified from Gannon and Meier 1974).

TABLE IX-2. Drought flow characteristics of the Boardman River at Mayfield (m^3/min) (after Gannon and Meier 1974)

Return Period	1-day	7-day	14-day	30-day
Most Probable	184	226	233	248
5-year	138	170	185	216
10-year	119	150	163	197
20-year	102	127	141	182

Boardman River is the most significant tributary source contributing 92% of the average flow, whereas in the east arm the Elk River contributes 93% of the hydrologic input.

Contaminant Sources

Summary

The results obtained from the hydrologic and tributary monitoring studies permit a clear identification of the relative loading contributions from bay tributaries. These results are summarized in Tables IX-3 and IX-4. Major nutrient, organic, major ion, and trace metal concentrations were relatively low in most of the tributary discharges. Of all samples analyzed the average organic and nutrient concentrations were 1.65 mg/ℓ of BOD_5, 530 μgN/ℓ of nitrate, 120 μgN/ℓ of ammonia, 13 ∂gP/ℓ of total phosphorus, and 3.4 mgSi/ℓ of silicon. Concentrations varied but were always of the same magnitude. The Boardman River typically had higher concentrations, with averages of 3.35 mg/ℓ BOD_5, 177 μgN/ℓ of ammonia, and 32 μgP/ℓ. Silicon and nitrate concentrations in the Boardman River were not significantly higher than the other tributaries. Trace metal and major ion concentrations in the Boardman River were also low and relatively consistent, with average tributary measurements of 71.5 mg/ℓ of calcium, 3.35 mg/ℓ of sodium, 16.7 mg/ℓ of magnesium, 1.37 mg/ℓ of potassium, 2 μg/ℓ of chromium, 6 μg/ℓ of manganese, 42 μg/ℓ of iron, 7 μg/ℓ of cobalt, 7 μg/ℓ of nickel, 24 μg/ℓ of copper, 8 μg/ℓ of zinc and 42 μg/ℓ of strontium. The variance from these averages among all tributaries was minimal. In all cases these levels reflect relatively unpolluted background river water concentrations. A comparison of the average Grand Traverse Bay tributary concentrations as compared to other tributaries to Lake Michigan and Saginaw Bay show no serious contamination in Grand Traverse Bay tributary waters (Table IX-5). The relative significance of nitrogen and phosphorus concentrations is small

Table IX-3. Average tributary BOD and major nutrient concentrations and loadings, 1970--1971.

	BOD$_5$		NO$_3$-N		NH$_3$-N		Si		TDP		TP	
Location	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day
Open Bay												
Northport Cr	1.4	9,556	.453	3,092	.059	403	2.70	18,430	.013	89	.015	102
% tot. Bay		.19		.54		.13		.26		.20		.18
% Spec. Area		82.05		71.64		89.76		70.04		89.00		88.70
Ennis Cr.	.96	2,090	.562	1,224	.021	46	3.62	7,882	.005	11	.006	13
% tot. Bay		.04		.21		.02		.11		.02		.02
% Spec. Area		17.95		28.36		10.24		29.96		11.00		11.30
West Arm												
Bellangers Cr	1.35	27,381	.722	14,644	.052	1,055	3.10	62,874	.007	142	.012	243
% tot. Bay		.55		2.56		.35		.88		.32		.43
% Spec. Area		.86		5.97		.64		1.92		.40		.63
Setterbo Cr	.95	1,325	1.286	1,793	.047	66	3.42	4,769	.004	6	.009	13
% tot. Bay		.03		.31		.02		.07		.01		.02
% Spec. Area		.04		.73		.04		.15		.02		.03
Sutton's Bay Cr	.98	3,453	1.496	5,271	.035	123	3.66	12,894	.007	25	.015	53
% tot. Bay		.07		.92		.04		.18		.06		.09
% Spec. Area		.11		2.15		.07		.39		.07		.14
Leo(Wheaton)Cr	1.49	14,800	.635	6,308	.060	596	2.45	24,336	.010	99	.014	139
% tot. Bay		.30		1.10		.20		.34		.22		.25
% Spec. Area		.47		2.57		.36		.74		.28		.36
Cedar Cr.	1.77	39,970	.203	4,584	.058	1,310	2.87	64,810	.027	610	.028	632
% tot. Bay		.80		.80		.44		.90		1.39		1.12
% Spec. Area		1.26		1.87		.79		1.98		1.72		1.63
Brewery Cr	1.28	5,668	1.138	5,039	.064	283	4.09	18,112	.007	31	.011	49
% tot. Bay		.11		.88		.09		.25		.07		.09
% Spec. Area		.18		2.06		.17		.55		.09		.13
Creek #1	1.94	2,136	.437	481	.074	81	4.66	5,130	.006	7	.008	9
% tot. Bay		.04		.08		.03		.07		.02		.02
% Spec. Area		.07		.20		.05		.16		.02		.02
Creek #2	3.34	5.965	.180	321	.118	211	5.50	9,823	.006	11	.009	16
% tot. Bay		.12		.06		.07		.14		.02		.03
% Spec. Area		.19		.13		.13		.30		.03		.04
Boardman R.	3.35	3068588	.221	202,435	.177	162,131	3.35	3068588	.032	29,312	.041	37,556
% tot. Bay		61.32		35.44		53.92		42.78		66.64		66.38
% Spec. Area		96.82		82.56		97.75		93.80		82.82		97.02
East Arm												
Mitchell Cr.	1.87	76,678	.49	20,092	.082	3,362	2.73	111,942	.010	410	.014	574
% tot. Bay		1.53		3.55		1.12		1.56		.93		1.01
% Spec. Area		4.21		6.24		2.50		2.89		4.83		3.23
Bakers Cr.	1.76	7,708	.109	477	.062	272	4.04	17,693	.007	31	.010	44
% tot. Bay		.15		.08		.09		.25		.07		.08
% Spec. Area		.42		.15		.20		.46		.36		.25
Acme Cr.	1.30	46,245	.055	1,957	.063	2,241	2.88	102,451	.007	249	.009	320
% tot. Bay		.92		.34		.75		1.43		.57		.57
% Spec. Area		2.54		.61		1.67		2.64		2.93		1.80
Yuba Cr.	1.58	35,254	.786	17,538	.047	1,049	2.73	60,914	.007	156	.011	245
% tot. Bay		.70		3.06		.35		.85		.35		.43
% Spec. Area		1.93		5.45		.78		1.57		1.84		1.38
Elk River	1.30	1657063	.221	281,701	.100	127,466	2.81	3581805	.006	7,648	.013	16,571
% tot. Bay		33.12		49.30		42.39		49.94		17.39		29.29
% Spec. Area		90.90		87.55		94.85		92.44		90.04		93.34
% Total Bay												
Open Bay		.23		.76		.15		.37		.23		.20
West Arm		63.34		42.92		55.16		45.61		80.46		68.42
East Arm		36.43		56.32		44.69		54.02		19.31		31.38
Totals gms/day												
Open Bay		11,646		4,316		449		26,312		100		115
West Arm		3,169,286		245,192		165,856		3,271,336		35,391		38,710
East Arm		1,822,948		321,765		134,390		3,874,805		8,494		17,754
Total		5,003,880		571,273		300,695		7,172,453		43,985		56,579

Table IX-4. Trace metal loadings - Grand Traverse Bay

Location	Na		Mg		K		Cr		Mn		Fe	
	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day
Open Bay												
A. Northport Cr.	4.07	27,782	19.40	132,423	1.82	12,423	.002	14	.007	48	.044	300
% total Bay		.34		.41		.43		.25		.37		.37
% Open Bay												
West Arm												
A. Bellangers Cr.	2.24	45,432	17.96	364,266	1.34	27,178	.003	61	.006	122	.027	548
% total Bay		.56		1.13		.94		1.08		.95		.67
% West Arm		1.32		2.67		2.06		2.16		1.29		.95
B. Setterbo Cr.	2.72	3,793	21.90	30,541	1.33	1,855	.001	1	.003	4	.018	25
% total Bay		.05		.09		.06		.02		.03		.03
% West Arm		.11		.22		.14		.03		.04		.04
C. Suttons Bay Cr.	3.95	13,916	20.30	71,518	1.92	6,764	.002	7	.005	18	.046	162
% total Bay		.17		.22		.23		.12		.14		.20
% West Arm		.41		.52		.51		.24		.19		.28
D. Leo(Wheaton)Cr.	6.11	60,691	14.80	147,010	1.60	15,893	.002	20	.007	70	.067	666
% total Bay		.75		.45		.55		.35		.54		.82
% West Arm		1.77		1.08		1.20		.69		.74		1.15
E. Cedar Cr.	3.24	73,165	17.71	399,925	1.23	27,776	.002	45	.002	45	.013	294
% total Bay		.90		1.24		.96		.79		.35		.36
% West Arm		2.13		2.93		2.10		1.56		.48		.51
F. Brewery Cr.	2.75	12,178	20.30	89,894	1.11	4,915	.001	4	.007	31	.062	275
% total Bay		.15		.28		.17		.07		.24		.34
% West Arm		.35		.66		.37		.14		.33		.48
G. Boardman River	3.59	3,284,914	13.71	12,544,893	1.35	1,235,274	.003	2745	.010	9150	.061	55,816
% total Bay		40.48		38.82		42.68		28.41		70.90		68.52
% West Arm		95.68		91.92		93.61		95.21		96.93		96.59
East Arm												
A. Mitchell Cr.	3.64	149,257	15.60	639,671	1.41	57,816	.002	82	.010	410	.056	2296
% total Bay		1.84		1.98		2.00		1.45		3.18		2.82
% East Arm		3.21		3.45		3.70		2.96		12.00		9.82
B. Bakers Cr.	2.73	11,956	16.50	72,259	1.46	6,394	.001	4	.007	31	.059	258
% total Bay		.15		.22		.22		.07		.24		.32
% East Arm		.26		.39		.41		.14		.91		1.10
C. Acme Cr.	2.80	99,605	14.25	506,917	1.10	39,130	.002	71	.007	249	.058	2063
% total Bay		1.23		1.57		1.35		1.25		1.93		2.53
% East Arm		2.14		2.74		2.51		2.56		7.28		8.82
D. Yuba Dr.	2.68	59,798	16.11	359,458	1.39	31,015	.003	67	.008	179	.041	915
% total Bay		.74		1.11		1.07		1.18		1.39		1.12
% East Arm		1.28		1.94		1.99		2.42		5.24		3.91
E. Elk River	3.40	4,333,857	13.30	16,953,027	1.12	1,427,623	.002	2549	.002	2549	.014	17,845
% total Bay		53.40		52.47		49.33		44.96		19.75		21.91
% East Arm		93.11		91.48		91.40		91.92		74.58		76.34
% of total Bay												
1. Open Bay		.34		.41		.43		.25		.37		.37
2. West Arm		42.31		42.24		45.60		50.85		73.14		70.94
3. East Arm		57.35		57.35		53.97		48.90		26.49		28.69
Totals gms/day												
1. Open Bay		27,782		132,423		12,423		14		48		300
2. West Arm		3,433,398		13,648,047		1,319,655		2,883		9,440		57,786
3. East Arm		4,654,473		18,531,332		1,561,978		2,773		3,418		23,377
TOTAL		8,115,653		32,311,802		2,894,056		5,670		12,906		81,463

(Part II) Table IX-4. Trace metal loadings - Grand Traverse Bay

	Co		Ni		Cu		Zn		Sr		Ca	
Location	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day	mg/ℓ	gms/day
Open Bay												
A. Northport Cr.	.008	55	.008	55	.003	20	.010	68	.085	580	69	471,000
% total Bay		.36		.38		.29		.30		.66		.38
% Open Bay												
West Arm												
A. Bellangers Cr.	.008	162	.008	162	.002	41	.008	162	.038	771	82	1,663,000
% total Bay		1.05		1.12		.59		.72		.87		1.33
% West Arm		2.34		2.72		1.42		1.86		1.65		2.67
B. Setterbo Cr.	.009	13	.010	14	.002	3	.003	4	.054	75	95	132,000
% total Bay		.08		.10		.04		.02		.09		.11
% West Arm		.19		.24		.10		.05		.16		.21
C. Suttons Bay Cr.	.008	28	.008	28	.004	14	.013	46	.058	204	90	317,000
% total Bay		.18		.19		.20		.21		.23		.25
% West Arm		.41		.47		.49		.53		.44		.51
D. Leo(Wheaton)Cr.	.009	89	.009	89	.002	20	.009	89	.044	437	80	795,000
% total Bay		.58		.62		.29		.40		.50		.64
% West Arm		1.29		1.50		.69		1.02		.93		1.28
E. Cedar Cr.	.008	181	.006	135	.002	45	.007	158	.007	158	61	1,377,000
% total Bay		1.17		.94		.64		.71		.18		1.10
% West Arm		2.62		2.27		1.56		1.81		.34		2.21
F. Brewery Cr.	.008	35	.007	31	.003	13	.007	31	.062	275	84	372,000
% total Bay		.23		.22		.19		.14		.31		.30
% West Arm		.51		.52		.45		.36		.59		.60
G. Boardman River	.007	6405	.006	5490	.003	2745	.009	8235	.049	44,826	63	57,646,000
% total Bay		41.47		38.12		39.34		36.85		50.88		46.11
% West Arm		92.65		92.28		95.28		94.38		95.89		92.53
East Arm												
A. Mitchell Cr.	.009	369	.007	287	.003	123	.007	287	.045	1845	68	2,788,000
% total Bay		2.39		1.99		1.76		1.28		2.09		2.23
% East Arm		4.35		3.42		3.02		2.12		4.52		4.48
B. Bakers Cr.	.007	31	.008	35	.003	13	.008	35	.032	140	74	324,000
% total Bay		.20		.24		.19		.16		.16		.26
% East Arm		.37		.42		.32		.26		.34		.52
C. Acme Cr.	.007	249	.007	249	.002	71	.008	285	.029	1032	64	2,777,000
% total Bay		1.61		1.73		1.02		1.28		1.17		2.22
% East Arm		2.94		2.96		1.74		2.10		2.53		4.46
D. Yuba Cr.	.008	179	.008	179	.002	45	.009	201	.036	803	69	1,540,000
% total Bay		1.16		1.24		.64		.90		.91		1.23
% East Arm		2.11		2.13		1.10		1.48		1.97		2.47
E. Elk River	.006	7648	.006	7648	.003	3824	.010	12,747	.029	36,965	43	54,811,000
% total Bay		49.52		53.10		54.81		87.04		41.95		43.84
% East Arm		90.23		91.07		93.82		94.04		90.63		88.06
% of total Bay												
1. Open Bay		.36		.38		.29		.30		.66		.38
2. West Arm		44.76		41.31		41.29		39.04		53.06		49.84
3. East Arm		54.88		58.31		58.42		60.66		46.28		49.78
Totals gms/day												
1. Open Bay		55		55		20		68		580		471,000
2. West Arm		6,913		5,949		2,881		8,725		46,756		62,302,000
3. East Arm		8,476		8,398		4,076		13,555		40,785		62,240,000
TOTAL		15,444		14,402		6,977		22,348		88,121		125,015,000

TABLE IX-5. Average river concentrations in Grand Traverse Bay and selected other Great Lakes tributaries

Location	NO_3 (mg/ℓ)	NH_3 (mg/ℓ)	Si (mg/ℓ)	TDP (mg/ℓ)	TP (mg/ℓ)	Na (mg/ℓ)	Mg (mg/ℓ)	K (mg/ℓ)	Co (μg/ℓ)	Ni (μg/ℓ)	Cu (μg/ℓ)	Zn (μg/ℓ)
<u>Grand Traverse Bay Tributaries</u>	0.53	0.12	3.4	0.010	0.013	16.7	16.7	1.37	7.	7.	2.4	8.
Boardman River	0.22	0.18	3.35	0.032	0.041	13.71	13.7	1.35	7.	6.	3	9.
Elk River	0.22	0.10	2.81	0.006	0.013	13.3	13.3	1.12	6.	6.	3	10
<u>Lake Michigan Tributaries</u>												
Manistique River	0.26	0.21	2.71	0.013	---	2.1	7.6	0.8	--	2.	8.	2.
Sheboygan River	0.87	0.63	1.82	0.13	---	17	24.	3.2	--	14.	9.	11.
Milwaukee River	0.80	1.5	1.31	0.20	---	23	18.	3.0	--	4.	11.	6.
Grand River	0.72	0.68	2.48	0.17	---	28	26.	2.8	--	4.	14.	ND
Muskegon River	0.24	0.17	2.62	0.02	---	9.4	14.	1.1	--	3.	11.	ND
Fox River	0.10	1.6	4.39	0.09	---	14.	14.	3.8	--	2.	9.	ND
<u>Saginaw Bay Tributaries</u>												
Au Gres River	0.58	>0.1	---	0.037	0.038	---	19.3	---	5.	12.	--	23.
AuSable River	0.07	---	---	0.014	0.025	---	11.6	---	2.	5.	--	6.
Kawkaulin River	1.29	0.2	---	0.050	0.125	---	21.4	---	4.	8.	--	9.
Rifle River	0.19	>0.1	---	0.019	0.052	---	16.4	---	4.	7.	--	8.
Saginaw River	1.25	0.5	---	0.145	0.235	---	23.2	---	7.	10.	--	14.
Sebewang River	4.74	0.2	---	0.050	0.139	---	23.4	---	5.	7.	--	7.
Tawas River	0.14	0.5	---	0.029	0.068	---	9.6	---	3.	13.	--	14.

(Sources listed in Appendix A.)

when compared with more polluted streams such as those existing in the Saginaw Bay basin of Michigan. The trace metal and major ion contaminant concentrations are also relatively low. The use of the term "contaminant sources" in this discussion may be misleading considering the low concentrations in tributary discharges. These levels are often of same magnitude as those found in open waters of the Great Lakes (see Tables X-1, X-2). However, the effects of the Boardman and Elk Rivers are at times realized as changes in bay water quality, hence the term contamination is appropriate. In addition, because the bay water concentrations respond directly to tributary loadings all tributaries can be considered potential contaminant sources.

The bay received an average 1970-71 tributary organic load of 5,000,000 gms of BOD_5/day, over 570,000 gms NO_3-N/day, approximately 300,000 gms NH_3-N/day, over 7,000,000 gms Si/day and almost 57,000 gms P/day. The respective average metal and major ion loads were approximately 125,000 gms Ca/day, 8,100,000 gms Na/day, 32,300,000 gms Mg/day, 2,900,000 gms K/day, 81,500 gms Fe/day, 13,000 gms Mn/day, 5,700 gms Cr/day, 15,500 gms Co/day, 14,500 gms Ni/day, 7,000 gms Cu/day, 22,340 gms Zn/day and 88,000 gms Sr/day. The quantitative effects of these loadings are difficult to realize without the use of a detailed limnological model which considers flow, circulation, absorption/desorption, biological uptake, etc. Such models have been constructed and used to describe the response of the bay to some of these loadings (Canale 1973, Canale and Green 1972, Canale et al. 1973).

Tributary flow and concentration data can be used directly to compare relative loads to the bay. The Boardman and Elk Rivers, as expected from their hydrologic dominance, are the two most significant tributary discharges. The Boardman River, which contributes about half as much flow as the Elk River (one-third as much during the monitored dates) contributes the majority of the organic, ammonia, and phosphorus loading to the bay. During the 1970-1971 monitoring period, the Boardman River contributed an average of 61% of the total organics (BOD_5), 54% of the ammonia, and 61% of the phosphorus loading to the bay. The Elk River accounted for 33% of the BOD_5, 42% of the ammonia and 27% of the phosphorus. The Elk River was the major source of nitrate and silicon, contributing 45% and 50% respectively, with the Boardman River contributing only 35% and 43%. The Elk and Boardman Rivers combined contribute between 85% and 95% of all organics and major phytoplankton growth nutrients to the bay. The third largest river in the Grand Traverse Bay basin, Mitchell Creek, contributes typically less than 15% of the tributary load. All other contamination is distributed among the other smaller streams, principally in accordance with their relative flow.

The trace metal and major ion tributary loadings to the bay are also dominated by the Boardman and Elk Rivers. These loads are however more in accordance with the relative flow contribution of each stream. The main source of iron and manganese is the Boardman River, which contributes 71% and 49% of the total loads.

Industrial and municipal contamination to Grand Traverse Bay is minimal. During the first two years of this study, however, there were significant discharges from the Traverse City Waste Water Treatment Plant and several fruit processing companies located in Traverse City, Suttons Bay, and Elk Rapids. The Traverse City WWTP contributed significant loadings to the Boardman River, often elevating the phosphorus concentrations and resultant loadings five to 10 fold over upstream values. Since the end of 1973, however, a new treatment facility has operated with high efficiency, reducing the loadings drastically. It might be expected that in the future the lower west arm's water quality will be improving as a result of this abatement. Two other municipal treatment plants operate in the Grand Traverse Bay area, one in Suttons Bay which discharges to the bay and a second in Elk Rapids which discharges to the Elk River. Because of their relatively small size neither is expected to have significant impact on Grand Traverse Bay.

In addition to the reduction in municipal treatment discharge to the Boardman River, no fruit processing plants have been discharging directly to surface waters in the basin since 1975. In the past these seasonal discharges had dramatic localized effects on receiving water quality, resulting in waters which had high organic content, suspended solids, color, bacterial counts and nutrients. During the period of this study, however, the discharges were being eliminated and were not then considered to be significant factors affecting offshore bay water quality. They did however have some localized effects.

The following subsections are a detailed accounting of the contaminant sources to Grand Traverse Bay.

Industrial Discharges

Although today there exist no significant direct industrial discharges in the Grand Traverse Bay area, in the very recent past the system received large seasonal (late summer) waste loadings from fruit processing plants. Numerous cherry, apple and plum processing plants exist in the area. Several were responsible for discharging untreated wastes to the bay and its tributaries. These discharges were characterized by high suspended solids (40-100 mg/ℓ), high BOD_5 (400-800 mg/ℓ), high nutrient content (7,000-12,000 μg N/ℓ of Kjeldahl nitrogen and 400 to 600 μg P/ℓ) and bacterial counts often as high as 30,000,000 cells of total coliform per 100 ml (Michigan Water Resources Commission 1971a, 1971b). In years prior to this investigation discolored waters, floating cherry particles, and slime growths were commonly noted in waters receiving fruit processing wastes. Such observations, however, were not made during this study.

Direct discharges from fruit processing plants have decreased until the end of 1974, when the last plant ceased its surface water discharge. Today the fruit processing industry still flourishes in the region but all such industries dispose of their wastes either to municipal sewerage systems or to spray irrigation sites. The following discussion describes each of these industrial dischargers separately.

Frigid Foods, located on Suttons Bay, was the last fruit processor to abate a direct discharge to Grand Traverse Bay. The company switched to on-land disposal in 1974, and presently discharges only non-contact cooling waters to the bay. During the first four years of this investigation (1970-1973) Frigid Foods discharged untreated screened wastes to Suttons Bay. According to a Michigan Water Resources Commission Study (1971a)the plant discharged an average of 5.8 m^3/min of wastewater during its 20-30 day period of operation. Analysis of the wastewaters showed high levels of major nutrients averaging 0.63 mgP/ℓ and 6.9 mgN/ℓ of total Kjeldahl nitrogen, and high sulfate levels (12.5 mg SO_4/ℓ). The effluent was also characteristically high in turbidity, color, and bacterial concentrations. Fecal coliform counts of 12,000/100 ml were typical, whereas total coliform counts were measured to be 31,000,000 cells/100 ml.

The daily loads computed from the measured discharge concentrations are approximately 3,500,000 gms BOD_5/day, 455,000 gms suspended solids/ day, 5475 gms P/day, and 58,300 gms TKN/day. This effluent is equivalent in BOD to the raw wastes generated by 45,000 people daily, a number larger than twice the population of the Traverse City region, the most densely populated area in the basin (Colby 1971). The relative significance of these loads must be realized through comparison with the tributary loads of the system as given in Table IX-3. The organic loading rate (BOD_5) from this processing plant is equal to 70% of the average total tributary BOD_5 loadings to the entire bay (5,000,000 gms/day) and is 17% larger than the BOD_5 loadings coming from the Boardman River during a period when it was receiving poorly treated municipal wastes. The significance of this load cannot be overstressed. Fortunately, however, the waste waters were diluted sufficiently by the receiving waters so that the high oxygen-demanding organic wastes did not create severe oxygen depletion problems. The nutrient loads from the discharge were also significant but not as dramatic. Frigid Foods' phosphorus loadings accounted for a load equivalent to 8% of the bay's total phosphorus loading. Aside from Boardman and Elk Rivers, however, it would be the most significant discharge in the bay; an order of magnitude larger than all of the remaining tributaries. It should be noted, however, that the above discussion concerns daily rates and does not account for Frigid Foods' seasonally limited (3 to 4 week) discharge period. If the loads were integrated over a year's time, this industrial discharge would appear to be less significant. During its brief period of operation, however, its contamination to the bay is severe. Temporary and localized drops in receiving water quality would be expected.

The last fruit processing plant to abate a direct tributary discharge was Elk Rapids Packing Co. of Elk Rapids. Until 1975 this plant discharged screened but untreated sour cherry processing wastes to Elk Lake. A 1971(b) Michigan WRC industrial wastewater survey measured an average discharge waste of 2.5 m^3/min with average concentrations of 785 mg BOD_5/ℓ, 88 mg/ℓ suspended solids 50 μg P/ℓ, and 10.2 mg TKN/ℓ. Excessive color and turbidity were also observed. The resultant calculated loadings to Elk Lake and, hence, indirectly in part to Grand Traverse Bay were 2,950,000 gms BOD_5/day, 33,250 gms S.S./day, and 188 gms P/day. This load had an equivalent BOD discharge of 38,000 people. Gannon and Meier

(1974), however, estimated the Elk River Packing Company's discharge to be 5,400,000 gms BOD_5/day, equivalent to 69,500 people daily. In either case it is clear that this plant discharged excessive organic loadings to the Grand Traverse Bay system. The magnitude of these BOD_5 loadings is the same as the sum total of all other average tributary discharges to the bay. Again it must be noted that these discharges are only short term, and on a yearly basis would amount to between 5 and 10% of the bay's total organic loads. Temporary and localized effects might be realized near the mouth of the Elk River during periods of industrial discharge. Unfortunately no observations were made of water quality in the Elk River during periods of industrial discharge. Phosphorus loads from this plant were insignificant (less than 1% of the bay's total average tributary loading) quite in contrast with the Frigid Foods plant.

Another major fruit processing concern in the region, the Morgan-McCool Co., operated two cherry processing plants in Traverse City until 1972. Before this time one of its plants discharged directly to the bay just west of the Boardman River. Its second plant, early in its operations, discharged its wastes to the Boardman River approximately 3.5 km from the mouth, but during the course of this investigation was discharging to the Traverse City Waste Water Treatment Plant. No industrial waste surveys of the two plants were available. From the relative sizes of the plants it is estimated that they each discharged approximately 1,400,000 gms BOD_5/day. No phosphorus load estimate can be made.

Three additional fruit processing plants have discharged directly to the Grand Traverse Bay system in recent years, none of which have operated since 1971. Two of these companies, Cherry Growers, Inc. and F & M Packing Co., discharged directly to Grand Traverse Bay. They were both located approximately 1.5 kilometers east of the Boardman River mouth. Cherry Growers, Inc. closed its Traverse City operations in 1967 and F & M Packing Co. moved soon afterwards. Traverse City Canning Co. was the third plant, and was located on the Boardman River approximately 9 km upstream of the mouth. This plant's wastewater discharges were divided between a direct discharge to the Boardman River and a sewer linkup with the Traverse City Waste Water Treatment Plant. The last year of operation for this processing plant was 1971, after which it moved further south into the Boardman River basin and changed its waste disposal operations to a spray irrigation system. No specific information was available on the relative concentrations and loads from these processing plants.

Nutrient and organic loadings from fruit processing plants were, in the past, very significant contaminant contributors to the bay during their periods of operation. Temporary and localized effects were noted. The abatement of their discharges was important to the improvement and maintenance of Grand Traverse Bay water quality.

Municipal Discharges

The majority of the communities in the Grand Traverse Bay region are not presently served by municipal treatment systems but rather handle their wastes through individual septic tanks. Three areas are, however, served by municipal treatment systems which discharge directly or indirectly into the bay; they are: Traverse City, Elk Rapids, and Suttons Bay. Information on these plants is given in Table IX-6.

TABLE IX-6. Municipal sewage treatment facilities (1975).

Location	Population Served	Type	Estimate Flow (m^3/min)
Traverse City	21,000	Activated Sludge	9.44*
Elk Rapids	975	Trickling Filter	0.53
Suttons Bay	300	Stabilization Pond	0.14

*Includes phosphorus removal

The Traverse City plant serves a population of 21,000 people and discharges a mean flow of 13,600 m^3/day. The plant today uses secondary activated sludge treatment with phosphorus removal. This system replaced an outdated primary plant in late 1972. System failures, however, prevented consistent successful implementation of the secondary treatment with phosphorus removal until late in 1973. The plant operated in both phases during the duration of this study. Before the implementation of secondary treatment, the plant efficiency was very poor, removing only about 20% of influent BOD_5, 40-50% of the suspended solids and less than 10% of the influent phosphorus. Effluent concentrations averaged 140 mg BOD_5/ℓ, 95 mg/ℓ suspended solids, and 8000-9000 μg/ℓ total phosphorus. The resulting respective loads were 190,000 gms/day of BOD_5, 130,000 gms/day of suspended solids and 122,400 gms/day of total phosphorus. These loadings, particularly that of the phosphorus, had significant influences on the Boardman River and the bay which will be discussed in a later section. After implementation of a secondary treatment program coupled with phosphorus removal, the loading impact of the treatment plant dropped drastically. BOD_5 removal efficiency increased to 95% and the plant effluent consistently contains less than 10 mg BOD_5/ℓ . Similarly, suspended solids and phosphorus loadings were also reduced drastically. Plant phosphorus removal efficiency usually exceeds 95%. Phosphorus concentrations in the effluent are now 500 to 1000 μg P/ℓ with total effluent loadings to the Boardman River averaging about 9000 gms/day. The system today is no longer a major pollutant source to the Boardman River and Grand Traverse Bay. The plant discharge and operating statistics are summarized in Figures IX-3, IX-4, and IX-5. These figures clearly reveal the benefits derived from implementation of secondary treatment.

The two other municipal treatment systems operating in the Grand Traverse Bay area are both secondary plants. The Elk Rapids treatment

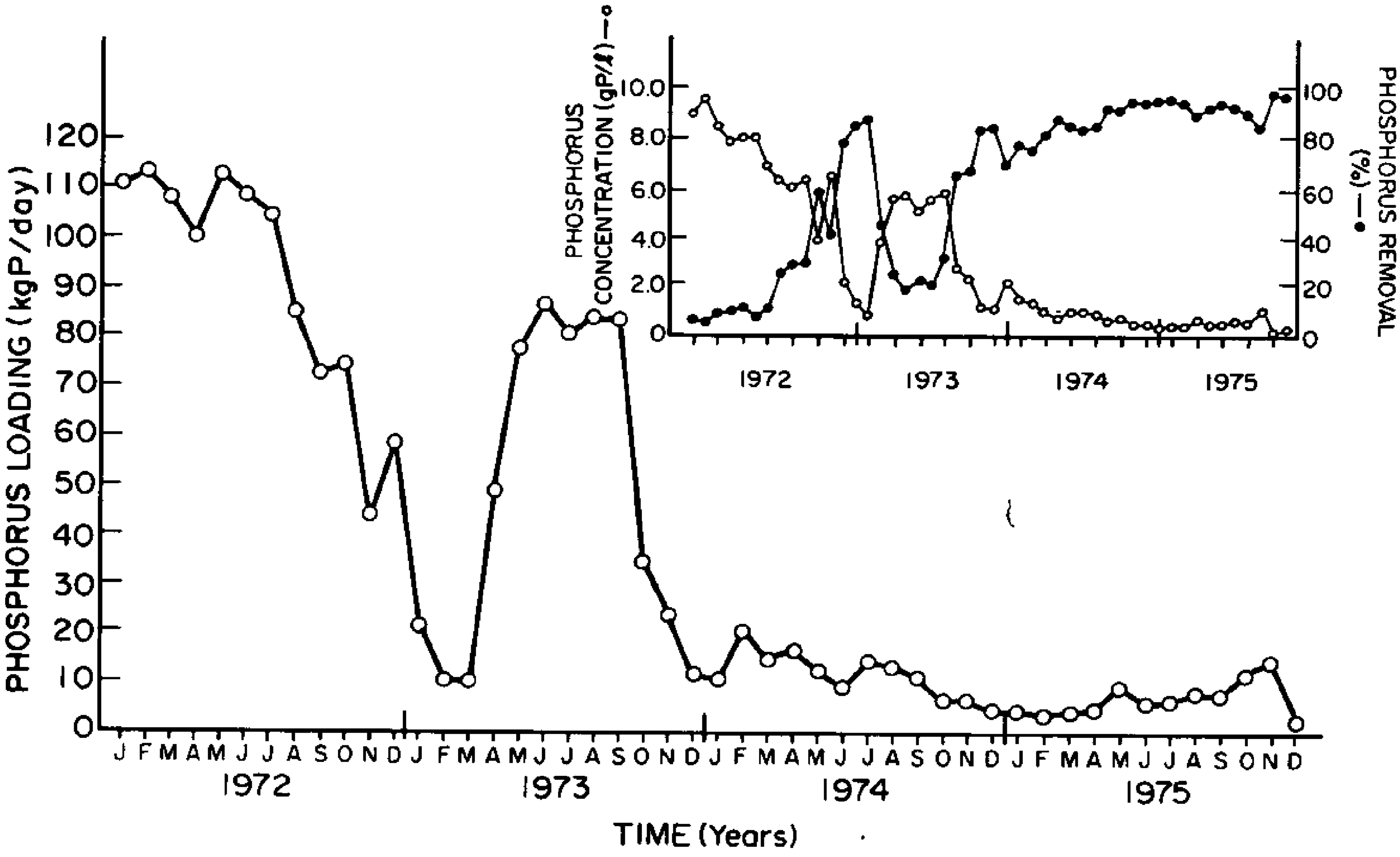


FIGURE IX-3. Phosphorus loading to the Boardman River by the Traverse City WWTP 1972-1975.

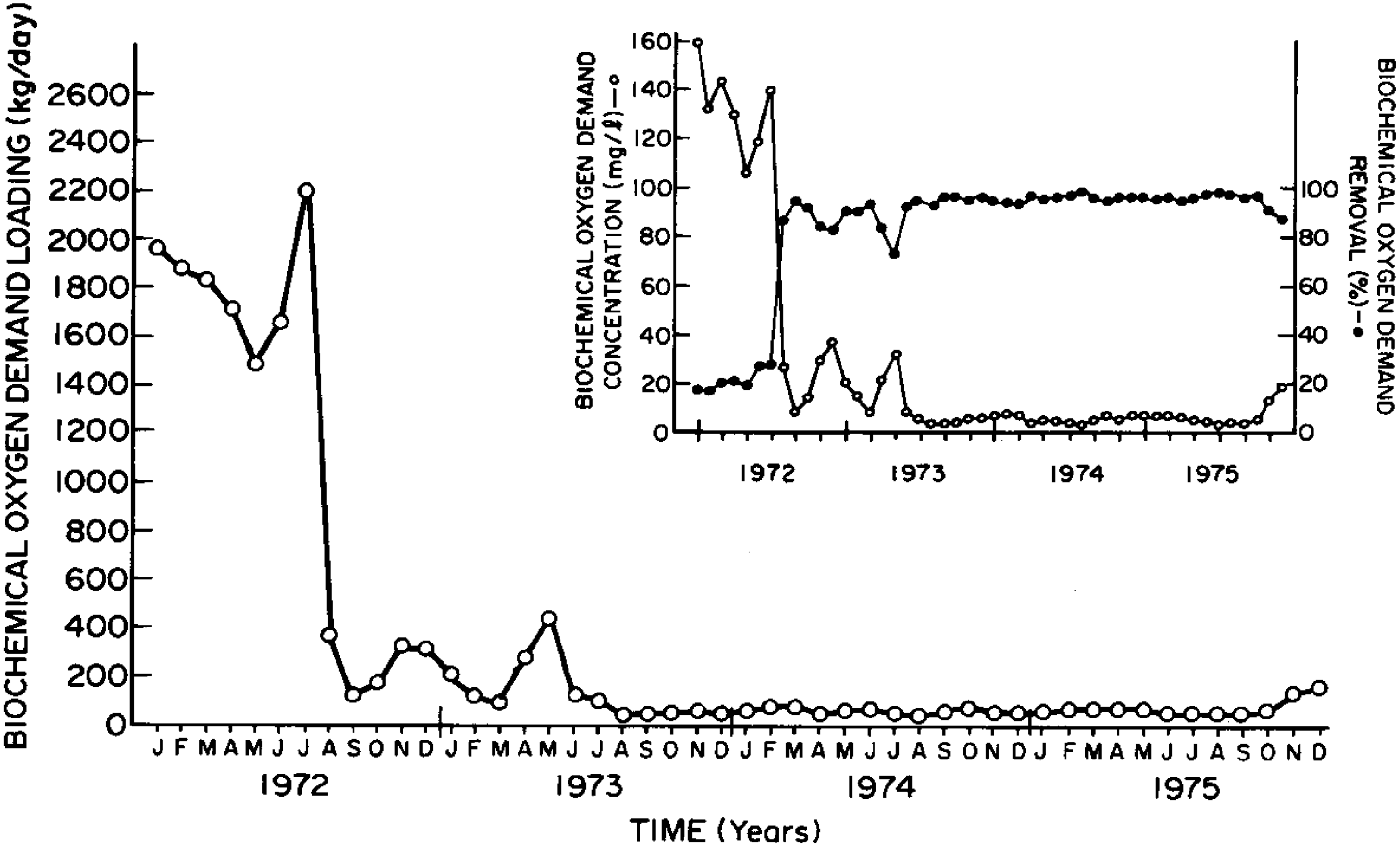


FIGURE IX-4. BOD loading to the Boardman River by the Traverse City WWTP 1972-1975.

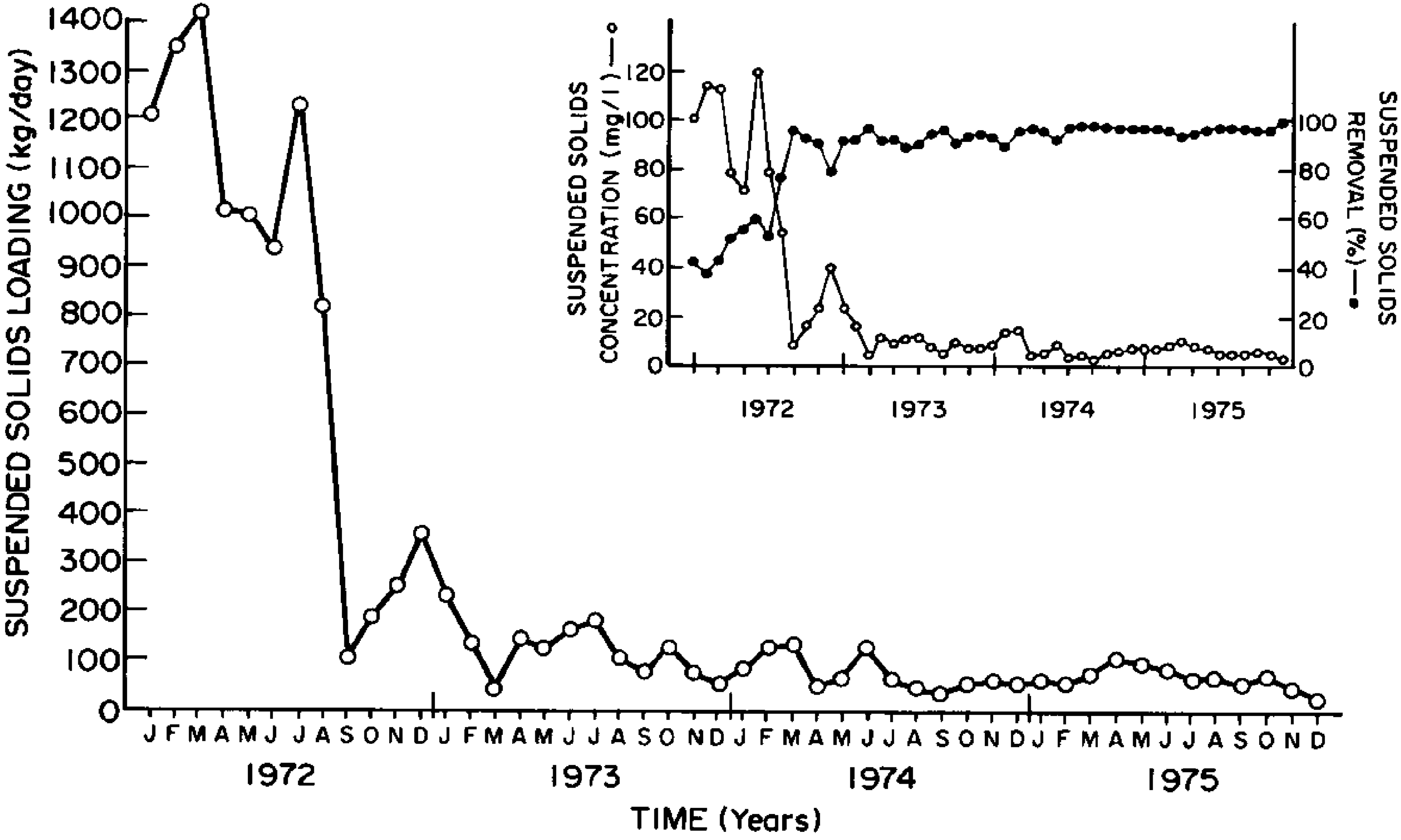


FIGURE IX-5. Suspended solids loading to the Boardman River by the Traverse City WWTP 1972-1975.

facility which serves 975 people is a trickling filter plant. It has an estimated average flow of 760 m^3/day and discharges to the Elk River system. The Suttons Bay treatment plant serves a community of 300. Stabilization ponds process approximately 200 m^3/day of wastewater. Because of their relatively low flows neither plant appears to have significant effects on water quality in Grand Traverse Bay.

Tributary Discharges, West Arm Tributaries

Boardman River

The Boardman River originates in the center of Kalkaska County, Michigan, and flows west-southwest and then north, eventually discharging into the west arm of Grand Traverse Bay. The river drains an area of 722 square kilometers. It is the largest tributary discharging to the west arm, although somewhat smaller than the Elk River. The USGS gauges the Boardman River flow routinely at Mayfield, Michigan. This location accounts for 68% of the river drainage basin. Flow at the mouth of the river can be calculated from gauged flows by a correlation factor of 1.47 as found by Brater (1972). The annual average calculated flow at the river mouth is 5.4 m^3/min. This is more than 90% of the entire hydrologic inflow to the west arm.

The Boardman River flows through Traverse City and receives waste discharges from the Traverse City Waste Water Treatment Plant and numerous storm sewer overflows. Before 1972 the river also received seasonal discharges from several fruit processing plants. During these periods the nutrient and organic contents of the river were elevated significantly above normal levels.

During the first phase of the Grand Traverse Bay investigation, the Boardman River was sampled for major nutrients, major ions, and trace metal concentrations on 19 dates and for river flow on eight occasions (see Tables IX-3 and IX-4). During 1972 and 1973 the river was monitored more frequently to accurately quantify the river loadings and their sources. The concentrations measured during these years are shown in Figures IX-6 through IX-11. Shown in Figures IX-12 through IX-14 are estimates of phosphorus and dissolved inorganic nitrogen loadings to the bay from the Boardman River.

The first phase of this investigation identified the significance of the Boardman River load to Grand Traverse Bay in relation to other tributary discharges. Prior to 1972 the Boardman River was the most significant contributor of BOD_5, ammonia, and phosphorus. It contributed 61% of the total organic loads as measured by BOD_5, 54% of the total ammonia loads, and 61% of the total phosphorus. The average 1970-1971 river concentrations of 3.35 mg BOD_5/ℓ, 177 $\mu g\ N/\ell$ of ammonia, and 41 $\mu g\ P/\ell$ were the highest of any of the tributaries measured. They were additionally much higher than those concentrations found in Grand Traverse Bay waters.

Concentrations measured in 1972 and 1973 (see Figures IX-6 through IX-11) were of the same magnitude as observed in 1970 and 1971. The plots

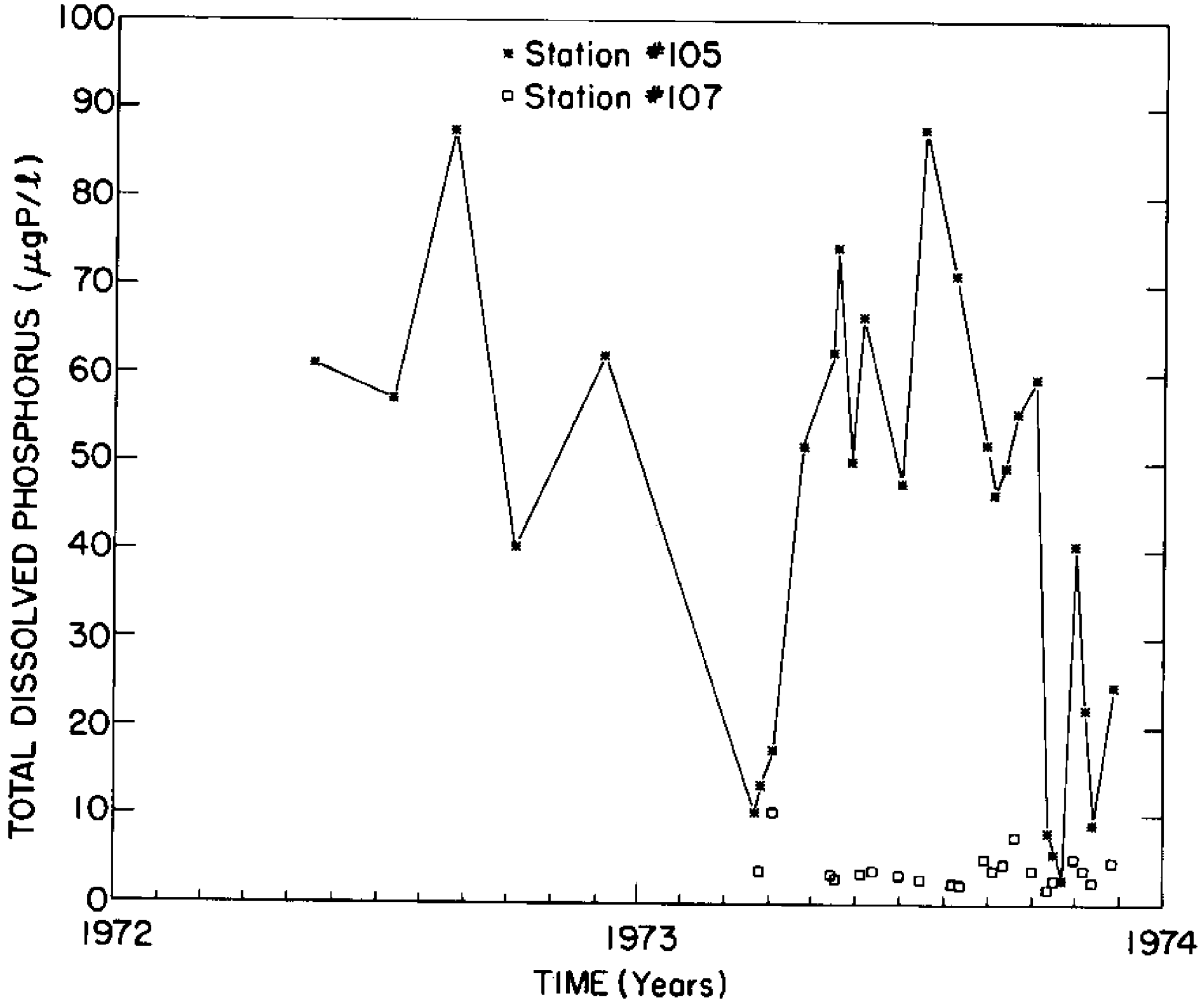


FIGURE IX-6. Total dissolved phosphorus concentrations in the Boardman River in 1972 and 1973.

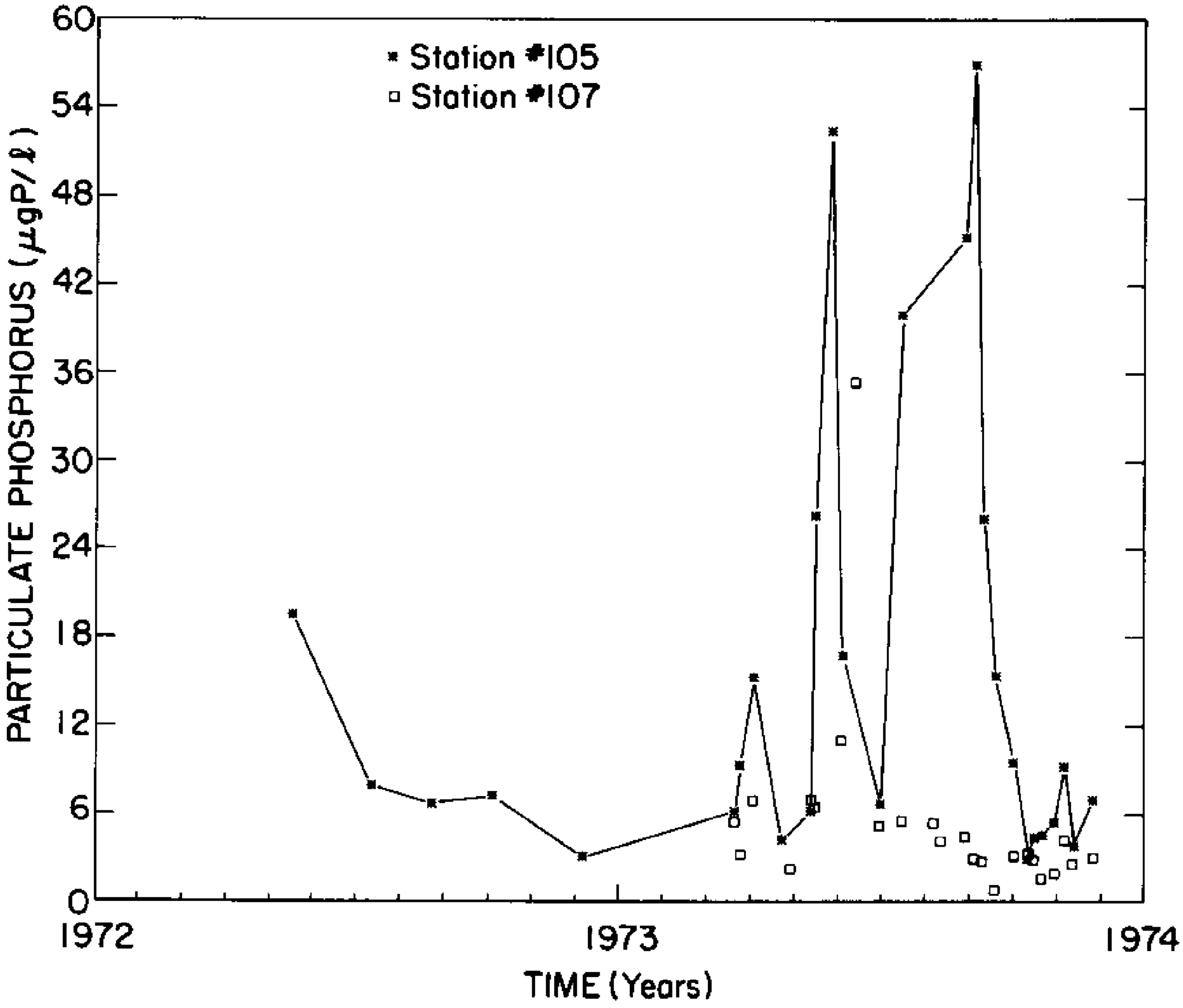


FIGURE IX-7. Particulate phosphorus concentrations in the Boardman River in 1972 and 1973.

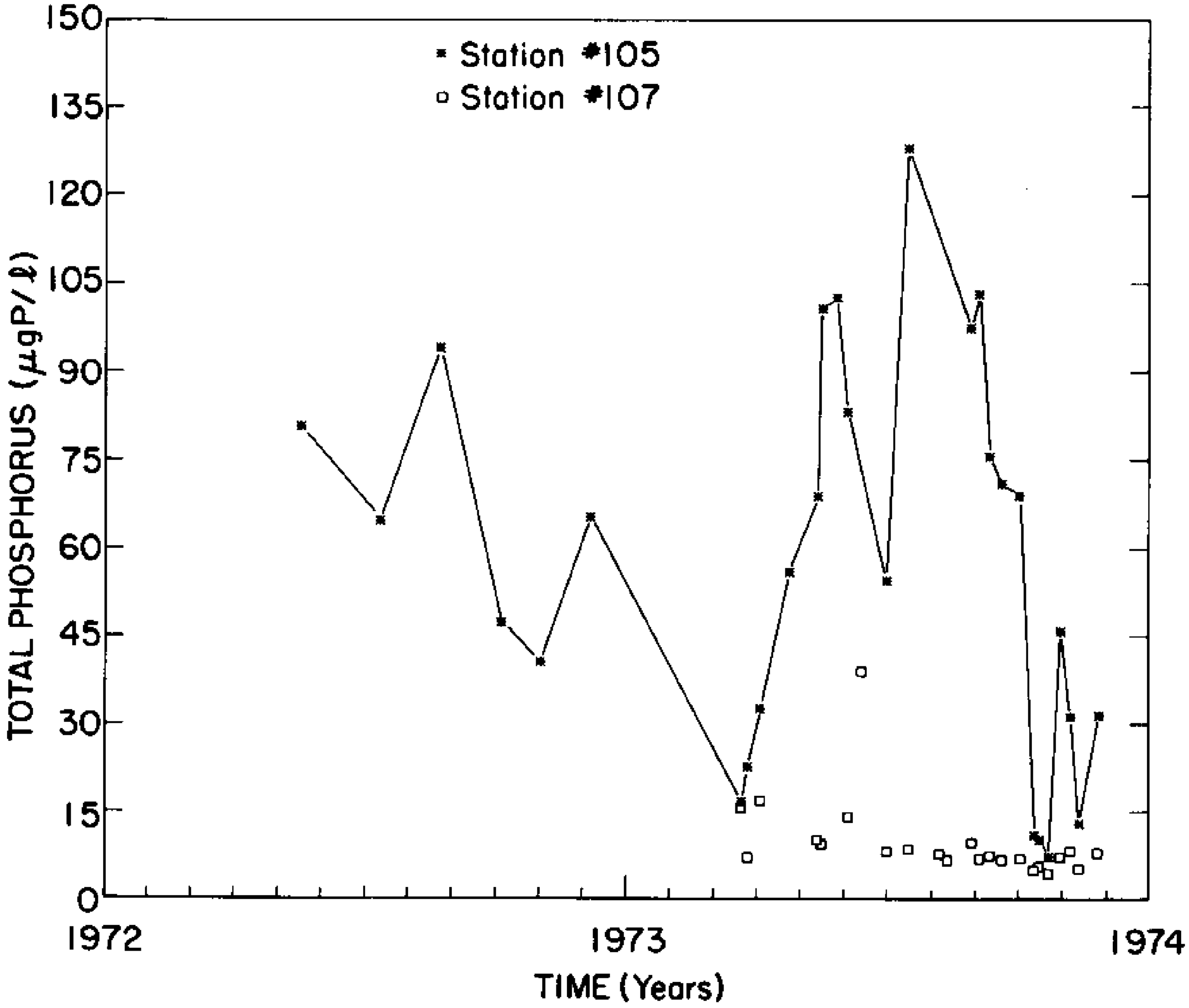


FIGURE IX-8. Total phosphorus concentrations in the Boardman River in 1972 and 1973.

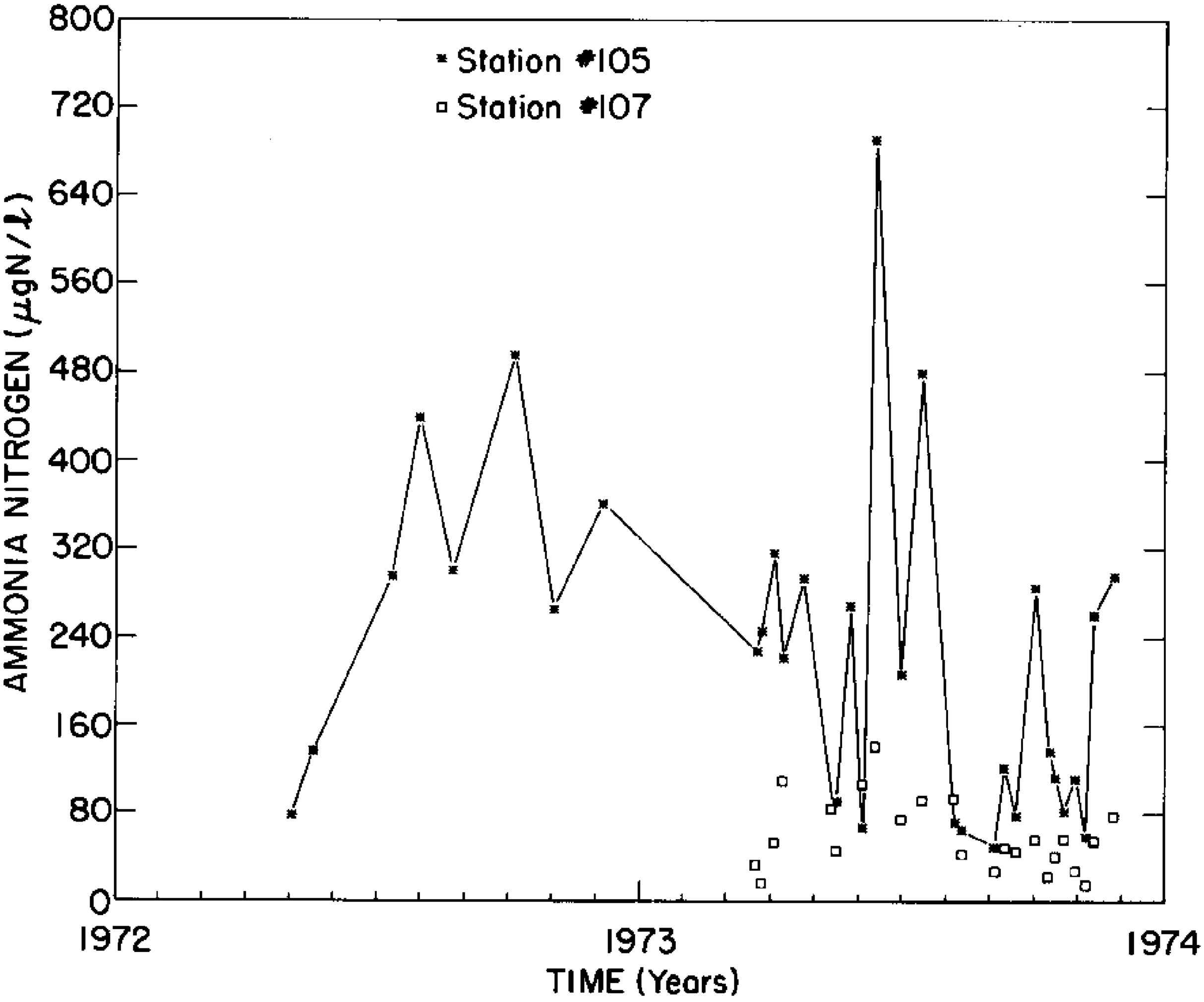


FIGURE IX-9. Ammonia-nitrogen concentrations in the Boardman River in 1972 and 1973.

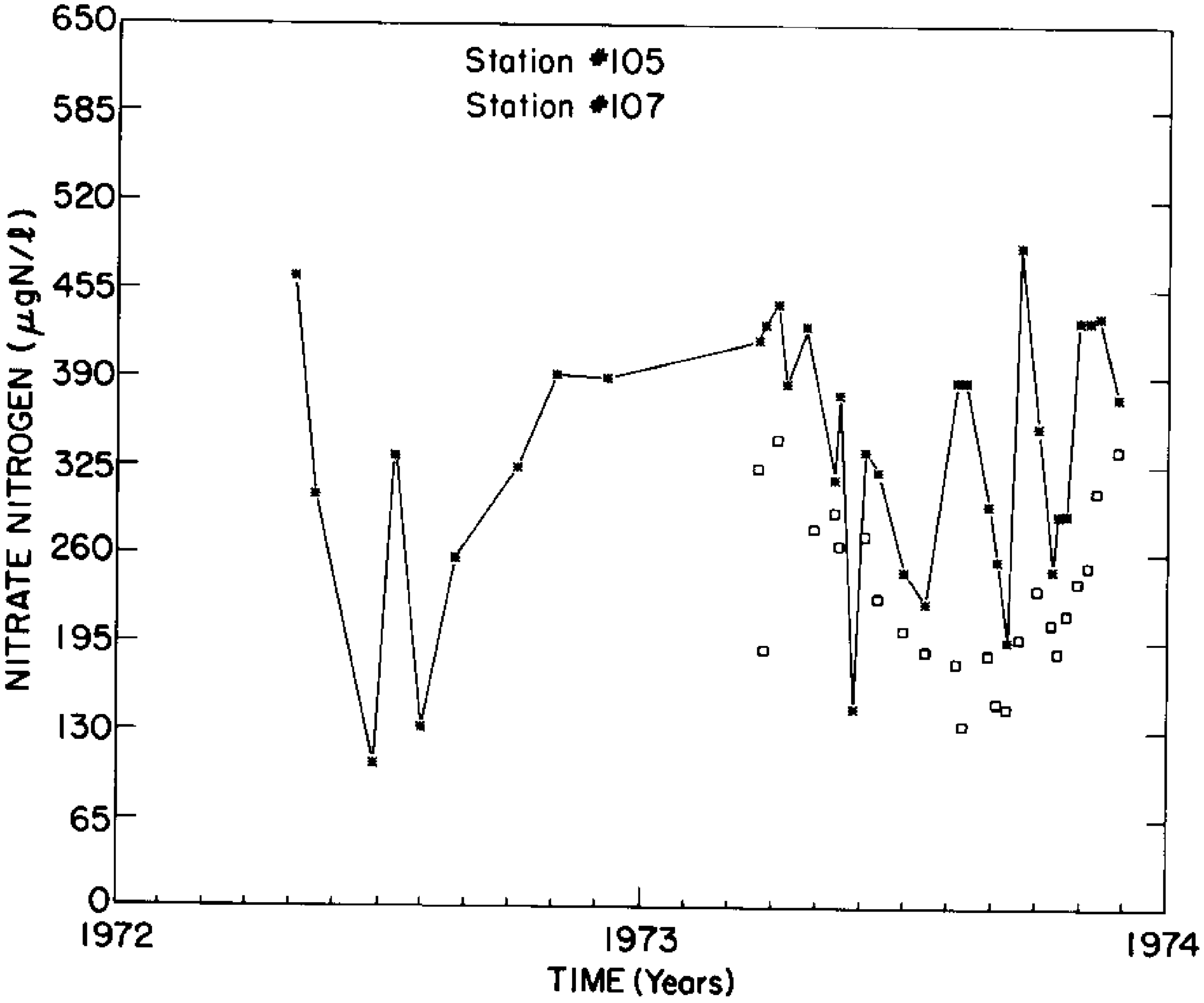


FIGURE IX-10. Nitrate-nitrogen concentrations in the Boardman River in 1972 and 1973.

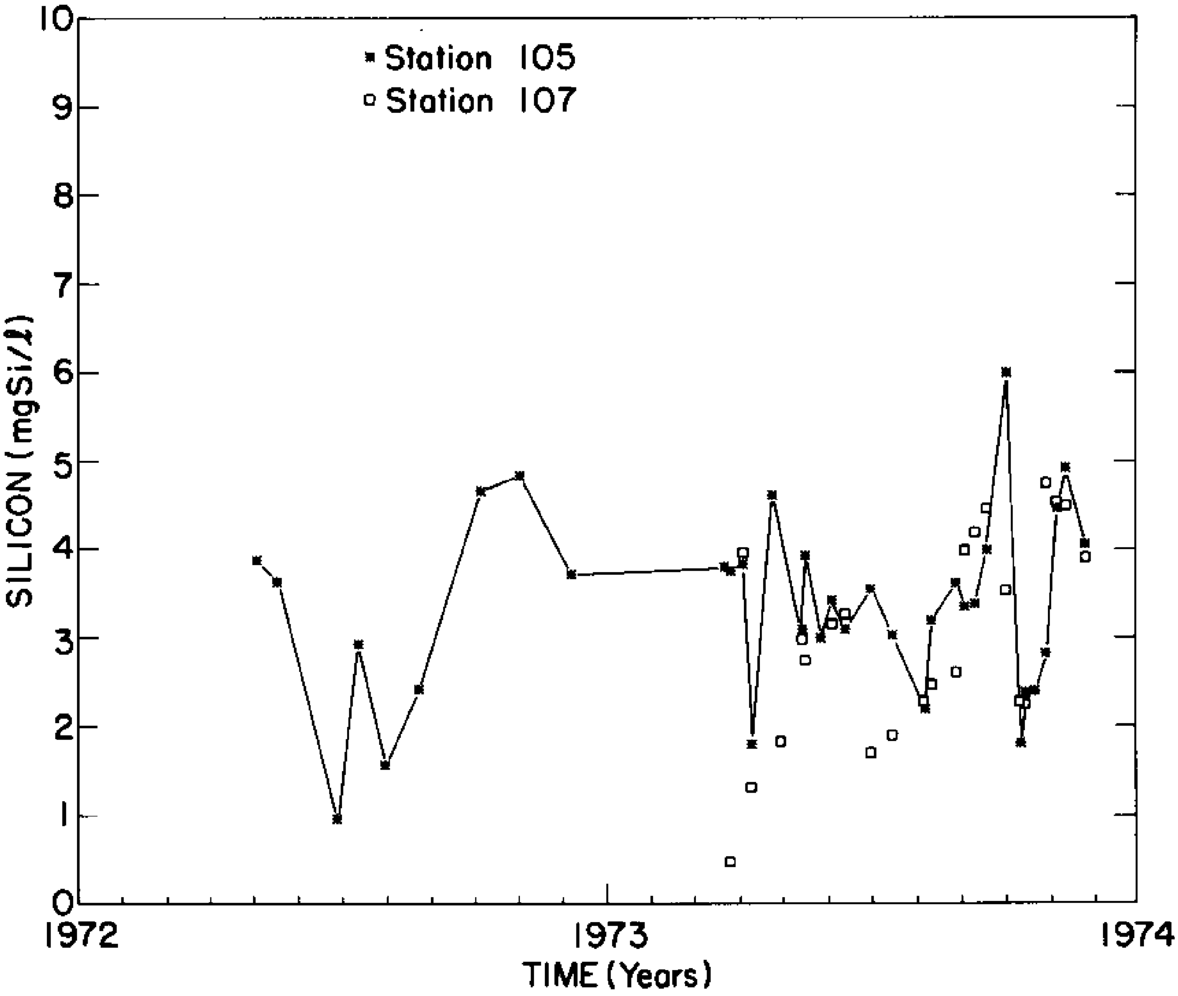


FIGURE IX-11. Silicon concentrations in the Boardman River in 1972 and 1973.

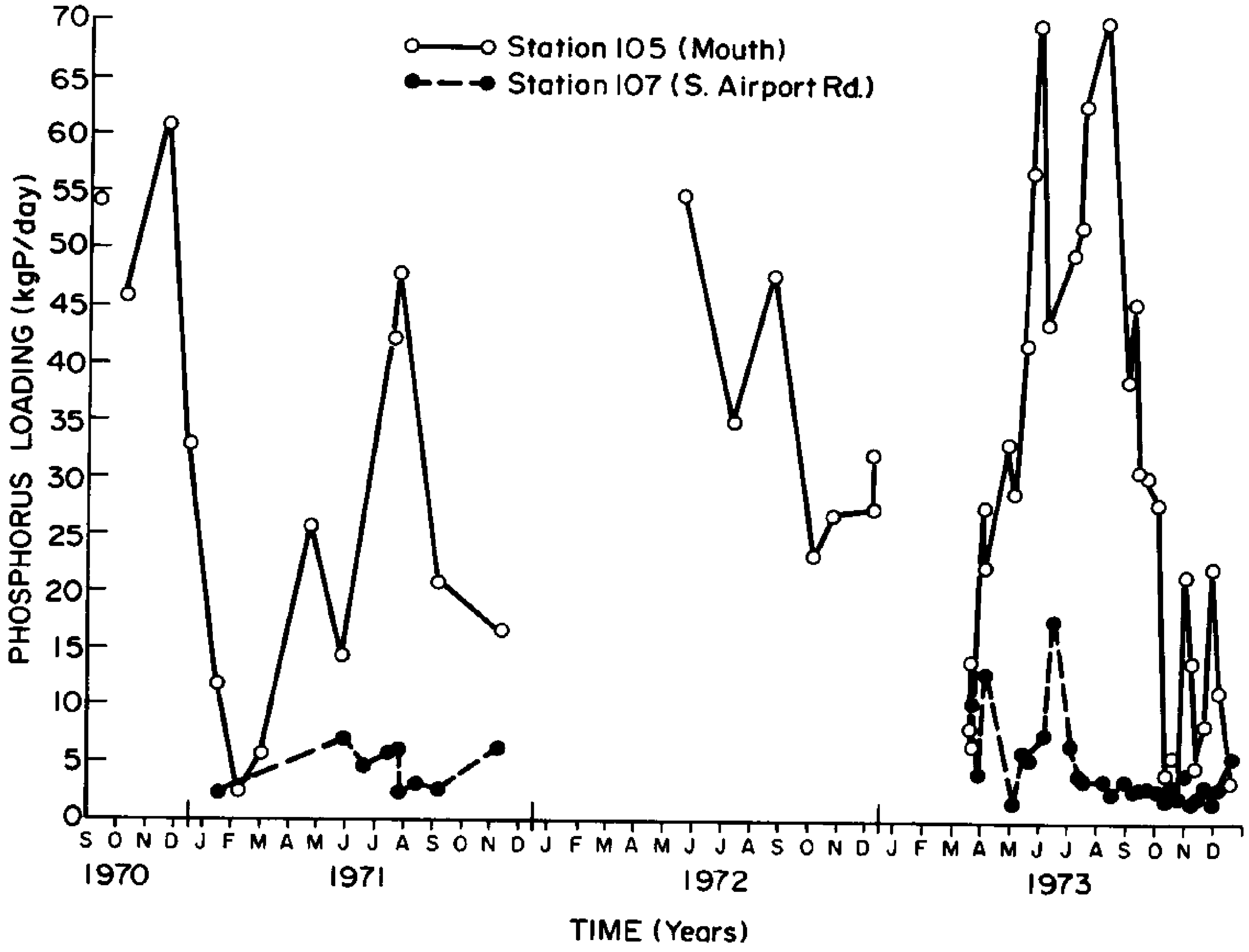


FIGURE IX-12. Phosphorus loading to Grand Traverse Bay by the Boardman River 1970-1973.

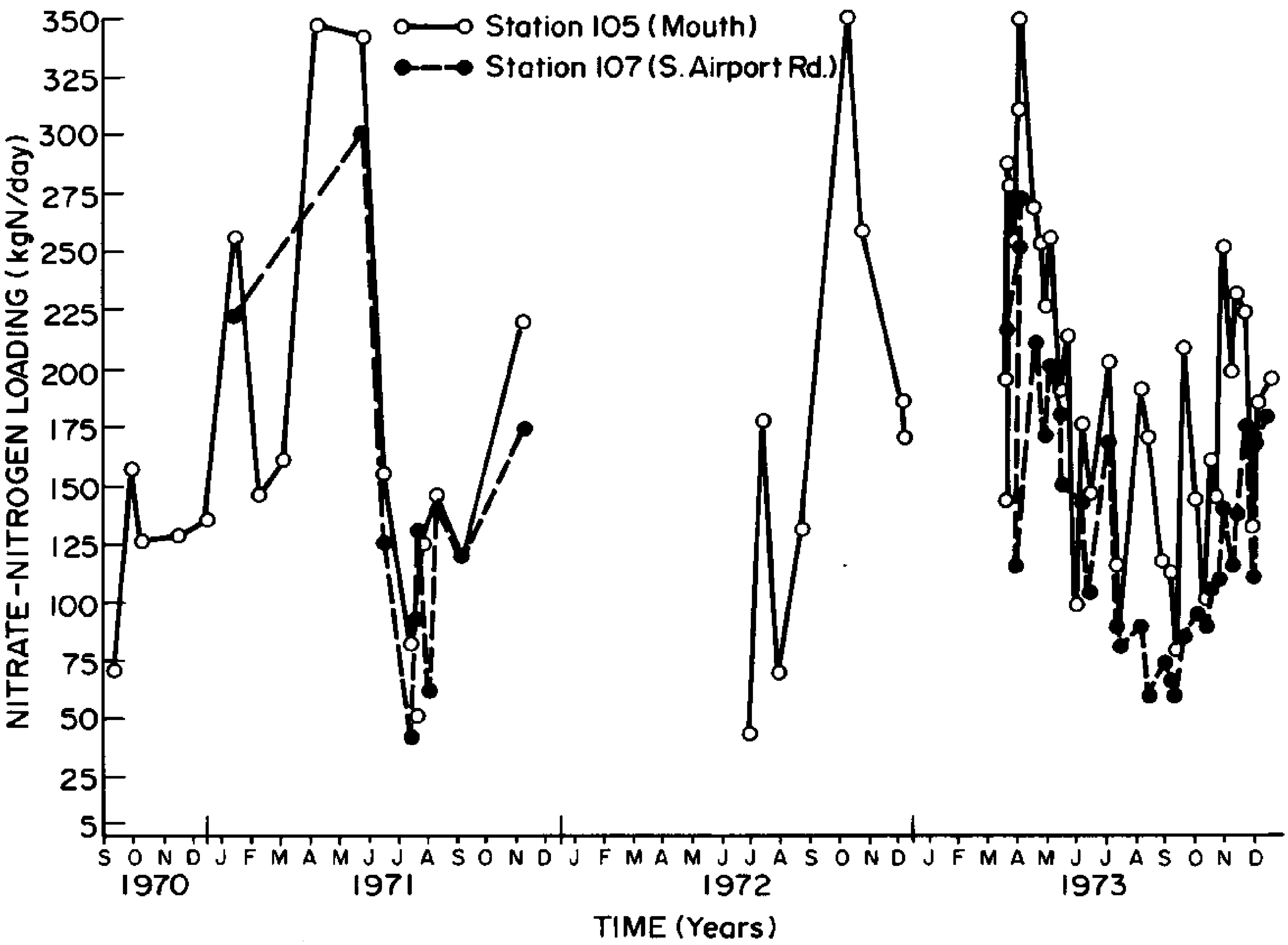


FIGURE IX-13. Nitrate-Nitrogen loading to Grand Traverse Bay by the Boardman River 1970-1973.

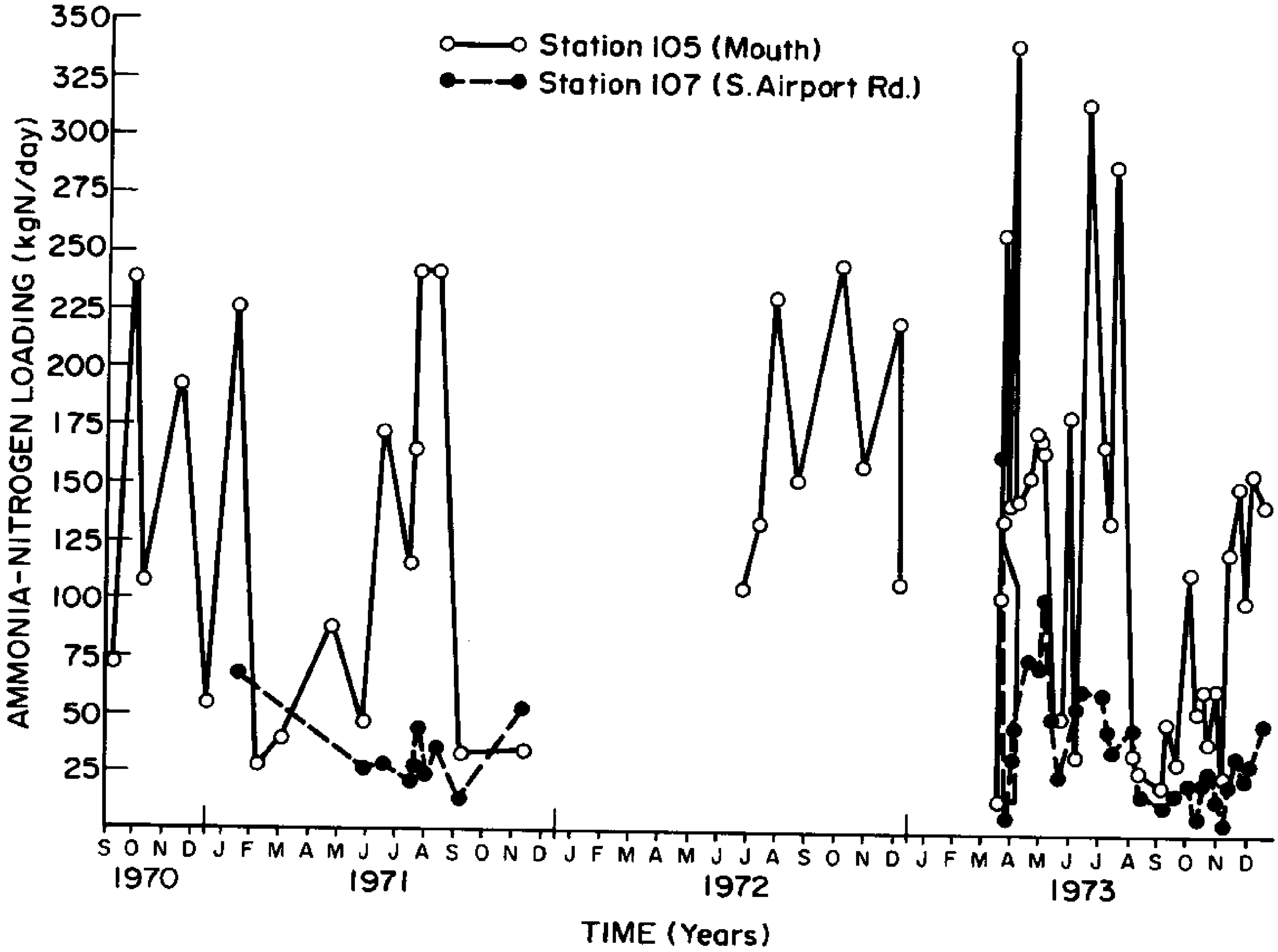


FIGURE IX-14. Ammonia-nitrogen loading to Grand Traverse Bay by the Boardman River 1970-1973.

of these concentrations reveal wide fluctuations. Total phosphorus concentrations varied from 10.0 μg P/ℓ to 128 μg P/ℓ, and ammonia concentrations varied from 40 μg N/ℓ to 690 μg N/ℓ. The cause of these high concentrations was principally the Traverse City WWTP discharge and numerous storm sewer overflows, and to a lesser extent the seasonal discharges from the fruit processing plants. This effect can be seen by examining Figures IX-6 through IX-14. These figures show the differences in concentrations and loadings upstream and downstream of Traverse City on the Boardman River (stations #105 and #107 respectively) and the operating records of the WWTP. The Traverse City WWTP discharges to the Boardman River at a location between these two stations (see Figure VII-1).

Concentrations for phosphorus and ammonia increase significantly downstream from the WWTP and storm sewer overflows. These changes in concentrations are also reflected in the river loadings measured at the two stations. The phosphorus loadings can increase as much as 20 fold. A comparison of the difference in loadings between these two stations with the estimated sewage treatment plant loadings to the river demonstrate good agreement. For example, the peak 1973 summer Boardman River phosphorus loading was calculated to be an increase of 79,000 gsm/day over the upstream load. The estimated WWTP phosphorus loading on this date was 81,000 gms/day. An examination of more data reveals the same consistent comparison, although some differences are expected because of averaging and estimating techniques and due to differences in the WWTP laboratory and Sea Grant laboratory analytical techniques. It is unfortunate that river monitoring did not continue intensively beyond 1973, after which phosphorus removal was consistently effective in the Traverse City Waste Water Treatment Plant. During the winter and late fall of 1972 and 1973 the secondary treatment plant and phosphorus removal equipment were in only partial operation, and this effect can be seen on both the WWTP operating charts and Boardman River concentration and loading plots. These effects though could be slightly masked by the smaller operating conditions of the Waste Water Treatment Plant during off-season. Today, the WWTP has only a small effect on the Boardman River phosphorus and BOD_5 concentrations, and the relative contribution of organics and nutrients to the bay by the river have decreased in agreement with its relative flow contribution to the bay. Phosphorus concentrations at the mouth of the river are now often less than 20 μg P/ℓ. In general the changes in phosphorus and ammonia concentrations in the Boardman River coincided with changes in WWTP loadings.

Although the relative loadings of phosphorus and ammonia are still the most significant in the basin, the nitrate and silicon contributions have remained practically constant. In 1970-1971 the average nitrate and silicon concentrations were 221 μg N/ℓ and 3.35 mg Si/ℓ . These values are slightly less than the average tributary concentrations of 530 μg N/ℓ and 3.4 mg Si/ℓ. The 1972 and 1973 nitrate and silicon concentrations show observations of similar magnitude with fluctuations having very little correlation to WWTP efficiency. The 1973 monitoring data which show concentrations at stations upstream and downstream from the urban influence of Traverse City reveals little difference in the concentrations in contrast to phosphorus and ammonia.

Waste Water Treatment Plant and storm water discharges typically do not have excessive nitrate or silicon content but contribute more heavily in terms of ammonia, phosphorus and organics.

The major ion and trace metal content of the Boardman River and the relative significance of these loadings to Traverse Bay are given in Table IX-4. The average 1970-1971 concentration of solium was 3.59 mg/ℓ magnesium 13.71 mg/ℓ, calcium 63 mg/ℓ, potassium 1.35 mg/ℓ, manganese 0.01 mg/ℓ, iron 0.061 mg/ℓ, chromium 0.003 mg/ℓ, cobalt 0.007 µg/ℓ, nickel 0.006 µg/ℓ, copper 0.003 µg/ℓ, zinc 0.008 µg/ℓ, and strontium 0.026 mg/ℓ. These concentrations are not significantly elevated and generally compare well with the average concentrations measured in all of the bay tributaries. As a consequence, the relative contribution from the Boardman River of major ions and trace metals to the bay is principally dependent on flow. Iron and manganese are possible exceptions inasmuch as the Boardman River contributes about 69% and 71% of the total sources to the bay. The relative contributions of major ions and trace metals by the Boardman River to the west arm are revealed in Tables IX-3 and IX-4. As expected, because of high flow, the Boardman River contributes 85% to 90% of all contaminant loadings to the west arm. The influence of the river on the chemistry and ecology of the west arm is very apparent and is discussed later in the report.

Belangers Creek

Belangers Creek drains an area of 23 km^2 and discharges to the bay at the northernmost boundary of Suttons Bay. It has a measured average flow of 14.1 m^3/min. Except for a small impoundment, the river has relatively large velocities that result in a rubble and stone stream bed. The watershed is principally rural. Average measured river concentrations of nutrients, organics, trace metals, and major ions were equal to or less than the average value of all of the tributary discharges to the bay. The relative significance of the loadings of the creek to the bay is therefore minor, and consistent with its relative hydrologic contribution (see Tables IX-3 and IX-4). All of its contaminant contributions to the bay were less than 1% of the total loadings except for nitrate. A higher average nitrate concentrations of 722 µg N/ℓ resulted in a 2.5% contribution of nitrate by Belangers Creek, still an insignificant amount. Concentrations of all constituents were considered to be low enough that there should exist no detrimental effects on bay water quality resulting from its discharge. Trace metals concentrations were small and major ion concentrations were at acceptably low levels.

Setterbo Creek

Setterbo Creek is one of the smallest identified creeks in the Grand Traverse Bay system discharging on the northern shore of Suttons Bay. It has a drainage area of undetermined size and a measured average flow of 0.97 m^3/min. It is somewhat peculiar in that it has a hard calcium carbonate cemented stone bottom. As a result of its small size its relative contribution of nutrients, ions and metals to the bay is insignificant, usually amounting to about 0.1%. Measured concentrations and loads are given in Tables IX-3 and IX-4. Concentrations of all chemical constituents were low and of a magnitude similar to all of the bay's discharges. No adverse effects are expected resulting from this discharge.

Suttons Bay Creek

Suttons Bay Creek is a small stream which passes through the village of Suttons Bay and discharges at the southernmost tip of its namesake. It has a drainage basin of less than 5 km^2 and a 1970-1971 measured average flow of 2.4 m^3/min. Concentrations of nutrients and other ions in the river waters are consistent with those found in other bay tributaries. The only chemical concentration measured and found to be above average was nitrate. The average nitrate concentration in Suttons Bay Creek was 1500 μg N/ℓ compared to the total tributary average of 530 μg/ℓ. As a consequence of its low flow, the relative contribution of Suttons Bay Creek nutrients, metals, and ions to the bay amounted to less than 0.2% of the total tributary loads. Again no adverse effect on the bay water quality is expected from this creek.

Leo Creek

Leo Creek, also known as Wheaton Creek, discharges a measured average flow of 6.9 m^3/min to Suttons Bay. Its drainage area of 9 km^2 includes some swamp lands, and as a consequence its waters are characteristically brown. This circumstance does not, however, adversely effect other river water quality parameters. Its average BOD_5 concentration of 1.5 mg/ℓ reflects little organic contamination. Nutrient and ion concentrations in the creek are also small: the average measured concentrations were 635 μg NO_3-N/ℓ, 60 μg NH_3-N/ℓ, 2.45 mg Si/ℓ, and 15 μg P/ℓ. These compared very well with the system averages. Heavy metal and ion concentrations were also at relatively low levels. Since the concentrations of most chemical constituents were low the relative loads to Grand Traverse Bay from Leo Creek were typically less than 1%. This is in agreement with its relative flow contribution of 0.43%. No adverse effects on bay water quality are expected from Leo Creek.

Cedar Creek

Cedar Creek has a drainage area of 16 km^2. It discharges a 1970-1971 average measured flow of 15.7 m^3/min into the lower west arm of Grand Traverse Bay. Average nutrient, organic, and ion concentrations measured in the river were consistently less than or equal to the averages of all the tributary concentrations. No significant contamination was evident. The relative significance of Cedar Creek loads to the total bay was small. Relative contributions ranged from 0.35% for iron to 1.39% for total dissolved phosphorus. This agrees well with the 1% relative flow contribution from the creek. Cedar Creek is not believed to have a significant effect on Grand Traverse Bay water quality.

Brewery Creek

Brewery Creek discharges a measured average flow of 3.07 m^3/min to the lower west arm of Grand Traverse Bay. It drains a rural area of approximately 5.7 km^2. The only measured chemical constituent that departed significantly from the system average was nitrate. The Brewery Creek average concentration was 1140 μg N/ℓ, compared to an average tributary concentration of 530 μg N/ℓ. As is the case with all the small tributaries of Grand Traverse Bay, Brewery Creek loadings are insignificant in comparison to the total tributary budget. Its maximum relative contribution was 0.88% for nitrate, however its contribution of most other elements was less than 0.5% and averaged about 0.2%. The low relative flow of the creek (0.19%) is the controlling factor. Brewery Creek is not expected to have any effect on bay water quality because of this low flow and its close proximity to the Boardman River.

Creek #1 and Creek #2

These two small unnamed creeks discharge average flows of 0.76 and 1.24 m^3/min respectively to the lower west arm of Grand Traverse Bay. Creek #1 passes through the Traverse City coal storage area and is often contaminated with coal particles during rain run-off events. This effect was not, however, reflected in monitored chemistry parameters which reveal little variation from other tributary averages. Creek #2 passes through an oil refinery and is often characterized by surface oil slicks. The average BOD_5 of the creek is 3.34 mg/ℓ, which is slightly higher than the other streams without such contamination. In general however, the concentrations, flows and subsequent loads from these creeks are minor relative to the entire system. Creek #1 contributes less than 0.1% of the total tributary loads for all species monitored while Creek #2 contributes consistently less than 0.15%. The creeks have little effect on the Grand Traverse Bay chemistry, being heavily overshadowed by the neighboring Boardman River discharge. Surface oil slicks on Creek #2 may affect the aesthetic quality of receiving waters in the bay, although no such observations were made.

Tributary Discharges, East Arm Tributaries

Mitchell Creek

Mitchell Creek has a drainage area of 36.3 km^2 and discharges an average flow of 28.5 m^3/min into the southernmost tip of the east arm of Grand Traverse Bay. The river receives flow from six or seven tributaries which drain low swampy areas, consequently its color is sometimes slightly darkened. After the Boardman and Elk Rivers, Mitchell Creek is the largest tributary in the system. Average measured nutrient and organic concentrations in the creek waters were 1.87 mg/ℓ BOD_5, 490 μg N/ℓ nitrate, 0.82 μg N/ℓ ammonia, 2.73 mg Si/ℓ silicon, and 14 μg P/ℓ total phosphorus. These concentrations were not significantly different from the overall tributary averages. Trace metal and major ion concentrations were also in agreement with the overall averages. The loadings to the east arm from Mitchell Creek accounted for only 1% to 4% of the total east arm loadings because its effects are heavily overshadowed by the Elk River loads. Despite being the third largest tributary in the Grand Traverse Bay system, Mitchell Creek contributes insignificant amounts of contaminants to the bay when compared with the Boardman and Elk Rivers.

Bakers Creek

Bakers Creek is a relatively small brown-colored stream having a drainage area of only 6.5 km^2 and an average flow of 3.0 m^3/min. The average nutrient and organic concentrations of 1.76 mg BOD$_5$/ℓ, 109 μg NO$_3$-N/ℓ, 62 μg NH$_3$-N/ℓ, 4.04 mg Si/ℓ and μg P/ℓ total phosphorus are in close agreement with or below the overall tributary averages. The same is true for the trace metal and major ion concentrations. The relative loadings of contaminants to the bay from Bakers Creek are small as expected from the average flow. The highest two loading contributions were for silicon (0.25%) and for iron (0.32%). All contaminant loads are insignificant in the overall chemical budget for Grand Traverse Bay and no reduction in water quality is expected from this discharge.

Acme Creek

Acme Creek is a very stable ground-water-fed cold water creek discharging to the southern east arm of Grand Traverse Bay. It drains an area of 33.7 km^2 and discharges an average flow of 24.7 m^3/min. It is the fourth largest tributary to Grand Traverse Bay. As a consequence of its ground water character, contaminant concentrations are low, usually much below the overall tributary averages. The average BOD$_5$ concentration was 1.3 mg/ℓ, the nitrate concentration was 55 μg N/ℓ, ammonia 63 μg N/ℓ, silicon 2.88 mg Si/ℓ, and total phosphorus 9 μg P/ℓ. The relative loading contribution to the bay was minor. Its relative contribution to the bay ranged from 0.34% to 1.43%. The creek's trace metal and major ion relative contributions were slightly larger but still insignificant, ranging from 1.17 to 2.53%.

Yuba Creek

Yuba Creek has a drainage area of 21.2 km^2 and discharges an average flow of 15.5 m^3/min to the east arm of Grand Traverse Bay. Concentrations of all chemical contaminants, nutrients, trace metals and major ions were typical of the overall tributary average. This tributary discharged insignificant loadings to the bay totaling typically less than 2% for the total bay and 6% for the east arm. No detrimental impacts are expected from this discharge.

Elk River

The Elk River is the largest river that discharges to Grand Traverse Bay. It drains an area of 1270 km^2 with a calculated average flow of 965 m^3/min. The drainage basin of the river is interrupted by two of Michigan's largest inland lakes, Elk Lake and Torch Lake. The general water quality character of the river is good and typical of a river with an undeveloped watershed. Average nutrient and BOD concentrations were 1.3 mg BOD$_5$/ℓ, 221 μg NO$_3$-N/ℓ, 100 μg NH$_3$-N/ℓ, 2.81 mg Si/ℓ, and 13 μg P/ℓ.

These concentrations average 20% below the overall tributary average concentrations. Measured trace metal and major ion concentrations were of similar magnitude. Because of the large flow of the Elk River it is a major source of nutrient and chemical loading to the bay. The relative loading contributions to the bay are 33.1% for BOD_5, 49.3% for nitrate, 42.39% for ammonia, 49.94% for silicon, 26.85% for phosphorus, 19.75% for manganese, 21.91% for iron and, as an approximate average, 50% in all of the other trace metal and major ion contributions. The Elk River is the largest single tributary discharger for all contaminants except phosphorus, BOD_5, ammonia, manganese and iron. The Boardman River contributes more of these contaminants as a result of its elevated concentrations. The Elk River contributes 90% to 95% of the total contaminant loading to the east arm. No significant impacts on water quality were observed as a result of discharges from the Elk River and the Elk Rapids WWTP. No flow measurements were made during periods of discharge by the Elk River Packing Co. because of equipment limitations; loading data for this period are thus not available.

In general, although the Elk River is the most voluminous discharge to the bay, the relative concentrations in the discharge are low and not supportive to serious water quality degradation.

Tributary Discharges, Open Bay Tributaries

Only two identified tributaries, Northport and Ennis Creeks, discharge into the open bay. Northport Creek drains an area of 10.3 km^2 and discharges an average flow of 4.7 m^3/min. The river is dammed forming a reservoir upstream of the village of Northport. In the summer the reservoir is overgrown with aquatic plants and algae, however no reduction in downstream water quality was observed. The average concentrations of nutrients and ions in Northport Creek were typical of the overall average. Its relative loadings to the bay were less than 0.5% of the total tributary loadings. It is, however, the major direct discharger to the open bay, contributing 70 to 90% of all loadings.

The only other discharger to the open bay, Ennis Creek, drains an area of less than 4 km^2 and has an average discharge of 1.51 m^3/min. Nutrient and organic concentrations in the creek were also typical of the overall average. Although the river flows through some swamp areas and retains a brownish color, it does not otherwise display undesirable characteristics. The relative load of Ennis Creek to Grand Traverse Bay averages approximately 0.08%.

Summary of Tributary Loadings by Parameter:

Biochemical Oxygen Demand

The average concentration of BOD_5 in Grand Traverse Bay tributaries was 1.65 mg/ℓ during the 1970-1971 sampling program. The highest individual tributary average concentration was 3.35 mg/ℓ, measured in the Boardman River. This was a consequence of the discharge from the Traverse City Waste Water Treatment Plant and from urban runoff storm water. The lowest average concentration was 0.95 mg/ℓ, measured in Setterbo Creek. Most concentrations were in the 1-2 mg/ℓ range. The total average BOD_5 loading to the bay was 5,003,880 gms BOD_5/day, of which the Boardman River accounted for 61% and the Elk River 33%. All other tributary contributors were individually less than 2%. Of the total organic loadings to the bay 64.8% were discharged to the west arm, 34.9% to the east arm and 0.23% to the open bay. The waste discharges from the seasonally discharging fruit processing plants were not significant compared to other sources. Their daily discharge loadings were of the same order of magnitude as the total tributary loadings to the bay. As of 1975, however, these sources no longer discharge directly to the bay.

Nitrate-Nitrogen

The average tributary nitrate concentration was measured to be 530 μg N/ℓ. Of all of the chemical parameters measured, nitrate varied the most among the rivers. The highest concentrations were observed in Suttons Bay Creek, which had an average concentration of 1400 μg N/ℓ. Setterbo and Brewery Creeks also had average concentrations of over 1000 μg N/ℓ. The lowest average concentration was 55 μg N/ℓ measured in Acme Creek. The total tributary nitrate load to Grand Traverse Bay was 571,273 gms N/day. The Boardman and Elk Rivers combined accounted for 85% of the loadings, each contributing an amount proportionate to its flow. No other major contributors existed. The west arm received 66.6% of the total tributary nitrate loadings, whereas the east arm received 32.9%. Waste discharges from the Traverse City WWTP and the seasonal discharges of cherry processing wastes did not contribute significantly to the nitrate loadings. Although high concentrations of nitrate-nitrogen have been observed in Grand Traverse Bay watershed ground waters (Rajagopal et al. 1975), there is no indication that this contaminant is being transferred to the bay (Brater 1972).

Ammonia-Nitrogen

The average 1970-1971 ammonia concentration measured in the tributary surveys was 70 μg N/ℓ. The highest average ammonia concentration was 177 μg N/ℓ measured in the Boardman River. This elevated concentration resulted principally from inadequately treated wastes discharged by the Traverse City WWTP. The Elk River average ammonia concentration was also high and measured 100 μg N/ℓ. The high average may be a consequence of the Elk Rapids WWTP discharge or an effect of Elk Lake. Of the total tributary ammonia load to the bay (300,695 gms N/day) 53.9% came from the Boardman River and 42.4% from Elk River. The west arm received 56.3% of the total tributary ammonia loads, whereas the east arm received 43.6%. The seasonal industrial ammonia loads from the fruit processing plants were minor. The Kjeldahl nitrogen load (which can represent in a sense organic ammonia) was significant. Each specific plant might discharge typically 60,000 gms TKN/day or approximately 20% of the size of the total daily tributary ammonia loadings.

Silicon

The average silicon concentration measured in tributary discharges was 3.4 mg Si/ℓ. Individual river average concentrations varied from a high of 5.5 mg Si/ℓ in Creek #2 to a low of 2.45 mg Si/ℓ in Leo Creek. The total tributary silicon loading to the bay was estimated to be 7,172,453 gms Si/day. The Boardman and Elk Rivers were again the most significant contributors, contributing 42.8% and 49.9% respectively. The east arm of the bay received 52.5% of the total tributary silicon loadings, whereas the west arm received 47.2%. No significant municipal or industrial discharges of silicon were observed.

Phosphorus

The average total phosphorus tributary concentrations was 13 μg P/ℓ, with an individual tributary maximum of 41 μgP/ℓ measured in the Boardman River. This elevated phosphorus concentration is a consequence of the discharge of incompletely treated wastes from the Traverse City WWTP. A total tributary phosphorus load of 56,579 gms P/day was estimated, of which 61% was contributed by the Boardman River. Of the Boardman River's 37,500 gms P/day average loading, as much as 90% was often due to the Traverse City sewage discharges. The relative distribution of phosphorus loads to the bay changed drastically in late 1973 with the implementation of an improved secondary treatment plant with phosphorus removal at Traverse City. After this date Boardman River phosphorus concentrations returned to normal low background levels of between 5 and 20 μg P/ℓ. Available data are not sufficient to calculate change in loading following treatment, however it is expected that the loads would correlate better with each tributary's relative flow contribution. During 1970 and 1971, 72% of the total phosphorus was discharged to the west arm. Industrial discharges of phosphorus from the fruit processing plants were considered to be marginally significant, amounting to approximately 10% of the tributary phosphorus discharges during the plant operating seasons. Today these discharges no longer exist.

Major Ions

The average tributary concentrations of the major ions were 71.5 mg/ℓ calcium, 3.35 mg/ℓ sodium, 16.7 mg/ℓ of magnesium, and 1.37 mg/ℓ potassium. High and low average tributary concentrations varied less than 25% from these overall averages. The sum of the average tributary loadings was 125,015,000 gms Ca/day, 8,115,653 gms Na/day, 32,311,802 gms Mg/day and 2,894,056 gms K/day. The Boardman River contributed an average of about 40% of these loads whereas the Elk River contributed approximately 50%. All other tributary sources contributed relative loads dependent principally on their flows. No serious dissolved solids contamination was observed in any of the rivers.

Trace Metals

The average 1970-1971 tributary trace metal concentrations were 2 μg/ℓ chromium, 6 μg/ℓ manganese, 42 μg/ℓ iron, 7 μg/ℓ cobalt, 7 μg/ℓ of nickel, 24 μg/ℓ copper, 42 μg/ℓ strontium, and 8 μg/ℓ of zinc. The individual average tributary concentrations typically did not vary significantly except for manganese and iron. Concentrations were generally so small that the variances often approached the confidence limits of the analysis. The respective total tributary loadings to the bay were 5,670 mg Cr/day, 12,406 mg Mn/day, 81,463 mg Fe/day, 15,444 mg Co/day, 14,402 mg Ni/day, 6,977 mg Cu/day, 22,348 mg Zn/day and 88,121 mg Sr/day. The Boardman River contribution of these elements varied from 38% for nickel to 71% for manganese.

Storm Sewer Contamination

Traverse City operates a separate storm water and sanitary sewer system which transports the domestic wastes to the wastewater treatment plant and discharges the storm runoff to bay and river surface waters. Urban runoff typically contains undesirable matter including animal droppings, vehicular exhaust residue, debris, pesticides, fertilizers, etc. The Traverse City storm sewer system has 12 discharge sites to the west arm of Grand Traverse Bay, 3 to the east arm and a number of discharges to the river. As part of Phase 1 of this investigation, samples were taken at three of these discharges to assess the extent of storm runoff contamination of the bay (Gannon and Meier 1974). Table IX-7 summarizes the range of concentrations of pollutants measured in the storm water discharges. Average concentrations were 3.5 mg BOD_5/ℓ, 406 μg P/ℓ, 50 μg NH_3-$N\ell$, 239 mg NO_3-N/ℓ, 41.1 mg suspended solids/ℓ, 258 mg total solids/ℓ and maximum fecal coliform concentrations in the thousands. These concentrations suggest serious potential contamination of the bay from storm sewer discharges. The BOD_5 concentrations were over twice the average tributary concentration (1.65 mg/ℓ) and the phosphorus levels were 30 times larger than the average (13 mg P/ℓ). Nitrate and ammonia levels in the storm sewer effluents were generally less concentrated than average tributary inputs.

The relative loading resulting from these discharges was difficult to establish because the flows are highly time-variable and no accurate flow and duration information was available. Flow measurements were made only at a limited number of sewer discharges and were not distributed frequently enough throughout the storm events to permit a quantitative evaluation of the total volume of water discharged. Storm sewer loadings of BOD_5 from these sources were estimated by Gannon and Meier (1974) during one severe storm event (0.83 inches of rain). The average loading rate from these discharges was 111,608 gms BOD_5/day. Multiplying this by fifteen, the number of direct bay discharges, an approximate loading rate to the bay is calculated to be about 1.6×10^6 gms BOD_5/day. This level is one third the magnitude of the total tributary BOD_5 loadings to the bay (5×10^6 gms BOD_5/day). Storm water loadings were, however, rates of discharge during the storm event only, and are not averaged over the entire day or even the duration of the storm. Reducing these loads by appropriate factors would reduce the relative significance of this source. Considering, for example, the discharge to be constant at the monitored level for a four hour period would result in a daily averaged load of 277,000 gms BOD_5/day or only 4% of total tributary loadings. It should also be noted that 0.83 inches of precipitation is a large storm event that is not typical of most other storm water discharges. With

TABLE IX-7. Selected observations of storm sewer discharge in Grand Traverse Bay (Gannon and Meier 1974)

Parameter	Avg. Site A* (range)	Avg. Site B* (Range)	Avg. Site C* (range)	System Avg.	Avg. Loadings/ Storm Sewer Effluent
BOD_5 mg/ℓ	2.8 (0.1-9.2)	4.42 (1.6-8.5)	3.3 (0.5-6.6)	3.5	21,678
Total P µP/ℓ	281 (34-510)	448 (315-645)	491 (298-810)	406	2,515
NH_3 µg N/ℓ	46.8 (7-82)	56.4 (0-165)	47 (5-84)	50.1	310
NO_3+NO_2 µg N/ℓ	129 (28-225)	349 (15.5-602)	239 (137-406)	239	1,480
Suspended Solids (mg/ℓ)	41 (5-115)	41.7 (1-104)	40.7 (3-124)	41.1	254,567
Total Solids (mg/ℓ)	301 (280-325)	198 (143-237)	276 (165-328)	258	1,598,012
Fecal Coliform (counts/100mℓ)	4373 (100-13,000)	>13,100 (200-TNTC)	>>1778 (170-TNTC)	>>6417	--
Flow (m^3/min)	1.58 (0.75-3.79)	5.85 (0.88-18.35)	4.72 (0.61-8.84)	4.33	--

* The locations of these sample sites are shown in Figure XI-6. The data obtained at these sample stations should not be construed to represent an average but rather merely typical values.

this consideration in mind the BOD_5 loadings to Grand Traverse Bay are not considered highly significant in a very localized and temporary scope.

Although estimates of the nutrient loadings to Grand Traverse Bay were not made by Gannon and Meier, rough estimates of these parameters and BOD_5 loadings can be made by multiplying average monitored storm sewer discharge concentrations by the average flow, both measured on a very limited basis over the course of a year. Multiplying these estimates by the number of discharges to the bay the following loadings are calculated: 325,170 gms BOD_5/day, 37,725 gms P/day, 4,650 gms NH_3-N/day and 22,200 gms NO_3-N/day. The corresponding total average tributary loadings to the bay are 5,003,880 gms BODs/day, 61,727 gms P/day, 300,695 gms NH_3-N/day and 571,273 gms NO_3-N/day. A comparison of the magnitude of the storm loadings to these tributary loadings shows the BOD_5 to be 6.5%, the phosphorus to be 59%, the ammonia to be 1.3% and the nitrate to be 3.8%. The nitrogen and BOD_5 loading appear insignificant. Considering the intermittent nature of storm events throughout the year, and the probability that the above-mentioned measurements were made during the peak intensity of larger storm events, it is believed that the storm sewer contribution of phosphorus is also insignificant. This again, roughly, can be conservatively demonstrated by considering the frequency of storm discharges. If it is assumed that the average discharge duration during a storm event is conservatively 4 hours and that precipitation occurs an average of twice a week, the resultant reduction in annual average daily storm sewer discharge of phosphorus is one twelfth. This means conservatively that the storm sewer phosphorus loading is less than 5% of the total tributary loadings.

In general, storm sewer discharges were not adequately monitored in frequency or location to quantify their loadings. It can be roughly estimated, however, that the annual average loadings directly to the bay were not significant with respect to the overall tributary loadings to the bay. Temporary and local effects may however result from these discharges, particularly that of coliform which had very elevated concentrations. This situation is discussed in more detail in another section. No estimates were made of storm sewer discharges to the Boardman River.

Atmospheric Fallout

The relative importance of air particulate and rainfall contamination to the Great Lakes has come under recent investigation. Murphy and Doskey (1975) have estimated that rainfall contributes approximately 18% of the phosphorus loadings to Lake Michigan. Gatz (1975) has estimated that wet and dry inputs from the atmosphere are approximately equal. This assumption would elevate the air fallout contribution to approximately 36%. Winchester and Nifong (1971) have estimated that air fallout contributes significantly to the trace metal budget of Lake Michigan. Estimates of air particulate loadings vary widely depending upon the region of study.

Unfortunately the atmospheric loadings to Grand Traverse Bay were not monitored, and hence no quantitative estimate of their contribution can be made. This source may, however, represent a significant contribution to the trace element chemistry budget of the bay.

X. GENERAL WATER QUALITY CONDITIONS

Introduction

This general discussion will provide an analysis of each of the physical, chemical, and biological parameters as they relate to both present and future water quality conditions in the bay. Grand Traverse Bay will be compared with Lake Michigan and the other Great Lakes. Tables X-1 and X-2 present water quality characteristics for various areas in the Great Lakes.

The objective of this chapter is to discuss in layman's terms some of the historical, physical and chemical perturbations which have occurred in the bay and evaluate the response of the indigenous flora and fauna to these distrubances. However, it is important to recognize that, although there are some evidences of increased productivity and pollution resulting from man's impact, Grand Traverse Bay is still an oligotrophic system having high overall water quality (Lauff 1957 and Stoermer et al. 1972).

Major Ions and Physical/Chemical Parameters

Alkalinity

Alkalinity is not a specific substance but rather a measure of the ability of water to neutralize acids and is measured in milliequivalents per liter (meq/ℓ). It results from the combined effects of several substances and conditions. In natural waters this ability is due primarily to the salts of weak acids, although weak and strong bases may also contribute. Bicarbonates, carbonates, and hydroxides constitute the major sources of alkalinity since they leach heavily into waters through the action of carbon dioxide on soils and rocks. Borates, silicates, phosphates, and organic substances also contribute, but to a lesser extent.

Alkalinity is also an indirect measure of the buffer capacity of water and its ability to resist changes in pH due to the addition of acids or bases. This buffering ability is important to prevent large changes in pH that might prove harmful to the biotic community. Most organisms are acclimated to a specific pH range and, if exposed to conditions outside of this range, can experience deleterious effects. Diurnal photosynthetic activity can cause fluctuations in pH. These changes are controlled by the alkalinity and, hence, are usually sufficiently temporary and small so as not to cause harm.

Lethal effects on fish resulting from those substances associated with high alkalinities are not generally noted at $\text{pH} < 9$. Other effects on fish have only been noted under very low alkalinity and pH conditions (McKee and Wolf 1963).

Levels of alkalinity in Grand Traverse Bay ranged from 1.74 to 4.04 meq/ℓ with a mean for all samples of 2.29 meq/ℓ. The vast majority of samples were in the range 2.00 to 3.00 meq/ℓ. The mean is very close to that reported for Lake Michigan (2.22 meq/ℓ) and higher than

Table X-1. Mean concentrations of nutrients, chlorophyll a and transparency in the Great Lakes

Chemical Species	Lake Superior (Open Lake)	Lake Huron (Open Lake)	Lake Huron (Saginaw Bay)	Lake Erie (Western Basin)	Lake Erie (Central Basin)	Lake Erie (Eastern Basin)	Lake Ontario (Whole Lake)	Lake Michigan (Lower Green Bay)	Lake Michigan (South End)	Lake Michigan (Open Lake)
NO_3 (µgN/ℓ)	257	217	158	210	102	82	253	90	173	128
NH_3 (µgN/ℓ)	7	19	33	176	89	74	12	172	33	18
Total Dissolved Phosphorus (µgP/ℓ)	2.0	4.5	5.8	35.8	13.6	10.4	17.2	100	9.8	2.1
Particulate Phosphorus (µgP/ℓ)	1.6	4.4	11.1	29.0	10.5	8.4	8.1	187	ND	4.2
Total Phosphorus (µgP/ℓ)	4.5	10	30	61			20	304	14.6	8.5
Silicon (mgSi/ℓ)	1.00	0.76	0.49	0.42	0.31	0.15	0.24	1.15	0.53	0.85
Secchi Disk (m)	10.4	8.1	2.2	1.3	4.0	4.5	3.6	1.8	5.2	6.7
Chlorophyll a (µg/ℓ)	0.7	1.6	12.2	9.5	5.8	4.2	5.0	15.8	2.3	1.8

(Sources listed in Appendix A)

TABLE X-2. Major ions and trace metal concentrations measured in Grand Traverse Bay and the Great Lakes Proper.

	Grand Traverse Bay				Great Lakes				
Element	Mean	Std. Deviation	Maximum	Minimum	L. Superior	L. Huron	L. Michigan	L. Erie	L. Ontario
Ca(mg/ℓ)	37.4	14.4	91.7	5.3	13.0	24.8	33.7	36.9	39.0
Mg(mg/ℓ)	14.2	1.6	19.3	8.4	2.8	6.4	11.2	8.3	8.2
Na(mg/ℓ)	4.7	2.7	5.5	2.2	1.1	2.5	4.0	10.6	11.6
K (mg/ℓ)	1.5	0.16	2.1	0.8	0.6	1.0	1.1	1.3	1.4
Sr(μg/ℓ)	136.6	46.8	266.1	42.8	32.5	119	112	173	188
Fe(μg/ℓ)	4.9	7.8	48.2	ND	8	22	5.6	48	8
Mn(μg/ℓ)	1.05	1.2	6.9	ND	3.2	0.5	0.5	11.8	3.0
Co(μg/ℓ)	1.04	1.11	6.6	ND	6.7	3.0	2.2	9.3	26.6
Zn(μg/ℓ)	7.1	11.9	58.9	ND	13.9	33.0	19.8	5.9	29.2
Ni(μg/ℓ)	2.7	2.4	8.4	ND	2	4.0	11.0	3	5.6
Cr(μg/ℓ)	0.57	0.53	3.34	ND	6.0	1.6	--	1.6	0.4

(Sources listed in Appendix A)

ND = below detection limits

that reported for the other Great Lakes: Lake Superior (0.92 meq/ℓ), Lake Huron (1.61 meq/ℓ), Lake Erie (1.85 meq/ℓ) and Lake Ontario (1.92 meq/ℓ). The relatively high alkalinities in Lake Michigan and Grand Traverse Bay are a result of the geologic composition of the drainage basin and represent a well buffered system.

Samples collected in the period 1970-1974 display a very slight downward trend in alkalinity. During 1971 and 1972, fall levels averaged higher than those for spring and summer. This trend was not evident in 1973.

Alkalinity displayed very little horizontal variation within the bay. Non-river surface water values ranged from 2.26 meq/ℓ to 2.34 meq/ℓ among zones, while averages for the entire water column ranged from 2.28 to 2.34 meq/ℓ among zones. Zone VI, the Boardman River, averaged slightly higher than non-river stations at 3.22 meq/ℓ (surface).

The rather static condition of alkalinities serves to underscore the stability of the Grand Traverse Bay system. Fluctuations in alkalinity would be expected in highly productive or polluted waters.

Hydrogen Ion Activity (pH)

The concentration of the hydrogen ion in a solution is generally expressed in terms of the pH which is the negative logarithm of the molar concentration. The pH is a measure of the intensity of the acid or alkaline condition of a solution and is a master control parameter that governs such phenomena as solubility, degree of dissociation, and acid-base equilibria. Variations in the pH can severely effect the toxicity of chemical species in the water as well as the productivity and viability of aquatic organisms. The Michigan water quality standards for all uses generally require a pH of between 6.5 and 8.8 with an induced variation of no more than 0.5 units. The International Joint Commission (GLWQB 1975) recommends that no pH value fall outside the range 6.7-8.5. The pH data for Grand Traverse Bay were sparse but values generally ranged from 7.9 to 8.7. The majority of values were in the 8.3 to 8.5 range. Average values for pH approached those expected for Lake Michigan (8.25), were less than those for Lake Erie (8.52), and greater than those for the other Great Lakes (Superior 7.67, Huron and Ontario 8.17). The occurrence of high alkalinity and low productivity in Grand Traverse Bay dictate the observed alkaline pH with low variability.

Conductivity

Conductivity is a measure of the ability of a solution to conduct an electrical current. It is reported as the specific electrical conductance, the reciprocal of the resistance in μohms (μmhos) of a one centimeter column of solution at a specified temperature. Pure water is itself an insulator. Ions present in solution enhance the conductive characteristics of water. The higher the ion content or salinity, the greater is the conductivity. Conductivity is, therefore, an indirect measure of salinity. This property is important because all aquatic organisms have adapted themselves to conditions of salinity which exert a specific osmotic pressure. Normally they tolerate small changes in the relative amounts of salts but not in overall concentration. Larger changes in salinity will effect osmotic conditions and can result in harmful effects for aquatic flora and fauna.

Conductivities ranged between 192 and 363 μmhos/cm^2, but most values were restricted to a small range (240-260 μmhos/cm^2). The average conductivity for Lake Michigan (260 μmhos/cm^2) is intermediate to the lower values of Lakes Superior (93 μmhos/cm^2) and Huron (195 μmhos/cm^2) and the higher values of Lakes Erie (289 μmhos/cm^2) and Ontario (315 μmhos/cm^2). Conductivity, like chlorides and alkalinity, is a function of the bedrock geology of the region and thus has a stable value.

Conductivity showed the least spatial fluctuation, both vertically and horizontally, of any parameter measured. Total water column values (zone averaged) ranged from 253 to 259 μmhos/cm^2 at non-river stations. River conductivities averaged more than 20% higher than the bay average of 256 μmhos/cm^2.

The fluctuation of conductivity as well as alkalinity, pH, and chloride is small in Grand Traverse Bay. Only the input of gross pollution would serve to alter this parameter. Higher levels (∿20%) observed at the Boardman River mouth are quickly assimilated such that increases are barely noticeable in the plume.

Calcium

The ions of calcium salts are among the most common constituents of natural waters. Calcium is the principal cation imparting hardness into most surface waters and hence is an important parameter when considering the suitability of waters for industrial or municipal uses. Sources of calcium include natural leaching from soils and rocks, and discharges from municipal and industrial wastes.

Calcium has not been shown to be harmful to aquatic life at reasonable levels. Fish have survived in synthetic concentrations of calcium larger than 2500 mg/ℓ (Doudoroff and Katz 1953). Calcium has further been shown to be antagonistic toward the toxicity of lead and zinc. Although no U.S. Public Health Service drinking water standards or Michigan water quality standards have been set regarding calcium the World Health Organization recommends 200 mg/ℓ as the acceptable limit on calcium content (AWWA 1971).

The average calcium concentration measured in Grand Traverse Bay was 37.9 mg/ℓ with isolated occurrences ranging as high as 91.7 mg/ℓ. A comparison with the averages of reported values in the Great Lakes show Grand Traverse Bay to have a median concentration somewhat elevated from its parent Lake Michigan level. The noted increase in calcium concentrations eastward through the Laurentian Great Lake system is a consequence of increased tributary loadings from erosion, mineralization, and industrialization. The slightly elevated Grand Traverse Bay concentration might be a consequence of its relatively higher volume to perimeter and drainage area ratios, making tributary influence larger. The average tributary concentration in the basin is 71.5 mg/ℓ of which 90% is loaded to the system by the Elk and Boardman Rivers; they have respective concentrations of 43 mg/ℓ and 63 mg/ℓ. The average bay concentration is slightly less than these levels probably due to Lake Michigan water dilution and possibly precipitation. In general, all calcium measurements were well below the World Health Organization's acceptable limits for drinking waters, and are believed not to cause any hazards to aquatic life or detract from its suitability for municipal or industrial use. Calcium concentrations do not show any evidence of severe bay contamination.

Sodium

Sodium is the sixth most abundant element yet it never occurs in its elemental form in nature. This element is a very active metal whose salts are highly soluble in water. It is involved in very few removal processes and is often considered to be limnologically conservative. Sodium ions found in surface waters may be of natural origin or can be introduced from industrial and municipal sources. The sodium ion has not been shown to be toxic at levels normally found in fresh waters. Sodium chloride has been found to decrease toxicity of certain metallic compounds towards fish (Jones 1940). No present United States Public Health Service drinking water standards exist for sodium. For industrial use a limiting concentration of 2 to 3 mg/ℓ is recommended in feed waters destined for high pressure boilers (APHA 1971).

Monitored sodium concentrations ranged from 2.2 to 5.5 mg/ℓ with an arithmetic mean of 4.7 mg/ℓ. Observations of sodium in other Great Lakes ranged from an average of 1.1 mg/ℓ in Lake Superior to 11.6 in Lake Ontario. Lake Michigan has a mean value of 4.0 mg/ℓ. The general increase in sodium concentrations through the Great Lakes system is a consequence of variation in minerology and runoff and depends heavily on increased industrial and municipal discharges. The use of de-icing road salts is a factor (O'Connor and Meuller 1970). The sodium level in Grand Traverse Bay is not considered to be excessively high, its level lying between that of Lake Michigan and Lake Erie. The levels of sodium in the bay only restrict unusual industrial usages requiring low dissolved solids levels.

The average bay tributary concentration of sodium was 3.35 mg/ℓ, less than the mean bay concentration. The Boardman and Elk Rivers, the bay's major tributaries, also had low sodium concentrations measured as 3.59 and 3.40 mg/ℓ respectively. The elevation in bay sodium concentrations above these values may be attributed to air particulate loadings or seasonal surface runoff not monitored.

Potassium

Although potassium is the seventh most abundant element, it, like sodium, is never found in its elemental form in nature. It is an active metal and reacts vigorously with oxygen. It is only found in nature incorporated into molecular compounds or in its ionic form.

Potassium salts are highly soluble and as a consequence the ion is considered to be conservative in nature. Sources of potassium include municipal and industrial discharges, irrigation waters (it is a major component of fertilizers), and in leachate from soils and rocks.

Potassium is a necessary nutrient for all algal and higher plant growth but has never been demonstrated to limit growth in a natural water system. Potassium has not been shown to be toxic to aquatic life below 400 mg/ℓ (McKee and Wolf 1963).

The average potassium concentration monitored was 1.52 mg/ℓ, with a range of measurements from 0.8 to 2.1 mg/ℓ. These levels are considered not to be problems to any intended use of the bay's waters nor should it be detrimental to any aquatic life. Average concentrations of potassium measured elsewhere in the Great Lakes are 1.1 mg/ℓ in Lake Superior, 2.5 mg/ℓ in Lake Huron, and 11.6 mg/ℓ in Lake Ontario. The Grand Traverse Bay concentration of potassium is second lowest among all of these values and indicates conditions of pollutional contamination are very low to the system. The average tributary concentration was 1.37 mg/ℓ, very much in line with the mean response of the bay.

Magnesium

Magnesium is a common constituent in natural waters. It is a divalent active metal rarely found in its elemental form but rather typically in its ionic form. All magnesium salts have high solubility in natural waters except for hydroxides which are insoluble at high pH's. Magnesium is the second most important contributor to hardness in natural waters. Sources for magnesium include dissolution from soils and rocks and industrial and municipal discharges. Magnesium has been reported to be toxic to fish at concentrations above 476 mg/ℓ, however no adverse effects to aquatic life have been found from concentrations below 100 mg/ℓ (McKee and Wolf 1963). The United States Public Health Service drinking water standard for magnesium is 125 mg/ℓ.

The average concentration of magnesium measured in Grand Traverse Bay was 14.2 mg/ℓ. The range of concentrations measured was 8.43 to 19.3 mg/ℓ. These concentrations meet drinking water standards and are suitably low to be satisfactory for all major industrial and municipal uses. Average levels of magnesium in other portions of the Great Lakes range from a low of 2.8 mg/ℓ in Lake Superior to a high of 11.2 mg/ℓ in Lake Michigan. Levels in Lakes Erie, Huron, and Ontario are respectively 6.4 mg/ℓ, 83 mg/ℓ, and 8.2 mg/ℓ. The concentration of magnesium in Grand Traverse Bay probably reflects peculiarities in the geology of the Lake Michigan basin that tend to contribute more magnesium than the other Great Lake basins. The average tributary concentration to Grand Traverse Bay is 16.7 mg/ℓ, which corresponds to the elevated bay concentration. The principal contributors of magnesium, the Boardman River (39%) and the Elk River (52%), have average concentrations of 13.7 mg/ℓ and 13.3 mg/ℓ respectively, slightly less than the tributary averages. Hence the response of the bay is as expected.

Chlorides

The chloride ion is a common constituent of most natural waters and has high solubility characteristics. The chloride ion is involved in very few natural removal reactions. It is, therefore, considered to be a conservative ion and is often used as a tracer in pollution and flow studies. Sources of chlorides include mineral solution, agricultural runoff, ground water, and industrial and municipal wastewater discharges. Human excreta contributes chlorides to wastewater at an average rate of 6 grams/person/day. This raises wastewater effluent chloride concentrations approximately 15 mg/ℓ above the carriage water (Sawyer and McCarty 1967). Chloride levels as low as 250 mg/ℓ may impart salty taste, although the usual taste threshold is 400 mg/ℓ (U.S.E.P.A. 1971). Higher levels of chloride increases oxidative corrosion rates.

Effects of chloride on aquatic life vary. Trout appear to be the most sensitive fish with reported harmful effects at 400 mg/ℓ (McKee and Wolf 1963). Effects in general, however, often depend on the presence and amounts of other salts. Changes in natural chlorinity can exert harmful effects because of alterations in osmotic conditions. The United States Public Health Service has set 250 mg Cl/ℓ as a recommended upper limit to chloride concentrations for drinking water.

Chloride concentrations in Grand Traverse Bay ranged from 1.0 to 11.5 mg/ℓ, with most values falling in the range 7.0 to 8.5 mg/ℓ. The mean surface chloride concentration was 7.25 mg/ℓ, while the total water column average was 7.27 mg/ℓ. A problem was encountered with adsorption and leaching of chlorides by the sample storage containers. For this reason, small differences and low values are suspect.

The chloride levels in Grand Traverse Bay do not differ appreciably from those in Lake Michigan (7.2 mg/ℓ) and are intermediate to those of Lakes Superior (1.5 mg/ℓ) and Huron (6.8 mg/ℓ) which are lower and Lakes Erie (21.5 mg/ℓ) and Ontario (25.4 mg/ℓ) which are higher. Increased chloride levels in the Great Lakes reflect higher levels of urbanization (O'Connor and Mueller 1970). The concentrations of chlorides in Grand Traverse Bay indicate uncontaminated waters.

In the non-river stations chlorides in the surface waters ranged from 7.18 to 7.47 mg/ℓ (zone averages) and from 7.21 to 7.49 mg/ℓ, averaged for the total water column. With the exception of isolated elevated values, at the Boardman River mouth, chloride levels are quite similar to those of the bay. The difference between downstream and upstream chloride concentrations indicates that chlorides are added by the wastewater treatment plant effluent as expected. The low chloride concentrations in Grand Traverse Bay are as expected because of the absence of gross pollution or ground water contact with salt deposits.

Dissolved Oxygen

Most living organisms are dependent on oxygen in one form or another to maintain their metabolic processes. The majority of processes in "healthy" lakes are aerobic and require free dissolved oxygen. For this reason the measurement of dissolved oxygen has become a standard method for assessing the conditions of natural waters. Low levels of oxygen can result in the death of fish and other aquatic life. If levels have not been depleted to this critical point, harmful effects may still be mainfested by disruption of growth, development, and strength characteristics of organisms or their eggs and young. Different organisms have various tolerances to low levels of dissolved oxygen. Michigan has set the following water quality standards to preserve aquatic life. For intolerant warmwater fish, the average daily dissolved oxygen value should not be less than 5 mg/ℓ nor should any single value be below 4 mg/ℓ; for intolerant coldwater fish not less than 6 mg/ℓ at any time; and for tolerant warmwater species an average not less than 4 mg/ℓ nor any value less than 3 mg/ℓ.

Oxygen levels are regulated by physical, chemical, and biological processes. Oxygen may enter water through two major mechanisms, photosynthetic activity and diffusion from the atmosphere. It is removed primarily through respiration by bacteria during stabilization of organic matter, respiration of other animal and plant life, and also chemical oxidation of material in water. The saturation or equilibrium concentration of dissolved oxygen in water is regulated by atmospheric pressure, water temperature, and salinity. The saturation concentration increases with atmospheric partial pressure of oxygen and decreases with salinity and temperature. Increases in temperature also increase respiratory rates which further accelerate oxygen depletion. In general, oxygen levels can vary widely both vertically and horizontally depending on physical, chemical, and biological conditions.

Dissolved oxygen concentrations in Grand Traverse Bay almost always approached saturation values. Thus the concentration at any point in time was more a function of temperature than of the presence of oxygen demanding materials.

Zone averages for surface waters ranged from 9.55 mg/ℓ (Zone V) to 11.43 mg/ℓ (Zone III); water column averages ranged from 9.63 mg/ℓ (Zone V) to 11.39 mg/ℓ (Zone III). Lower values in Zone V reflect shallower average depths and thus warmer waters as compared with other zones. Unless allochthonous organic loadings or productivity patterns within the bay change markedly, dissolved oxygen concentrations will continue at levels entirely suitable for support of a cold water fishery.

Temperature

Temperature is a critical control parameter in aquatic systems. It regulates seasonal stratifications and turnovers and effects the growth, productivity, and cycles of most aquatic organisms. Increasing temperature decreases gas solubility, particularly that of oxygen, and increases gross respiration rates and at times aquatic growth. This can increase oxygen consumption rates and may promote nuisance growths of plant life. Changes in temperature can alter or completely inhibit normal growth, development, and spawning activities of certain organisms.

Michigan has set water quality standards for various water uses and ambient water temperatures. In general these standards stipulate a maximum temperature and an induced variation of no more than 10 or 15°F, depending on water quality and usage.

The thermal structure in Grand Traverse Bay follows the classic dimictic pattern with two thermally stratified periods (winter and summer) and two homothermal overturn periods (spring and fall). There is no evident source of thermal pollution. Temperatures are optimum for maintenance of a cold water fishery and associated dissolved oxygen concentrations.

Trace Metals

Copper

Copper in trace amounts has been shown to be beneficial and possibly essential for the growth of all living organisms. However, in excessive quantities copper can be toxic to a wide variety of aquatic forms from bacteria to fish (Hale 1972) The adult human daily requirement of copper has been estimated as 2.0 mg. On the other hand, large dosages of copper can cause emesis in humans and subsequent liver damage (APHA 1971). The toxicity of copper to aquatic organisms can vary widely depending on the environmental conditions. Copper sulfate at concentrations of 0.2 mg Cu/ℓ is used as an algicide to control algae and weed growth in lakes and reservoirs (Babbitt et al. 1967). Hutchinson (1957) reporting the data of Hale, cites that concentrations as low as 0.030 mg/ℓ have shown adverse effects on some algae. Copper can be toxic to sensitive fish such as trout in concentrations as low as 0.15 mg Cu/ℓ. The United States Public Health Service drinking water standard for copper is 0.2 mg/ℓ.

Copper originates in the environment from mineral solution and from industrial and municipal sources. Corrosion of the metals copper, brass, and bronze may result in the introduction of large amounts of copper to the environment.

Copper concentrations observed in Grand Traverse Bay ranged from undetectable amounts to 6.3 μg/ℓ. The average was 1.01 μg/ℓ. The magnitude of these levels is insignificant in relation to detrimental effects on aquatic life and in governing municipal and industrial use of Grand Traverse Bay waters. The average levels of copper found in Great Lakes waters ranges from 2.2 μg/ℓ in Lake Michigan to 26.6 μg/ℓ in Lake Ontario. The level in Grand Traverse Bay is the lowest of all of these and indicates both very low levels of industrial contamination and copper mineral leaching. This paucity is reflected in the low levels of copper found in Grand Traverse Bay tributary waters, which have an average concentration of 2.4 μg/ℓ. Even the relatively developed basin of the Boardman River contributed low levels of copper waters averaging 3 μg/ℓ.

Chromium

Chromium is a heavy metal found typically only in traces in uncontaminated natural waters. Chromium salts are used extensively in industrial processes and often used to control corrosion. As a consequence, undesirable levels of chromium are often found in waters of urbanized regions. Chromium can exist in both hexavalent and trivalent states in natural waters, however the trivalent form rarely occurs. The hexavalent chromium ion is considered to be highly carcenogenic and the United States Public Health Service sets very strict standards for allowable concentration in drinking waters (50 µg Cr/ℓ). Toxic effects on fish have been reported as low as 5 mg/ℓ (U.S.E.P.A. 1971).

The average concentration of chromium observed in Grand Traverse Bay was 0.57 µg Cr/ℓ. The range of concentrations measured was from the undetectable to a maximum of 3.34 µg Cr/ℓ. Chromium at these levels is not hazardous nor does it indicate any significant industrial pollution. Reported chromium levels in the Great Lakes ranged from 0.4 µg/ℓ in Lake Ontario to 6.0 µg/ℓ in Lake Superior. The average level of chromium in Grand Traverse Bay is less than the level reported in all the Great Lakes, except Lake Ontario. The low levels of chromium in Grand Traverse Bay are again a reflection of the high quality of its tributary loadings. All tributary mean concentrations were less than 3 µg Cr/ℓ.

Iron

Iron is the second most abundant metal in the earth's crust and is an important trace metal requirement for all biologic life. Iron toxicity to benthos and fish has been reported to range from 0.32 mg/ℓ to 1.0 mg/ℓ (Warnick and Bell 1969, Doudoroff and Katz 1953). The notable significance of iron in water use is a consequence of its ability to precipitate and absorb onto materials. This dissolution results in yellow "rust" stains. Iron can also be very important in complexation chemistry of natural waters and nutrient cycling. The International Joint Commission has set water quality recommendations for the Great Lakes at 0.3 mg/ℓ (GLWQB 1975). The United States Public Health Service drinking water standard for iron is 0.3 mg Fe/ℓ.

The average measured concentration of iron in Grand Traverse Bay was 4.96 µg Fe/ℓ, with values ranging from a low of less than 1 µg/ℓ to a high of 48.2 µg/ℓ. These levels are much below the drinking water standards and below levels at which staining or taste problems would arise. Average reported levels of iron in the Great Lakes are 8 µg/ℓ in Lake Superior, 22 µg Fe/ℓ in Lake Huron, 48 µg/ℓ in Lake Erie, 8 µg Fe/ℓ in Lake Ontario and 5.2 µg Fe/ℓ in Lake Michigan. Levels found in Grand Traverse Bay are in close agreement with those found in Lake Michigan and do not indicate any serious deviation from natural parent Lake Michigan water quality. Almost 70% of the tributary loadings of iron to Grand Traverse Bay come from the Boardman River which has an average concentration of 61 µg Fe/ℓ. The significant drop in iron concentrations in bay water might result from dilution or from precipitation and absorption reactions which would tend to reduce the iron levels.

Manganese

Manganese is a multivalent cation which often occurs associated with iron. This is both because of their mineral association and their mineral association and their similarities in chemical oxidation reactivity. Manganese is very soluble in its divalent form but progressively less soluble in its trivalent and quadravalent forms. It is found in surface waters in all forms, the soluble portions are principally complexed forms of the trivalent state and the colloidal suspended forms are usually in the quadravalent state. The divalent state is typically oxidized by dissolved oxygen. Manganese, similar to iron, when present in excess in water supplies can form objectionable stains and precipitates. As a consequence the United States Public Health Service has set 1.0 mg/ℓ as the drinking water standard. Concentrations of manganese tolerated by fish have been found to be as high as 15 mg/ℓ for a seven day exposure (Schweiger 1957).

The average measured Grand Traverse Bay concentration of manganese was 1.05 μg/ℓ. The range of concentrations measured was from undetectable levels to 6.96 μg Mn/ℓ. The average reported concentration for the Great Lakes is 3.2 μg Mn/ℓ for Lake Superior, 0.5 μg/ℓ for Lake Huron, 0.5 μg/ℓ for Lake Michigan, 11.8 μg/ℓ for Lake Erie and 3.0 μg/ℓ for Lake Ontario. The Grand Traverse Bay concentration of manganese is very much in line with the measured parent Lake Michigan concentration, especially considering the limits of detection of the test. The observed levels obviously do not reflect contamination or impaired suitability for wide usage. Tributary concentrations of manganese average 0.06 μg/ℓ. The Boardman River, which contributes 70% of the manganese to the bay, had a concentration of 10 μg/ℓ. Because of the complexity of the manganese chemistry no explanation can be given for the resulting reduction in concentration in the bay waters.

Nickel

Nickel is a trace metal found geologically usually in association with iron. In natural waters its concentrations are usually very low and little toxicity research has been done on its influence. Nickel is commonly added to steel to improve its tensile strength and hardness characteristics. As a consequence high nickel concentrations are at times noted in waters draining highly industrialized areas.

The average nickel concentration measured in Grand Traverse Bay was 2.72 μg/ℓ. The observed concentrations ranged from 0.1 μg/ℓ to 8.46 μg/ℓ and are considered to be low enough to have no effect on water quality in the bay. Average concentrations in the Great Lakes proper ranged from 2 μg/ℓ in Lake Superior to 5.6 μg/ℓ in Lake Ontario. Average concentrations in Lake Michigan were measured on two separate cruises and found to be 2.5 and 19.5 μg/ℓ (Ayers 1970). The level of nickel in Grand Traverse Bay is therefore considered to be relatively low in comparison with the rest of the Great Lakes and suggests very little contamination. The average concentration of nickel in tributaries in the bay was 6 μg/ℓ. The Boardman and Elk Rivers both had average concentrations of 6 μg/ℓ, contributing respectively 38% and 53% of the total tributary loading to the bay.

Strontium

Strontium is an alkalai-earth element that chemically resembles calcium but is much rarer in the environment. Concentrations of strontium in waters vary with the geology of the region. No United States Public Health Service drinking water standard exists. Strontium does tend to accumulate in bone structures of animals becuase of its similarity to calcium and hence is of concern.

The average measured level of strontium in Grand Traverse Bay was 136.88 μg/ℓ. The observed range in concentration was from a low of 42.5 μg/ℓ to a maximum of 266.1 μg/ℓ. The average concentration of strontium reported in the Great Lakes proper are 32.5 μg/ℓ in Lake Superior, 119 μg/ℓ in Lake Huron, 112 μg/ℓ in Lake Michigan, 173 μg/ℓ in Lake Erie, and 188 μg/ℓ in Lake Ontario. The levels measured in Grand Traverse Bay are near the middle of this range. The strontium concentrations are in general agreement with the Lake Michigan observations, but are much larger than the mean Grand Traverse Bay tributary concentration of 42 μg/ℓ. No lapses in Grand Traverse Bay water quality occurred resulting from strontium contamination.

Zinc

Zinc is a heavy metal commonly found in trace quantities in surface waters. It is an essential plant micronutrient, being an important constituent in the formation of enzymes. Zinc is used extensively in industrial processes including galvanization, dye manufacture, and alloy production. High concentrations of zinc in surface waters typically result from discharges originating in industrialized areas.

Zinc toxicity to aquatic life varies widely depending on the species involved and the environmental conditions. Calcium hardness has been shown to reduce zinc toxicity (Lloyd 1960). It has been reported that for mature fish the toxicity limit for zinc is 0.3 mg/ℓ in waters containing 1 mg/ℓ of calcium (Jones 1938). The United States Public Health Service drinking water standard for zinc is 5 mg/ℓ (AWWA 1971).

The average monitored zinc concentration in Grand Traverse Bay was 7.1 μg/ℓ. The range measured was from the undetectable to 58.9 μg/ℓ. Reported average concentrations in the Great Lakes proper ranged from 5.9 μg/ℓ in Lake Erie to 33.0 μg/ℓ in Lake Huron. The Lake Michigan reported average concentration was 19.8 μg/ℓ. The Grand Traverse Bay concentrations were within this range and are not considered to be contaminated levels. The average tributary discharge to the bay had a concentration of 8 μg/ℓ. The Elk River which contributed 57% of the zinc loading to the bay had a concentration of 10 μg/ℓ. The elevation in the bay water concentration over that of its tributaries could be a result of air particulate contamination or influx of material from Lake Michigan proper.

Major Phytoplankton Nutrients

Nitrogen

Nitrogen is an essential nutrient to all life processes. Is is a necessary constituent of all proteins. The aquatic chemistry of nitrogen is complex because it can occur in many forms and valence states. Nitrogen occurs in natural waters in six major forms. It can be incorporated into suspended biomass and detritus which is termed particulate nitrogen. In this state nitrogen usually has a valence of 3- and is incorporated into proteins. Organic nitrogen is also found in the soluble state. The inorganic forms of soluble nitrogen include nitrate, nitrite, ammonia, and nitrogen gas having valences of 5+, 3+, 3-, and 0 respectively. In this report nitrate and nitrite values will be summed and considered as a single parameter. In nature, nitrogen is cycled through these various forms as plant and animal life conduct their metabolic processes.

The concentration of total nitrogen is significant when considering the trophic aspects of a lake, while specific forms are important in evaluating responses of various types of organisms. Inorganic nitrogen is normally utilized by phytoplankton (some can fix atmospheric nitrogen) to synthesize biomass. Organic nitrogen is oxidized by bacteria or other heterotrophs and incorporated into more biomass or broken down into organic forms.

Bacterial nitrification is a process which may occur in lakes during which bacteria derive energy from the conversion of ammonia to nitrite and nitrite to nitrate under aerobic conditions. The reverse process, dentrification, usually takes place in lake sediments and is generally not important in well-aerated waters. These processes are carried out by very specific organisms. Nitrogen enters the aquatic biosystem through nitrogen gas fixation, industrial and municipal wastes, runoff of fertilizers and the solublization of certain mineral deposits. Nitrogen levels are often critical in control of algal and other plant growths. Various researchers have reported levels of inorganic nitrogen in lakes well above those considered excessive for algal growth. This level can vary, however, depending on the balance and abundance of other nutrients. Critical winter concentrations of dissolved inorganic nitrogen may be 0.3 mg/ℓ, provided that the inorganic phosphorus is below 0.015 mg/ℓ (Sawyer 1947). Also of importance is the weight ratio of nitrogen to phosphorus. Allen and Kramer (1972) report that such ratios vary from 3-15:1, with a ratio of 5:1 considered typical. Ammonia and ammonium salts have been shown to be toxic to aquatic fauna. The degree of toxicity is related to pH which controls the dissociation of ammonium hydroxide. Higher pH values increase toxicity. The International Joint Commission (GLWQB 1975, p. 17) recommends that,

> "Concentrations of un-ionized ammonia (NH_3) should not exceed 0.020 milligrams per litre for the protection of aquatic life. Concentrations of total ammonia should not exceed 0.50 milligrams per litre for the protection of public water supplies."

Ammonia and nitrate nitrogen concentrations were among the most dynamic parameters measured in Grand Traverse Bay. The influence of the Boardman River is most pronounced in relation to ammonia nitrogen and phosphorus loadings. These plant nutrients have a direct influence on chlorophyll *a* and primary productivity (phytoplankton) which in turn effect transparency, dissolved oxygen, zooplankton, benthos, and fish populations.

Ammonia

The concentration of ammonia at non-river stations in Grand Traverse Bay varied between trace and 138 μgN/ℓ, with the vast majority of samples falling in the 10-30 μgN/ℓ range. The average surface water value for the bay was 15 μgN/ℓ, and the average for the total water column was 17 μgN/ℓ. It should be noted that these concentrations in many cases approach the limit of detection.

Ammonia concentrations are extremely variable in lakes, with excessive levels generally being associated with high productivity. Ammonia levels in Grand Traverse Bay are lower than any other regions of Lake Michigan including: Green Bay (172 μg/ℓ), south end (33 μg/ℓ) and open lake (18 μgN/ℓ). Grand Traverse Bay ammonia concentrations are higher than those observed in Lake Superior (7 μgN/ℓ), are essentially equivalent to concentrations in Lakes Huron (19 μgN/ℓ) and Ontario (12 μgN/ℓ), and are less than those for Lake Erie (210, 102, and 82 μgN/ℓ for the west, central, and east basins).

The Boardman River (Zone VI) provides 54% of the ammonia-nitrogen load to the bay. Ammonia-nitrogen concentrations for the river ranged from 35 to 690 μgN/ℓ, with an average value of 240 μgN/ℓ. Ammonia levels below the waste water treatment facility averaged about double those upstream; the upstream levels, however, are already an order of magnitude higher than bay values. The river upstream of the waste water effluent discharge contributes approximately 60% of the final river concentration of ammonia.

The influence of the Boardman River loadings is reflected in higher average ammonia concentrations in Zone V, the lower west arm (26 μgN/ℓ surface, 27 μgN/ℓ total water column). Average concentrations in the remainder of the bay ranged from 13-16 μgN/ℓ.

Long range trends in the inner (Zone V) and outer (Zones II, III, and IV combined) bays are reflected in seasonal patterns. Summer ammonia concentrations have been decreasing during the period 1970-1975 in both the inner and outer bays. Although spring and fall levels were sampled less regularly than those of summer, it seems that spring concentrations of ammonia have increased slightly over the period 1971-1973 while fall concentrations have fallen sharply between 1972 and 1973. This trend holds for both surface and total water column levels.

In summary it may be stated that the Boardman River has an observable elevating effect on ammonia concentrations in the lower west arm

(Zone V) of Grand Traverse Bay. Average values in the remainder of the bay are low in comparison to most other locations in the Great Lakes. Overall trends appear to indicate a reduction in average concentration. Although many subtle aspects of algal nitrogen metabolism are yet incompletely understood, it may be suggested that since ammonia only represents about 10% of the total inorganic nitrogen, its impact on phytoplankton nutrition is not of great importance.

Nitrate

Nitrate (including nitrite) accounts for approximately 90% of the total dissolved inorganic nitrogen in Grand Traverse Bay. The concentration of nitrate at non-river stations ranged from 33 to 502 μgN/ℓ, with most values measured falling into the 100-200 μgN/ℓ range. The average surface water value for the bay was 147 μgN/ℓ; for the total water column concentrations averaged 161 μgN/ℓ.

In contrast to ammonia levels, the concentration of nitrate in lakes is generally more stable. In addition, high levels of nitrate are not always associated with high aquatic productivity. Concentrations of nitrate in Grand Traverse Bay are on the average higher than those for Green Bay (90 μgN/ℓ) and open Lake Michigan (128 μgN/ℓ) and roughly equivalent to those for the south end of Lake Michigan. When compared with the other Great Lakes, nitrate levels are lower than any of the average values with the exception of Saginaw Bay and the central and eastern basins of Lake Erie. All other averages fall in the 210-250 μgN/ℓ range.

Inputs of nitrate (in terms of concentration) from the Boardman River are slightly more than twice the average concentration in the bay and represent 35.4% of the total loading. The river upstream of the waste water effluent discharge contributes approximately 75% of the total river concentration. Thus, as would be expected, the waste water contribution of nitrate nitrogen is, on a *percentage* basis, less than the ammonia-nitrogen contribution. On a *concentration* basis, however, the wastewater effluent discharge contributions to nitrate and ammonia concentrations in the bay are roughly equivalent, with ammonia concentrations being very slightly higher.

The input of nitrate by the Boardman River is not reflected in surface or total water column concentration averages in the lower west arm (Zone V). Surface water averages for nitrate in the bay ranged from 141 μgN/ℓ (Zone IV) to 164 μgN/ℓ (Zone II). Total water column values followed an identical pattern.

Long range trends in nitrate levels do not seem to exactly parallel those of ammonia levels. Concentration differences between the inner and outer bays are very small. Summer and spring concentrations of nitrate are generally stable, while fall concentrations appear to be decreasing slightly.

Nitrate concentrations in Grand Traverse Bay do not present any current or potential ecological problems. Total inorganic nitrogen levels are generally less than those in other waters of similarly low productivity. Nitrogen concentrations appear to be of secondary importance in Grand Traverse Bay with phosphorus concentrations being most critical, since dissolved inorganic nitrogen is comparatively abundant. The average weight ratios of combined inorganic nitrogen to total dissolved and total phosphorus for Grand Traverse Bay are 43:1 (dissolved P) and 22:1 (total P). Published estimates regard a weight ratio of greater than 5:1 as being representitive of a phosphorus limiting environment.

Phosphorus

Phosphorus, like nitrogen, is essential for all aquatic life. This element is intimately involved in the energy storage and release systems of all organisms. Becuase of its role in natural and cultural eutrophication, phosphorus has become one of the most discussed chemical species in the aquatic environment. Although total agreement has not been reached concerning the relative role of phosphorus in eutrophication, it is accepted that large quantities of phosphorus must be available to support algal blooms.

Phosphorus occurs in natural waters as a result of leaching from minerals and soils, agricultural drainage, municipal and industrial discharges, and degradation and release from organic matter. Once in a water system, phosphorus removal is controlled by associated adsorption and sedimentation processes, removal of phosphorus-containing biomass, and natural transfer due to flushing.

It is generally acknowledged that soluble reactive phosphorus is the form of phosphorus directly used by phytoplankton, although all forms of phosphorus represent a potential source of the nutrient as a result of biodegradation and hydrolysis. In water various forms of phosphorus are differentiated as soluble reactive phosphorus, soluble organic phosphorus, and particulate phosphorus which is that incorporated into biomass or detrital matter. Levels of dissolved reactive phosphorus are quite low in Grand Traverse Bay. Consequently, in this study both inorganic and organic forms are combined and reported as total dissolved phosphorus.

Although excessive amounts of phosphorus can cause nuisance algal blooms and associated odors and indirect detrimental effects on fish and other aquatic life, phosphorus itself does not exert direct toxic or other undesirable effects. Productivity studies of 17 Wisconsin lakes suggest a winter concentration of 10 μg/ℓ of inorganic phosphorus as a maximum value permissible without the danger of support of undesirable algal growths. It should be noted, however, that algal growth may be controlled by numerous other nutrient and physical conditions as well.

Phosphorus is unquestionably the most critical algal growth nutrient in Grand Traverse Bay at the present time. As discussed earlier, elemental ratios of the major algal growth nutrients (N, P, Si) indicate that phosphorus concentrations will determine the abundance and species distribution of phytoplankton in Grand Traverse Bay.

Three types of phosphorus data are available for Grand Traverse Bay: total dissolved phosphorus, total phosphorus and particulate phosphorus. The latter parameter is calculated by subtraction of dissolved from total phosphorus. It should be noted that, in many cases, levels of phosphorus in Grand Traverse Bay approach the lower analytical detection limit.

The phosphorus in Grand Traverse Bay is essentially equally divided between dissolved and particulate fractions. The concentration of total dissolved phosphorus (TDP) at bay stations ranged from trace to 22 μgP/ℓ, with the vast majority of samples being less than 6 μgP/ℓ. The average surface water value for TDP was 4.03 μgP/ℓ and for the total water column, 4.15 μgP/ℓ.

Particulate phosphorus (PP) concentrations at non-river stations ranged from trace to 28 μgP/ℓ, although considerably more fluctuation was observed in PP values than in TDP samples. The average surface water concentration in the bay was 4.00 μgP/ℓ and for the total water column 4.14 μgP/ℓ. Total phosphorus levels ranged from trace to 36 μgP/ℓ with a surface water average in the bay of 7.9 μgP/ℓ and a total water column average of 8.1 μgP/ℓ.

These levels of phosphorus rank Grand Traverse Bay among the most phosphorus deficient waters in the Great Lakes. Only Lake Superior (PP = 1.6 μgP/ℓ, TP = 4.5 μgP/ℓ, TDP = 2.0 μgP/ℓ) is actually lower than Grand Traverse Bay in all three categories. Lake Michigan (open water) and Lake Huron (open water) very closely approach the Grand Traverse Bay values. By comparison, the nitrogen-limited environment of lower Green Bay has extremely high phosphorus levels (TDP = 100 μgP/ℓ, PP = 187 μgP/ℓ, and TP = 304 μgP/ℓ). The major phosphorus input to Grand Traverse Bay is from the Boardman River. Concentrations of TDP at river stations averaged approximately ten times that of bay levles, with PP levels averaging about 3-4 times bay concentrations. The Boardman River contributes 66.6% of the total dissolved phosphorus loading and 65.5% of the particulate phosphorus loading to the bay.

As was the case with nitrogen, the influence of the Boardman River is reflected in higher concentrations of total dissolved and particulate phosphorus in Zone V (lower west arm). Levels of phosphorus in the other bay zones are extremely low and show little intrazonal variation.

While 70-75% of the concentration of TDP in the river is contributed by the waste water effluent, less than 60% of the concentration of PP originates from this source. These calculations do not reflect the effect of the advanced phosphorus removal treatment provided at the Traverse City Waste Water Treatment Plant since most samples were collected before the system went into effect.

Without phosphorus removal, the phosphorus loading by the Traverse City effluent ranged from 80-110 grams of P/day (monthly averages). However, when the plant was fully operational, the phosphorus loading at the plant was 5-15 grams P/day. This represents a 90-95% removal efficiency.

Summer concentrations of total and total dissolved phosphorus appear to have increased in the period 1971-1976. Concentrations decreased in 1975. Fall and spring concentrations of TDP decreased in the period 1971-1973, while TP concentrations remained essentially constant.

The critical nature of phosphorus in the biogeochemistry of Grand Traverse Bay mandates that the concentration and dynamics of this element be monitored in the future. The installation of phosphorus removal equipment at the Traverse City Waste Water Treatment Plant is an excellent first step in maintaining the existing oligotrophic conditions in Grand Traverse Bay.

Silicon

Silicon is the second most abundant element on earth, representing 28% of the earth's crust. It is, however, rarely found in the elemental form in nature but occurs as silica in sand or quartz and as silicates in feldspar, kalonite, and other minerals. Silicon usually occurs in natural waters as silicon dioxide. It is associated with colloidal or suspended matter or incorporated into biomass and detrital matter. Silicon is an essential nutrient used in the structural portions of many algae, particularly diatoms.

Since the predominant algae in Grand Traverse Bay are diatoms, the availability of silicon is important in determining their relative presence. Schelske and Callender (1970) have presented the hypothesis that silicon depletion has occurred in Lake Michigan (particularly the south end) as a result of increased phosphorus levels. The hypothesis further suggests that silicon depletion may change original species composition to less desirable blue-green algae. The importance of silicon levels in Grand Traverse Bay may best be interpreted in light of this hypothesis.

Silicon levels for non-river stations ranged from 0.02 to 3.51 mgSi/ℓ, with a baywide surface water average of 0.43 mgSi/ℓ and a total water column average of 0.46 mgSi/ℓ. Silicon levels less than 0.25 mg/ℓ are common zone averages in the summer months in Grand Traverse Bay. Hutchinson (1957) reports silicon limitation for various species of diatoms to occur in the range 0.23-0.37 mg Si/ℓ. Average surface water values in Grand Traverse Bay approach this range: Zone II (0.34), Zone III (0.41), Zone IV (0.43), and Zone V (0.51). These values are much lower than those reported by Lauff (1957) for July 1954. For those samples silicon ranged from approximately 0.85 to 1.15 mg Si/ℓ.

Average silicon values in Grand Traverse Bay are lower than those in other regions of the Great Lakes except Lakes Erie (0.42, 0.31, and 0.15 mgSi/ℓ for west, central and east basins) and Ontario (0.24 mgSi/ℓ). Larger silicon levels are found in less productive systems-Lakes Michigan (0.85 mgSi/ℓ), Huron (0.76 mgSi/ℓ) and Superior (1.00 mgSi/ℓ).

Surface silicon levels during the summer decreased in the period 1972-1975 and during 1972-1973 (only data available) for spring and fall values. The input of silicon comes from predominately two sources: recycling from diatom decomposition and river loadings. Concentrations of silicon in the Boardman River (Zone VI) averaged 3.40 mgSi/ℓ (surface).

It is known that average concentrations of silicon in the bay are approaching limiting levels. Since silicon is not stored by algae (but rather taken up as needed) its use is governed by the availability of other nutrients. Silicon is noramlly absorbed according to stoichiometric equation, i.e., Si:N:P = 10:5:1. Thus, the more phosphorus that is introduced into a system, the more silicon which will be utilized by algae. Since the sources which introduce phosphorus into lakes and streams do not usually contain concomittant levels of silicon, algal growth eventually results in silicon depletion. Low silicon levels limit the growth of diatoms and results (Schelske and Callender 1970) in shifts of algal species composition usually toward less desirable organisms.

Biological Conditions

Four groups of organisms will be discussed under biological parameters: coliform bacteria, phytoplankton, zooplankton and benthos. A fifth major group, fish, are covered in a separate Sea Grant publication (Price and Kelly in press).

Coliform Bacteria

The concentration of fecal or total coliform bacteria in natural waters is important because these organisms are indicators of fecal contamination which is of public health concern. The State of Michigan Water Quality Standards (MWRC 1973) require that the concentration of fecal coliform should not exceed 200 cells/100 ml in waters used for total body contact recreation. Important economic and cultural considerations dictate that Grand Traverse Bay be protected for such use. The Michigan Sea Grant Program has sought to: (1) define the spatial and temporal distribution of coliform in the bay, (2) evaluate the sources of coliform contamination, (3) study the factors which affect the distribution and survival of coliform and, (4) seek ways to predict the influence of man's activities on bacterial pollution of the bay.

Historically, the bay has experienced periods of excessive summer coliform concentrations at both beach sites and at the municipal water intake. It has been shown that the major cause of this pollution was bacteria associated with carbohydrate wastes discharged by the fruit processing industry. Such waste waters are no longer discharged directly to the bay, consequently pollution levels have declined dramatically. Summer average facal coliform concentrations now meet the state requirements for total body contact recreation and east arm municipal water intake concentrations are an order of magnitude lower than those recorded in 1965 when the water intake was located in the west arm. On the other hand, water quality standard violations have been detected for short periods of time at local beaches following rainfalls. This pollution results from discharges from the storm water collection system in Traverse City. It is recommended that any total water quality control program consider collection and treatment of storm sewer overflows.

The factors which affect the survival and distribution of coliform in the bay have been evaluated by Sea Grant researchers. The natural die-away rate of the bacteria has been enumerated by laboratory and *in situ* studies. This information combined with knowledge of the dilution influence of bay circulation patterns has facilitated the development of predictive mathematical models for coliform in the bay. These models are useful tools which can be used by water quality planners to estimate the impact of man's activities on coliform levels in the bay.

Phytoplankton

Phytoplankton are the free-floating (planktonic) algae found in lakes and oceans. These organisms are the orignial source of energy fixation in an aquatic ecosystem and thus are the base of the food pyramid. In excessive numbers, these organisms may lead to taste and odor problems, oxygen depletion, and objectionable surface mats and scum.

In relation to phytoplankton, five parameters will be evaluated: cell counts (species composition), chlorophyll *a*, primary productivity, assimilation ratio, and transparency (Secchi disc). Although all of these parameters relate to a specific group of organisms (phytoplankton) each measurement provides slightly different information from the past.

Cell Counts and Species Composition

Studies by Stoermer et al. (1972) and Moore (unpublished data) have described the phytoplankton of Grand Traverse Bay. Cell numbers were comparable to those observed at inshore stations of Lake Michigan. Species diversity was high and the species composition was indicative of oligotrophic conditions. Higher productivities were noted in the lower west arm of the bay. Details of this research are summarized in Chapter XIII, Phytoplankton Studies.

Chlorophyll *a*

This plant pigment is present in all algae. As such, the chlorophyll *a* concentration in water may be directly related to the amount of phytoplankton biomass present.

Chlorophyll *a* concentrations in Grand Traverse Bay ranged from 0.03 to 7.01 μg/ℓ, with most values falling in the 0.5 to 2.5 μg/ℓ range. Surface water values averaged 1.58 μg/ℓ, while the total water column averaged 1.18 μg/ℓ. The surface water average is virtually identical to that for Lake Huron and slightly lower than that for open Lake Michigan (1.8 μg/ℓ). Only Lake Superior (0.7 μg/ℓ) had a lower average chlorophyll *a* level. Concentrations greater than 10 μg/ℓ are characteristic of highly productive waters such as Green Bay and Saginaw Bay.

The average concentration in the west arm (Zone IV) was 1.63 μg/ℓ. This level did not differ from that of the more nutrient rich lower west arm (1.63 μg/ℓ). The east arm (Zone III) was very much lower in average surface chlorophyll *a* concentration (1.06 μg/ℓ) when compared to the west arm. The open bay (Zone II) again appeared to be a mixing zone with concentrations intermediate to those of the east and west arms (1.32 μg/ℓ) and identical to those of the open Lake Michigan stations (Zone I). The horizontal distribution of chlorophyll *a* within the bay between 1972 and 1974 follows the pattern described by Stoermer et al. (1972) during earlier productivity studies.

Chlorophyll *a* concentrations fluctuate with the seasonal variation in phytoplankton populations. Long range changes in chlorophyll *a* concentration were not observed because of the short sampling period.

Primary Productivity and Assimilation Ratio

The process involving the uptake by plants of carbon dioxide and subsequent incorporation of carbon into carbohydrate with the release of oxygen is referred to as photosynthesis. This process may be summarized as follows:

$$6CO_2 + 6H_2O \xrightarrow[\text{nutrients}]{\text{light}} C_6H_{12}O_6 + 6O_2$$

The uptake of carbon dioxide is an indication of the quantity of photosynthate produced and thus growth (primary productivity). The level of primary productivity (μgC absorbed/ℓ/hour) is a function of the standing stock of phytoplankton (e.g. chlorophyll *a*) and environmental growth conditions (e.g., temperature, light, phosphorus, nitrogen, etc.). When the effects of standing stock are normalized by dividing the primary productivity by the chlorophyll the result is an assimilation ratio which reflects only growth conditions.

Primary productivity in Grand Traverse Bay ranged from trace to 10.28 μgC/ℓ/hour, with a more general range of 0.5 to 5.0 μgC/ℓ/hr. Levels of primary productivity were variable. The average surface uptake in Grand Traverse Bay was 2.03 μgC/ℓ/hr; the surface and mid-depth average was 1.76 μgC/ℓ/hr. These values are consistent with earlier measurements in Grand Traverse Bay and significantly less than those reported for other areas in Lake Michigan (3.4 to 6 μgC/ℓ/hr). Extremes in uptake levels are represented by Lake Superior (0.37 μgC/ℓ/hr) and Saginaw Bay (50 μgC/ℓ/hr).

Evaluation of the horizontal distribution of primary productivity levels between zones provides information not evident in the chlorophyll *a* data. It was suspected that due to nutrient loadings from the Boardman River, higher plankton productivity would be noted in the lower west arm (Zone V). This was not the case with chlorophyll *a*, however: the highest levels of primary productivity were noted in this zone. In addition, primary productivity at the Elk River plume (Zone IIIb) was higher than for the remainder of the east arm (Zone IIIa). An anomoly at this location was noted for only one other parameter (zooplankton).

With the exception of very high carbon uptake rates in Zone V (3.25 μg/C/ℓ/hr), and the relatively high rates in Zone IIIb (1.80 μgC/ℓ/hr), the primary productivity followed a general pattern similar to that of chlorophyll *a* in Grand Traverse Bay. West arm surface levels were highest (2.17 μgC/ℓ/hr), with east arm levels low (1.51 μgC/ℓ/hr). and virtually identical to those in the open bay (1.41 μgC/ℓ/hr). When surface and mid-depth values are averaged the primary productivity follows exactly the pattern described for chlorophyll *a* (again except high values for Zone IIIb and V).

As with chlorophyll *a*, primary productivity levels follow seasonal patterns associated with phytoplankton populations. Seasonal and vertical variations in this and other parameters will be discussed in a later section.

Complete data are not available for the computation of the assimilation ratio. Good data are available for Zones IV and V, however. The average assimilation ratio for Zone V (3.10) was higher than for Zone IV (2.70) as would be expected. Although data were limited, the ratios for Zones II and IIIb were calculated and are 2.08 and 2.55 respectively. The west arm assimilation ratios follow patterns expected from observing nutrient concentrations.

Assimilation ratios reported in the literature for regions of the Great Lakes vary widely. Grand Traverse Bay assimilation ratios lie intermediate to the low values reported for Lakes Superior (0.82), Huron (1.89), and Ontario (1.2-1.6) and the high values for Saginaw Bay (4.16) and Lake Erie western basin (4.33). Assimilation ratios for lower Lake Michigan (2.9) are quite similar to those found in Grand Traverse Bay.

Transparency (Secchi Disc)

Transparency is that quality of water which governs light penetration or extinction. It is typically measured in the field as the maximum depth at which the Secchi disc can be observed from the surface. It is important to aquatic life because it defines the extent of the euphotic zone which governs primary production. The depth of the Secchi disc reading when compared with values at other times of the year, in other parts of the lake, or in other lakes, provides a measurement of the plankton community. In many eutrophic lakes, production can be limited by energizing light rather than by chemical nutrients.

Secchi depth ranged from 1.5 to 12.5 meters in Grand Traverse Bay. Average Secchi depth in the various zones followed a pattern similar to that for other phytoplankton indicators. The average Secchi depth in the lower west arm (Zone V) was 6.1 m, while in the west arm (Zone IV) the average was 7.0 m. Although less data were available for other zones, the averages for these zones are as follows: east arm (Zone III) 7.1 m, (Zone II) 7.7 m, and Lake Michigan (Zone I) 7.2 m. These transparencies are generally in line with phytoplankton patterns evidenced in other parameters in both temporal and spatial distribution. These Secchi disc readings are generally higher than those for other regions of Lake Michigan (open lake 6.7 m, Green Bay 1.8 m), but not as high as those for Lakes Huron (8.1 m) and Superior (10.4 m). Such high readings indicate very clean water.

Zooplankton

Zooplankton are important organisms in aquatic ecosystems because they are the principal route for the transfer of nutrients and energy between primary producers and fish. As such, zooplankters are often referred to as secondary producers. Zooplankton, through species differences in grazing rates and size preference, may affect the numbers and composition of phytoplankton. Finally zooplankton are of value in lakes as sensitive indicators of changes or perturbations in conditions of nutrients, temperature, dissolved oxygen, or toxic substances which may result from pollutional loads and may introduce deleterious effects further up the food chain.

Total crustacean zooplankton in Grand Traverse Bay averaged 20.5 individuals/ℓ over the three year study period. The total population consisted of 42.2% calanoid copepods, 34.4% cyclopoid copepods, and 23.4% cladocerans. The peak zooplankton abundance in Grand Traverse Bay varied among years, but no clear pattern in annual variation is evident. Variation in species composition was also slight, with a small increase in *Bosmina* and *Leptodora* in 1973 the only change noted. The Grand Traverse Bay crustacean zooplankton numbers are comparable with those found for open Lake Michigan (6-28 individuals/ℓ) and less than those observed in Green Bay (71.5 individuals/ℓ) and southeastern Lake Michigan (100 individuals/ℓ).

Horizontal distribution of zooplankton numbers in Grand Traverse Bay reflects the input of the Boardman and Elk River systems to the bay. The zooplankton loadings due to the rivers are important in terms of composition in both the west arm (Zone IV) and the Elk River plume (Zone IIIb), and in terms of numbers in the Elk River plume. The latter effect (increased numbers) is possibly a result of the Chain-Of-Lakes drained by the Elk River.

Secondary productivity as evidenced by the zooplankton populations may be classified as low to moderate. The levels of secondard productivity in Grand Traverse Bay appear to be sufficient to support the existing and future fishery. No significant pollution of any kind was detected using zooplankton as an indicator; however, there are some signs of increased eutrophication in the west arm over the rest of the bay.

Benthos

Benthic macroinvertebrates are useful indicators of water quality because of the overall stability of the community under a given set of physical and chemical conditions. The communities of clean water systems generally respond drastically to pollutional inputs. Such communities will be replaced by different organisms; those tolerant of the existing conditions. Organisms can often be classified as being associated with a particular environment.

The benthic fauna of Grand Traverse Bay were sampled between 1970 and 1975 to obtain an inventory of existing populations and allow a comparison with other regions. As compared with Lake Michigan, the Grand Traverse Bay benthic macroinvertebrate populations were smaller in total numbers but quite similar in composition to the deeper waters of the lake. The organisms collected were characteristic of an oligotrophic system. The lower densities are most probably a result of lower overall productivity in the bay and reflect the depauperate nutrient conditions in the bay. Benthos populations do not reflect the influence of the Boardman River as observed in relation to other parameters.

Surface Sediment

It is well known that toxic trace elements can accumulate in lake sediment at concentrations many orders of magnitude greater than corresponding levels in the water itself. As a result trace element enrichment of sediment has been a topic of research interest for geochemists and other environmental scientists. Microbial and geochemical alterations of the sediments can liberate large amounts of trace elements to the overlying aquatic environment. In this way, potentially toxic trace elements can be made available to the aquatic food chain and thus pose ecological and public health hazards (Baker-Blocker et al. 1975). Possible sources of trace elements to the sediment are runoff from the land, leaching of minerals, and atmospheric transport. The distribution of trace elements in sediment has been related to particle diameter size and organic carbon content (Glenn and Van Atta 1973, Schoettle and Friedman 1973).

Baker-Blocker et al. (1975) investigated the surface sediment of Grand Traverse Bay on two separate sampling cruises in 1970. A sampling grid of 67 stations was laid out in the bay; 29 stations were located in the west arm, 22 in the east arm, and 16 in the outer bay. Surface sediment was sampled by duplicate grabs at each station. The sediments were analyzed for texture, grain size, and trace metal and ionic content. The details of this work were previously published (Baker-Blocker et al. 1975) and only a brief description of the data and results are given in this report.

Grand Traverse Bay sediment is principally calcareous in nature (average calcium concentration 4.63 wt%). The sediment types range from colloidal silt to sandy silt. The organic carbon content of the sediment is slightly higher than that observed in Lake Michigan sediment, although about the same as that observed in Lake Superior sediment. In general the mean organic carbon content of 2.31 wt% did not indicate pollutional contamination.

The spatial distribution of sediment grain size and organic content appeared to be governed by the physical limnology of the bay. Smaller particles associated with high organic content were found in the deeper more quiescent regions of the bay, whereas the larger particles with lower organic content were found in shallower areas. The exception to this rule was in the Boardman River plume where organic content was slightly elevated despite its shallow nature.

Trace metal and major ion concentrations in the sediment did not reveal any significant contamination. Most levels were well within the range of reported values for other unpolluted regions of the Great Lakes. The acid peroxide extract concentrations reported in Grand Traverse Bay sediment were 56.7 μg/gm barium, 18.6 μg/gm copper, 41.7 μg/gm strontium, 90.5 μg/gm zinc, 1.23 wt% iron, 1.92% magnesium, and 0.03 wt% manganese. The spatial distribution of trace metal concentrations generally revealed higher concentrations in the Boardman River plume and in deep water areas. This was closely correlated with the distribution of grain sizes.

In summary, the surface sediments of Grand Traverse Bay do not indicate the existance of any serious pollutional contamination, nor do they pose any ecological or health hazard.

XI. COLIFORM BACTERIA

Significance of Coliform Bacteria

Water is a common mode for transmission of disease in many parts of the world. Although pathogenic bacteria such as *Salmonella typhosa, Shigella dysenteriae* and *Vibrio comma* do not ordinarily grow in relatively pure water, they may survive for several days after contamination. This results in a potential hazard to public health. Unfortunately, detection techniques for these bacteria are complicated and difficult to conduct on a routine basis. Because of these difficulties, indicator organisms which suggest the presence of fecal matter are normally used to specify water quality standards. The coliform bacteria were once thought to be entirely of fecal origin, and for many years were used to define safe limits for drinking and recreational use of water. However, it has recently been shown that certain soil bacteria such as *Aerobacter* are included in this group, and therefore the presence of fecal contamination is not always directly linked to coliform group. The 13th edition of Standard Methods (APHA 1971) describes an elevated temperature technique which has been accepted as a means for separating fecal coliform from total coliform. Thus, most water quality standards are now written in terms of fecal coliform rather than total coliform alone.

In Michigan, water quality standards have been established for each of several water uses. Recreational activities in Grand Traverse Bay involving swimming and other total body contact uses are protected by Rule 1062 of the 1973 State of Michigan water quality standards (MWRC 1973):

> "(1) Waters of the state protected for total body contact recreation shall contain not more than 200 fecal coliforms per 100 milliliters and all other waters of the state shall contain not more than 1000 fecal coliform per 100 milliliters. These concentrations may be exceeded if due to uncontrollable non-point sources.
>
> (2) Compliance with the fecal coliform standards prescribed by subrule (1) shall be determined on the basis of the geometric average of any series of 5 or more consecutive samples taken over not more than a 30 day period."

Chapter III of this report has described the economic and cultural importance of protecting the recreational value and drinking water quality of Grand Traverse Bay. Figure XI-1 shows the location of six beaches, one marina, the old drinking water intake pipe used before 1966 and the new location used after this date. All these resources are located on Grand Traverse Bay within the influence zone of urban activities such as the Traverse City Wastewater Treatment Plant and storm sewer discharges. The recreational value of these resources is in part a function of the degree to which the waters of the bay meet the above fecal coliform standards. Thus, several studies supported by the Michigan Sea Grant Program have been directed toward (1) determining the extent of compliance with the fecal coliform standard, (2) evaluating the sources of coliform bacteria, and (3) studying the factors which affect the survival and

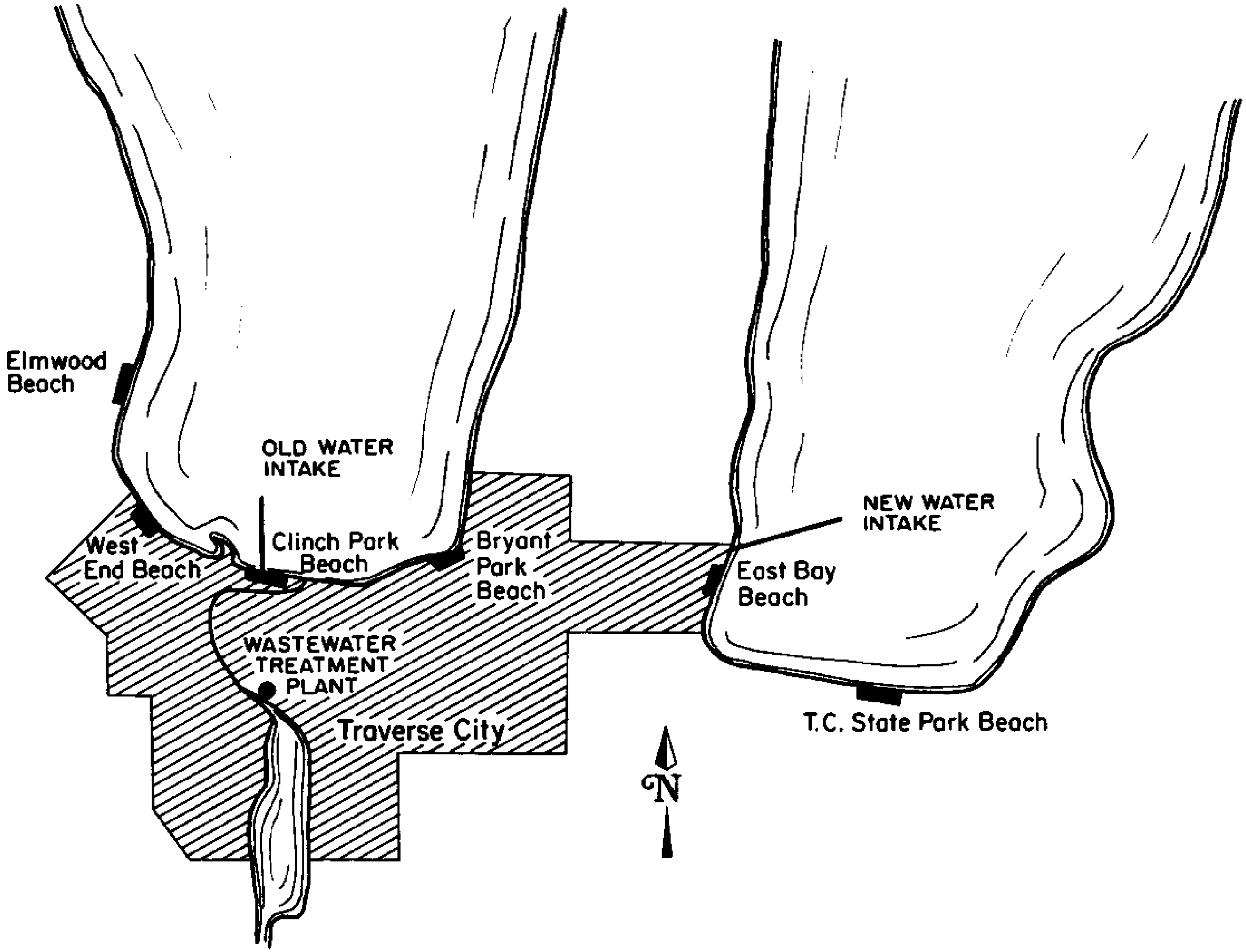


FIGURE XI-1. Location of features in Grand Traverse Bay relating to coliform studies.

distribution of coliform within Grand Traverse Bay. This section summarizes the results of numerous projects conducted between 1969 and 1972.

Historical Conditions

Before 1966 Traverse City obtained its domestic water supply from the pipe located in the west arm of the bay as shown in Figure XI-1. During this period total coliform bacteria concentrations were recorded on a daily basis at the intake. These data illustrate distinct seasonal and long-term trends. Figure XI-2 shows a plot of weekly average total coliform concentrations at the water intake location between 1956 and 1965. In 1956 the maximum weekly average concentration was about 500 cells/100 ml, while in 1965 this value increased to approximately 2800 cells/100 ml. The seasonal distribution of total coliform in 1964 is shown in Figure XI-3. The summer peak is in the order of 100 times greater than the late winter baseline. Nearshore waters in the extreme southern region of the western bay have also experienced extremely high concentrations of total coliform. Figure XI-4 shows the results of water quality surveys conducted during August 1964. Also shown are the location of two industrial discharges (cherry processing wastes) operative during this time. The observed seasonal trends and shoreline distributions are the result of such industrial discharges, wastes and uncontrolled summer tourist activity, and loading from the Boardman River and several storm sewers.

A number of Michigan Sea Grant studies (Canale et. al. 1973, Canale 1973, and Canale and Green 1972) have shown that the overwhelming cause of these high summer total coliform concentrations was the bacteria associated with organic wastes due to the fruit processing industry. In comparison, the Boardman River (and therefore the Traverse City Waste Water Treatment Plant) and the city storm sewers were relatively minor sources of bacteria during this period. During other periods of the year levels of contamination were relatively low.

Present Conditions

The major historical source of total coliform to Grand Traverse Bay has been the fruit (especially cherry) processing industry. By the year 1972 direct discharge of this source of contamination was eliminated. As a result the most important sources of coliform to Grand Traverse Bay are now land runoff, septic tank discharge, storm sewer flow, and municipal sewage treatment plants. Although boat holding tank disposal is a potentially significant source of pollution (Canale 1973), such discharges are strictly controlled by state of Michigan law.

Between 1970 and 1972 Dr. J.J. Gannon of the Michigan Sea Grant Program conducted several field studies to evaluate the distribution and sources of coliform in the Traverse City area (Gannon 1970, Gannon 1972, Gannon and Meier 1974). These studies included an assessment of both total and fecal coliform (as well as fecal streptococcus) for which only limited historical data are available.

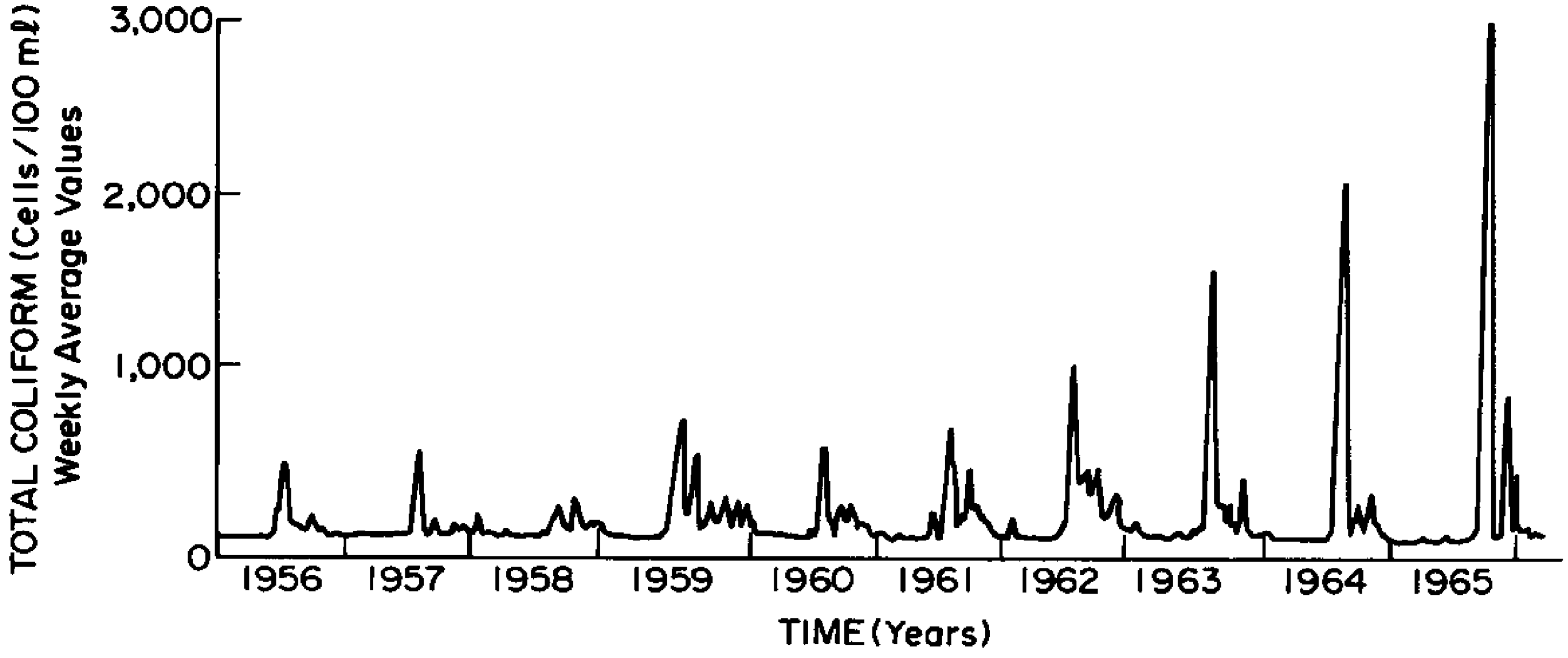


FIGURE XI-2. Weekly average total coliform concentration at the west arm water intake pipes in Grand Traverse Bay between 1956 and 1965.

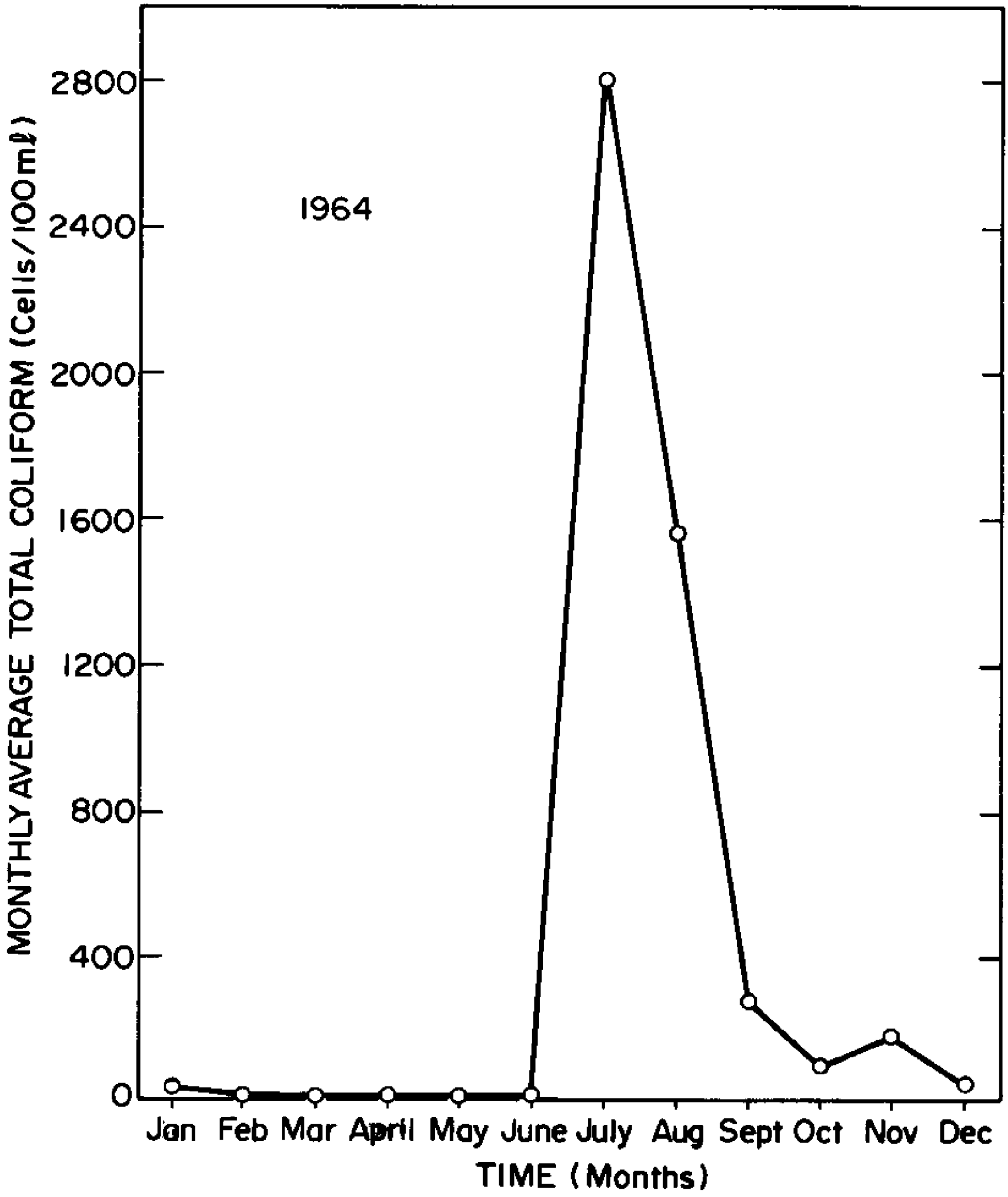


FIGURE XI-3. Monthly average total coliform count at west arm water intake in 1964.

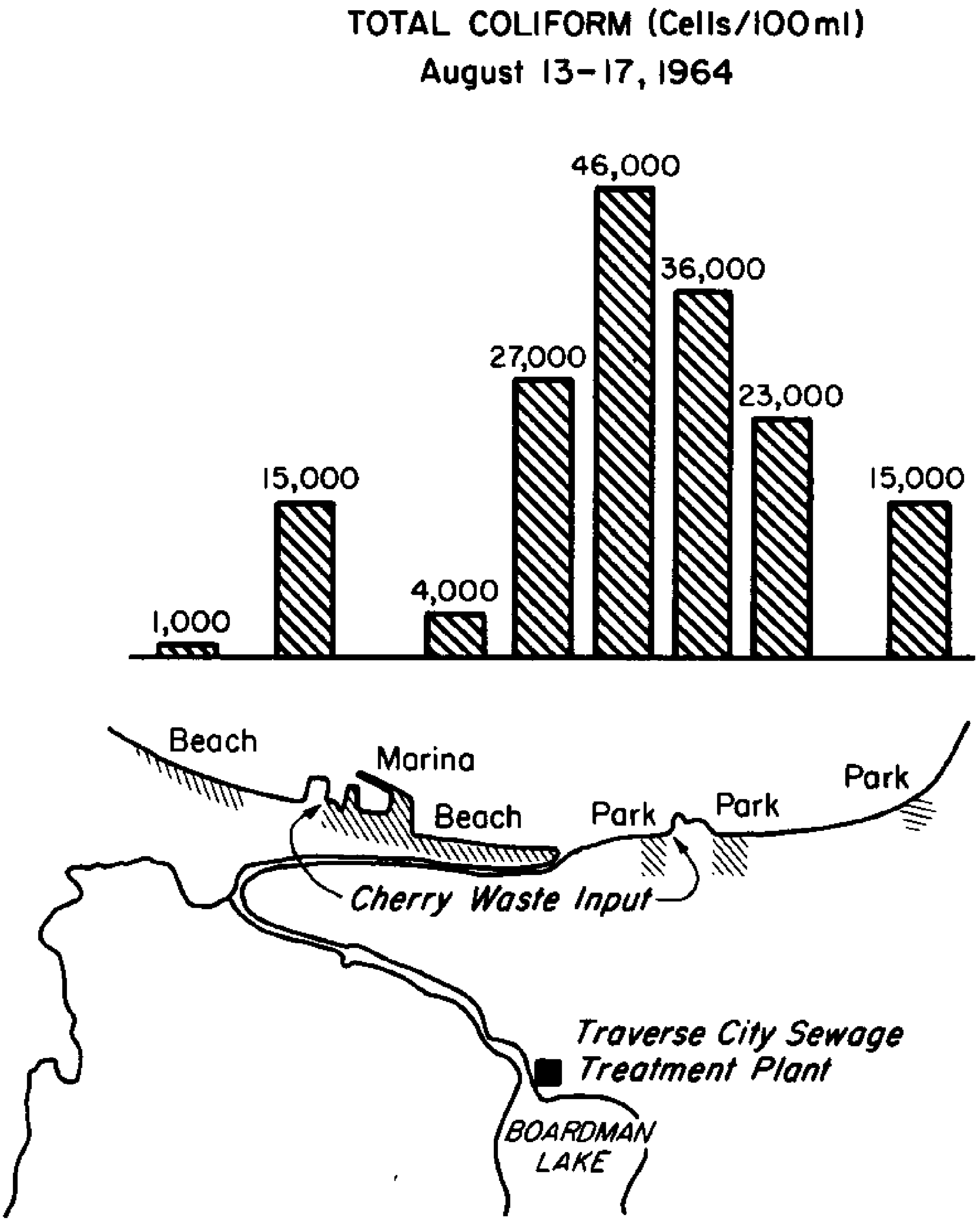


FIGURE XI-4. Total coliform distribution: 1964 water quality study.

Table XI-1 lists a summary of available data from Gannon and Meier (1974) which define the relative magnitude of tributary sources of total coliform to both arms of Grand Traverse Bay. (See Figure XI-1 for the location of these tributaries). It is observed that the highest concentrations of total coliform occur in Baker Creek, Mitchell Creek, Northport Creek, and the mouth of the Boardman River. On the other hand, because of flow considerations, the most significant sources to the bay appear to be Mitchell Creek and the Boardman River. It is noted that the Elk River, having an average flow of 1.28×10^6 m^3/day, is still a minor measured source of contamination because of its low concentration. It is seen that total coliform in the Boardman River measured upstream of the influence of Traverse City at Airport Road is relatively free of contamination compared to the river mouth. The major inputs to the river between these points are the Traverse City Waste Water Treatment plant, several storm sewer outfalls, and Hospital Creek. In 1972 a special study was conducted to evaluate the relative importance of these inputs to the Boardman River. Figure XI-5 shows the location of several sampling stations on the Boardman River and Table XI-2 presents results of surveys conducted during the summer of 1972. The results show a general trend toward increasing concentration as the river passes through the city. The total coliform concentrations increase significantly downstream from the sewage treatment site despite the chlorination facilities at the plant. Fecal coliform concentrations increase markedly in the river after Hospital Creek. The continued increase in coliform concentration as the river proceeds toward the bay is apparently the result of nonpoint sources such as the Traverse City storm sewer system. These sources appear to be of sufficient magnitude to overshadow expected losses by natural die-away of the bacteria.

Traverse City has separate sanitary and storm water sewers. Sanitary sewers transport domestic and industrial effluents to the wastewater treatment plant, while storm water sewers discharge directly to the Boardman River or Grand Traverse Bay without treatment. Twelve storm sewers discharge into the west arm of the bay while three discharge into the east arm. These discharges represent a potential source of fecal coliform as well as of organic matter, algal nutrients, and toxic materials. Immediately after heavy rainfall, high concentrations of fecal coliform have been measured at beaches near storm sewer outfalls (Gannon and Meier 1974).

The task of monitoring the pollution potential of storm water runoff is difficult because of the time variable nature of the problem. Nevertheless, Gannon and Meier (1974) have reported flow and water quality characteristics of three storm sewers in Traverse City (see Figure XI-6 for locations) for a number of storms during the summer of 1971 and 1972. Sampling was conducted during and immediately following rainfall events. The results of the sampling at each site normally follow a pattern where initial bacterial levels are low prior to the first flush of contaminants through the system. During the first flush period the concentration of bacteria reaches a maximum. As the rainfall continues water quality in the sewer system eventually improves due to dilution and the depletion of contaminant sources. Figure XI-7 is a plot of data reported by Gannon and Meier (1974) which shows such a sequence of events.

Table XI-1. Tributary sources of total coliform to Grand Traverse Bay during 1970, 1971, and 1972 (Gannon and Meier 1974).

Tributary	Average Flow m^2/min	Average Total Coliform (cells/100 ml)
Northport Creek	4.74	462
Ennis Creek	1.51	36
Belanger Creek	13.96	140
Setterbo Creek	0.96	101
Suttons Bay Creek	2.44	216
Leo Creek	6.89	123
Cedar Creek	15.68	117
Brewery Creek	3.07	72
Creek #2	0.76	360
Creek #3	1.24	323
Boardman River (mouth)	635.50	668
Boardman River (Airport Rd.)	594.72	8
Mitchell Creek	28.47	537
Baker Creek	3.04	873
Acme Creek	24.70	117
Yuba Creek	15.49	127
Elk River	885.28	

Table XI-2. Average total and fecal coliform distribution in Boardman River during 1972 (Calculated from Gannon and Meier 1974).

Location	Average Fecal Coliform (cells/100 ml)	Average Total Coliform (cells/100 ml)
Airport Road	83	270
Boardman Lake	140	265
Eighth Street	196	1551
Union Street	180	245
Hospital Creek	2632	20771
Front Street	1346	1471
Cass Street	2081	6029
Michigan Highway 31	3091	4514

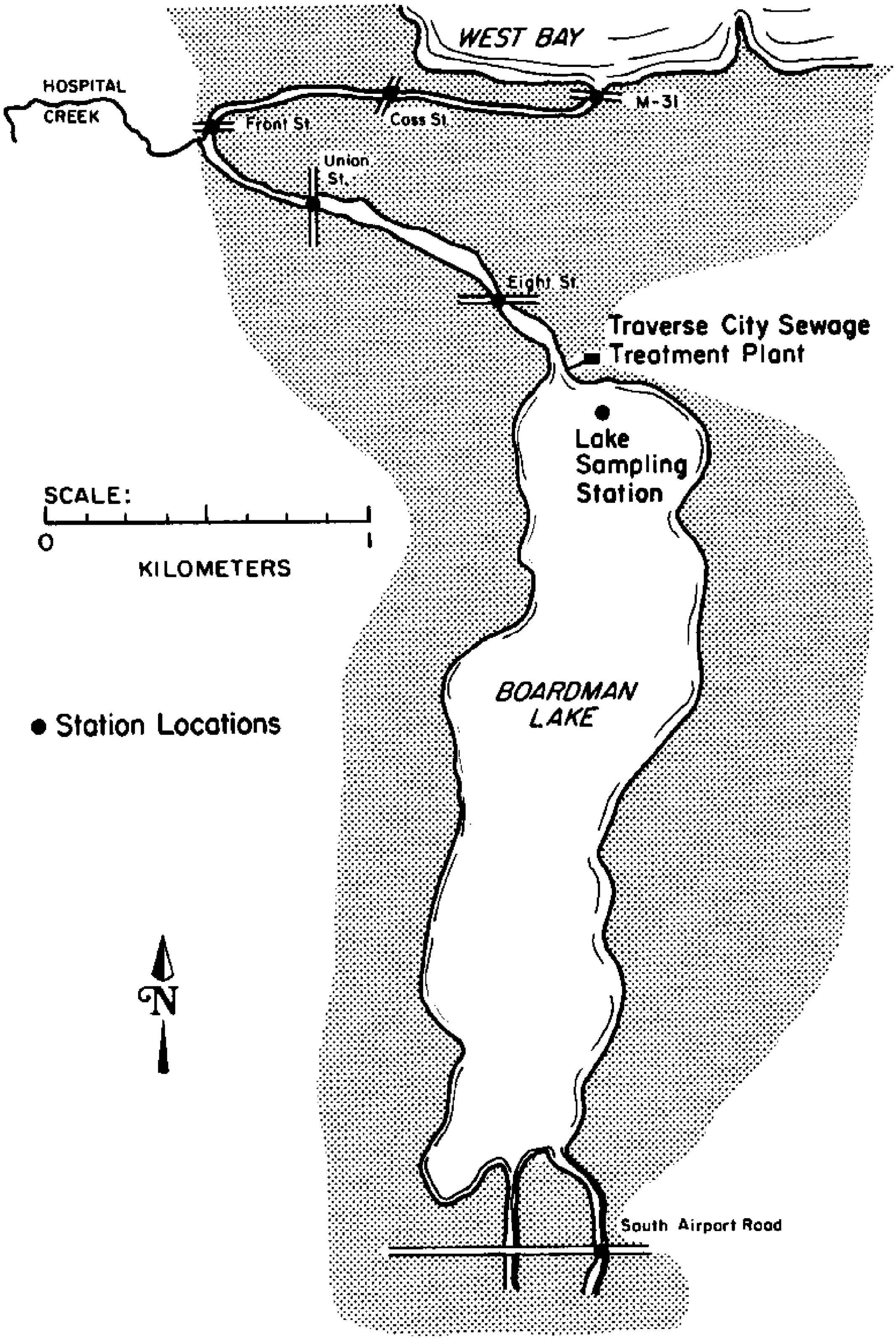


FIGURE XI-5. Coliform sampling station locations on the Boardman River - 1972 (modified by Gannon and Meier 1974).

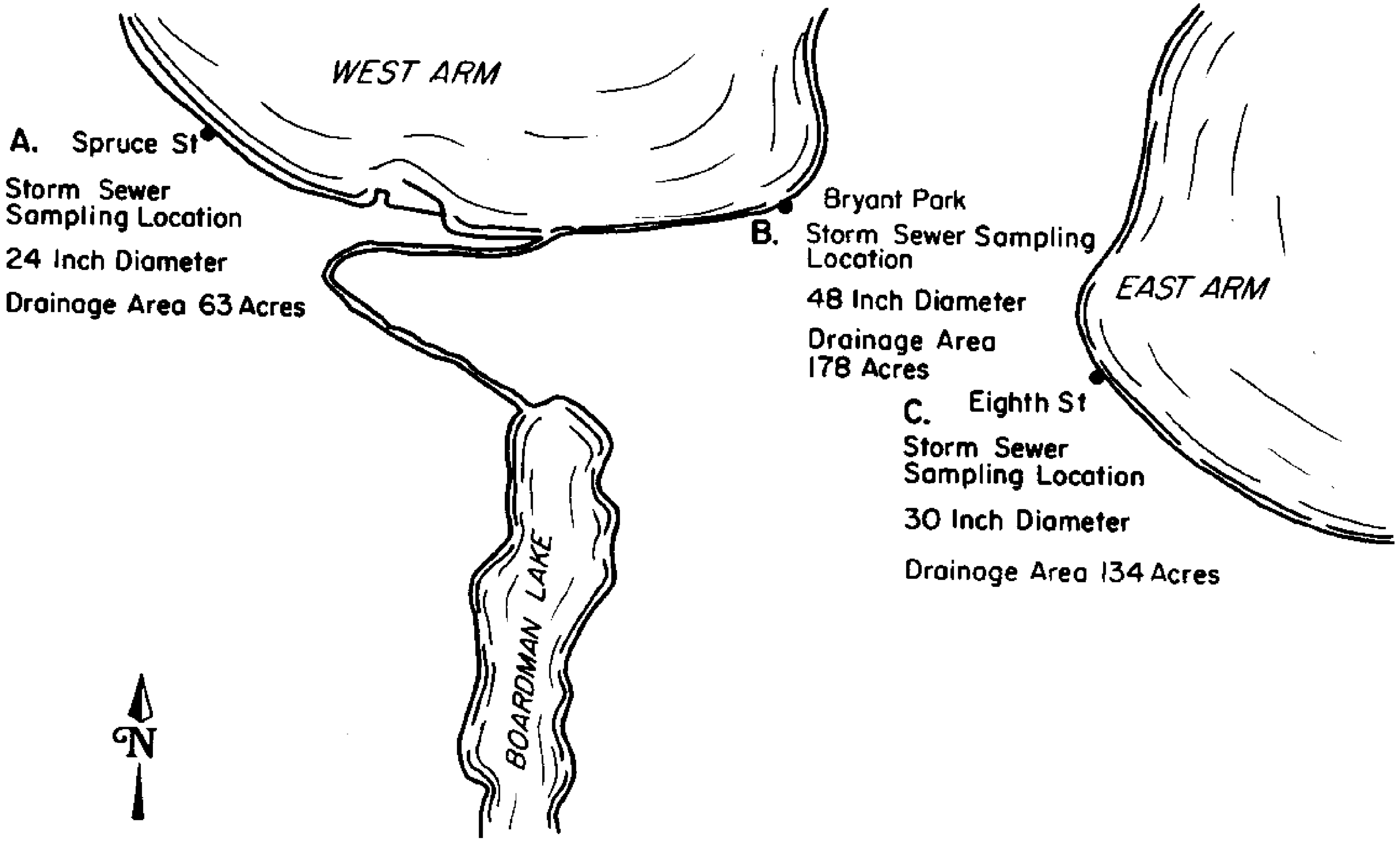


FIGURE XI-6. Storm sewer locations sampled at Traverse City, Michigan - 1971 and 1972.

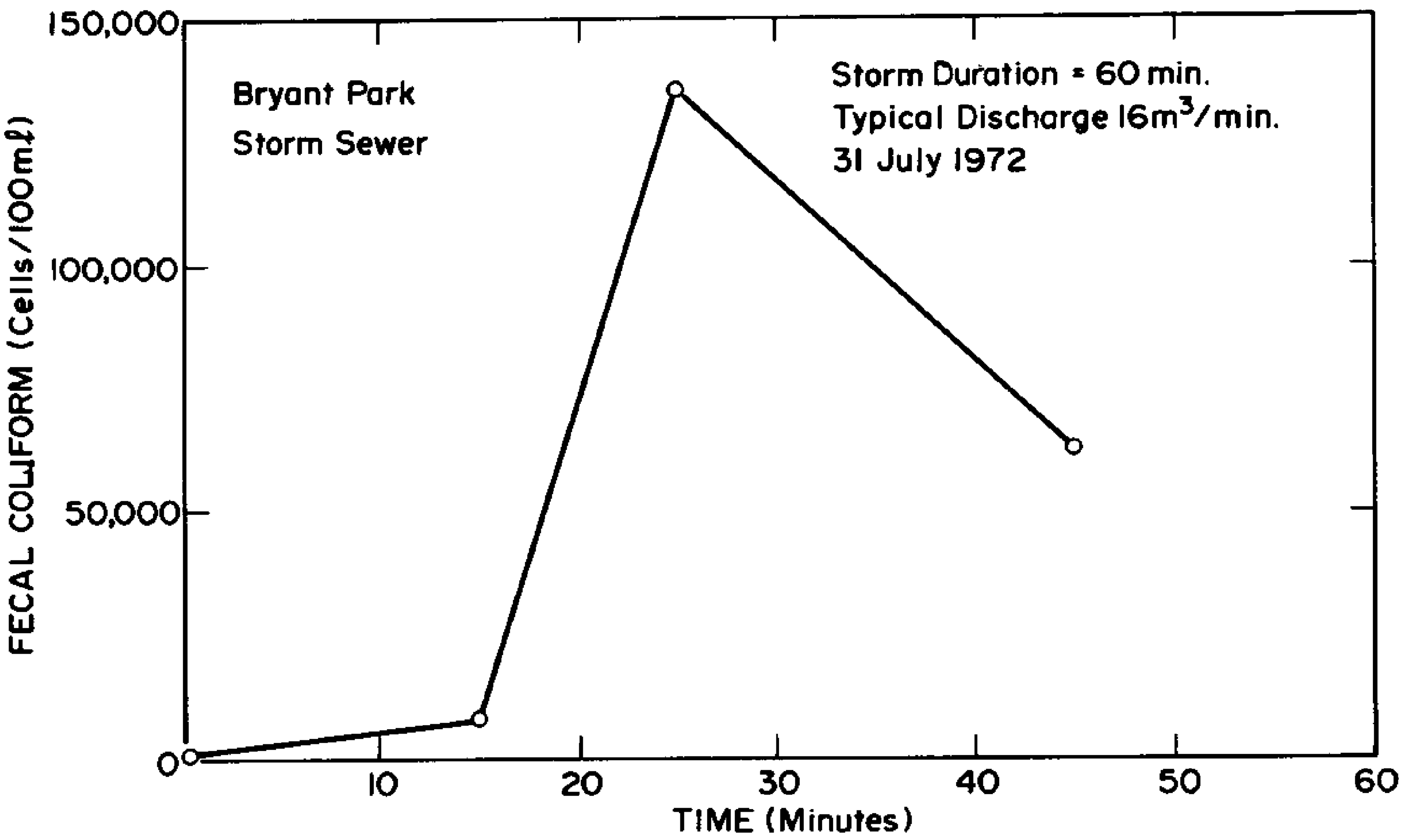


FIGURE XI-7. Transient variation of fecal coliform concentration in storm sewer overflow (data from Gannon and Meier 1974).

The Bryant Park storm sewer is one of fifteen which discharge directly to the bay. Other storm sewers discharge into the Boardman River or Boardman Lake. It is estimated that storm sewer discharge flow can easily be of the order of 5×10^5 m^3/day for periods during rainfall. Furthermore, the maximum measured fecal coliform concentration in storm sewer overflow is 2 to 3 orders of magnitude greater than the average concentration observed in the Boardman River (see Table XI-1). Thus it is concluded that, with the fruit processing plants gone, storm sewer overflow is the most important source of fecal coliform during wet periods. It is also important to note that the discharge locations of many storm sewers are near public beaches located on the bay, thus posing a potential health hazard during these periods. These results suggest that a meaningful program for management of water quality in the Grand Traverse Bay area should give careful consideration to control of storm water inputs.

The distribution of total coliform in the surface waters of Grand Traverse Bay in 1970 had improved dramatically when compared to concentrations recorded in 1964 and 1965. Figure XI-8 shows the monthly average total coliform measured at the east bay intake site. The maximum value occurs in September when the concentration reaches 109 cells/100 ml, whereas in 1964 a maximum concentration 2800 cells/100 ml occurred in July (see Figure XI-3). The improved conditions reflect the relocation of the water intake pipe to the east arm of the bay and reduced input of coliform from the fruit processing industry.

Table XI-3 shows summer 1972 geometric mean concentrations of total and fecal coliform at several beach sites and at the Traverse City marina, as calculated from data reported by Gannon and Meier (1974).

Table XI-3. Shoreline fecal and total coliform geometric mean concentrations during summer 1972 (calculated from Gannon and Meier 1974).

Location	Geometric Mean Fecal Coliform (cells/100 ml)	Geometric Mean Total Coliform (cells/100 ml)
West End Beach	94	75
Traverse City Marina	403	761
Clinch Park Beach	21	55
Bryant Park Beach	87	129
East Bay Beach	72	55
Traverse City State Park Beach	52	47
Elmwood Beach	35	71

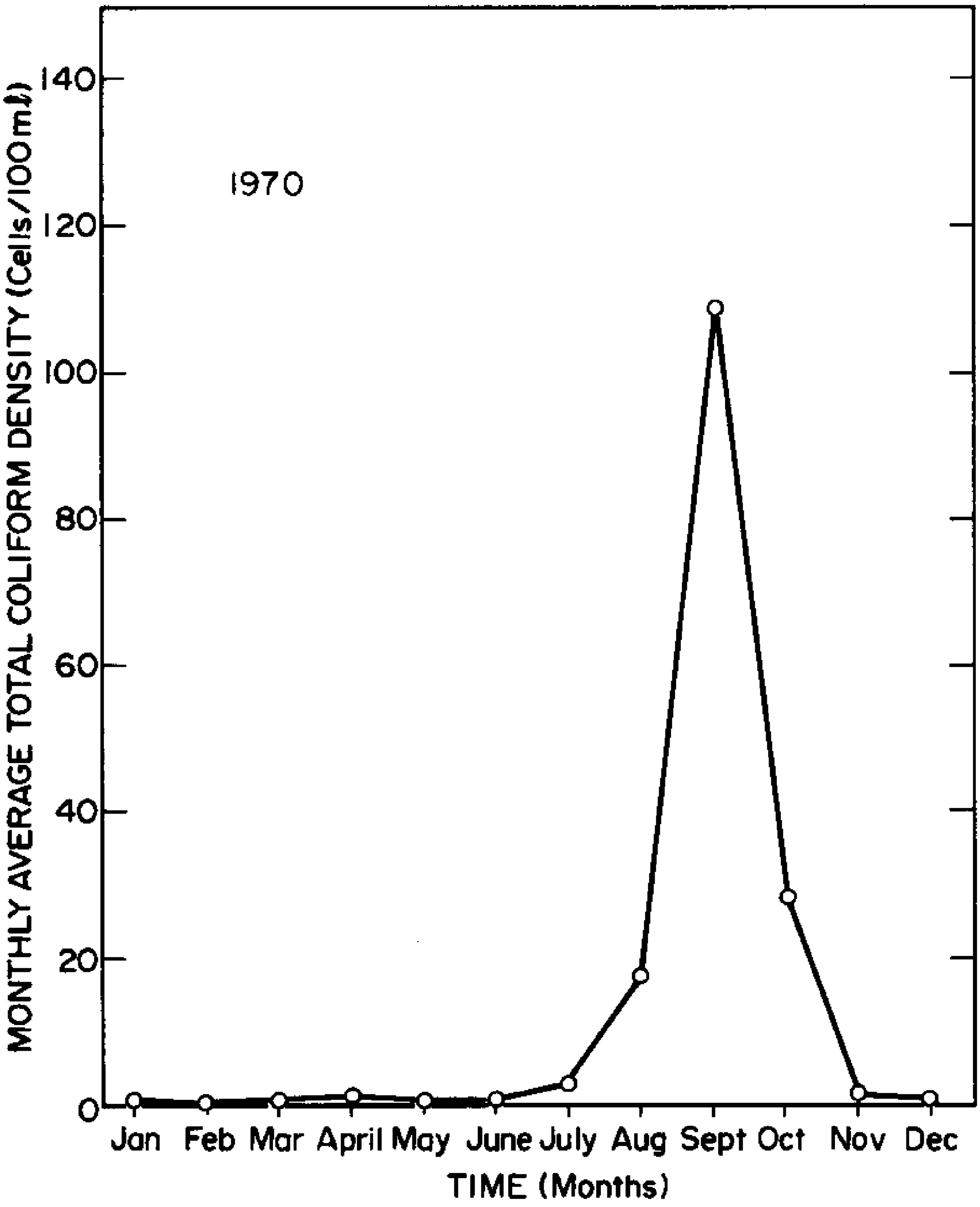


FIGURE XI-8. Monthly average total coliform count at east arm water intake in 1970.

With the exception of the isolated waters of the marina, the long-term averages at all locations appear to meet state of Michigan water quality standards for total body contact recreation. Over the short-term, especially during wet periods, data from Gannon and Meier (1974) show that the 200 cell/100 ml goal is not met on numerous occasions. Thus it is concluded that although the general level of water quality as measured by the concentration of fecal coliform is satisfactory, public health standards are violated for short intervals of time during wet periods due to sewer overflows.

Factors Affecting Survival and Distribution of Coliform

Several factors play a significant role in the ultimate fate of waste water bacteria in lake water. The most important are (a) algal toxins, (b) bacteriophage, (c) predators, (d) sedimentation and adsorption, (e) bacterial nutrients, (f) sunlight, and (g) temperature. The survival of coliform bacteria in fresh water has received much less attention than similar phenomena in seawater. Studies dealing directly with the Great Lakes have been rarer still. Hedrick (1961) has shown that the toxicity of Lake Michigan water toward *Shigella sonnei* is influenced by heating and the storage of samples. It was also observed that the response can vary with the seasons. Generally, waters are more toxic during summer than in winter. In subsequent studies, Hedrick et al. (1962) have shown that pure cultures of various strains of *Shigella* and *Salmonella typhosa* suffer over 50 percent loss within 24 hours when stored at 20°C in Lake Michigan water. Cells of *Escherichia coli* and *Salmonella schottmuelleri* usually decreased less than 50 percent when stored under similar conditions.

Scarce et al. (1964) have studied the survival of coliform bacteria and fecal streptococci when waste water treatment plant effluent was combined with Lake Michigan water. Survival patterns varied with storage temperature, dilution factors, and illumination. In many cases, coliform bacteria tended to increase before decreasing, whereas fecal streptococci usually did not. Chlorination before storage usually repressed the after-growth of both groups while only slightly changing the death rate. Gannon and Meier (1974) have studied the survival of total and fecal coliform as well as fecal streptococci in Grand Traverse Bay water. The results of *in situ* bottle studies indicate that survival of the bacteria is highly dependent on light conditions, with prolonged survival favored during dark periods which offer protection from ultraviolet radiation.

Bacterial decay and die-away is normally described by Chick's Law which suggests a first order kinetic loss:

$$r = -KC \qquad \text{(XI-1)}$$

where r is the decay rate in cells/100 ml/day, K is the first order rate coefficient in units day^{-1}, and C is the organism concentration in cells/100 ml. As discussed above, the numerical value of K varies seasonally, and is a function of light, temperature, and the quality of local waters.

Data from some of the above studies and from the Michigan Water Resources Commission (1968) have been compiled for the purpose of obtaining a relationship between K (base e) and temperature. These data are plotted in Figure XI-9. A linear fit of the data results in the equation

$$K(T) = 0.2 + 0.0223T \qquad (XI-2)$$

where T is in °C. This rate equation is consistent with findings on die-off rates in rivers such as the Missouri, Ohio, and Sacramento, as reported by Velz (1970) and Kittrell and Furfari (1963). Orlob (1965) has shown similar temperature effects in Pacific Ocean water. Equation XI-2 appears adequate to define fecal and total coliform bacterial survival of only about 5% after 4 days of exposure at 25°C. As a result, bacterial contamination in Grand Traverse Bay does not usually persist significantly beyond the immediate region of source locations.

The spatial distribution of coliform bacteria in the bay can be calculated if knowledge of survival kinetics is combined with information about the dilution effect of circulation patterns in the bay. The combined effects of these factors can be used to calculate concentration profiles if mathematical models based on mass continuity equations are written and solved. The development of such equations are described by Canale and Green (1972). In this paper the results of the model calculations were favorably compared with field data collected during 1963, 1964, and 1971. Overall it was shown that laboratory and field studies of coliform survival and knowledge of the flow patterns in the bay have been used to construct a model which can be used to obtain reasonable predictions of bacterial quality in the bay following perturbations by man.

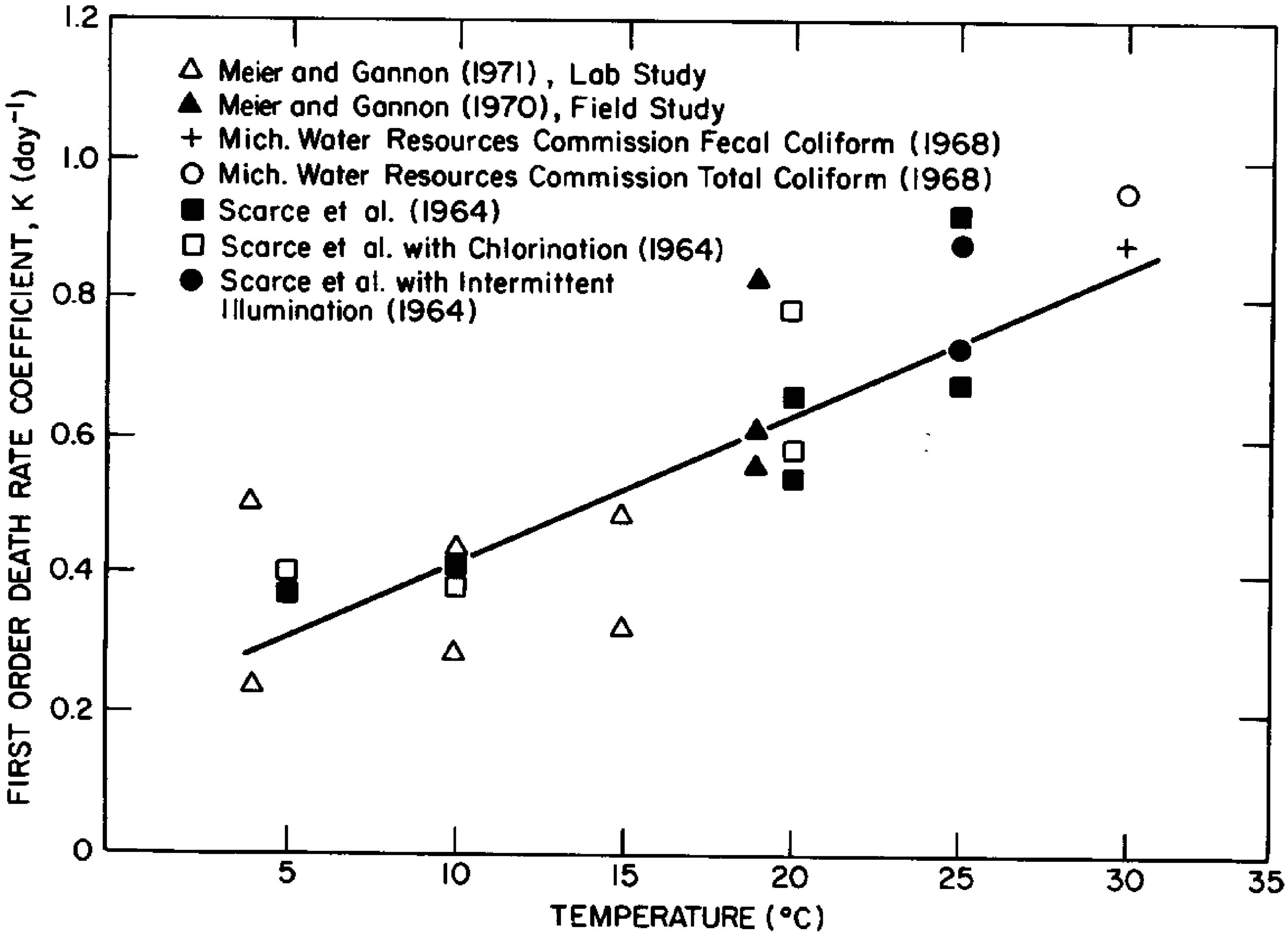


FIGURE XI-9. First-order total coliform death rate coefficient.

XII. PHYTOPLANKTON INDICATORS AND MAJOR PHYTOPLANKTON NUTRIENTS

Introduction

An earlier section in this report has discussed pragmatic aspects of the relationships between phytoplankton and the major phytoplankton nutrients. That portion of the report presented bay-wide and intrazonal averages, compared these data with other regions of the Great Lakes, and discussed variations in levels of nutrients and productivity in various parts of the bay.

This section will deal with Grand Traverse Bay phytoplankton and major nutrient data as they relate to more theoretical (less applied) limnological principles and hypotheses. Characteristic horizontal, vertical and seasonal distributions of phytoplankton and major nutrients will be presented as well as a discussion of other specific phenomena of interest such as nutrient cycling, silicon depletion, parameter correlations, etc. Three major biological parameters will be discussed (chlorophyll *a*, Secchi disc, and primary productivity) along with two physical parameters (light and temperature). The major phytoplankton nutrients referred to in this discussion are nitrogen (ammonia and nitrate), phosphorus (total dissolved, particulate and total) and silicon.

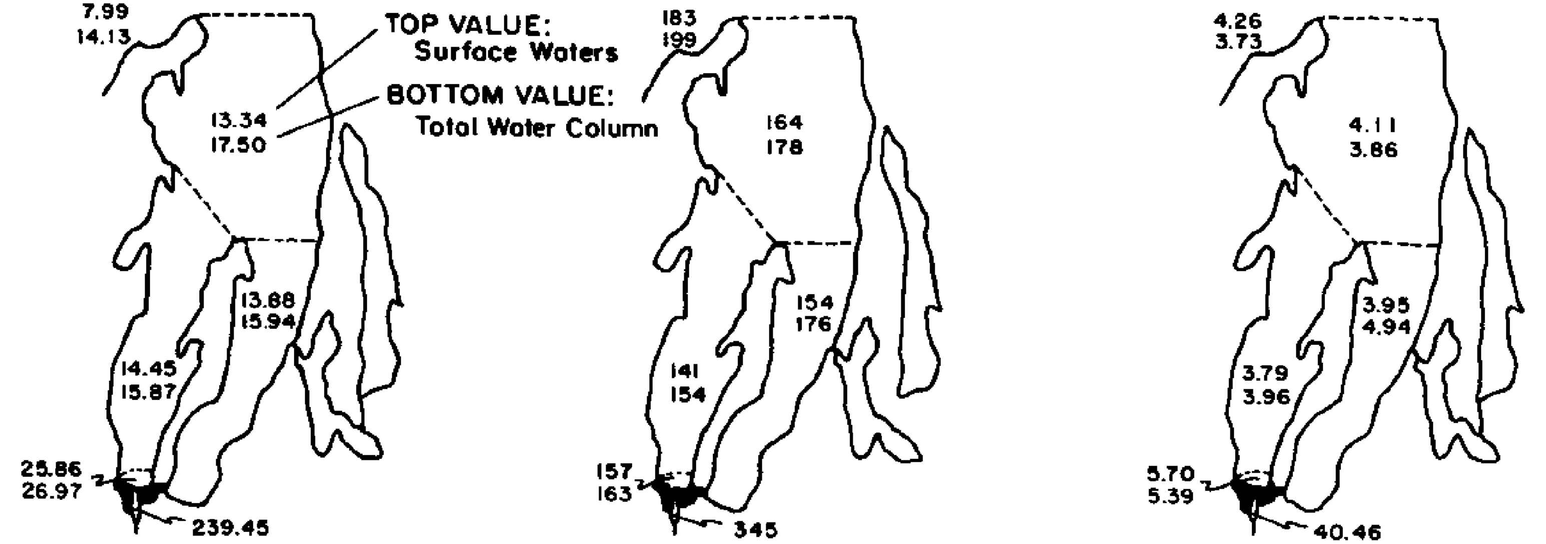
Distribution Patterns

Horizontal Distribution

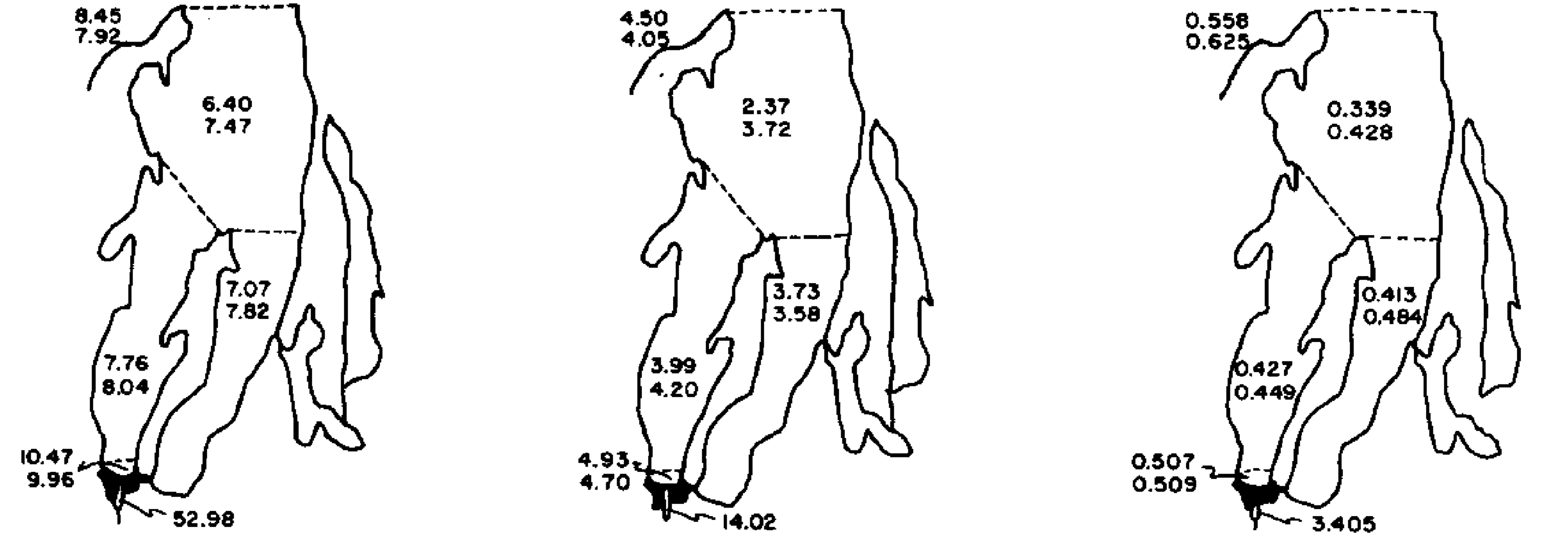
Horizontal distributions are those existing among various water columns in Grand Traverse Bay. As discussed earlier, the bay is divided into six regions or zones. Differences in water quality among these zones is a function of depth, stream loadings, water circulation, morphometry and other factors. Figures XII-1 and XII-2 summarize the values for various chemical and biological parameters in the different zones established for the bay.

Grand Traverse Bay, excluding the Boardman River and Lake Michigan, is divided into four zones: open bay (II), east arm (III), west arm (IV), and lower west arm (V). The only major input of phytoplankton nutrients to the west arm of Grand Traverse Bay is through the Boardman River. The horizontal distribution patterns observed in Grand Traverse Bay are a reflection of this input. The east arm (Zone III) does not receive any influential nutrient input and generally serves as a baseline.

Horizontal distributions of major nutrients and productivity parameters follow the pattern established by these inputs and morphological restrictions. Average concentrations of particulate phosphorus and chlorophyll *a* and average primary productivity levels are lowest in the east arm. Average nitrate and (with the exception of the lower west arm) silicon levels are highest in the east arm. The lack of nitrate and silicon depletion would be an expected result of low productivity. Dissolved phosphorus in the east arm also indicates low productivity. Ammonia and Secchi disc values for the east arm are essentially equivalent to those of the west arm and intermediate to the lower values of the open bay and higher values of the lower west arm.



AMMONIA NITROGEN (μg N/ℓ) NITRATE NITROGEN (μg N/ℓ) TOTAL DISSOLVED PHOSPHORUS (μg P/ℓ)



TOTAL PHOSPHORUS (μg P/ℓ) PARTICULATE PHOSPORUS (μg P/ℓ) SILICON (mg Si/ℓ)

FIGURE XII-1. Average phytoplankton nutrient concentrations by zone.

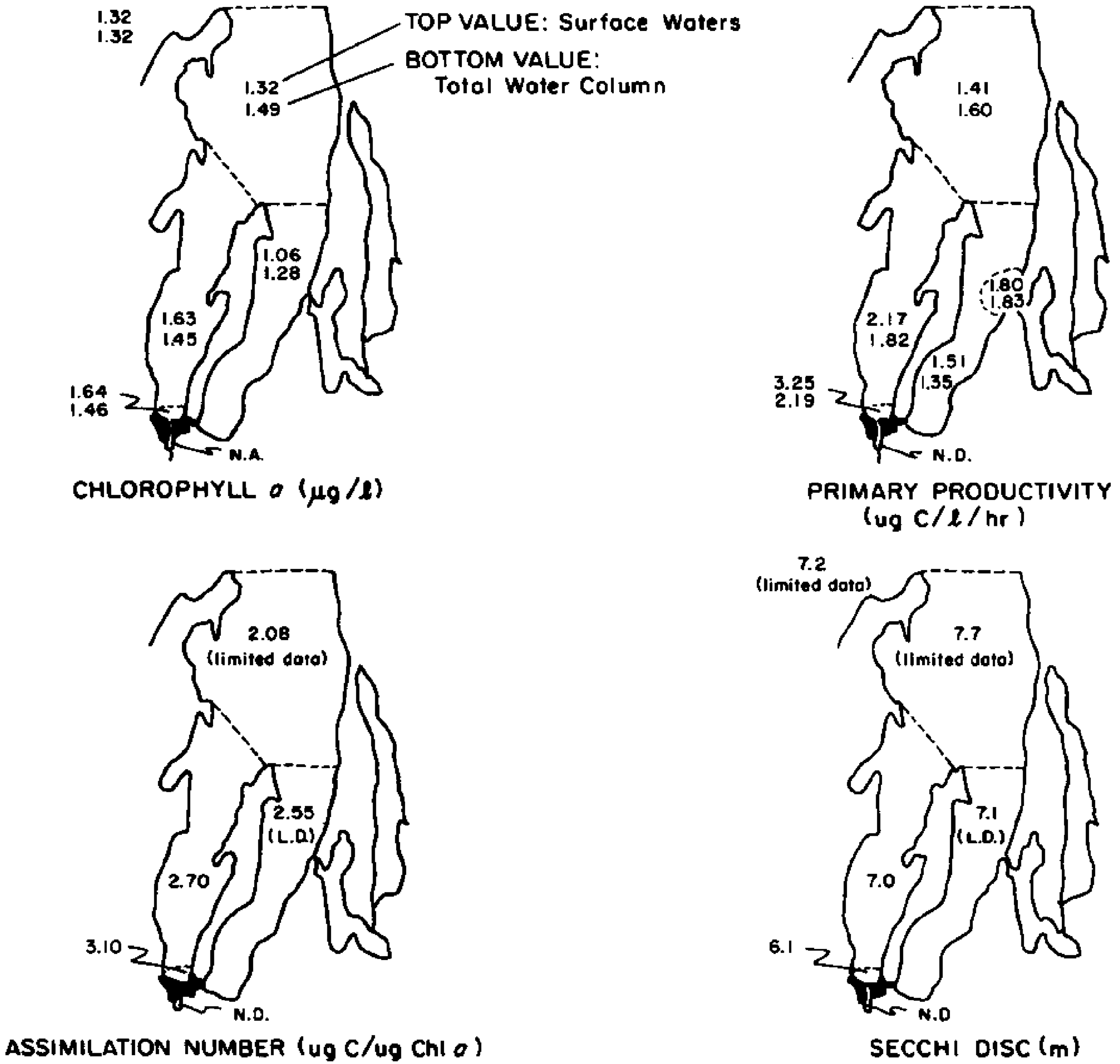


FIGURE XII-2. Average phytoplanktonindicator measurements by zone.

The lower west arm of Grand Traverse Bay is the most nutrient rich area in the system. Average ammonia, phosphorus and silicon concentrations were highest in this zone. Nitrate concentrations were lower in this zone than in either the open bay (Zone II) or the east arm (Zone III). This phenomenon reflects a relatively higher phytoplankton uptake to tributary loading ratio for this nutrient.

Primary productivity, assimilation ratio, and Secchi disc readings all indicate higher levels of phytoplankton activity in the lower west arm. This trend is not as sharply reflected in chlorophyll *a* levels. The concentration of pigment in the lower west arm (Zone V) is certainly greater than those of the east arm and open bay, but is essentially equal to that observed for the west arm. Since nutrient levels are higher in the lower west arm than in the west arm, higher chlorophyll *a* levels would be expected. This higher level is not achieved, most probably due to grazing by zooplankton, higher turbidity and the existence of a steady-state relationship between loading and water mass flux through the zone.

In terms of nutrients and phytoplankton parameters, the west arm (Zone IV) is generally a region of dilution, maintaining the elevated levels of the lower west arm, but to a lesser extent when compared with the remainder of the bay. The open bay (Zone II) acts as a mixing zone for the east and west arms. In some instances, the open bay displays nutrient levels lower than either the east arm or west arm, and at other times higher levels. This trend may not be quantitative, in that levels are so low that the differences cited often are not significant.

In summary it may be said that horizontal distribution patterns in Grand Traverse Bay reflect the introduction of major phytoplankton nutrients (particularly phosphorus) in the lower west arm, and the subsequent dilution and mixing of this loading with the nutrient poor waters of the east arm. Figure XII-3 depicts this distribution.

Vertical Distribution

Four chemical parameters (NH_3-N, NO_3-N, TDP and Si) and one biological parameter (primary productivity) were examined at seven stations (1, 5, 8, 10, 12, 55 and 158) for the presence of vertical distribution patterns. These stations were chosen as a result of the large amount of data available from them and because each serves to represent a particular zone or area within a zone. The concentrations of ammonia and total dissolved phosphorus often approached the lower limit of analysis, and therefore small changes in vertical profiles for these species could not be interpreted to the same extent as that of nitrate and silicon.

Conceptually there are four major process groups affecting the vertical distribution of nutrients: 1) phytoplankton uptake; 2) biochemical conversion; 3) precipitation and dissolution reactions; and 4) sediment release. Superimposed on these processes are transfer phenomena associated with settling and thermal stratification.

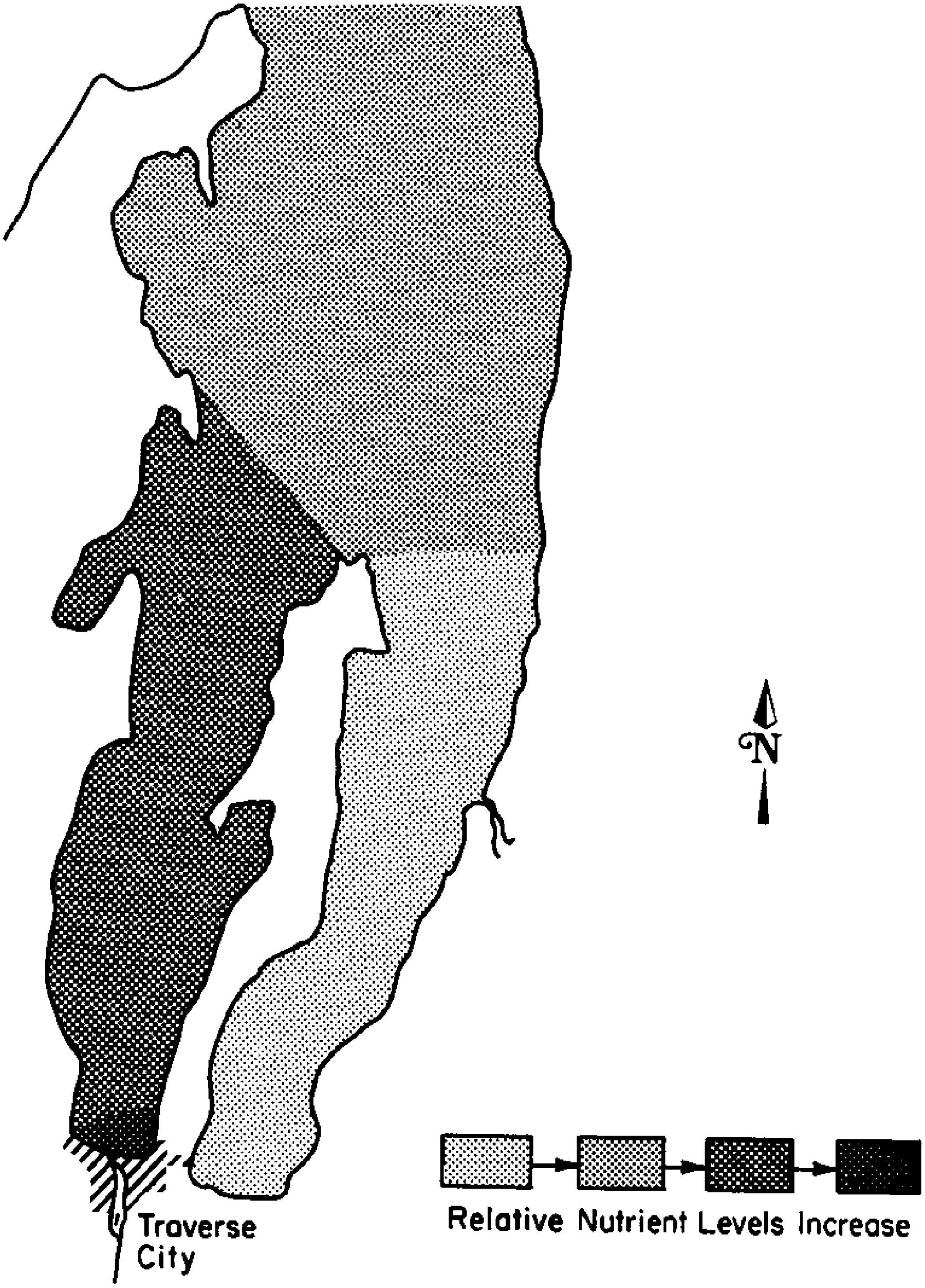


FIGURE XII-3. General distribution pattern of major phytoplankton nutrients in Grand Traverse Bay.

Primary productivity was routinely measured at three depths: 2, 10 and 20 meters. Uptake at 20 m was almost exclusively the lowest value. The peak primary productivity occurred at either the 2 m or 10 m depth which was primarily a function of season as will be discussed later.

The data plotted for station 55 seemed to most clearly illustrate vertical distributions of chemical constitutents. Eight cruises are plotted in Figure XII-4 for silicon, nitrate, total dissolved phosphorus and ammonia versus depth. The first three cruises (61-63) represent a homothermal mixing period in the spring of 1973. The remaining 5 cruises (72-76) represent a thermally stratified period in late summer and early fall of 1973.

Concentrations of silicon, nitrate and ammonia were unchanged with depth during cruises 61-63, reflecting the mixing conditions. Phosphorus concentrations fluctuated more, but were essentially unchanged. Surface levels of phosphorus followed no distinct pattern between mixed and unmixed periods, but bottom concentrations were generally higher in the unmixed period than in the mixed period. This increase could be due to breakdown of organic material or sediment release. Since anoxic conditions do not develop in the hypolimnion, the former process is probably more significant.

The greatest variation in vertical distributions occurred during the thermally stratified period. Silicon concentrations in the bottom waters were much higher than in the surface waters. This difference is due to a combination of factors, among which are surface assimilation by phytoplankton and breakdown of diatom frustules with the subsequent release of silicon to the bottom waters. Surface concentrations of total dissolved phosphorus were variable, but occasionally higher than spring levels. Bottom water phosphorus concentrations were elevated both above surface water values and spring bottom water values. This difference is most likely a function of decomposition as mentioned earlier.

Nitrate and ammonia distributions were dynamic and perhaps related. Summer surface concentrations of nitrate were lower than spring surface levels (75-100 μgN/ℓ vs. 150 μgN/ℓ). This surface depletion was due to algal uptake. Surface concentrations of ammonia appeared to decrease with time during the summer period but always approached the limit of detection. Nitrate concentrations displayed an orthograde distribution during summer. Deep-water concentrations exceeded spring levels by 40-50 μgN/ℓ. This occurrence suggests an input of nitrate to the system; since stratification limits movement from above, this input must come from the sediments or from the biochemical conversion of hypolimnetic ammonia.

Decomposition in bottom waters does not usually result in the direct production of nitrate; rather, the breakdown of proteinaceous materials usually results in the production of ammonia. Subsurface ammonia concentrations approach zero in the summer and are certainly lower than spring levels. This suggests that the process of bacterial nitrification is operating in the bottom waters during the summer.

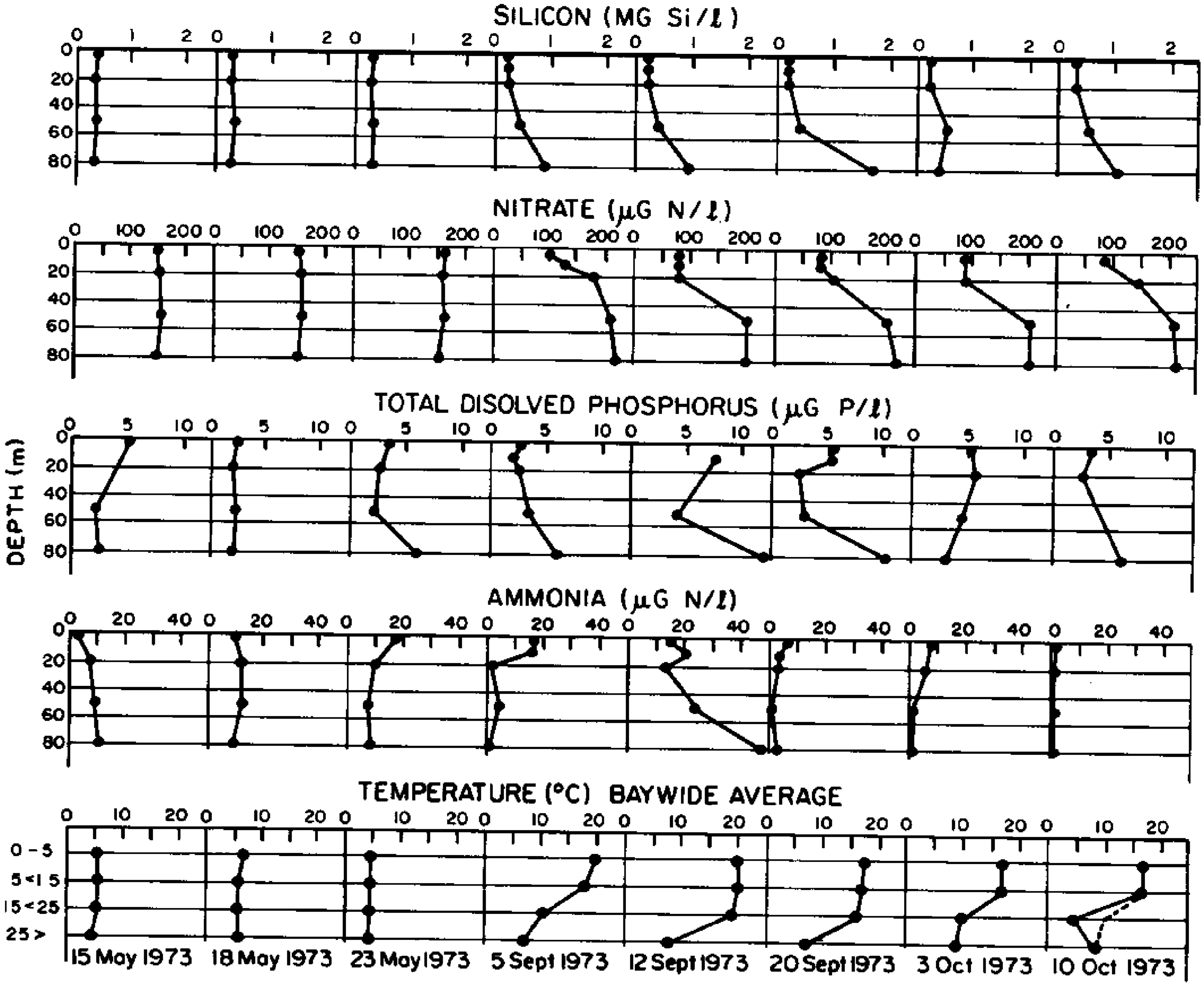


FIGURE XII-4. Vertical distribution of selected physical and chemical parameters at Station #55.

In general, there were less observable vertical trends in the Grand Traverse Bay water chamistry data than expected. Some of the lack of classic vertical distributions was undoubtedly due to depth and shoreline effects. The extremely low nutrient concentrations in Grand Traverse Bay further serve to obscure vertical patterns of nutrient distribution.

Seasonal Distribution

The seasonal distribution of nutrients generally responds to annual cycles in stream loadings, light and temperature fluctuations and mixing. Data are available on a seasonal basis for three biological indicators (chlorophyll *a*, primary productivity and Secchi disc) and for six chemical parameters (ammonia and nitrate-nitrogen, silicon, and particulate, total and total dissolved phosphorus). Chlorophyll *a* data are complete only for 1972 and 1973. Transparency and primary productivity data are available for 1971, 1972, and 1973. Nutrient data are available for the entire sampling period (1970-1975) but only sporadic data occur in 1970, 1974, and 1975. Observed seasonal trends will be discussed by year. Figures XII-5 through XII-20 are plots of these data over the period of sampling. For phytoplankton nutrients, surface and bottom water concentrations are graphed separately. Data for each parameter are presented by zone or by outer bay/inner bay designation.

1971

Primary productivity values displayed two peaks: August/September and November. A small peak was also noted in June at Station 1 but cannot be considered of general significance since this was the only station sampled. Transparency reached minimum levels in early March, June, and August/September. The November primary productivity peak was not reflected in the transparency data.

Surface concentrations of all forms of phosphorus followed an identical pattern: peak levels occurring in winter, slowly decreasing to a minimum in midsummer and remaining low through fall. Ammonia in the surface waters varied considerably with lowest values recorded in April and a slight depression observed in August/September. Nitrate concentrations increased through the winter and spring with a peak in July. A severe surface depletion of nitrate occurred in September/October, followed by a gradual return to high winter levels. Surface silicon concentrations showed two depletion periods: spring/summer and late fall, with a maximum in August/September.

Surface ammonia and phosphorus concentrations could not be correlated closely with primary productivity and transparency patterns. Phosphorus disappeared from the surface waters as the year progressed, presumably through phytoplankton uptake, (as evidenced by cell numbers) and was not replaced until the following winter/spring period. The fluctuations in ammonia appear to be more closely associated with processes such as ammoniafication and nitrification rather than with phytoplankton uptake.

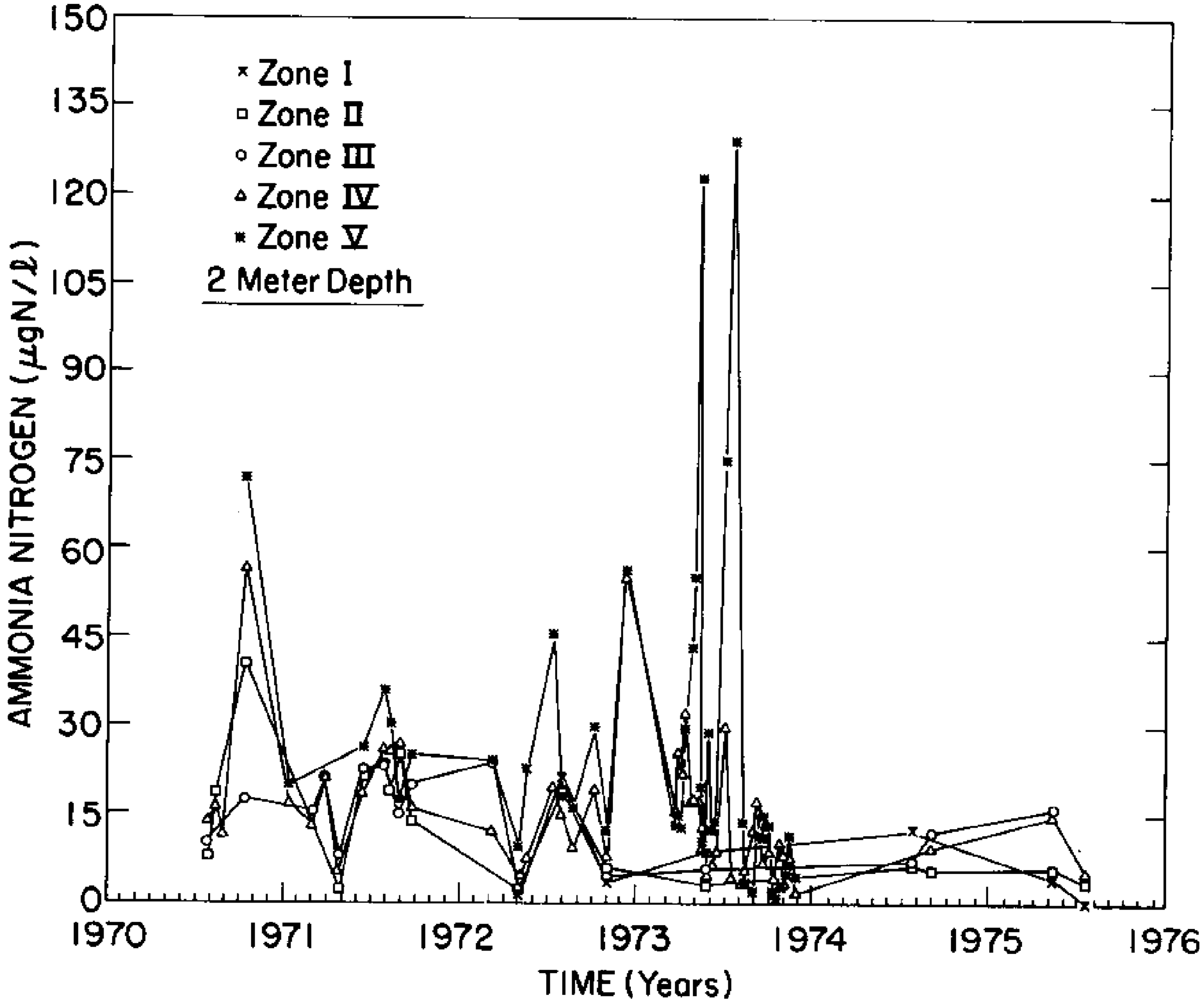


FIGURE XII-5. Surface water ammonia-nitrogen concentrations in Grand Traverse Bay for 1971-1975.

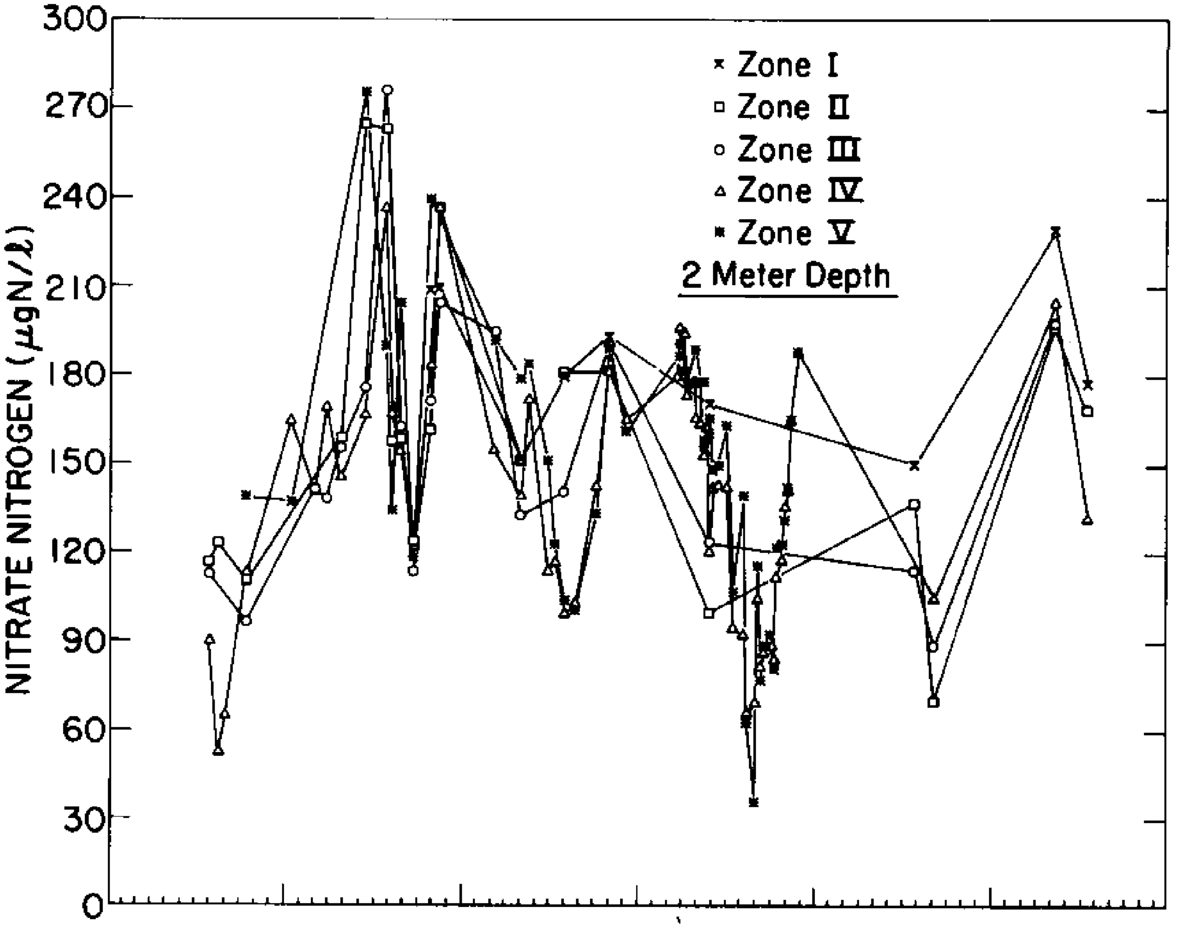


FIGURE XII-6. Surface water nitrate-nitrogen concentrations in Grand Traverse Bay for 1971-1975.

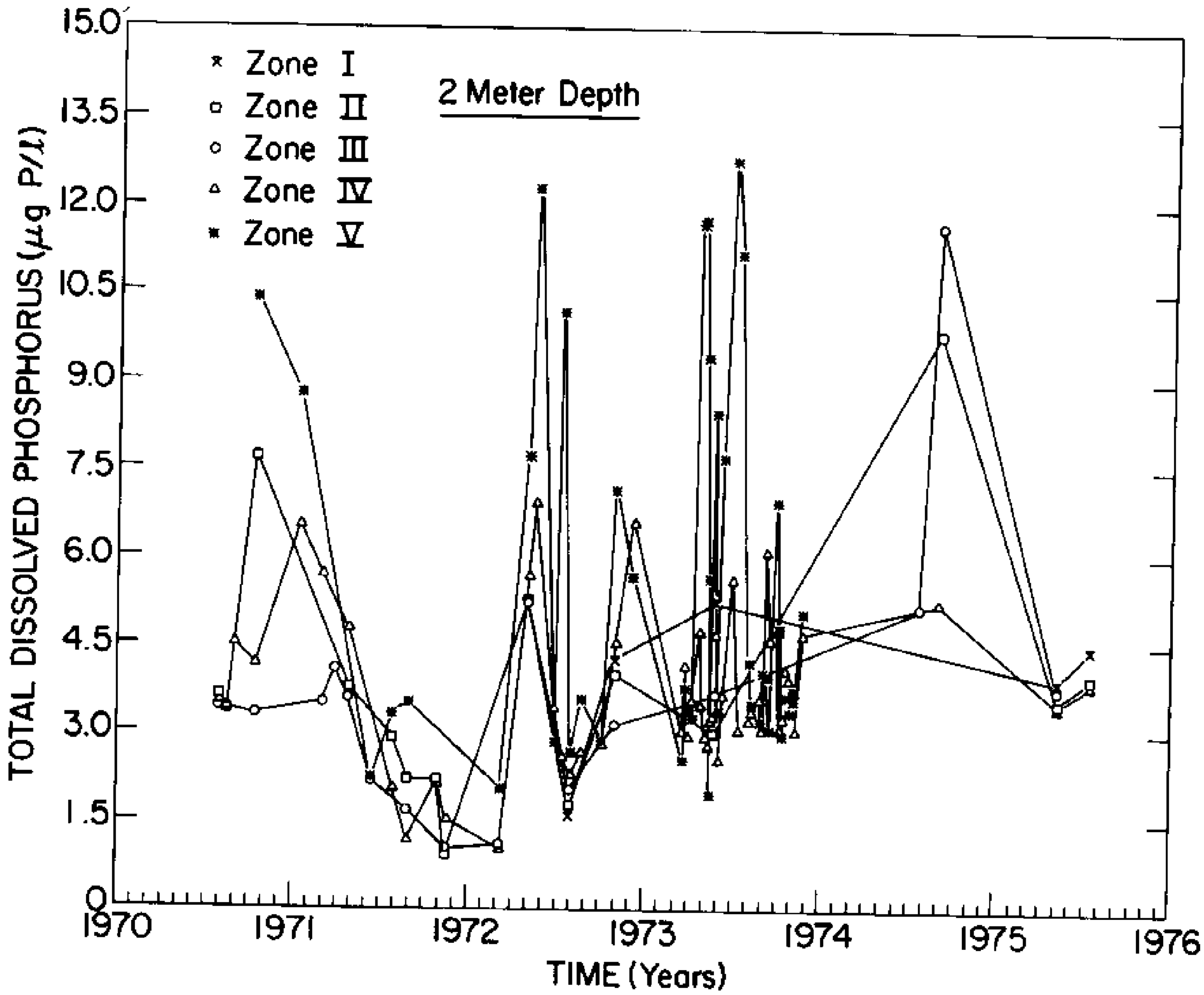


FIGURE XII-7. Surface water total dissolved phosphorus concentrations in Grand Traverse Bay for 1971-1975.

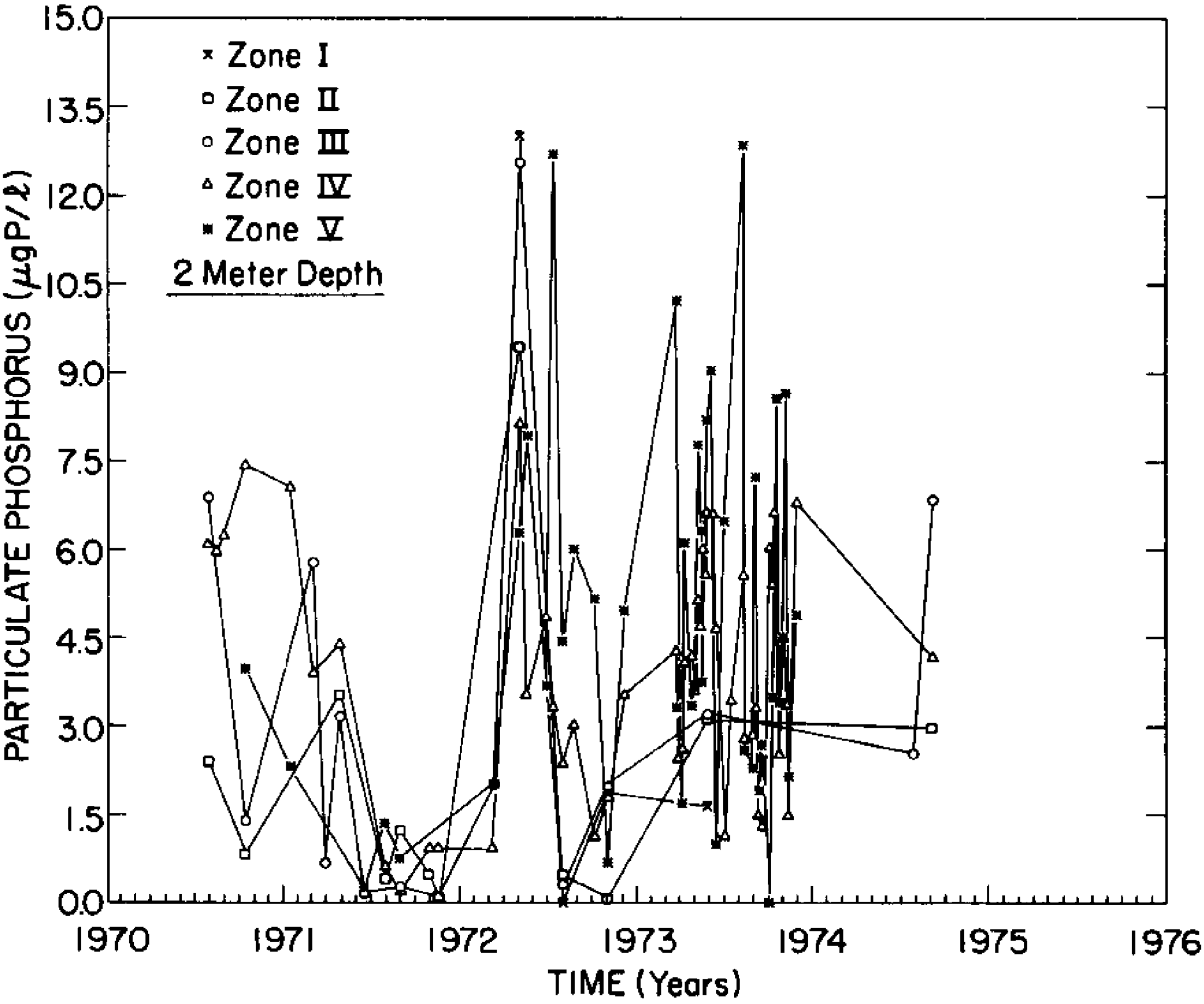


FIGURE XII-8. Surface water particulate phosphorus concentrations in Grand Traverse Bay for 1971-1975.

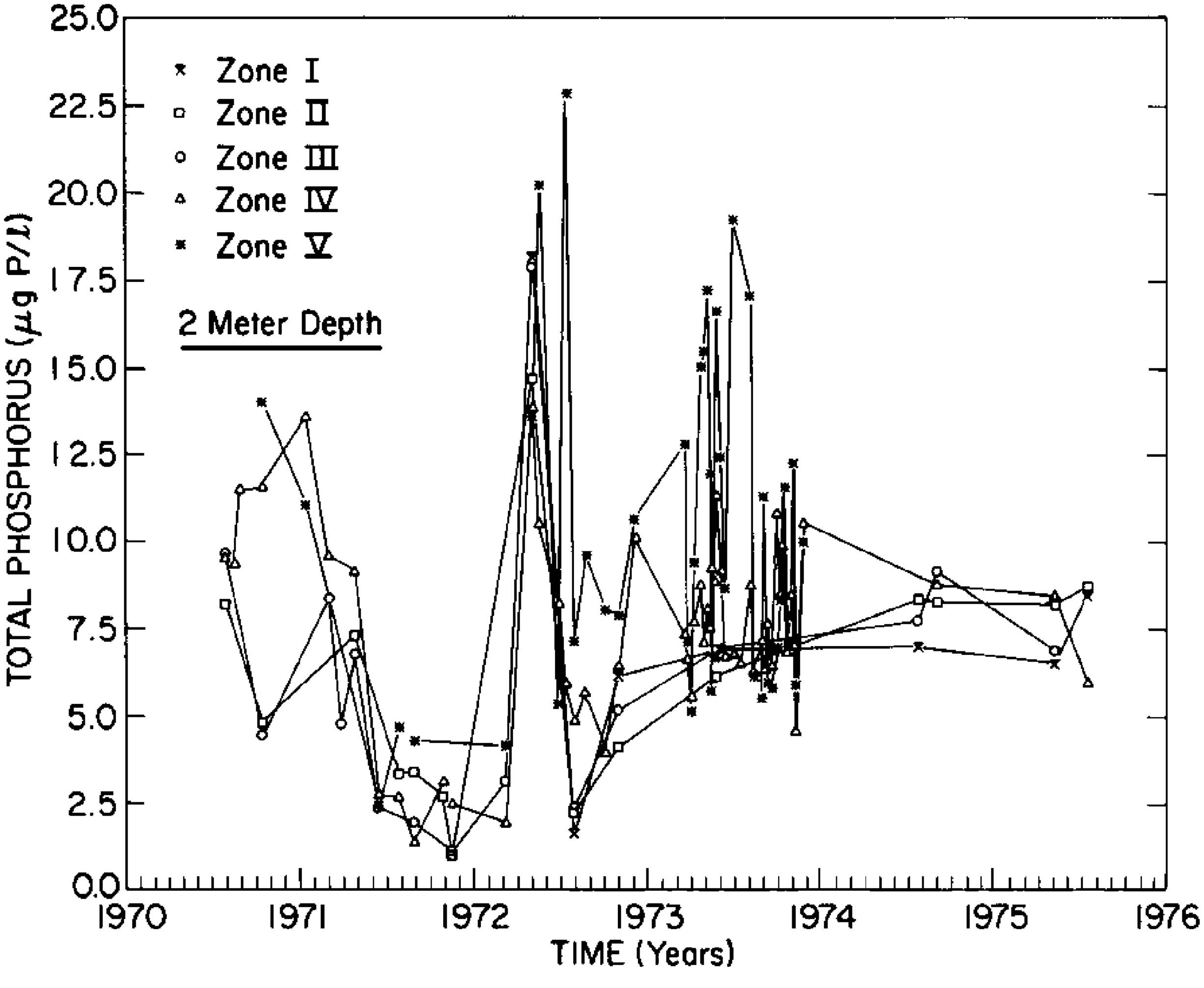


FIGURE XII-9. Surface water total phosphorus concentrations in Grand Traverse Bay for 1971-1975.

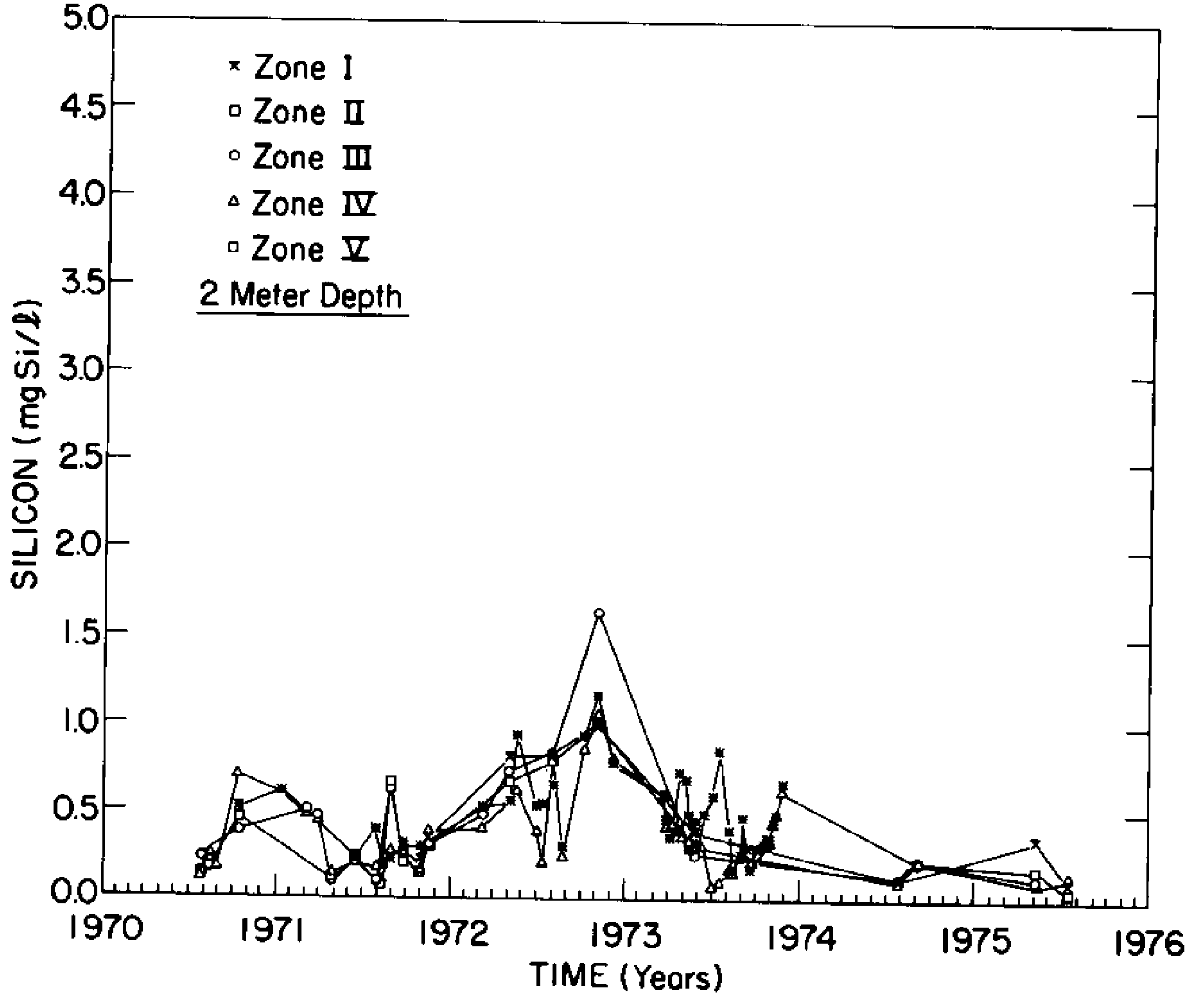


FIGURE XII-10. Surface water silicon concentrations in Grand Traverse Bay for 1971-1975.

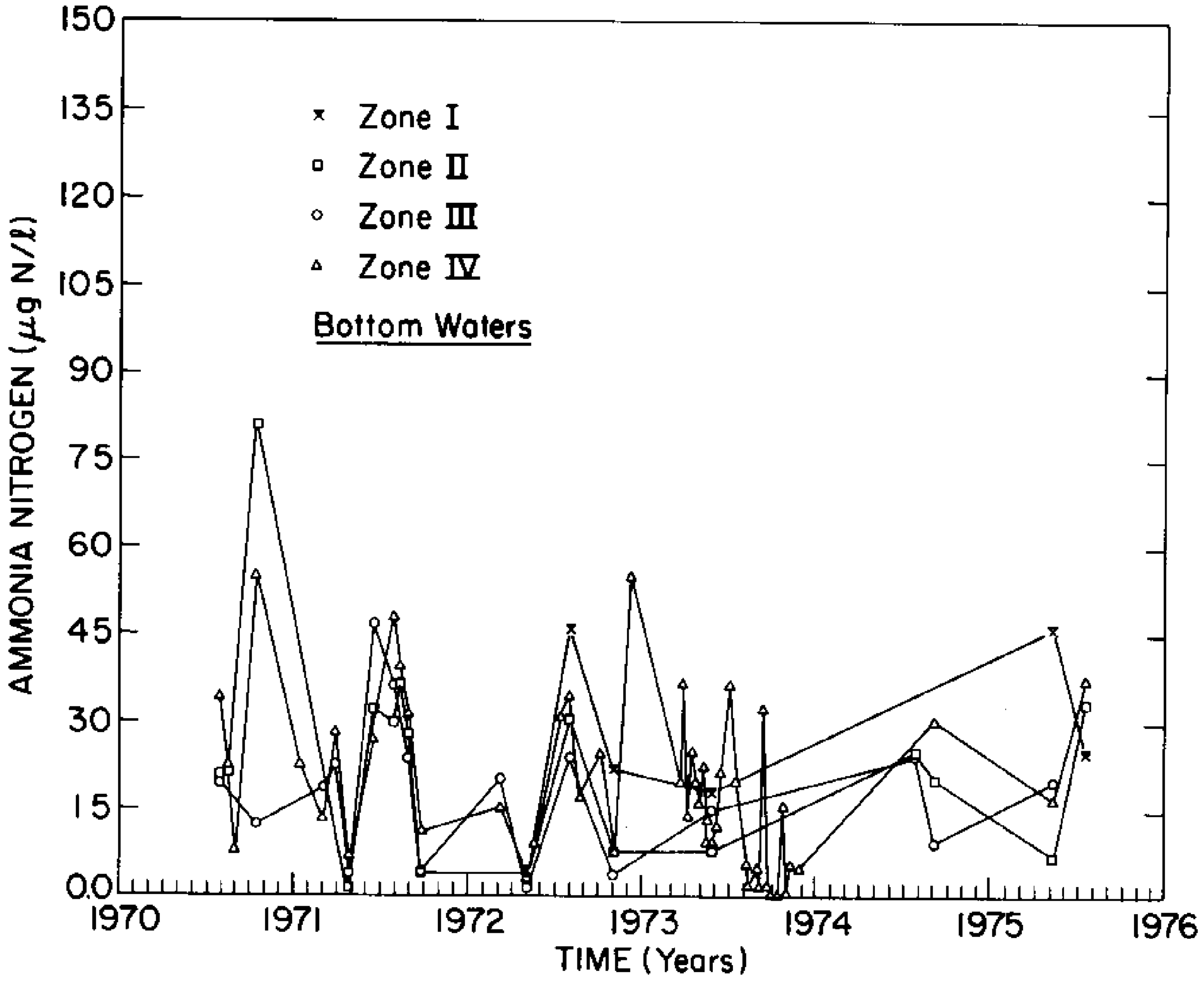


FIGURE XII-11. Bottom water ammonia-nitrogen concentrations in Grand Traverse Bay for 1971-1975.

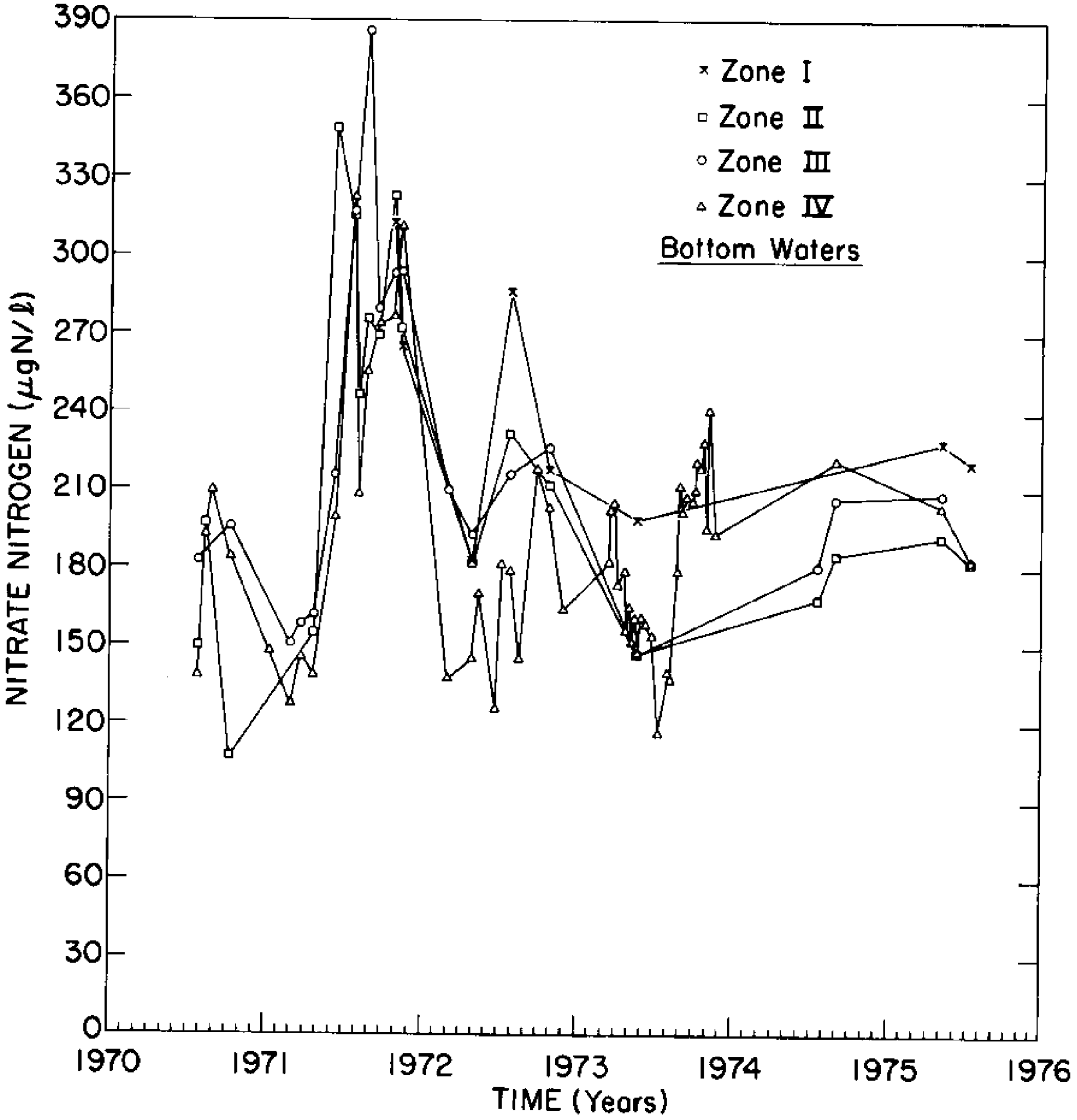


FIGURE XII-12. Bottom water nitrate-nitrogen concentrations in Grand Traverse Bay for 1971-1975.

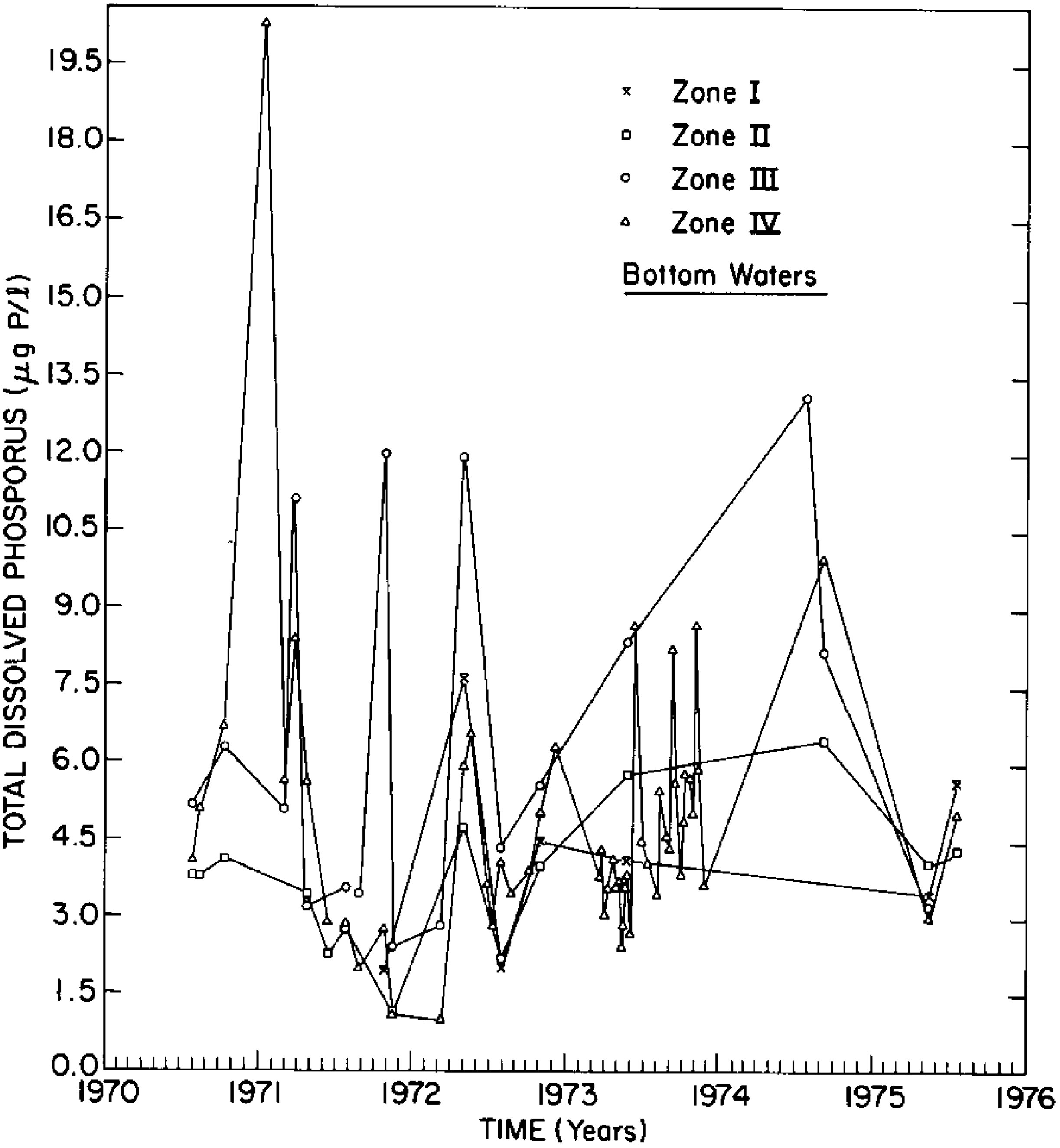


FIGURE XII-13. Bottom water total dissolved phosphorus concentrations in Grand Traverse Bay for 1971-1975.

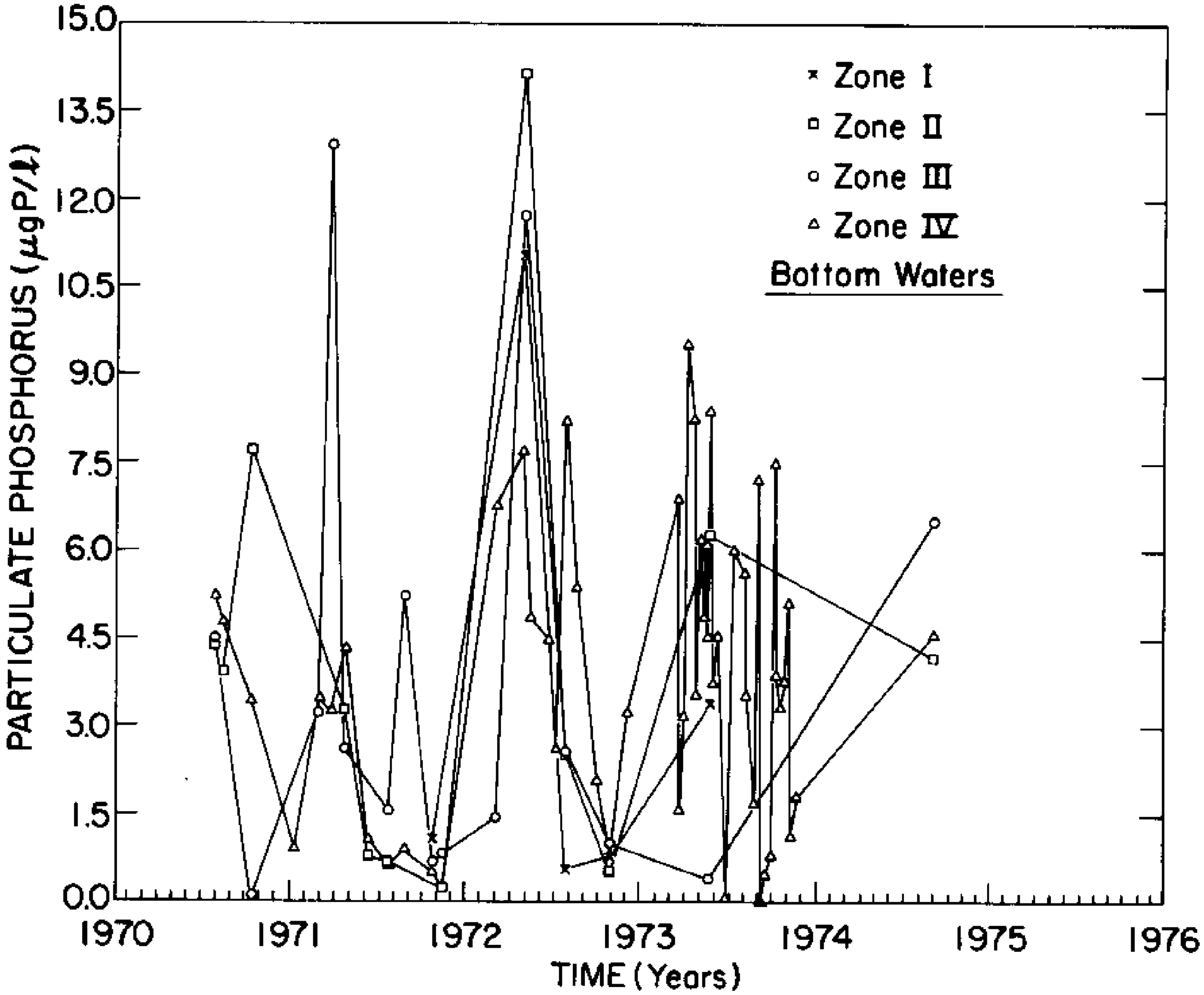


FIGURE XII-14. Bottom water particulate phosphorus concentrations in Grand Traverse Bay for 1971-1975.

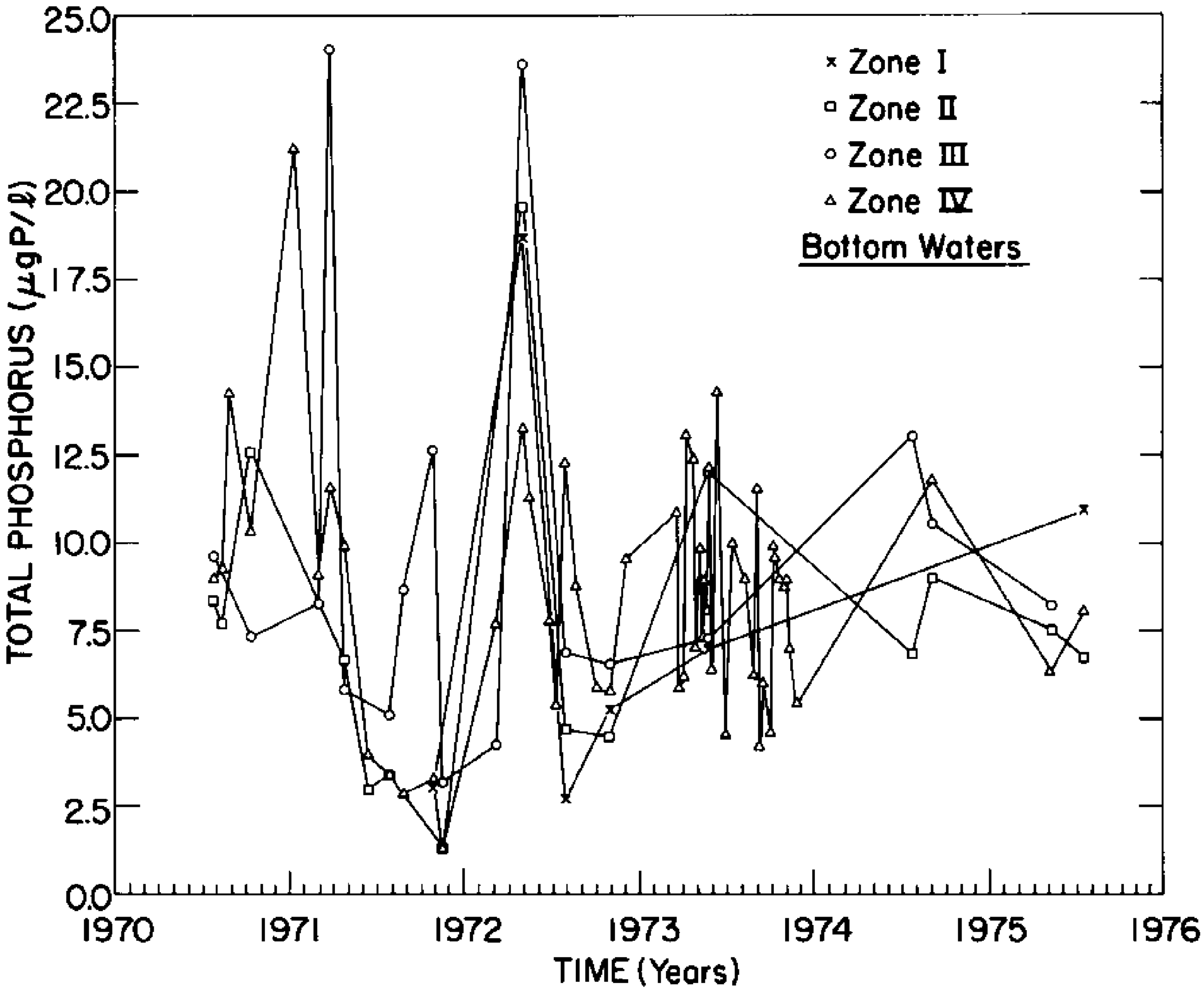


FIGURE XII-15. Bottom water total phosphorus concentrations in Grand Traverse Bay for 1971-1975.

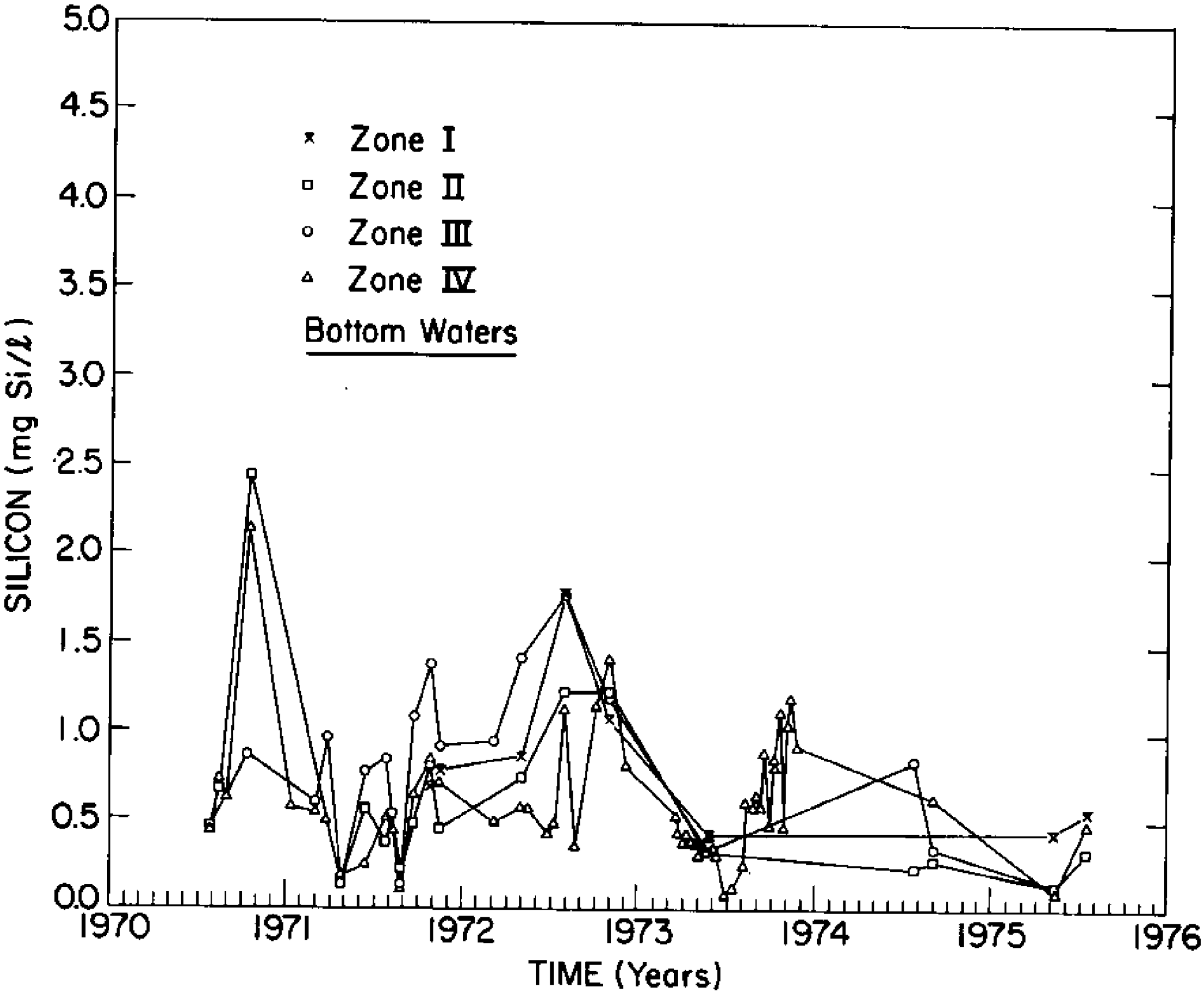


FIGURE XII-16. Bottom water silicon concentrations in Grand Traverse Bay for 1971-1975.

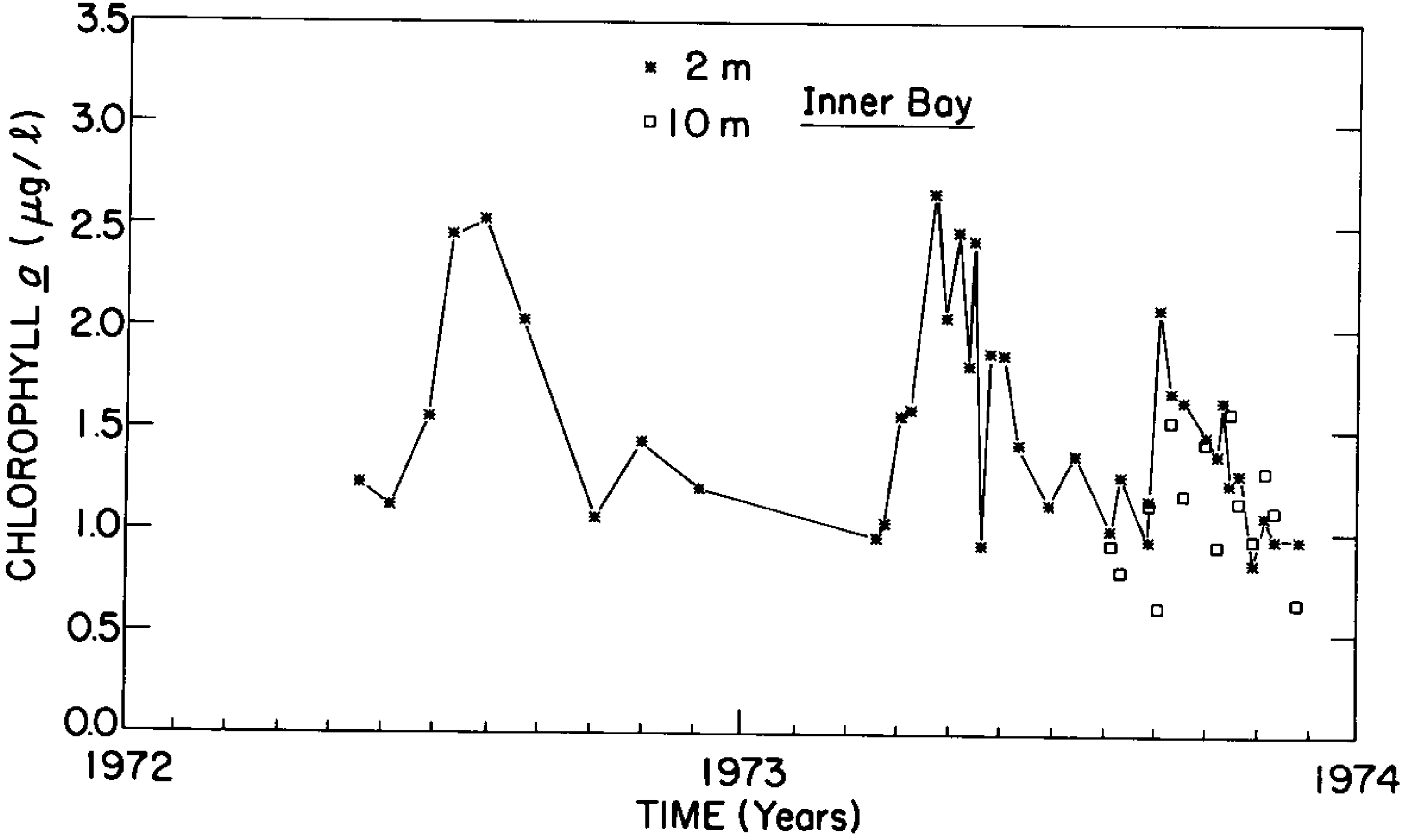


FIGURE XII-17. Chlorophyll *a* concentrations for the Inner Bay in 1972 and 1973.

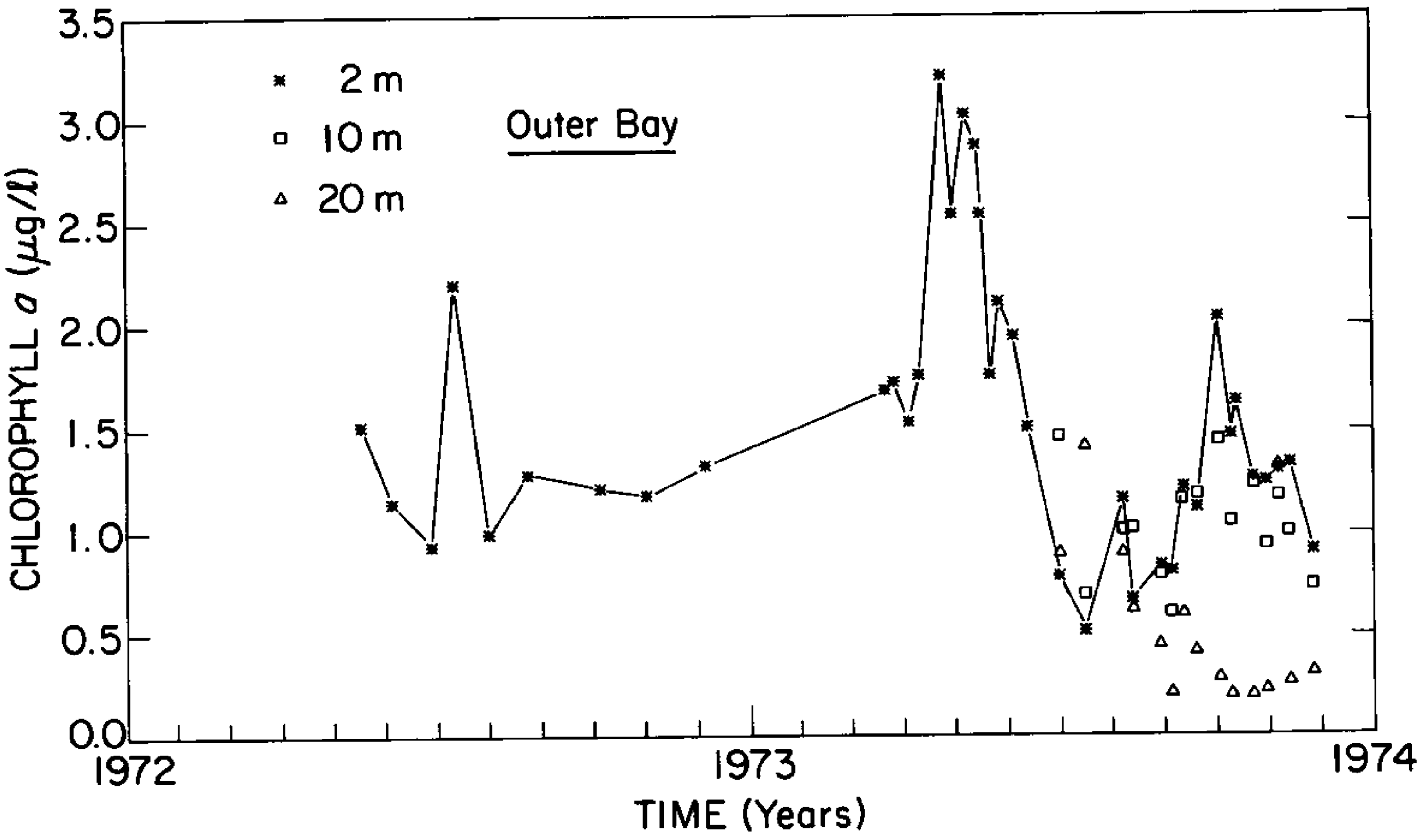


FIGURE XII-18. Chlorophyll *a* concentrations for the Outer Bay in 1972 and 1973.

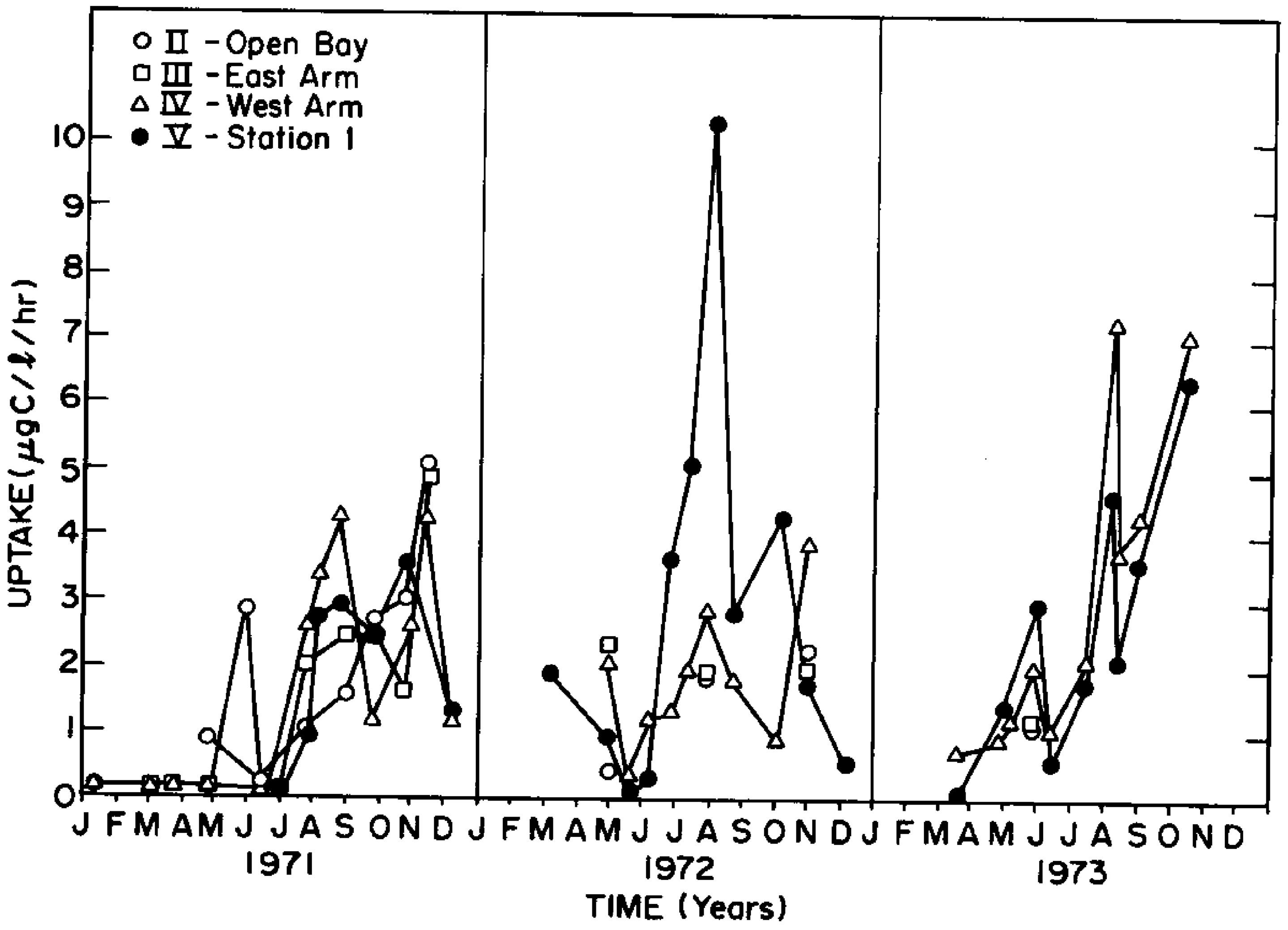


FIGURE XII-19. Primary productivity in Grand Traverse Bay 1971-1973.

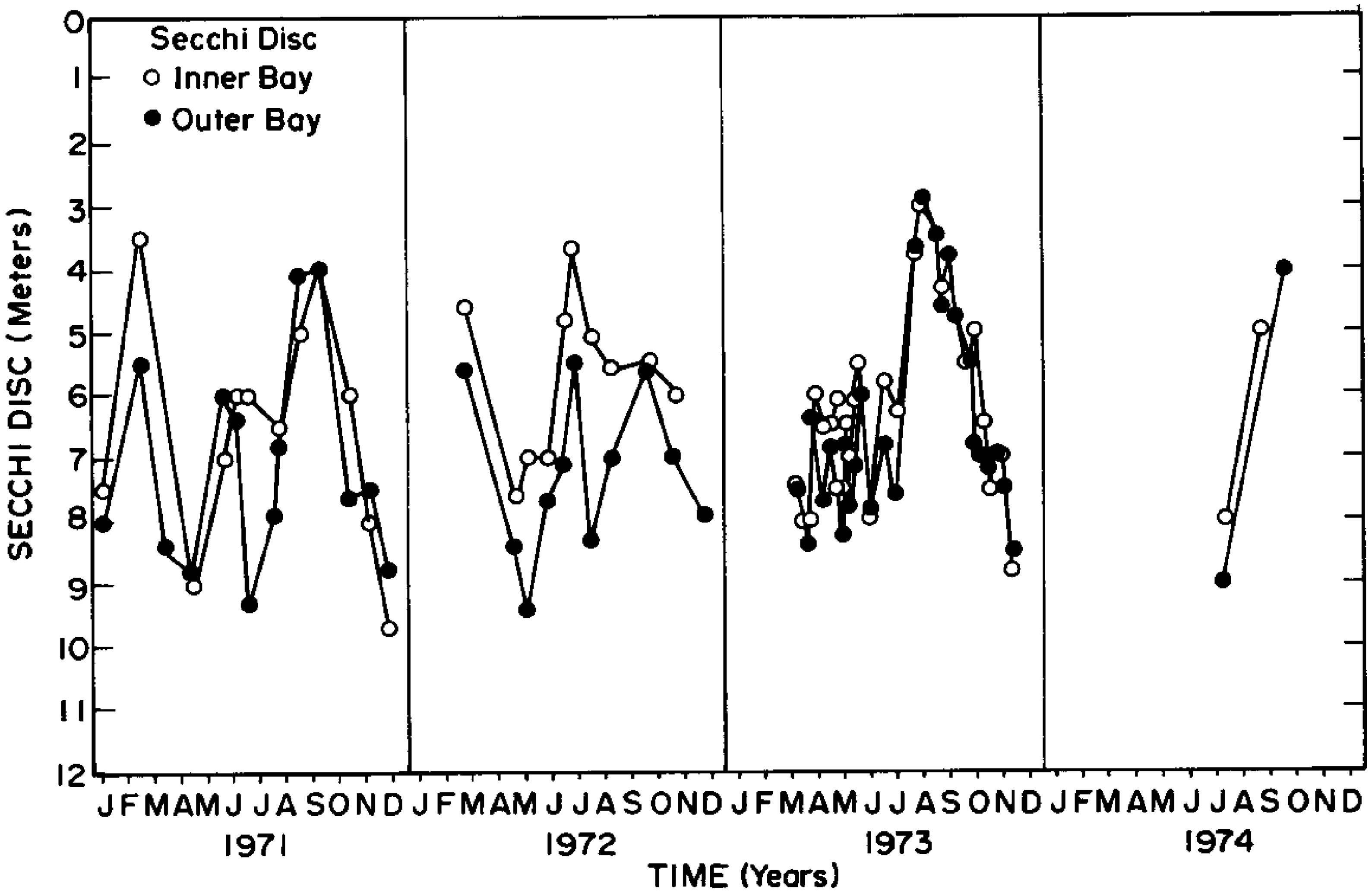


FIGURE XII-20. Secchi disc measurements in Grand Traverse Bay 1971-1974.

Surface nitrate and silicon levels were moderately well correlated with the biological indicators. The severe nitrate depletion in late summer appears to be the result of phytoplankton assimilation and transport limitation caused by stratification. Spring and summer silicon levels (with the exception of isolated values) were quite low. Apparently, this nutrient is supplied to the surface waters during spring and fall overturns and is then depleted over the growing season.

With the exception of two isolated measurements, bottom water phosphorus patterns were identical to those of surface concentrations. Silicon concentrations in the bottom waters were higher and followed a more distinct pattern than surface values. Depletions in bottom silicon occured in April/May and August/September. The latter depletion coincides nicely with the peak primary productivities and low Secchi disc values measured for that period.

The nitrate depletion noted for bottom waters was much less pronounced than that for surface waters. Lowest values occurred in the January-May period; concentrations then increased throughout the year. The elevation of nitrate concentrations with the concomittant depletion of ammonia in the spring may suggest the presence of nitrification. Increase in bottom water ammonia concentrations is presumably associated with increased decomposition accompanying warming of the bottom waters and thermal stratification.

1972

The biological trends in Grand Traverse Bay in 1972 showed a difference between the inner bay (Zone V) and the outer bay (Zones II, III and IV). Chlorophyll *a* peaked twice in both regions; once in July and again in October/November. The summer chlorophyll *a* peak in the inner bay started earlier, was more intense, and lasted longer than the corresponding peak in the outer bay. The fall increase in both regions was much less intense and occurred slightly later in the year (October in the inner bay, and November in the outer bay). Primary productivity followed a pattern very similar to that of chlorophyll *a*; summer peaks were observed in both regions in August and again in the fall. As with chlorophyll *a*, the inner bay primary productivity peak occurred earlier than the peak in the outer bay. The magnitude of primary productivity was much higher in the July peak in the inner versus the outer bay. This trend was reversed but to a much lesser extent in the fall peaks. Transparency also followed the bimodal pattern with particularly low Secchi disc readings observed in July and, to a lesser extent, in later October.

All three forms of phosphorus followed a similar pattern to transparency throughout the year in surface waters. Highest concentrations were observed during the spring; these levels dropped rather rapidly to a minimum in July/August, then slowly returned to approximately 50% of the spring level. A slight pulse in particulate (and therefore total) phosphorus occurred at approximately the same time as the summer chlorophyll *a* peak. This phenomenon was observed in both the inner and outer bays.

Surface silicon levels fluctuated widely, but were generally higher than either 1971 or 1973. The two major depletion periods occurred in July and early September; apparently these depletions were associated with phytoplankton assimilation. The increase in silicon at the surface during August possibly points to transfer or replenishment from the bottom waters through upwellings, even though the system was stratified.

Surface ammonia concentrations were highly variable, especially in the nutrient rich waters of the lower west arm. In general, three depletion periods were noted: late April, August and early November. The latter two troughs are associated with phytoplankton growth; the late April trough may be associated with both phytoplankton assimilation and nitrification. This relationship seems plausible. It is supported by the May pulse observed in surface nitrate concentrations. Chlorophyll *a* data is not complete in this period.

Surface nitrate appears to have peaked in the late winter months. This level then decreased slowly to the May pulse. Concentrations in the west arm (Zone IV) and the lower west arm (Zone V) further decreased and attained a minimum in August. This observation may result from a growth peak which occurred in the west and lower west arms but not in the east arm or open bay. Concentrations in all zones then increased through the fall due to lower productivity and replenishment from the bottom waters.

Bottom concentrations of all forms of phosphorus followed a pattern identical to that of surface values. The summer pulse in particulate phosphorus was slightly higher in the bottom waters. Silicon concentrations followed a pattern that was difficult to explain. Data for the west arm could be nicely correlated with phytoplankton parameters, but open bay and east arm data did not show this trend. It is suspected that less frequent sampling in the open bay and east arm resulted in missing the silicon depletion troughs.

Bottom ammonia levels showed depletion during the spring and fall mixing periods with an increase during the summer months. As previously suggested this increase is most probably associated with decomposition. Nitrate concentrations in the bottom waters reached their lowest level in the early spring, then slowly increased through the summer before being reduced again at fall overturn. West arm concentrations were lower than those in the open bay or east arm, probably due to higher levels of productivity.

1973

Chlorophyll *a* concentrations in 1973 displayed the classic bimodal spring/fall peak generally associated with a diatom dominated ecosystem. Both the inner and outer bays peaked at the same time in the spring, but the fall peak in the outer bay occurred later than that in the inner bay. Primary productivity levels corresponded to chlorophyll *a* patterns in the spring and fall but produced an additional peak in August which was not reflected in pigment concentrations. This productivity peak was not reflected by Secchi disc data. It should be noted that the relative magnitude of peaks measured as chlorophyll do not always correspond in the same manner to primary productivity, since the former is standing stock and the latter is a rate. Spring Secchi disc data were highly variable, but low transparencies in the late summer and early fall matched chlorophyll peaks.

Surface concentrations of total dissolved phosphorus varied widely over the year. Concentrations in the lower west arm (and to a lesser extent in the west arm) were higher and displayed much more variation than other zones. A general tendency toward lower levels in late winter/ early spring and late fall was observed due to fall phytoplankton blooms with no replenishment occurring until spring. This depletion was most likely associated with the phytoplankton peaks occurring at this time. Particulate phosphorus showed the highest concentrations during periods of high chlorophyll *a* concentrations as would be expected. Again, the lower west arm had much higher levels than the remainder of the bay.

With the exception of some erratic pulses in the levels in the lower west arm, surface silicon values decreased throughout the spring and summer from a winter maximum until mid-fall where they began to ascend toward the next winter maximum. The elevated levels observed in the lower west arm reflect the input of the Boardman River, whose concentrations average two or three times the surface bay concentrations.

Surface nitrate concentrations again followed the pattern of depletion from a winter maximum during the spring and summer followed by a return to high values during the fall. With the exception of some summer pulses in the lower west arm, surface ammonia concentrations followed a similar trend to nitrate levels.

Bottom water total dissolved phosphorus was depleted in the spring followed by a gradual increase in concentration over the remainder of the year. Bottom water particulate phosphorus showed peaks corresponding to the surface chlorophyll *a* peaks and an additional midsummer peak. Silicon concentrations in the bottom water decreased sharply through the spring and summer to a minimum in June/July and then increased towards its winter maximum through the fall.

Nitrate nitrogen levels in the bottom waters again fell through the spring to a summer minimum and then increased through the fall. The minimum was reached much sooner in the bottom than in surface waters, and concentrations began to increase at depth while surface levels were still being reduced.

1974 and 1975

Water chemistry data were collected on two cruises each during 1974 and 1975. These data are insufficient for seasonal trend analysis.

In summary, it may be said that although concentrations varied widely, a general trend toward high phosphorus levels early in the year followed by depletion during the summer months was in evidence. Ammonia levels were also highly variable but displayed a characteristic summer minimum in surface water samples. Both nitrate and silicon displayed high concentrations in the early spring followed by a late spring and summer depletion; levels were replenished at fall turnover.

Chlorophyll *a* concentrations followed a seasonal pattern similar to that for primary productivity values. Peaks in phytoplankton growth did not occur at the same time each year. A peak occurred each year in the fall, preceded by another peak in either the spring or summer. Transparency values generally followed the patterns of chlorophyll *a* and primary productivity, but not as closely as might be expected.

Parameter Correlations

Chemical and biological data from 101 samples representing 19 cruises were analyzed statistically for the existence of correlations between parameters. Scatter plots of the data and corresponding linear regression analyses were prepared using MIDAS (Michigan Interactive Data Analysis System). Due to the large number of data points present, correlation coefficients of 0.4 or greater were within the 99% confidence interval. Correlation coefficients (r) for each parameter regressed against each other parameter are presented in Table XII-1.

The correlation among parameters was generally not as high as expected. This occurrence is probably due to the fact that more than one factor affects a given parameter. Ten relationships appeared to display better correlations than the remaining forty-five.

Temperature was found to be negatively correlated with nitrate (r = -.606) and chlorophyll *a* (r = -.608) concentrations. This reflects the tendency of chlorophyll *a* peaks to occur in the spring and fall and also further points out the summer minimum in surface nitrate concentrations. Temperature was also positively correlated with primary productivity (r = +0.427) and assimilation ratio (r = +0.594). These correlations are a result of the improved light conditions during the warmer months and are consistent with observations of uptake values in the bay.

Secchi disc measurements were found to be negatively correlated with primary productivity (r = -0.453) and positively correlated with nitrate concentrations (r = +0.422) Since Secchi disc measurements are a function of factors other than phytoplankton, and are related by a feedback mechanism to both standing stock and primary productivity, interpretation of such correlations is obscured. Loss of transparency due to non-biologic suspended material should not be important in Grand Traverse Bay. Although not reflected by chlorophyll *a*, the standing crop of phytoplankton and detrital material may have been high in summer months; particulate phosphorus seems to support this hypothesis. The Secchi disc response is then related to phytoplankton and detrital material but not chlorophyll *a* concentrations. The positive correlation with nitrate again reflects the summer nitrate minimum.

TABLE XII-1. Correlation coefficients.

Parameter	Light	Temperature	Chl *a*	Pri. Pro.	Secchi	TDP	PP	NO_3	NH_3	A.R.	Si
Light											
Temp	-.008										
Chl *a*	+.211	-.608									
Pri. Pro.	-.246	+.427	-.093								
Secchi	+.349	-.187	-.063	-.453							
TDP	-.079	+.115	+.086	-.170	-.011						
PP	+.067	-.142	+.225	+.113	-.254	-.060					
NO_3	-.134	-.606	+.137	-.366	+.422	+.054	-.109				
NH_3	+.034	-.005	-.027	-.177	+.039	+.363	-.001	+.178			
AR	-.131	+.594	-.485	+.726	-.304	-.196	-.049	-.360	-.134		
Si	-.539	-.362	-.086	-.118	+.047	-.034	-.203	+.544	+.205	-.128	-

Silica was found to be positively correlated with nitrate (r = +0.544) and negatively correlated with light (r = -0.539). Again this shows that depletion of silica and nitrate in the summer months and the increase in concentrations in the fall are associated with peaks in phytoplankton growth.

Two good correlations with the assimilation ratio, primary productivity (r = +0.726) and chlorophyll *a* (r = -0.485), cannot be considered because of the fact that the assimilation ratio is derived from these parameters.

Various researchers have compared phosphorus, chlorophyll *a*, and Secchi disc data to aid in the understanding of phytoplankton nutrient relationships and in ranking lakes by productivity.

Tierney et al. (1975) plotted clorophyll *a* concentration versus Secchi disc transparency for 42 Michigan lakes. (Figure XII-21 and Table XII-2). Calculations from the present study place both the inner and outer bays in the extremely unproductive region of this graph; the outer bay being similar to Lake George and Pine Lake Basin 2, and the inner bay being similar to Corey Lake and Palmer Lake.

Dillon and Rigler (1974), using data from Japan and the United States, plotted summer average chlorophyll *a* versus total phosphorus concentration at spring overturn (Figure XII-22). Again calculations from the present study show good fit to their plot, with Grand Traverse Bay being placed low on the productivity scale. In a later paper, Dillon and Rigler (1975) plotted Secchi disc transparency versus chlorophyll *a* concentration for approximately 60 southern Ontario lakes (Figure XII-23). The results were similar to those of Tierney et al. (1975) for Michigan lakes. Average summer values from this study again fit the plot nicely and place Grand Traverse Bay at a position similar to the unproductive lakes of southern Ontario.

Phytoplankton Nutrient Ratios

As mentioned briefly earlier, various researchers have suggested that the nutrient status of a lake may be interpreted through an examination of major phytoplankton nutrient ratios, i.e., Si:N:P. Hutchinson (1957) reports a ratio by mass in Linsley Pond of 50-220:1 for combined inorganic nitrogen to combined inorganic phosphorus. The ratio in the lake's seston was 9.4-25.5:1. Hutchinson (1957) felt that these ratios indicated phosphorus limitation. Kramer and Allen (1972) report a typical nitrogen to phosphorus value for plankton as being approximately 5:1 by weight. With regard to silicon:phosphorus ratios, a value of 50:1 may be considered typical. All ratios calculated for this study are by weight.

Spring ratios of Si:N:P in Grand Traverse Bay ranged from 95-571:32-224:1 with a mean of 296:111:1. Spring ratios were similar at the stations representing the east and west arms. Summer ratios ranged from 30-1102:30-181:1. The east and west arm ratios varied widely with respect to silicon. The east arm had a mean ratio of 508:92:1 while the west arm mean was 89:94:1 (Tables IXX-3 and XII-4).

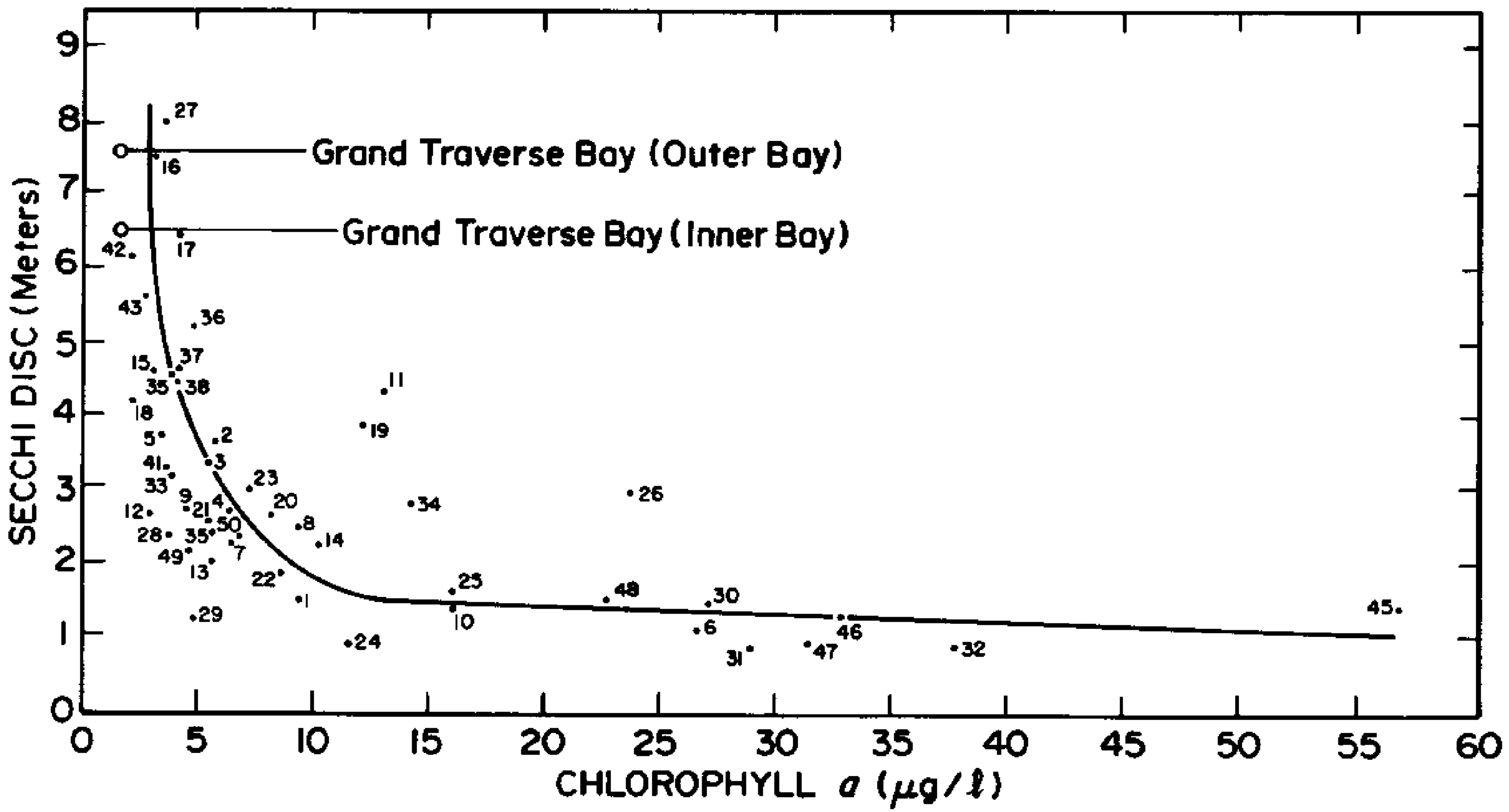


FIGURE XII-21. Relationship between chlorophyll *a* and Secchi disc depth for 42 Michigan lakes. (After Tierney et al. 1975).

TABLE XII-2. Key to lakes plotted in Figure XII-21 (after Tierney et al. 1975).

1. Clear L. (Montmorency Co.)
2. Big Twin L. (Kalkaska Co.)
3. Starvation L. (Kalkaska Co.)
4. Higgins Lake (Roscommon Co.)
5. Higgins Lake (Roscommon Co.)
6. Taylor L. (Oakland Co.)
7. Big Blue L. (Kalkaska Co.)
8. L. Voorheis (Oakland Co.)
9. Pine L. (Oakland Co.)
10. Walnut L. (Oakland Co.)
11. Bryan L. (Genesee Co.)
12. Wolf L. (Lake Co.)
13. Baetcke L. (Livingston Co.)
14. Clear L. (Berrien Co.)
15. Crooked L. (Alcona Co.)
16. Pine L. Basin 1 (Barry Co.)
17. Corey L. (St. Joseph Co.)
18. Middle Straight L. (Oakland Co.)
19. Sandy Bottom L. (Livingston Co.)
20. L. Miramichi (Mecosta Co.)
21. Morgan L. (Oakland Co.)
22. Shingle L. (Clare Co.)
23. Pine L. Basin 2 (Barry Co.)
24. Coon L. (Livingston Co.)
25. Marl L. (Genesee Co.)
26. Long L. (Livingston Co.)
27. L. George (Clare Co.)
28. Williams L. (Oakland Co.)
29. Cass L. (Oakland Co.)
30. Pleasant L. (Washtenaw Co.)
31. Long L. (Iosco Co.)
32. Eagle L. (Cass Co.)
33. Independence L. (Washtenaw Co.)
34. Silver L. (Genesee Co.)
35. Round L. (Livingston Co.)
36. Bass L. (Mason Co.)
37. Horseshoe L. (Washtenaw Co.)
38. Cedar L. (Alcona Co.)
39. Long Lake (St. Joseph Co.)
40. Kent L. Station 1 (Oakland Co.)
41. Victoria L. (Clinton Co.)
42. Palmer L. (St. Joseph Co.)
43. Kensington L. (Oakland Co.)
44. Dewey L. (Cass Co.)
45. Sturgeon L. (St. Joseph Co.)
46. Gemini L. (Macomb Co.)
47. Kent L. Station 3 (Oakland Co.)
48. Kent L. Station 2 (Oakland Co.)

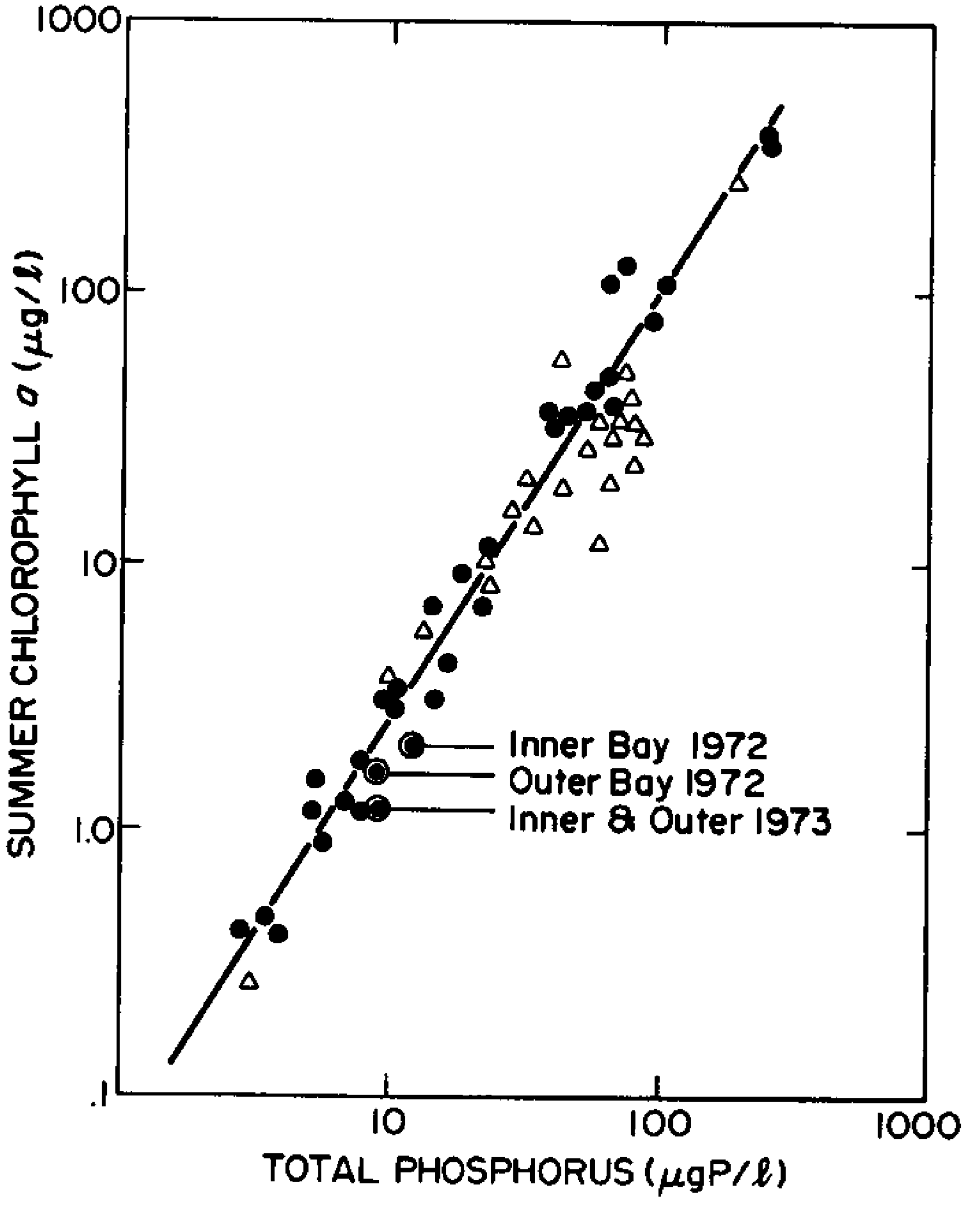


FIGURE XII-22. Summer chlorophyll *a* plotted *versus* total phosphorus (After Dillon and Rigler 1974).

The Si:N:P ratios for Grand Traverse Bay indicate a severely phosphorus limited system. The difference between summer ratios in the east and west arms reflects the higher productivity leading to silicon depletion in the latter. The evidence of extreme phosphorus depletion is supported by factorial enrichments of Schelske et al. (1974) in which phosphorus was also found to be limiting.

Uptake ratios (Si:N:P) were calculated using the difference between minimum summer levels and maximum winter levels of total dissolved phosphorus and total phosphorus. These ratios were 116:42:1 using TDP and 81:30:1 using TP. These uptake ratios are very close to the stoichiometric composition values reported by Allen and Kramer (1972) for natural waters, especially considering the rapid recycling of phosphorus compared to nitrogen and silicon.

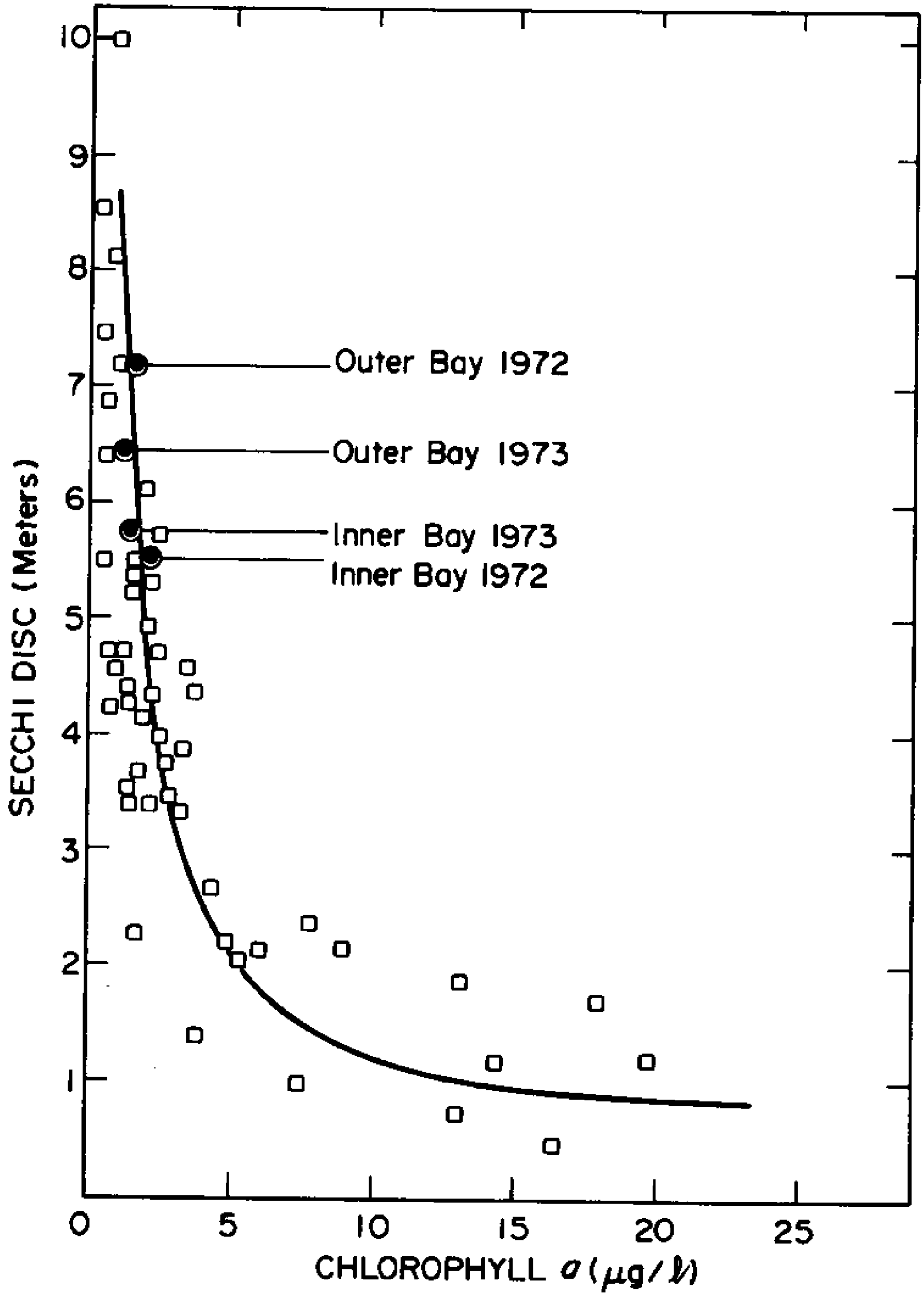


FIGURE XII-23. Chlorophyll *a* plotted *versus* Secchi disc reading (Modified from Dillon and Rigler 1975).

TABLE XII-3. Ratios, by weight, of silicon: dissolved inorganic nitrogen: total dissolved phosphorus in Grand Traverse Bay water.

Date	Station	Depth	Si	:	N	:	P
July 1971	1	surface	166		164		1
	1	bottom	27		171		1
July 1972	1	surface	69		37		1
	1	bottom	208		114		1
July 1973	1	surface	30		30		1
	1	bottom	36		44		1
March 1971	1	surface	171		60		1
	1	bottom	134		43		1
March 1972	1	surface	386		202		1
	1	bottom	571		137		1
March 1973	1	surface	346		100		1
	1	bottom	267		99		1

East Arm	Station	Depth	Si	:	N	:	P
Aug. 1971	8	surface	1102		181		1
	8	bottom	32		73		
July 1972	8	surface	333		61		1
	8	bottom	564		51		1
Summer 1973	-	---	---		---		-
	-	---	---		---		-
March 1971	8	surface	157		54		1
	8	bottom	95		32		1
March 1972	6	surface	435		224		1
	6	bottom	400		159		
Spring 1973	-	---	---		---		-

TABLE XII-4. Mean weight ratios of silicon: dissolved inorganic nitrogen: total dissolved phosphorus in Grand Traverse Bay water.

	Si:N:P	
	East Arm	West Arm
Mean Spring Surface	296:139:1	301:121:1
Mean Spring Bottom	248:96:1	324:93:1
Mean Summer Surface	718:121:1	88:77:1
Mean Summer Bottom	298:62:1	90:110:1

XIII. PHYTOPLANKTON STUDIES

Phytoplankton affect the aesthetic quality of water and, as a direct and indirect food supply, are essential to most nonphotosynthetic forms of aquatic life. Two studies of phytoplankton numbers, distribution and diversity in Grand Traverse Bay have been reported. Two cruises, one each in May and June of 1970, were conducted in Grand Traverse Bay by the Great Lakes Research Division of the University of Michigan. The results of this work are presented in a paper by Stoermer, Schelske, Santiago and Feldt (1970). The second study involved phytoplankton samples collected by the Michigan Sea Grant Program in 1971. Data from this sampling program were analyzed independently by Wendy W. Moore, but have not been previously published.

Information regarding cell numbers and species composition of the phytoplankton in Grand Traverse Bay has been published by Stoermer et al. (1972). Levels of standing crop were difficult to compare with other portions of Lake Michigan because of the time of sampling however, it was stated (p. 188) that, "Levels of standing crop ... were higher than those reported from southern Lake Michigan by Stoermer and Kopczynska (1967) based on samples collected in 1962 and 1963. More recent data would seem to indicate that the highest standing crop densities reported in this study were comparable to current average values for the inshore waters of southern Lake Michigan in May and only on the order of one-fifth as high as the extreme highs encountered in that region of the lake."

This study further revealed that the phytoplankton in Grand Traverse Bay are composed almost exclusively of diatoms with 11 species representing 71.5% of the assemblage on the average. Unidentified flagellates accounted for another 16.5%; thus twelve groups resulted in 88% of the population. Dominant species in all cases were characteristic of oligotrophic conditions with pollution tolerant phytoplankton at very low levels. The dominant phytoplankton at all stations sampled were very similar and the diversity was quite high and very uniform.

Stoermer et. al. (1972) concluded that phytoplankton were more abundant in the west arm than the east arm and that a gradient of increasing productivity existed from north to south in the west arm . The open bay represented a region of mixing between the two arms.

Phytoplankton data from Grand Traverse Bay in 1971 were analyzed by Moore (unpublished). Cell counts from stations in the east arm, west arm and open bay were grouped so that these regions could be compared (see Figures XIII-1 and XIII-2). The maximum standing crop (mean total cells/ml) at 2 m occurred in June in the west arm and in July in the east arm and outer bay. The earlier peak in the west arm may reflect the more favorable nutrient conditions in that region. There was no significant difference between zones in any month except June and July.

Maximum standing crop at 20 m occurred at the same time (June) in all three regions. Reduction in total cell density in July in the west arm (as opposed to August in the east arm) may indicate the presence of a small phytoplankton bloom in that zone. In general, phytoplankton density was somewhat greater in the west arm than in other zones.

The Shannon-Weaver Information Measure, a diversity index, was computed for stations in the east arm, west arm and open bay, and for the total bay. General diversity patterns were the same in all areas of the bay (Figure XIII-3). The maximum diversity occurred in April with a relatively large number of taxa and a moderate number of cells. A secondary maximum occurred in August; in this case the number of taxa and cell density were low.

Diversity in the west arm was slightly greater than for stations in the east arm and open bay. It is not clear, however, how this elevated diversity relates to higher nutrient levels in this zone.

Taxa comprising at least 5% of the phytoplankton during any month are listed in Table XIII-1. The general pattern of seasonal succession is typical of freshwater lakes in the temperate zone. Diatoms (Bacillariophyceae) dominate the winter and spring populations with midsummer composition reflecting a mixture of diatoms and green algae (Chlorophyceae). The fall phytoplankton populations contain fewer diatoms and green algae and blue-green algae (Cyanophyceae) are more abundant.

Species which were significantly more abundant in either the east or west arm are presented in Table XIII-2. Those taxa considered to be tolerant of high nutrient levels (Stoermer et al. 1972) are marked with an asterisk (*). Taxa generally considered to be indicators of oligotrophic conditions (Stoermer et al. 1972) are marked by a hyphen (-).

Except during the month of April, significant numbers of "pollution tolerant" taxa occur only in the west arm. The abundance of these taxa in April in both arms probably reflects the high nutrient levels associated with spring turnover. Taxa indicative of oligotrophic conditions occur equally in both regions.

In summary, stations in the west arm show some evidence of eutrophication compared to the east arm and open bay. This trend is reflected in higher cell numbers, earlier maximum density peaks and the presence of more taxa tolerant of eutrophic conditions.

Table XIII-1. Dominant species (5% or greater in the phytoplankton of Grand Traverse Bay.

		JAN	e MAR	l MAR	APR	JUN	e JUL	l JUL	c AUG	l AUG	SEP	OCT-DEC
Bacillariophyceae	*Fragilaria crotonensis*	X	X	X	X	X	X	X		X	X	
	Stephanodiscus minutus	X	X	X	X	X	X	X				
	Cyclotella stelligera	X	X	X	X		X	X		X	X	
	Tabellaria fenestrata	X	X	X		X	X	X			X	
	Synedra filiformis	X	X	X	X	X	X					
	Stephanodiscus spp. #1	X	X	X	X							
	Asterionella formosa	X	X		X		X	X			X	
	Melosira islandica	X			X							
	Stephanodiscus alpinus	X										
	Stephanodiscus spp. #2		X	X	X							
	Rhizosolenia gracilis				X	X	X					
	Rhizolsolenia eriensis					X						
	Cyclotella michiganiana						X	X		X		
	Fragilaria capucina						X					
	Stephanodiscus subtilis							X				
	Amphora ovalis v. ped.									X		
	Flagellate Species	X	X		X	X	X	X		X	X	
	*Dinobryon divergens**					X						
Chlorophyceae	*Gloeocystis* spp.							X		X	X	
	Sphaerocystis Schroeteri							X		X	X	
	Dictyosphaerium spp.							X		X		
	Oocystis spp.							X		X	X	
	Crucigenia irregularis									X		
	Crucigenia quadrata									X		
Cyanophyceae	*Anabaena flos-aquae*							X		X	X	
	Anacystis thermalis									X	X	
	Anacystis incerta									X	X	
	Anacystis cyanea										X	
	Anacystis minimus										X	
	Gomphosphaeria spp.										X	

e = early l = late * Chrysophyceae

Table XIII-2. Species of phytoplankton significantly more abundant in east or west arms of Grand Traverse Bay.

MONTH	WEST	EAST
APRIL	_Cyclotella stelligera_ (2m) *_Stephanodiscus alpinus_ (2&20)	*_Stephanodiscus minutus_ (2&20m) *_Diatoma tenue_ (2&20)
JUNE	*_Diatoma tenue_ (2)	-_Melosira islandica_ (2) _Cyclotella stelligera_ (20)
JULY	-_Tabellaria fenestrata_ (20) -_Cyclotella comta_ (2&20) *_Stephanodiscus minutus_ (2&20)	_Dictyosphaerium sp._ (20) _Cyclotella michiganiana_ (2) _Cyclotella stelligera_ (2&20)
AUGUST	_Anacystis thermalis_ (20) *_Stephanodiscus minutus_ (2) _Gloeocystis sp._ (20) -_Amphora ovalis v. ped._ (2) _Anabaena flos-aquae_ (20)	_Anacystis thermalis_ (2) _Anacystis incerta_ (20) _Cyclotella michiganiana_ (2&20) _Cyclotella stelligera_ (2&20)
SEPTEMBER	-_Amphora ovalis v. ped._ (2&20) -_Tabellaria fenestrata_ (2&20) _Gloeocystis sp._ (2)	_Dictyosphaerium sp._ (2&20) _Anacystis incerta_ (2&20) _Gloecystis sp._ (20) _Anacystis thermalis_ (2&20)

* high nutrient tolerant organisms

- low nutrient tolerant organisms

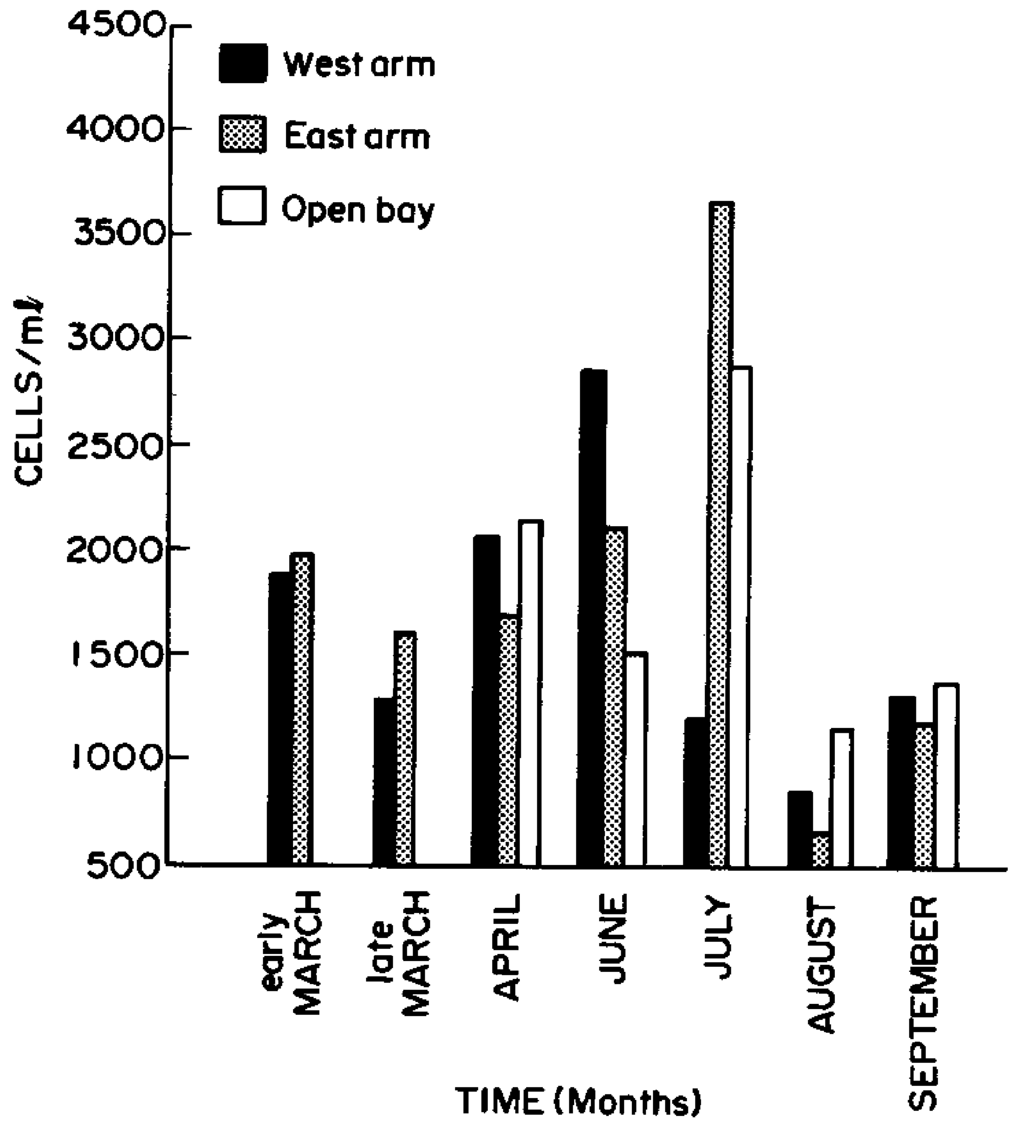


FIGURE XIII-1. Phytoplankton numbers (cells/mℓ) in Grand Traverse Bay at 2m depth - 1971.

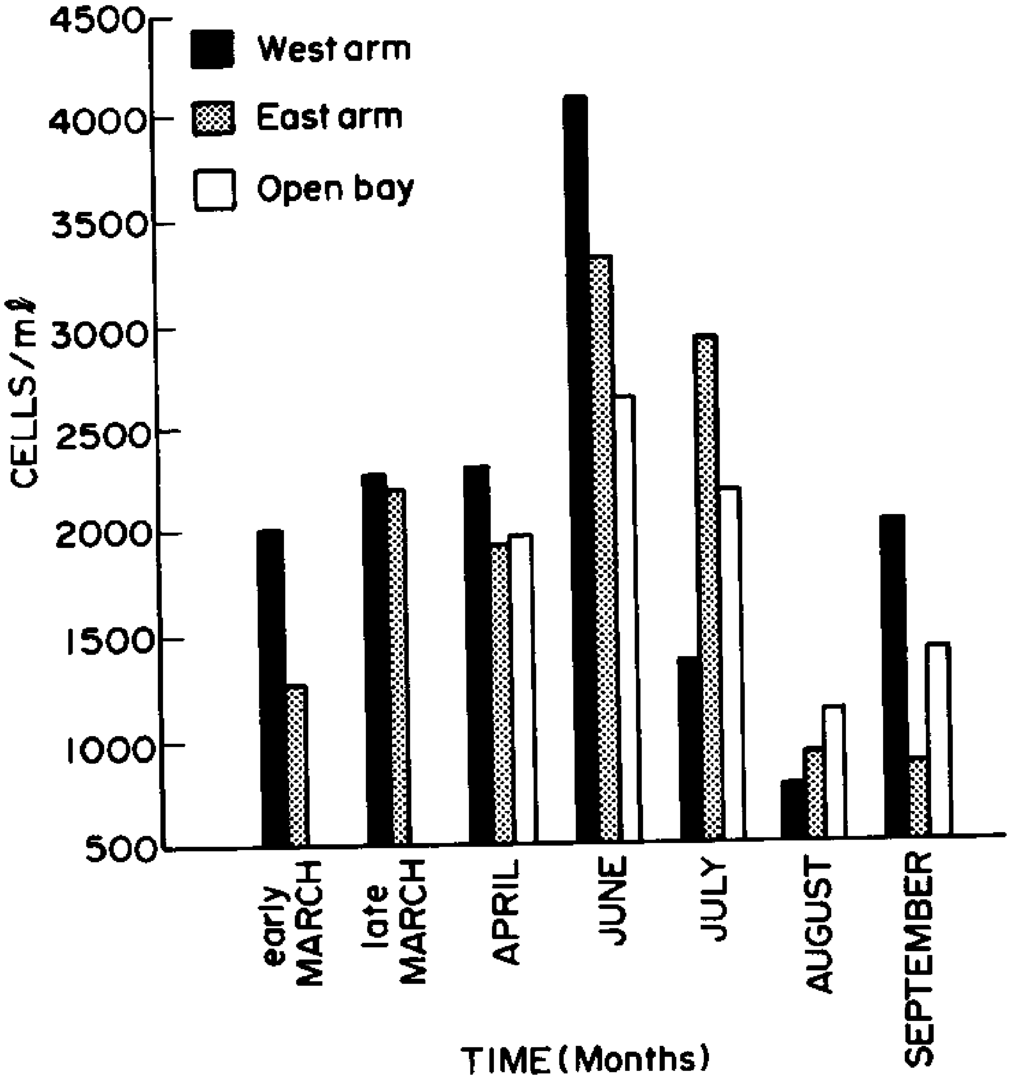


FIGURE XIII-2. Phytoplankton numbers (cells/mℓ) in Grand Traverse Bay at 20m depth - 1971.

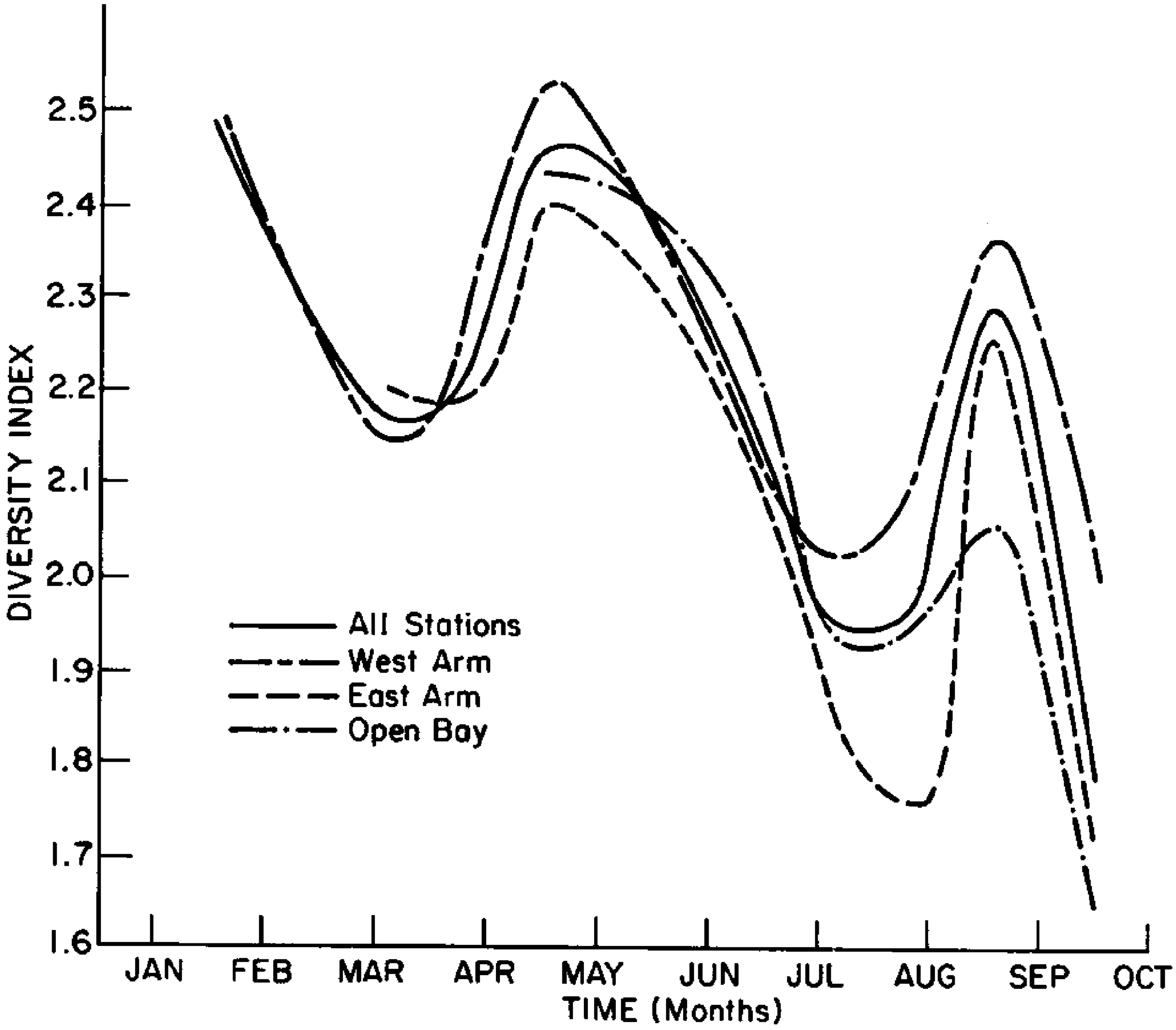


FIGURE XIII-3. Phytoplankton diversity (Shannon-Weaver Index) for Grand Traverse Bay - 1971.

XIV. ZOOPLANKTON

An important role of organisms such as zooplankton and benthic macroinvertebrates in aquatic ecosystems is to transfer nutrients and energy from the primary producers (chiefly phytoplankton and benthic algae) to the fish. As a result, these organisms help control the magnitude and duration of algal blooms and provide support for forage and predator fish populations. In many lakes benthic macroinvertebrates are the major aquatic organisms which provide a link between primary production and fish. However, the littoral zone is small in Grand Traverse Bay and planktonic food chains predominate.

The native coregonids are an important commercial fish in the Great Lakes. The larval and fry stages of these fish feed heavily upon zooplankton as a source of food throughout this portion of their life cycle (Dryer and Beil 1968, Wells and Beeton 1963). Fish such as the alewife (Wells 1970) and smelt (Price 1963) are mainly planktonivorous and occasionally even salmonids will eat the larger zooplankton of the Great Lakes (Galbraith 1967, Brooks 1969).

Changes in the community structure of the zooplankton have been used as indicators of eutrophication in the Great Lakes with mixed results. Brooks (1969) has shown that changes between *Bosmina longirostris* and *Eubosmina coregoni* in the Great Lakes cannot be explained on the basis of eutrophic conditions alone. However on a generic level, Gannon (1974), Watson (1975), and McNaught and Scavia (1976) suggest that in oligotrophic waters calanoid copepods such as *Limnocalanus* and *Diaptomus* dominate the zooplankton. In moderately enriched waters, the community becomes dominated by cyclopoid copepods and large cladocerans such as *Daphnia*. Enriched systems favor development of small cladocerans such as *Bosmina*. These shifts in community composition usually occur first in the nearshore regions of lakes then move offshore.

Zooplankters as indicators of pollutants other than nutrients have been studied less extensively. However, Gannon and Beeton (1971) have shown that *Limnocalanus macrurus* is sensitive to low dissolved oxygen concentrations. Preliminary studies by Muirhead-Thomson (1971) on zooplankton and pesticides suggest that generally cladocerans are very sensitive to organophosphorus pesticides while cyclopoid copepods are more sensitive to chlorinated hydrocarbons.

The Michigan Sea Grant Program has sampled Grand Traverse Bay for the purpose of determining the composition and distribution of the zooplankton community. A map showing the location of the sampling stations is shown in Figure XIV-1. The number of times each station was sampled is indicated in parenthesis and itemized in Table III-3. Zooplankton samples were taken 320 times at 20 stations within five zones in Grand Traverse Bay over the three years. The spatial distribution was uneven, with 59% of the total number of samples collected from the west arm, 3% from the lower west arm, 13% from the east arm, 6% from the Elk River plume, and 19% from the open bay. The seasonal distributions of samples taken in each zone are shown in Table XIV-1. During 1971 a total of 123 samples were taken on 12 cruises at 20 stations. In 1972 there were 13 cruises at 13 stations, and a total of 112 samples. A total of 79 samples were collected from 3 stations over 23 cruises in 1973. Modifications between 1972 and 1973

TABLE XIV-1. Seasonal distribution of zooplankton sample collection in Grand Traverse Bay.

Zone	West Arm	Lower West Arm	East Arm	Elk River Plume	Open Bay
Winter 1971	7	1	3	0	0
Spring 1971	7	0	7	1	4
Summer 1971	9	0	7	1	6
Fall 1971	26	8	11	4	23
Winter 1972	2		3	0	0
Spring 1972	11		3	1	7
Summer 1972	24		4	2	6
Fall 1972	24		5	10	14
Spring 1973	40				
Summer 1973	12				
Fall 1973	27				
	189	9	43	19	60

were designed to improve sampling frequency and spatial resolution in the lower half of the west arm of the bay. Seasonally over the three years there were 16 samples taken during the winter, 81 in the spring, 71 in the summer, and 152 in the fall. Some gaps in sampling occurred between December and March and between August and September. These were due to ice problems and ship routing conflicts.

Samples obtained for zooplankton enumeration in this report were collected using vertical haul techniques (see Chapter VII). Vertical haul sampling does not account for possible variation and patchiness due to the time of day. Special studies were conducted to evaluate the significance of this phenomenon. It was found that zooplankton abundance can vary in vertical hauls taken 4 hours apart by a factor of 4. The adequacy of zooplankton sampling is also dependent on the fact that some zooplankters are planktonic during only part of the year. On the positive side this study consisted of relatively intensive horizontal and temporal zooplankton samples taken over a three year period. Furthermore, supportive primary productivity and nutrient data were obtained to account for variations of the zooplankton populations.

Horizontal zones (as shown in Figure XIV-1) were established for the purpose of examining possible horizontal differences in either zooplankton composition or abundance. These zones are identical to those previously established for analysis of major nutrient and phytoplankton parameters. The zones or regions are: the open bay; the east arm (including the Elk River plume), the west arm, and the lower west arm.

Composition of Grand Traverse Bay Zooplankton

Crustacean Zooplankters

Two crustacean taxa account for over 99% of the total zooplankton counted in Grand Traverse Bay. These taxa are the copepods and the cladocerans. The remaining crustaceans were mostly mysids and ostracods. Three orders of copepods have been found in Grand Traverse Bay: Calanoida, Cyclopoida, and Harpacticoida. However, only the first two are euplanktonic. Five calanoid and three cyclopoid genera were found (see Table XIV-2). *Diaptomus*, *Cyclops*, *Limnocalanus*, and *Epischura* were routinely encountered. *Senecella* was observed on occasion and *Eurytemora* was found only once during the three years. No separate count is available for *Tropocyclops* or *Mesocyclops*. *Limnocalanus macurus*, *Epischura lacustris*, *Diaptomus minutus* and *Cyclops bicuspidatus thomasi* were the major species found.

Of the 14 cladoceran genera found in Lake Michigan by Wells (1970) ten were encountered in Grand Traverse Bay during the present study. These were *Daphnia*, *Bosmina*, *Leptodora*, *Polyphemus*, *Holopedium*, *Diaphanosoma*, *Ceriodaphnia*, *Eurycerus*, *Chydorus*, and *Alona*. The average abundances of crustacean zooplankton found in Grand Traverse Bay are listed in Table XIV-3. As can be seen, the significant zooplankton in terms of abundance are *Diaptomus*, Cyclopoids, *Bosmina*, and *Daphnia*. Although the actual numbers of the other two calanoids and the predatory cladocerans are quite low, they may be ecologically significant from an energetics and food web view point. *Holopedium* is the only other genus with an abundance near or greater than 1%. *Senecella*, *Eurytemora*, *Diaphanosoma*, *Ceriodaphnia*,

TABLE XIV-2. Crustacean zooplankton identified in Grand Traverse Bay.

COPEPODS	CLADOCERA
Calanoids	
Diaptomus sicilis	*Daphnia galeata mendotae*
D. ashlandi	*D. retrocurva*
D. minutus	*D. longiremis*
D. oregonensis	*D. pulex*
Senecella calanoides	
Limnocalanus macrurus	*Bosmina*
Epischura lacustris	
Eurytemora affinis	*(B.) longirostris*
	(E.) coregoni
Cyclopoids	
	Leptodora kindtii
Cyclops biscuspidatus thomasi	*Polyphemus pediculus*
Cyclops vernalis	*Holopedium gibberum*
Medocyclops edax	*Diaphanosoma leuchtenbergianum*
Tropocyclops prasinus	*Ceriodaphnia sp.*
	Chydorids
	Eurycerus lamellatus
	Chydorus sphaericus
	Alona spp.

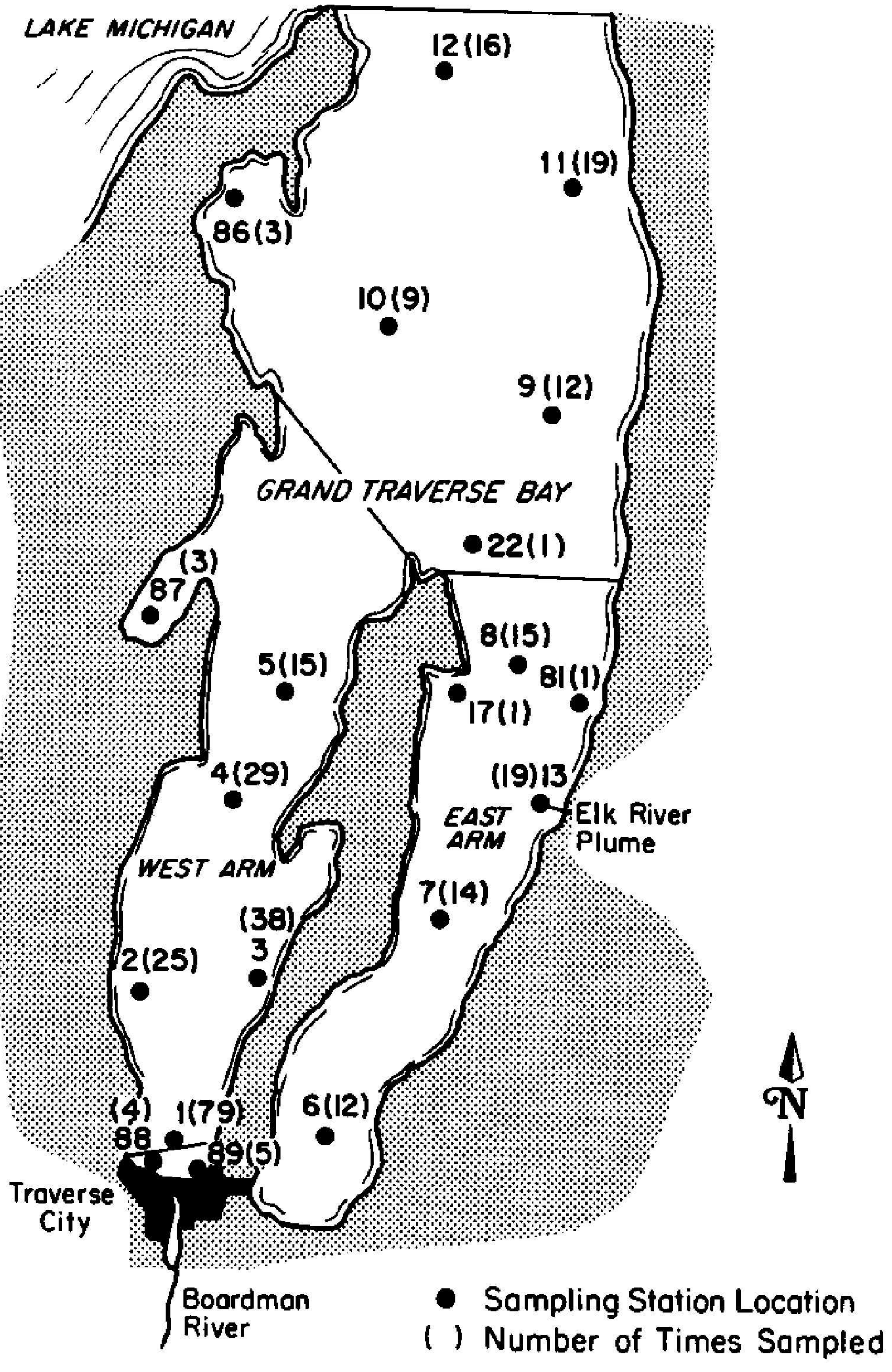


FIGURE XIV-1. Zooplankton sampling station locations and collection frequency in Grand Traverse Bay.

and the chydorids, mysids, ostracods, and conchostracans account for less than one quarter of one percent of the total number of crustacean zooplankton.

Rotifers

There were eight genera of rotifers identified during the study; *Asplanchna, Brachionus, Filinia, Gastropus, Kellicottia, Keratella, Polyarthra, and Synchaeta.* Four genera, *Asplanchna, Kellicottia, Keratella, and Polyarthra* were routinely encountered and enumerated. The other four were less often observed and were included only as miscellaneous unidentified rotifers.

Stemberger (1974) identified 17 genera of rotifers in Lake Michigan offshore of Milwaukee. Among the common genera found by this researcher, only one, *Conochilus*, was not collected during this study. *Conochilus*, and most of the other rarer forms found by Stemberger (1974), are probably present in Grand Traverse Bay. However, because the collection efficiency of #20 nets is low for these small organisms, representative samples were not obtained. Thus, most of the rotifer data available are inadequate for extensive analysis. However, data are plotted in the following section which define the temporal variation of *Asplanchna* in the west arm of Grand Traverse Bay.

Miscellaneous Zooplankton

Three groups of benthic crustaceans (mysids, ostracods, and concostracans) were collected on rare occasions during this study. Collections were probably random and occurred when the nets may have been lowered too close to the bottom. All three groups were collected infrequently and data resulting from such collections do not justify analysis. The protozoan *Codonella* was the only zooplankter other than rotifers and crustaceans commonly encountered during this investigation. Unfortunately, separate and accurate data regarding the density and distribution of this protozoan are not available.

Horizontal Distribution of Crustacean Zooplankton

The average concentration and standard deviation of zooplankton found in the five zones of Grand Traverse Bay are listed in Table XIV-4. The west arm averages in Table XIV-4 do not include limited data from Stations 86 and 87 which appeared aberrant. The large standard deviations found in Table XIV-4 are the result of wide seasonal differences in zooplankton densities and occurrences of natural perturbations. The data were separated by date and an analysis of variance was performed to detect differences among the various regions of the bay. A summary of the significant results obtained from the analysis of variance is given in Table XIV-5. Only the test results producing a level of significance greater than 75% have been included in this table, while the others were disregarded as inconclusive. The predatory zooplankters, *Leptodora, Polyphemus, Limnocalanus,* and *Epischura,* and the rare herbivore, *Ceriodaphnia,* do not have significantly different concentrations in various regions of the bay. The east arm has

TABLE XIV-3. Average concentrations of crustacean zooplankton taken in Grand Traverse Bay between 1971 and 1973 (in numbers /ℓ).

	No/ℓ	% of total
COPEPODS	15.70	76.6
Calanoids		
Diaptomus	8.60	42.0
Limnocalanus and Epischura	0.04	0.2
Cyclopoids	7.06	34.4
CLADOCERANS	4.80	23.4
Daphnids	1.93	9.4
Daphnia	1.924	
Ceriodaphnia	0.006	tr
Bosmina	2.62	12.8
Leptodora and Polyphemus	0.02	0.1
Holopedium	0.19	0.9
Diaphanosoma	0.02	0.1
Chydorus	0.014	tr
Alona	0.006	tr

TABLE XIV-4. Mean concentrations (and standard deviation) of the Grand Traverse Bay zooplankton over the years 1971 to 1973 by region (in numbers/m^3).

Organism	West Arm	Lower West Arm	Open Bay	East Arm	Station #13
Diaptomus	9529(±8937)	8614(±5283)	7196(±7104)	4413(±4526)	13171(±12753)
Limnocalanus and Epischura	39(± 51)	11(± 20)	25(± 29)	35(± 39)	49(± 113)
Cyclopoids	7405(±6404)	2807(±8363)	6008(±4909)	6233(±7762)	5977(± 4723)
Daphnia	2011(±4098)	6341(±4235)	960(± 849)	434(± 629)	5237(± 8032)
Bosmina	2784(±4531)	6089(±8369)	2602(±6234)	1015(±2150)	3061(± 3507)
Leptodora and Polyphemus	16(± 48)	80(± 128)	25(± 77)	11(± 38)	13(± 26)
Holopedium	183(± 643)	897(±1350)	125(± 139)	39(± 88)	478(± 1170)
Diaphanosoma	17(± 55)	143(± 151)	19(± 44)	7(± 19)	46(± 97)
Chydorids	4(± 12)	9(± 11)	1(± 3)	0	266(± 960)
Ceriodaphnia	8(± 44)	7(± 20)	3(± 12)	0	12(± 50)

TABLE XIV-5. Significant differences in zooplankton numbers among regions of Grand Traverse Bay.

Taxa	Difference	Level of Significance (%)
Diaptomus	East Arm lower than rest of Bay	95
Cyclopoids	East Arm lower than rest of Bay	99
Cyclopoids	West Arm greater than Open Bay	95
Bosmina	East Arm lower than rest of Bay	90
Daphnia	East Arm lower than rest of Bay	95
Daphnia	West Arm greater than Open Bay	95
Holopedium	East Arm lower than rest of Bay	75
Diaphanosoma	East Arm lower than rest of Bay	95
Diaphanosoma	West Arm greater than Open Bay	95
Chydorids	East Arm lower than rest of Bay	95
Chydorids	West Arm greater than Open Bay	95

a significantly lower density of the other zooplankton groups when compared with the rest of the bay. *Daphnia* and *Diaphamosoma*, as well as cyclopoids and chydorids, attain significantly higher densities in the west arm of the bay than in the open bay. Because the lower west arm can be differentiated from the remainder of the west arm on the basis of nutrient and phytoplankton concentrations, an analysis of variance was performed to determine possible unique patterns of zooplankton species composition and numbers in this zone. No significant differences were found between the two zones. Data shown in Table XIV-4 demonstrate that Station 13 is much different in terms of total numbers and species composition than the rest of the east arm. The occurrence of elevated numbers of chydorids and *Ceriodaphnia* at Station 13 is particularly noticeable.

Discussion of the Factors Influencing the Horizontal Distribution of Zooplankton

It is apparent that the east arm has a significantly lower zooplankton standing stock than the rest of the bay. This is probably a reflection of lower phytoplankton concentrations in this region which are a result of relatively low nutrient loading (see Table IX-3). Only small differences exist among the zooplankton between the west arm and the open bay, probably as a consequence of hydraulic mixing between the west arm and the open bay. The specific factors which result in an increase in the west arm over the open bay in cyclopoids, *Daphnia*, and *Diaphanosoma* while not of *Diaptomus*, *Bosmina* and *Holopedium* are not clear; however, competition and predation interactions may be involved. The cyclopoids prey mainly upon large diatoms (such as *Rhizosolenia*) and detritus. *Daphnia* and *Diaphanosoma*, which are rather large herbivorous cladocerans, can consume larger diatoms than can either *Bosmina* or *Holopedium*. Large diatoms are more abundant in the west arm than in the open bay. Stoermer and Yang (1969) have also noted that very small diatoms are dominant in offshore Lake Michigan. An inner bay versus outer bay difference much like an inshore versus offshore difference in phytoplankton may be passed up the food chain. Alternatively planktonivorous fish may be more common in the open bay and tend to select large cladocerans over small cladocerans or copepods and cyclopoids over calanoids (Brooks 1969).

The predatory zooplankton are more uniformly distributed among different regions of Grand Traverse Bay. These genera are probably not limited in growth by the availability of prey, i.e. crustacean zooplankton. They either graze upon organisms not collected in the study (e.g. nauplii and rotifers; Cummins et al. 1969) or are themselves limited by predation due to alewives (Wells 1970), deepwater coregonids (Dryer & Beil 1968, Wells and Beeton 1963), and smelt (Price 1963).

Thus, it appears that high nutrient input to the west arm of the bay, exchange of these waters with the open bay, and nutrient depleted east arm waters affect the horizontal distribution of all herbivorous zooplankton. *Daphnia*, *Diaphanosoma*, cyclopoids and chydorids are particularly high in the west arm, probably because there is more food available in this region than can be utilized by the other herbivorous zooplankton. Input of tychoplanktonic crustaceans by the Elk and Boardman Rivers in the fall seems to be the only other major factor influencing horizontal distribution patterns.

Temporal Distribution

Results

The seasonal succession of the ten major zooplankton groups found in the west arm of the bay is shown in Figures XIV-2 through XIV-11. Data for the other regions are less extensive and are therefore not plotted. The populations of herbivorous copepods (*Diaptomus* and the cyclopoids) reach a peak in late June or early July and slowly decline. A smaller secondary peak may occur in October (see Figures XIV-4 and XIV-3). The cladoceran herbivorous zooplankters, *Daphnia* and *Bosmina*, also peak early in the year (see Figures XIV-4 and XIV-5.) *Bosmina* also seems to develop a second peak. The maximum seasonal abudance of *Diaphanosoma* and *Holopedium* (also herbivorous forms) occurs in late September or October with no tendency for secondary peaks (see Figures XIV-6 and XIV-7). The predators *Leptodora* and *Limnocalanus* reach a maximum population in late September or early October (see Figures XIV-8 and XIV-9). The overall abundance of chydorids in Grand Traverse Bay is extremely low and the seasonal patterns of change are erratic and irregular (see Figure XIV-10). The seasonal succession of the predatory rotifer, *Asplanchna*, is shown in Figure XIV-11. This organism appears to peak once early in the year (June) and perhaps again in August or September.

With the exception of station 13, the Elk River plume, the general seasonal patterns of zooplankton in other regions of Grand Traverse Bay are similar to those in the west arm shown in Figures XIV-2 through XIV-11. At station 13 the peak populations are larger and/or seem to occur later in the year for organisms such as *Diaptomus*, *Cyclops*, *Bosmina*, *Daphnia*, *Holopedium*, *Limnocalanus*, *Diaphanosma*, and the chydorids.

A major concern in Grand Traverse Bay is eutrophication due to increased loadings of domestic and agricultural wastes. Therefore comparisons were made regarding long-term changes in zooplankton numbers (seasonally) over the three years sampled. The west arm of the bay was sampled in 1971, 1972, and 1973 and provided sufficient data for the analysis. Four statistically significant year-to-year differences were found. *Diatomus* was more abundant in 1972 and 1973 then in 1971 (.75 significance). *Bosmina*, *Leptodora*, and *Limnocalanus* were all more abundant in 1973 than in 1971 or 1972 (.90, .90, and .75 significance, respectively).

Discussion of Seasonal Cycles

Understanding the seasonal cycles among the zooplankton is complicated by complex life cycles, competition for available food, and losses by predation. As a result, simple explanations of the seasonal patterns of the zooplankton are not available. Mathematical modeling has been used to provide a framework for understanding these phenomena with some success by Canale et al. (1975) and McNaught and Scavia (1967). Occasionally it is relatively simple to associate responses to perturbations. Increased fall concentrations of *Diaptomus*, *Holopedium*, *Limnolcalanus*, *Diaphanosoma*, and the chydorids in the Elk River plume are apparently due to inputs of nutrients and zooplankters from Elk Lake and Torch Lake through the Elk River. High inputs of nutrients in the fall may be the result of such factors as terrestrial leaf fall, decaying macrophytes, and fall turnover in these lakes. The addition of such nutrients may stimulate primary and

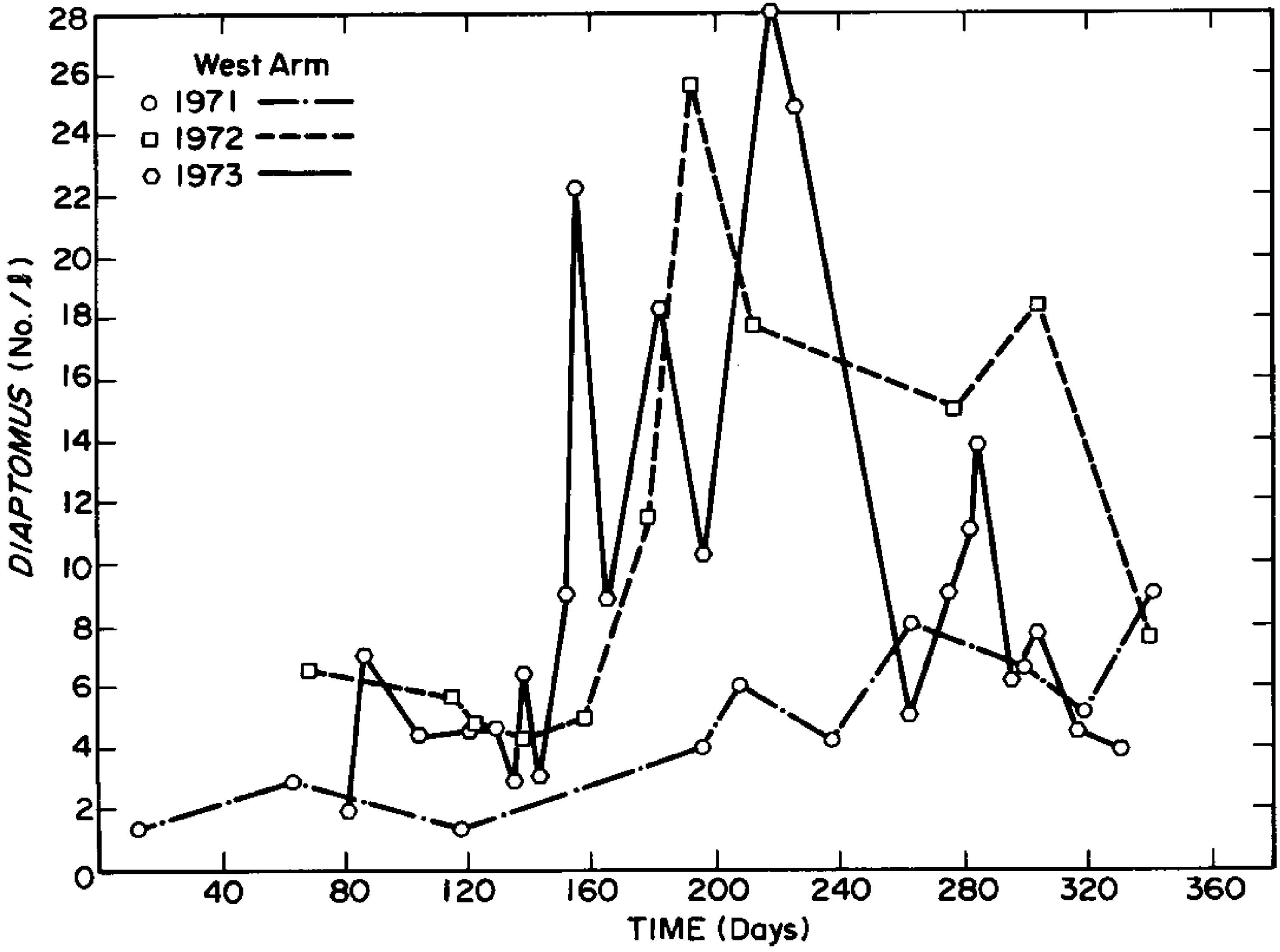


FIGURE XIV-2. Concentration of *Diaptomus* in Grand Traverse Bay 1971-1973.

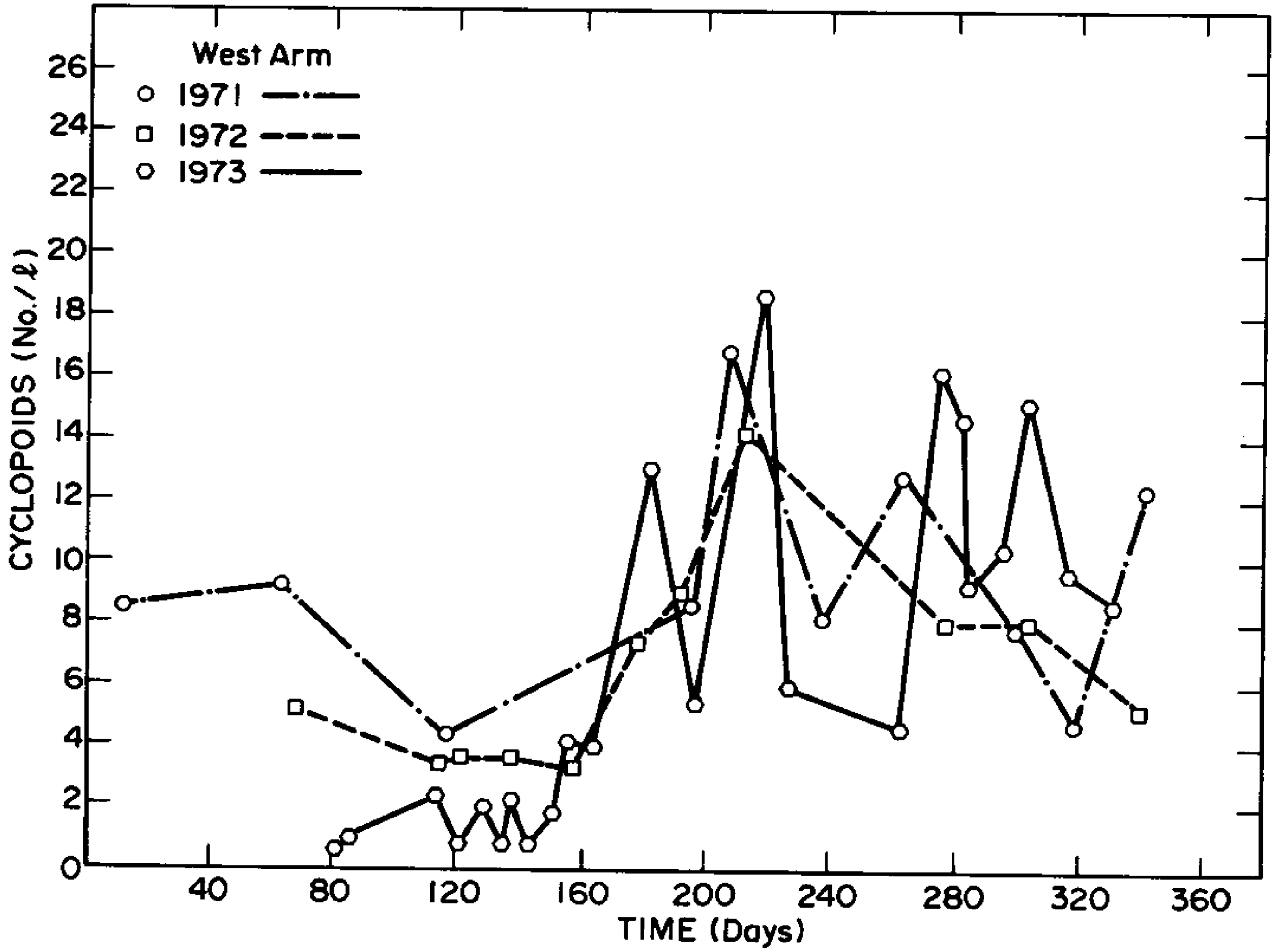


FIGURE XIV-3. Concentration of Cyclopoids in Grand Traverse Bay 1971-1973.

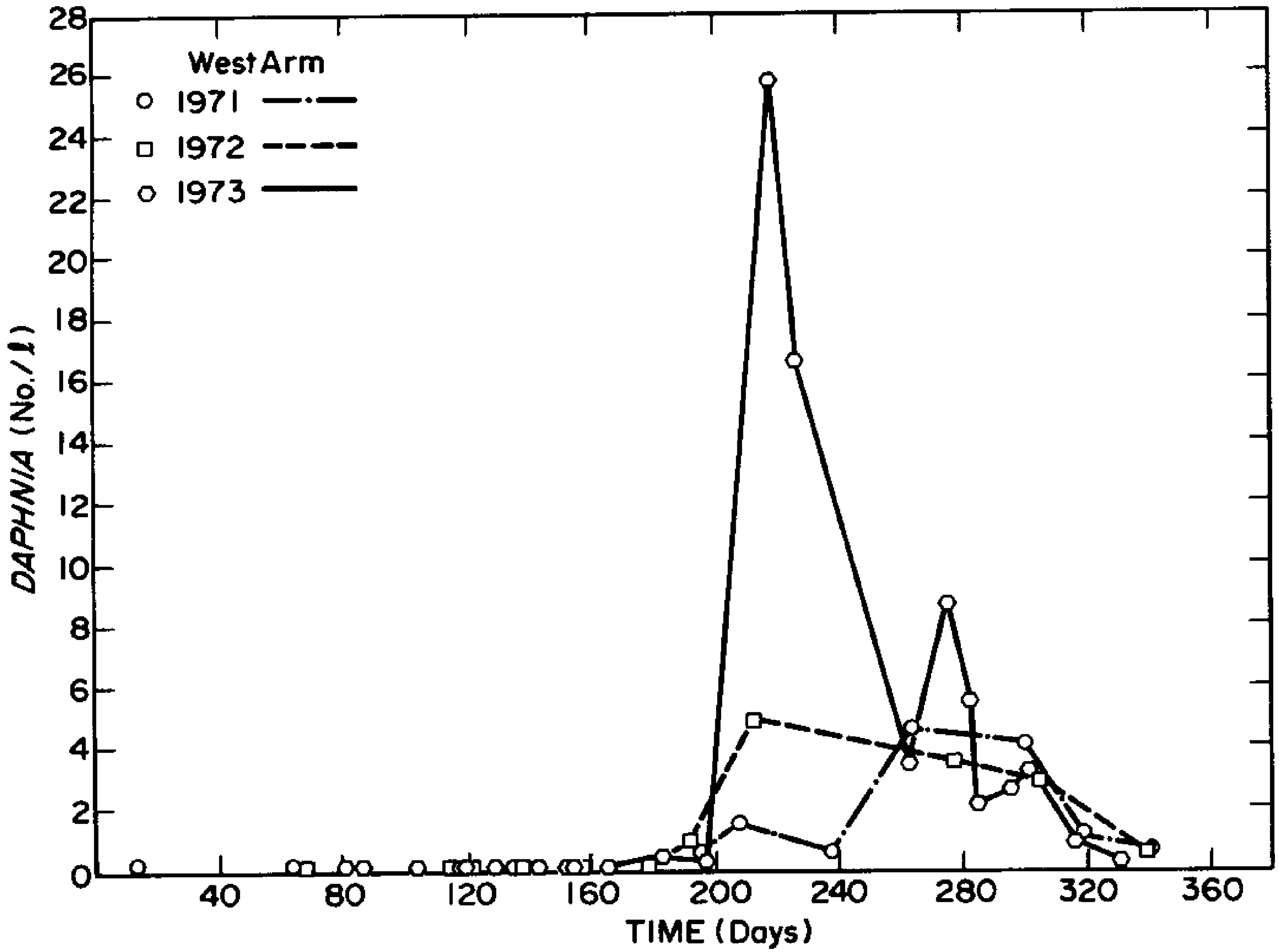


FIGURE XIV-4. Concentration of *Daphnia* in Grand Traverse Bay 1971-1973.

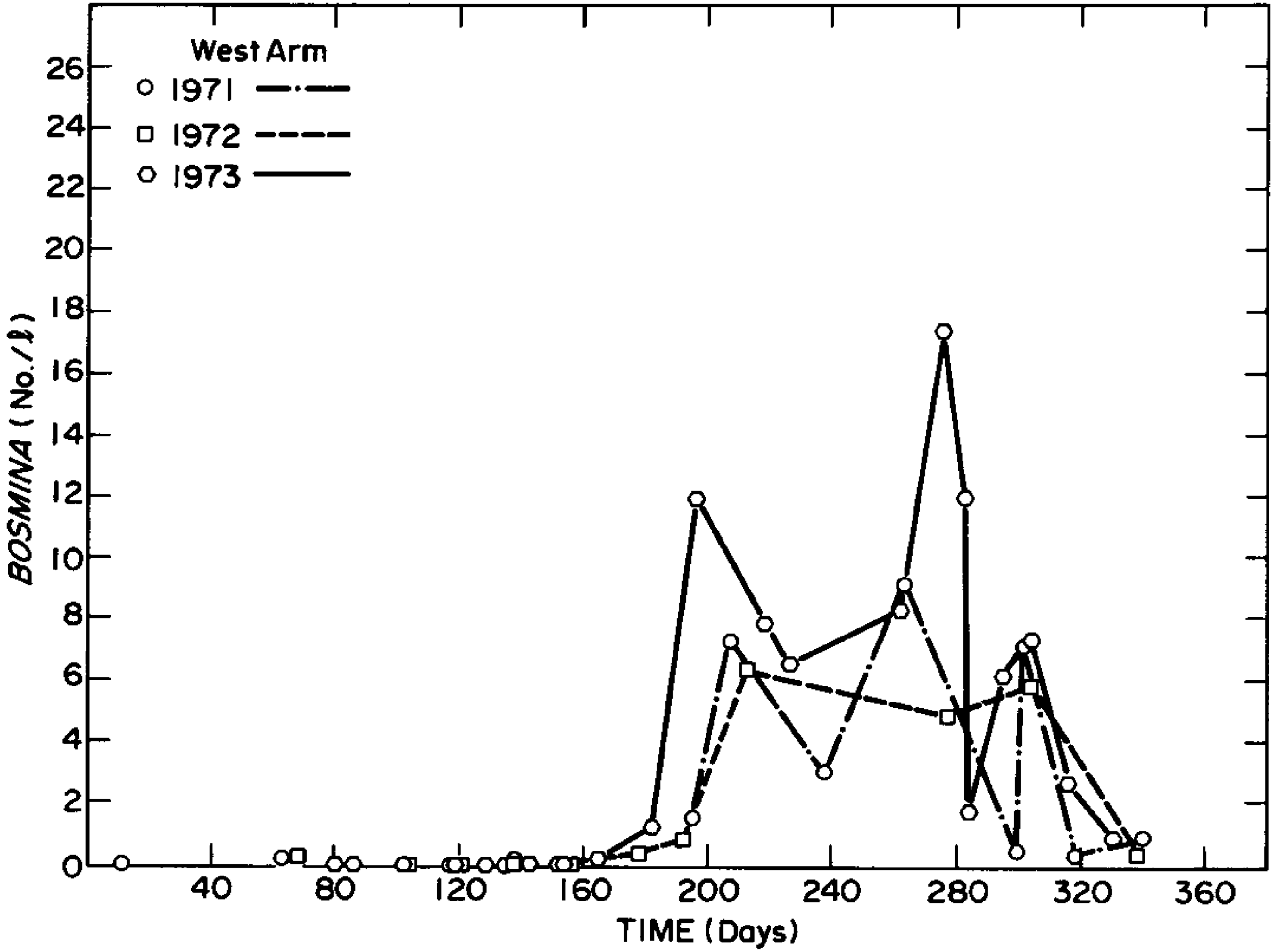


FIGURE XIV-5. Concentration of *Bosmina* in Grand Traverse Bay 1971-1973.

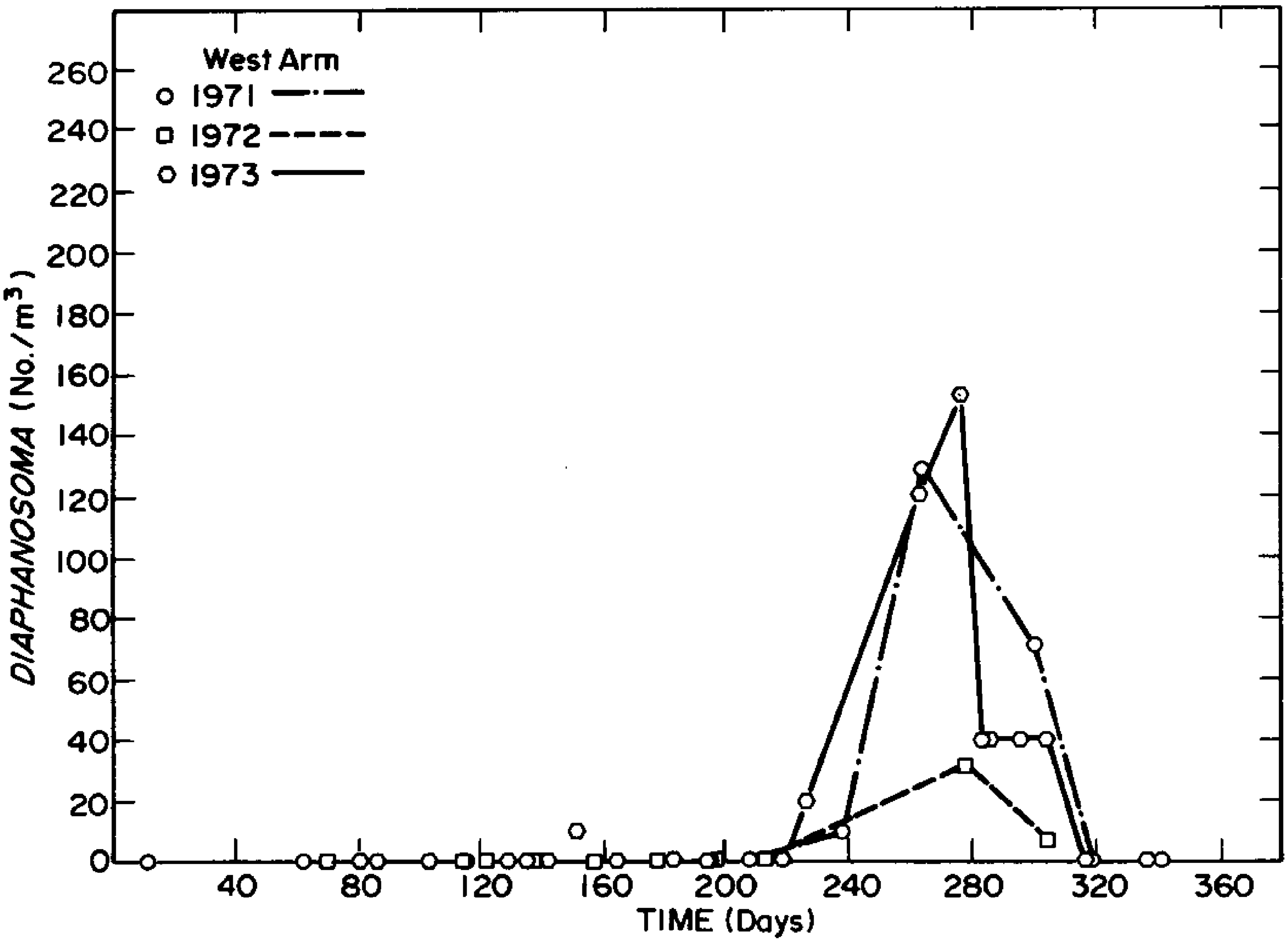


FIGURE XIV-6. Concentration of *Diaphanosoma* in Grand Traverse Bay 1971-1973.

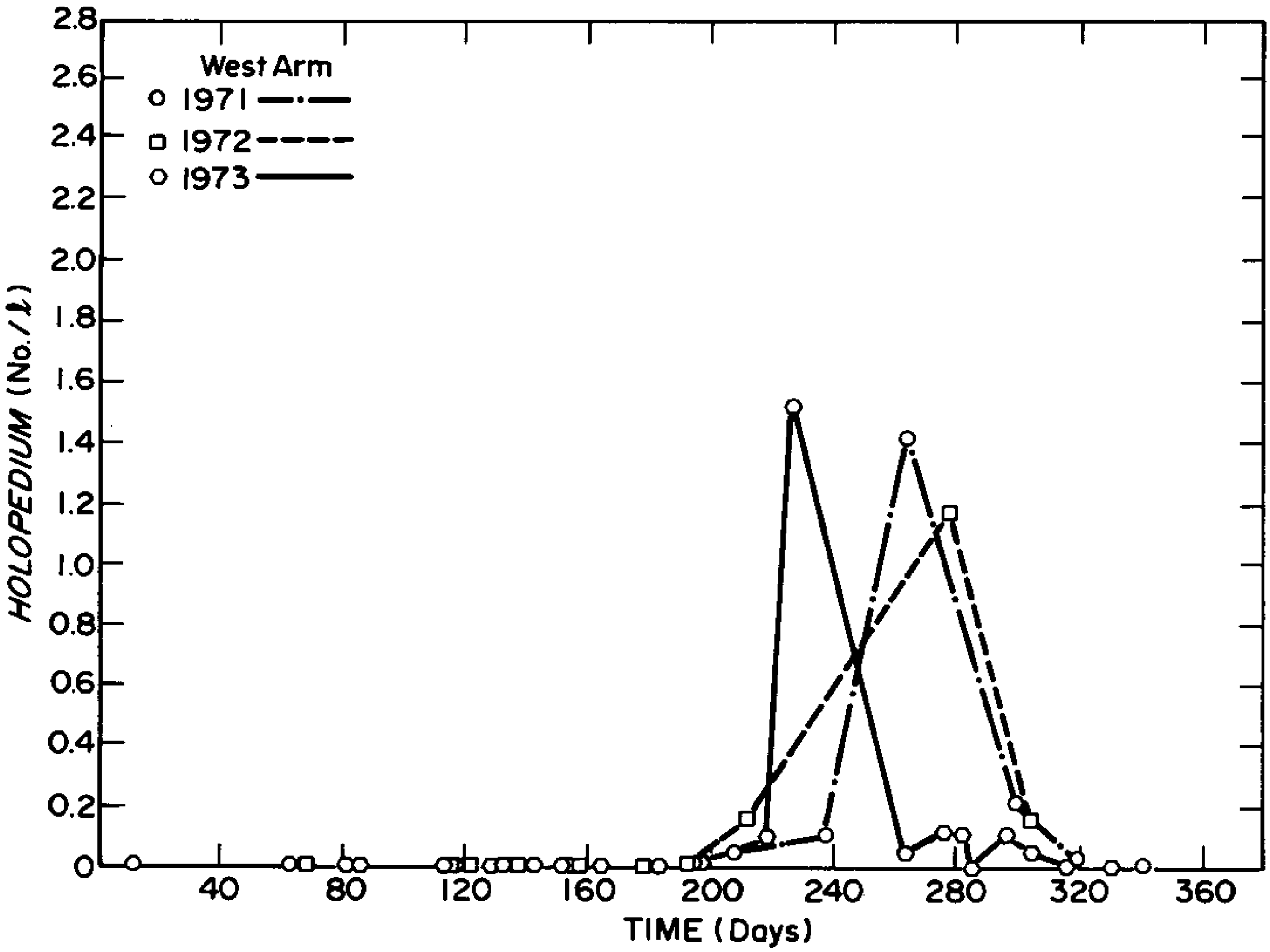


FIGURE XIV-7. Concentration of *Holopedium* in Grand Traverse Bay 1971-1973.

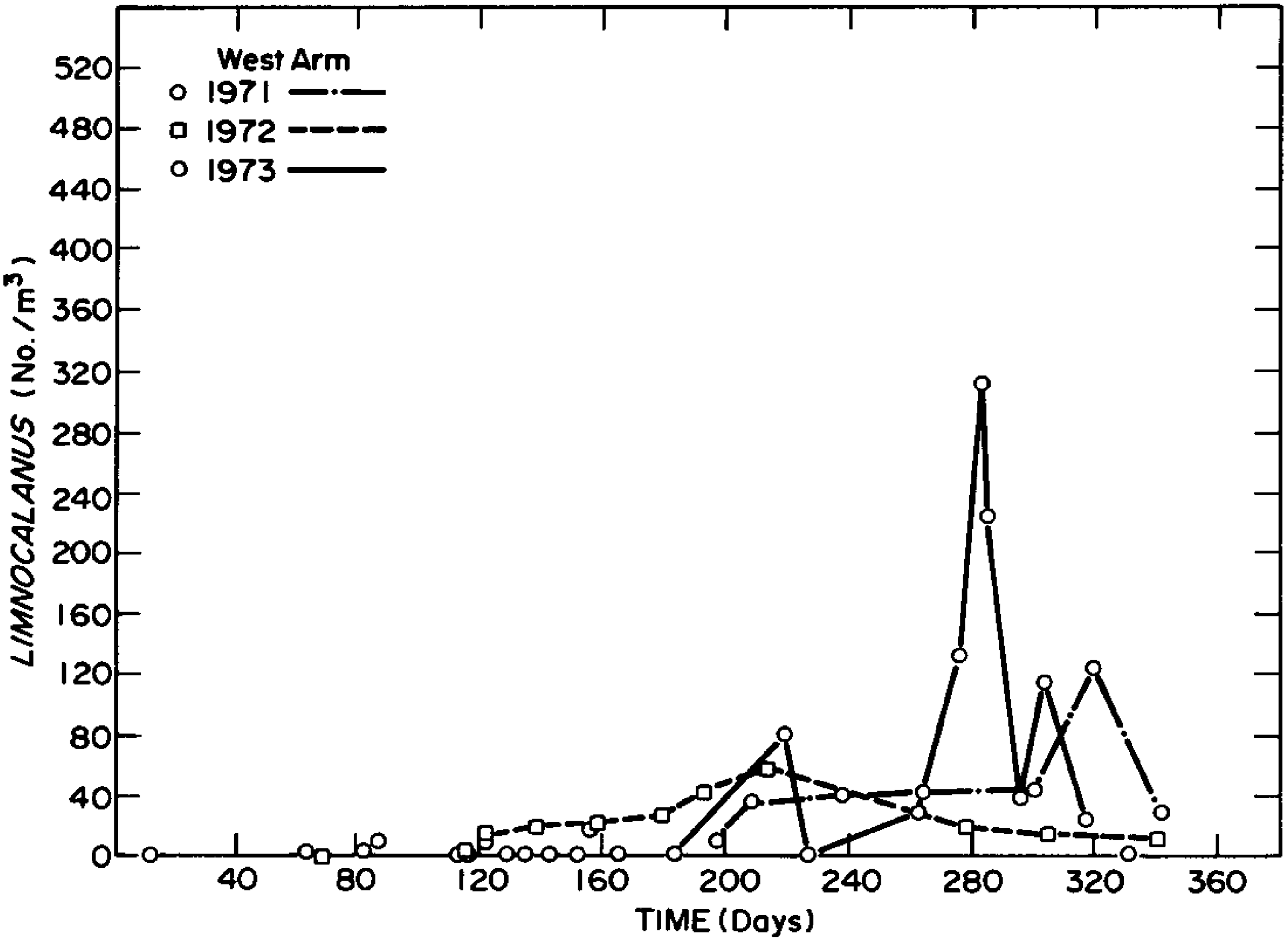


FIGURE XIV-8. Concentration of *Limnocalanus* in Grand Traverse Bay 1971-1973.

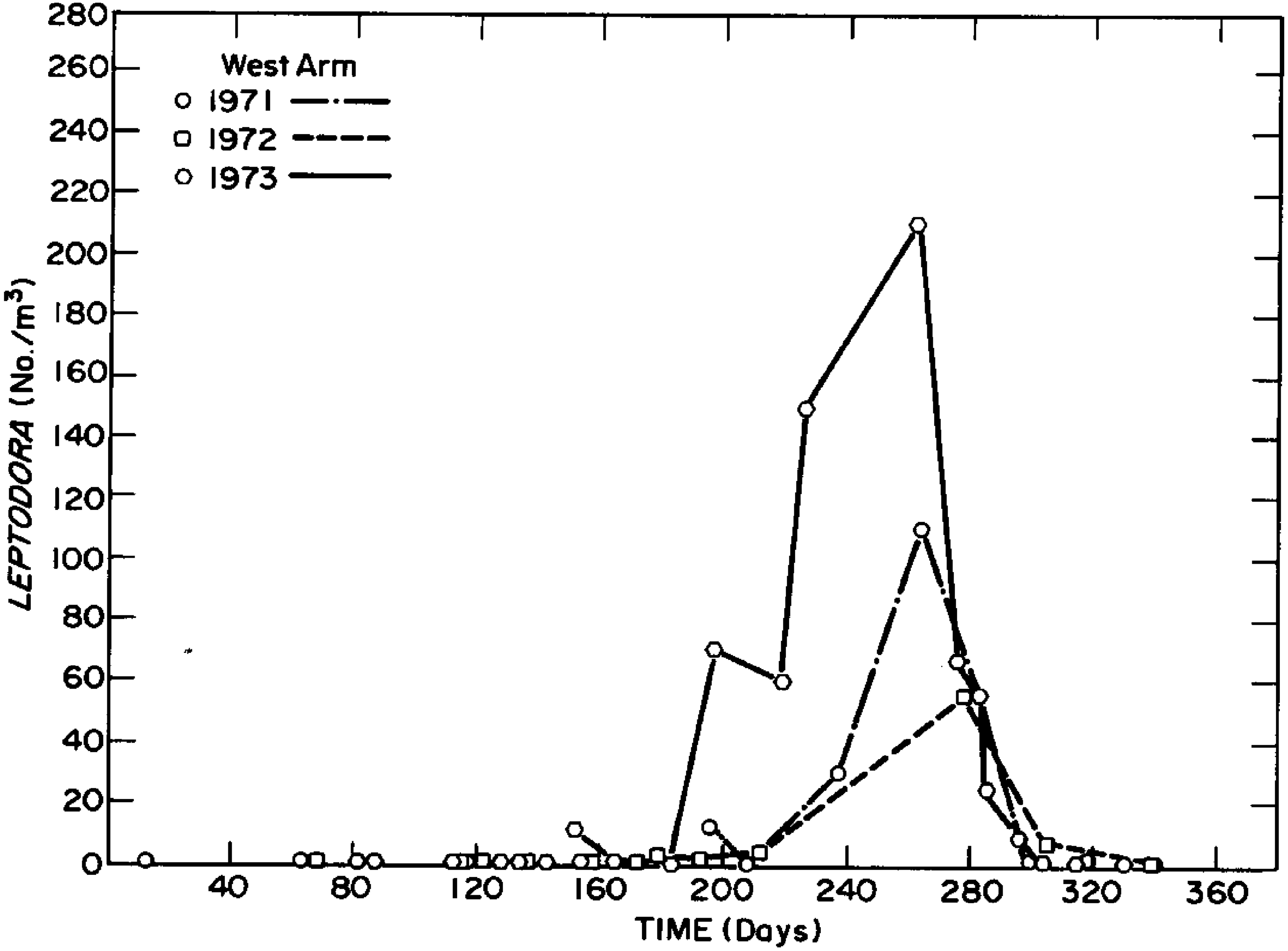


FIGURE XIV-9. Concentration of *Leptodora* in Grand Traverse Bay 1971-1973.

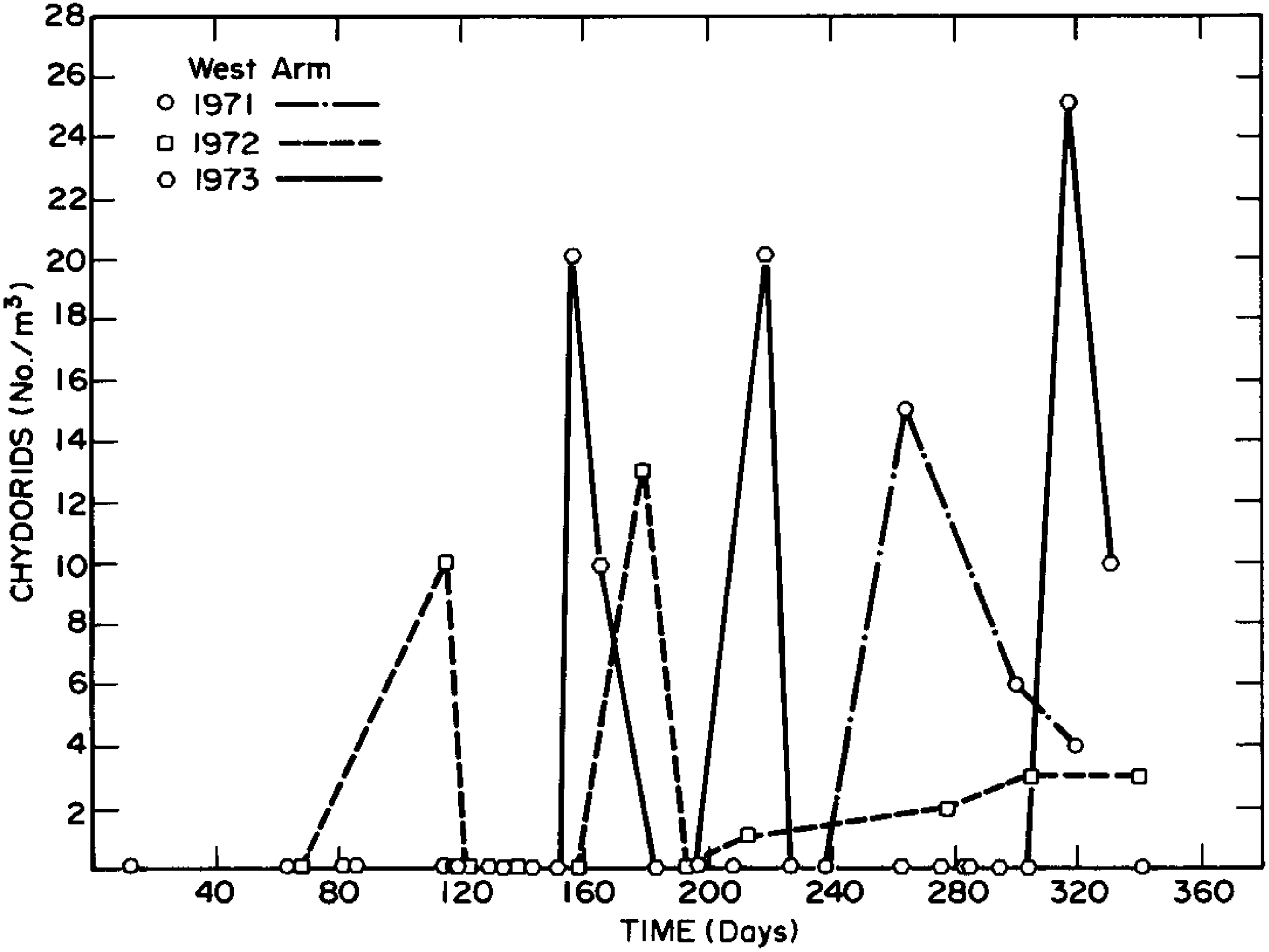


FIGURE XIV-10. Concentration of Chydorids in Grand Traverse Bay 1971-1973.

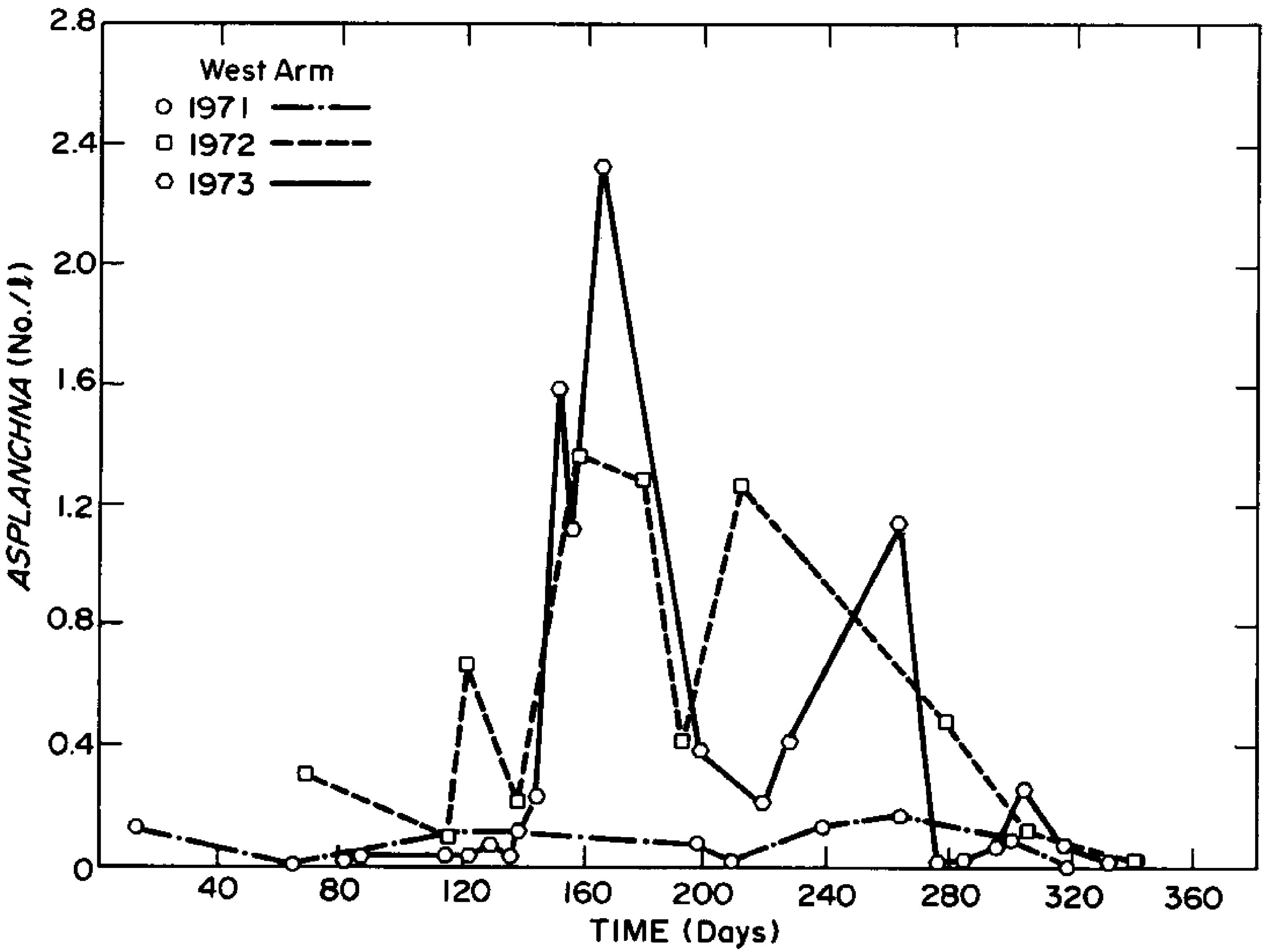


FIGURE XIV-11. Concentration of *Asplanchna* in Grand Traverse Bay 1971-1973.

zooplankton productivity.

Eutrophication, as evidenced by increased zooplankton standing stocks, has probably not advanced at a detectable rate in Grand Traverse Bay during this study. However, caution must be applied to this conclusion. Canale et al. (1975) suggest that the effects of increased eutrophication due to the addition of phosphorus can be transferred up the food chain and are reflected in higher standing stocks at the top levels. Furthermore when nutrients were increased in the modeling simulations, there were only moderate responses by the herbivorous zooplankton. In both simulations by the model and studies in southeastern Lake Michigan (Johnson 1972, Roth and Stewart 1973), it was shown that the combination of increased nutrients and increased alewife predation greatly increased *Bosmina* and decreased other zooplankton. Because alewife numbers are not known for the bay (nor are numbers for those of any other planktonivorous fish populations), relative changes in zooplankton composition provide only a tentative means to assess the impact of increased nutrient input on the west arm.

In summary, an analysis of zooplankton data suggests only minor enrichment of the west arm of Grand Traverse Bay. However, zooplankton data alone are incomplete and inconclusive. For a comprehensive understanding of the limnology of the bay zooplankton abundance and composition must be interpreted in light of data which define nutrient and phytoplankton conditions in the bay.

Comparison with Previous Lake Michigan Zooplankton Studies

Grand Traverse Bay zooplankton data should most appropriately be compared with either equivalent regions of the lake or with the entire lake. Green Bay should not be included in such comparisions because it has a different hydrographic regime (Beeton 1969), different predominant phytoplankton (Stoermer and Yang 1969), fish (Beeton 1969), and zooplankton (Gannon 1974). Green Bay contains some crustacean zooplankton species otherwise limited to Lake Erie and Saginaw Bay (Gannon 1974).

Crustacean Zooplankton

The maximum abundance of crustacean zooplankton in Grand Traverse Bay is about 85 organisms/ℓ. Roth and Stewart (1973) and Johnson (1972) found average concentrations of about 250 organisms in southeastern Lake Michigan waters. Large populations of *Bosmina longirostris* in the southeastern part of the lake are primarily responsible for the difference. This species varies between 50 organisms/ℓ, offshore, and 180/ℓ, inshore (Roth and Stewart 1973, Johnson 1971).

Wells (1970) reported total zooplankton concentrations of about 3 organisms/ℓ off Grand Haven and Frankfort as sampled with #2 nets using horizontal tows. These nets are much coarser than nets used in Grand Traverse Bay. As a result low collection efficiencies are expected, especially for the smaller cladocerans such as *Bosmina* and *Ceriodaphnia* and copepods such as *Diaptomus*. The composition of the larger zooplankters reported by Wells (1970) was similar to results of this study.

Gannon (1975) used a #25 mesh net during sampling of a transect between Milwaukee and Ludington with vertical tows. Samples were taken six times between March, 1969 and January, 1970, and represent the closest comparable data collection system to this study. The open lake samples were close to Grand Traverse Bay in terms of composition of major taxonomic groups (44.4% cyclopoids in Lake Michigan versus 34.4% in Grand Traverse Bay; 54.4% calanoids versus 42.0% in Grand Traverse Bay; 10.2% cladocerans in Lake Michigan versus 23.4% in Grand Traverse Bay). The species composition of offshore Lake Michigan and Grand Traverse Bay samples was also similar. On the other hand calanoid copepods became rare and cladocerans increased sharply in the more productive waters near Milwaukee and Ludington.

Patterns of seasonal succession in Grand Traverse Bay and southeastern Lake Michigan are similar, although *Bosmina* appears in significant numbers about one month earlier in the southeastern part of the lake. This is apparently due to warmer water and higher phytoplankton concentrations. Seasonal patterns in Grand Traverse Bay in terms of annual succession and the timing and abundance of peaks were similar to the results reported by Gannon (1975) and Wells (1970).

In summary, the crustacean zooplankton in Grand Traverse Bay resemble offshore Lake Michigan in terms of composition, seasonal succession, and abundance. Inshore communities in the rest of the lake have higher concentrations of *Bosmina*, a pattern which was not observed in Grand Traverse Bay.

Rotifers

Rotifers in Grand Traverse Bay have been very poorly surveyed in this study. Ahlstrom (1936) and Stemberger (1974) have conducted rotifer studies which included open Lake Michigan samples. Ahlstrom (1936) commonly encountered *Gastropus stylifer* which was rarely observed in this study and was uncommon in the Stemberger (1974) investigations. *Keratella, Synchaeta, Polyarthra, Conochilus,* and *Asplanchna* were also commonly found by Ahlstrom (1936). Stemberger (1974) found 5 genera common with Ahlstrom (1936): *Polyarthra, Keratella, Notholca, Synchaeta,* and *Conochilus*. *Asplanchna, Kellicottia, Keratella, Polyarthra, Synchaeta, Brachionus* and *Filinia* were encountered routinely in this study. The most important differences between the rotifer community offshore of Milwaukee and the one in Grand Traverse Bay is the absence of *Conochilus* from Grand Traverse Bay (probably due to sampling or identification problems) and higher relative abundance of *Kellicottia* in Grand Traverse Bay. This later genus is abundant in inshore waters of western Lake Michigan in July and August but is nearly absent offshore (Stemberger 1974). This difference may be the result of higher plankton productivity rates in the lower west arm of Grand Traverse Bay. *Asplanchna* numbers found during this study are similar to results of Stemberger (1974).

In summary it may be noted that low to moderate levels of zooplankton productivity were noted in Grand Traverse Bay. These levels of secondary productivity, however, appear to be sufficient to support the bay's fishery at present and in the future. Although some signs of elevated productivity were noted in the west arm, as compared to the remainder of the bay, no significant pollution was detected.

XV. BENTHIC FAUNA

Introduction

Aquatic invertebrates have relatively long life cycles and a somewhat immobile nature and thus are probably the best biological monitors of water quality presently available. Kolkwitz and Marrson (1909) took advantage of these traits and categorized reaches of rivers with relation to pollution by organic material. This saprobic system, as it became known, has been widely accepted in continental Europe for assessing water pollution, but has not been so readily accepted in the United States or in Great Britain. Probably the major disadvantages of the saprobic system are that it is very tedious, is very difficult to use, and only applies to an organically polluted river situation. A whole series of less complex indices of pollution have since been developed, which are being employed to some degree of success in the water pollution area (Wilber 1969).

Even though we live in an era of complex technology, many seemingly simple problems remain to be solved. Among these is the need for a widely applicable method to analyze the response of benthic organisms to various perturbations. In order to understand the aquatic invertebrate community the following areas need to be examined: sampling methodologies for both lentic and lotic environments, the organisms' life histories and taxonomies, and ecological relationships among the macroinvertebrate community and those communities occupying the lower, the same, and higher trophic levels.

The categorization of organisms by response to pollution has been more successfully attempted in rivers than in lakes, possibly because of earlier concern over lotic conditions. On the other hand, the benthic fauna in North American lake studies received less interest than the phytoplankton and zooplankton communities. With the increasing concern regarding eutrophication of our lakes, members of the lentic community are being sampled, analyzed, identified and modeled to gain greater insight into the intricate ecological relationships that exist in aquatic habitats. It is from these types of studies that some general trends of ecological succession of the benthic fauna can be observed as the waters become more enriched.

The macroinvertebrates of the profundal area belong to four major groups, three of which (Oligochaeta, Chironomidae, and Sphaeriidae) have been summarized by Brinkhurst et al. (1968); while the other group (Amphipoda, scuds) are well documented in terms of taxonomy, abundance, and distribution by Bousfield (1958) and Holsinger (1972). The littoral areas, which are characterized by highly variable conditions, as compared to the profundal area, have a richer diversity of macroinvertebrates.

Oligochaete fauna (segmented worms) tend to increase in number and shift towards tubificid communities with increase in productivity. In addition, a decrease of the sphaeriid population and elimination of mayflies (*Hexagenia*, Ephemeroptera) was shown by Schneider et al. (1969). The midge population (Chironomidae, Diptera) tends to increase in the numbers of organisms that are able to withstand lower dissolved oxygen values such as *Chironomus plumosus* and *C. anthracinus*.

The benthic community of Grand Traverse Bay was sampled between 1970 and 1975 by the Michigan Sea Grant Program. The objective of this study was to obtain an inventory of the existing population of benthic invertebrates and determine how they relate to communities that occupy similar aquatic habitats, i.e. Lake Michigan. Initially, identification was only to broad taxonomic groups, however this was dramatically improved during the last year of study.

This discussion is based on comparisons of seasonal and yearly variations of the indigenous benthos population of Grand Traverse Bay. In addition, the 1975 data are compared with benthos that have been collected from other aquatic habitats.

Results and Discussion

To predict biological productivity, (primary productivity) a series of sampling stations were established in the east and west arms and the open bay (Figure XV-1). In conjunction with collecting physical, chemical, and additional biological information, replicate PONAR samples were collected from designated stations for benthos evaluation. Samples were taken during July, August and October 1970; April, June, July, August, September and October 1971; May, July, October and November 1972; May and June 1973; and May of 1975. The stations from which benthos were collected are scattered fairly well throughout the bay and include a wide variety of depths and substrates.

Grand Traverse Bay was divided into five zones for the purpose of comparing these benthic macroinvertebrate data. Justification of the partitioning was based on the physical nature of the bay, its depth, and the potential effects of man's activity.

The data collected in this study from 1970 through 1974 are summarized in Tables XV-1 and XV-2, while the macroinvertebrate data for 1975 are presented in Table XV-3. As mentioned in the earlier section, comparisons of sampling stations will be discussed in broad terms for each zone due to the insufficient breakdown of taxonomic groups. In addition, data collected from several cruises for the same station during the same year were combined for summary purposes. The existing data do not lend themselves to seasonal comparisons for each year and from year to year due to the irregular timing of collection.

Zone I (Lake Michigan) may be characterized as typical Great Lakes water in that the major portion of the profundal community is composed of *Pontoporeia affinis* (Amphipoda), while the oligochaetes (segmented worms), pelecypods (bivalve mollusks, clams), and midges make up in order the remaining fraction. The data from these stations (#31, #144, #145) are comparable in terms of taxa and numbers. The number of organisms per square meter ranged from 1736 to 8636. The data are insufficient to discuss alterations in the community over time. There appears to be an increase in total numbers through 1973 at all three stations; whereas, a decrease of numbers at station #31 was observed in 1975. No samples were collected from stations #144 and #145 during 1975 to support the trend of reduction of numbers at station #31.

The open bay (Zone II) contains four sampling stations. The data are comparable from stations #9, #10, and #11, but not at #12 which is located in shallower water. This is reflected by the low concentration of total organisms, *Pontoporeia affinis*, and the relatively large percentage of midges (Chironomidae, Diptera) and snails (Gastropoda) at this station. The other stations in the open bay are dominated by *P. affinis*, which is followed in order of decreasing percentage by oligochaetes, pelecypods and midges. Concentrations of organisms range from 593 to 5226 per square meter. No specific patterns can be observed from these data, except possibly the absence of pelecypods from stations #9 and #11 for 1973 and 1975.

The east arm of Grand Traverse Bay (Zone III) contains stations #6, #7, #8, and #13. Stations #6 and #13 are comparable in that the major group of the community is the midges, followed by the oligochaetes, amphipods, gastropods (univalve mollusks, snails), and pelecypods. Also, the total number of organisms per square meter is lower at stations #6 and #13 than that of the other two stations. Differences between the two stations (#6 and #13) do exist in terms of numbers and the relatively large increase of the oligochaetes and midges at station #13 from 1972 to 1975. Stations #7 and #8, on the other hand, are deep water stations and their main profundal member is *P. affinis*, followed by oligochaetes, *Mysis relicta* (Decapoda), pelecypods and midges. One trend that appears over the years for all stations in this zone is the decrease in the complete absence of pelecypods and gastropods by the year 1975.

Zone IV comprises the west arm of the bay and contains stations #2, #3, #4, #5, #59, and #87. The first four stations are morphologically comparable in that they are located in 60 meters or more of water. *P. affinis* is the dominant member of the population at these stations. Although somewhat variable from year to year, oligochaetes, midges and pelecypods make up the remaining fraction. The shallow water stations, #59 and #87, are dominated by midges. Oligochaetes and amphipods were also abundant. Both these stations are located in areas where deposition of material is enhanced due to currents. A general trend that applied to all stations within this zone is that there appears to be a decrease in numbers of oligochaetes from 1970 to 1975.

The portion of the lower west arm (Zone V) receiving the greatest influence by the Boardman River actually contained only two sampled stations, #88 and #89. Each of these was different in terms of species composition and relative numbers. Although station #89 is deeper (20 meters) than #88 (7 meters), the community is the opposite of what one would expect. The shallow water station (#88) contains a higher percentage of amphipods (40%) than station #89 (1%). In addition, the midge and oligochaete populations comprise the major percentage at #89. Station #88, besides its abundant amphipod population, has oligochaetes, isopods, and midges in that order of concentration. Station #1, for which benthos data exists for all the dates of collection, shows a decline

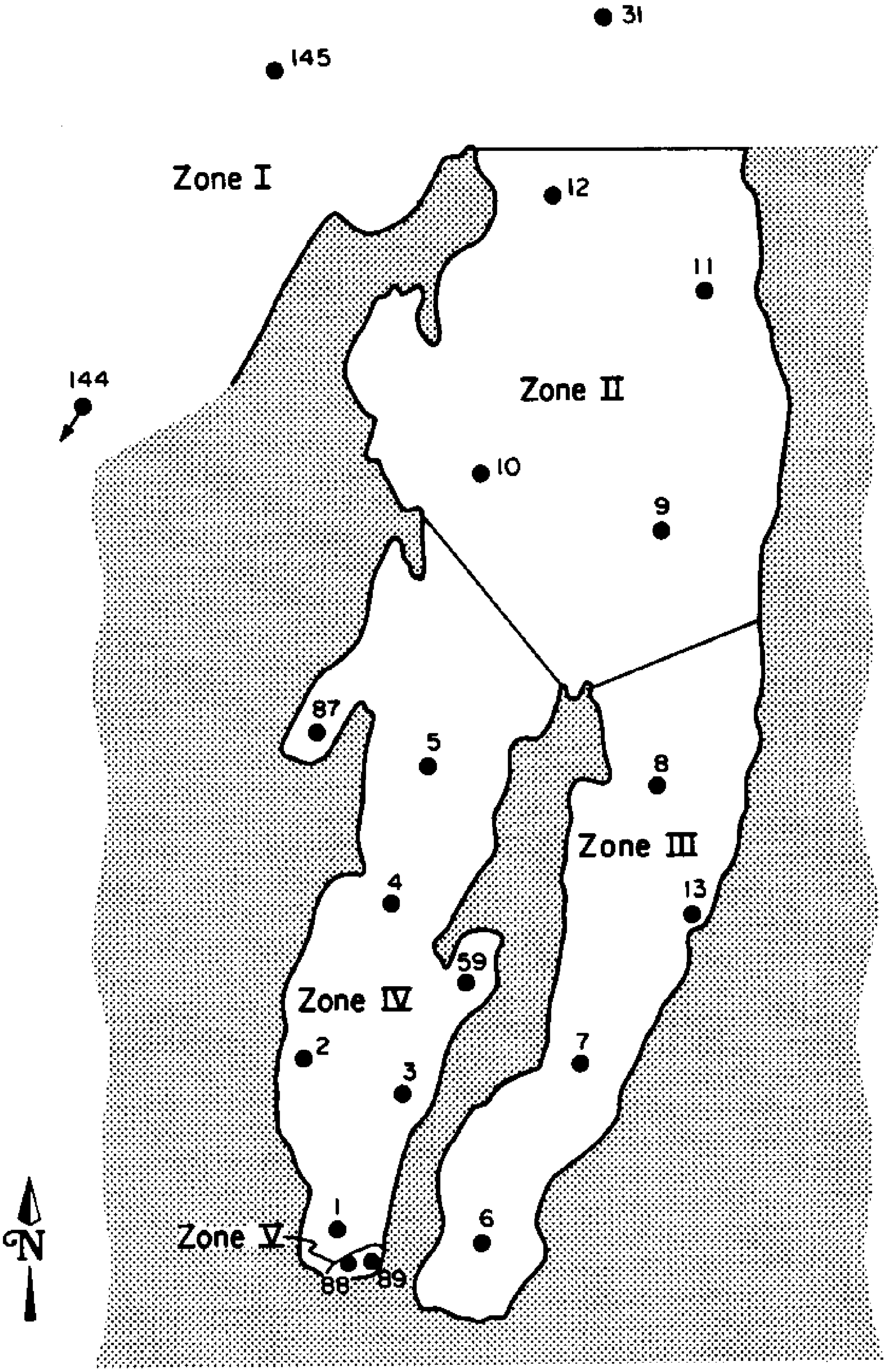


FIGURE XV-1. Benthos sampling station locations in Grand Traverse Bay.

TABLE XV-1. Benthos composition of Grand Traverse Bay from 1970-1975 expressed in organisms/meter^2

Zone I (Lake Michigan)

	Oligo	Gastro	Pelecy	Cope	Deca	Iso	Amp	Dip	Ephem	Tricho	Ostra	Nema	TOTAL
Station #31 Depth 112M													
1970	0	21-1%	0	0	21-1%	0	1694-98%	0	0	0	0	0	1736
1971	155-5%	0	201-6%	201-6%	26-<1%	0	2681-82%	5-<1%	0	0	0	0	3269
1972	759-20%	*	*	15-<1%	31-<1%	0	3026-78%	41-1%	0	0	0	0	3872
1973	1031-23%	*	*	21-<1%	*	0	3349-74%	124-3%	0	0	0	0	4524
1975	529-18%	0	0	0	19-<1%	*	2278-79%	57-2%	0	0	0	0	2883
Station #144 Depth 91M													
1970	*	*	*	*	*	*	*	*	*	*	*	*	---
1971	795-18%	*	309-7%	31-<1%	52-1%	*	3347-74%	*	*	*	*	*	4534
1972	875-18%	*	558-12%	41-<1%	73-2%	*	3158-66%	36-<1%	*	*	21-<1%	*	4762
1973	2865-33%	*	21-<1%	10-<1%	103-1%	*	5513-64%	124-1%	*	*	*	*	8636
Station #145 Depth 93M													
1971	31-2%	0	52-3%	83-5%	0	0	1570-90%	10-<1%	0	0	0	0	1746
1972	685-16%	*	320-7%	124-3%	34-<1%	*	2968-69%	52-1%	*	*	124-3%	21-<1%	4328
1973	629-16%	*	10-<1%	*	31-<1%	*	3123-78%	186-5%	*	*	*	*	3979

Key: Amph - Amphipoda (Primarily <u>Pontoporeia affinis</u>)

Cope-Copepoda
Deca-Decapoda
Dip-Diptera
Ephem-Ephemeroptera
Gastro-Gastropoda
Iso-Isopoda

Nema-Nematoda
Oligo-Oligochaeta
Ostra-Ostracoda
Pelecy-Pelecypoda
Tricho-Trichoptera

*-No Data

TABLE XV-1. Benthos composition of Grand Traverse Bay from 1970-1975 expressed in organisms/meter^2

Zone II (Open Bay)

	Oligo	Gastro	Pelecy	Cope	Deca	Iso	Amp	Dip	Ephem	Tricho	Ostra	Nema	TOTAL
Station #9 Depth 61.5 M													
1970	112-6%	0	145-8%	0	31-2%	10-<1%	1606-85%	0	0	0	0	0	1894
1971	210-7%	0	141-5%	114-4%	7-<1%	0	2502-81%	52-2%	0	0	0	48-2%	3074
1972	561-27%	*	175-8%	10-<1%	31-1%	*	1132-54%	144-7%	*	*	*	31-1%	2084
1973	124-4%	*	*	10-<1%	11-<1%	*	2916-89%	186-6%	*	*	*	21-<1%	3268
1975	216-13%	0	0	19-<1%	0	0	2505-79%	227-7%	0	*	0	0	3167
Station #10 Depth 83M													
1970	21-<1%	0	661-18%	0	21-<1%	0	3027-80%	31-1%	0	0	0	0	3761
1971	582-22%	0	196-17%	23-<1%	17-<1%	0	1718-65%	85-3%	0	0	0	19-<1%	2640
1972	754-16%	*	474-10%	21-<1%	41-<1%	*	3087-67%	93-2%	*	*	144-3%	17-<1%	4631
1973	845-16%	*	21-<1%	*	21-<1%	*	4184-80%	155-3%	*	*	*	*	5226
1975	123-16%	0	19-3%	19-3%	0	0	520-69%	76-10%	*	*	*	0	757
Station #11 Depth 41M													
1970	0	0	806-56%	0	21-1%	0	517-36%	83-6%	0	0	0	0	1427
1971	265-7%	0	401-11%	10-<1%	8-<1%	0	2817-77%	146-4%	0	0	0	23-<1%	3670
1972	1349-27%	*	196-4%	31-<1%	10-<1%	*	3133-63%	186-4%	*	*	21-<1%	45-1%	4971
1973	1288-28%	*	*	*	*	*	3081-68%	134-3%	*	*	*	10-<1%	4503
1975	869-36%	*	0	66-3%	0	0	1304-54%	156-7%	0	0	*	0	2395
Station #12 Depth 20M													
1970	134-11%	72-6%	42-4%	0	0	72-6%	155-13%	0	0	0	0	0	1175
1971	67-15%	119-27%	90-21%	8-2%	0	0	38-9%	116-26%	0	0	0	0	438
1972	34-5%	155-22%	278-40%	*	*	21-3%	31-4%	110-16%	*	10-1%	21-3%	31-4%	691
1973	21-23%	*	*	*	*	*	31-33%	41-44%	*	*	*	*	93
1975	170-23%	19-3%	19-3%	19-3%	10-1%	0	100-14%	395-54%	0	0	0	0	732

TABLE XV-1. Benthos composition of Grand Traverse Bay from 1970-1975 expressed in organisms/meter^2

Zone III (East Arm)

	Oligo	Gastro	Pelecy	Cope	Deca	Iso	Amp	Dip	Ephem	Tricho	Ostra	Nema	TOTAL
Station #6 Depth 46M													
1970	52-42%	0	0	0	10-8%	0	62-50%	0	0	0	0	0	124
1971	356-20%	286-16%	88-5%	17-<1%	4-<1%	434-25%	199-11%	355-20%	8-<1%	0	3-<1%	20-1%	1770
1972	119-29%	*	41-10%	10-2%	*	*	83-21%	141-35%	*	*	10-2%	*	404
1973	52-12%	*	*	*	10-2%	*	*	361-86%	*	*	*	*	423
1975	10-4%	0	0	0	10-4%	0	57-25%	152-66%	0	0	0	0	229
Station #7 Depth 175M													
1970	1663-67%	10-<1%	41-2%	0	41-2%	0	733-29%	0	0	0	0	0	2488
1971	582-38%	4-<1%	3-<1%	146-10%	50-3%	0	649-43%	69-5%	6-<1%	0	2-<1%	4-<1%	1515
1972	1136-43%	*	*	52-2%	76-3%	*	1247-47%	26-<1%	*	*	103-4%	10-<1%	2650
1973	824-36%	*	*	*	10-<4%	*	1371-60%	62-3%	*	0	*	10-<1%	2277
1975	2618-35%	0	0	75-1%	29-<1%	29-<1%	4716-63%	28-<1%	0	0	0	0	7495
Station #8 Depth 175M													
1970	0	10-1%	10-1%	0	10-1%	0	878-97%	0	0	0	0	0	908
1971	124-6%	0	108-5%	179-9%	65-3%	0	1478-75%	5-<1%	0	0	0	7-<1%	1966
1972	282-9%	*	103-3%	55-2%	47-1%	*	2665-84%	31-1%	*	*	*	*	3183
1973	866-17%	*	*	*	10-<1%	*	4153-81%	82-2%	*	*	*	21-<1%	5132
1975	520-19%	0	0	19-<1%	66-2%	66-2%	2099-76%	0	*	*	*	0	2770
Station #13 Depth 27M													
1970	10-<1%	992-74%	10-<1%	0	0	21-2%	176-13%	93-7%	31-2%	10-<1%	0	0	1343
1971	96-11%	181-21%	28-3%	5-<1%	3-<1%	2-<1%	53-6%	486-55%	23-3%	0	0	5-<1%	882
1972	113-12%	155-17%	144-16%	*	10-1%	*	31-3%	440-48%	31-3%	*	*	*	924
1975	1173-54%	0	0	0	29-1%	0	10-<1%	954-44%	0	0	0	0	2166

TABLE XV-1. Benthos composition of Grand Traverse Bay from 1970-1975 expressed in organisms/meter^2

Zone IV (West Arm)

	Oligo	Gastro	Pelecy	Cope	Deca	Iso	Amp	Dip	Ephem	Tricho	Ostra	Nema	TOTAL
Station #2 Depth 67M													
1970	134-17%	3-<1%	0	0	17-2%	0	420-54%	176-23%	7-1%	0	0	17-2%	774
1971	142-13%	1-<1%	10-1%	146-13%	13-1%	0	661-59%	140-13%	0	0	0	2-<1%	1115
1972	375-11%	*	124-1%	878-25%	21-1%	10-<1%	1935-56%	76-2%	*	*	36-1%	21-<1%	3476
1973	176-12%	*	*	*	31-2%	*	1229-83%	52-3%	*	*	*	*	1488
1975	6-1%	0	0	0	0	0	895-93%	63-7%	0	0	0	0	964
Station #3 Depth 61M													
1970	176-30%	0	0	0	10-2%	0	362-62%	32-6%	0	0	0	0	580
1971	196-43%	0	0	12-3%	5-1%	0	136-30%	103-22%	2-<1%	0	0	4-1%	458
1972	703-26%	*	134-5%	306-11%	24-1%	*	1271-46%	100-4%	*	*	114-4%	103-4%	2755
1973	341-25%	*	*	0	10-1%	0	888-64%	134-10%	10-1%	*	*	*	1383
1975	32-25%	0	6-5%	0	0	0	76-60%	13-10%	0	0	0	0	127
Station #4 Depth 114M													
1970	279-25%	0	72-6%	0	21-2%	0	744-66%	10-1%	0	0	0	0	1126
1971	250-14%	0	96-5%	239-14%	17-1%	0	1042-59%	119-7%	0	0	0	5-<1%	1750
1972	813-19%	*	398-9%	1296-30%	93-2%	*	1498-35%	93-2%	*	*	134	*	4325
1973	835-25%	*	*	*	10-<1%	*	2401-72%	82-2%	*	*	*	*	3328
1975	441-13%	0	0	0	6-<1%	0	2798-84%	76-2%	0	0	0	0	3321
Station #5 Depth 120M													
1970	455-40%	0	155-14%	0	93-8%	0	248-22%	196-17%	0	0	0	0	1147
1971	165-12%	0	82-6%	389-29%	59-4%	0	420-31%	184-14%	0	3-<1%	0	0	1348
1972	654-14%	*	296-6%	2028-43%	59-1%	*	1508-32%	76-2%	*	*	103-2%	103-2%	4745
1973	1092-21%	*	*	*	21-4%	*	4050-78%	31-<1%	*	*	*	*	5194
1975	958-32%	0	0	0	151-5%	38-1%	1733-57%	145-5%	0	0	0	0	3025
Station #59 Depth 26M													
1970	517-51%	0	21-2%	0	0	0	145-14%	331-33%	0		0	0	1014
1975	277-29%	0	0	0	0	0	25-3%	698-73%	0		0	0	950
Station #87 Depth 15M													
1971	106-17%	3-<1%	52-8%	5-1%	7-1%	0	36-6%	398-65%	5-1%		0	3-<1%	615
1975	0	0	0	6-1%	0	13-1%	44-5%	813-93%	0		0	0	876

TABLE XV-1. Benthos composition of Grand Traverse Bay from 1970-1975 expressed in organisms/meter^2

Zone V (Lower West Arm)

	Oligo	Gastro	Pelecy	Cope	Deca	Iso	Amp	Dip	Ephem	Tricho	Ostra	Nema	TOTAL
Station #1 Depth 29M													
1970	31-16%	0	0	0	0	0	62-32%	103-53%	0	0	0	0	196
1971	110-21%	0	10-2%	3-<1%	2-<1%	2-<1%	136-26%	178-34%	0	0	2-<1%	76-15%	519
1972	305-29%	*	42-4%	31-3%	*	11-1%	129-12%	294-28%	*	*	196-19%	31-3%	1039
1973	83-21%	*	*	*	10-3%	10-3%	62-16%	227-58%	*	*	*	*	392
1975	340-30%	0	0	0	6-<1%	44-4%	57-5%	643-57%	0	0	0	38-3%	1128
Station #88 Depth 7M													
1971	351-23%	77-5%	54-3%	21-1%	0	225-14%	614-40%	196-13%	10-<1%	0	0	7-<1%	1555
Station #89 Depth 20M													
1971	357-38%	15-2%	99-11%	0	0	14-1%	10-1%	363-39%	0	0	62-7%	18-2%	938

TABLE XV-2. Summary of Grand Traverse Bay benthos organisms/meter^2

	Oligo	Gastro	Pelecy	Cope	Deca	Iso	Amp	Dip	Emphem	Tricho	Ostra	Nema	TOTAL
		(shallow water stations, less than 60 meters)											
1970	124-17%	177-24%	133-18%	0	5-<1%	16-2%	186-25%	101-13%	5-<1%	2-<1%	0	0	749
1971	214-14%	419-28%	103-7%	7-<1%	3-<1%	85-6%	488-32%	280-19%	6-<1%	0	8-<1%	19-1%	1502
1972	384-20%	117-6%	140-7%	24-1%	21-1%	16-<1%	844-43%	243-13%	31-2%	10-<1%	76-4%	36-2%	1942
1973	361-22%	*	*	*	10-<1%	10-<1%	1058-65%	191-12%	*	*	*	10-<1%	1640
1975	406-33%	3-<1%	3-<1%	13-1%	8-<1%	8-<1%	228-19%	544-45%	0	0	0	5-<1%	1218
		(deep water stations, greater than 60 meters)											
1970	316-20%	5-<1%	120-7%	0	29-2%	1- 1%	1079-67%	48-3%	1-<1%	0	0	2-<1%	1601
1971	294-14%	1-<1%	107-5%	142-7%	28-1%	0	1471-69%	77-4%	1-<1%	0	0	9-<1%	2130
1972	690-18%	*	280-7%	439-12%	48-1%	5-<1%	2136-56%	70-2%	0	0	78-2%	36-1%	3782
1973	875-22%	*	17-<1%	10-<1%	26-<1%	0	3016-74%	91-2%	5-<1%	*	*	13-<1%	4053
1975	605-22%	0	4-<1%	36-1%	30-1%	17-<1%	1958-72%	76-3%	0	0	0	0	2726

TABLE XV-3. Grand Traverse Bay benthos 12-14 May 1975 organisms/meter^2 using PONAR 529 cm^2

Station - Depth	1 29M			2 87M			3 61M			4 114M		
	A	B	C	A	B	C	A	B	C	A	B	C
Oligochaeta	378	170	473			19		38	59	340	586	396
Nematoda	38	19	58									
Copepoda												
Limnocalanus macrurus												
Senecella calanoides												
Isopoda												
Asellus racovitzai rac.	38	95										
Lirceus lineatus												
Amphipoda												
Hyallela azteca	19											
Pontoporeia affinis	76		76	926	227	1531		95	132	2231	2892	3270
Decapoda												
Mysidaceae												
Mysis relicta	19											19
Pelecypoda												
Sphaeriidae												
Sphaerium sp.				19				19				
Pisidium sp.												
Gastropoda												
Amnicola sp.												
Valvata sp.												
Insecta												
Chironomidae												
Polypedilum sp.												
Paracladopelma sp.												
Trissocladius sp.												
Tanytarsus sp.	359	95	170	19		132					113	
Chironomus riparius	38	132	76									
Chironomus sp.A.	38	246	76						19			
Psectrocladius sp.	246		132									
Psuedodiamesa sp.	19		19							57		
Procladius sp.	19	38							19			
Glyptotendipes sp.												
Heterotrissocladius sp.	38	95	38							19	19	19
Cricotopus sp.		19										
Cryptcchironomus sp.				38								
Stictochironomus sp.												
Orthocladius sp.												
Pentaneura sp.												
Stenochironomus sp.												
Diamesinae	19	19	19									
Orthocladinae												

TABLE XV-3. Grand Traverse Bay benthos 12-14 May 1975 organisms/meter^2 using PONAR 529 cm^2

Station - Depth	5 120M			6 53M		7 175M		8 175M		9 61.5M	
	A	B	C	A	B	A	B	A	B	A	B
Oligochaeta	888	605	1380		19	1002	4234	38	1002	718	113
Nematoda											
Copepoda						38	113		38	38	
Limnocalanus macrurus											
Senecella calanoides											
Isopoda		57	57			38	19		132		
Asellus racovitzai rac.	19		38								
Lirceus lineatus											
Amphipoda											
Hyallela azteca											
Pontoporeia affinis	1909	1796	1493	57	57	4802	4631	1645	2552	2514	2495
Decapoda											
Mysidaceae											
Mysis relicta	227	38	189	19				19	113		
Pelecypoda											
Sphaeriidae											
Sphaerium sp.											
Pisidium sp.											
Gastropoda											
Amnicola sp.											
Valvata sp.											
Insecta											
Chironomidae											
Polypedilum sp.											
Paracladopelma sp.											
Trissocladius sp.											
Tanytarsus sp.	57	208	113	38	170					284	38
Chironomus riparius											
Chironomus sp.A.			19								
Psectrocladius sp.				19							
Psuedodiamesa sp.					57						
Procladius sp.	19										
Glyptotendipes sp.											
Heterotrissocladius sp.	19			19		19	38				132
Cricotopus sp.											
Cryptcchironomus sp.											
Stictochironomus sp.											
Orthocladius sp.											
Pentaneura sp.											
Stenochironomus sp.											
Diamesinae											
Orthocladinae											

TABLE XV-3. Grand Traverse Bay benthos 12-14 May 1975 organisms/meter^2 using PONAR 529 cm^2

Station - Depth	10		11		12		13		31		59			87		
	83M		41M		20M		27.5M		112M		26M			12.8M		
	A	B	A	B	A	B	A	B	A	B	A	B	C	A	B	C
Oligochaeta	227	19	170	1569	38	302	851	1493	662	396	284	473	76			
Nematoda																
Copepoda	38		19	113		57										19
Limnocalanus macrurus				19					19	19						
Senecella calanoides																
Isopoda																
Asellus racovitzai rac.														38		
Lirceus lineatus																
Amphipoda																
Hyallela azteca														132		
Pontoporeia affinis	907	132	1059	1550	132	57		19	2325	2231	19	57				
Decapoda																
Mysidaceae																
Mysis relicta						19	19	38	19	19						
Pelecypoda																
Sphaeriidae					19	19										
Sphaerium sp.	38															
Pisidium sp.																
Gastropoda																
Amnicola sp.					19											
Valvata sp.						19										
Insecta																
Chironomidae														19	19	
Polypedilum sp.								19			19				19	
Paracladopelma sp.						57	19									
Trissocladius sp.						19										
Tantarsus sp.	19			189	19	38	396	586	57	19	548	284	19	435	340	302
Chironomus riparius							151	170			57	208	19	151	132	38
Chironomus sp.A.											76	95	38	19		
Psectrocladius sp.						76					95	38	19		19	
Psuedodiamesa sp.		19			19	19		19					19			
Procladius sp.					38	19	321	151			113	38	19	151	340	57
Glyptotendipes sp.											76	95	38			
Heterotrissocladius sp.	76	38	38	57	38	340	19		19	19	113	38	19	76	113	38
Cricotopus sp.							19									
Cryptochironomus sp.						57								19	38	19
Stictochironomus sp.					19			19							19	
Orthocladius sp.					19											
Pentaneura sp.														19		
Stenochironomus sp.																57
Diamesinae					19			19								
Orthocladinae					19											

of amphipods and an increase in midges from 1970 to 1975. The oligochaeta population stays somewhat constant over the years. The isopods, although present at all stations, are at the highest concentration at the shallow water station #88. The only other trend that can be observed from these data are that pelecypods were not collected from station #1 during 1973 and 1975.

After an inspection of the data for all zones in Grand Traverse Bay, it becomes obvious that the depth of the water was the controlling factor for the composition of the profundal population. Hence the existing data were separated into shallow and deep water stations and summarized for each year (Table XV-2). Utilizing this approach, no differences in population composition were observed within either the shallow or the deep water stations. It should be repeated that data from 1970 includes only oligochaetes and amphipods, while the remaining members of the community were not reported. Even though this is the case, these data are still applicable for comparative purposes.

In references to Table XV-2, the pelecypods and gastropods appear to decrease while the midges and oligochaetes are increasing in the shallow water stations from 1971 to 1975. No apparent trend is observed in the amphipod populations for the same period. In the deep water stations, the only observed change is a decrease in the pelecypods from 1971 to 1975. The remaining groups, although fluctuating in number from year to year, appear to be relatively stable.

In summary, the shallow water benthos population is dominated by amphipods (36.8%), oligochaetes (21.2%), gastropods (11.8%), midges (11.4%), pelecypods (6.6%), isopods (1.8%), and others. The Grand Traverse Bay profundal community consists of amphipods (67.6%), oligochaetes (19.2%), pelecypods and copepods (each 4%), midges (2%), decapods (1%), and others. These findings compare well with those by Eggleton (Cook 1974) and Powers and Alley (1967) from Lake Michigan with one exception. These studies show the pelecypod population to be diminishing in Grand Traverse Bay. The concentration of organisms from 1971 - 1975 for Grand Traverse Bay deep water benthos (61 - 175 meters) is 2858/m^2, which is considerably lower when compared to the 4229/m^2 observed by Cook (1974) and 4265/m^2 measured by Powers and Alley (1967) for Lake Michigan. Merna (1960) collected a series of samples from two stations in the east arm of Grand Traverse Bay near stations #6 and #8. He found a concentration of 3789/m^2 and 4456/m^2, respectively, of which the dominant organism in each case was *P. affinis* (86% and 81% respectively). In contrast to these results, a study carried out by governmental agencies (FWPCA 1968) collected benthic samples that resulted in only 70 and 520 organisms per m^2 in the east arm.

As indicated earlier, the 1975 benthos data (Table XV-2) show a considerable diversity of the midge population in Grand Traverse Bay. Approximately 17 genera of midges and at least that many species were identified. The shallow water stations were dominated by *Tanytarsus sp.*, *Chironomus sp. A*, *Psectrocladius sp.*, *Chironomus* nr. *riparius*, *Procladius sp.* and *Heterotrissolcladius sp.* The deep water stations' midge population included *Tanytarsus sp.* and *Heterotrissocladius sp.* as the two dominant forms. Only one station (#8) out of those sampled during 1975 was devoid of midges. The more detailed analyses of the 1975 benthos data will serve as a basis for comparisons for future studies.

Conclusion

Benthic macroinvertebrate data collected from Grand Traverse Bay during 1970 through 1975 are similar in composition to those macroinvertebrates that are found in the deeper areas of Lake Michigan but, in terms of concentration, are much lower. This relatively low number of profundal organisms could be attributed to the relatively unproductive overlying waters of this bay. Although the bay receives numerous storm sewer discharges, industrial fruit processing wastes, wastewater treatment effluent, and other urban runoff, the benthic community is unaffected because of the high assimilation capacity of the bay.

XVI. SURFACE SEDIMENT

The surface sediment of Grand Traverse Bay was sampled and analyzed for various physical and chemical parameters. This work supplied an additional indicator of the eutrophication and pollutional status of Grand Traverse Bay. A comprehensive article documenting the trace element and organic carbon content of Grand Traverse Bay surface sediment has been published (Baker-Blocker et al. 1975) and only a brief discussion of these results will be presented here.

Physical Composition of Sediment

The surface (most recently deposited) sediment in Grand Traverse Bay can be classified as calcareous mud, composed of a mixture of sands, silts, and clays. The mean grain size ranged from 2.2 to 8.2ϕ units [$\phi = -\log_2$ (mean size fraction of sediment in mm)]. The areal distribution of the sediment with respect to grain size is shown in Figure XVI-1. Baker-Blocker et al. (1975) determined that this distribution is correlated closely with the relative energy levels associated with the water movement in Grand Traverse Bay. The sediment of larger particle sizes (grain sizes less than 4ϕ) was located principally in shallow shoals and shore areas. In these regions currents were able to carry away the smaller-sized suspended sediment, preventing deposition. The embayments, which typically have restricted circulation, had sediment with grain sizes between 4ϕ and 7ϕ. The deeper areas of the bay collected the smaller sediment particles of grain size greater than 7ϕ. Fine-grained sediment was also observed in the bay within the plume of the Boardman River. This is a consequence of silt loading carried by the Boardman River from its watershed.

The distribution of organic carbon content expressed in weight percent of dry sediment also reflects the physical limnology of the bay (see Figures XVI-2, XVI-3 and IV-2). The organic carbon content ranged from 0.3% to 5.3% by weight. The organic carbon content of the sediment is largest in the southernmost tip of the west arm, a consequence of the tributary loadings from the Boardman River. Other areas of high organic carbon content were in the deep channel of the east arm and the deeper portions of the basin in the west arm. Baker-Blocker et al. (1975) concluded that the high energy environments in the bay (shallow shoals, etc.) are not conducive to the preservation of organic materials.

A logarithmic relationship was reported to exist between mean grain size and organic carbon content (Figure XVI-4). This is consistent with the supposition that the organics are associated more closely with the silts and clays and less with the coarser sands. This correlation agrees with findings in Lake George by Shoettle and Friedman (1973) who concluded that areas of minimal wave and current actions allow deposition of organic-rich sediments.

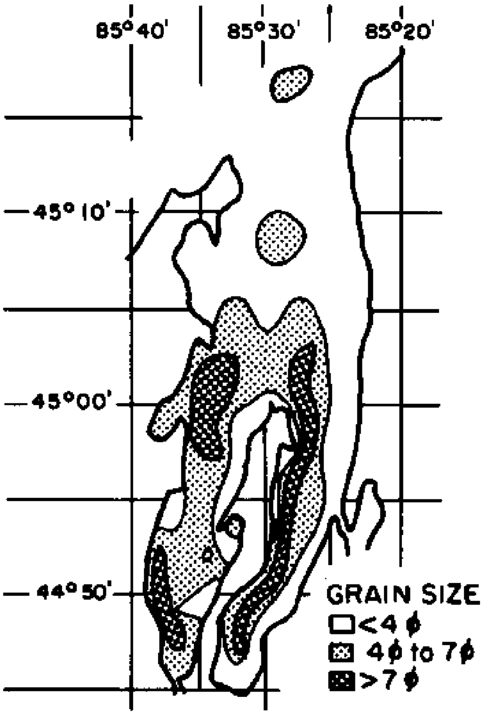


FIGURE XVI-1. Areal distribution of sediment grain size. (After Baker-Blocker et al. 1975).

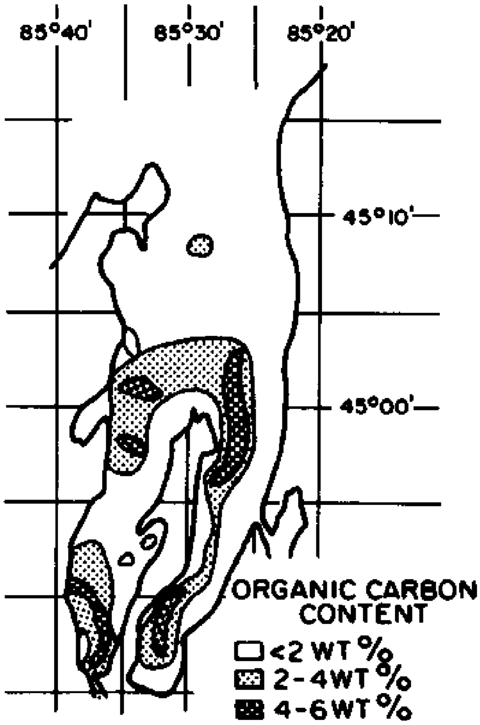


FIGURE XVI-2. Organic carbon content of surface sediment. (After Baker-Blocker et al. 1975).

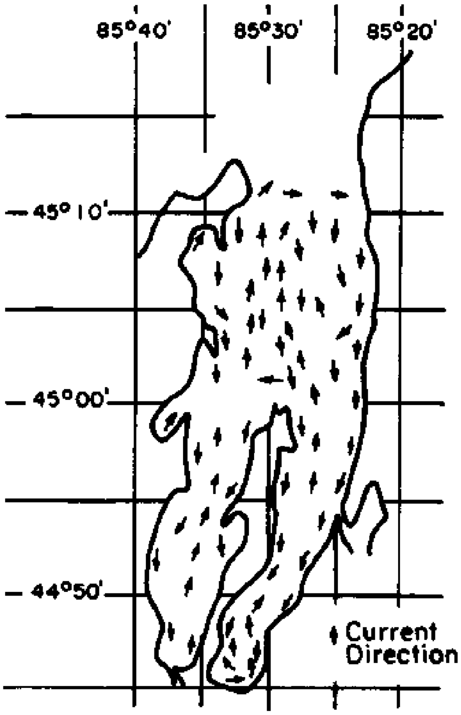


FIGURE XVI-3. Generalized current pattern (NW wind) for Grand Traverse Bay. (After Baker-Blocker et al. 1975, as adapted from Smith 1973).

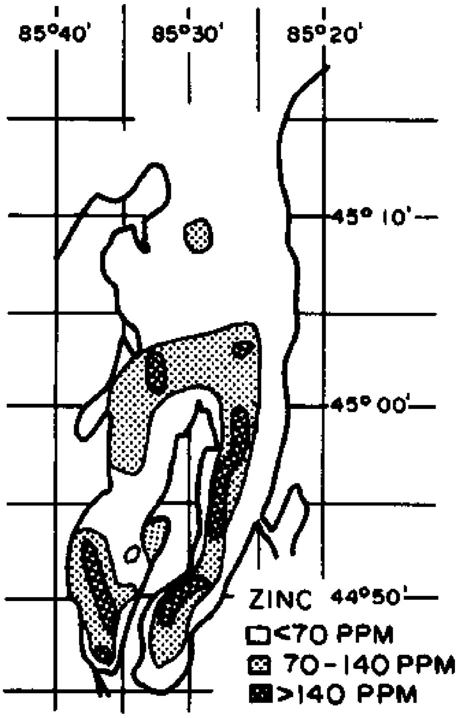


FIGURE XVI-5. Areal distribution of zinc concentrations in extracts of surface sediment. (After Baker-Blocker et al. 1975).

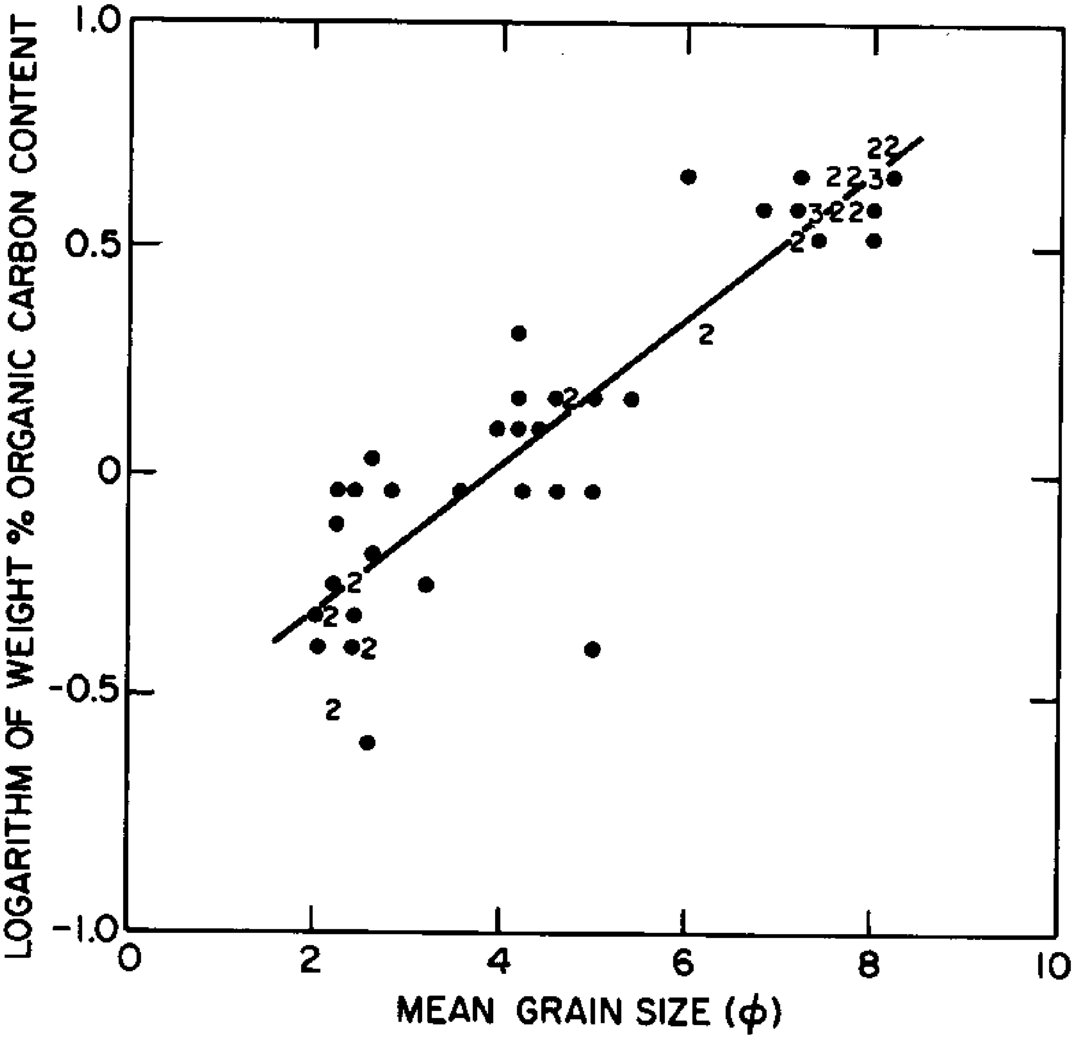


FIGURE XVI-4. The relationship between organic carbon content and grain size (After Baker-Blocker et al. 1975).

Trace Metal Composition

A summary of the trace metal and specific ion analyses on acid peroxide sediment extracts is shown in Table XVI-1. The relative levels of concentrations do not deviate significantly from measurements found in other parts of the Great Lakes (see Table XVI-2). A direct comparison of values is somewhat inappropriate because of the wide variance of techniques used in extracting and measuring the elements from the sediment and because of the diversity associated with the sampled sites with respect to depth, location, etc. A comparison of the relative magnitudes of these concentrations would be useful, however, and might give the reader an indication of the level of contamination in the bay.

The data summarized in Table XVI-2 are derived from the following sources: 1) a study by Ayers (1970) of the sediment of Lake Michigan using acid-peroxide extraction techniques, and 2) a study by Callender (1969) investigating the sediment of Lake Superior and Lake Michigan using acid-peroxide extraction techniques, and 2) a study by Callendar carried out on Great Lakes sediments, comparisons were only performed with respect to these two to avoid erroneous comparisons of results from different types of analysis. The methods used in Ayers (1970) and Callender (1969) were similar to those of Baker-Blocker et al. (1975).

The mean level of calcium and magnesium in Grand Traverse Bay sediment was 4.63 wt% and 1.92 wt% respectively. These concentrations were higher than those found in Lake Superior, and slightly higher than the average concentration found in Lake Michigan (see Table XVI-2). This trend is consistent with the observations of calcium and magnesium in Grand Traverse Bay and Great Lakes waters (see Table X-2). Calcium and magnesium are two cations normally found in close mineral association in nature and their similar occurence in the sediments is logical. The slightly elevated concentrations in the bay over those measured in Lake Michigan probably do not reflect significant industrial or municipal discharges but rather larger erosional and precipitated loads from the watershed. As can be noted in Table XVI-2, concentrations in Lake Michigan can vary widely depending on the area sampled. Neither calcium nor magnesium is considered to be present in Grand Traverse Bay sediments in excessive amounts.

The extracts of iron and manganese, two other elements found closely associated in nature, had measured mean concentrations of 1.23 wt% and 0.03 wt% respectively. These levels were similar to observations in other Great Lakes regions. Interpretation of any trend or differences is difficult because of the high chemical mobility of iron and manganese compounds in sediment, resulting from their redox sensitivity and because of their association with manganese nodules. It is sufficient, however, to conclude that iron and manganese do not exist in excessive concentrations in Grand Traverse Bay sediment.

The mean copper and zinc concentrations measured from Grand Traverse Bay sediments were 18.6 µg/gm dry weight and 90.5 µg/gm dry weight, respectively. These average measurements are well within the reported

TABLE VXI-1. Average concentration of selected parameters in Grand Traverse Bay surface sediment.

	Org.C wt%	Ca wt%	Mg wt%	Na wt%	K wt%	Ba ug/gm	Cu ug/gm	Fe wt%	Mn ug/gm	Zn ug/gm
Mean	2.31	4.63	1.92	0.046	0.40	56.7	18.6	1.2	300	90.5
Standard deviation	(1.71)	(2.79)	(0.93)	(0.020)	(0.19)	(46.0)	(21.9)	(0.77)	(200)	(58.5)
No. of observ.	66	67	67	67	67	67	67	67	67	67

TABLE XVI-2. Levels of selected heavy metals, ions, and organics, in Great Lakes sediment.

Study Area	Org.C wt%	Ca wt%	Cu ug/gm	Fe wt%	Mg wt%	Mn ug/gm	Sr ug/gm	Zn ug/gm
Grand Traverse Bay (mean)	2.31	4.63	18.6	1.23	1.92	300	41.7	90.5
Lake Superior	2.39	1.59		2.23	1.07	105		
Lake Michigan	1.87	2.74	32.1	1.95	1.65	186	35.2	499
S. Basin, Lake Michigan	1.56	5.95		1.80	2.32	70		
N. Lake Michigan	1.69	5.72		1.77	1.15	140		
Green Bay, Lake Michigan	2.59	2.99		1.60	0.82	140		

range of concentrations found in other Lake Michigan and Lake Superior sediments and do not indicate any severe levels of contamination. High concentrations of these elements in the sediments would suggest heavy industrialization, which does not exist in the region, or the presence of manganese nodules.

The average level of strontium reported in Grand Traverse Bay sediments was 41.7 μg/gm dry weight. The mean reported in Lake Michigan was similar: 35.2 μg/gm. The average barium concentration measured in the bay sediment was 56.7 μg/gm dry sediment weight.

In general, the average concentrations of sediment trace metals are not considered to be indicative of serious contamination in the bay or indicative of the presence of manganese nodules. A spatial analysis of the distribution of these concentrations does indicate differences in concentrations and demonstrates contamination from bay tributaries, particularly the Boardman River. The horizontal distribution of trace metal concentrations in sediments is summarized in Table XVI-3.

The general distribution of trace elements can be seen most dramatically in Figure XVI-5, which shows the spatial distribution of zinc concentrations in the bay. Concentrations of zinc and generally most other trace metals (including Cu, Fe and Mn) were highest in the plume area of the Boardman River and in the deeper parts of the bay. The higher concentrations in the Boardman River plume are a result of sediment loadings coming from the river. The elevated concentrations of metals in the deeper regions of the bay can be explained by the correlation between trace metals and sediment grain size. Baker-Blocker et al. (1975) reported that the metals concentrations had a good positive correlation with grain size. Higher concentrations of metals were associated with smaller particle sizes. As noted previously the smaller sediment particles are deposited principally in the deep areas where current velocities are lower. As a consequence trace metal concentrations are found in deeper regions. The organic carbon content of the sediment was also found to be correlated with particle size and a similar distribution was noted. It is not clear whether the trace metals are associated with the smaller particles because of their generally larger organic component or because of their larger clay content. Clays generally have much higher absorption capacities for metal cations than do sands. The higher concentrations of metals noted in the Boardman River plume area and the deep basins is still not considered to be hazardous or indicative of significant pollution.

Although the work of Baker-Blocker et al. (1975) is thorough in documenting the acid peroxide sediment extract concentrations in Grand Traverse Bay, it is still difficult to establish the relative influence of sediment trace metals on the ecology of Grand Traverse Bay. Sediment interstitial water concentrations were not measured. Without this information it is impossible to estimate the exchange of chemicals between the sediments and the overlying waters. Rough calculations suggest that significant amounts of trace metals do exist in the sediment. If all of the acid peroxide extractable zinc in the upper 10 cm of sediment were

TABLE XVI-3. Mean grain sizes and trace-element concentrations, Grand Traverse Bay.

	Open Bay	West Arm	East Arm		Boardman Plume
			Depth >96 m	Depth <85 m	
	Mean	Mean	Mean	Mean	Mean
Mean grain size (ϕ)	3.1	5.8	7.8	3.2	7.4
Organic C (wt %)	0.7	2.8	4.0	0.9	5.0
Ca (wt %)	2.0	4.3	8.9	4.5	5.2
Mg (wt %)	1.1	2.2	2.6	1.4	2.6
Na (wt %)	0.06	0.04	0.04	0.05	0.04
K (wt %)	0.3	0.4	0.5	0.2	0.5
Ba (ug/gm)	41	65	69	25	82
Cu (ug/gm)	7	23	32	6	40
Fe (wt %)	0.6	1.5	1.9	0.5	2.2
Mn (ug/gm)	160	386	663	91	689
Sr (ug/gm)	25	39	71	38	46
Zn (ug/gm)	42	102	160	47	198

Modified from Baker-Blocker et al. 1975

suddenly released to the overlying waters the estimated effect on Grand Traverse Bay water quality would be an increase of 400 μg Zn/ℓ, or 40 times its present concentration. The sudden release of this zinc is, however, highly unlikely. It has accumulated in the sediments slowly over long periods of time and its release and recycle is a slow process, given the present environmental conditions. Any analysis of the sediment chemical exchange and its contribution to Grand Traverse Bay water quality is impossible to estimate with the available data base.

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Appendix A. SOURCES USED IN THE COMPILATION OF TABLES OF GENERAL VALUES

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Appendix B. A BIBLIOGRAPHY OF SEA GRANT PAPERS AND REPORTS ON GRAND TRAVERSE BAY.

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