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NEARSHORE HYDRODYNAMICS STUDIES IN WESTERN LAKE MICHIGAN, 1993-1995

P.C. LIU, Editor

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DEPARTMENT OF COMMERCE

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NOTICE

 This is GLERL Contribution No. 1058.

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Foreword

P. C. Liu

In early 1993, following two brief workshops in Madison and Milwaukee, Wisconsin, the Great Lakes Environmental Research Laboratory (GLERL) initiated and implemented an interdisciplinary research program on nearshore hydrodynamics studies in western Lake Michigan with the following objectives:

- Synthesize the results of research studies on coastal hydrodynamics, biological processes, and water chemistry of the nearshore region and apply them to practical problems of coastal environmental management and planning.
- Sponsor basic scientific research on outstanding coastal environmental problems.
- Cooperate with other agencies to develop comprehensive biological, chemical, and physical knowledge of the nearshore area.

The program was carried out during 1993-1995 by an interdisciplinary group of scientists from University of Wisconsin - Milwaukee (UWM) and GLERL. Through concerted efforts under sometimes uncertain funding conditions, the objectives have been generally achieved to a large extent. Perhaps a rather interesting coincidence was that shortly after the implementation of the GLERL Nearshore Hydrodynamics Program, a drinking water crisis occurred in the spring of 1993 in Milwaukee as a result of *Cryptosporidium* contamination. The modeling effort initiated as part of the GLERL program found immediate practical applications.

This GLERL Technical Memorandum presents some highlights of the efforts contributed by the participants of the Nearshore Hydrodynamics Program. There are seven articles in this collection that can be broadly divided into three groups: two papers on thermal fronts studies by Brooks and Sandgren of UWM and Johengen and Bratkovich of GLERL; two papers related to water quality modeling and the pollution plume by Lee et al. of UWM and Christensen and Phoomiphakdeephan of UWM; and three papers on basic measurements of currents, waves, and sediments by Miller, Liu, and Hawley of GLERL, respectively. The model studies performed by Lee prompted the City of Milwaukee to adopt the recommendations for relocating the present water intake by adding a 4,000 ft. extension and providing improved filtration.

Finally, on a very sad note, our colleague Alan Bratkovich of GLERL passed away in early 1995. Alan was a major participant of the Nearshore Hydrodynamics Program and an able and enthusiastic advocate of the program. He shared the coordination efforts of the program during 1993 - 1994 and organized the Nearshore Hydrodynamics Science Workshop held in GLERL in November 1994. Alan's passing was a great loss to the GLERL Nearshore Hydrodynamics Program. He is sorely missed by his colleagues, family, and many friends. A memorial article prepared for the J*ournal of Great Lakes Research* by our GLERL colleague Michael J. McCormick is reproduced here. We dedicate this GLERL Technical Memorandum to the memory of Alan Bratkovich.

Biological Productivity Along Thermal Fronts and in Coastal Waters

A.S. Brooks and C. D. Sandgren
University of Wisconsin-Milwaukee

Introduction

This research program was conducted in the Wisconsin waters of Lake Michigan off Milwaukee in partnership with the Center for Great Lakes Studies (CGLS) at the University of Wisconsin-Milwaukee and the National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory (NOAA, GLERL) through the Cooperative Institute for Limnology and Ecosystem Research (CILER). The program has addressed problems of common interest among the cooperating entities and has resulted in a better understanding of physical, chemical, and biological dynamics in the coastal waters of the Great Lakes.

The objectives of this project were to describe the physical and chemical conditions in the water column on either side of coastal fronts and thermal bars in order to learn more about onshore-offshore gradients of chemical variables, biological activity, and their interaction with physical processes in the coastal zone of Lake Michigan near Milwaukee.

The primary producers in the Great Lakes are at the interface between the physical/chemical environment and the biosphere. In the open waters of the Great Lakes and in the coastal zone near Milwaukee, phytoplankton are the major contributors to primary prodution. Primary producers require both light and chemical nutrients. Both of these variables are influenced by physical conditions in the lake that are determined by meteorologically-driven physical processes, such as cloud cover and wind mixing. The physical and chemical nature of the lake prior to and following the development of spring thermal fronts is quite different; with each condition imposing different environmental constraints under which the primary producers must function. The role of spring thermal front progression is significant in that this process marks the transition from winter to spring.

Approach

Sampling was done at two stations; one nearshore at the Linnwood Water Purification Plant intake which is in 21 m of water, and the other offshore at the 100 m deep Fox Point station. Vertical profile casts were taken at each station with a Sea Bird SBE 25 CTD. Data from the vertical profiles were inspected upon completion of each cast to reveal any vertical structure in the water column and to determine the depths at which samples should be taken. Continuous transect data were collected along the cruise track between stations with the Sea Bird instrument placed in a container on the deck of the ship. Water pumped from a depth of 2 m continuously flowed over the Sea Bird sensors. Ship position data were continuously obtained by LORAN and logged with the Sea Bird data. For this study, from mixing to summer stratification. One of the main objectives of this study was to examine how the development of thermal fronts and the formation of stratification influence primary production in the coastal waters of Lake Michigan.

In the Great Lakes, numerous reports have cited the importance of variable weather conditions on the primary productivity of the lakes during spring. Brooks and Torke (1977) showed that spring weather conditions over Lake Michigan influenced the duration and magnitude of the vernal phytoplankton bloom. Scavia and Fahnenstiel (1987) suggest that spring diatom production in Lake Michigan is initially controlled by temperature and light and that the extent of the bloom should be predictable based on nutrient concentration and on meteorological events influencing the timing of thermal stratification. More recently, Brooks and Edgington (1994) report a four fold increase in mass of total phosphorus in Lake Michigan water coincident with the spring phytoplankton bloom. They suggest that “new” phosphorus is released from the sediment and incorporated by the primary producers in the fully mixed water column. Spring primary production continues at a high rate as long as wind-driven mixing links the lighted euphoric zone near the surface with nutrient stores in the bottom sediments. As soon as the spring thermal front moves through an area, thermal stratification forms, full mixing ceases, and the spring bloom ends. It is, therefore, important to understand the processes associated with these frontal movements and upwelling events with respect to the productivity of the lakes.

Sea-Bird was configured to record specific conductance, temperature, depth, *in-situ* chlorophyll fluorescence, dissolved oxygen, redox potential, photosynthetically active radiation (PAR), and light transmittance (5 cm path length). All Sea Bird CTD data were processed using Sea Bird software and graphical packages as described in the 1993 project progress report. ASCII data files for all transects and profiles taken over the life of the project from 1993-1995 are included here on diskette for incorporation in the CD database being prepared at GLERL.

In addition to the Sea Bird data, samples were collected at each station from 2 m and at greater depths for extracted chlorophyll *a*, primary productivity, Si, NO_3-NO_2.N, total P, dissolved P, and particulate P, N, and C. Whole-water phytoplankton samples were collected and preserved at each depth sampled for water chemistry. Zooplankton samples were obtained as bottom-to-top vertical hauls of a 1 m, 135 µm mesh plankton net. These samples have been archived for future counting and analysis. All discrete chemical samples have been processed and entered in a common spreadsheet.

Primary production was measured using the ^{14}C uptake technique with incubations run at 15 different light intensities in a temperature controlled photosynthetron. Analysis of the resulting P vs I curves produced values of P_{max}, I^k and alpha, which are indicative of the physiological state of the phytoplankton community.

NOAA CoastWatch AVHRR sea surface temperature (SST) images were obtained for each cruise date, or the cloud-free day nearest the ruise. These images were used in planning the cruise course and interpreting data collected.

Conclusions

The results of this study, as reported in the Final Report on file, have shown the important role physical variables play in influencing primary production in Lake Michigan. As long as the lake remains fully mixed, nutrients are available from the sediments to support primary production. Full mixing, however, also imposes some limitation on production as algal cells mixed to great depths do not receive as much light as those confined to the surface by the shallowness of the nearshore environment or by the imposition of a themmocline that inhibits mixing in deeper waters. As the spring thermal front moves offshore and stratification becomes established, the coupling between the nutrients at the bottom sediments and the euphotic zone near the surface is lost and spring production is temminated. Concurrent with the offshore migration of the thermal front, nearshore warming creates a habitat suitable for nurturing the young of several species of economically-important fish that reproduce in the nearshore waters.

With only one well-defined upwelling event sampled during the period of this project, it is difficult to add much to our understanding of the role of such events on primary production in the lake. It appears evident, however, that there is a potential for production to be enhanced during upwellings of extended duration. Given the ephemeral nature of such events, the use of moored, continuous recording instruments will be necessary to provide the needed data to adequately assess the overall significance of upwellings on production.

Much remains to be gleaned from the data collected on this project. Work is continuing on the nutrient chemistry in the lake water and the elemental composition of the plankton. The knowledge gained from the data presented here and from future analysis and publication of other data obtained on this study will enhance our understanding of the nearshore waters of the Great Lakes and the importance of complex physical-chemical interactions for determining the productivity of the ecosystem.

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Brooks, A.S., and B.G. Torke. Vertical asobution of Chlorophyll *a* in Lake Michigan. *Journal of Fisheries Board of Canada* 34:2280-2287 (1977).

Scavia, D., G.L. Fahnenstiel, M.S. Evans, D.J. Jude, and J.T. Lehman. Influence of Salmonine Predation and Weather on Long-term Water Quality Trends in Lake Michigan. *Canadian Journal of Fisheries and Aquatic Sciences* 43:435-443 (1987).

Figures 1-4. Enlargements of the thermal surface water temperature maps for the research area near Milwaukee reveal details of the progressive warming of the lake from nearshore to offshore during late April and May. Overlain on the satellite-sensed temperature pattern are isolines of algal abundances (as in vivo Chlorophyll fluorescence) measured continuously along transects during research cruises on the same dates. Algal primary production measured at stations shows complex spatial patterns related to thermal warming and riverine discharge from Milwaukee Harbor.

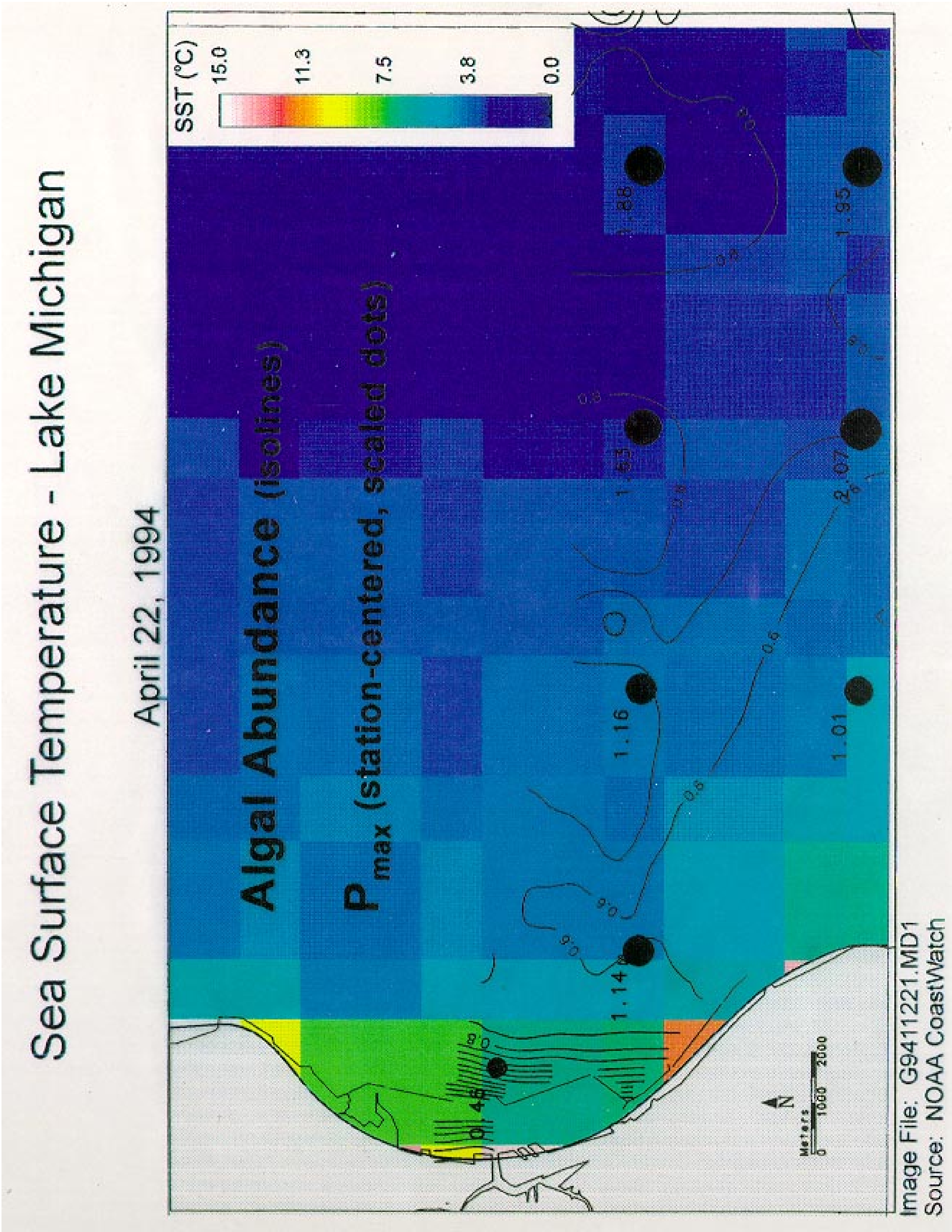
Sea Surface Temperature - Lake Michigan
April 22, 1994
Algal Abundance (isolines)
P_{max} (station-centered, scaled dots)
SST (°C)
15.0
11.3
7.5
3.8
0.0
Meters
0
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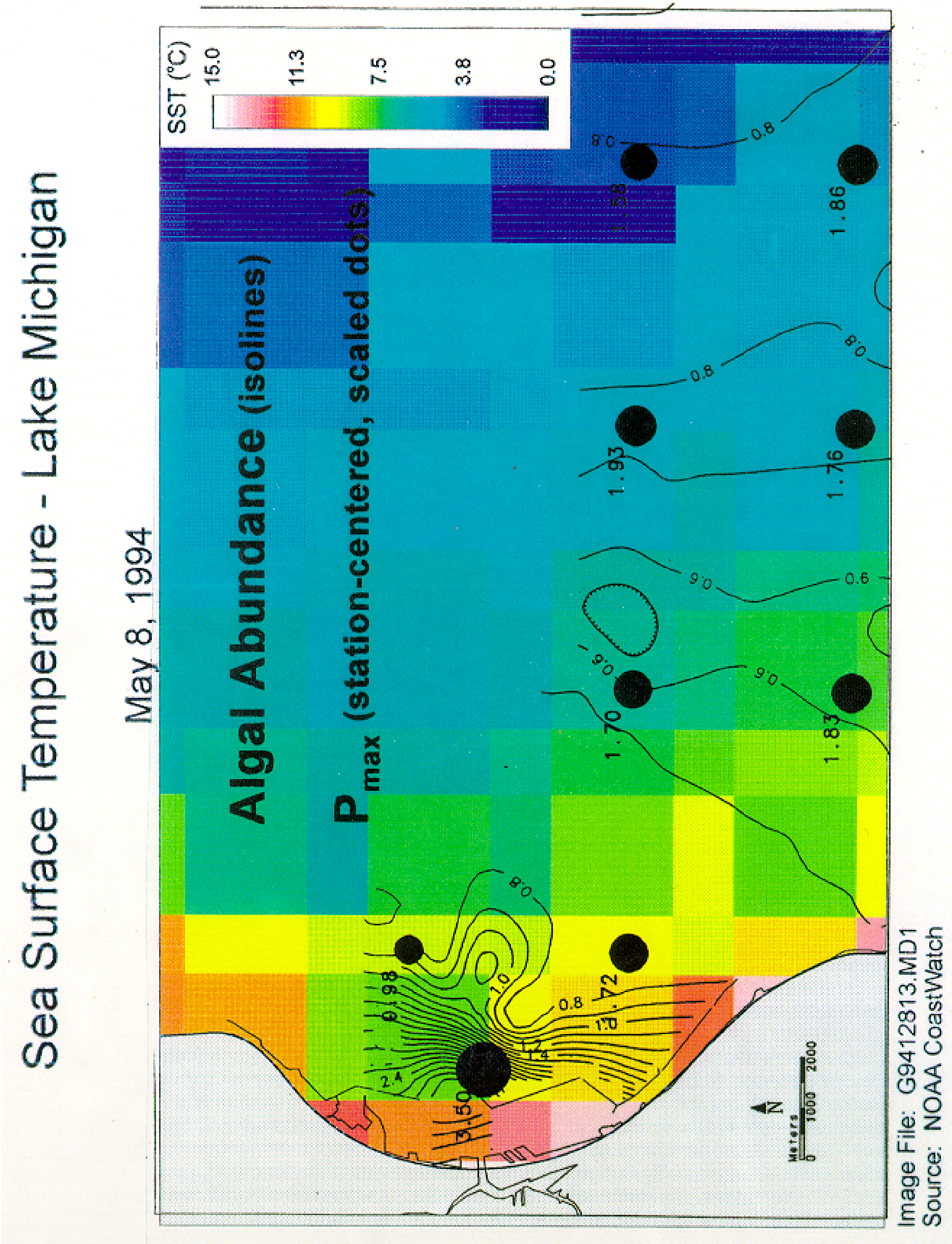
Image File: G9411221.MD1
Source: NOAA CoastWatch

Figure 1.


Sea Surface Temperature - Lake Michigan
May 8, 1994
Algal Abundance (isolines)
Pmax (station-centered, scaled dots)
SST (°C)
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7.5
3.8
0.0
Image File: G9412813.MD1
Source: NOAA CoastWatch

Figure 2.

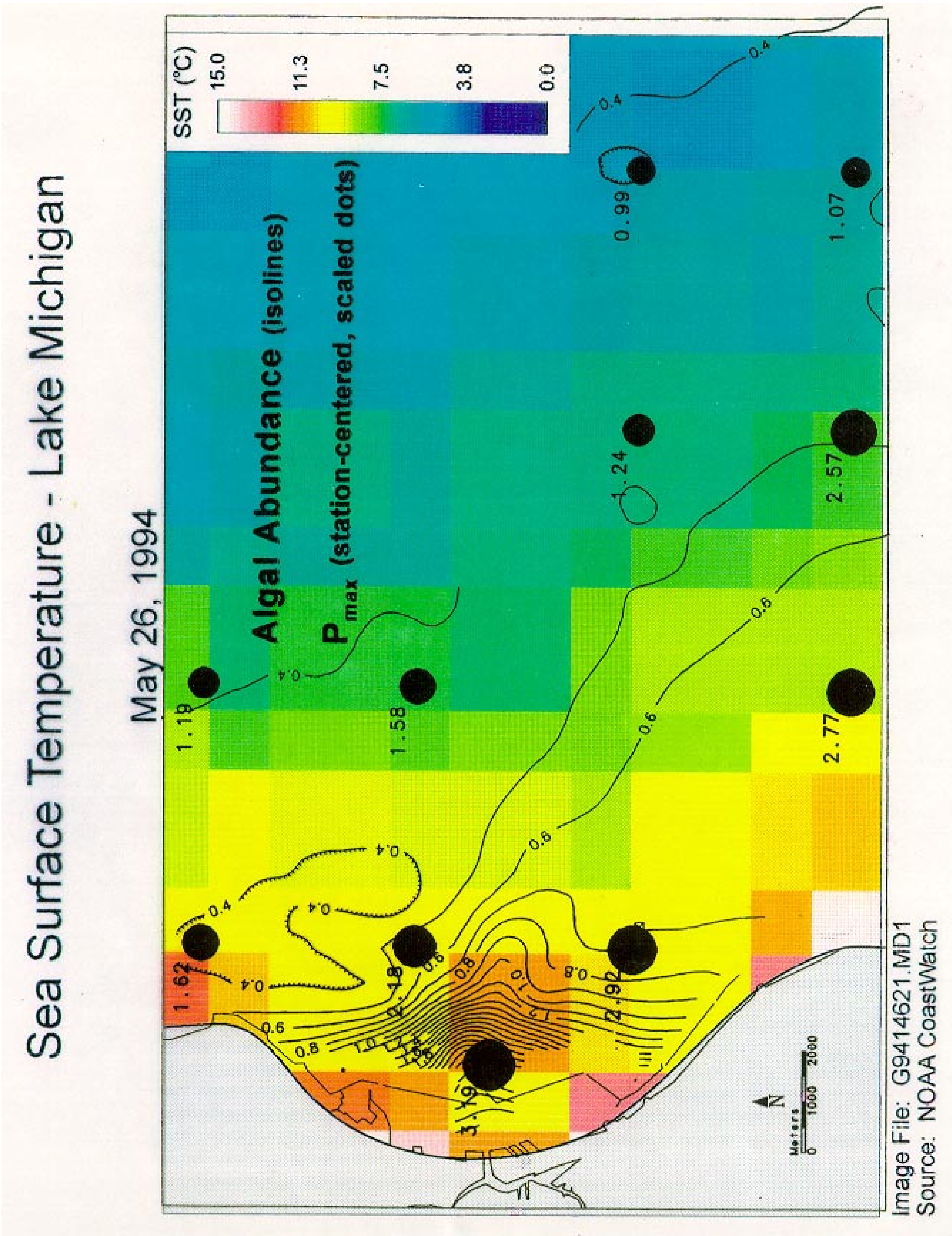
Sea Surface Temperature - Lake Michigan
May 26, 1994
Algal Abundance (isolines)
P max (station-centered, scaled dots)
SST (°C)
15.0
11.3
7.5
3.8
0.0
Image File: G9414621.MD1
Source: NOAA CoastWatch

Figure 3.

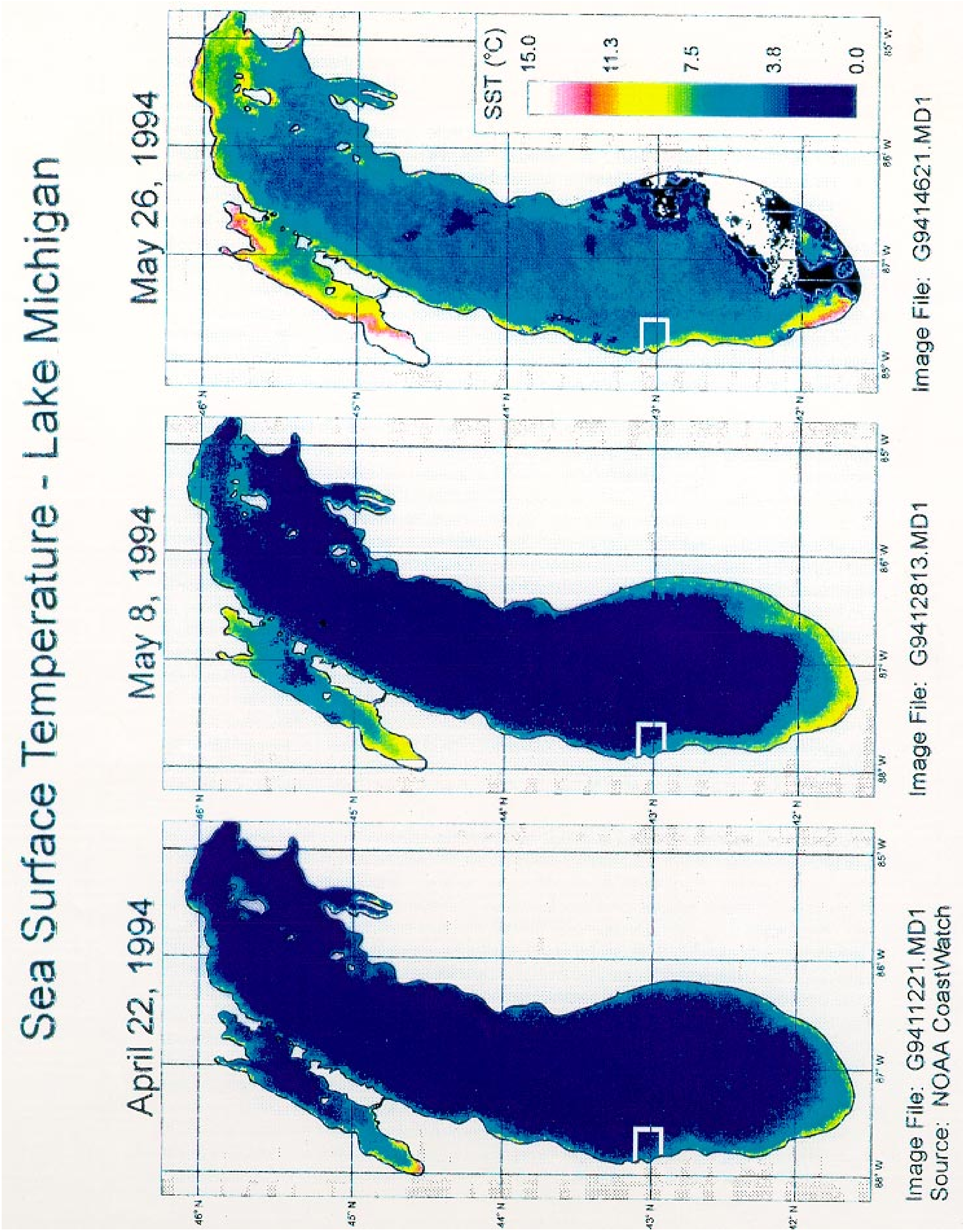
Sea Surface Temperature - Lake Michigan
April 22, 1994
May 8, 1994
May 26, 1994
SST (°C)
15.0
11.3
7.5
3.8
0.0
Image File: G9411221.MD1
Source: NOAA CoastWatch
Image File: G9412813.MD1
Image File: G9414621.MD1

Figure 4.

A Synopsis of the Lake Michigan Vernal Thermal Fronts Study: Coupling Biological and Chemical Observations to Physical Processes of the Thermal Front

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[1]Cooperative Institute for Limnology and Ecosystems Research, Univ. of Mich.
[2]NOAA, Great Lakes Environmental Research Laboratory

Introduction

From 1991 to 1994 sampling cruises were conducted on an approximately weekly basis during April and May in southeastern Lake Michigan in conjunction with the development and migration of the vernal thermal front. The boundary of the thermal front was defined by a nearly vertical 4 ^{o}C isotherm. In our study area, the front typically formed around April 1 approximately 2 km off the coast, and migrated lakeward at a rate of approximately 0.5 km per day. Current velocities developed within the frontal region typically reached 10-15 cm/sec and could advect a water parcel several kilometers within an inertial cycle of a few days.

The objectives of the chemical/biological sampling component of the fronts study were to (1) relate the distribution and transport of dissolved and particulate nutrients to physical processes governing the fronts formation and migration, and (2) determine patterns in the distribution and abundance of phytoplankton and zooplankton on similar temporal (days) and spatial scales (kilometers) as those governing frontal processes.

Methods

The thermal front sampling transects were located in southeastern Lake Michigan along the 43^0 00' N and 42^0 52' N lines of latitude (Figure 1). Sampling cruises were conducted approximately weekly during April and May. CTD and fluorometric profiles of the entire water column were taken at every minute of longitude (ca. 1.4 km apart) along the transect over a distance of 15-20 km. During each cruise nutrient and chlorophyll concentrations were sampled at 5 stations, 4 depths per station, using discrete samples collected with 5 L Niskin bottles. The chemical parameters monitored were total and soluble phosphorus, nitrate and ammonia nitrogen, silica, and chloride. Approximately every 2 weeks zooplankton samples were collected at three stations along the transect with a 1 meter diameter 163-micron mesh net towed vertically through the water column. Twice each in 1992 and 1993, primary productivity experiments were carried out using the ^{14}C method and in situ incubations.

Photosynthesis versus light intensity curves were established for surface water from two stations, one inshore and one offshore of the position of the thermal front. The primary productivity data will not be discussed here.

Nutrient and chlorophyll samples were processed on board and analyzed back at the Great Lakes Environmental Research Lab. Nutrients were determined using standard calorimetric techniques on an autoanalyzer 11 system. Chlorophyll was determined fluorometrically after grinding and extracting in cold, 90% acetone. Chlorophyll results from discrete samples were regressed against fluorometric data to provide continuous estimates of chlorophyll throughout the water column. Zooplankton were preserved in sugar formalin after narcotizing with carbonated soda, and were identified and enumerated under 1OOX magnification.

Results

Representative results from the chemical/biological sampling program are presented in Figures 2-4. Figure 2 is a contour plot of temperature and chlorophyll *a* along transect E on May 7, 1992. Contours were generated from CTD/fluorometer profiles taken approximately 1.4 km apart. The front was located approximately 12 km offshore in 60 m of water, as denoted by the nearly vertical 4 ^{o}C isotherm (Figure 2a). Inshore of the front isotherms were much more horizontal and the water column was beginning to stratify. The contour plot for chloro-

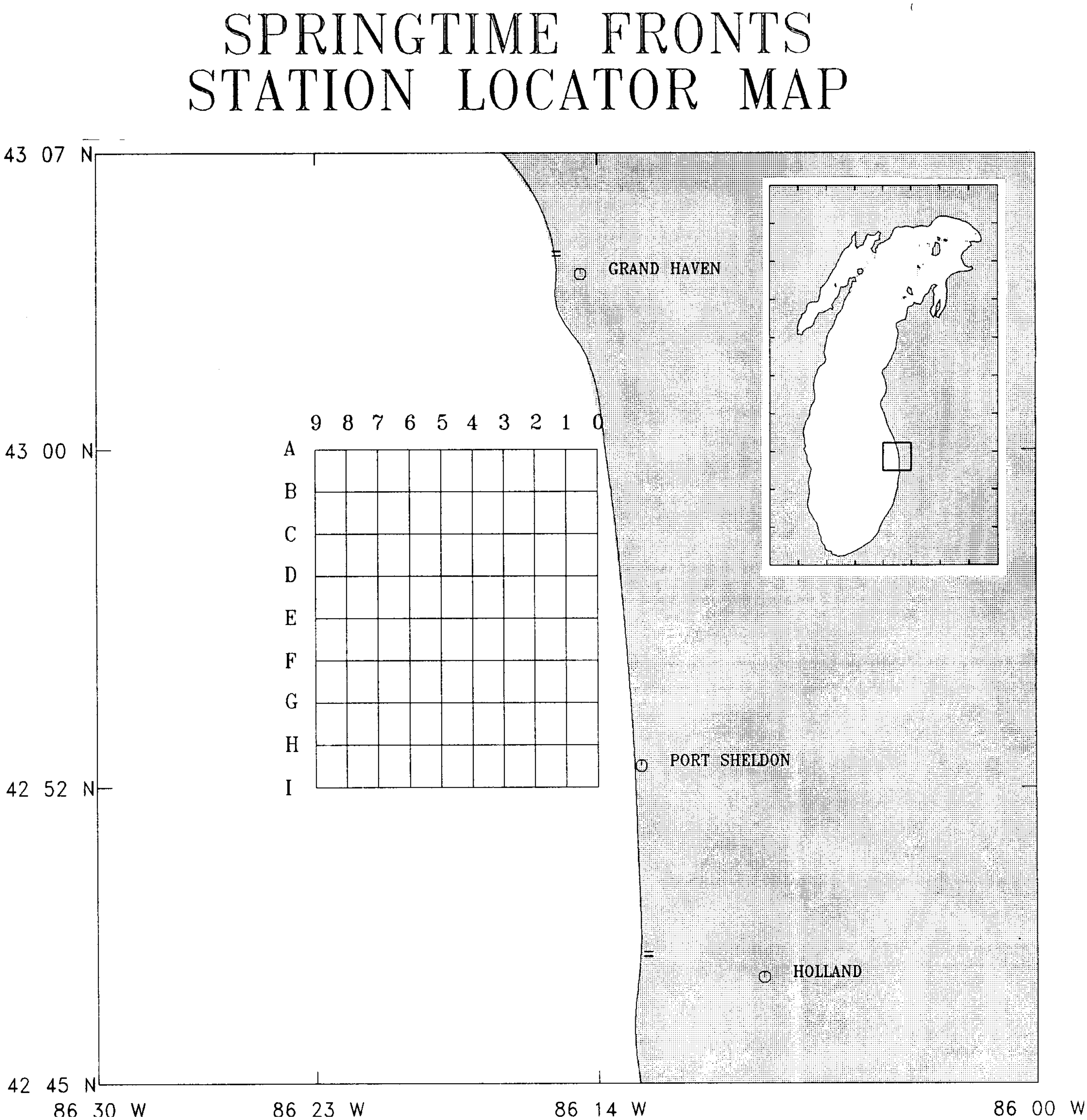

Figure 1. Station location map for the Lake Michigan vernal thermal fronts study. The sampling grid was located south of Grand Haven, Michigan between 42^0 52' and 43^0 00' north latitude. Sampling stations were located at the intersection of minutes of latitude and longitude. Most cruises were conducted along transects A and E.

phyll (Figure 2b) looked remarkably similar to the temperature profile. Near the boundary of the front chlorophyll concentrations were very uniform with depth, whereas inshore of the front, isopleths were horizontal and a subsurface chlorophyll maximum was already beginning to form.

Figure 3 shows results for total phosphorus and nitrate nitrogen from discrete samples taken at 5 station along transect E also on May 7, 1992. The outer boundary of the front was located at station 8, therefore stations E2 through E7 were inshore, and station E9 offshore of the front. Both nitrate and total phosphorus exhibited sharp gradients from inshore to offshore. Concentrations were about 60 percent higher near the coast at station E2 than at station E9. Additionally, concentrations outside of the front were much more uniform with depth than at the inshore stations. The sharp differences between station E6 and E7 may be produced by oppositely flowing alongshore currents which are frequently found in this coastal zone. Immediately inshore of the front, at station E7, there appears to be a dilution effect within the top 20 meters of the water column. This pattern may have resulted from circulation patterns which are set up as the frontal bar migrates past the position. For example, Mortimer (1979) described how the lakeward migration of the thermal bar results in convergent circulation pattern with downwelling occurring at the 4 ^{o}C isotherm.

Figure 4 describes results of zooplankton net tows taken on April 21, 1991. Zooplankton were sampled at three stations along both transects A and E. In both cases, elevated concentrations of zooplankton were observed at the station just inshore of the position of the thermal front. It is unclear whether the accumulation of zooplankton is in response to physical forcing, such as temperature or advection, or whether it is a biological response to perhaps higher prey densities in the region. If, however, zooplankton are able to respond this rapidly to the positioning of the front, then grazing pressure might be great enough to prevent any subsequent buildup of phytoplankton biomass. Zooplankton distributions might therefore be helpful in interpreting trends in chlorophyll data.

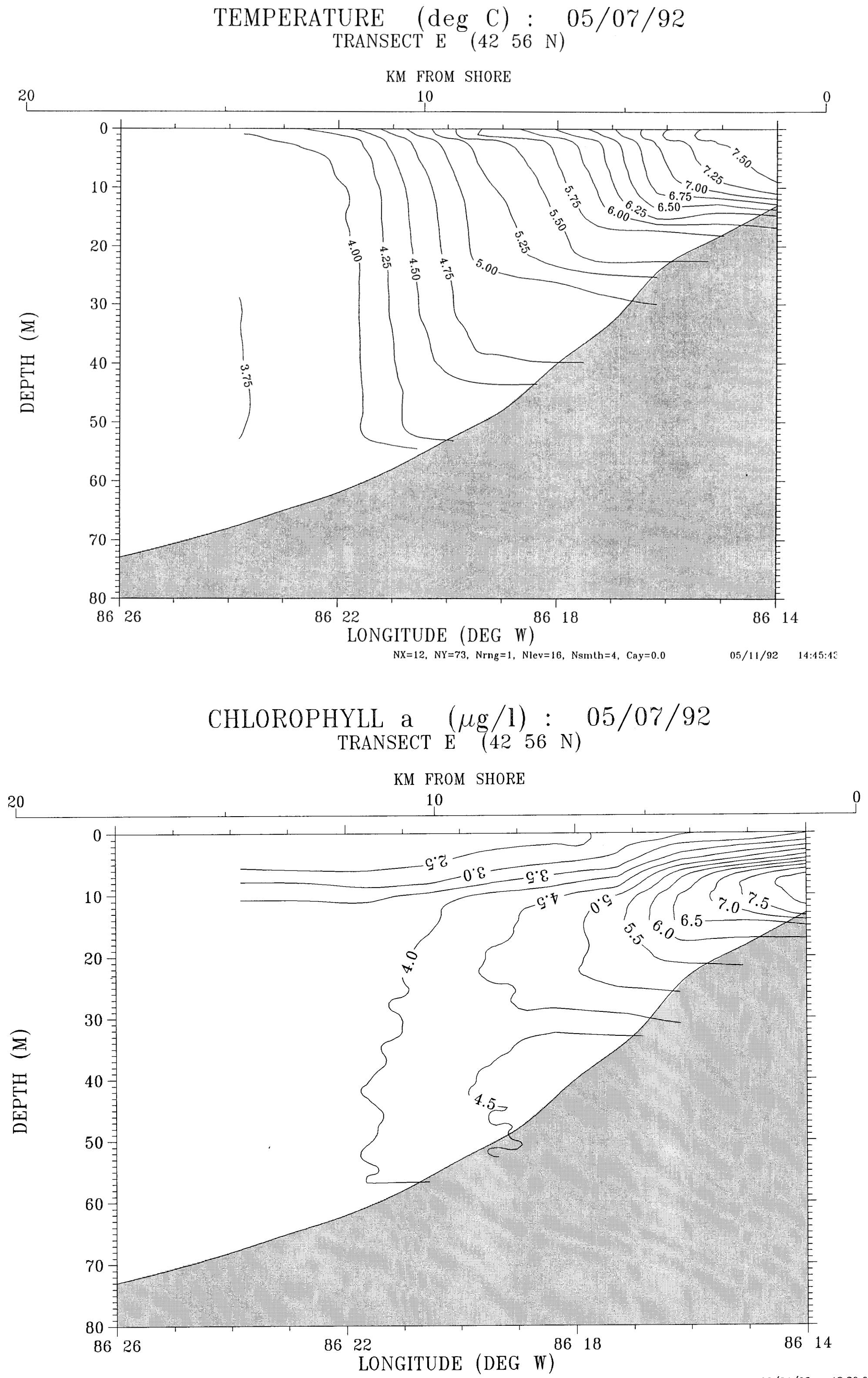

Figure 2. Contour plots of temperature and chlorophyll *a* along transect E on May 7, 1992. Contours were generated from CTD and fluorometric profiles taken approximately 1.4 km apart. Fluorometric data was converted to chlorophyll *a* by linear regression against 20 discrete chlorophyll determinations made at 5 stations, 4 depths each, on the same sampling date and location.

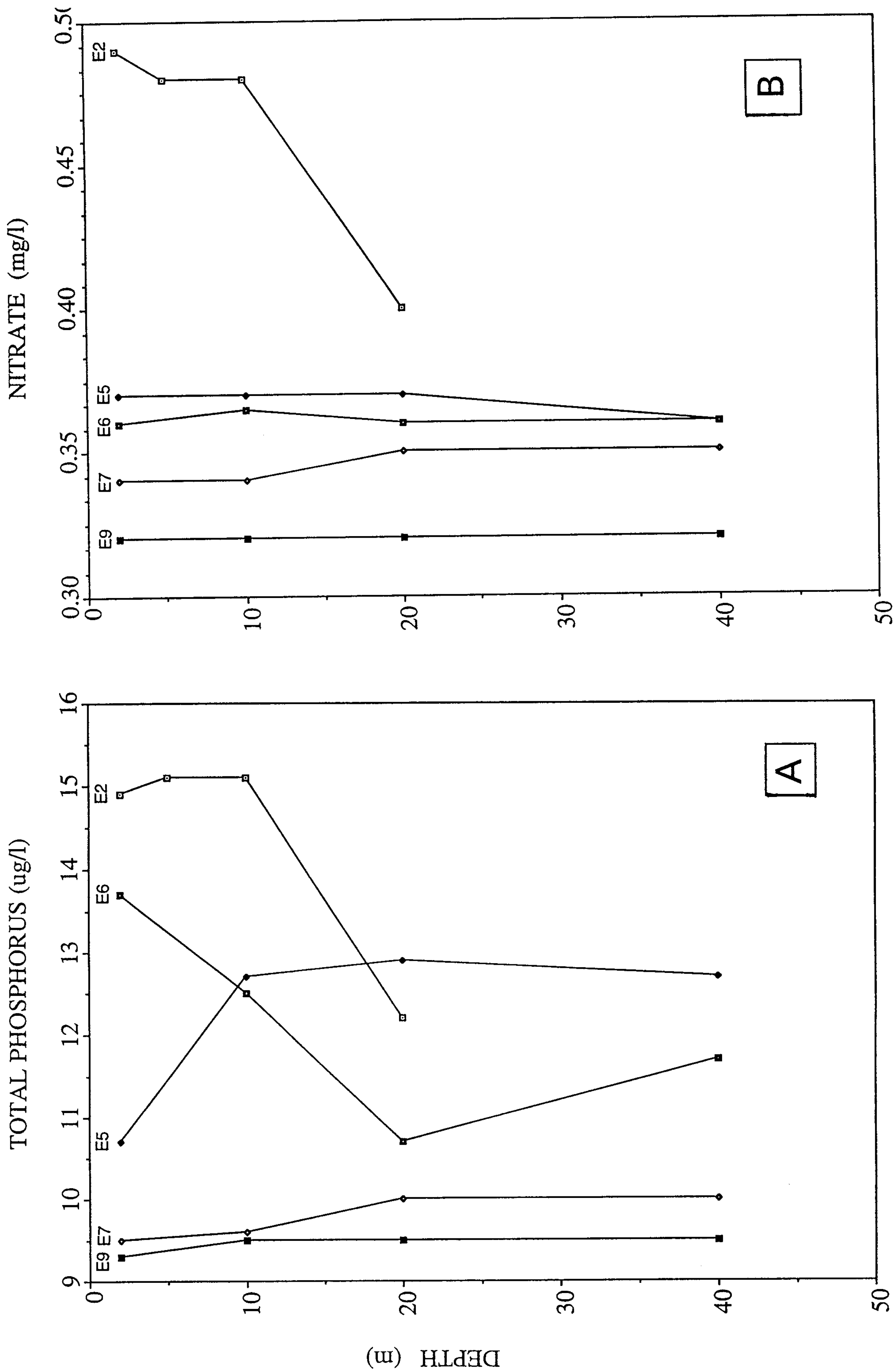

Figure 3. Total phosphorus and nitrate concentrations observed at five stations along transect E on May 7, 1992. Discrete samples were collected at four depths per station as denoted by the symbols.

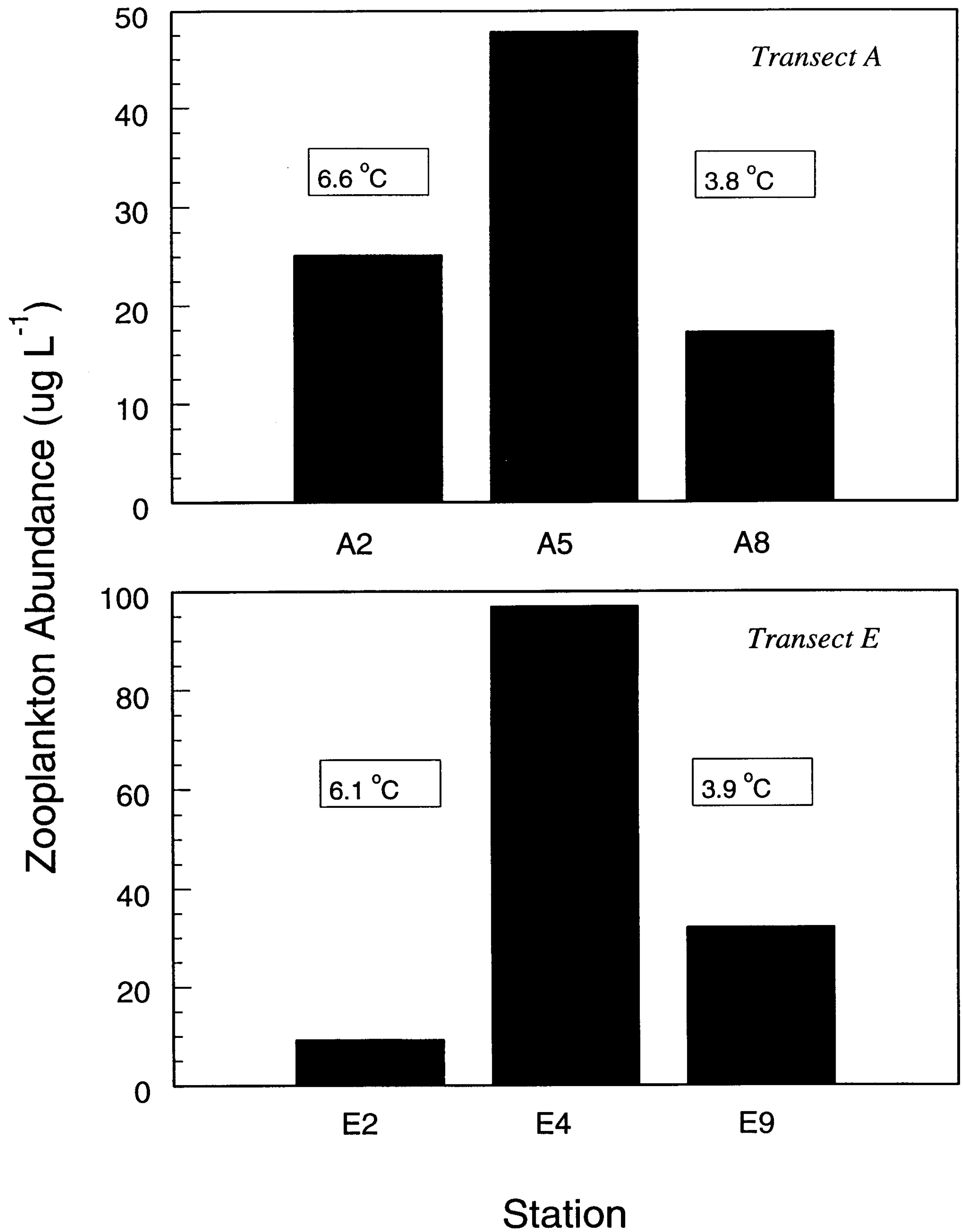

Figure 4. Total zooplankton abundance measured at three stations along transects A and E on April 23, 1991. Samples were collected by vertical net tows with a 163-micron mesh net through the entire depth of the water column. The surface temperature of each station is denoted in boxes.

Nearshore Hydrodynamic and Water Quality Modeling for Water Intake Evaluation and Design

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Abstract. The nearshore water of the Great Lakes is of vital interest to millions of residents. Lake water is often the focal point in issues concerning economic development, recreation, and public health. These lakes receive river water, storm water, and other point and diffused discharges which often carry contaminants along the shoreline. The transport of contaminants has threatened water intakes in the region and has been linked to serious epidemic illness such as the outbreak of cryptosporidiosis. These incidents heighten the interest in nearshore hydrodynamic and water quality modeling for water intake evaluation and design.

A high resolution nearshore hydrodynamic and contaminant transport model was developed to simulate various hydrodynamic and water quality conditions in the nearshore area to evaluate possible impacts on water intake. Through a sequence of simulations, an optimal location and design may be decided for a new intake, and a performance evaluation may be made for an existing water intake. The finite element model incorporates nearshore physical, hydrographical, and hydrological features relevant to water intake functions. The model has been through field verifications in the Great Lakes. Several real applications are presented. The method has aided engineers in water supply intake evaluation and raw water crib design.

Introduction

Lake Michigan receives rivers, storm water, and other diffused and point source effluents which often carry contaminants along the shoreline. Lake Michigan water is also the major source of drinking water for the region. Therefore, water quality and pollutant transport in the vicinity of major water intakes are of great concern. The drinking water crisis occurred in the Spring of 1993 due to the presence of *Cryptosporidium* in the Texas Avenue Water Intake causing an epidemic illness in the City of Milwaukee. More recently, in the early spring of 1994, a similar crisis occurred in the water intakes of adjacent cities. These serious incidents have heightened public interest in nearshore lake water hydrodynamics and contaminant transport.

The Hydrodynamic and Transport Model

The nearshore hydrodynamic project is centered at the nearshore area of Milwaukee on Western Lake Michigan. A two-dimensional depth-averaged hydrodynamic model developed by the author (Chen and Lee,1991) has been adapted to suit the Milwaukee hydrodynamic study. Figure 1 illustrates the Milwaukee Harbor, breakwater configuration, and water intake location.

The model utilizes a finite element method to solve the unsteady state non-linear problem. The model requires specified boundary conditions at all boundaries. At solid boundary, normal velocity is set to zero. At open boundary, either water level or current velocity should be specified in terms of time series as surface wind, speed, and direction. The computer code and the finite element grid data are further developed and have undergone extensive testing for the Milwaukee project. The model grid data included the design and development of a detailed finite element grid system to cover the Milwaukee Harbor and nearshore lake waters. There is a particular concern about the contaminants carried by the river flows and other effluents and pollution in the harbor. In order to account for the pollutant transport and its mixing with lake water in the harbor, and the transport of pollutants eventually outside the harbor into the nearshore lake water, the high resolution grid system was designed to reflect the intricate detail of the breakwater configuration. The finite element grid system for the

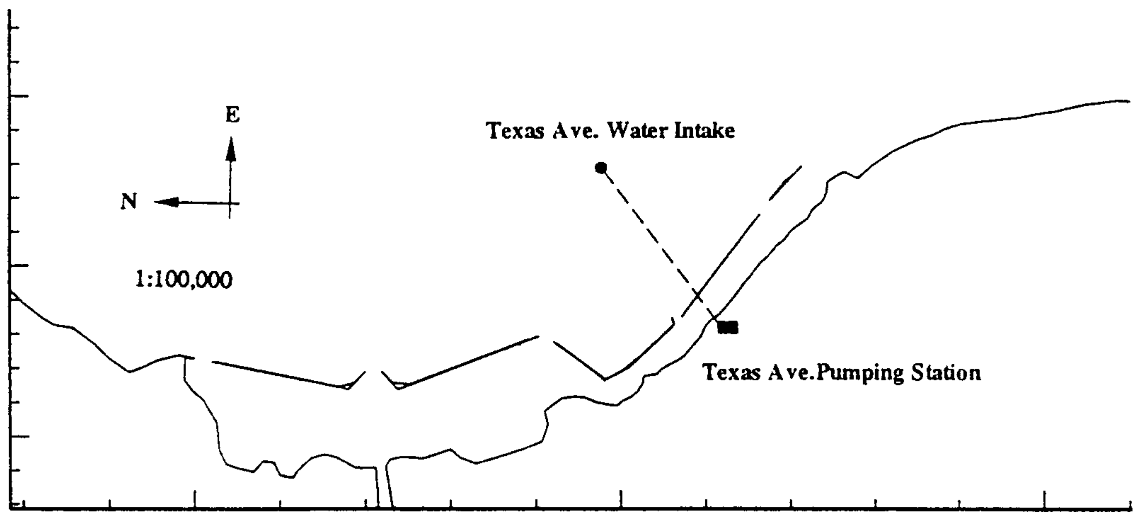

Figure 1. Milwaukee Harbor and the Texas Avenue Water Intake Location

Milwaukee Harbor and nearshore area are shown in Figure 2. The grid system consists of 1724 nodes and 3160 elements. The grid system is designed in agreement with the lake bottom topography, shoreline, and the Milwaukee Harbor breakwater geometry.

The transport model used in the effort was previously developed by the author and his students (Lee and Chen, 1986; Cheong, 1988). The model is a finite element model in close compatibility with the hydrodynamic model. In the case of the Milwaukee Study, the hydrodynamic and transport modeling is unified in a single model. The computational scheme is streamlined and efficient. The requirement for internal data storage is therefore greatly reduced.

The Milwaukee Model Results

The harbor, which receives contaminated river inflows and sewage effluents, interacts through three main openings with Lake Michigan. Depending on the wind direction, the lake water may enter the harbor through some openings, and the polluted harbor water may exit into the lake by way of the remaining openings. The harbor water and contaminant transport system is integrated with the lake system and reacts to the nearshore lake hydrodynamics. The contaminants that are discharged into the Milwaukee Harbor are eventually transported into

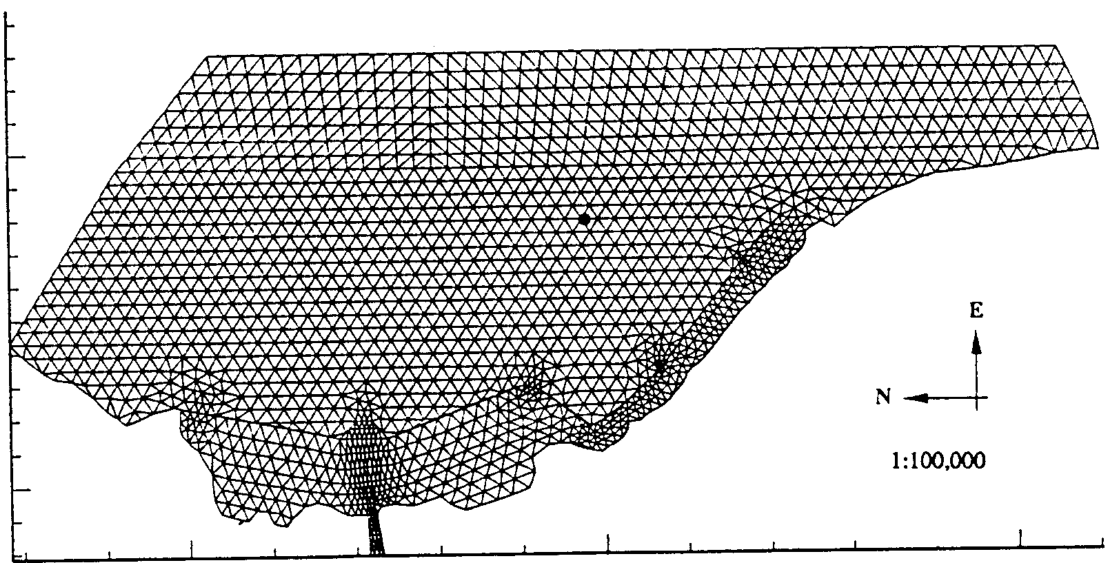

Figure 2. Finite Element Grid System of the Study Area.

the lake. Of particular importance to the Milwaukee drinking water supply is the effect of this contaminant transport plume on the raw water quality at the Texas Avenue Water Intake. Figure 3 shows the turbidity measurements of the raw water at the Texas Avenue Water Intake in 1993 when the water supply crisis occurred.

The model, after appropriate field verification, can continuously simulate the hydrodynamic flow and the contaminant transport plume under various river flow and weather wind conditions. The seasonal river flow, weather, and lake conditions were used to generate a sequence of simulation cases to study its influence on the Texas Avenue Water Intake. Figure 4 shows an example of the water flow from the hydrodynamic model simulation.

Figure 5 and Figure 6 illustrate an example of the flows and the corresponding transport plume. The plume shows the percent of river effluents in the plume under a spring high river and sewage effluent flow, and a 18 km/hr wind from the southeast and northwest directions after 96 hours.

The example shows the percentages of polluted river the sewage effluent originated at the main channel, and transported and spread in the nearshore area. The extent of plume covers the Texas Avenue Intake illustrating the contamination and its severity by the river and effluent flow. Similar exercises under other seasonal and wind conditions are made to reveal the broad impact on the intake by the flow and contaminant transport.

Summary

The NOAA Nearshore Hydrodynamics Program provided the early support and interest in the modelling of Milwaukee harbor and the nearshore area. Because of the timely model development and the model's capabilities and results, the model has been selected by the City of Milwaukee and used extensively to evaluate the transport of contaminants in the Milwaukee Harbor and nearshore Lake Michigan. It is particularly important for city engineers and consultants to evaluate the present intake location and the raw water quality. Model results clearly indicate that the Texas Avenue Intake is ill-suited as a raw water source. In conjunction with the City of Milwaukee, the University of Wisconsin began a cooperative engineering study on an alternative intake for the Howard Avenue Water Purification Plant. This study was completed successfully using the model simulation and addi-

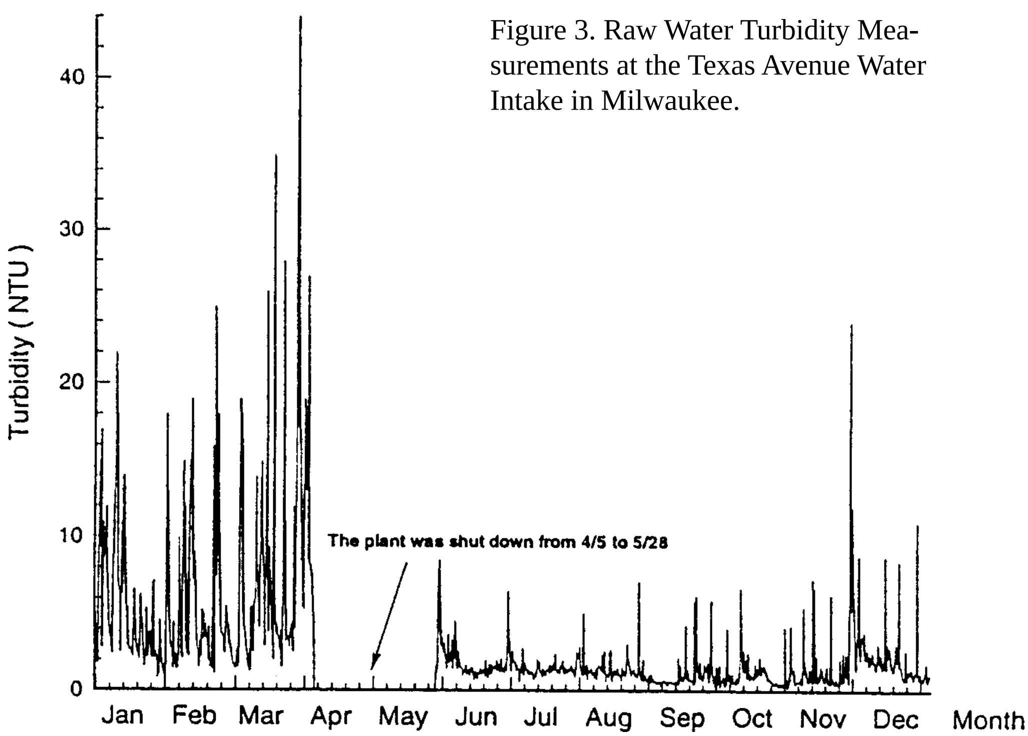

Figure 3. Raw Water Turbidity Measurements at the Texas Avenue Water Intake in Milwaukee.

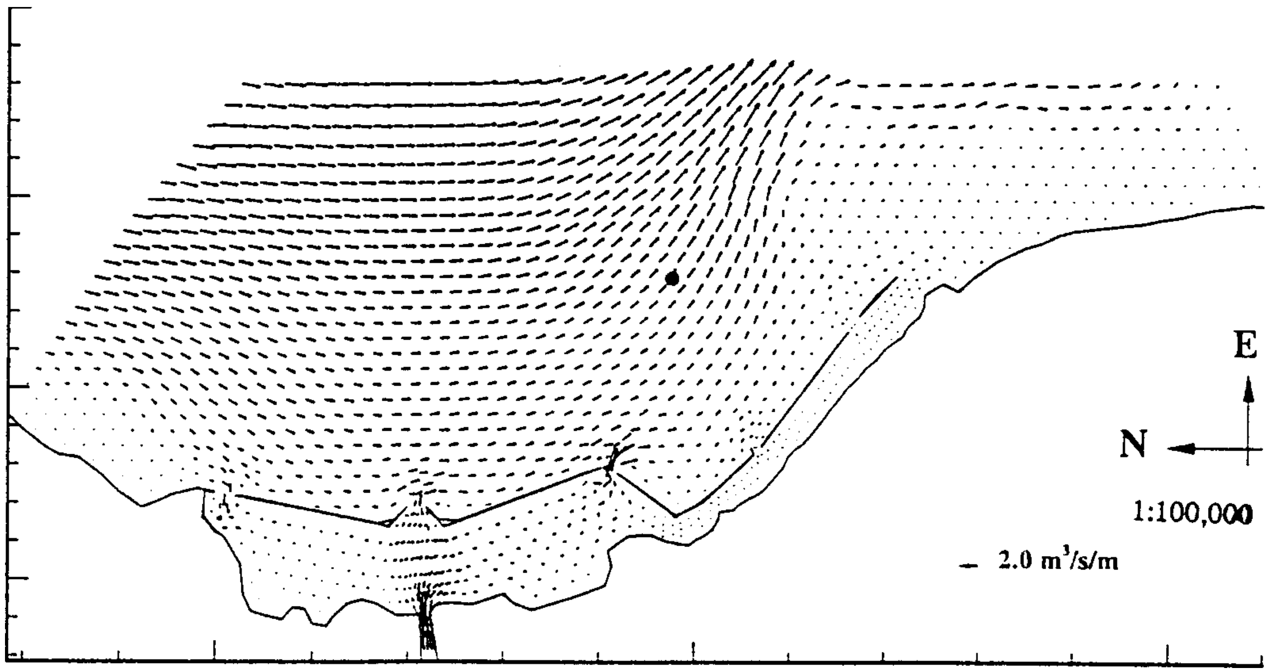

Figure 4. Water Flow Simulation Results for a northwest wind at velocity 28 km/hour at 48 hours.

tional field data collection. A new location to the north-northeast from the existing location is recommended (Lee and Brook, 1994). In addition, an intake extension of 4000 feet is also recommended.

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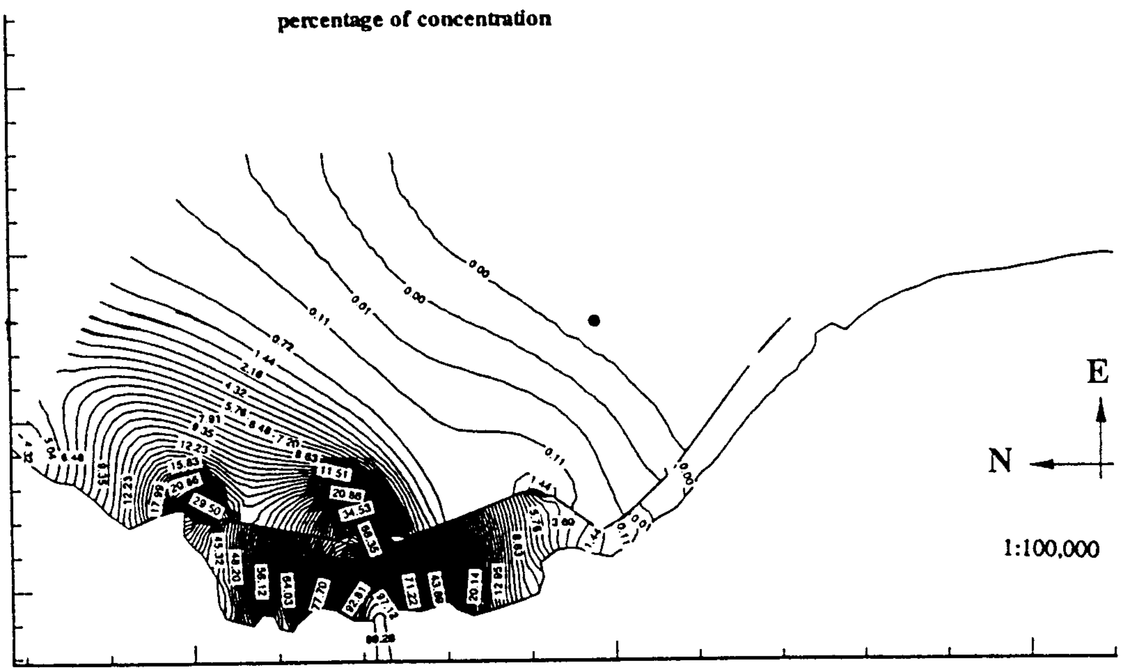

Figure 5. The concentration distribution of a marker pollutant from the river inflow under a southeast wind.

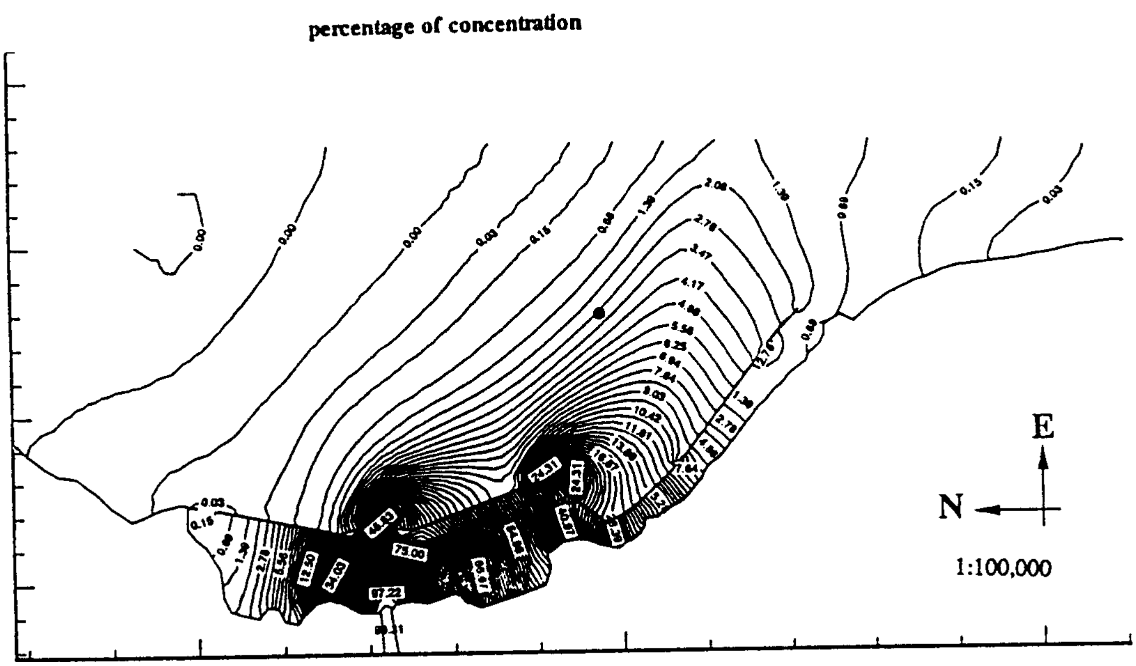

Figure 6. The concentration distribution of a marker pollutant from the river inflow under a northwest wind.

Water Taken into the Linnwood and the Howard Avenue Filtration Plants

E. R. Christensen and W. Phoomiphakdeephan
Department of Civil Engineering and Mechanics, University of Wisconsin-Milwaukee

Introduction

Lake Michigan serves both as a source of drinking water for Milwaukee residents and as a recipient of storm water runoff and treated wastewater. Runoff is carried by the confluence of the Milwaukee, the Menomonee, and the Kinnickinnic Rivers and empties into the Outer Milwaukee Harbor, where treated wastewater is also discharged. There are two water intakes: the Linnwood intake pipe is located north of the harbor, and the Howard Avenue pipe is located to the south of the harbor (Figure 1). It is well known (Mortimer, 1981) that the pollution plume moves mainly towards the southeast. Thus, water from the Howard Avenue intake may be more impacted by pollution than water from the Linnwood intake.

There was a major outbreak of cryptosporidiosis in Milwaukee in April, 1993 (Fox and Lytle, 1994) that was linked to several factors. *Cryptosporidium* is thought to come from cattle, and it's possible that it was introduced into the river through spring farm runoff. However, runoff from urban areas and wastewater effluent are also possible carriers of this organism.

The objectives of this work are (1) to estimate seasonal variations and pollution plumes, (2) to calculate correlations between pollutants at the confluence of the rivers or the wastewater effluent point and Milwaukee Metropolitan Sewerage District (MMSD) stations close to the water intake pipes, and (3) to estimate pollution levels at actual and alternative intake crib locations for the Howard Avenue Plant. Objectives were accomplished using MMSD data (MMSD, 1993; 94)

Ammonia, Chloride, Turbidity Data, 1983-92 vs. 1994

Of the several water quality parameters collected by MMSD (1991), we focused on data for ammonia, chloride, and turbidity. Ten nearshore (NS-01 to -10) and 14 Outer Harbor stations (OH-01 to -14) were considered. Data were available for the surface (S, 1 m from top), the middle (M, mid-depth), and the bottom (B, 1 m from bottom) of the water column.

<u>Seasonal variations and pollution plumes 1983-92.</u> For stations OH-13,B and NS-07,B, both of which are close to the Howard Avenue and Linnwood intakes, respectively, the turbidity in late March (3/26/87) had a high value (13 NTU) characteristic of runoff. This value is associated with somewhat elevated chloride levels. Ammonia seems to have little relation to the chloride and turbidity values. Ammonia values are high during the summer months, and also in late October.

Hand-drawn, estimated turbidity contours for spring (average values for March, April, and May) 1987 are shown in Figure 1. The plume moves in an east-southeast direction.

<u>Correlations 1983-92.</u> The Outer Harbor Channel carrying river runoff (OH-01,M) and the Jones Island Wastewater Treatment Plant outfall area (OH-02,S) are potential sources of turbidity. The receptor areas are OH-13,B (Howard Avenue intake), and NSS-07,B (Linnwood intake). When comparing turbidity vs. time, and from calculations, there is a strong correlation between stations OH-02,S and OH-13,B, a weak one between OH-01,M and OH-13,B, and a negative correlation between the considered sources and NS-07,B. Thus, Jones Island effluent, rather than river runoff appears to be the major source of turbidity to the Howard Avenue intake.

Results of similar calculations for all three pollutants, 1983-92, are summarized in Table 1. The number of years considered is given in parenthesis. From this table, turbidity at OH-13,B, is, as above, linked mainly to sewage effluent, while chloride at OH-13,B is linked to both runoff and sewage effluent.

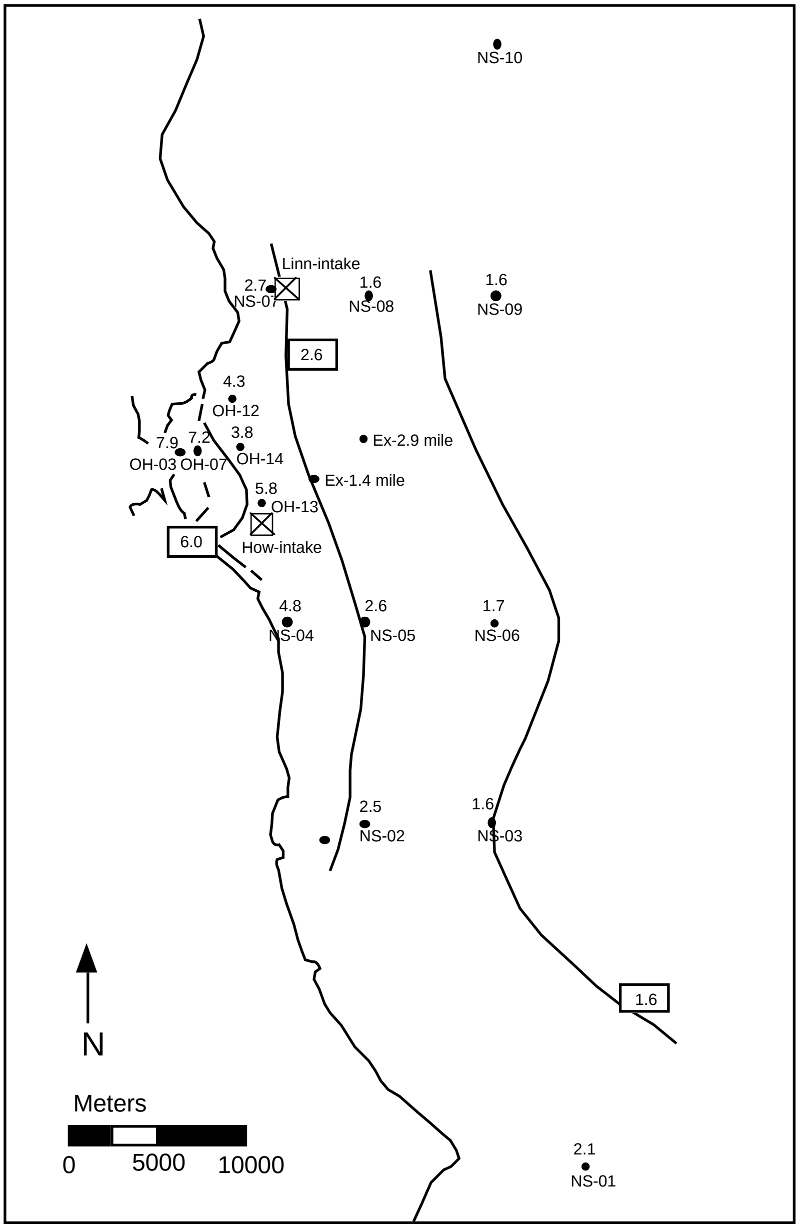

Figure 1. Milwaukee Nearshore area with MMSD Sampling Stations and Estimated Turbidity Contours for Spring 1987. Water Intakes and Hypothetical Extensions of the Howard Avenue Intake Pipe are Indicated.

<u>Kriging estimates 1983-92 vs. 1994 .</u> Pollutant levels at the filtration plant intakes and hypothetical extensions of the Howard Avenue pipe (1.4 and 2.9 miles) were estimated by simple kriging (Gilbert and Simpson, 1985). The semivariogram was established based on pollutant levels at stations NS-07, OH-12, OH-14, OH-13, and NS-04 in the north-south direction. The total kriging system for estimating pollutant levels at extensions of the Howard Avenue pipe consisted of stations NS-07, NS-08, OH-12, OH-14, OH-13, NS-04, and NS-05. For the Linnwood intake the stations were NS-07, NS-08, and OH-12 (Figure 1). The semivariograms and estimates were based on average spring data for 1985, 86, 87, 91.

Sampling for 1994 did not start until May 3. Turbidity levels during this period were quite moderate and were, in part, related to the chlorophyll levels. In fact, the turbidity during May and June was higher at NS-07,B than at OH-13,B.

The semivariogram for turbidity was found to be represented by a spherical model with a sill of 1.2 $(NTU)^2$ and a range of 7000 m. In contrast, the chloride semivariogram was a straight line, without nugget, of slope 0.000278 $mg^2 1^{-2} m^{-2}$ (Phoomiphakdeephan, 1994).

The results of the kriging estimates are shown in Table 2. For 1985, 86, 87, 91, the turbidity and chloride levels gradually approached the values at the Linnwood intake as the Howard intake pipe was extended to 1.4 and 2.9 miles. When the pipe was extended to 2.9 miles, the water quality was comparable to the water quality found at the Linnwood intake. The recommendation in CH2MHILL'S report (1994) was to extend the pipe 0.8 miles on a 30 degree bearing east to northeast from the present intake crib.

For 1994, the first year of operation of the in-line storage system (deep tunnels), there is an actual increase in turbidity as the Howard Avenue intake pipe was extended. Whether this is related to the effect of the deep tunnels or just reflects slow diatom-related natural turbidities is not clear. Sampling earlier in the spring, i.e. March and April, that would catch runoff events, could have clarified this.

		Ammonia		Chloride		Turbidity	
Year	Stations	OH-01,M	OH-02-S	OH-01,M	OH-02-S	OH-01,M	OH-02-S
Average	OH-13,B	-0.157+0.387 [10]	-0.068+0.232 [10]	-0.483+0.398 [10]	-0.415+0.326 [10]	-0.690+0.271 [10]	-0.157+0.387 [10]
	OH-13,B	-0.158+0.383 [3]	-0.048+0.507 [3]	-0.493+0.445 [3]	-0.385+0.537 [3]	-0.200+0.547 [3]	-0.011+0.329 [3]

Table 1. Correlation coefficients between Stations for Ammonia, Chloride, and Turbidity.

Estimated Stations	Turbidity Concentration (N.T.U.)		Chloride Concentration (mg/l)	
	Avg. Spring 85,86,87,91	Avg. Spring 94	Avg. Spring 85,86,87,91	Avg. Spring 94
Linn-intake	2.7 ± 0.6	1.6 ± 0.6	8.6 ± 0.6	4.8 ± 0.6
How-intake	4.0 ± 0.6	1.3 ± 0.6	10.7 ± 0.6	9.5 ± 0.6
Ex-1.4 mile	3.6 ± 1.0	1.4 ± 1.0	9.9 ± 1.0	8.0 ± 1.0
Ex-2.9 mile	3.3 ± 1.2	1.5 ± 1.2	9.2 ± 1.2	6.3 ± 1.2

Table 2. Estimated Values of Turbidity and Chloride at Unsampled Locations by Kriging Interpolation.

Conclusion

Turbidity and chloride concentrations generally decline with hypothetical extensions of the Howard Avenue intake pipe, based on data for 1985, 86, 87, 91. A tripling of the length makes the intake water quality comparable to that of the Linnwood intake. The turbidity levels of 1994 are low, but it is uncertain whether this is due to the operation of the deep tunnels.

Improved kriging estimates after 1994 may be obtained by (a) sampling early in the spring to catch significant spring runoff, and (b) sampling all Outer Harbor and nearshore stations on the same day.

Acknowledgments

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Current and Temperature Measurements

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Abstract. Currents in the nearshore region of western Lake Michigan were characterized using measurements recorded at several mooring sites near Milwaukee Harbor, Lake Michigan during 1993-94. The observational array consisted of one mooring 7 km offshore in 23 m water that recorded current velocity and water temperature data for 450 consecutive days, two current meter moorings near the City of Milwaukee water intakes during summers in 1993 and 1994, and an additional mooring 10 km offshore during the 1994 summer. Meteorological and water temperature data were recorded on a National Data Buoy Center (NDBC) meteorological buoy moored 6 km offshore during the 1993 and 1994 open-water months.

Current patterns were strongly dependent on wind direction and speed during all seasons with the most effective winds corresponding to directions with the greatest fetch. Flow was generally constrained to shore-parallel directions interspersed by periods of very weak currents. Variability during summer stratification was generated by near-inertial baroclinic internal oscillations (Poincare'-type waves) superimposed on a quasi-steady barotropic current. Maximal current magnitudes were generally less than 30 cms^{-1}. Upwelling and downwelling events, a consequence of alongshore wind stress, were a regular feature, though the intensity was less than that generally observed on the eastern shore of Lake Michigan. Limited cross-shore transport was associated with the rotary, near-inertial currents and the upwelling/downwelling activity during spring and summer when the lake was well stratified.

Water temperatures cooled to 4 ^{o}C by mid-December, decreased to near zero from mid-January to mid-March, and warmed to 4 ^{o}C by mid-April. Flow was southward during the isothermal months of December through June, with limited variability at subinertial (>2-day) time scales. Current magnitudes were markedly reduced when ice cover was present in the region. Cross-shore transport at the measurement sites off Milwaukee was minimal when the water mass was vertically homogenous as indicated by the lack of onshore-offshore flow. In winter, any cross-shore transport that occurred was primarily associated with flow over bathymetric features and the coastline geometry.

Results from this project were published in April 1997 in NOAA Technical Memorandum ERL GLERL-102. **Nearshore Current and Temperature Measurements, Western Lake Michigan. Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 11 pp (1997).**

Wind and Wave Measurements

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Introduction

Wind and waves are the primary driving forces for water movements in the ocean and lakes and are the major basic factors determining nearshore hydrodynamics. A collection and synthesis of wind and wave data are the first and foremost tasks in a comprehensive nearshore hydrodynamics study. The NOAA National Data Buoy Center (NDBC) has deployed equipment and collected meteorological and wave data for National Weather Service (NWS) in the center locations of the Great Lakes since 1979, but data in the nearshore areas has been completely lacking. As nearshore areas of the Great Lakes are the most intensively utilized and environmentally sensitive, a similar data collection system for the Great Lakes nearshore area is urgently needed. Recognizing this need for nearshore data, and recognizing that nearshore waves are resolutely affecting the transport, fate, suspension, and resuspension of coastal sediments and pollutants, the GLERL Nearshore Hydrodynamics Program was implemented. As part of this program, an additional instrumented NDBC buoy 45010 (Figure 1) was deployed to collect nearshore wind and wave data in western Lake Michigan near Milwaukee, Wisconsin (at 43-00-02N and 87-48-02W) from 1993 to 1995 in a water depth of approximately 15 m. This paper presents a brief description of the instrumentation and measurements, the information and availability of data, and some highlights of the results of the analysis.

The Buoy and Measurements

The NDBC buoy 45010 deployed during 1993-1995 was made with a 2.4 m diameter foam discus hull that contains the sensors, electronics, and batteries. Although smaller than the traditional 3 m hull buoys, it has identical measurement capabilities, but small enough for easy handling and large enough to provide adequate reserve buoyancy and survivability for the total payload. The onboard equipment includes a Data Acquisition and Control Telemetry (DACT) payload, a Directional Wave Analyzer (DWA) board for the DACT, a Datawell HIPPY 40 heave-acceleration, pitch and roll sensor, a two-axis magnetometer, two barometers, two compasses, and a water temperature sensor. The HIPPY 40 analogs provide, in addition to hull pitch and roll, vertical acceleration and displacement. The displacement analog was generated by a double integrator fed by the accelerometer.

Also mounted in the cylindrical compartment are primary and secondary batteries and a power control system. The batteries provide adequate power supply to the buoy system for up to 8 months. Solar panels mounted on the buoy superstructure provide the power to recharge the secondary batteries. Main sensors mounted on the buoy superstructure consist of two wind sensors located at 4 m above water level, each measuring wind speed and wind direction relative to the buoy bow, an air temperature sensor, and a fin to orient the buoy when the wind speed is sufficient. Voltage output from the sensors on the superstructure route to the interior package. Samples were transmitted from the DACT every hour to a shore receiving station through the Geostationary Operational Environmental Satellite (GOES). Directional wave data from the buoy were further processed to correct for hull mooring effects, and distributed in FM 65 WAVEOB format on WMO circuits. The meteorological data were also transmitted to other National Weather Service circuits. All data were received monthly at GLERL on 9-track magnetic tapes and were further processed to provide monthly ASCII matrix data files that can be accessed at the GLERL anonymous FTP site.

An Overview of Measured Wind and Wave Data

The basic data acquired from the NDBC buoy consists of hourly measurements of air and water temperatures, wind speed, wind direction, significant wave height, dominant wave period, average wave period, mean wave direction, and non-directional and directional wave spectrum. The availability of these measurements establishes a source of data for practical as well as research use.

In general the 3 years during which the buoy 45010 was deployed have been relatively calm and mild with no significant storm events. The maximum measured wind speed and significant wave height are respectively 14.9 m/s and 3.4 m, 12.9 m/s and 2.8 m, and 16.4 m/s and 3.8 m for 1993, 1994, and 1995. Figures 2, 3, and 4 present an overview of the general distribution of some of the measured wind and wave parameters during 1993, 1994, and 1995, respectively. The composed patterns of these distributions are basically similar from year to year. The unprecedented availability of nearshore wave direction measurement has provided an interesting glimpse of the characteristics of wave spreading in the nearshore area. It appears that while wind directions were rather evenly distributed among southeast, south, southwest, west, and northwest directions, wave directions were predominately from the southeast. That is most likely due to the shoreline effect. These nearshore wind and wave direction distributions distinctly contrast the open lake measurements from NDBC buoy 45007 in which wind and wave direction were both predominately from the south.

Time Series Measurements

Collecting and archiving the basic hourly wind and wave parameters and wave spectra are important not only because they are of practical interest to weather forecasters, mariners, engineers, and scientists, but they are also helpful in decreasing and facilitating the volume of data being handled. However, omitting the original time series that produced the available information prohibits the opportunity to reexamine the data with other newly developed and improved approaches. With the recent advances of time frequency analysis beyond the long standing Fourier analysis, interests in time series measurements have renewed. In the early 1990's, the international program of Surface Wave Dynamics Experiment (SWADE) implemented extensive recordings of time series data. Since then, time series measurements have increasingly become the focal interest of research studies on wind and waves. NDBC has also started to conduct tests of time series measurements on the NDBC buoys. In 1995 additional wind and wave time series measurements were added to buoy 45010 for an exploratory test of operations in the Great Lakes. Along with the recently advanced Wavelet Transform analysis, the availability of continuous high quality time series data for both wind and waves not only provided a new and exciting direction of wind waves study, it can also led to completely new conceptual insights that might significantly revise many of the well known and well established thoughts on wind wave analysis.

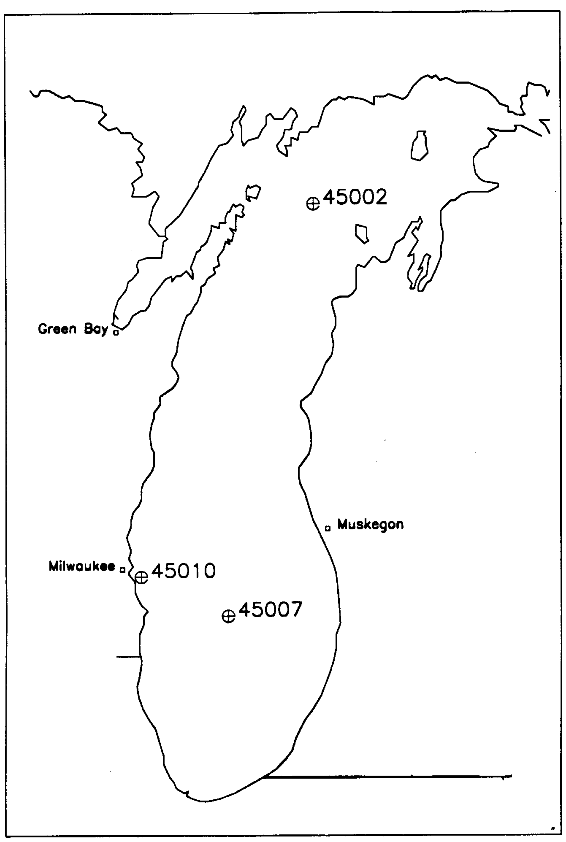


Figure 1. Location map of NDBC buoys in Lake Michigan.

An Episode of Nearshore Wind Wave Growth

While there were no real significant storm events during 1993-1995, the collection of time series data in 1995 still provided a unique and useful data set of wind and wave time series for detailed wind wave studies. To facilitate the selection of an appropriate subset of time series data for detailed study, it is useful to start with plots of basic measurements. An illustra-

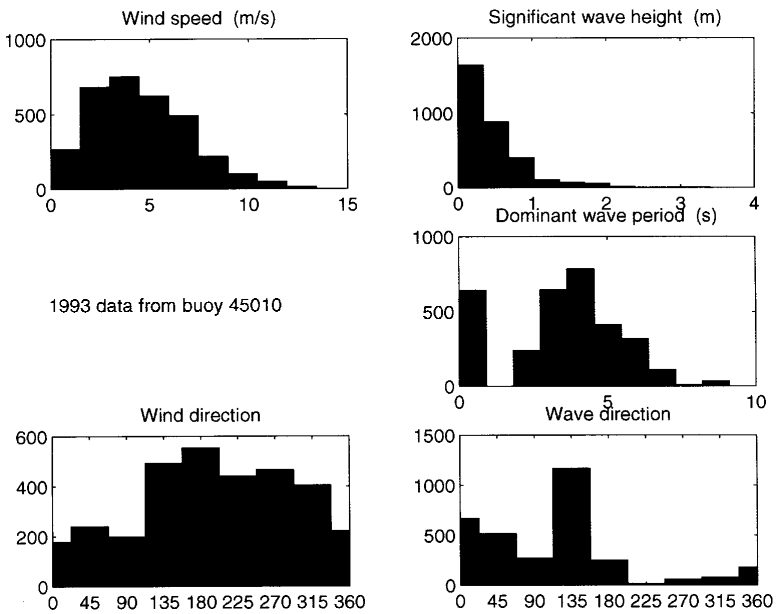


Figure 2. Distributions of the wind speed, wind direction, significant wave height, dominant wave period, and wave direction for the data measured in 1993.

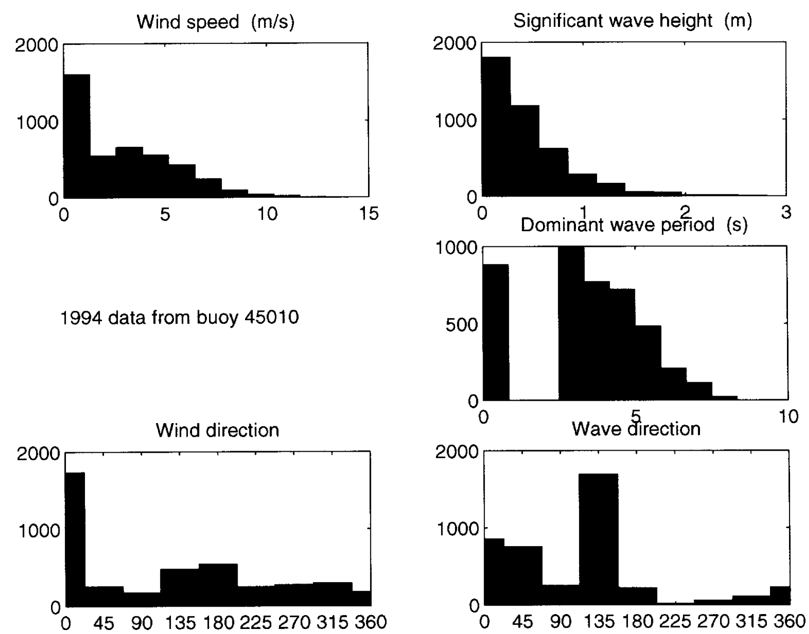


Figure 3. Same as Figure 2 for data measured in 1994.

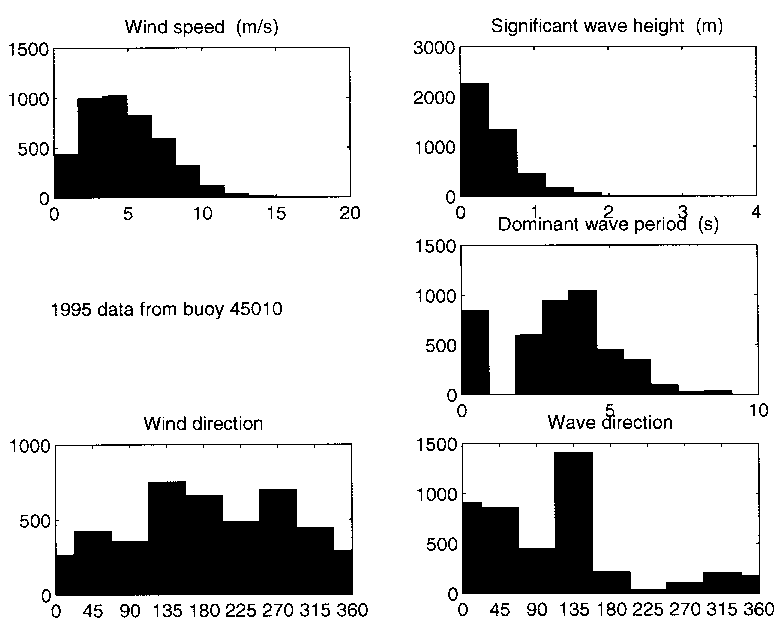
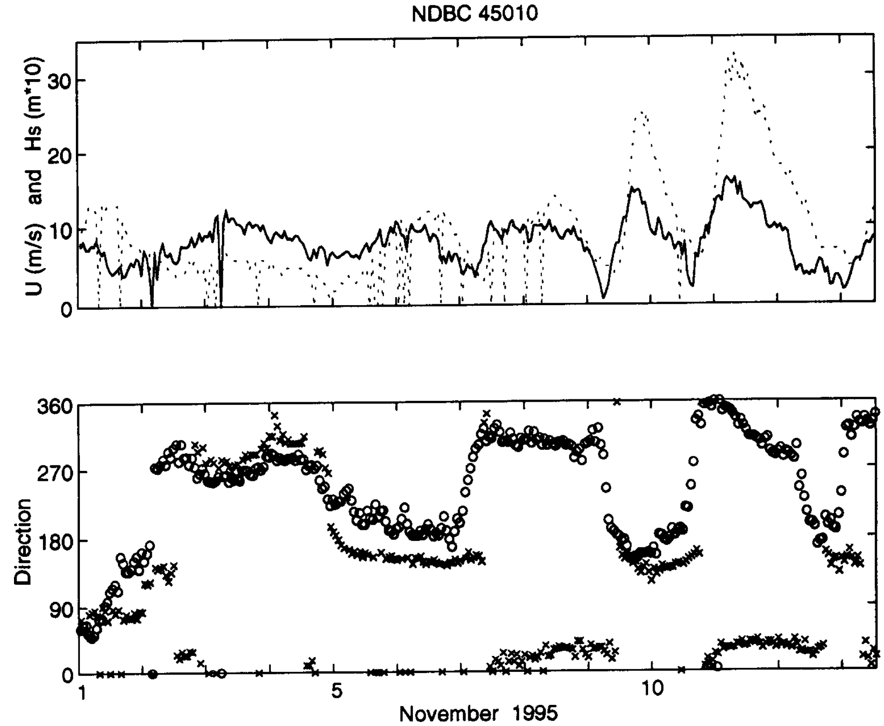


Figure 4. Same as Figure 2 for data measured in 1995.

Figure 5. A data plot for NDBC buoy 45010 during November 1995. The upper panel shows wind speed with a solid line and significant wave height with a dotted line. The lower panel shows wind direction with open circles and wave direction with x’s.



tion that presents measured hourly wind and wave conditions for the month of November 1995 from NDBC 45010 is given in Figure 5. The upper panel shows wind speeds represented by the solid line and significant wave heights represented by the dotted line. The lower panel presents the corresponding wind and wave directions in open circle and x’s respectively. An immediate observation of this figure would be the obvious close correlations between wind and waves. The growth and decay of significant wave heights closely follows the increase and decrease of wind speeds with wind and wave directions responding similarly. The last part of the plot, during 9-12 November 1995 just before the buoy was retrieved for the winter, there were two consecutive moderate storm events that raised wind speeds to over 15 m/s and significant wave heights to nearly 3 m.

To explore the detailed wave growth characteristics, we focused our interest on the first part of the event where wind and waves grew continuously while their directions remain unchanged. We obtained an episode of 8 hours of continuously recorded time series for wind speed and surface displacement as shown in Figure 6.

We first followed the conventional approach. For each of the 8 hours, the first 20 minutes of the data were used to calculate a frequency wave spectrum. This is shown in the lower panel of Figure 7. This is indeed an ideal wave growth case, the hourly frequency wave spectra grew consecutively with spectral peak, and front face shift continuously toward lower frequencies, while the high frequency side of the spectra formed the saturated equilibrium range.

However, this is also where the conventional approach ended. Conventionally, the spectral energy and spectral peaks are used to correlate the constant hourly wind speed. Now from the upper panel of Figure 7 we see that the corresponding hourly wind speeds are by no means constant. Each of the hourly wind speeds has their own frequency spectrum, and they grow continuously just like the growth of the wave spectrum. Therefore, the use of a constant hourly wind speed to correlate with the spectral parameters is clearly unrealistic.

Furthermore, the well behaved spectral wave growth as shown in the lower panel of Figure 7 also becomes questionable when we calculate the Wavelet Transform for the data and obtained the time-frequency wavelet spectrum shown in Figure 8. Figure 8 shows the contour plots of the wavelet energy density in the time-frequency domain. While integration of the hourly result in Figure 8 would still lead to Figure 7, the implications

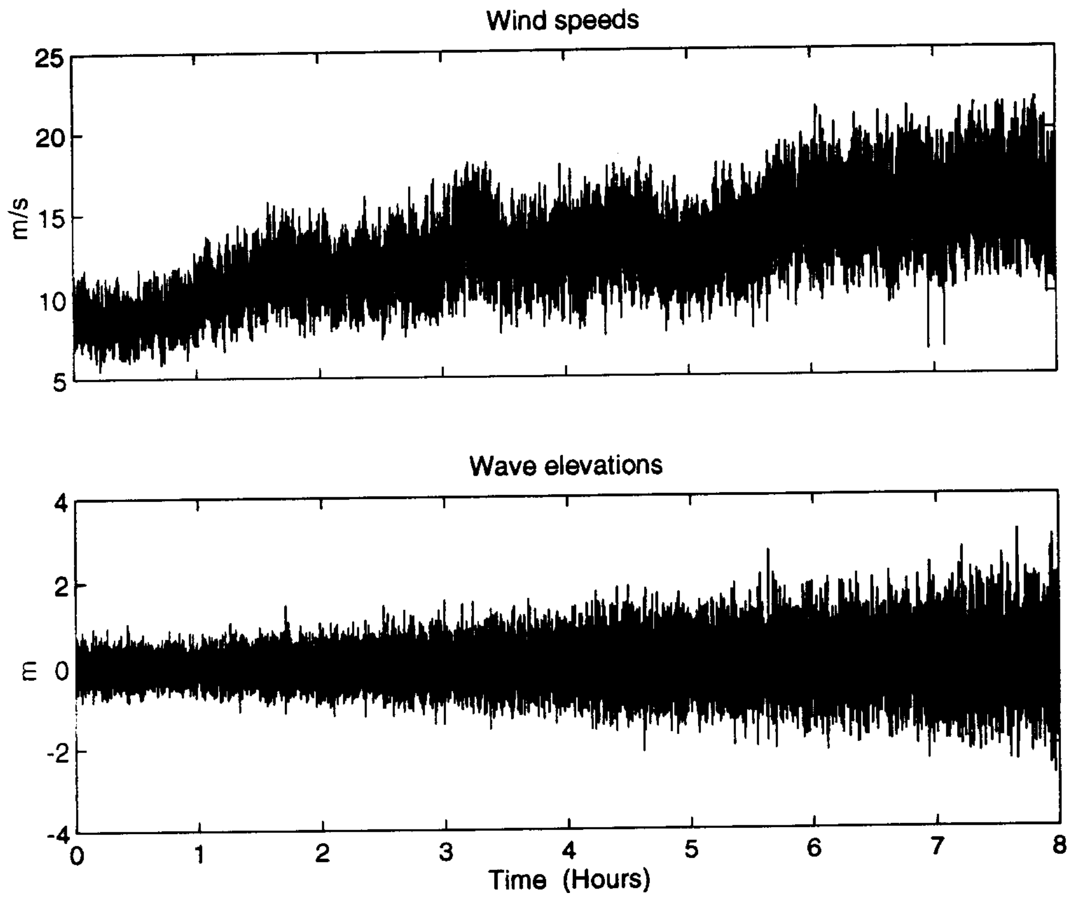


Figure 6. Continuous time series plot of wind speeds and wave elevations.

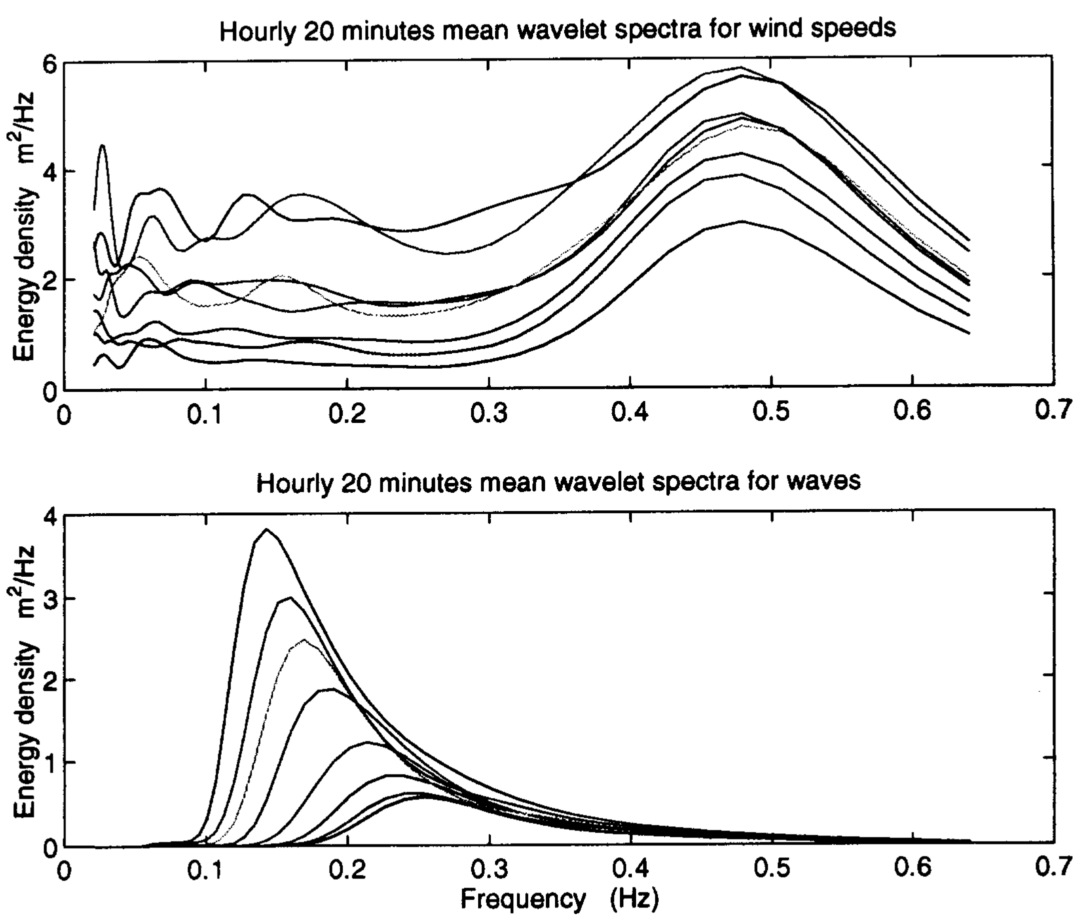


Figure 7. Hourly 20 minutes mean wavelet spectra for wind speeds and waves.

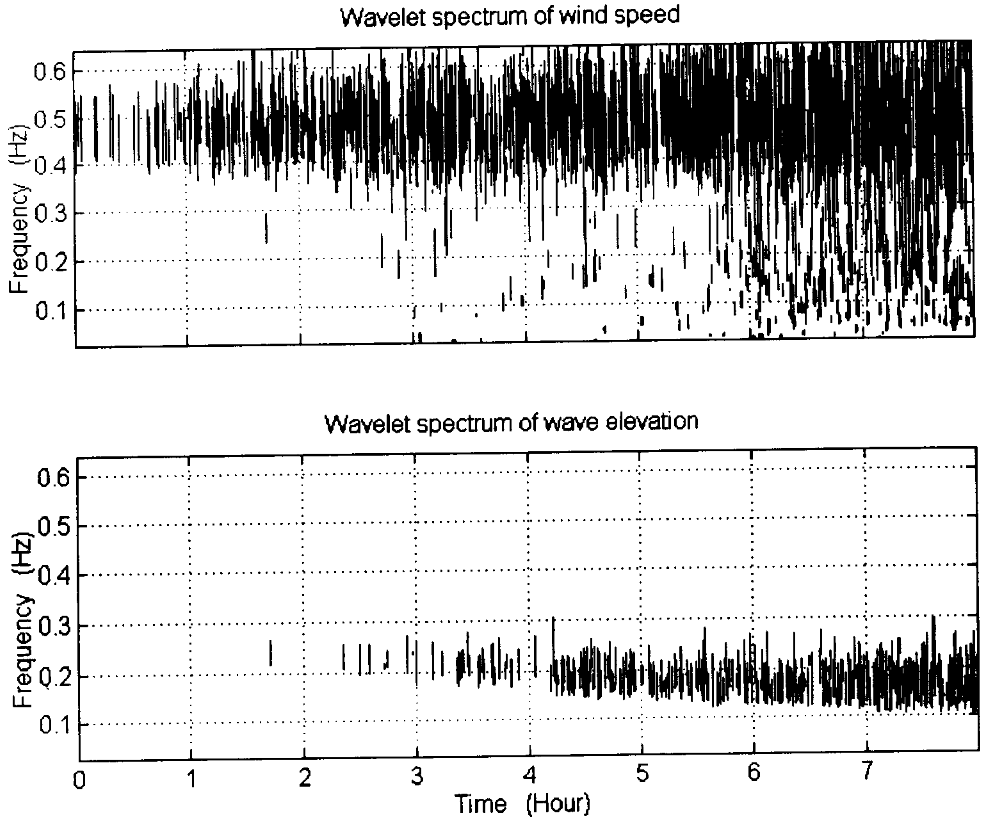


Figure 8. Contour plots of wavelet spectra for wind speed and wave elevation.

one may draw from Figures 7 and 8 will be clearly different. Figure 7 may give an impression that the wave growth would be continuous and smooth, but Figure 8 shows the growth was neither continuous nor smooth. A better way to visualize the detailed behavior of Figure 8 is by the three dimensional hourly plots for waves and wind speed as shown in Figures 9 and 10, respectively. These figures show that the growth of both wind and waves took place through many intermittent time-localized growth and decay events. For waves, these intermittent time-localized growth and decay events may very well be represented by the relatively unexplored wave grouping characteristics.

This new time series data set has posed questions of many of the well established conventional approaches to wave studies and, therefore, presented new challenges for a fresh, new approach to wind wave studies.

Conclusions

The 3 years of wind and wave measurements in western Lake Michigan have provided a useful data set for practical applications as well as model development and verifications. The added time series measurement in 1995 also provided new challenges to the overall wind wave studies and approaches. This is the first time systematic nearshore wind and wave measurements were made, representing only a small portion of the vast nearshore areas of the Great Lakes. The current state of knowledge of wind and waves only provides approximate understanding. Long-term monitoring of wind and waves in many of the nearshore areas is needed to develop a detailed understanding of the processes of wind waves.

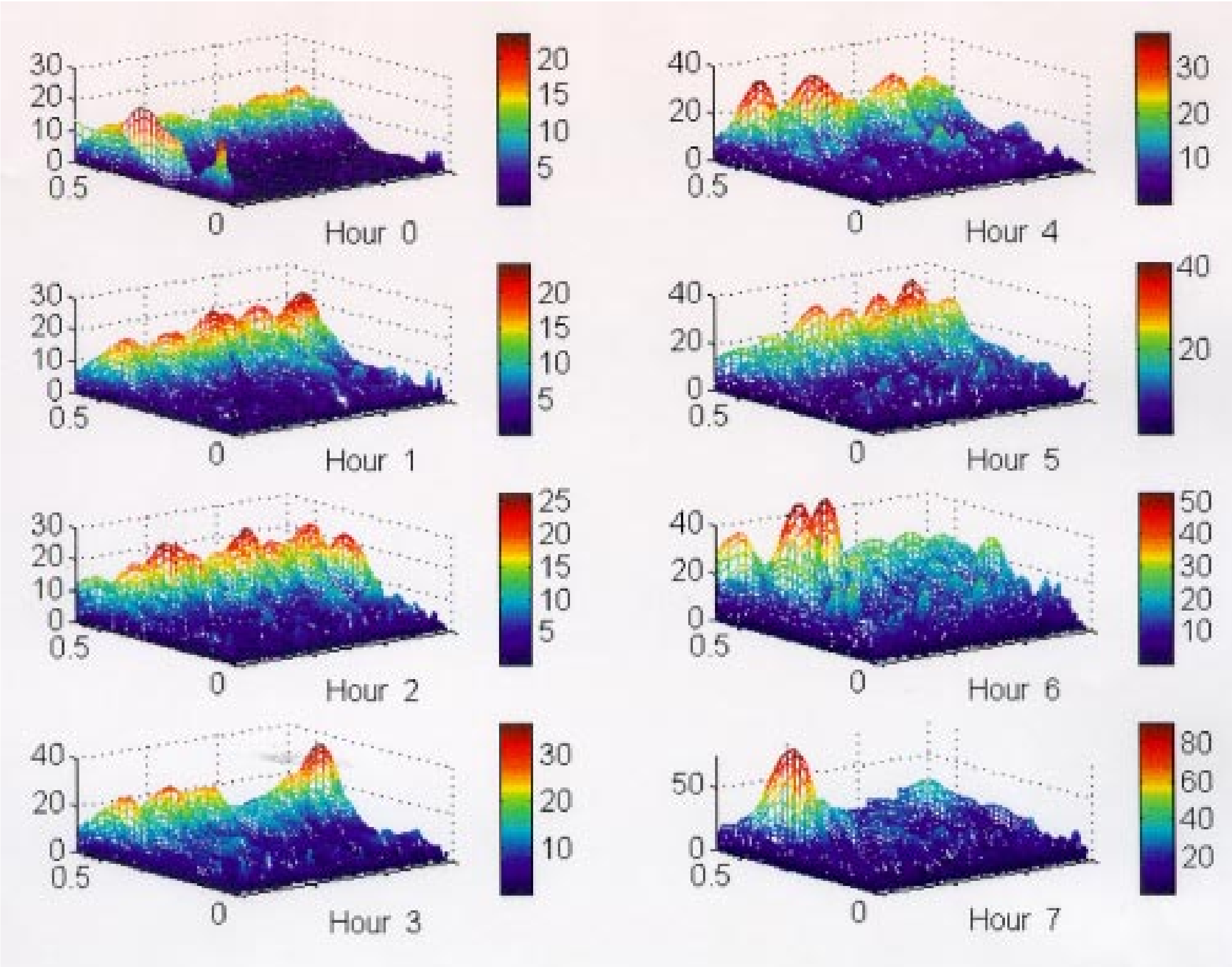


Figure 9. Hourly 3-D plots for wave wavelet spectra.

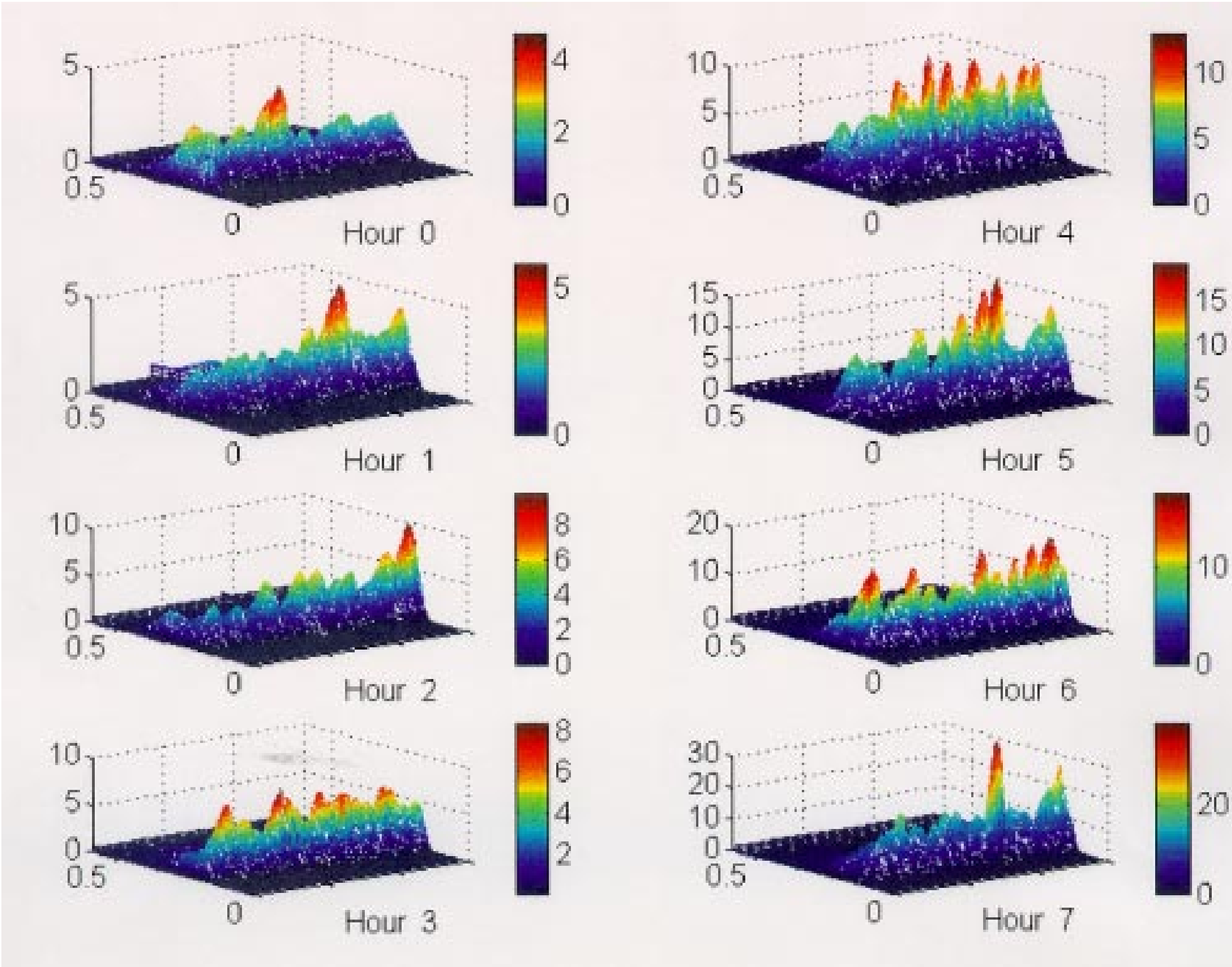


Figure 10. Hourly 3-D plots for wind speed wavelet spectra.

Sediment Resuspension in Green Bay

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Introduction

Lack of knowledge regarding the processes responsible for the transport and deposition of cohesive sediment remains one of the main difficulties in developing accurate models of pollutant pathways in the Great Lakes. One facet of this problem is the prediction of sediment resuspension as a function of wave and/or current action. In this project, previously collected time series observations of wave action, current velocity and suspended sediment concentration were analyzed with the goal of developing an empirical criterion for the onset of sediment resuspension in southern Green Bay. The main objective is to develop an empirical relationship which predicts bottom resuspension in southern Green Bay as a function of wave and current activity.

Results

Time series measurements of current velocity and suspended sediment concentration had previously been made at five sites in southern Green Bay during 1988 and 1989 as part of the EPA's Green Bay Mass Balance Study (Figure 1). In addition, wind and wave conditions were monitored at station 40. Initial analysis of the data showed that no resuspension events occurred at any of the stations except for station 40. This was the shallowest of the 5 stations (water depth of 9.5 m), and the only one where (based on wave theory) surface wave action would be expected to reach the bottom. Thus it appears that current action alone is inadequate to resuspend bottom sediment in the bay. Initial calculations also showed that the interaction between waves and currents was a second-order effect, and that surface wave action was the primary cause of sediment resuspension in the bay. Since theory predicts that the effects of surface waves would not penetrate below 15 m, it appears that sediment resuspension would not be expected to occur in a large part of the bay.

Figure 2 shows the observations from the Fall of 1988 at station 40. These show two instances (on September 27 and October 4) where the increases in suspended sediment concentration 0.9 meters above the bottom (mab) is clearly related to increased wave activity (as measured by the shear stress at the bottom). The observations also show that the suspended sediment concentration 2.4 mab frequently differs from that at 0.9 mab, and exceeds that at 0.9 mab on several occasions. The observations made during 1989 (Fig. 3 and Fig. 4) show no clear episodes of sediment resuspension although on several occasions the shear stress is almost as high as during the fall of 1988. In fact the episode that most resembles a resuspension event (that on June 28) occurs on a day when the shear stress is extremely low. There appears to be no consistent correspondence between wave shear stress and suspended sediment concentration, so factors other than wave action are at least partially responsible for the observed changes in suspended sediment concentration.

Since the concentration of suspended sediment is not constant throughout the water column, a vertically-integrated model of sediment resuspension - such as the one used by Hawley and Lesht in Lake St. Clair (1992) - is inappropriate for this data set. We obtained and implemented the code for three one-dimensional models of resuspension - those of Lavelle and Baker (1984), Glenn and Grant (1987), and Vongvisessomjai (1986) - but found that none of them could accurately simulate the observations. There are certain difficulties specific to each model, but a common (and probably the most important) one is that because of the large changes in the bays' bathymetry over short distances, lateral transport is probably an important cause of changes in the concentration of suspended material. Since all vertical one-dimensional models assume lateral homogeneity, models of this sort are incapable of simulating observations in which lateral transport is important - unless the effects of advection can be removed. Although we attempted to do this, we were unsuccessful. To accurately model the observations, a three-dimensional model of the circulation in the bay is needed. It might then be possible to couple a one-dimensional model of sediment resuspension to this model in order to simulate the observations. Unfortunately

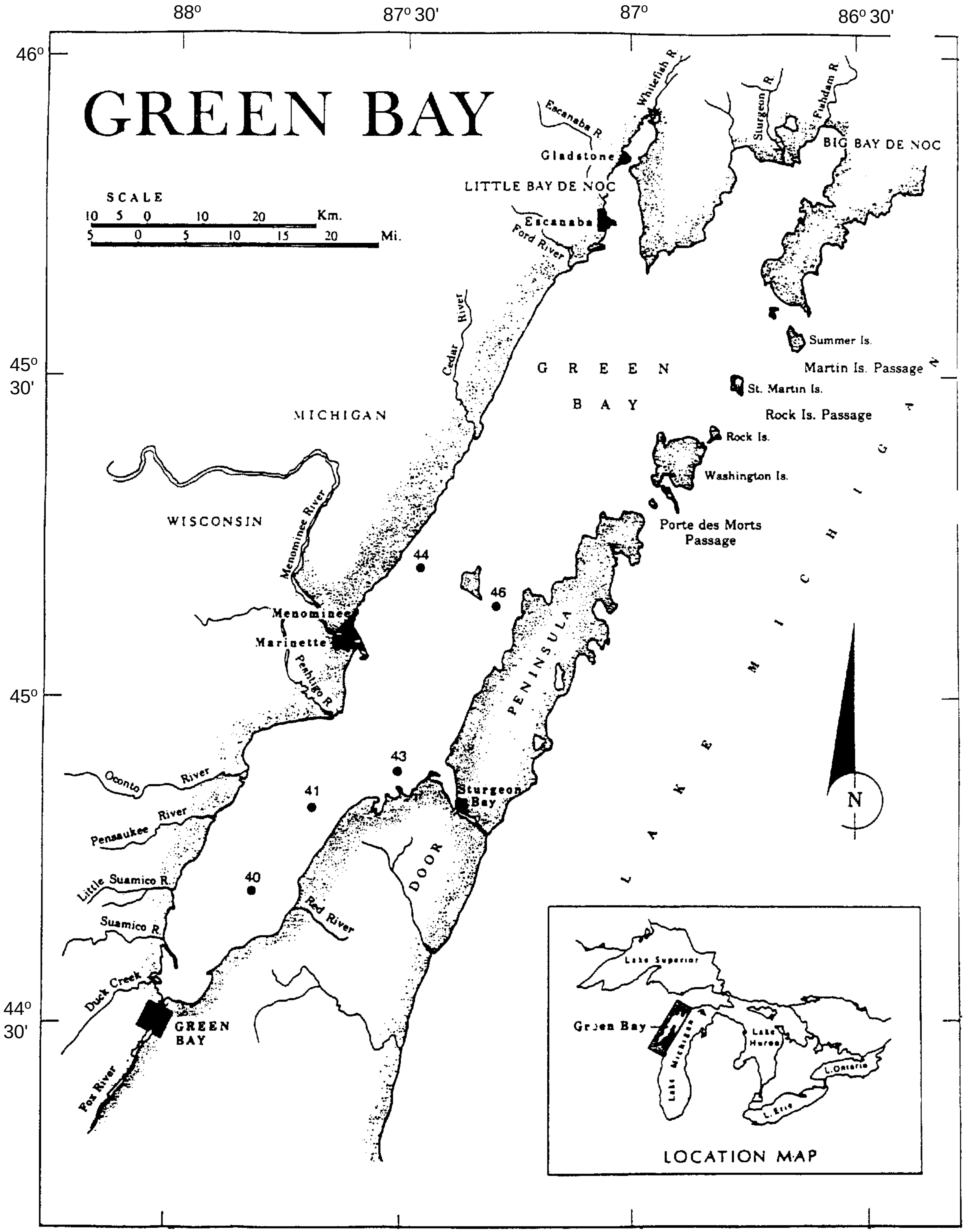
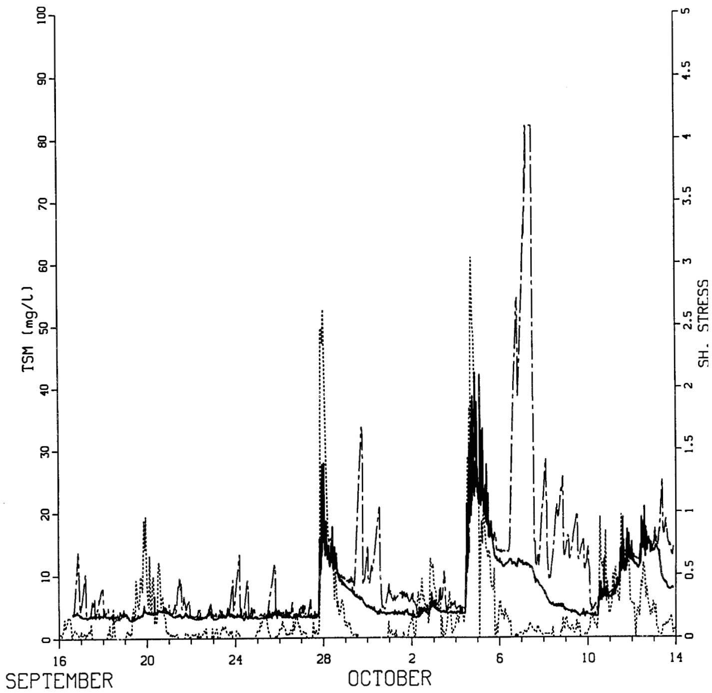
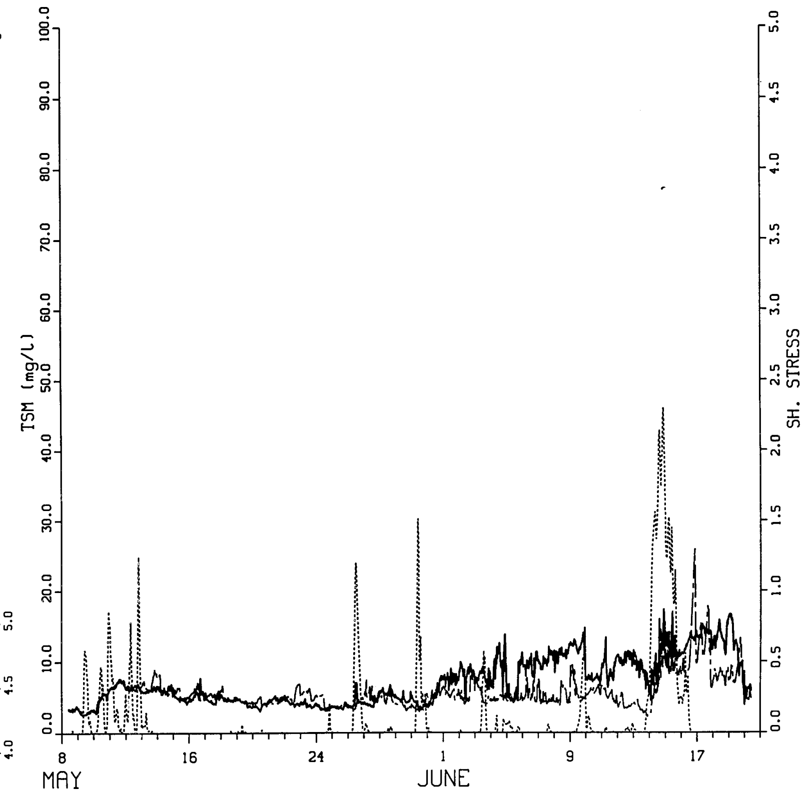
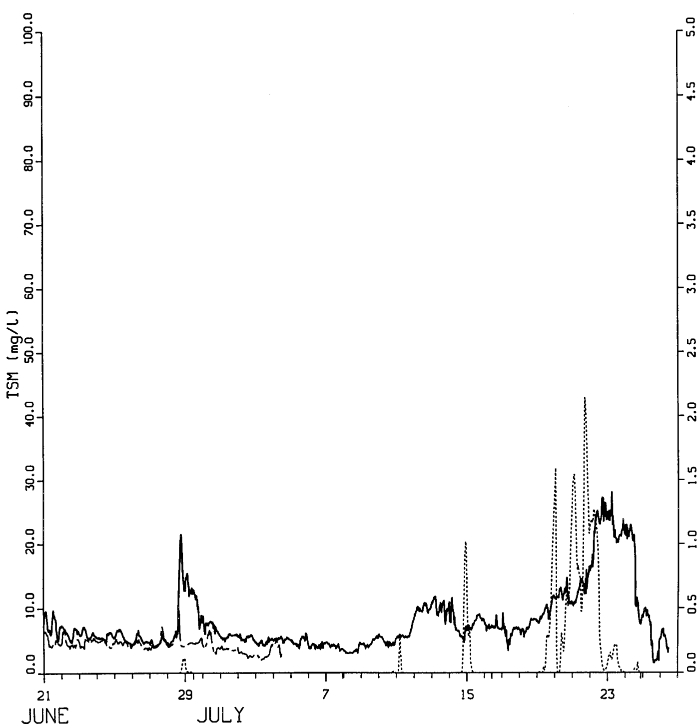


Figure 1. Five sites in southern Green Bay previously measured during 1988 and 1989 as part of the EPA's Green Bay Mass Balance Study.



Figures 2-4. Observations of suspended sediment concentration at 0.9 meters above the bottom (solid line), 2.4 meters above the bottom (interrupted line) and bottom wave shear stress (dotted line), during 1988 and 1989. In Fig. 4, the sensor 2.4 meters above the bottom failed on July 4.





such a model is not yet available, although the EPA is working on a project of this sort as part of its Lake Michigan Mass Balance Study. Thus, although we can say that resuspension probably only occurs in shallow water (less than 15 m deep), and that surface wave action is the primary cause, at this time we cannot develop a quantitative relationship between wave action and sediment resuspension for Green Bay.

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Alan Bratkovich -- In Memoriam

Alan W. Bratkovich. Alan was a well known and respected Physical Oceanographer that the Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, Michigan was fortunate enough to hire in May 1988. Prior to joining GLERL he worked as a Research Assistant Professor at the University of Southern California and previous to that was employed at Scripps Institution of Oceanography as a Research Associate. His academic career began in the engineering sciences at Purdue University where he obtained both B.S and M.S. degrees. He completed his Ph.D. work in Oceanography at Scripps.

While working in California, Alan's major research activities focused on the dynamics, energetics, and predictability of coastal tides in stratified waters with varying topography; the use of planktonic organism distribution as an indicator of physical variability in marine environments; and studies on the seasonal and inter-annual variability of the coastal circulation along Central California. After coming to GLERL he became involved in studies on the physical, chemical, and biological variability near fronts. This work was concentrated on springtime fronts in Lake Michigan. Concurrently, he joined research teams working in two major NOAA research programs that were conducted in the Gulf of Mexico and in the Southeast Atlantic Bight.

Demands on Alan's time continued to increase throughout his career because of his broad interests, many talents, and admirable personal style. Consequently, once he joined NOAA he also became an active committee participant in NOAA's Coastal Ocean Program, NOAA's Scientific Ship Usage Committee, served on NSF and Sea Grant-sponsored review panels, taught classes at The University of Michigan, and served on Ph.D. committees. Despite the demands, Alan was extremely generous with his time. It seemed that he would never turn down a request for help from his colleagues, and because of this, ended up involved in many research and non-research activities including serving as vice-president of the GLERL employee union. Those who worked with Alan admired his high personal ethics and courage and enjoyed his good humor. He would readily speak his mind even if he knew it would be unpopular and, yet, he would do it without being offensive. When a friend asked him how he was able to do this he said that he always tried to separate the personality from the issue.

Alan was involved. He lived with a quiet passion and worked hard for what he believed in because of his convictions and not for the potential of personal gain. He enjoyed working with people from a wide variety of backgrounds and interests and earned a well deserved reputation as one of those "physical" folk that biologists should seek out when the need arises.

Alan passed away on 7 January 1995 at the age of 43 from pancreatic cancer. He is survived by his wife, Debbie, and their two children, Erin and Gregory. NOAA lost one of its very best when Alan died, not just because of his work but also for the rare leadership traits that he possessed. Even though his physical presence is gone, his influence on those who knew him will continue by remembering and by aspiring to live by the example he set.

Michael J. McCormick
GLERL