Hydrobiologia 157: 271–278 (1988)

Changes in the abundance of blue-green algae related to nutrient loadings in the nearshore of Lake Michigan

William Y. B. Chang & Ronald Rossmann
Great Lakes Research Division, Great Lakes and Marine Waters Center, The University of Michigan, 2200 Bonisteel Blvd., Ann Arbor, MI 48109, USA

Received 30 September 1986; in revised form 25 March 1987; accepted 5 May 1987

Abstract

Nutrient loadings to the nearshore of southeastern Lake Michigan have undergone a remarkable reduction. This reduction can affect the nutrient supply and result in biological changes. Changes in phytoplankton community, particularly the blue-green algae, can be related to nutrient changes. After thermal stratification, sudden increases in the blue-green algae population were significantly correlated to soluble reactive phosphorus concentrations. Phosphorus-stimulated low dissolved silica and phosphorus limitations after stratification appear to be primary factors contributing to the success of these algae.

Introduction

The dynamics of eutrophication in large lakes can produce significant inshore-offshore differences. These differences, which are more important and distinct than any other horizontal differentiation, are evident in phytoplankton production rates and standing crops. Production rates are higher in the nearshore and reach their maximum in April and May, when primary production rates are still in the ascending phase in the offshore region (Ladewski & Stoermer, 1973; Rousar, 1973). Chlorophyll concentrations are substantially higher on the average in the nearshore zone than in the offshore zone and reach highest levels in the areas close to tributary inputs (Schelske *et al.,* 1980). The nearshore zone receives direct nutrient inputs from point and non-point sources and serves as a buffer between the source and the offshore. In the nearshore zone, nutrients are utilized by phytoplankton and are subsequently sedimented in the offshore water (Bartone & Schelske, 1982). Because this area acts as a buffer between sources of inputs and offshore waters, biological changes related to nutrient reduction in this region can be used as an early indicator of eutrophication trends in the offshore water (Beeton & Edmondson, 1972).

The nearshore waters, waters with a depth ≤27 m (Rossmann & Seibel, 1977), in southeastern Lake Michigan receive nutrient inputs, especially phosphorus, from the St. Joseph River (Fig. 1) and are recognized as being enriched relative to the offshore waters (Schelske *et al.,* 1980). Reductions in nutrient inputs into this region can lead to a critical reduction in nutrients available for phytoplankton growth. A reduction in loading has been observed for the St. Joseph River, which is a major point source of inputs to southeastern Lake Michigan (Fig. 2). Rossmann (1986) found a reduction in soluble reactive phosphorus between 1974 and 1981 for the nearshore zone of this region. This reduction can be attributed to progressive pollution controls implemented in the early 1970s which reduced point source loadings of nutrients, especially phosphorus, to the Great Lakes (IJC, 1982).

The succession of major phytoplankton species is influenced by nutrient supply and concentration,

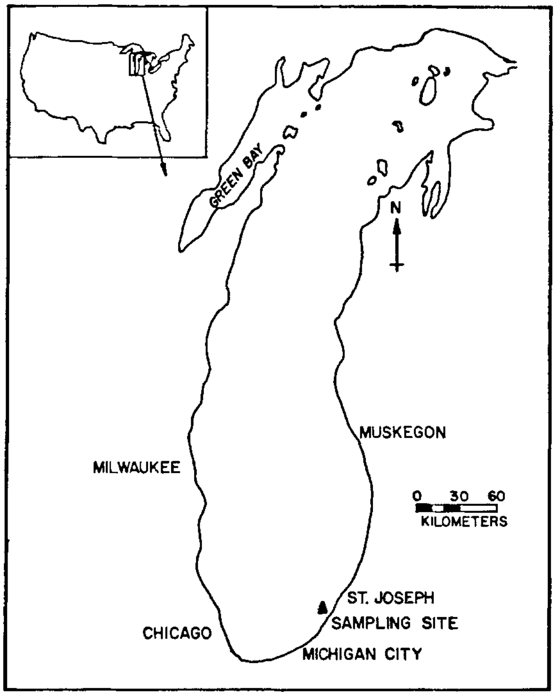

Fig. 1. Sampling site in Lake Michigan for the period of 1970 through 1982.

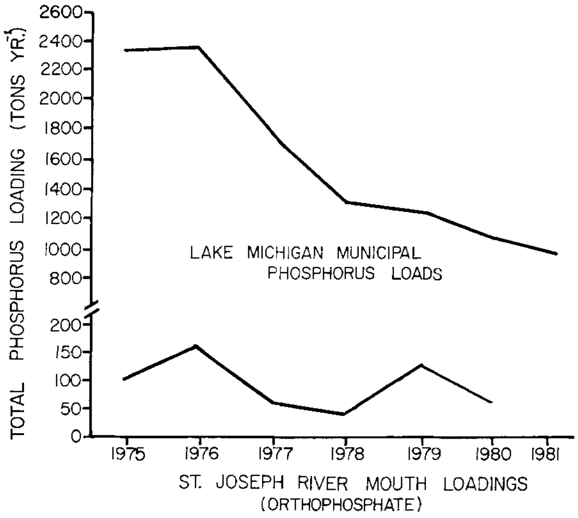

Fig. 2. Phosphorus loadings from municipal sources and St. Joseph River mouth to Lake Michigan (IJC, 1982). Data for calculation of orthophosphate loadings for St. Joseph River during 1979–1980 water years retrieved from STORET by the International Joint Commission.

which are directly related to loadings. Reduced loadings of phosphorus led to major changes in the phytoplankton community of southeastern Lake Michigan. Increases in the abundance and occurrence of blue-green algae have been observed (Fig. 3) and have been found to be related to changes in the concentration of nutrients in a statistical analysis.

Methods

Samples Analysis

Between 1970 and 1981, one-liter phytoplankton samples were collected in duplicate from the nearshore of southeastern Lake Michigan using water bottles from the R/V *Mysis,* and similar samples

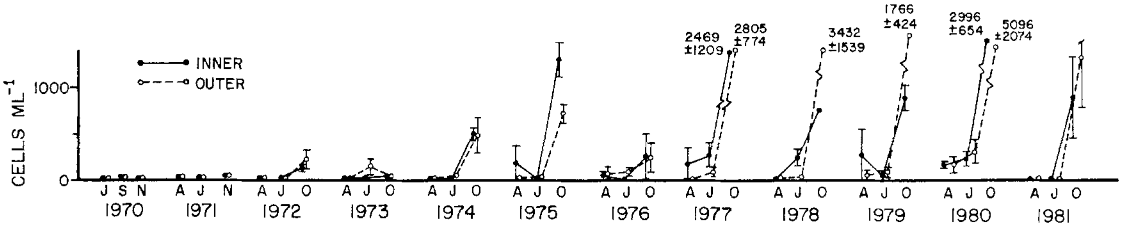

Fig. 3. Mean abundances of coccoid blue-green algae in the seasonal surveys of 1970 through 1981, where A – April, J – July, S – September, O – October, and N – November. All samples were collected from the nearshore zone of southeastern Lake Michigan, where the inner region is an area within 3.2 Km of the plant's discharge and the outer zone represents the water in the control area free from the power plant heat effluent.

from the intake and discharge forebays of the D C Cook Nuclear Power Plant (Bridgman, Michigan) were collected from 1975 to 1981 using diaphragm pumps. Each sample was preserved with 6 mL of Lugol's solution. Samples were enumerated on slides prepared by the settle-freeze method (Sanford *et al.*, 1969). Enumeration was made at 1250× with a microscope having a stage micrometer calibrated to a field width of 90 µm. Two 2.25 cm transects were made on each slide, one horizontal and one vertical, to help offset any patchiness that could occur during settling. A minimum of 500 cells was enumerated for each slide to ensure a reasonable representation from the transects counted; more transects and/or higher counts were made if a fairly large number or proportion of the cells were colonial. Phytoplankton abundance was expressed in cells per milliliter, except for blue-green filaments with cylindrical trichomes, which were expressed in filaments per milliliter. The phytoplankton were enumerated to the species level and were tabulated as coccoid blue-greens, filamentous blue-greens, coccoid greens, filamentous greens, pennate diatoms, centric diatoms, flagellates, desmids, or others.

Beginning in 1974, nutrient samples were concurrently collected with the phytoplankton samples. Water samples filtered through 0.45 µm membrane filters were analyzed for nitrogen (nitrate and nitrite), dissolved silica, and soluble reactive phosphorus. Soluble reactive phosphorus and dissolved silica were determined by the methods of Sutherland *et al.* (1966). Nitrate and nitrite were analyzed by the methods of Strickland & Parsons (1972).

Statistical Analysis

Multiple linear discriminant analysis was used to examine the relationship between environmental factors and observed increases in blue-green algae. For these algae, the analysis focuses on *Anacystic incerta* and *Gomphosphaeria lacustris,* the most abundant and consistently appearing species of blue-green algae in this region of Lake Michigan. After stratification, they often accounted for 90% of the total blue-green algae cells.

To ascertain the factors which best explained the sudden abundance increases in blue-green algae, the periods before and after sudden increases in the population of these species were categorized as 'low abundance' and 'high abundance'. The times for these sudden increases usually began immediately after the onset of thermal stratification. Periods of sudden increases were characterized by blue-green algae being greater than ten percent of the total number of cells. Prior to the sudden increase, blue-green algae constituted less than 10% of total assemblages.

The biotic variables considered in the analysis were redundancy (Wilhm & Dorris, 1968), number of forms, total density, and chlorophyll *a;* the abiotic variables were temperature, nitrate, soluble reactive phosphorus (SRP), dissolved silica, the nitrate/SRP ratios, dissolved silica/SRP ratios, and dissolved silica/nitrate ratios. The stepwise option in discriminant analysis was used, and variables that significantly ($P < 0.05$) explained the low and the high abundance populations were selected. The Mahalanohis distance (D^2) was used to evaluate whether the low-high abundance separation with respect to a variable was statistically significant (Afifi & Azen, 1972). The distance is calculated using the following equation:

$$D^2 = (X - \bar{X}' S^{-1} (X - \bar{X})$$

where X is the observation vector, and S is the covariance matrix.

Results

Community Structure

The groups of phytoplankton which constitute a large percentage of total assemblages and which are considered important in southeastern nearshore Lake Michigan are diatoms (centric and pennate), blue-green algae (coccoid and filamentous), and flagellates. Diatoms are of major importance in this region and contribute an average of more than 50% of the total cells in spring (Fig. 4). Their abundance decreases sharply after stratification and increases after a return to isothermal conditions in the fall

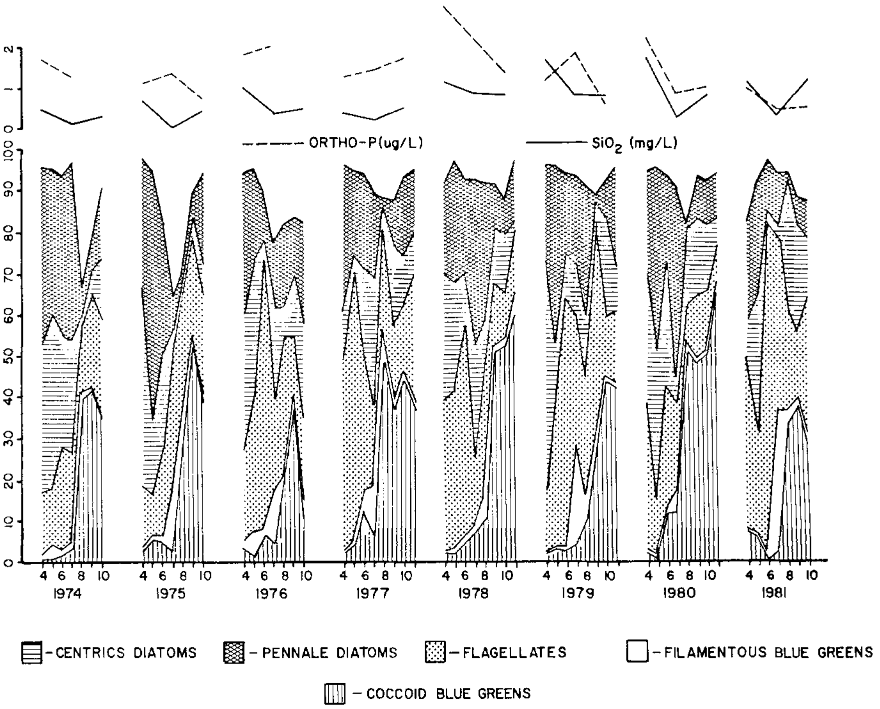

Fig. 4. Long-term changes in phytoplankton assemblage and nutrient concentration in the nearshore of southeastern Lake Michigan.

(Fig. 4). Flagellates are a second major group in this region. Their abundance peaks in June as diatoms are waning and blue-green algae begin to increase (Fig. 4). Blue-green algae become abundant in July after the development of thermal stratification. Their increase correlates inversely with the diatom decrease. Sharp increases in blue-green algae abundance usually occur in August (Fig. 4). This group of algae has been consistently increasing in this region, especially since 1973 (Fig. 3). In September and October of some years, blue-green algae are extremely abundant. Green algae appear in low abundance briefly after the onset of thermal stratification in July.

Parameters used to describe the phytoplankton community structure of southeastern Lake Michigan included number of forms, diversity index, and redundancy index. These parameters did not significantly change between 1974 and 1981; for example, the monthly averaged number of forms varied from 51 in 1974 to 53 in 1981. The average redundancy index (an index for measuring species dominance) ranged from 0.30 in 1974 to 0.33 in 1981, and the average diversity index ranged from 3.9 in 1974 to 3.7 in 1981.

Nutrients

Dissolved silica and soluble reactive phosphorus are important to the variation of phytoplankton in this region. Dissolved silica concentrations are generally high in the spring and decrease in July after the onset of thermal stratification (Figs. 4 and 5). Concentrations increase during a return to isothermal conditions in the fall, but concentrations are usually lower than those in the spring and rarely exceed 1 mg l^{-1}. The seasonal pattern of soluble reactive phosphorus concentrations is distinctly different from that of dissolved silica (Fig. 5). Highest concentrations are usually found in April or during upwellings in July. Except for 1977, lowest dissolved orthophosphate concentrations are found in October (Fig. 4).

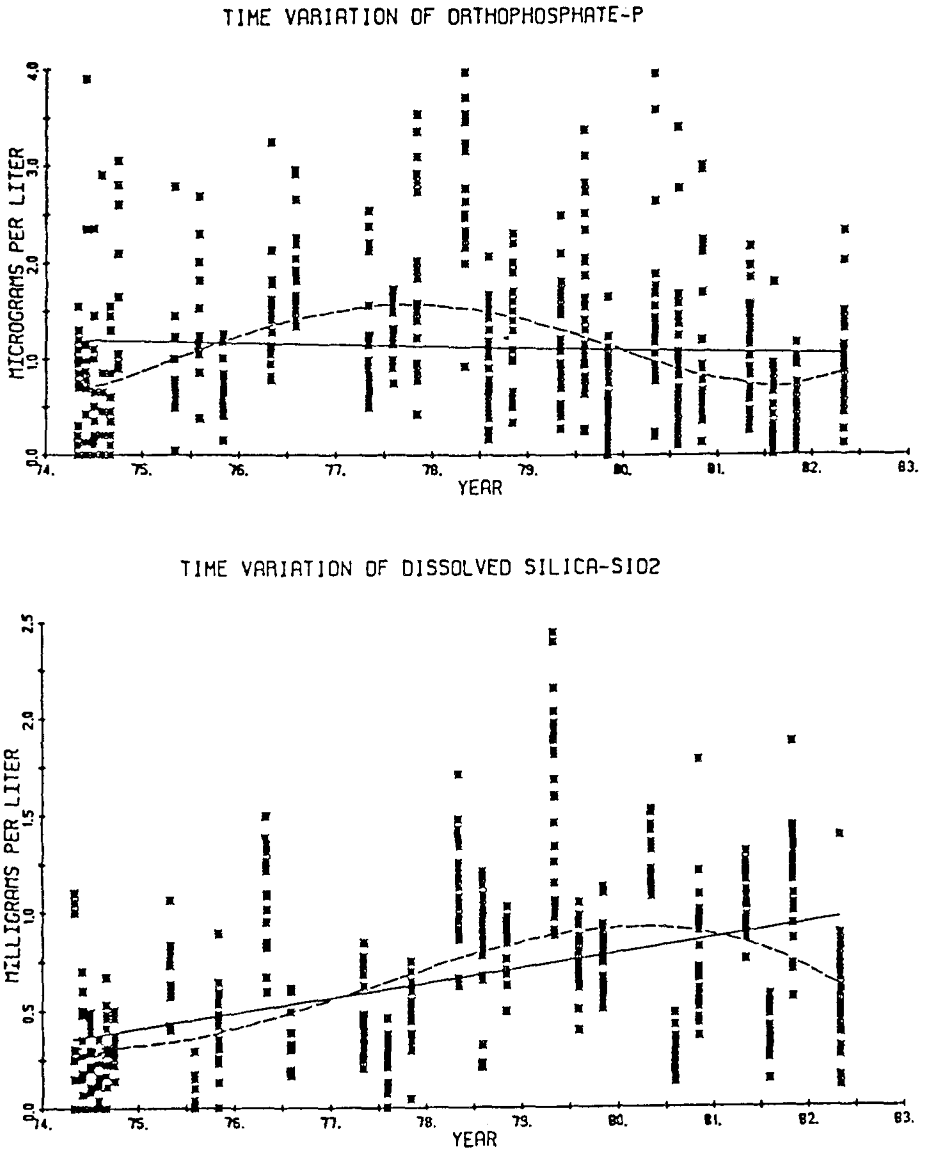

Fig. 5. Time variation of orthophosphate-P and dissolved silica in southeastern Lake Michigan (Rossmann, 1986). The solid line is the linear regression fit and the dash line represents a high order polynomial fit to the data. The linear rate of change is $-0.019\ \mu g\ l^{-1}\ yr^{-1}$ for ortho-P and is $74\ \mu g\ l^{-1}\ yr^{-1}$ for dissolved silica taken from Rossmann (1986). An inverse relationship is observed for the polynomial fit between long-term ortho-P and silica.

Annual Succession

Based on phytoplankton community structure and nutrient concentrations, three stages of annual succession are found from this region of Lake Michigan. The first is a diatom-dominated stage with high dissolved silica concentrations. The duration of this stage is dependent upon the time required to decrease dissolved silica to a concentration that becomes limiting, usually after the onset of thermal stratification.

The second stage is dominated by those species which do not require dissolved silica. During this stage, diatom numbers wane, blue-green algae become dominant, and flagellates make a brief strong appearance. Orthophosphate concentrations at the beginning of this stage are often higher than those in spring (April) (Fig. 4).

The third stage corresponds to the breakdown of summer thermal stratification which leads to gradual and intermittent enrichment of the nearshore waters with dissolved silica. The dissolved silica concentration increases during this period, and there is a slight increase in diatoms. The blue-green algae are dominant, and the dissolved orthophosphate concentration decreases to levels lower than during the other two stages.

Nutrient-Phytoplankton Relationships

Discriminant analysis was used to ascertain relationships between phytoplankton and nutrients. Of the variables considered, soluble reactive phosphorus and nitrate correlated significantly to the changes in the total number of blue-green algae, soluble reactive phorphorus ($p \leq 0.001$) was negatively and nitrate ($p \leq 0.05$) was positively related to the occurrence and abundance of *Anacystis incerta* ($D^2 = 2.67$, $p \leq 0.001$), and soluble reactive phosphorus ($p \leq 0.05$) was negatively related to the increased occurrence and abundance of *Gomphosphaeria lacustris* ($D^2 = 1.03$, $p \leq 0.05$). Other factors did not appear to correlate with either the rapid increase in blue-green algae after thermal stratification or the long-term concentration increase of this group.

Discussion

Increases in nutrient supply can cause increases in standing crop and production of phytoplankton and alter the composition of the phytoplankton community. These changes were noted for the southern basin of Lake Michigan throughout the 1960s. As pollution controls were implemented, the total density (cells/ml) of net phytoplankton in the Chicago area declined during the period of 1968 to 1975. All major species in the assemblage also declined except those of blue-green algae (Danforth & Ginsburg, 1980; Baybutt & Makarewicz, 1981).

A remarkable increase in the abundance of blue-green algae species occurred in southeastern Lake Michigan (Fig. 3); nearly twice the number of blue-green algae were found in the fall of 1981 than in that of 1974. The single most significant phenomenon was the sharp increase in abundance of the blue-green algae after thermal stratification began. The blue-green algae not only were more abundant than other species but also occurred in bloom condition more frequently (Conway *et al.,* 1977). The blue-green algae were primarily *Anacystis incerta* and *Gomphosphaeria lacustris* which increased in their occurrence as dominant forms in the phytoplankton community. The increase in the abundance of these species was strongly negatively associated with changes in soluble reactive phosphorus concentration of this region.

Phosphorus is a major plant nutrient which limits phytoplankton growth in Lake Michigan (Schelske *et al.,* 1974; Schelske *et al.,* 1978). Increases in phosphorus input have accelerated the rate of eutrophication and phytoplankton production in natural waters. After the implementation of pollution controls on phosphorus in the 1970s, there was a marked reduction in point sources of phosphorus; municipal loads to Lake Michigan were reduced from 2361 ty^{-1} in 1975 to 933 ty^{-1} in 1981 (Fig. 2). At the time that the phosphorus load to the lake was reduced, the input of soluble reactive phosphorus from the St. Joseph River, a major source of nutrients to this region, to the nearshore zone of southeastern Lake Michigan declined from 96 ty^{-1} in 1975 to 49 ty^{-1} in 1978 (Fig. 2). Because the nearshore zone receives nutrient inputs and acts as a buffer zone where nutrients are biologically utilized, this reduction of inputs of phosphorus can reduce the available forms of phosphorus in this area and consequently lower the concentration of available phosphorus in these waters. The decline of total phosphorus concentration in the Ontario nearshore zone of the Great Lakes was attributed to a detergent phosphorus removal program in the Ontario portion of the Great Lakes Basin in the early 1970s (Ongley, 1978; Gregor & Ongley, 1982).

For southeastern nearshore Lake Michigan, Rossmann (1986) found a significant decline in dissolved orthophosphate between the years 1974 and 1982 (Fig. 5). The reduction rate was about 0.019 $\mu g\ l^{-1}$

y^{-1}. This slow rate can have an impact on the observed dissolved orthophosphate concentration after stratification. Small reductions in the amount of available phosphorus can expand the period of phosphorus limitation and enhance the relative abundance of those species which can utilize lower concentrations of available phosphorus. These species would be more successful than those lacking this ability.

In many cases, low total nitrogen-to-total phosphorus ratios (<29) are reported to favor dominance by blue-green algae in lake phytoplankton (Smith, 1983). In the nearshore zone of southeastern Lake Michigan, the ratios after stratification are between 40 and 50. Deficiency in inorganic nitrogen which allows blue-green algae species to maintain high growth rates is unlikely to be the major explanation for the success of the blue-green algae in this region of Lake Michigan.

Though resource limitations due to low phosphorus are credited with the success of *Anacystis incerta* and *Gomphosphaeria lacustris,* the prime reason for their success is believed to be associated with the phosphorus-stimulated dissolved silica limitation of diatoms. Increased inputs of phosphorus stimulated the growth of diatoms in spring, reducing the euphotic zone dissolved silica concentration to levels which limited diatom growth during summer thermal stratification. These conditions induced a major species change in phytoplankton assemblages (Schelske & Stoermer, 1971; Conway *et al.,* 1977; Schelske *et al.,* 1983), permitting the blue-green algae to gain a competitive advantage in the assemblages. Once the blue-green algae took a stronghold in the phytoplankton community after stratification, the coccoid forms of *Anacystis incerta* and *Gomphosphaeria lacustris* successfully competed with other blue-green algae for low concentrations of available phosphorus and became predominant. Because the reduction in phosphorus concentrations following the implementation of pollution controls has not yet proceeded far enough to reduce the strong demand for dissolved silica after stratification, dissolved silica limitation and strong competition for low concentrations of available phosphorus continue to characterize this region of Lake Michigan.

Anacystis and *Gomphosphaeria* are known to form blooms in the waterways of the North Central States (Palmer, 1964). *Anacystis incerta* occurs in the Great Lakes primarily during periods of dissolved silica limitation (Schelske *et al.,* 1976). This is an evidence that a phosphorus-stimulated dissolved silica limitation is a major factor in the success of these blue-green species. However, these phytoplankton growth dynamics can also be affected whereby silica limitation reduces the competitive advantage of diatoms and allows the blue-green species to become dominant; the reduction of phosphorus additionally limits those species which cannot utilize the low phosphorus concentrations. These conditions favor the coccoid forms of blue-green algae, *Anacystis incerta* and *Gomphosphaeria lacustris.*

Summary

Significant decreases in river loadings of nutrients have reduced their supply to the nearshore of southeastern Lake Michigan. This reduction corresponded to sharp increases in the abundance of blue-green algae in this region of Lake Michigan after stratification, particularly *Anacystis incerta* and *Gomphosphaeria lacustris.* Phosphorus-stimulated low dissolved silica concentrations and phosphorus limitation after stratification are the primary factors contributing to the success of these algae.

Acknowledgements

The comments from Drs. John Ayers, Alfred Beeton, and Claire Schelske are gratefully acknowledged. Contribution No. 471, Great Lakes Research Division, The University of Michigan.

References

Afifi, A. A. & S. P. Azen, 1972. Statistical Analysis: A Computer Oriented Approach, Academic Press, New York.

Bartone, C. R. & C. L. Schelske, 1982. Lake-wide seasonal changes in limnological conditions in Lake Michigan in 1976. J. Great Lakes Res. 8: 413–427.

Baybutt, R. I. & J. C. Makarewicz, 1981. Multivariate analysis of the Lake Michigan phytoplankton community at Chicago. Bull. Torrey Bot. Club. 108: 255–267.

Beeton, A. M. & W. T. Edmondson, 1972. The eutrophication problem. J. Fish. Res. Bd Can. 29: 673–682.

Conway, H. L., J. I. Parker, E. M. Yaguchi & D. L. Mellinger, 1977. Biological utilization and regeneration of silicon in Lake Michigan. J. Fish. Res. Bd Can. 34: 537–544.

Danforth, W. F. & W. Ginsburg, 1980. Recent changes in the phytoplankton of Lake Michigan near Chicago. J. Great Lakes Res. 6: 307–314.

Gregor, D. J. & E. D. Ongley, 1982. Data filtering for large area analysis – an example from the Canadian nearshore zone of the Great Lakes. J. Great Lakes Res. 8: 470–481.

International Joint Commission, 1982. Report on Great Lakes Water Quality, 1982. International Joint Commission, Windsor, Ontario.

Ladewski, T. B. & E. F. Stoermer, 1973. Water transparency in southern Lake Michigan in 1971 and 1972. In Proc. 16th Great Lakes Res: 791–807. Int. Ass. Great Lakes Res.

Ongley, E. D., 1978. Land use, water quality, and river mouth loadings: a selective overview of Southern Ontario. Technical Report of the Pollution from Land Use Activities Reference Group. International Joint Commission, Windsor, Ontario.

Palmer, C. M., 1964. Algae in water supplies of the United States. Algae and Man., D. Jackson (ed), Plenum Press, 239–261.

Rossmann, R. & E. Seibel, 1977. Surficial sediment redistribution by wave energy: element-grain size relationships. J. Great Lakes Res. 3: 258–262.

Rossmann, R., 1986. Waters of southeastern nearshore Lake Michigan. In Southeastern nearshore Lake Michigan: impact of the Donald C. Cook Plant, ed. R. Rossmann. Publ. No. 22, Great Lakes Res. Div., Univ. Michigan.

Rousar, D. C., 1973. Seasonal and spatial changes in primary production and nutrients in Lake Michigan. Water, Air, and Soil Poll. 2: 497–514.

Sanford, G. R., A. Sands & C. R. Goldman, 1969. A settle-freeze method for concentrating phytoplankton in quantitative studies. Limnol. Oceanogr. 14: 790–794.

Schelske, C. L. & E. F. Stoermer, 1971. Eutrophication silica depletion and predicted changes in algal quality in Lake Michigan. Science 173: 423–424.

Schelske, C. L., E. D. Rothman, E. F. Stoermer & M. S. Santiago, 1974. Responses of phosphorus limited Lake Michigan phytoplankton to factorial enrichments with nitrogen and phosphorus. Limnol. Oceanogr. 19: 409–419.

Schelske, C. L., E. F. Stoermer, J. E. Gannon & Mila S. Simmons, 1976. Biological, Chemical, and Physical Relationships in the Straits of Mackinac, US Environmental Protection Agency, Ecol. Res. Series, EPA Rep. No. EPA-600/3-76-095, Duluth, Minnesota.

Schelske, C. L., E. D. Rothman & M. S. Simmons, 1978. Comparison of bioassay procedures for growth limiting nutrients in the Laurentian Great Lakes. Mill. Int. Ver. Limnol. 21: 65–80.

Schelske, C. L., L. E. Feldt & M. S. Simmons, 1980. Phytoplankton and physical-chemical conditions in selected rivers and the coastal zone of Lake Michigan, 1972. Univ. Michigan, Great Lakes Res. Div. Publ. No. 19.

Schelske, C. L., E. F. Stoermer, D. J. Conley, J. A. Robbins & R. M. Glover, 1983. Early eutrophication of the lower Great Lakes: new evidence from biogenic silica in sediments. Science 222: 320–322.

Smith, V. H., 1983. Low nitrogen to phosphorus ratios favor dominance by blue-green algae in lake phytoplankton. Science 221: 669–671.

Strickland & Parsons, 1972. A practical handbook of seawater analysis. 2nd ed. Fish. Res. Bd Can. Bull. No. 167. 310 pp.

Sutherland, J. C., J. R. Kramer, L. Nichols & T. D. Kurtz, 1966. Mineral-water equilibra, Great Lakes: silica and phosphorus. Great Lakes Res. Div. Pub. No. 15: 439–445.

Wilhm, J. L. & T. C. Dorris, 1968. Biological parameters for water quality criteria. Bioscience 18: 477–481.