PROJECT COMPLETION REPORT
Wisconsin Department of Natural Resources
Lake Planning Aids Grant LPL-455

Big Elkhart Lake Water And Nutrient Mass Balance Study

Start Date of Project: June 2, 1997 **End Date of Project:** December 31, 2000

On behalf of the Elkhart Lake Improvement Association
Charles B. Windsor, President
Thomas Nelson, Past-President

Principal Investigators Drs. David Edgington and Russell Cuhel

UW-Milwaukee Great Lakes WATER Institute
600 E. Greenfield Avenue
Milwaukee WI 53204

Prepared by Drs. Russell Cuhel and Carmen Aguilar, December 2001

Acknowledgments

Elkhart Lake has been a source of scientific inspiration for many years. Over time, many dozens of people, from high school students to Professors Emeritus have contributed to its study. The original enthusiasm for studying interdisciplinary aspects of the Elkhart Lake Ecosystem came from Professors **David N. Edgington** and **Bruce Brown**, both of the University of Wisconsin-Milwaukee Center for Great Lakes Studies and now both Emeritus (retired). Professor Arthur Brooks made occasional forays into the habitat with his limnology class in the mid-1980s. Now-Dr. **Carmen Aguilar** and the author Dr. Russell Cuhel were motivated by the peculiar red algae living deep in the water column, and soon had a cadre of high school and undergraduate students measuring "everything under the sun" for several summers. The true potential of Elkhart Lake as a nirvana of ecological and biogeochemical research was realized thanks to Wisconsin Sea Grant, which funded a massive effort for four years, supplemented by the Wisconsin Department of Natural Resources (especially **Bob Wakeman**), the Elkhart Lake Improvement Association, and a variety of environmental education activities. Interest in and techniques for zooplankton analysis came from Dr. **Richard C. Back III**, originally a graduate student at UWM and later the first Post-Doc on the Elkhart Project. He was succeeded by the able **Sarah Meyer**, MS. During the period of the study presented herein, the following personnel made their indelible marks both against the wall of ignorance and for the wonder of hard work resulting in stellar observations:

Natalie Dingledine, MS: able ecosystem biologist and field supervisor with special interests in aquatic macrophytes and groundwater chemistry, and a principal driver in the laboratory's work ethic and struggle for excellence;

Sarah Cook: Environmental activist and intern turned superlative analytical chemistry technician;

Jason Villwock: High school volunteer and pre-college summer employee with a burning interest in hydrogeology and groundwater;

Sharon Zsebe, BS: Boston Store employee who couldn't put aside her Biology degree and became a steadfast full-time component of the laboratory's environmental efforts, with particular skills in the rigorous and difficult analyses of phosphorus compounds;

Heather Hewitt: Undergraduate student employee adept at precision instrumented analysis and the major force behind several large-scale investigations on the chemical composition of zebra mussels;

Sarah Berquist, BS: Invertebrate specialist from Michigan who as a part-time employee has broadened the reach of the laboratory into the realms of animal population dynamics;

Carmen Aguilar, Ph.D.: Biogeochemist and research enthusiast, limnologist and oceanographer, collaborator on both research and education activities, equally participant and leader of interdisciplinary research programs, and a 12-year veteran of Elkhart Lake research.

These and many short-term participants have made this site a lifetime thrill.

EXECUTIVE SUMMARY

Four years of water column investigations (1996-2000) bracketed by ongoing interest have identified one or more major new perturbations to the Elkhart Lake Ecosystem. Known factors include establishment of vigorous zebra mussel populations and occurrence of an unusually strong El Niño-La Niña meteorological event during 1997-1999. Both of these incidents are consistent with some or most of massive observed changes in lake ecology and nutrient cycling. From some points of view, Elkhart Lake has become even more excellent in water quality terms. The following key points are documented in the report:

- The maturation of zebra mussel populations (one five-year life cycle) coincided with two sequential years of highly unusual meteorological conditions (El Niño / La Niña) which could have contributed to or even caused the observed changes;

- Phytoplankton biomass decreased substantially over the study period, principally due to a nearly complete eradication of the Cyanobacterial deep chlorophyll maximum which had been first observed by Birge and Juday in 1906;

- The magnitude of nutrient remobilization from sediment efflux was greatly curtailed in later years of the study, associated with less pronounced deep basin anaerobiosis;

- The magnitude and extent of spring bloom phytoplankton population development was likewise curtailed;

- Surface nutrient concentrations tended to remain at higher levels during mid-summer than in previous years;

- Integrated water column inventory of biomass-related parameters including chlorophyll a, several forms of phosphorus, and ammonium declined dramatically throughout 1996-2000 while hypolimnetic oxygen inventory in summer increased;

- Integrated, annual areal primary production decreased to a limited extent during the later years of the study, primarily through loss of deepwater production capacity;

- A small but persistent increase was observed in gross water clarity (i.e., Secchi depth);

- Surface samples during summer for chlorophyll a, total phosphorus, and Secchi depth yielded Trophic Status Index values of mesotrophic to oligotrophic, with a clear long-term trend towards oligotrophic conditions;

- Net zooplankton populations showed little or no systematic response to the changing conditions;

- Zebra mussel populations increased continuously between 1996-1999 and became effectively established as a new component of the benthic ecosystem.

- Evidence from conservative minerals and nutrients implicated groundwater influx as a more significant contributor to lake biogeochemistry than had previously existed;

- The chemical composition of groundwater was highly consistent from year to year at any given site, and regions of the lake had distinctly different groundwater signatures;

- Mass balances indicated that a major new loss term for biomass-related components had entered the equation during or shortly after 1996.

BENEFITS:

The research described above is a significant step towards understanding ecosystem perturbations such as zebra mussel colonization because the smaller, nearly closed nature of the study sites allows budgeting by mass balance approach. Based on this work, some tools for prediction of zebra mussel success in other inland lakes have been well established. The nature of inland lake effects, virtually unstudied until now, provides a valuable comparison with well-studied larger open Great Lakes habitats.

FOLLOW-UP:

The question of motorboat activity affecting the ecosystem function at Elkhart Lake remains. A thermistor chain deployed by Dr. Edgington and associates in the large basin recorded temperature at short intervals to address this question, but it could not be found after the summer. Perhaps the orange buoy only 10 feet below the surface was too great of a temptation for vandals. Several other experimental deployments have disappeared or been conscientiously turned in to the Elkhart Lake police. Nonetheless, inspection of the nutrient and biomass profiles demonstrates that there were no limiting nutrients or turbidity-causing materials available for mixing. Several physical oceanographers agree that turbulence would be restricted to much less than ten times the depth of the prop, which for most recreational craft would be about 30 feet (10m) or less. However, that influence could be of significance in shallower near-shore contours and might be followed up by specifically designed sampling by personnel on site during the summer.

Unquestionably the most important follow-up activity would be to assess whether observed changes in Elkhart Lake water column and rooted plant variables resulted from meteorological (El Niño-La Niña) or biological (zebra mussels) forcing. This will require continued monitoring through several seasonal cycles in years with earlier fall overturn and later ice-out than during 1997-1999. The work of 2000 and its continuation (unfunded) through 2001 will provide the necessary continuity if another large-scale effort is supported. In addition, formulation of expected zebra mussel establishment patterns with the biogeochemical characteristics of the intensively studied lakes should be completed so that recently infested (or future target) lakes may be compared with hypotheses. Finally, incorporation of the results into the Elkhart Lake Improvement Association web page and publication-dissemination of the results is necessary.

INTRODUCTION:

Elkhart Lake (Sheboygan County, WI) has been studied intensely for about a decade and that background provides continuity from which long-term assessments of ecosystem function may be made. It is a deep (to 35m) kettle lake with >70% of its area deeper than 10m. Elkhart Lake's twin kettles become strongly stratified for the dominant portion of the lake surface area. The lake has experienced a wide variety of both human- and naturally-applied stresses since its first description by Birge and Juday in 1911. Many of these, including substantial shoreline development for residential and recreational uses and periodic stocking of sport fish have had little apparent long-term influence on lake water quality (Edgington and Cuhel 1997). Many of the characteristics of Elkhart Lake are well documented in that previous report and will not be reiterated here. Since 1996 at least three new or increased stresses have been applied to the lake: establishment of zebra mussel populations, a protracted and severe El Niño-La Niña meteorological event during winter 1997 through 1999, and greatly increased motorboat activity in the late 1990's to present. This report describes hydrological, chemical, and biological measurements undertaken in an effort to elucidate causes of recent perceived changes in characteristics of the Elkhart Lake ecosystem.

OBJECTIVES:

Specific objectives for the study included

1) Measuring groundwater inflow;
2) Measuring nutrients in precipitation;
3) Measuring nutrients in groundwater;
4) Measuring nutrients in intermittent surface water inputs;
5) Installing a thermistor chain in the deepest sounding of the lake; and
6) Refining mass balance models for the lake

These objectives were intended to provide a basis for understanding biological changes in the Elkhart Lake ecosystem as they relate to residential and recreational use of the lake and for the improvement of management practices based on thorough knowledge of ecosystem function. Changes in availability of personnel with specific skills during the study period led to modification of the approaches taken, favoring a more direct assessment of water column biological and chemical characteristics. Intentional or accidental vandalism of long-term sensors and in-lake experiments was also a problem, but many of the parameters were adequately sampled through repeated expeditions to the site using small boat sampling procedures. The focus on mass balances within the water column provided comprehensive and useful information regarding internal vs. external forcing of nutrient and biomass budgets for Elkhart Lake.

PROJECT RESULTS:

Water quality parameters, groundwater composition, phytoplankton biomass and productivity, zooplankton abundance and species composition, and zebra mussel recruitment were monitored in Elkhart Lake, Sheboygan County. It was invaded by zebra mussels in 1994 (first sightings): well-established populations of young (1-2 years) mussels were evident by 1996. The previous grant covered studies into early 1996 (Edgington and Cuhel 1997) and this report begins with January of 1996. Although the current study technically began in 1997, it is valuable to visualize the ecosystem variables in continuity, as there is much to be learned from both intra- and interannual progressions. The results of the work are presented as follows:

a) Temperature and oxygen progressions;
b) Surface water concentrations for key variables over the study period;
c) Time-depth contour plots for concentrations of key water column variables;
d) Areally-integrated water column content for key variables;
e) Transparency indices;
f) Carlson's Trophic Status Index;
g) Zooplankton abundance and species composition;
h) Zebra mussel recruitment;
i) Groundwater nutrient chemical composition;
j) Sediment grain characteristics

The results will be followed by a discussion of mass balances and overall conclusions regarding the trophic status of Elkhart Lake.

Hydrographic parameters included depth profiles taken by electronic instrumentation. For water quality parameters (temperature, dissolved oxygen, conductivity, pH, oxidation-reduction potential) a Hydrolab Datasonde was used. Light penetration was measured with a LiCor Underwater Quantum Sensor and with a Secchi Disk. In vivo algal fluorescence was obtained primarily with a SeaTech submersible fluorometer. Real time (on-boat) examination of these results provided the basis for specific sampling protocols.

Standing crop parameters included a variety of meaningful biomass (chlorophyll *a*), nutrient (inorganic N, several forms of P, and silicate), and dissolved mineral (chloride) components. Sampling frequency and intensity may be observed in the surface sample data following and is also visible in the contour plot and areal inventory examples further below.

Plankton parameters, particularly phytoplankton, are responsive to changes in nutrient availability, grazing, and other ecosystem perturbations. The population density of algae, expressed commonly a chlorophyll *a* concentration, is of particular significance to this study. During the study period, we analyzed plankton population density and productivity during early spring, spring, summer, fall, and winter seasons, with additional under-ice sampling when possible. Net zooplankton, also a key component of the aquatic food web, have been collected and preliminary data analysis has also been completed.

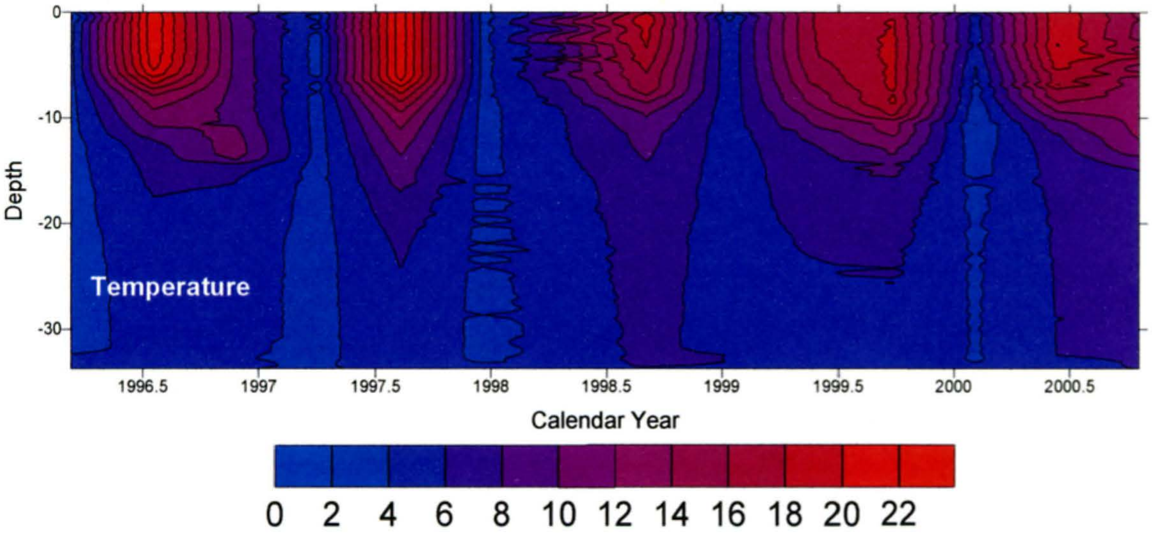
Sediment characteristics included a series of acoustic profiling transects that provided both new detailed bathymetry (lake depth) and estimates of fine-grained sediment thickness (deposition). Groundwater moving through sediments was collected with minipiezometers at up to 29 stations, though only 11 were routinely sampled.

a) Temperature and oxygen progressions

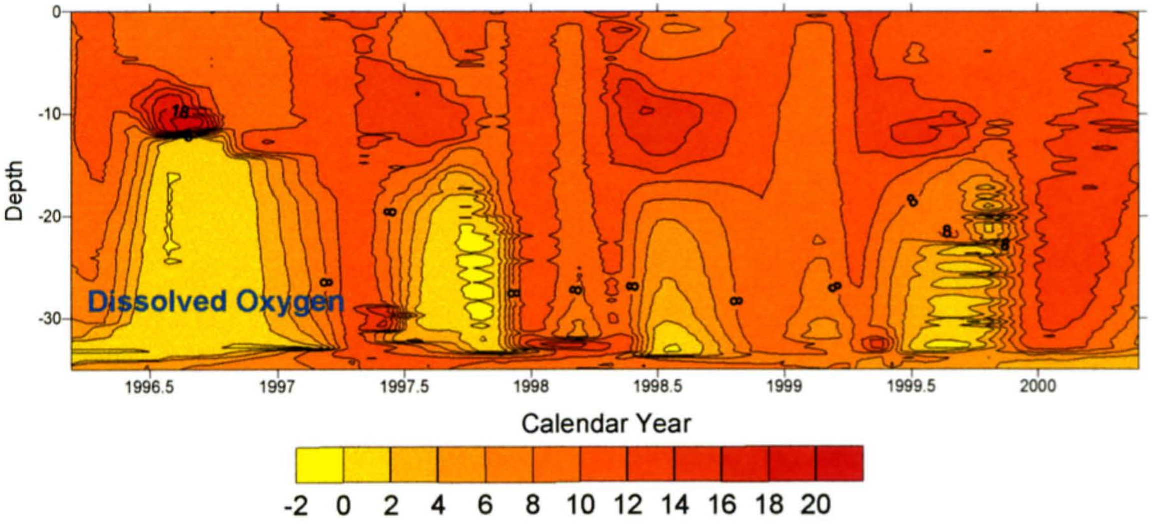
Vertical profiles using an electronic water quality transmitter (Hydrolab Corp.) were taken during most visits. Of the parameters collected, *temperature* and *dissolved oxygen* are the two most pertinent to water quality in Elkhart Lake. Contour plots of the two parameters for years 1996-2000 are presented on a following page, Figures **Temperature** and **Dissolved Oxygen**. Temperature obeyed the characteristic seasonal cycles of uniformly cold (blue or dark) winter conditions, followed by spring warming (purple to red) and stratification. Later in the summer cooling and deepening of the epilimnion returned the system ultimately to the cold mixed winter character. Ice cover occurred each year but is only apparent as an underlying light blue of very cold (<4°C) water. Likewise, dissolved oxygen followed a common pattern of uniform, high values (dark orange to red or darker) during winter to spring mixing, followed by summer stratification showing oxygen depletion in the bottom water (hypolimnion) and a zone of increased oxygen near 10m water depth. These features eroded to uniform high oxygen again during fall overturn. However, several significant deviations from "normality" were apparent, and are discussed below.

Temperature profiles contained several anomalies of note. For Elkhart Lake, 1996 was perhaps the most typical of preceding years and will be the basis for comparison. Deep water summer temperatures of 6°C were similar to previous years (Edgington and Cuhel 1997) as were systematic warming, July-August maximum, and steady cooling and deepening of the mixed layer. 1997 was qualitatively similar but the entire mid-year warm segment was constricted into a shorter season. The El Niño winter of 1997-1998 however exerted significant influences on the thermal structure of 1998. Initial warming occurred earlier than previous years but remained weak into June. Maximum temperatures in the surface were lower but deep water was warmer than expected, both consequences of heavily overcast and turbulent conditions during most of the 1998 spring and summer seasons. During 1999, surface warming began earlier than the previous year but was also very gradual. Deep water was also warmer than usual, though not to the extent of 1998. Year 2000 began to resemble more typical years, though the extent of surface warming was still less than normal and ice cover during 1999-2000 was still weak.

Dissolved oxygen displayed pronounced deviations from the normal conditions described for previous years (Edgington and Cuhel 1997), elements of which are well represented during 1996 (as with temperature) but which were never again fully repeated. Within the progression described above as "typical", normal extremes for Elkhart Lake included development of large scale bottom-water anoxia during the summer (lighter colors) reaching from the bottom all the way up to the base of the thermocline (ca. 15m) by late August. Oxygen depletion here is due to bacterial activity involved in decomposition of spring bloom organic material sedimenting to the bottom. Complete oxygen consumption is a prerequisite to denitrification, the anaerobic bacterial process that converts nitrate into nitrogen gas and hence is a loss term for nitrogen. This sharply contrasted with an adjacent oxygen supersaturation (dark color) within the lower part of the metalimnion (thermocline zone) most likely produced by the algae constituting the deep chlorophyll maximum (see depth contour section below). Extremely significant differences were apparent for the 1997-1999 profiles. First, the extent of oxygen depletion was much less than in 1996 and previously, with anoxic conditions compressed into both temporally- and spatially-restricted zones. In fact during 1998 most of the deep water remained aerobic, retaining only a



Depth
0
-10
-20
-30
Temperature
1996.5
1997
1997.5
1998
1998.5
1999
1999.5
2000
2000.5
Calendar Year
0 2 4 6 8 10 12 14 16 18 20 22



Depth
0
-10
-20
-30
18
8
Dissolved Oxygen
1996.5
1997
1997.5
1998
1998.5
1999
1999.5
2000
Calendar Year
-2 0 2 4 6 8 10 12 14 16 18 20

very small, near-bottom anaerobic region. In both 1997 and 1999 anaerobic conditions extended further from the bottom but occurred only late in the summer. The second major difference was that after 1996, supersaturated oxygen was not found in the lower metalimnion. Higher values relative to surface were those expected from cooler water temperatures (higher oxygen solubility) but did not reflect *in situ* oxygen production as was common for deep chlorophyll maximum populated waters. A new instrument was brought into use in mid-2000, and data from the oxygen sensor were corrupted in files from the latter half of the year, so oxygen profiles are truncated at the last reliable date. It is likely that these data will be recovered eventually, but for the moment late 2000 oxygen characteristics are unknown.

b) Surface water concentrations for key variables

Surface samples provide the perspective of the recreational user and the casual observer. Often criteria such as Carlson's Trophic Status Index (below) are based only on surface observations. Six parameters are shown below for the 1996-2000 period (Figure **SURFACE**; each panel individually labeled and described): they are also presented as depth profiles and integrated water column contents in following sections.

The pigment contained in all algae, *chlorophyll a*, is a direct measure of phytoplankton biomass. It showed pronounced spring bloom characteristics through 1996, including high values during April into early May, then diminishing to summer lows shortly after warming of surface waters (first year of Figure **Surface Chlorophyll a**; see also Edgington and Cuhel 1997). Following 1996, spring increases of plankton population density diminished considerably or were too short-lived to be sampled. Small peaks are apparent in April of both 1997 and 1998, but attain only half the magnitude of previous years. Almost no bloom was evident during 1999 or 2000. Due to the very warm winters of 1997-1999, ice was too thin for winter sampling, but boat samples were usually collected within a few days of ice-out. Stratification was evident much sooner than in pre-1997 years, leading to greatly decreased spring mixing needed for bloom development. Mid-summer lows were consistent at 1-3µg/L, but these values were higher than pre-1996 lows of usually <1µg/L. Based on Chl *a*, there was little evidence for effective clearing of surface waters expected of vigorous zebra mussel activity.

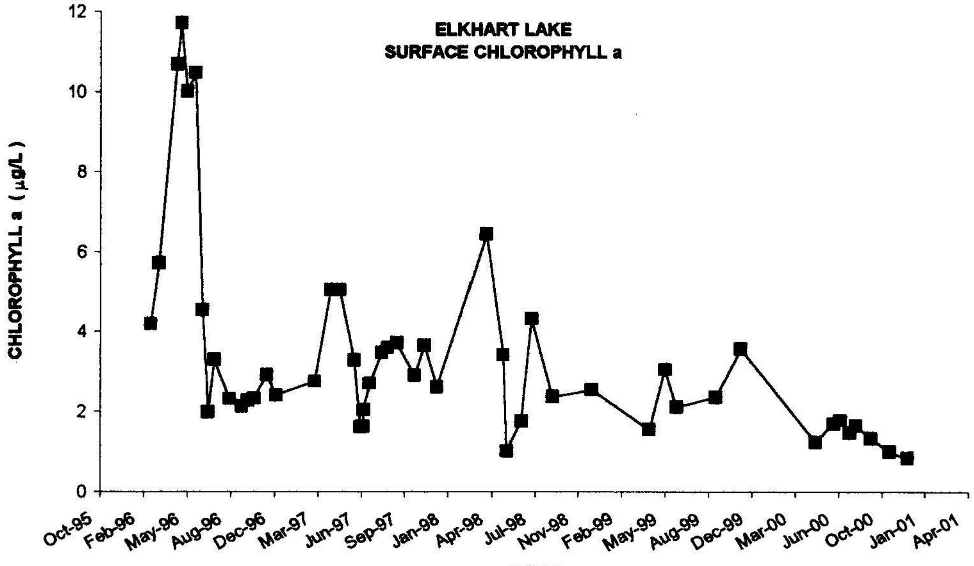
Phosphorus is considered by many to be a (not necessarily *the*) yield-limiting nutrient element in eastern waters of the US, including Elkhart Lake. Of its several chemical forms, the three most significant are presented here. *Total Phosphorus* (TP) is the sum of all organic and inorganic forms. *Soluble Reactive Phosphorus* (SRP) is the nutrient form available for use by algae for growth; both TP and SRP are shown in Figure **Surface Phosphorus**. *Particulate P* (Part-P) is a biomass component, not specific for algae but often dominated by them, reflective of the amount of biologically-available phosphorus incorporated into the food web (Figure **Surface Particulate Phosphorus**). At first glance it appears that both TP and Part-P decreased consistently since the beginning of the project. However, only spring bloom levels of P had actually decreased, while summertime minima remained consistently near 0.1 and 0.3µM respectively since the early 1990's. These results are consistent with seasonal nutrient and biomass profile data below and demonstrate significantly altered spring ecosystem function during the protracted El Niño-La Niña episode that coincided with years 4 and 5 of zebra mussel maturation. With rare exception, SRP as an available nutrient was very low throughout the study period as it has been since the early 1990's{In this meso- to oligotrophic lake, total P is predominantly locked up in plankton tissue, with little soluble P available at any time of year.} *

Surface nitrogen nutrient dynamics typically follow a seasonal cycle in which *ammonium* (NH_4^+) is high throughout the water column in fall due to overturn of deep nutrient inventories generated during the summer by decomposition. During winter and early spring ammonium is oxidized to *nitrate* (NO_3^-) by bacteria. Nitrate is then consumed by algae of the spring bloom, leaving both nutrients at low levels during summer. Both forms are documented in Figure **Surface Nitrate and Ammonium**. During this study period, ammonium was consistently higher in winter-spring from 1996-1998, but showed dampening seasonal cycles after 1996. Though 1999 had lower sampling frequency, the 11 November sample would have detected any ammonium available from fall turnover. Because fall-winter ammonium is derived from deep-water decomposition during the previous summer, the data suggest that lower phytoplankton sedimentation occurred during the spring of later years. In contrast, nitrate displayed progressively greater late spring concentrations and higher mid-summer lows during 1997-2000. Spring highs over 30μM were observed in 1997, 1999, and 2000, and late summer surface water only dropped to undetectable levels in 2000, though this had been routine previously (Edgington and Cuhel 1997). This could occur from either or both of two perturbations: lower phytoplankton biomass (consuming nitrate) or increased influx of groundwater nitrate. Based on summer consistency of surface chlorophyll a, the latter is favored, as will be seen with chloride below.

The primarily diatom-associated nutrient *silicate* obeyed very pronounced seasonal cycles of winter-spring (mixing period) maxima near 50μM followed by rapid late spring depletion to nearly undetectable levels at the surface, depicted in Figure **Surface Silicate**. As for nitrate, very low levels were rarer in later years, particularly in 1999, although sampling frequency was not as great due to other macrophyte and groundwater sampling trips.

Most interesting was the conservative mineral *chloride*, which decreases slightly with heavy rainfall and increases with enhanced groundwater input (see groundwater below). During 1996 and 1997 surface chloride averaged about 650μM (Figure **Surface Chloride**), with noticeable dips during spring runoff. Starting in 1998, however, chloride concentrations began an inexorable rise to nearly 800μM by the end of 1999. Year 2000 values were slightly lower but still about 15% higher than the 1993-1997 period. A good correlation between chloride and nitrate-silicate-ammonium was found for about half of the groundwater sampling stations, suggesting that the lake was receiving significantly greater inputs of these nutrients during the study period. On the basis of these findings, it appears that at least some of the unusual surface nutrient cycles were due to lake-groundwater interactions.

Nutrients in precipitation were measured routinely from collections in the Milwaukee area. The rain gauge at the lake itself could not provide meaningful chemistry data because it was usually full of dead insects and leaf litter, and was not readily accessible immediately after rainfall events. Rainfall, of course, first influences the surface water upon which it falls. In numerous collections over four years the following generalizations may be made about nutrients in southeastern Wisconsin rainfall: (1) both ammonia and nitrate were reliably present at concentrations of 10-


ELKHART LAKE
SURFACE CHLOROPHYLL a
CHLOROPHYLL a (µg/L)
0
2
4
6
8
10
12
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
Jul-98
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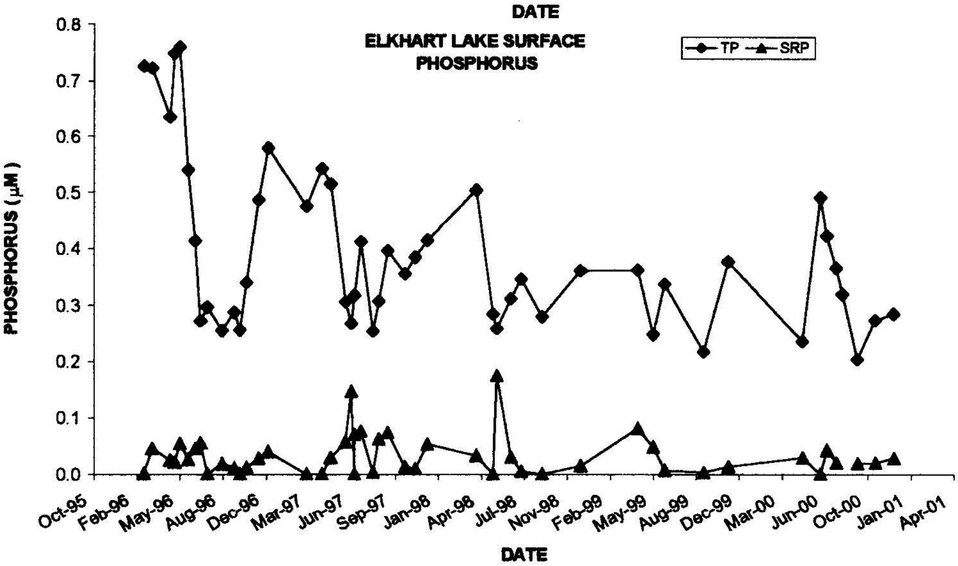
Oct-00
Jan-01
Apr-01
DATE


ELKHART LAKE SURFACE
PHOSPHORUS
TP
SRP
PHOSPHORUS (µM)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
Jul-98
Nov-98
Feb-99
May-99
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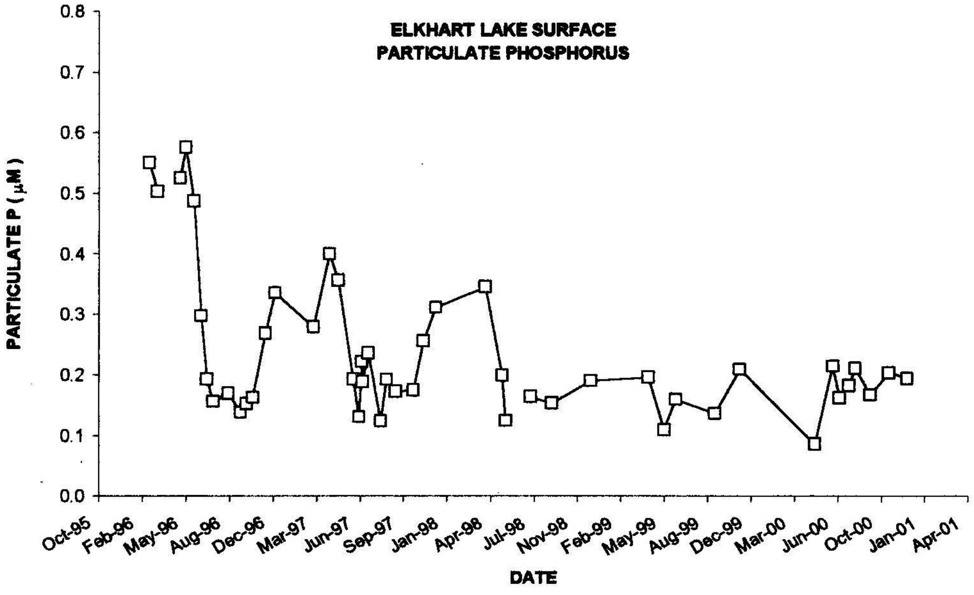
Jun-00
Oct-00
Jan-01
Apr-01
DATE


ELKHART LAKE SURFACE
PARTICULATE PHOSPHORUS
PARTICULATE P (µM)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
Jul-98
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Feb-99
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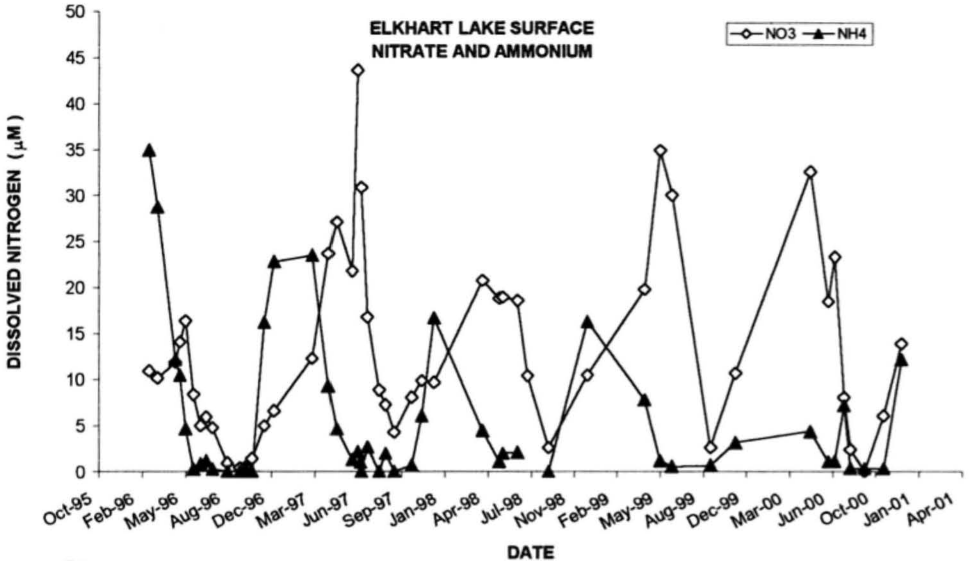
Oct-00
Jan-01
Apr-01
DATE


ELKHART LAKE SURFACE
NITRATE AND AMMONIUM
NO3
NH4
DISSOLVED NITROGEN (μM)
0
5
10
15
20
25
30
35
40
45
50
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
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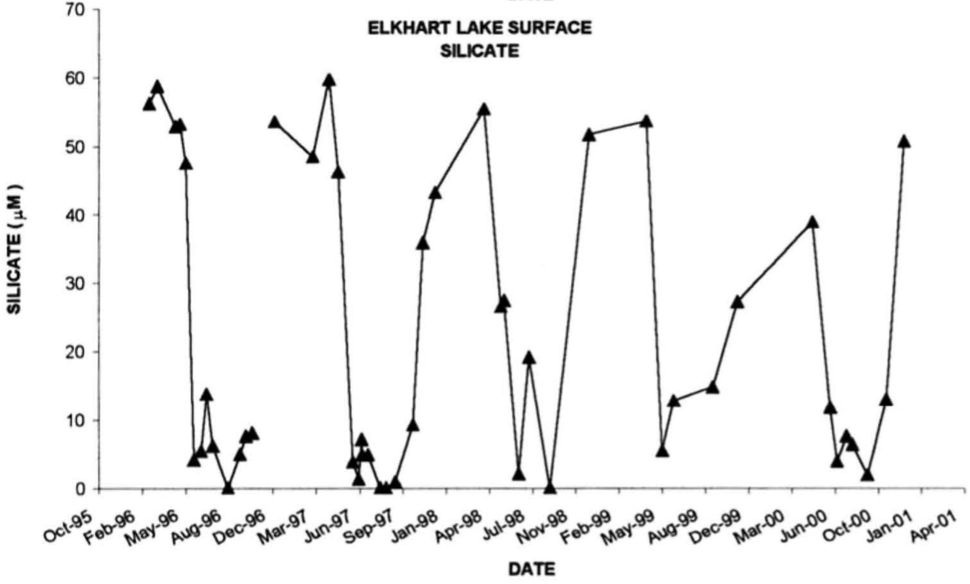
Oct-00
Jan-01
Apr-01
DATE


ELKHART LAKE SURFACE
SILICATE
SILICATE (μM)
0
10
20
30
40
50
60
70
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
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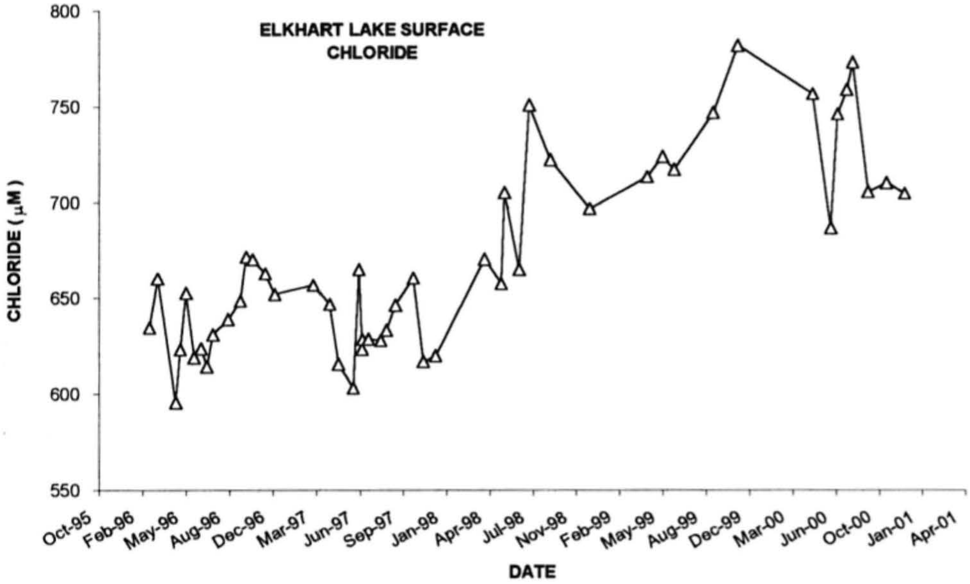
Oct-00
Jan-01
Apr-01
DATE


ELKHART LAKE SURFACE
CHLORIDE
CHLORIDE (μM)
550
600
650
700
750
800
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
Jul-98
Nov-98
Feb-99
May-99
Aug-99
Dec-99
Mar-00
Jun-00
Oct-00
Jan-01
Apr-01
DATE

100μM. Nitrate was more reliably present at 50-100μM, while ammonium was sporadically important but could reach 100μM on occasion. (2) Dissolved phosphorus of any form was rarely detected at concentrations >5μM and was in most cases much less than that. Although this remains an input, compared with "brown soda" (e.g., cola, root beer, etc.) at 5000μM concentration, water skiers may contribute much more P to the lake than rain does. (3) Neither chloride nor silicate were present at greater than trace levels, and surprisingly sulfate (from ? sulfuric acid rain) was also present at much less than lakewater concentrations. The actual calculation of rainfall input to mass balances has not yet been fully worked up, but the only nutrients available in local rainfall are of small consequence to the interpretation of recent ecosystem changes.

c) Time-depth contour plots for concentrations of key water column variables

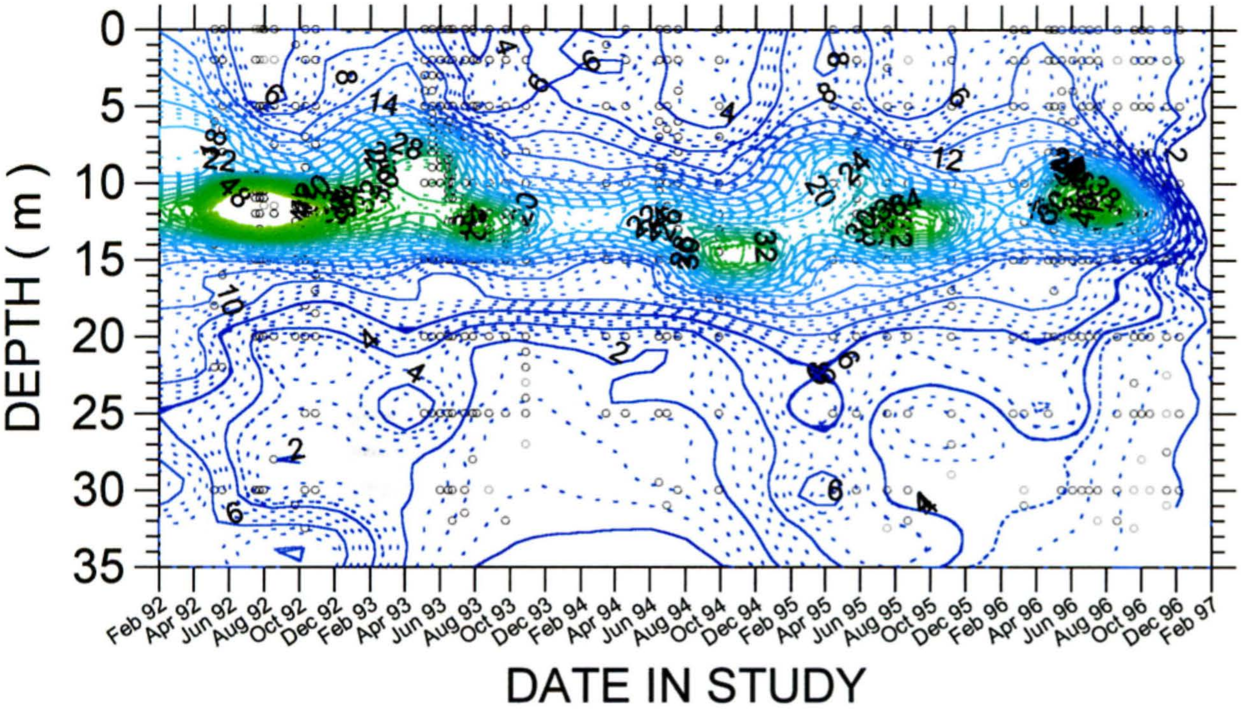
Surface samples are of great value in understanding lake behaviour at one level but may disguise large-scale processes occurring beneath the surface. Seasonal vertical profiles provide a much more detailed picture of biomass and nutrient behavior in the lake. Profile data have been used to create time-depth contour plots to expedite discussion, though these must be treated with caution. Inspection of individual profiles is necessary for many applications, but large-scale interannual features may be readily visualized in the contours. In these, reading is similar to a topographic map: the highest values are darker centers of "targets" and concentration changes are steepest where contour lines are closest together. The following have been optimized for gross level interpretation, and are presented in the same order as surface data above, using the same units of concentration.

Chlorophyll a is the most commonly used proxy for phytoplankton or algae. A semi-quantitative measure of algal biomass, water column chlorophyll typically increased during the spring bloom, then focused into a nearly unialgal, Cyanobacterium-dominated Deep Chlorophyll Maximum (DCM) near the 1% light level in Elkhart Lake. In the technical report (Edgington and Cuhel 1997) development of a strong deep chlorophyll maximum reaching 200μg/L was a persistent feature of the summer water column at 11-15m depth. For reference, both 1992-1996 and 1996-2000 contour plots for chlorophyll *a* are shown (Figures **Chlorophyll a**). In the early 1990's the DCM accounted for >80% of the chlorophyll during mid- and later summer sampling. Between 1995 and present the extent and intensity of the DCM decreased consistently. In the contour plot **1996-2000 Chl a**, a still-strong DCM can be seen at about 12m in 1996, but decreased in concentration and moved to deeper depths in subsequent years. By 1999 the DCM was nearly absent, maintaining barely 15μg/L of biomass between 14-18m. The same low-light adapted filamentous Cyanobacteria were present, but with greatly diminished biomass. Clearly substantial changes occurred in the phytoplankton community that were not visible at the surface.

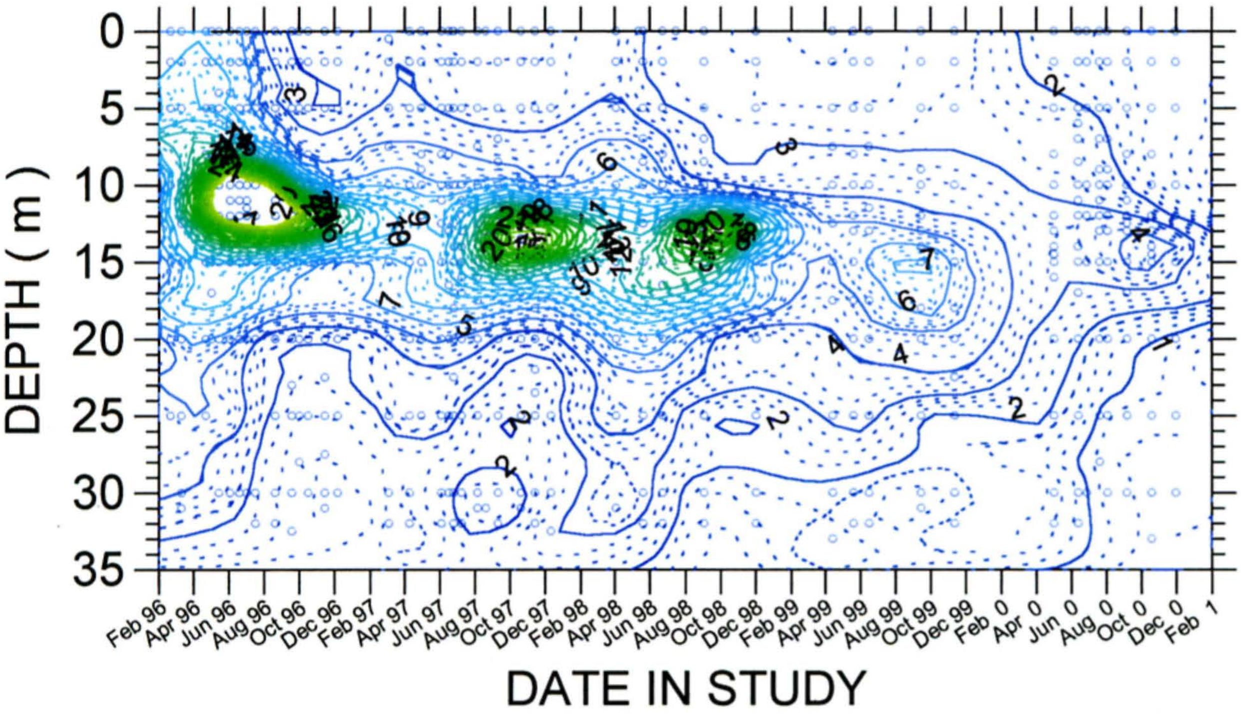
μg = ? mg

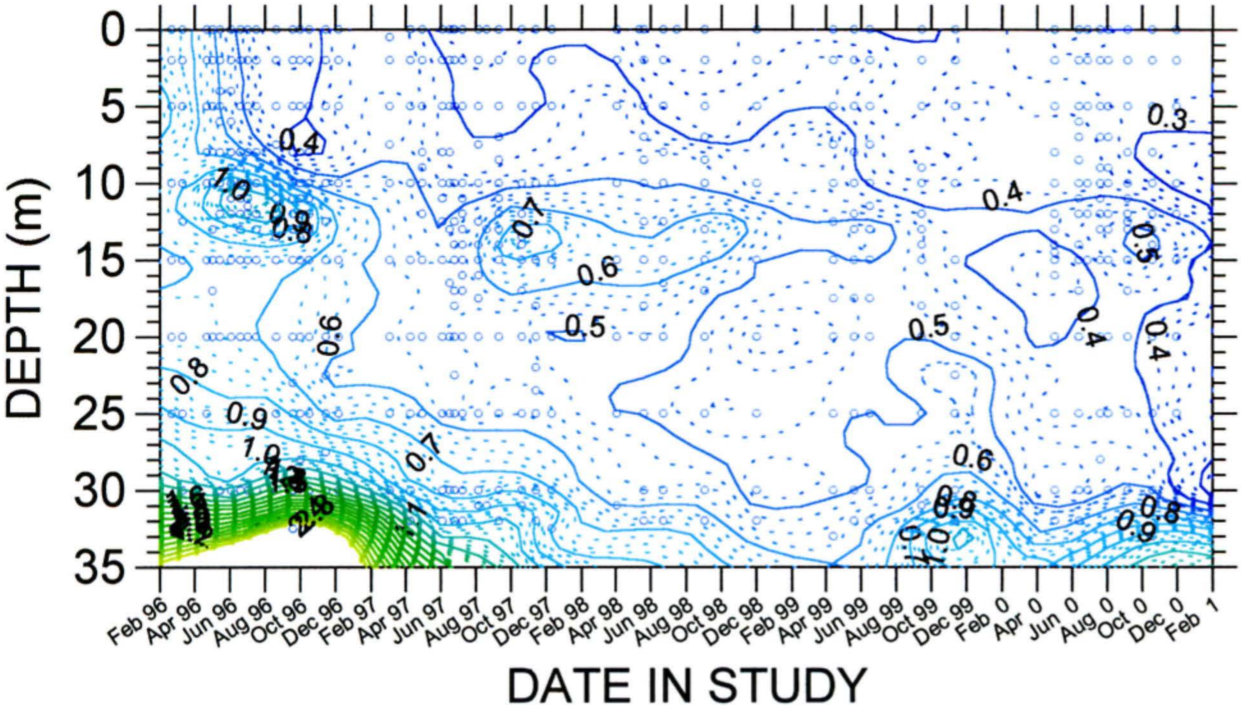
Total Phosphorus bears some similarities to chlorophyll, in part because the majority of P in Elkhart Lake is present as plankton biomass rather than as dissolved nutrient. Small but apparent maxima occurred at 9-15m where deep chlorophyll maxima were present in 1996 and to a lesser extent in 1997 (Figure **1996-2000 Total Phosphorus**). The absence of pronounced features in the TP contour demonstrates the relatively static phosphorus balance and lack of any strong external loading. In fact, the predominant input source was clearly sediment regeneration (decomposition)

1992-1996 CHLOROPHYLL a

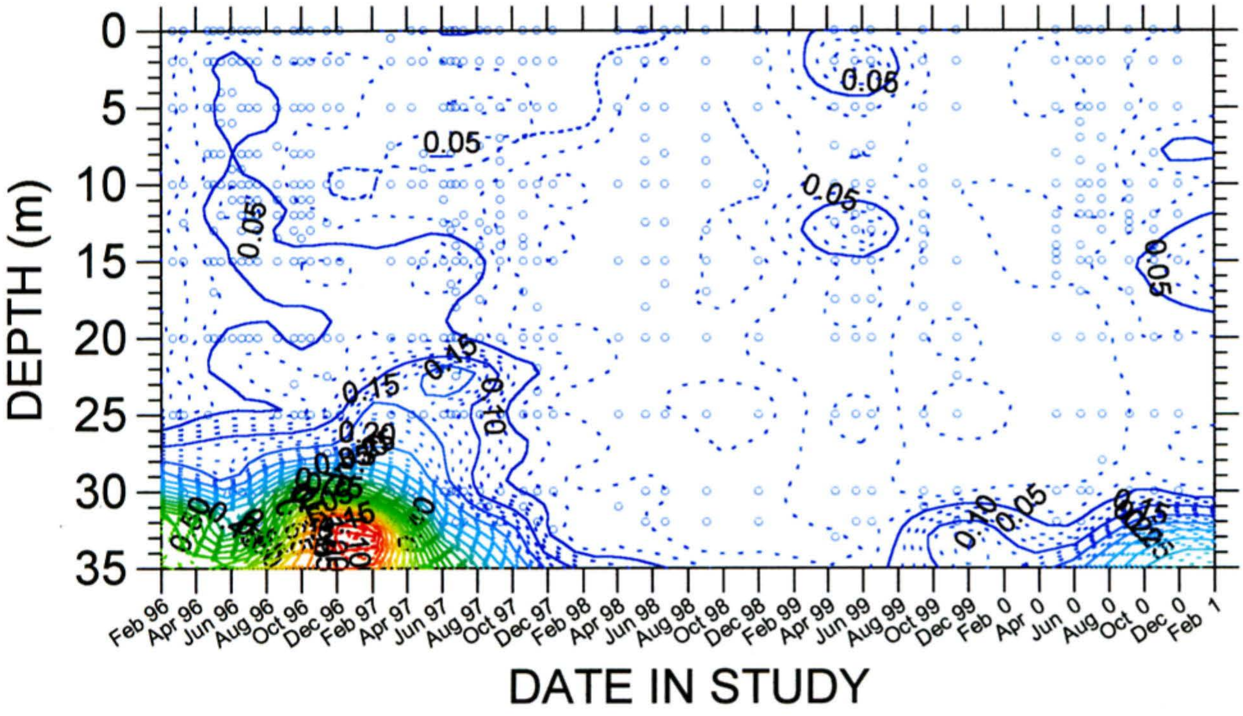


1996-2000 CHLOROPHYLL a





1996-2000 TOTAL PHOSPHORUS



1996-2000 SOLUBLE REACTIVE P

which was very evident in the deep water during the late summer and fall of 1996 but was inconsequential in 1998 and 1999.

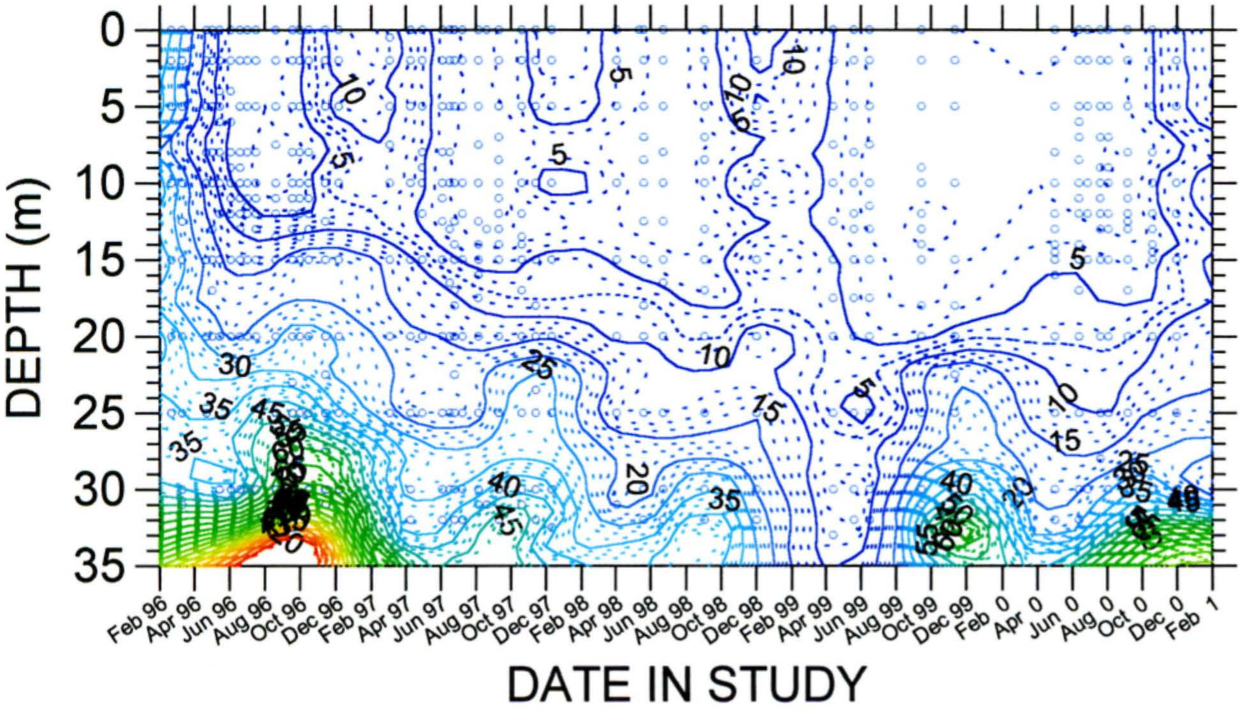
Soluble reactive phosphorus has been considered to be the main yield-limiting nutrient in Wisconsin lakes, and has been near the limit of detection in surface waters at all times during this study. Its regeneration during decomposition produced several μM SRP near the bottom through 1996 (20-100x surface concentrations), but in 1997-1999 SRP was almost undetectable even in the very bottom samples of late summer (Figure **1996-2000 Soluble Reactive P**). As with oxygen and ammonia, the lack of SRP efflux suggests weak anaerobiosis and greatly reduced organic matter flux to the deep sediments. However, the weak efflux also reduces the potential productivity of subsequent spring surface waters, thereby reducing biomass available for sedimentation.

Ammonium ion is produced primarily by decomposition of organic matter and hence builds up in the hypolimnion until fall overturn. Through 1996, late summer values of 100-200μM were common near the bottom of the lake. During the fall of 1997-1999, the highest concentrations observed were in the range of 55-80μM (Figure **1996-2000 Ammonium**). The decrease could be construed to mean that less organic matter was reaching the deep benthos of Elkhart Lake, consistent with greatly decreased phytoplankton populations in the deep chlorophyll maximum (above).

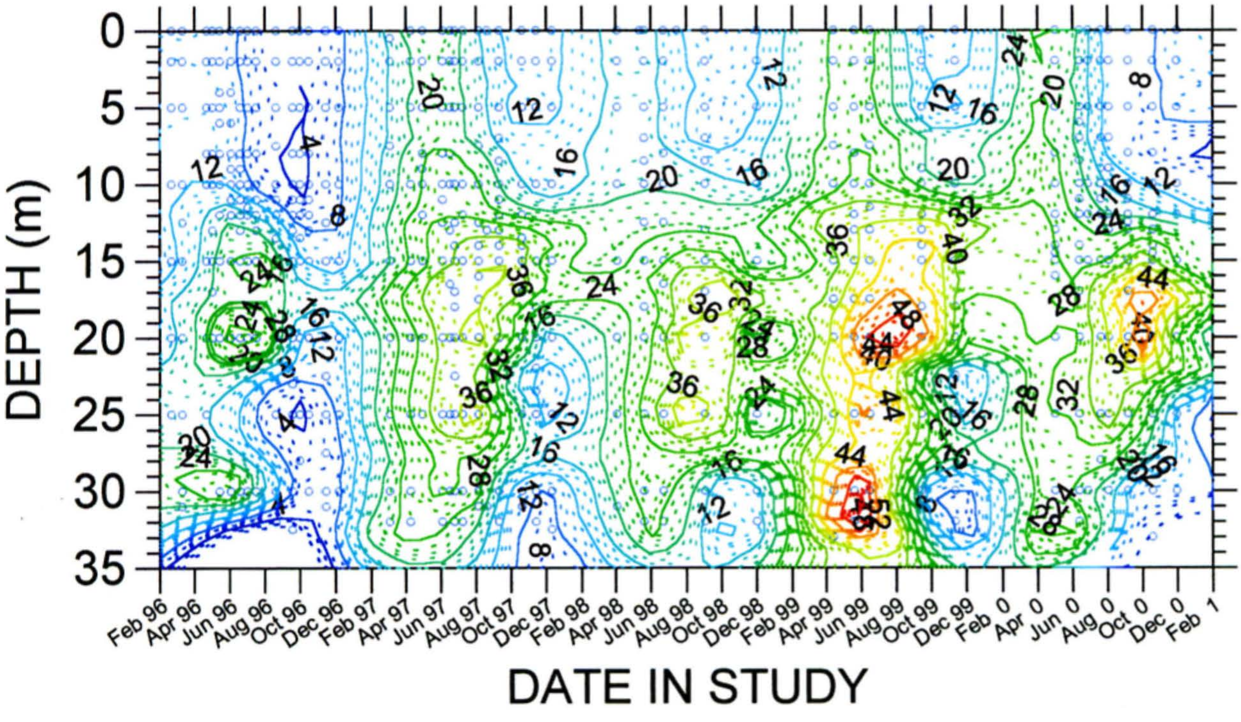
Nitrate, a nutrient for algal growth and a fine respiratory electron acceptor for bacteria in anaerobic hypolimnia, also displayed systematic changes between 1996-1999 (Figure **1996-2000 Nitrate**). In the first year nitrate was virtually absent from both surface waters and near-bottom waters with strong gradients of decrease into the DCM. Deep water depletion was much less pronounced in 1997 and low values were not found anywhere in the midwater column. Surface consumption by algae persisted with somewhat lower apparent efficiency than in previous years but still demonstrated expected seasonality. Not to be neglected however were groundwater inputs, especially high in nitrate, as described subsequently. In 1998-99, bottom water depletion was minimal, and total water column nitrate actually increased significantly during 1999. The progression in bottom water was associated with later and weaker development of oxygen depletion which inhibited denitrification-based nitrate depletion. These results point to a significantly reduced flux of organic carbon to the bottom sediments, consistent with the greatly depleted phytoplankton population in overlying waters. This would be an expected outcome of zebra mussel proliferation.

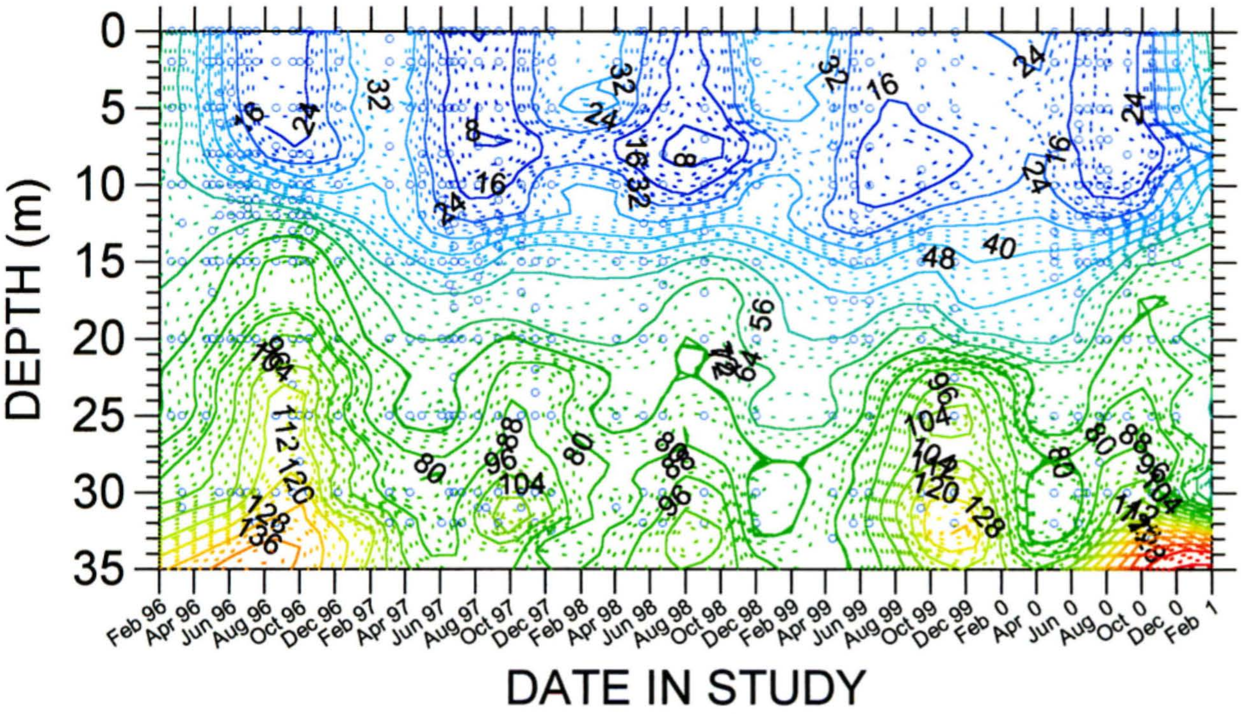
Silicate is a valuable contrast to nitrate, as it is a nutrient only to a select group of phytoplankton, primarily diatoms. In Figure **1996-2000 Silicate**, regular surface depletion in mid- to late summer through 1996 gave way to the appearance of sub-surface silicate minima during 1997-99. Undetectable silicate was still found for periods in early summer, but invasion of silicate into surface water preceded fall overturn significantly. In each of the later years, a distinct zone between 5-10m has lower silicate than either surface or deeper water in mid-summer. This zone is above the layer of Cyanobacteria usually dominant here, and the Cyanobacteria do not utilize silicate for growth. The suggestion is that smaller blooms of diatoms occurred in shallow but not surface waters, perhaps shading the deeper waters and thus contributing to the demise of the DCM. Because these blooms apparently occurred in the depth range of zebra mussel abundance

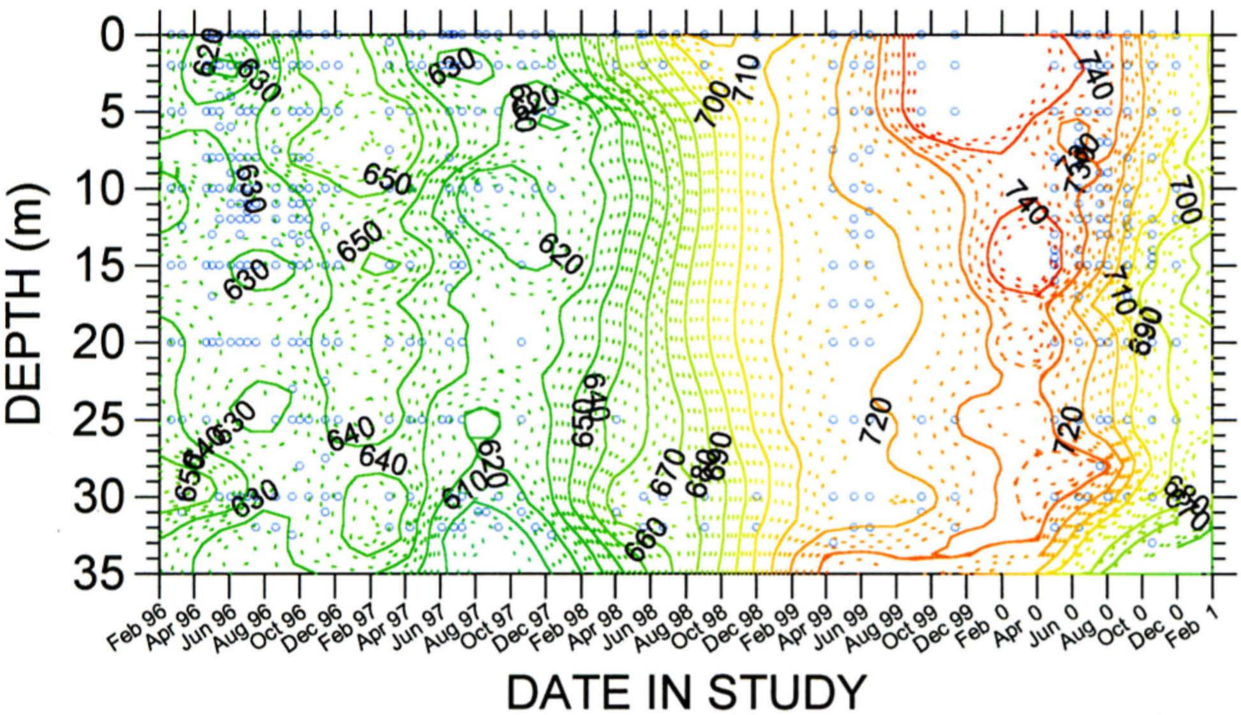
1996-2000 AMMONIUM



1996-2000 NITRATE




1996-2000 SILICATE


1996-2000 CHLORIDE

(5-10m), the diatom story may be inconsistent with zebra mussel feeding strategies. Again, groundwaters have been very high in silicate, and their contribution may obscure biological removal processes to some extent. Samples for phytoplankton species composition are in hand, but could not be analyzed due to their labor- and time-intensive nature. Consistent late-summer to early winter regeneration of silicate in bottom waters remained a strong force in the cycling of this nutrient however.

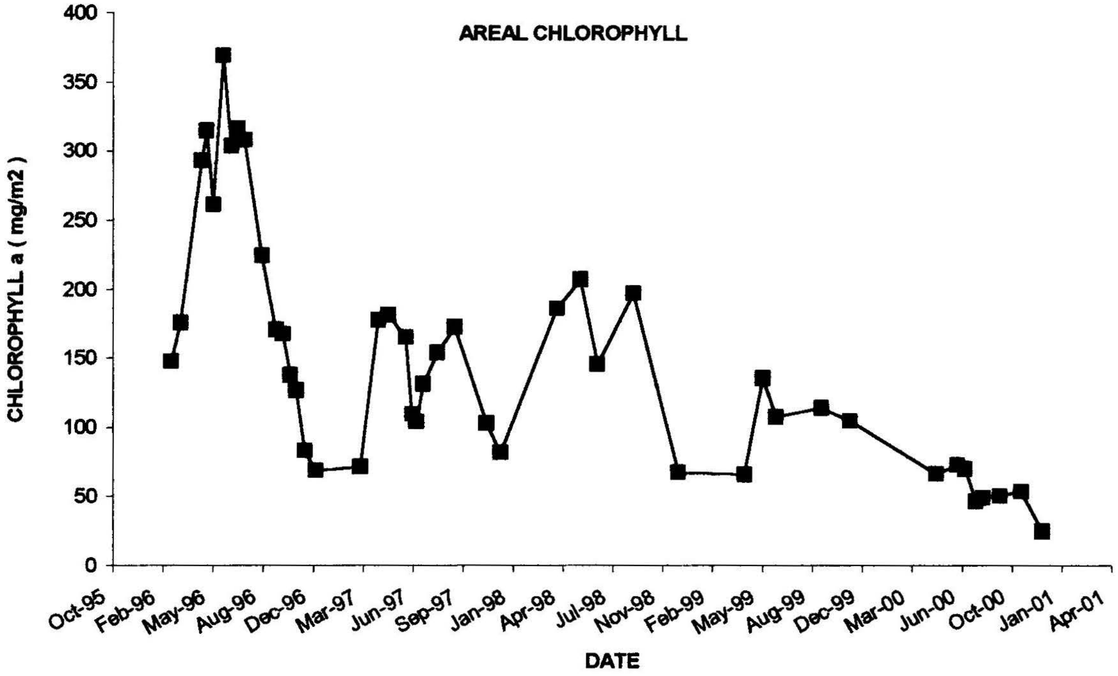
Chloride is a conservative (biologically and chemically inactive) mineral tracer of anthropogenic (road salting, erosion, agricultural application) and groundwater inputs. For a dimictic lake with relatively short residence time (ca. 6 years), chloride should show a weak seasonal cycle and nearly constant interannual concentration. The contour plot **1996-2000 Chloride** demonstrates that virtually no vertical structure and little overall change was observed through 1998. Starting in 1998 a consistent, continuous increase in chloride from means of 640-650μM to over 740μM occurred in Elkhart Lake. Zebra mussels cannot influence chloride concentration in any way. However, groundwater at this site was often highly enriched in chloride (see below), and may be largely responsible for the 1999 increase in this mineral. Indications of enhanced groundwater input have strong ramifications to nutrient budgets, because several key nutrients (nitrate, silicate) are positively related to chloride in groundwater (see below) and may contribute to observed persistence of surface nutrients.

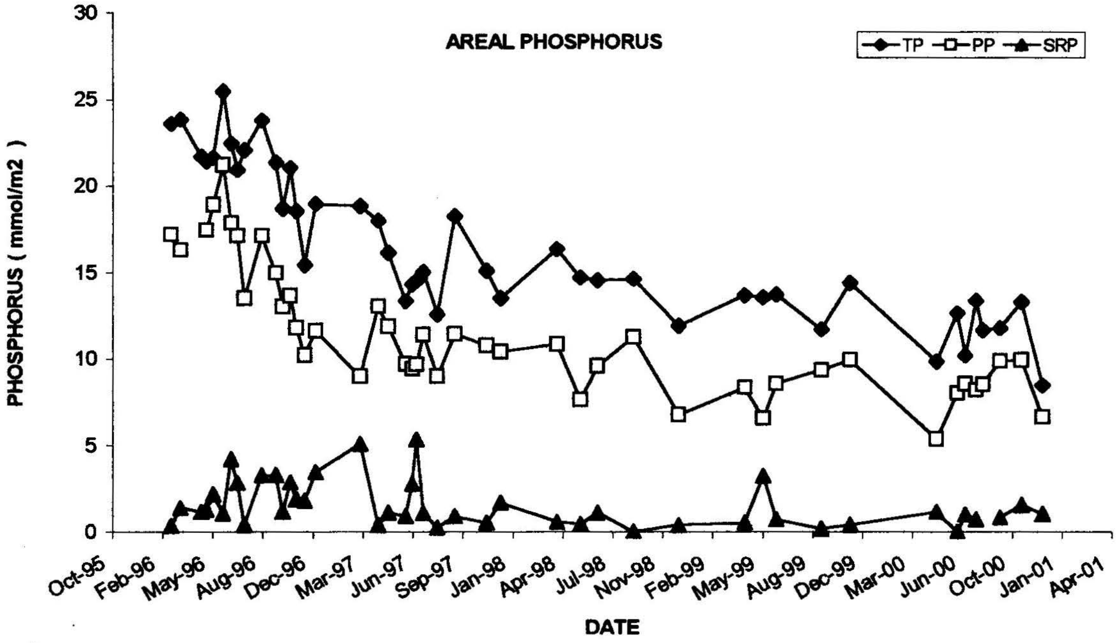
d) Areally-integrated water column inventory for key variables

From a management perspective, it is the total lake inventory (areal content, i.e., amount per square meter from surface to bottom) of key components that identifies trends resulting from point-source or diffuse inputs vs. exports. If total phosphorus increases consistently from year to year, for example, it is very likely that substantial loading from sewage or agricultural activities is occurring. This complement to surface water characteristics is a major aspect in understanding lake processes. Sampling with inventory in mind, vertical profile data were integrated by a simple trapezoidal method for each date in which profile chemistry was undertaken. These are presented in a series of figures identified by "Areal" for total inventory per square meter.

Algal biomass (Figure **Areal Chlorophyll *a***) displayed a trend of decreasing magnitude for spring and fall bloom conditions with consistent mid-winter low levels. By the year 2000, total *water column* inventory of algal biomass had dropped from about 300 mg/m^2 to less than 70 mg/m^2, with little evidence of spring bloom conditions remaining in later years. This represents an approximately 70% decrease in planktonic algae, with most of the loss being due to the absence of a deep chlorophyll maximum and extremely muted spring bloom biomass build-up.

Particulate Phosphorus, closely related to algal biomass, also declined persistently from 1996-2000 (Figure **Areal Phosphorus**, open symbols). An overall decrease from highs near 20 mmol/m^2 in 1996 to levels slightly less than 10 mmol/m^2 in 2000 document an approximately 50% reduction. Likewise, *Total Phosphorus* (Figure **Areal Phosphorus**, closed diamonds [top]) consistently declined from near 25 mmol/m^2 in 1996 to about 12 mmol/m^2, also a 50% decrease on average. Seasonal cycles were much less pronounced in these two parameters. *Soluble Reactive Phosphorus*, the bioavailable form, was typically low throughout the study (Figure **Areal**


AREAL CHLOROPHYLL
CHLOROPHYLL a (mg/m2)
0
50
100
150
200
250
300
350
400
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
Jul-98
Nov-98
Feb-99
May-99
Aug-99
Dec-99
Mar-00
Jun-00
Oct-00
Jan-01
Apr-01
DATE

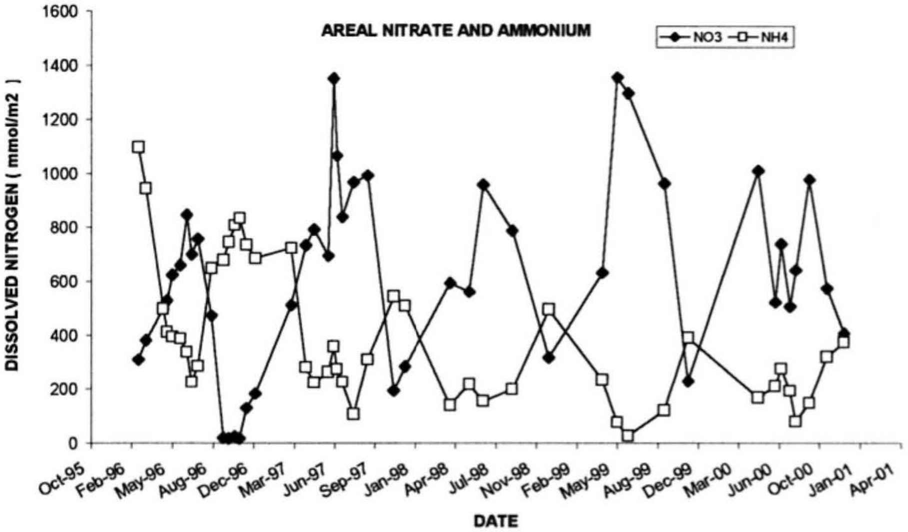

AREAL PHOSPHORUS
TP
PP
SRP
PHOSPHORUS (mmol/m2)
0
5
10
15
20
25
30
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
Jul-98
Nov-98
Feb-99
May-99
Aug-99
Dec-99
Mar-00
Jun-00
Oct-00
Jan-01
Apr-01
DATE

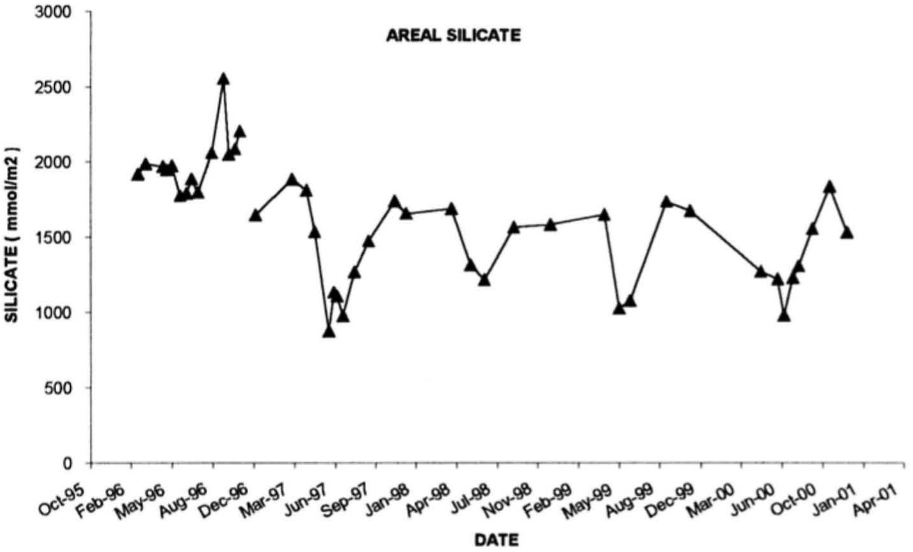
Phosphorus, closed triangles [bottom]). Irregular high values from unknown sources virtually disappeared after 1997, leading to persistently low inventory for this growth-promoting nutrient.

Nitrogenous nutrients *ammonium* and *nitrate* showed pronounced and temporally offset seasonal cycles of large magnitude (Figure **Areal Nitrate and Ammonium**). Ammonium was always highest during the period between fall mixing (late October) to spring stratification (April) due to release from sediment decomposition processes. Ammonium decreased during spring due to the combination of nitrification (ammonium oxidation by bacteria) and algal uptake during the spring bloom when present. Most notable, however, is the consistent decrease in winter high inventory from over 1000 mmol/m^2 in 1996 to less than 400 mmol/m^2 in 2000 (60% less). This was due to greatly reduced bottom water decomposition and ammonium release during the low biomass years later in the study. Because nitrate is produced from ammonium by bacteria in the spring, nitrate values increased sharply during March-May in every year. Additional inputs are found in groundwater recharge (below). It seems at first contradictory that nitrate inventories did not decrease as did ammonium, but two major ecosystem processes come into play to buffer nitrate content. First, greatly reduced magnitude of the spring bloom in later years led to lower planktonic uptake of nitrate. Second, and probably most important, is that decreased algal decomposition in bottom waters reduced the loss of deep water nitrate from anaerobic bacterial respiration. In previous years prior to 1997, nitrate inventory eventually dropped to near-zero values because of bacterial processes (nitrate respired to nitrogen gas) in the deep water (see 1996 and Edgington and Cuhel 1997). As a result, seasonal lows of nitrate inventory have increased from zero to about 300 mmol/m^2.

Diatom and scaled chrysophyte nutrient *Silicate* displayed consistent seasonal cycles throughout the 1997-2000 period at a mean level lower than 1996 but without subsequent trend (Figure **Areal Silicate**). Lowest inventories in mid-summer reflect sedimentation of diatom biomass to the bottom, with regeneration of available nutrient during the winter. Inventory highs of about 2000 mmol/m^2 during 1996 were followed by constant winter inventories of 1700 mmol/m^2, a 15% decrease. The inventory contrasts sharply with surface values (above) which decreased to near-undetectable levels most summers.

The conservative non-nutrient *Chloride* presented a sharply contrasting persistent increase in inventory after 1997 (Figure **Areal Chloride**). Chloride has no significant biological connection and is geochemically inert once in the water column. Its sources are restricted to groundwater and direct runoff, as it is absent in precipitation and is not produced in sediments by decomposition processes. Because of the absence of biological interaction, there was no vertical structure in chloride concentration (see contour Figure **1996-2000 Chloride** above). Inventory increased by 18% from 19,000 mmol/m^2 in 1996 to 22,500 mmol/m^2 in 1999-2000, uniformly throughout the water column. Using the lake volume of 1.67×10^7 m^3 (Edgington and Cuhel 1997) and an increase of 100 μM over the 1998-2000 period (surface values above), about 100 tons of sodium chloride were added to the lake (98×10^6 g). Assuming no significant increase in road salting activity, the suggestion is that either groundwater flow or groundwater chloride concentrations have grown consistently between 1998 and 2000. Groundwater chemistry is discussed below.


AREAL NITRATE AND AMMONIUM
NO3
NH4
DISSOLVED NITROGEN (mmol/m2)
0
200
400
600
800
1000
1200
1400
1600
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
Jul-98
Nov-98
Feb-99
May-99
Aug-99
Dec-99
Mar-00
Jun-00
Oct-00
Jan-01
Apr-01
DATE


AREAL SILICATE
SILICATE (mmol/m2)
0
500
1000
1500
2000
2500
3000
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
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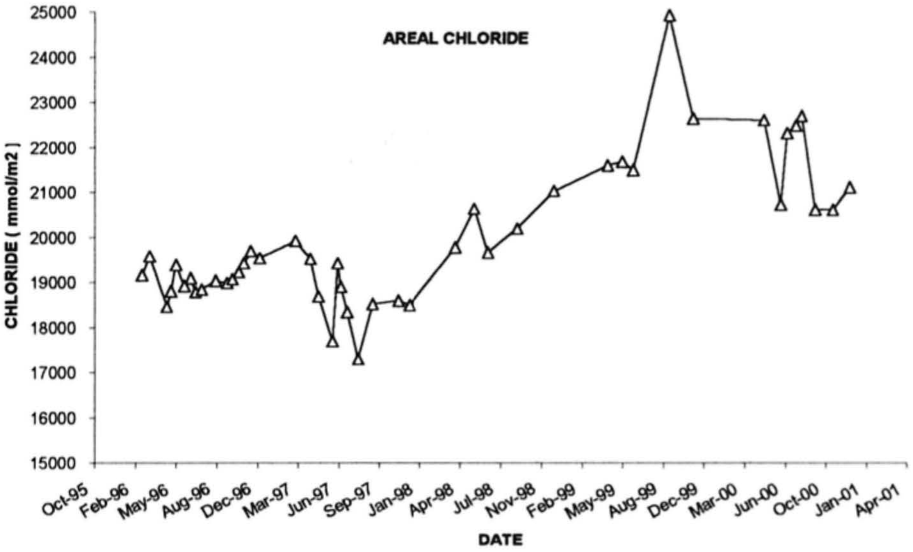
Oct-00
Jan-01
Apr-01
DATE


AREAL CHLORIDE
CHLORIDE (mmol/m2)
15000
16000
17000
18000
19000
20000
21000
22000
23000
24000
25000
Oct-95
Feb-96
May-96
Aug-96
Dec-96
Mar-97
Jun-97
Sep-97
Jan-98
Apr-98
Jul-98
Nov-98
Feb-99
May-99
Aug-99
Dec-99
Mar-00
Jun-00
Oct-00
Jan-01
Apr-01
DATE

Primary Productivity is a measure of the autochthonous input of new organic carbon into the ecosystem, thereby feeding both the food web and benthic process cycles of decomposition and nutrient regeneration. Driven by algal photosynthesis, it may be expected to vary systematically with lake trophic status. During the study period, annual areal productivity was measured for another related project by modeling photosynthesis-irradiance data using 14C-bicarbonate uptake (Fee 1990). Areal productivity was similar in 1996-1998 (482, 420, and 475 $gC/m^2/year$ respectively). In 1999 production dropped by over 25% to 327 $gC/m^2/year$ but rebounded in 2000 to 392 $gC/m^2/year$, still lower than average. However, based solely on decreased inventories of chlorophyll and total P (above) one might expect substantially lower areal productivity in the later years. The observed productivity in the absence of biomass build-up points to greatly increased recycling efficiency in the upper waters of Elkhart Lake, possibly aided by zebra mussel feeding activity. Key nutrient and biomass parameters for summer processes in 1993 (pre-zebra mussel) and 1996-2000 are summarized in Table **INTERANNUAL** below.

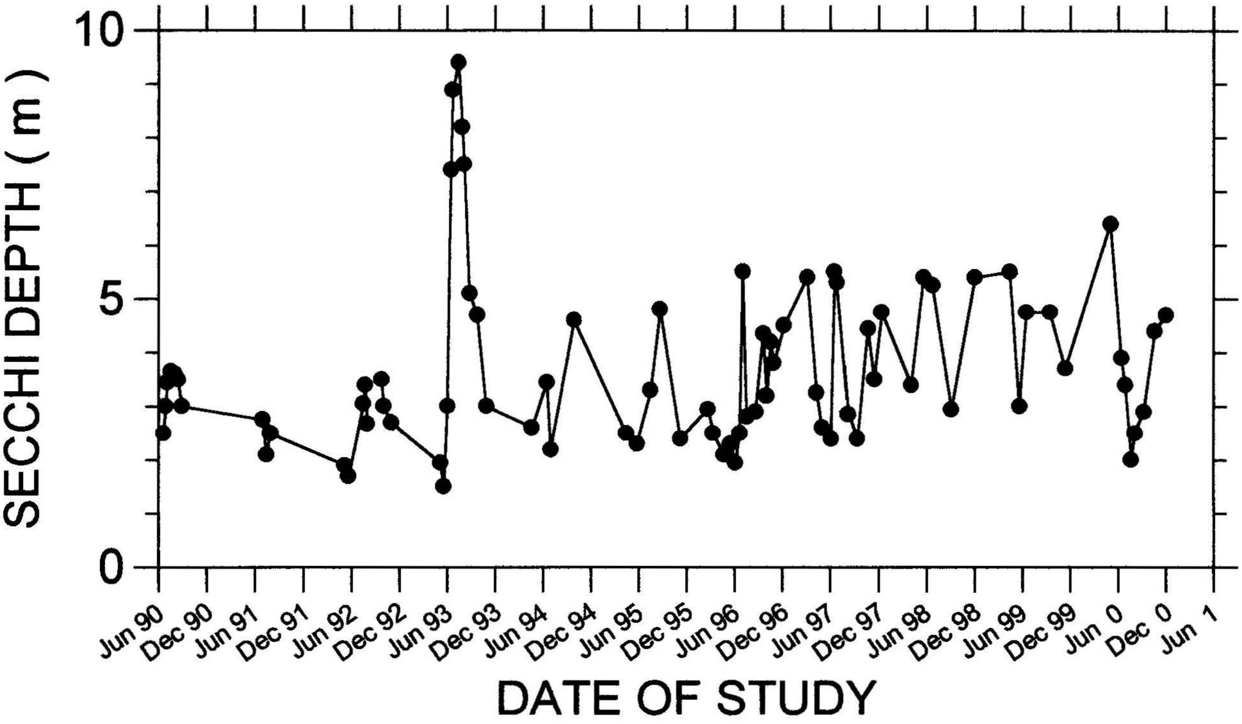
Table INTERANNUAL: Changes in select parameters during the study period 1996-2000, compared to values from pre-zebra mussel year 1993 (clearest on record). Appropriate maxima or minima during summer are provided for nutrients.

PARAMETER	UNITS	MIN/MAX	1993	1996	1997	1998	1999	2000
No. of trips	per yr		11	16	12	7	5	8
Secchi Depth	meters	max, sum	9.40	5.50	4.80	5.40	4.75	3.40
DCM Chl *a*	μg/L	max	128.3	158.8	42.84	36.9	12.2	6.9
Productivity	$gC/m^2/y$	n/a	N. D.	482	420	475	327	392
Surface NO_3^-	μM	min, sum	0	0.48	4.3	2.6	2.6	0
Surface SiO_2	μM	min, sum	75.2	0	0	0	5.5	2.0
Surface Chl *a*	μg/L	min, sum	0.57	1.98	1.61	1.00	2.10	1.46
Bottom NH_4^+	μM	max, sum	113	136	71.3	55.1	68.4	66.0

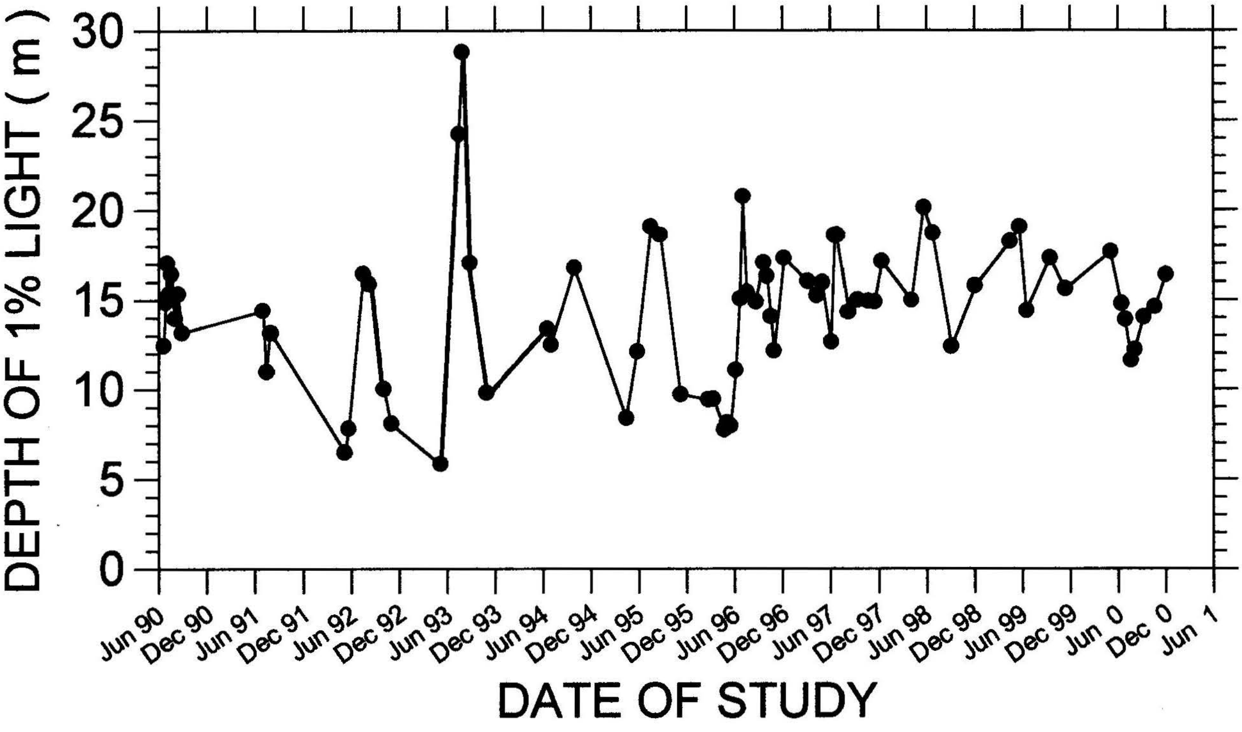
e) Transparency indices

Two measures of water clarity were used; the Secchi Disk depth and the depth of 1% surface light measured with an underwater quantum sensor. In Figures **1990-2000 Secchi Depth** and **1990-2000 Light Penetration** the entire Elkhart Lake dataset is presented for comparative purposes, with the exceptionally clear year of 1993 standing out distinctly. It is apparent that both measures show increased overall water clarity in later years of 1996-1999. Calculation of numerical mean values is not appropriate because of the intrinsic seasonal cycles of spring and fall mixing versus summer stratification and the irregular sampling frequency. However, the visual average values for both Secchi Depth and depth of 1% light penetration during 1996-1999 are similar to the *clearest* values prior to that time, except for 1993. Decreased water clarity and transmission may have occurred during early summer of 2000, consistent with biomass and nutrient results described above. It is certain that overall water clarity did not *decrease* during the 1996-2000 study period.

1990-2000 SECCHI DEPTH



1990-2000 LIGHT PENETRATION



f) Carlson's Trophic Status Index (TSI)

It is often difficult to relate the mass of numbers presented above to some understandable index of "ecosystem health", as well it should be. However, Carlson (1977) devise a series of equations that bring three frequently considered parameters, i.e., Secchi Depth, Total Phosphorus, and Chlorophyll *a* into a unified scale. The equations were previously presented (Edgington and Cuhel 1997). Based on *surface values* for these criteria, lakes may be ranked as eutrophic (>50 = rich; high nutrient supply), mesotrophic (40-50 = middle), and oligotrophic (<40 = very clear; low biomass potential). Two types of trends must be considered; seasonal changes and interannual or long-term progressions. In many cases, the Trophic Status Index is based on a single or small number of surface samples taken during summer, although inspection of the dataset above argues strongly that surface samples may provide only limited ecosystem understanding. To put Elkhart into the proper perspective, Figure **Carlson's Trophic Status Index** shows results from 1990 to 2000 as available.

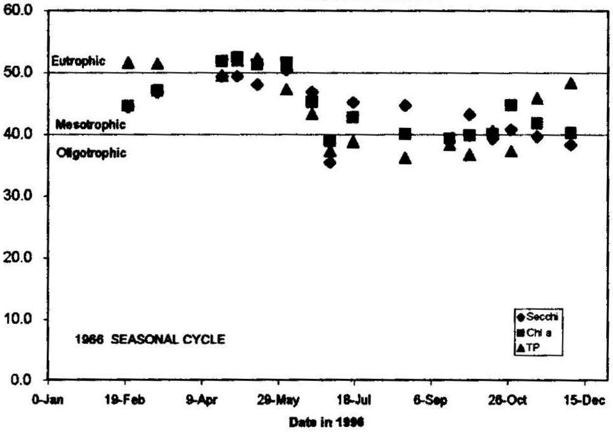
The upper panel demonstrates a typical seasonal progression, using 1996 data. The spring bloom (last of its kind) produced mesotrophic to eutrophic character from under-ice sampling in February and March through strengthened stratification in late May. During summer conditions all TSI indices declined into the mesotrophic to oligotrophic category. As nutrients and deep-dwelling biomass were mixed back into the surface during fall overturn, the TSI returned to mesotrophic character. It is noteworthy that all three parameters provided qualitatively and quantitatively similar interpretation, as was true in all years. During summer, Elkhart Lake might have been pronounced "meso-oligotrophic", a label considered to be "good to excellent" by resource managers.

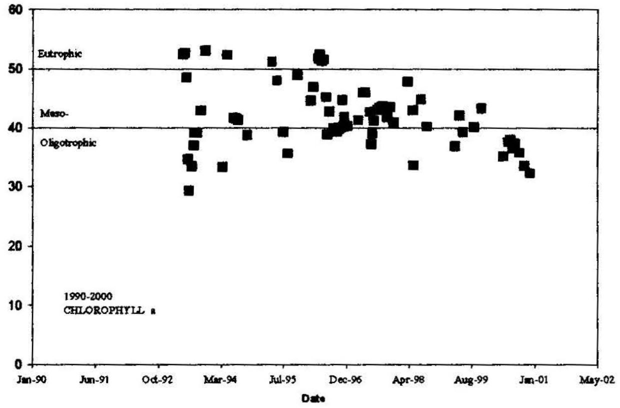
The lower three panels present all years for Chlorophyll *a*, Total Phosphorus, and Secchi Depth respectively. In the cases of Chlorophyll *a* and Total P, there is no question that overall values both trended to more meso-oligotrophic placement and contained few or no meso-eutrophic samples. Secchi Depth (lowest panel) remained predominantly in the mesotrophic placement, but eutrophic values were much rarer and oligotrophic values much more frequent between 1996-1999. The Trophic Status Index, like other features described above, contain the suggestion of a backswing toward previous conditions in 2000, but several more years will be required to fully document the longevity of the massive changes described above.

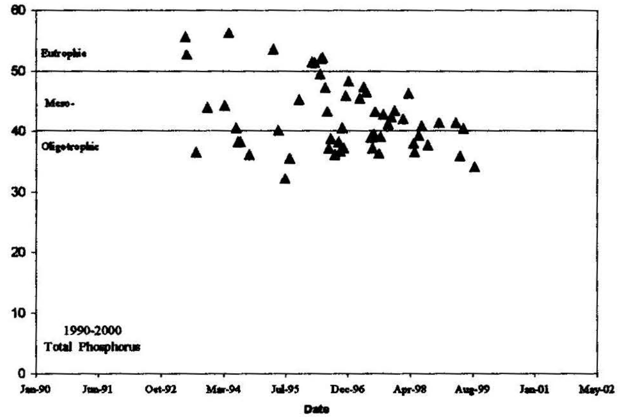
g) Zooplankton abundance and species composition

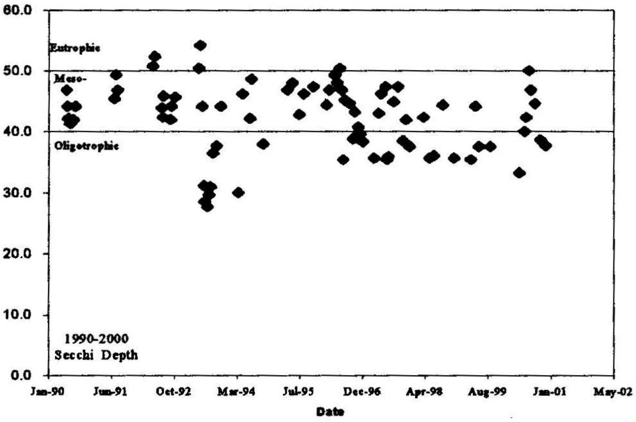
Linking pelagic algal community biomass and productivity to higher order consumers are the pelagic zooplankton. This group, consisting of herbivores and primary carnivores, may be expected to respond to significant redirection of algal biomass to zebra mussel competitors. On each sampling trip, vertical zooplankton tows were made by hand with a 250μm mesh Wisconsin (or "Egg") plankton net. Samples were split for enumeration and elemental analysis. Much work remains on this component, but Natalie Dingledine and later Sarah Berquist have counted enough of the samples to determine population composition and abundance for 1996-2000 at Elkhart Lake. The following figures show areal (animals/m^2) and seasonal abundance of 6 major groups of zooplankton. Spring plankton were dominated by Calanoid copepods, followed shortly by

CARLSON'S TROPHIC STATUS INDEX









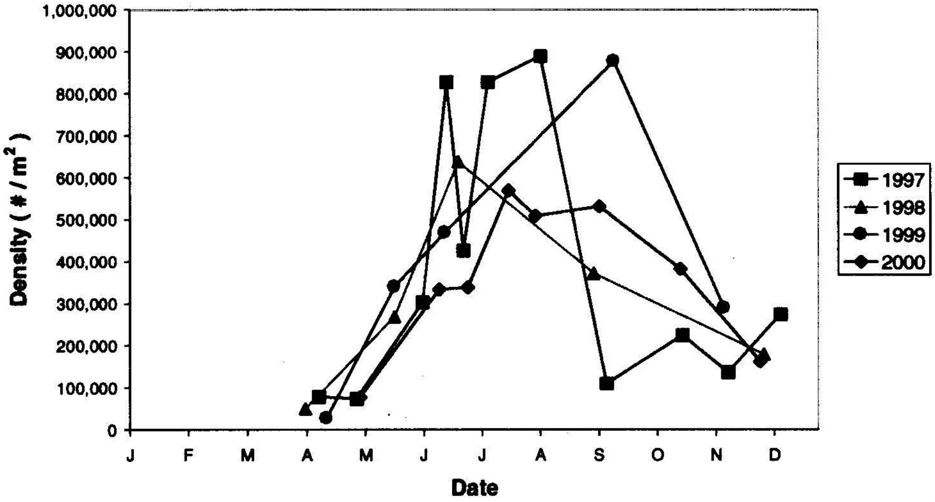
Cyclopoid copepods. Both are *omnivorous*, meaning that they eat both algae and other zooplankton. Calanoids have been known to consume early larval fish. Calanoids were consistently represented both in abundance and timing, and they constituted by far the most numerically abundant group in the zooplankton. Cyclopoids deviated only in an apparent enhancement during the high phytoplankton biomass spring of 1996. Another major group of zooplankton are the Cladocerans, including the genera *Daphnia*, *Bosmina*, *Chydorus*, and *Diaphanosoma*: these zooplankton have a more restricted diet of algae, bacteria, and the smaller of the microzooplankton (rotifers and ciliates, which are themselves herbivores). Collectively, *Daphnia* spp. appeared with regularity in timing and abundance, while Bosminid cladocerans showed slightly more sporadic distributions. *Chydorus* had always been rare (a few animals per sample) but in later years had been observed only once. Other organisms making regular appearances but with numbers too low to interpret objectively also showed little systematic, progressive change related to hydrographic, nutrient, or biomass parameters above. Altogether the total and specific numerical abundance and the distribution of zooplankton among these species groups showed no remarkable differences among years.

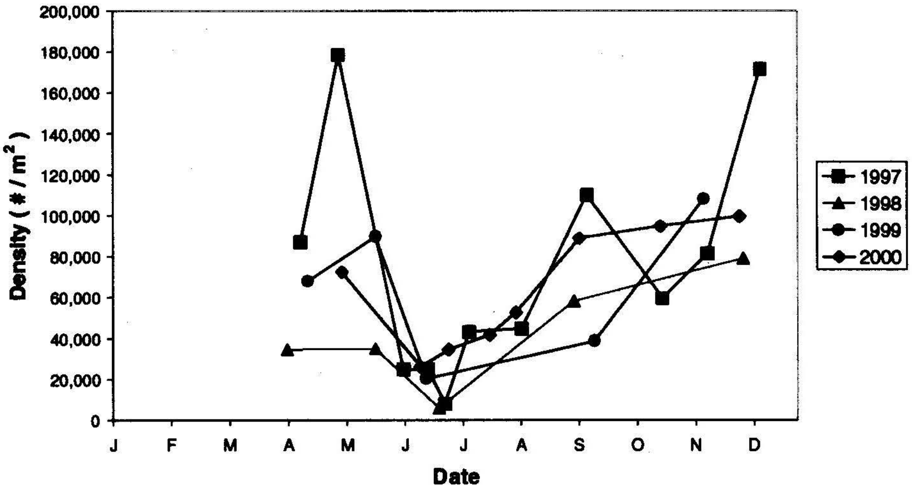
Though further sample analysis remains, one may conclude that at a gross level there has been no systematic change in abundance or species composition of zooplankton populations. The zooplankton results interface with the phytoplankton observations in that the former dominant alga was a large, filamentous Cyanobacterium with high microcystin content and observed impalatability to herbivores. Although a tremendous change in its biomass (decreasing) has been observed, the Cyanobacteria may have played little part in the pelagic food web based on the persistence of pelagic herbivore populations.

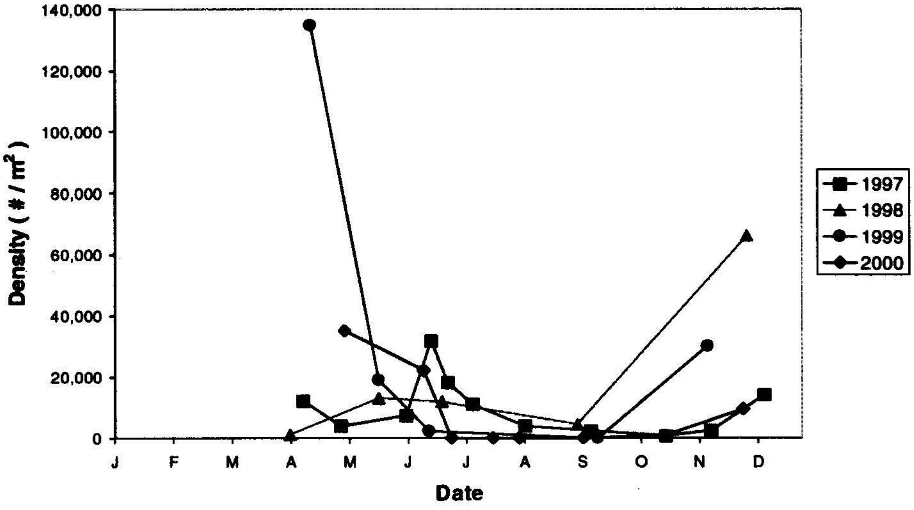
h) Zebra mussel recruitment

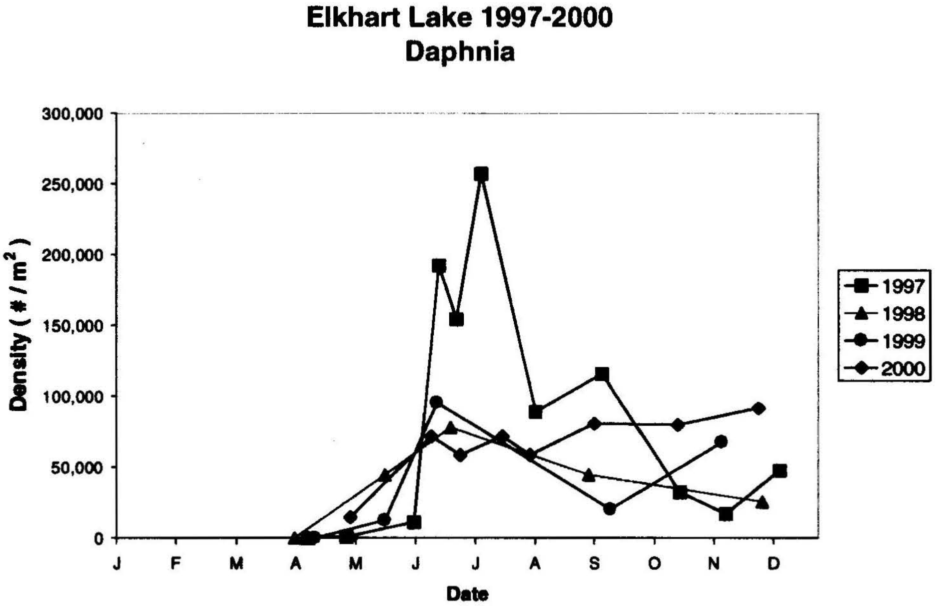
The influence of *zebra mussels*, relatively sessile benthic animals, on lake trophodynamics is likely to be a major perturbation in inland lakes, just as it has been in the shallower Great Lakes and estuaries. Measurement of zebra mussel populations, including recruitment of larval mussels into the attached adult population , has demonstrated their vigorous success in Elkhart Lake. First reported from plankton tows in late 1994, the first year of known colonization was 1995 when nearly invisibly-small attached mussels were noticed. The following zebra mussel recruitment data were provided by Dr. Jerry Kaster of the University of Wisconsin-Milwaukee for the purpose of identifying likely contributors to Elkhart Lake ecosystem change.

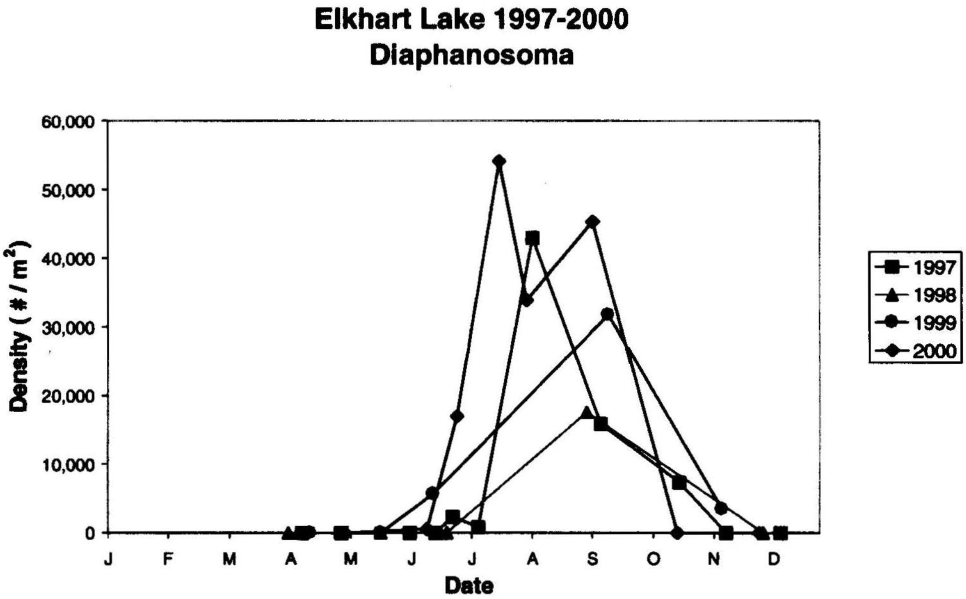
Colonization was definitively evident in 1996, when the greatest proportion of collected animals were 7-9mm in length. A continuous progression of mean size increase at 3-5mm/year was found for collections through 1999 (Figure **Zebra Mussel Size Distribution**). Likewise, adult zebra mussel population density in colonized areas increased 10 times from 1394/m^2 in 1996; 2474/m^2 in 1997; 7132/m^2 in 1998; to 14412/m^2 in 1999. Recruitment (new settlement) based on artificial substrate collections of post-veligers increased from just over 200/m^2 in 1996 to about 1200/m^2 in 1997, 1998, and 1999. Consistent and persistent recruitment in the later years demonstrates that Elkhart Lake was capable of sustaining reproductive populations of zebra mussels in the long term. Further evidence was found in 2000 when the first observations of numerous empty shells were made, in line with the 5-year life span of zebra mussel adults.

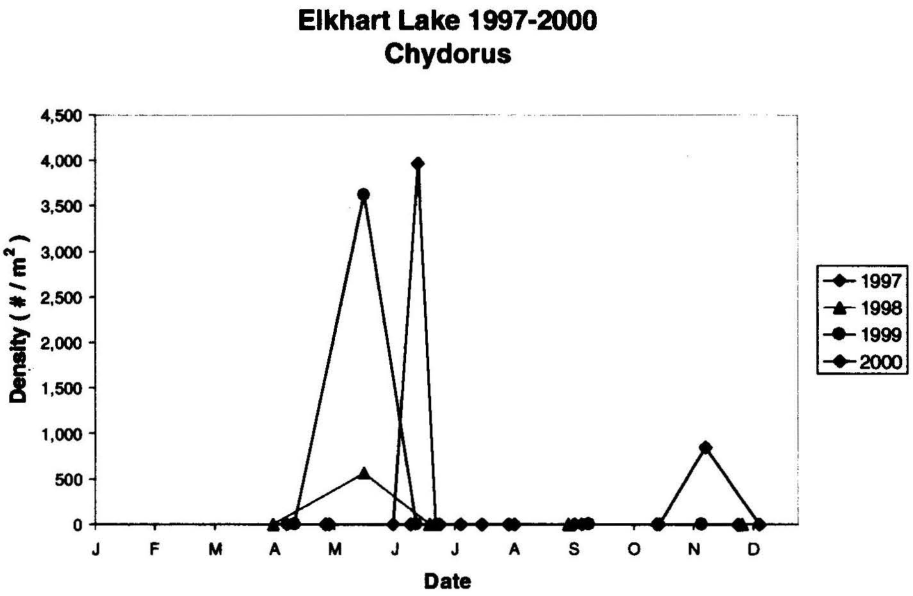

Elkhart Lake 1997-2000
Calanoid copepods

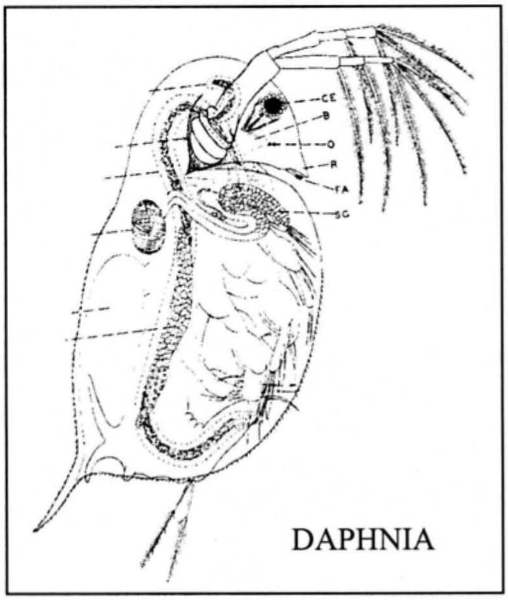

Elkhart 1997-2000
Cyclopoid copepods


Elkhart Lake 1997-2000
Bosmina

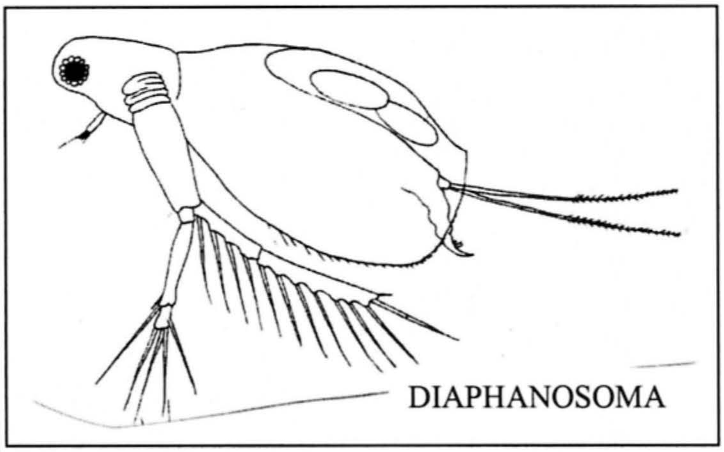

Elkhart Lake 1997-2000
Daphnia
300,000
250,000
200,000
150,000
100,000
50,000
0
Density (# / m²)
J
F
M
A
M
J
J
A
S
O
N
D
Date
1997
1998
1999
2000


Elkhart Lake 1997-2000
Diaphanosoma
60,000
50,000
40,000
30,000
20,000
10,000
0
Density (# / m²)
J
F
M
A
M
J
J
A
S
O
N
D
Date
1997
1998
1999
2000


Elkhart Lake 1997-2000
Chydorus
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Density (# / m²)
J
F
M
A
M
J
J
A
S
O
N
D
Date
1997
1998
1999
2000

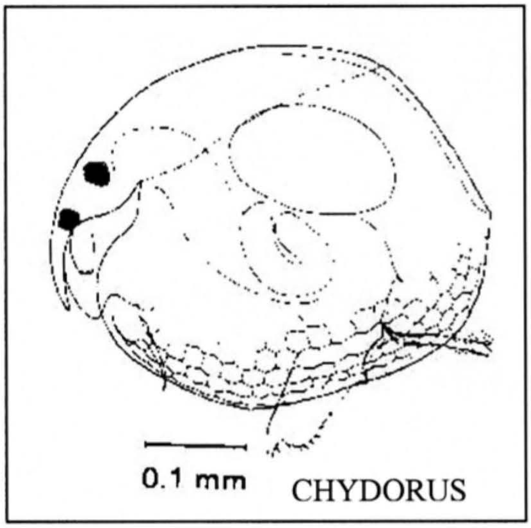


DAPHNIA



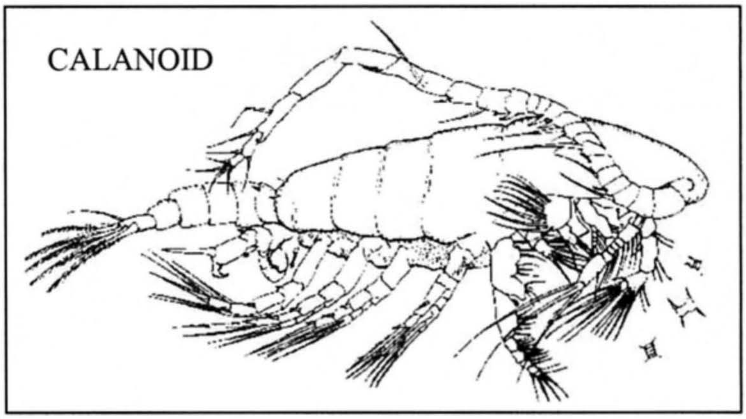
DIAPHANOSOMA

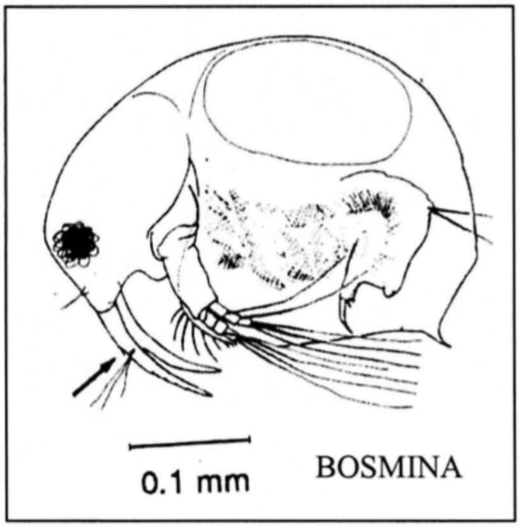
COPEPODS



CHYDORUS

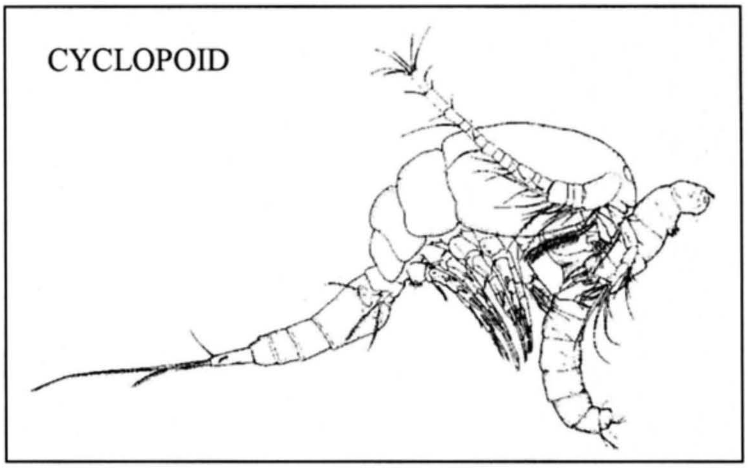
CALANOID

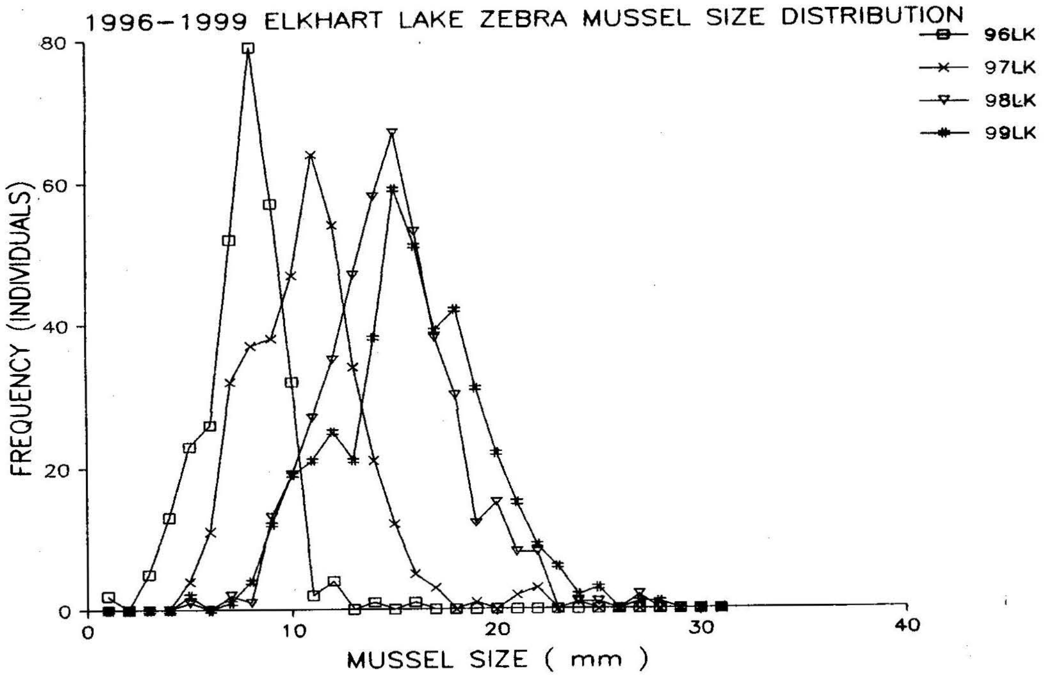




BOSMINA

CYCLOPOID





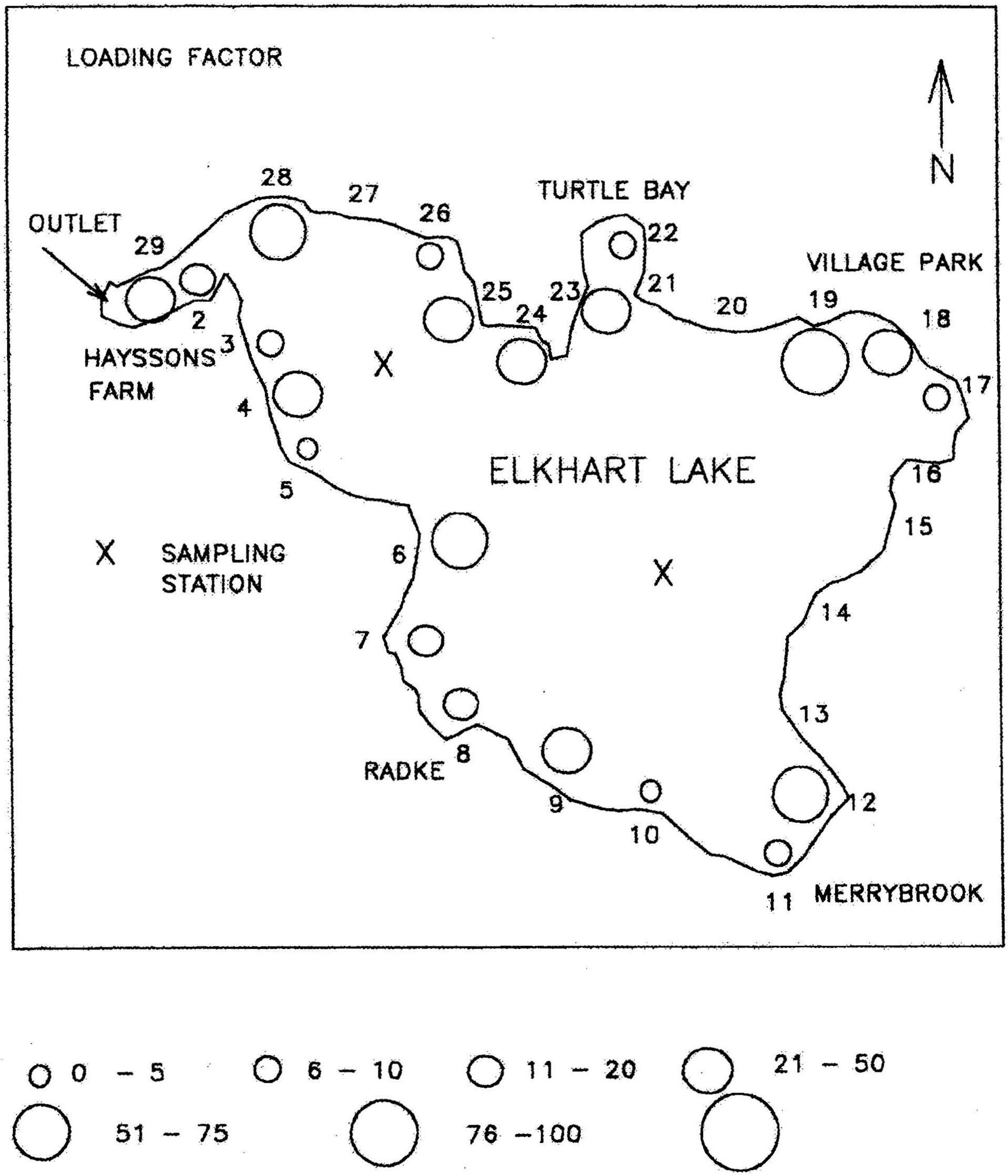
i) Groundwater nutrient chemical composition

For kettle lakes such as Elkhart Lake, groundwater is often a major if not predominant source of water flow. At Elkhart, a water budget suggested that more than 70% of the total lake flux was from groundwater sources. Following a one-time analysis of groundwater by USGS-Madison scientists (March 1996) and observation of very high nitrate and ammonia in an overflow standpipe draining into the lake, regular groundwater sampling was undertaken there. Minipiezometer emplacements at up to 24 stations around the perimeter (in about 3-4 feet of water just offshore; Figure **PZ Stations**) were sampled seasonally for all dissolved constituents from 1996-1999.

Spatial distribution of groundwater composition was remarkably consistent throughout the entire period of study. Four of the most important groundwater components are depicted.

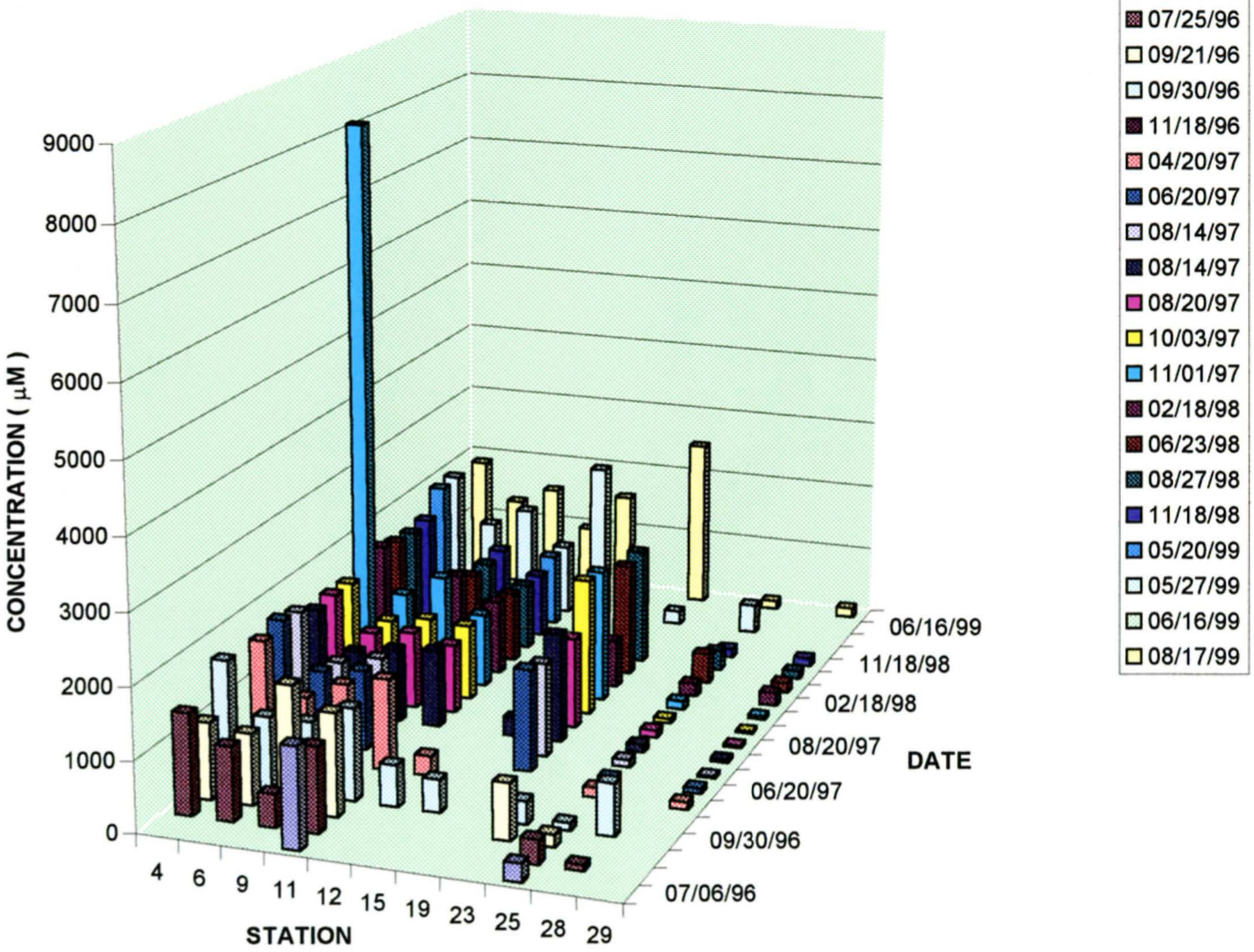
The conservative dissolved substance *chloride* is quite high in concentration in Elkhart Lake (ca. 650µM) relative to many systems (Lake Michigan = 250µM) and is absent from precipitation input. By sampling station (see map above) Figure **Groundwater Chloride** demonstrates that sites on the southern side of the lake (stations 2-11) reliably were enriched in chloride (1000-2000µM) relative to lakewater while northwestern site 23-29 were equally reliably depleted in chloride. The only northern site containing enrichment, site 19, is near the relatively new condominium development and the village park. The temporal fidelity of concentration at a given site, including samples throughout all the seasons, indicates the absence of any seasonally-restricted input term and hence suggests that the main flow is from a large aquifer. It is groundwater from the high strength sources that must be contributing enough flow to offset the fresh (chloride-free) inputs from precipitation and probably direct runoff. It is therefore of great interest to consider other,

Figure PZ Stations. Location of minipiezometer samples collected at Elkhart Lake, 1996-1999. Circles indicate proportion flow based on head height for one complete sampling in 1996.



LOADING FACTOR = Σ (Fractional flux)

ELKHART LAKE GROUNDWATER CHLORIDE



more biologically active nutrient compounds at these same site, as they would be expected to contribute to elemental mass balances.

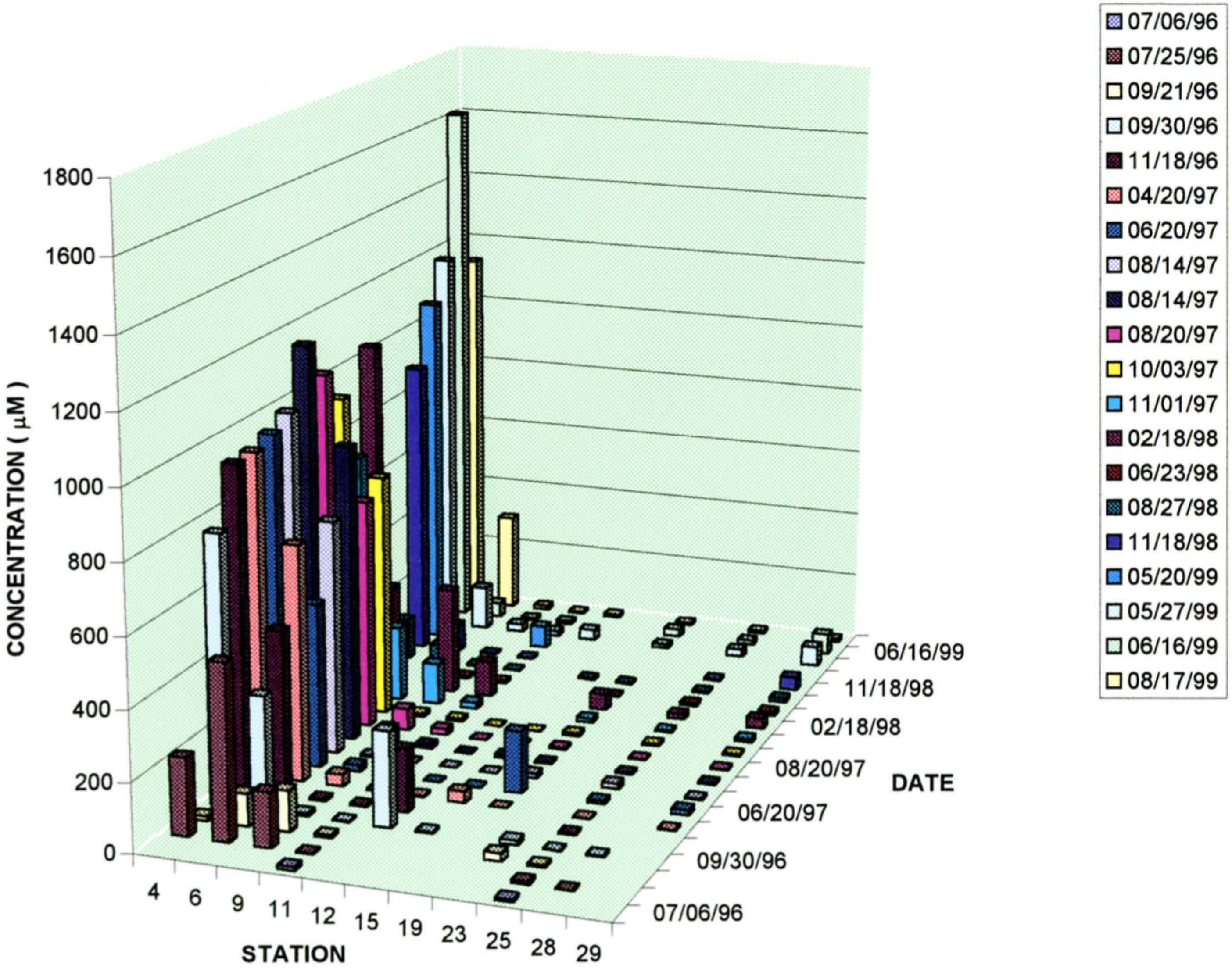
Nitrate has been of significant concern because of its role in promoting planktonic algal and macrophyte (large attached plants and algae) growth. In addition, because nitrate had been completely eliminated from the water column by denitrification during years prior to 1997, its recharge over the winter-spring period must include both groundwater and internal cycling terms. A close but not absolute relationship between groundwater chloride and nitrate is documented in Figure **Groundwater Nitrate**. The two southwestern sites 4 and 6 always contained extremely high concentrations of nitrate (200-1200µM) relative to even the highest lakewater observations (ca. 50µM). Adjacent site 9 frequently (as opposed to always) had somewhat elevated nitrate levels, while all the remaining stations were of no consequence. From this result, it appears that a large source of nitrate to the aquifer is focused to the southwest of Elkhart Lake. If this area is a strong contributor to the groundwater flow, there should be a detectable gradient between the smaller western basin and the larger eastern basin in transect studies, a possibility for future work.

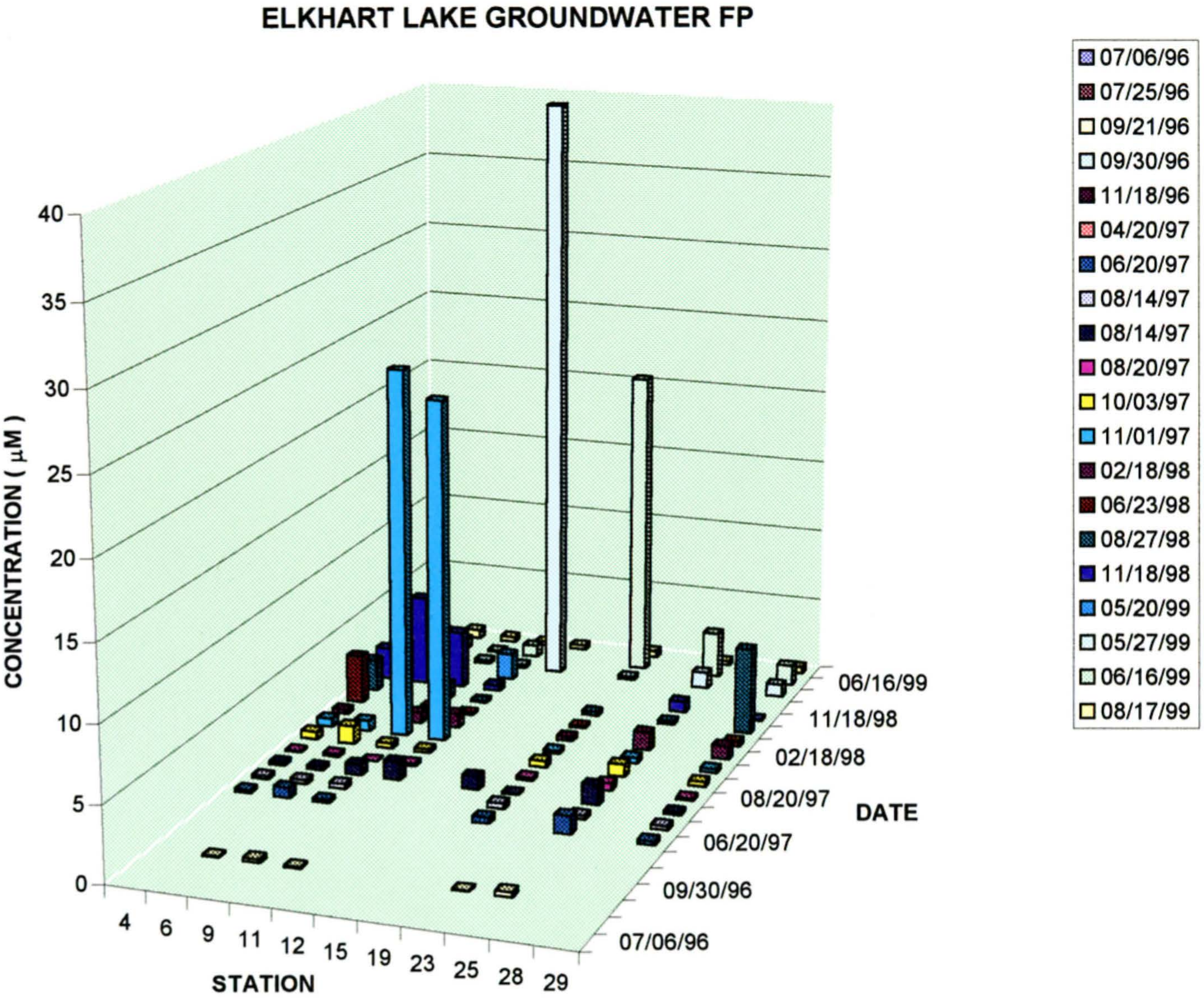
A second, perhaps even more important nutrient is *Phosphorus*. The geochemistry of phosphate (Soluble Reactive P or SRP) in calcium-rich carbonate sediments favors insoluble calcium hydroxyphosphate (apatite) formation and would immobilize groundwater SRP. Organic phosphorus forms would have greater survival in the aqueous phase under these conditions. Phosphorus was analyzed as *Filterable Phosphorus* (FP), which operationally contains SRP plus any polyphosphate (e.g., detergent-derived) and organic forms in the dissolved phase: it is therefore greater than or equal to the concentration of SRP. On a practical basis, soluble phosphorus was essentially absent from groundwater as predicted for SRP itself (Figure **Groundwater FP**). The limited amount of sample and large requirement for assay meant that not all samples were investigated for this parameter, yet the results clearly demonstrate the rarity of any P whatsoever in groundwater. Infrequent exceptionally high values were observed, though handling of the sediment-laden samples could have resulted in occasional solubilization of some of the very high levels of solid-phase P common to these sediments. In any case it did not appear that groundwater could contribute significantly to in-lake P cycling.

The diatom nutrient *Silicate* illustrated a completely different availability pattern (Figure **Groundwater Silicate**). Highest values (600-800µM) were consistently found in the northwestern part of the lake (sites 25-29) approaching the outlet on the north. Relative to lakewater (ca. 50µM), all sampling stations were enriched, however. Silicate has no anthropogenic source of consequence (e.g., farming, construction, sewerage) but is readily leached from silicate-rich soils and underlying rock. Unlike nitrate, groundwater enrichment was only a few-fold greater than lake levels.

Groundwater sampling over many consecutive dates at numerous locations delineated zones of specific chemical character that displayed extremely high consistency. Contributions of groundwater chemical content to Elkhart Lake element cycling may be quantified with additional work. Unfortunately, the United States Geological Survey discontinued maintenance of the gauging station at the outlet during 1996, so flow for the water budget has not been available since the first hydrologic model was presented (Edgington and Cuhel 1997). We have finally

ELKHART LAKE GROUNDWATER NITRATE




ELKHART LAKE GROUNDWATER FP
CONCENTRATION (µM)
0
5
10
15
20
25
30
35
40
STATION
4
6
9
11
12
15
19
23
25
28
29
DATE
07/06/96
09/30/96
06/20/97
08/20/97
02/18/98
11/18/98
06/16/99
07/06/96
07/25/96
09/21/96
09/30/96
11/18/96
04/20/97
06/20/97
08/14/97
08/14/97
08/20/97
10/03/97
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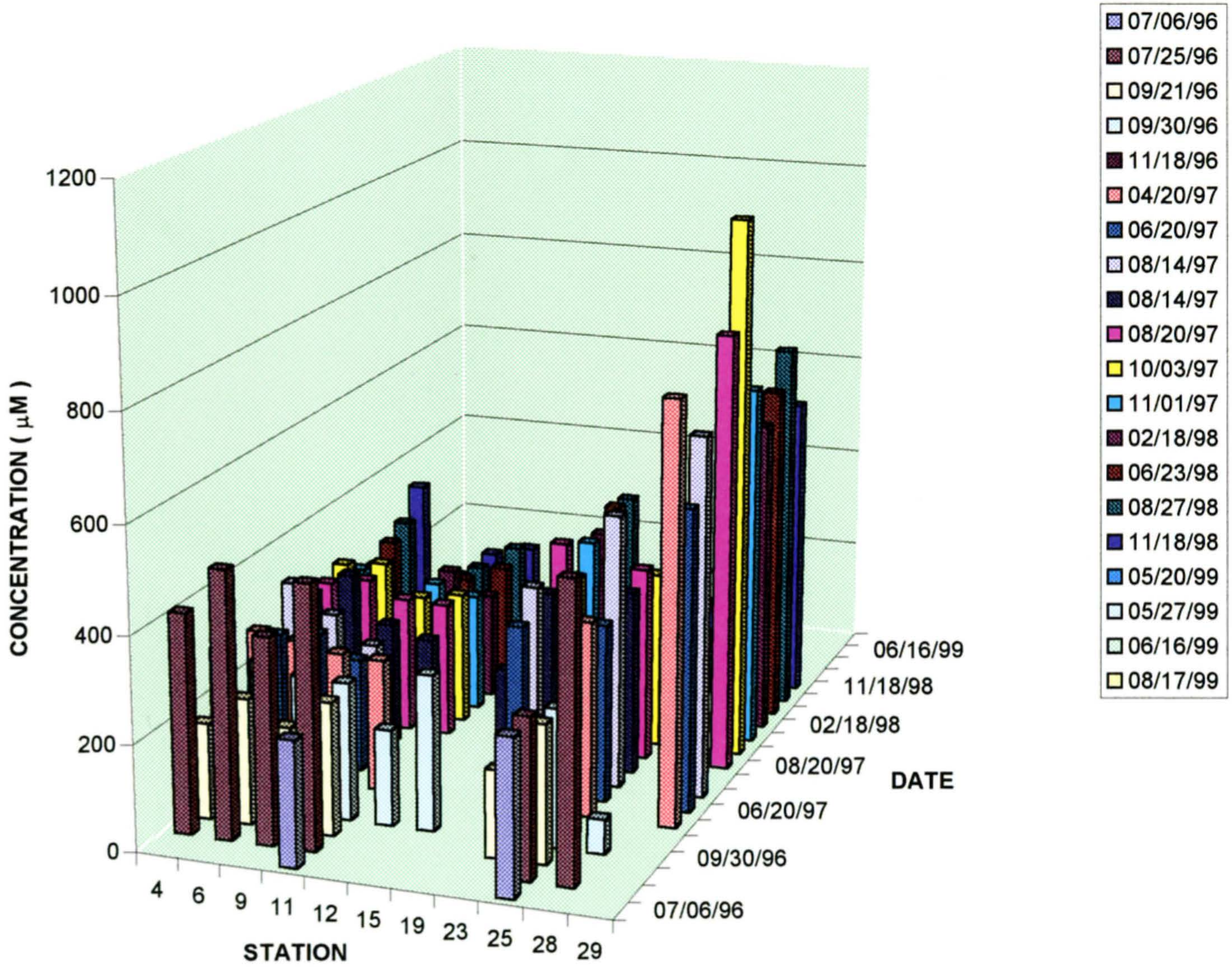
05/27/99
06/16/99
08/17/99


ELKHART LAKE GROUNDWATER SILICATE

succeeded in revitalizing the station in 2001, so future work will have access to this measurement. Expertise required for quantification of seepage rates did not come forth as anticipated, and the specific skills required for that component were not otherwise available. In conjunction with another faculty member, Dr. Timothy Grundl of the UWM Geosciences department, we did undertake a series permeability studies at 7 of the groundwater sites in July 2000. In the future he may provide the effort to calculate potential fluxes and help with deployment of some seepage meters, but this is not currently high on his list of free things to do. Given the dramatic entrance of a large unknown sink for biomass and nutrients, precise estimation of groundwater contribution to Elkhart Lake mass balances is not currently a priority. The results presented in this section, and the sedimentological component below, indicate that this issue remains tractable to future effort if warranted.

j) Sediment grain characteristics

Groundwater flow depends upon several factors, one of which is the permeability of the underlying sediment (in lakes) or soil. Sandy sediments are extremely conductive for water flow, whereas compacted fine-grained sediments restrict flow substantially. In order to further our refinement of groundwater contributions to Elkhart Lake mass balances, an acoustic survey of sediment distribution was undertaken with the help of Dr. Robert Taylor of the UWM Geosciences Department. The result is presented in Figure **Thickness of Fine-Grained Sediment**, and represents the synthesis of dozens of linear transects from shore to shore throughout the lake. In general, darker areas represent thicker sediment deposits, though the color of extremely thick sediments renders lighter in gray-scale. Pockets of sediment in the larger basin reach 20 feet thick or more, with thinner sediments in the small basin and on the periphery of the lake overall. A key observation is that thicker sediments (>8 feet) are common in most areas of the lake deeper than 10m. Because of this, groundwater flow is expected to be substantially greater in the shallower, nearshore areas of the lake, though this remains to be documented by more specific analyses beyond the scope of this study.

General summary: water column characteristics

1. The maturation of zebra mussel populations (one five-year life cycle) coincided with two sequential years of highly unusual meteorological conditions (El Niño / La Niña) which could have contributed to or even caused the observed changes;
2. Phytoplankton biomass decreased substantially over the study period, principally due to a nearly complete eradication of the Cyanobacterial deep chlorophyll maximum which had been first observed by Birge and Juday in 1906;
3. The magnitude of nutrient remobilization from sediment efflux was greatly curtailed in later years of the study, associated with less pronounced deep basin anaerobiosis;
4. The magnitude and extent of spring bloom phytoplankton population development was likewise curtailed;
5. Surface nutrient concentrations tended to remain at higher levels during mid-summer than in previous years;

6. Integrated water column inventory of biomass-related parameters including chlorophyll a, several forms of phosphorus, and ammonium declined dramatically throughout 1996-2000 while hypolimnetic oxygen inventory in summer increased;
7. Integrated, annual areal primary production decreased to a limited extent during the later years of the study, primarily through loss of deepwater production capacity;
8. A small but persistent increase was observed in gross water clarity (i.e., Secchi depth);
9. Surface samples during summer for chlorophyll a, total phosphorus, and Secchi depth yielded Trophic Status Index values of mesotrophic to oligotrophic, with a clear long-term trend towards oligotrophic conditions;
10. Net zooplankton populations showed little or no systematic response to the changing conditions;
11. Zebra mussel populations increased continuously between 1996-1999 and became effectively established as a new component of the benthic ecosystem.
12. Evidence from conservative minerals and nutrients implicated groundwater influx as a more significant contributor to lake biogeochemistry than had previously existed;
13. The chemical composition of groundwater was highly consistent from year to year at any given site, and regions of the lake had distinctly different groundwater signatures;
14. Mass balances indicated that a major new loss term for biomass-related components had entered the equation during or shortly after 1996.

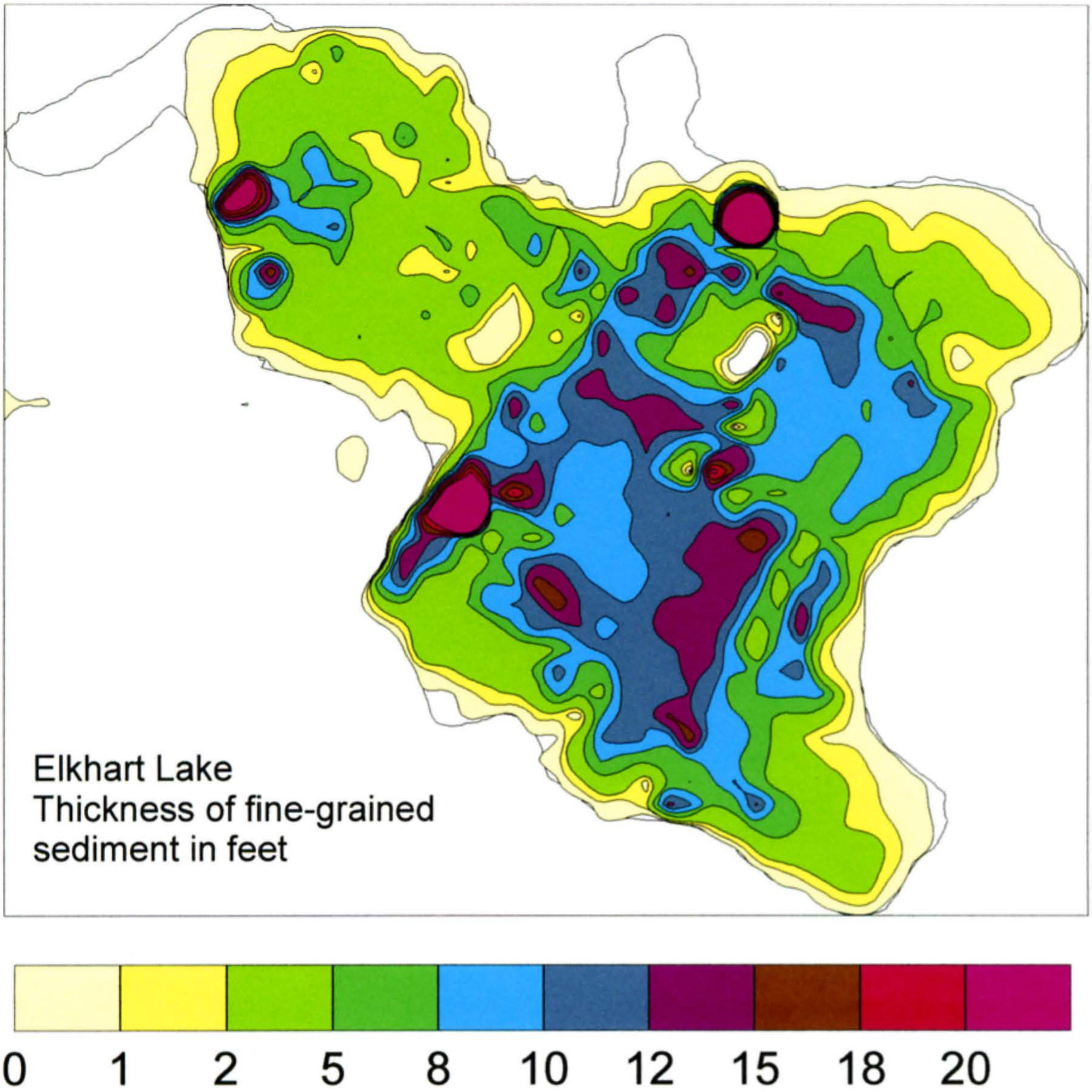
Mass balance considerations

In the previous report (Edgington and Cuhel 1997) a mass balance model was presented. In its simplest form it assumed an overall steady state in which Inputs = Outputs. Terms considered at that time expanded the equation into specific, identifiable components:

Rainfall + Groundwater + Septic Systems + Sediment Efflux + Unknown Terms =

Outflow + Burial In Sediments + Loss To Atmosphere + Sedimentation Not Buried

It was projected at that time that the model would be refined to further understand inputs under the "Unknown Terms" category with respect to biomass and eutrophication concerns. It is now clear that this characterization is not presently necessary for these components, as any unidentified inputs to Elkhart Lake have been overwhelmed by a major output term newly in force. Hence, the refinement of the model for the present day is to add terms to the Output side of the equation. Two such components may be readily considered: increased outflow and zebra mussel biomass. Increased outflow is an unlikely candidate for exerting the level of loss described above, because very little of the missing material is concentrated in the 0-5m stratum accessible to outflow into Sheboygan Marsh at the single outlet. Zebra mussel biomass, on the other hand, may draw a significant proportion of the biomass-related constituents into the shallower waters and remove it from the budget through tissue production and/or deposition in the benthos in the mussel beds themselves. If mussel biomass is a major sink, then it may be expected that the influence on biogeochemical cycling would increase consistently with mussel growth until the system reached its carrying capacity for mussel biomass, at which time it would flatten off and remain at a population turnover level. In this context it is relevant to note that in the last year of this study,


Elkhart Lake
Thickness of fine-grained sediment in feet

2000, several of the indicators of massive change appeared to be decreasing in magnitude. While this does coincide with the end of the first round of 5-year life cycle for zebra mussels in Elkhart Lake, it was also the first meteorologically "normal" year since the El Niño-La Niña sequence of 1997-1999. Because zebra mussels have a finite lifetime (5 years), new tissue production will continue. A pertinent new question will be: How is the mussel tissue recycled? This will, in some way, play into the overall biogeochemical cycling in the lake.

If deemed worthwhile, future work could focus more closely, with necessarily greater support, on applying all the more difficult methods required to actually close a mass balance for critical elements (C, N, P) in Elkhart Lake. With the outflow gauging station back in operation, a short but monumental effort in groundwater quantitative flow assessment would be valuable. Most importantly now, however, would be to undertake a robust, quantitative survey of zebra mussel population distribution, total amount, and elemental composition of the tissue.

BENEFITS:

The research described above is a significant step towards understanding ecosystem perturbations such as zebra mussel colonization because the smaller, nearly closed nature of the study sites allows budgeting by mass balance approach. Based on this work, some tools for prediction of zebra mussel success in other inland lakes have been well established. The nature of inland lake effects, virtually unstudied until now, provides a valuable comparison with well-studied larger open Great Lakes habitats.

Town Meetings: As a result of our work on Elkhart Lake, we have been invited, and attended several regional "town meetings" to discuss the implications of zebra mussel invasion and other water quality concerns. Recent appearance of zebra mussels in Pewaukee Lake led to our involvement in several such meetings with State Representatives and town council members, and we have also responded to numerous telephone requests from other locales. In each case, it is the Elkhart Lake project that is held as the model for more recently invaded locales.

FOLLOW-UP:

The question of motorboat activity affecting the ecosystem function at Elkhart Lake remains. A thermistor chain deployed by Dr. Edgington and associates in the large basin recorded temperature at short intervals to address this question, but it could not be found after the summer. Perhaps the orange buoy only 10 feet below the surface was too great of a temptation for vandals. Several other experimental deployments have disappeared or been conscientiously turned in to the Elkhart Lake police. Nonetheless, inspection of the nutrient and biomass profiles demonstrates that there were no limiting nutrients or turbidity-causing materials available for mixing. Several physical oceanographers agree that turbulence would be restricted to much less than ten times the depth of the prop, which for most recreational craft would be about 30 feet (10m) or less. However, that influence could be of significance in shallower near-shore contours and might be followed up by specifically designed sampling by personnel on site during the summer.

Unquestionably the most important follow-up activity would be to assess whether observed changes in Elkhart Lake water column and rooted plant variables resulted from meteorological (El Niño-La Niña) or biological (zebra mussels) forcing. This will require continued monitoring through several seasonal cycles in years with earlier fall overturn and later ice-out than during 1997-1999. The work of 2000 and its continuation (unfunded) through 2001 will provide the necessary continuity if another large-scale effort is supported. In addition, formulation of expected zebra mussel establishment patterns with the biogeochemical characteristics of the intensively studied lakes should be completed so that recently infested (or future target) lakes may be compared with hypotheses. Finally, incorporation of the results into the Elkhart Lake Improvement Association web page and publication-dissemination of the results is necessary.

Publications, Presentations, and Reports:

Technical Report: We have published 50 copies of UWM-WATER Technical Report #51:

Edgington, D.N. and R.L. Cuhel. 1997. Water, Nutrient Budgets, and Trophic Status of Elkhart Lake, Sheboygan County, Wisconsin, April 1993 - March 1996. Elkhart Lake Technical Report (published March 2000). UWM-WATER Technical Report # 51. 68pp.

Society Meeting Presentations:

Aguilar, C. and R. L. Cuhel. Primary Productivity of Mixed Vs. Stratified Lakes Using P vs I Modeling and Selective Truncation of Physical-Biological Input Parameters. American Society of Limnology and Oceanography Winter Meeting, Santa Fe, NM (February 1997). (Abstract p.79)

Cuhel, R. L., Edgington, D. N., and C. Aguilar. *In Situ* Growth Rates of Deep Phytoplankton populations Determined by Nitrogen Flux Along Ammonium and Nitrate Concentration Gradients. American Society of Limnology and Oceanography Winter Meeting, Santa Fe, NM (February 1997). (Abstract p.137)

Dingledine, N.A., Meyer, S.L., and R.L. Cuhel. The Water Column Structure of Elkhart Lake: Pre- and Post-Zebra Mussel Infestation. North American Lake Management Society 18th International Meeting, Banff, British Columbia (Nov. 1998)

Aguilar, C. and R.L. Cuhel. Small lake phytoplankton community ecological responses to large scale ecosystem perturbations. American Society of Limnology and Oceanography 2001 Winter Meeting, Albuquerque NM (February 2001)

University and Public Seminars and Presentations:

UWM-WATER Institute: CGLS Anchor Watch Series (8 Mar. 1996)
Water Column Biology and Chemistry of Elkhart Lake: Before Zebra Mussels. (R. Cuhel)

UWM-WATER Institute: CGLS Anchor Watch Series (15 Mar. 1996)
Modeling Chemical and Biological Parameters for Elkhart Lake: Mass Balances and Fluxes Prior to Zebra Mussels. (D.N. Edgington)

University of Wisconsin-Madison Department of Water Chemistry (Mar 1997)
Deep Chlorophyll Maxima: Growth Rate Control by Nitrate and Ammonium Flux from the Hypolimnion of Elkhart Lake, WI. (R. Cuhel)

S. C. Johnson Wax Research, Development, and Engineering Symposium (Golden Rondelle, Racine, WI, Sep 1997)
Exotic Species in Large and Small Lakes: Who's STILL Eating Well? (R. Cuhel)

UWM-WATER Institute: Storm Watch Seminars (12 December 2001)
Coupled Biogeochemical Cycles I: Elkhart Lake 1996-2000. (R.L. Cuhel)

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