Minnesota Pollution Control Agency

ENVIRONMENTAL BULLETIN

Reconstructing Historical Water Quality in Minnesota Lakes from Fossil Diatoms

By Steven A. Heiskary, Edward B. Swain and Mark B. Edlund*

September 2004
Number 4

Abstract—Diatom fossils preserved in the sediments of 79 lakes across Minnesota were used to reconstruct historical total phosphorus (TP) concentrations. Prior to these studies, people could only speculate about eutrophication trends since European settlement, including the nature of pre-settlement conditions and the magnitude of change. Reconstruction was accomplished using diatoms in sediment cores by first developing a calibrated mathematical model between water chemistry and diatom species that have grown over the past few years, and then calculating what the water quality must have been in the past by applying the model to diatoms found deep in sediment cores from the study lakes.

TP levels in lakes in the relatively undisturbed forests of northeast Minnesota do not exhibit any significant difference between pre-European settlement and modern times. For lakes in the rural portion of the central hardwood forest ecoregion, increased TP is correlated with the amount of the lake's watershed in agriculture. For the metropolitan portion of the region, increased TP is correlated with the amount of the watershed in urbanized uses. In predominantly agricultural southern Minnesota, five deep lakes show no significant changes over time, while seven shallower lakes exhibit a significant increase in TP from pre-European times to modern day. The results of this study are useful in setting water quality goals for these lakes and other lakes located in the same ecoregion. More importantly, they help place modern-day trends in perspective and aid in development of water quality standards for lakes.

Introduction

Diatom reconstructions of historical phosphorus concentration, based on sediment cores from 79 Minnesota lakes, provide a unique opportunity for examining temporal and spatial trends in eutrophication, validating eutrophication models, and providing historical perspective for developing water quality standards. There have been numerous diatom-based water quality reconstruction studies in Minnesota that focused on individual lakes, paired comparisons, or a few lakes representing different regions or degrees of anthropogenic influence. However, no previous study used sediment diatoms to assess spatial and temporal changes in trophic status across a wide geographic range of Minnesota lakes.

Quantitative diatom reconstruction of water quality can define the timing and extent of cultural disturbances and identify pre-disturbance conditions (Reavie et al., 1995). Reconstruction can also reveal geographic areas where lakes tend to be naturally eutrophic and hence whose remediation is not as likely to improve water quality. Numerous diatom-reconstruction studies have been conducted across North America (Dixit et al., 1992) and Europe for these and related purposes. For example, diatom reconstruction has been used to evaluate:

- the impact of shoreland development on a range of Ontario lakes (Hall and Smol, 1995);
- the effect of logging and shoreland development on soft-water and hard-water lakes in Wisconsin (Garrison and Wakemen, 2001);
- the impact of logging on British Columbia lakes (Laird and Cumming, 2001, Laird et al., 2001);
- changes in lake pH, conductivity and trophic status of 23 Connecticut lakes relative to changes in land use over the past 100 years; and (Siver et al., 1999);
- lake recovery from point source eutrophication (Anderson and Rippey, 1994).

* *Mark B. Edlund, Science Museum of Minnesota, St. Croix Watershed Research Station*

Diatoms are a group of microscopic golden-brown algae commonly found in any body of running or standing water (Figure 1). Diatoms are characterized and identified by their cell wall, which is made of biogenic opaline silica—essentially biologically produced glass. Because of the silica cell wall, diatoms are heavier than water and sink to the bottom of lakes, accumulating several million well-preserved diatoms per gram of sediment. The silica cell wall of each diatom species has characteristic patterns of spines, holes, and lines that allow researchers to identify each fossil diatom from among the estimated 10,000 and 100,000 species. Any environmental sample of living or fossil diatoms will usually contain between 10 and 400 species. Water chemistry is well known to affect diatom community makeup in lakes. Nutrients (phosphorus, nitrogen), pH, alkalinity (or acid-neutralizing capacity, ANC), dissolved organic carbon (DOC), and salinity (conductivity or even just chloride ion) are often the most important variables in determining the distribution of diatom species.

Methods

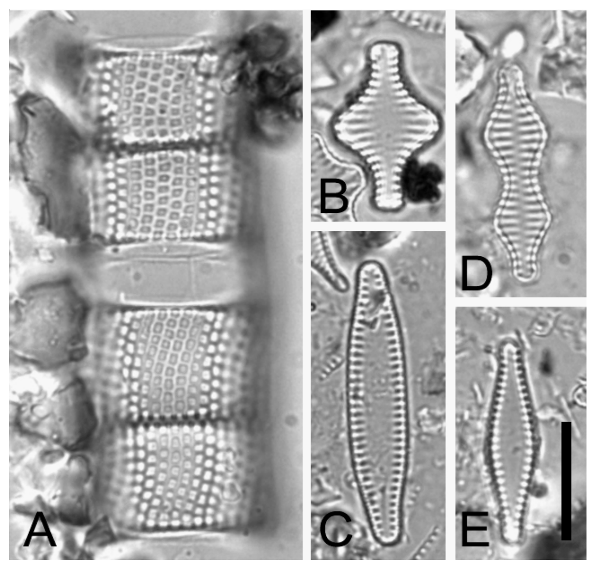
To reconstruct historical water quality using diatoms, this study was divided into two parts: 1) developing a calibrated mathematical model between recent water chemistry and diatom species that have grown over the past few years and 2) calculating what the water quality must have been in the past by applying the model to diatoms found deep in a core of sediment from a lake.

To construct a model relating modern diatom assemblages to modern water quality, this study first collected environmental and physical data from 79 lakes distributed throughout the state (Figure 2). Fifty-five of the lakes (referred to as "55 lakes study") were sampled between 1996 and 1998 on two to five sampling dates. Twenty-four more shallow lakes from southwestern Minnesota were added to the data set in 2002. An additional 31 shallow lakes in west-central Minnesota were sampled in 2003-2004; however, these data were not complete as of this assessment. On each sampling date, nutrients (phosphorus and nitrogen), pH, alkalinity, chloride, chlorophyll, and Secchi depth were measured using standard techniques. Data from each lake were pooled as May-September means. On one sampling date, a short sediment core (~25cm) was also collected with a Wiegner gravity corer. The top two centimeters of each sediment core were sampled; these surface sediments represented the last few years of sedimentation in each lake and contained the diatoms that were present during the time of water quality sampling.

Each sediment sample was digested in 30% hydrogen peroxide to remove organic matter and the diatoms were mounted on microscope slides. From each sample, approximately 400 diatoms were counted under 1000x magnification, identified to species, and the relative abundance of each species calculated. A multivariate statistical technique, canonical correspondence analysis (CCA), was used to explore the relationship among diatom assemblages and environmental variables to identify which environmental parameters independently explained significant variation in the diatom species data. Next, a transfer function that could be applied to historical diatom assemblages was developed. Transfer functions use weighted averaging regression to calculate the environmental optimum and tolerance for each diatom species (Birks et al., 1990). The strength of a transfer function is tested by using bootstrapping or jackknifing and iteratively applying the transfer function to recalculate an environmental variable using the diatom assemblages in the calibration set lakes; for the 79 lake calibration set there is a strong linear relationship between the observed total phosphorus and the total phosphorus modeled from the diatoms, the so-called diatom-inferred phosphorus concentrations or DI-P (R^2=0.85; Figure 3).

Long cores of geologically recent sediment were collected using a piston corer from 61 lakes throughout Minnesota. These cores were generally one to two meters long and may recover from several hundred to nearly a thousand years of sediment accumulation (Figure 4). The top 20-30 cm of a core is unconsolidated and is removed

Figure 1: Examples of fossil diatoms



Scale bar equals 0.01 mm. Fig. 1A. Aulacoseira granulata has a total phosphorus (TP) optimum of 118 ppb and is very common in hypertrophic shallow lakes in southern Minnesota. Figs 1B-E. Before European settlement, many Minnesota lakes were dominated by small "fragilarioid" diatoms whose TP optima are below 20 ppb including Staurosira construens (B), Pseudostaurosira brevistriata (C), Staurosira construens v. binodis (D), and Pseudostaurosira brevistriata v. inflata (E).

Figure 2: Location of study lakes

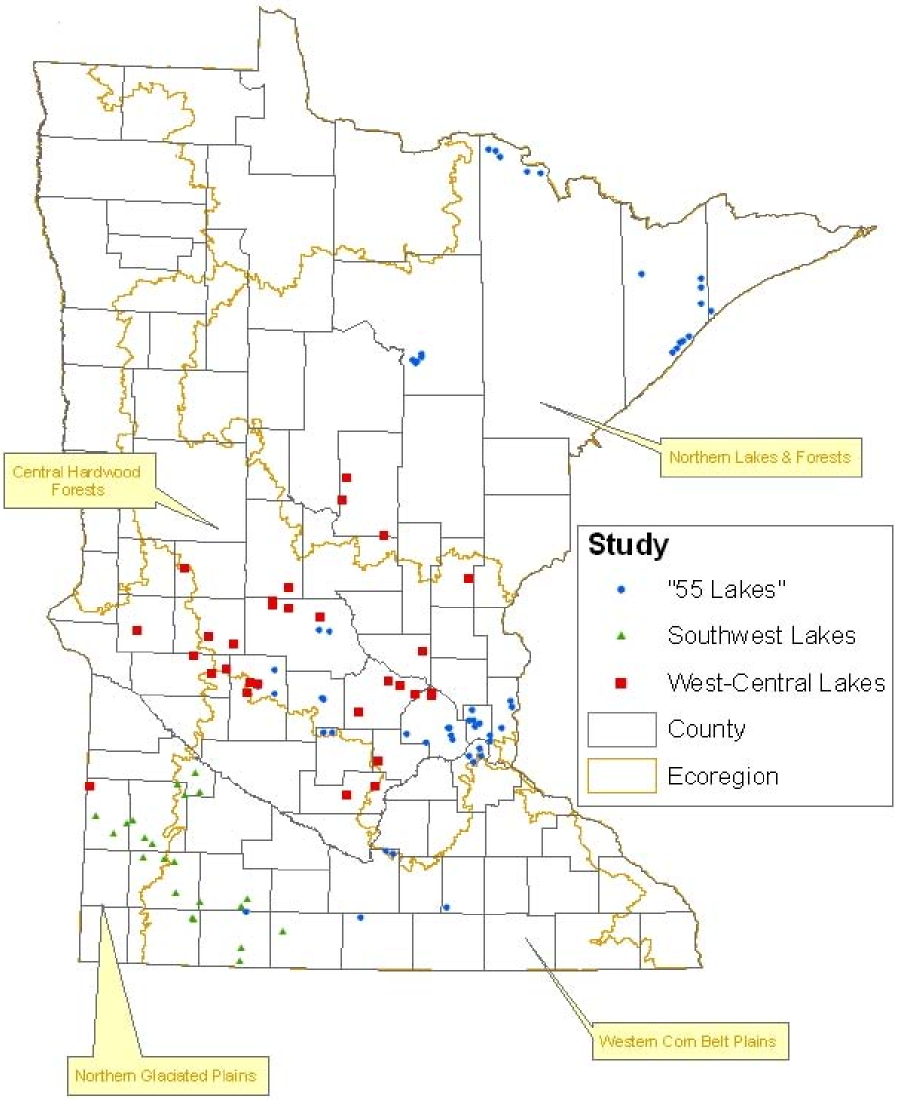


Figure 3: Comparison of diatom-inferred and observed TP

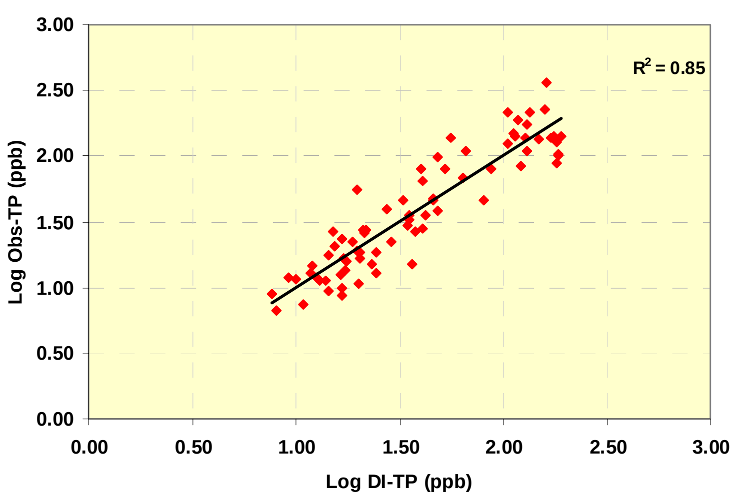
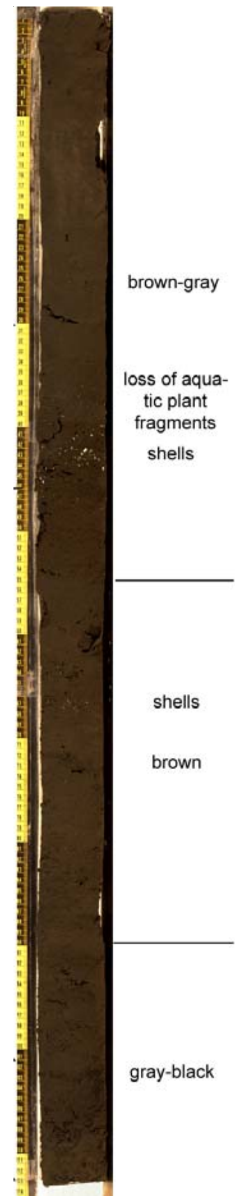


Figure 4: Bloody Lake sediment core



A sediment core from Bloody Lake, Murray Co., Minnesota, records the recent history of the lake. The original core was 1.33 m long; 20 cm at the top of the core were removed immediately after core recovery. The remainder of the core was split lengthwise and photographed. An obvious ecological shift was recorded in the core about two-thirds of the way up in the loss of aquatic plant fossils and mollusk shells. Diatom communities above and below this point were also different. Dating indicated this ecological shift occurred shortly after European settlement of the watershed (alternating yellow and black scale units are 10 cm each).

by extruding the core in 2-cm increments; the remaining core is sealed in the core tube and transported to the laboratory.

The sampling approach used for long cores was to first develop a dating model using several methods to associate a depth in the core with a calendar date. Most sediment cores were analyzed for lead-210 activity to determine age and sediment accumulation rates for the past 150 years. Lead 210 was measured at 16-20 depth intervals and dates and sedimentation rates were determined using the constant rate of supply (CRS) model. Other dating methods used included gamma analysis to determine the 1963-1964 peak in deposition of Cesium 137 from atmospheric nuclear testing, and magnetic analysis to identify erosional signals associated with European settlement and land clearance. Once a date model had been developed for each core, diatoms were quantified from four sediment levels deposited in approximately the 1990s A.D., 1970s A.D., 1800 A.D., and 1750 A.D. (Ramstack et al., 2003, 2004) to provide a measure of modern, 1970s (pre-Clean Water Act), and two measures of pre-European water quality. Diatoms were prepared and counted as described for surface sediments and estimates of historical total phosphorus were calculated using the transfer function.

Results and Discussion

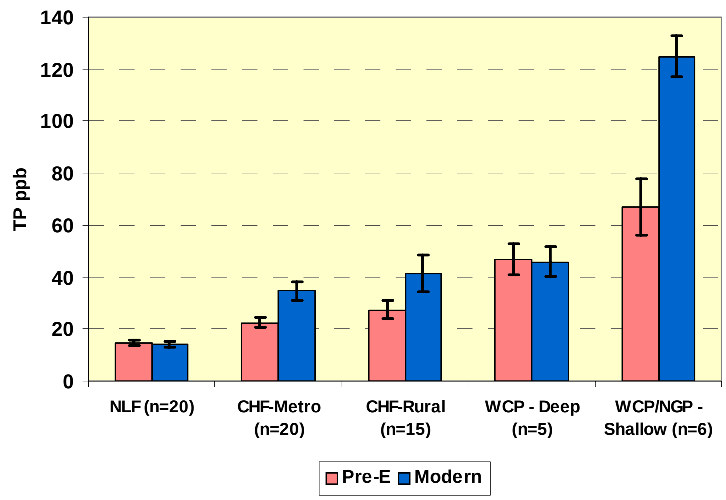
Spatial and temporal variability in lake trophic status

Diatom reconstruction provides an opportunity to examine both temporal and spatial trends in lake trophic status and related factors. Ecoregion-based patterns in lake trophic status have long been recognized in Minnesota (e.g., Heiskary et al., 1987). Lakes in the forested Northern Lakes and Forests (NLF) ecoregion are moderately deep and exhibit relatively low total phophorus (TP) while the shallow lakes in the highly agricultural Western Corn Belt Plains (WCP) and Northern Glaciated Plains (NGP) exhibit high TP concentrations. The transitional North Central Hardwood Forests (CHF) ecoregion, characterized by moderately deep lakes and a mosaic of land uses—is intermediate between these two extremes. See Figure 2 for ecoregion boundaries.

Ecoregion-based patterns are evident in the pre-European data as well. The NLF lakes were significantly lower in TP as compared to the CHF, WCP and NGP lakes based on a comparison of group-means plus or minus standard error (SE) (Figure 5). Likewise, the CHF lakes had lower TP than the WCP lakes. Within the CHF, there was no significant difference among the metro vs. the rural lakes.

Distinct differences among regions were evident in comparisons of pre-European and modern-day TP concentrations. For the NLF lakes, as a group, there was no significant difference in modern-day vs. pre-European TP (Figure 5). However, distinct increases in TP were noted for the CHF lakes and these increases exceeded the "natural variability" noted in comparisons of pre-European (1750 and 1800) TP concentrations (Ramstack et al., 2004). They also note that the degree of change in TP among the Metro

Figure 5. Pre-European and modern-day diatom-inferred TP by ecoregion



CHF lakes is significantly positively correlated with the percent of the watershed in urbanized land use, while those in the rural portion exhibit a significant positive correlation with the percent of land use in agricultural uses or, inversely, the percent in forested uses. The deeper WCP lakes also did not change significantly across the two time periods based on this analysis and no significant associations with land use were noted by Ramstack et al. (2004)—presumably because of the small sample size (five lakes) and the predominately agricultural land use in these watersheds. The shallow WCP and NGP lakes added in the recent study of southwestern Minnesota lakes exhibited a significant increase when pre-European and modern-day TP are compared (Figure 5). Agricultural land use predominates in all lakes in that study.

Case studies

Calhoun and Harriet are among the largest lakes in the Metro area at 420 and 340 acres and are the centerpiece of the Minneapolis park system. Calhoun has a very large drainage area (6,200 acres), while Harriet, which is immediately adjacent to Calhoun, has a relatively small watershed (955 acres). An extensive history of these lakes was assembled by the Minneapolis Park Board (Derby et al., 1997) and was summarized in Heiskary and Swain (2002). A few

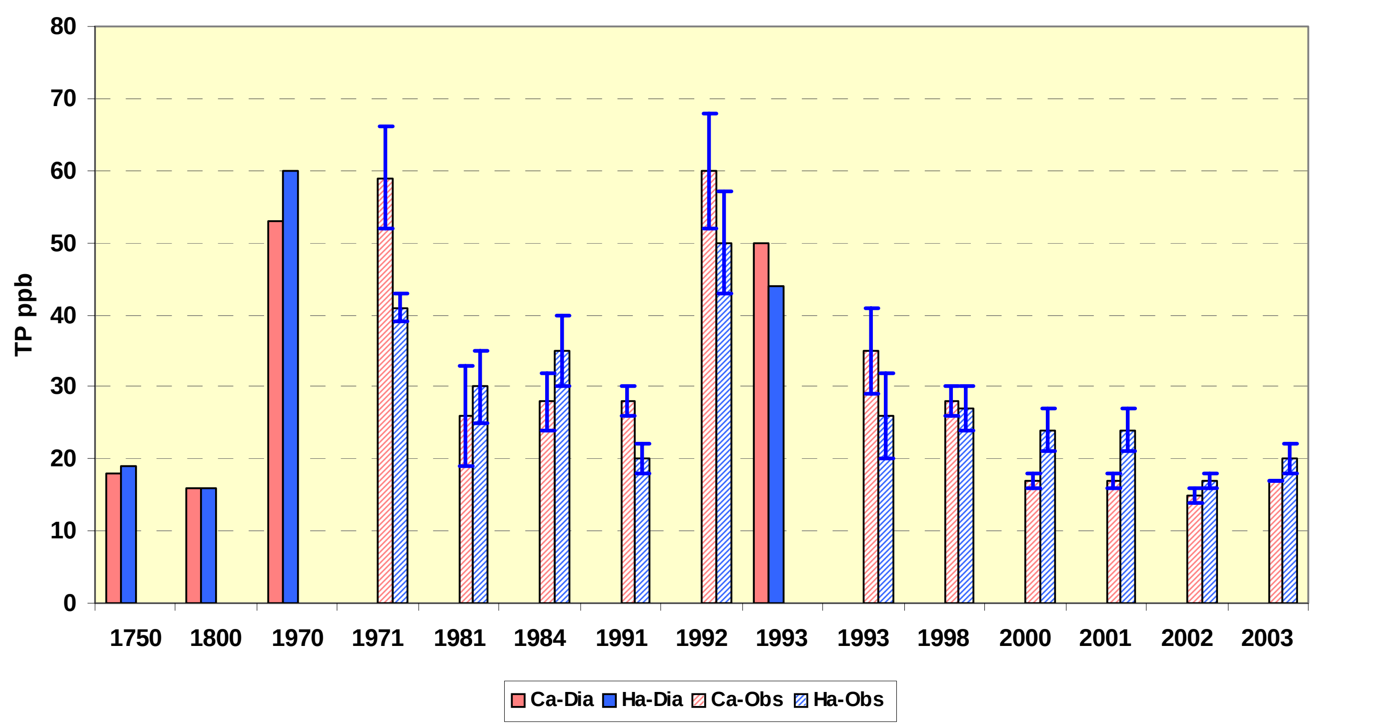
excerpts are offered here to provide perspective on the lakes and land use changes in their watersheds.

In 1857, one year after Minneapolis was incorporated as a town, land was first donated for park development. Land around Lake Harriet was brought into the park system in 1885 by donation and Calhoun followed in 1909. Throughout this time period and the decades to follow the watershed of these lakes became increasingly urbanized. However, adjacent parkland served to protect the riparian areas of these lakes.

Examination of events in the Chain of Lakes since European settlement provides some information about possible historical factors influencing water quality in the lakes. It is reasonable to assume that watershed development during the early 1900s and construction of a storm sewer system during 1910-1940 caused some degree of water quality degradation in the lakes. Brugam and Speziale (1983) noted increased rates of sediment accumulation (based on sediment core analysis) in the mid 1920s as the watershed area of the lakes increased with the installation of storm sewers. It is also evident that the majority of the development in the watershed and creation of storm water networks occurred over the first half of the 1900s and was substantially completed prior to the 1970s. According to Brugam and Speziale, this storm sewer network resulted in the sudden eutrophication of Lake Harriet in 1975 and it seems likely that the pumping station and pipeline from Calhoun in 1967 probably had the biggest single influence on Lake Harriet.

The diatom reconstructions for Calhoun and Harriet suggest similar pre-European P concentrations that were on the order of 16-19 ppb (Figure 6). However, by the 1970s, TP concentrations were on the order of 50-60 ppb based on the diatom reconstructions. This peak in TP followed the extensive storm sewering that had occurred during the 1920s-1960s. And for Harriet, this followed the connection with Calhoun in 1967. Water quality monitoring data from the early to mid-1970s serves to independently corroborate the diatom reconstruction (Figure 6). The reconstruction for the early 1990s indicated a small non-significant decrease in TP in Calhoun, but a significant decline in Harriet. Observed data from the late 1990s to early 2000s also suggest some significant declines in TP as compared to the 1970s. Based on data from 2000-2003, both lakes were in the 18-20 ppb range, which was a substantial improvement from the elevated concentrations of c. 1970 and relatively close to pre-European concentrations. These recent declines in TP could be attributed to aggressive implementation of best management practices including street sweeping, improvements in storm water treatment, and alum treatments in 2001.

Figure 6: Lakes Calhoun and Harriet diatom-inferred and observed TP

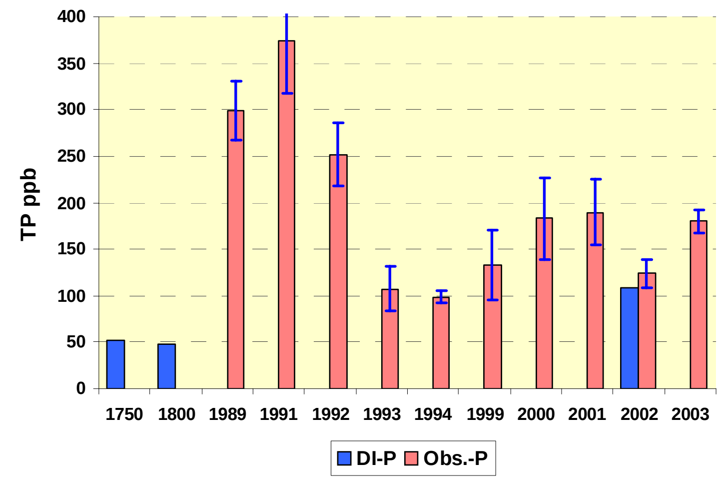


Lake Shaokotan in Lincoln County is among the most studied lakes in southwest Minnesota. With a maximum depth of about 12 feet and a predominately agricultural watershed it is fairly typical of lakes in the NGP ecoregion. The lake has a history of water quality problems including severe nuisance blue-green blooms, summer and winter anoxia, and periodic fish kills. These problems were the result of excessive nutrient loading to the lake. However pre-European TP concentrations were much lower than modern-day observed (Figure 7).

A detailed Clean Water Partnership Phase I diagnostic study was initiated in 1989 and restoration efforts were underway by 1991. This detailed monitoring allowed for the characterization of phosphorus exports for several subwatersheds. Subwatershed land uses ranged from relatively low intensity land uses, such as Conservation Reserve Program (CRP) acres to high intensity uses such as row crop cultivation and feedlots. Phase II implementation included rehabilitation of three animal feedlots, four wetland areas, and shoreline septic systems.

By 1994 significant reductions in in-lake P were realized with concentrations approaching the ecoregion-based and project P goal of 90 ppb, in contrast to the 200 to 350 ppb noted in previous summers (Figure 7). This resulted in reductions in the frequency and severity of nuisance algal blooms. Transparency had increased, and anecdotal evidence in 1999 suggested macrophyte populations were increasing. However, subsequent plant surveys in 2000 and 2002 found essentially no rooted plants. Water chemistry data indicated an increase in TP and chlorophyll-a from 1999 – 2001 (Figure 7). This increase was largely attributed to an abandoned feedlot operation in the near-shore area of the lake. Subsequent efforts by the Yellow Medicine Watershed District, Lincoln County and a local sportsman's group sought to address the problem. With the completion of this work and the Total Maximum Daily Load (TMDL) study that is under development, it is hoped that TP concentrations and chlorophyll-a will once again decline, which should lead to a reduction in the frequency of severe nuisance blue-green blooms that have characterized recent summers. Combined with some improvement in transparency, this may allow the return of macrophytes to the lake. Based on a pre-European TP of about 50 ppb, the "goal" of 90 ppb seems a reasonable water quality goal to pursue. Attaining this concentrations should result in measurable and perceptible changes in the water quality of the lake.

Figure 7. Lake Shaokotan diatom-inferred and observed TP

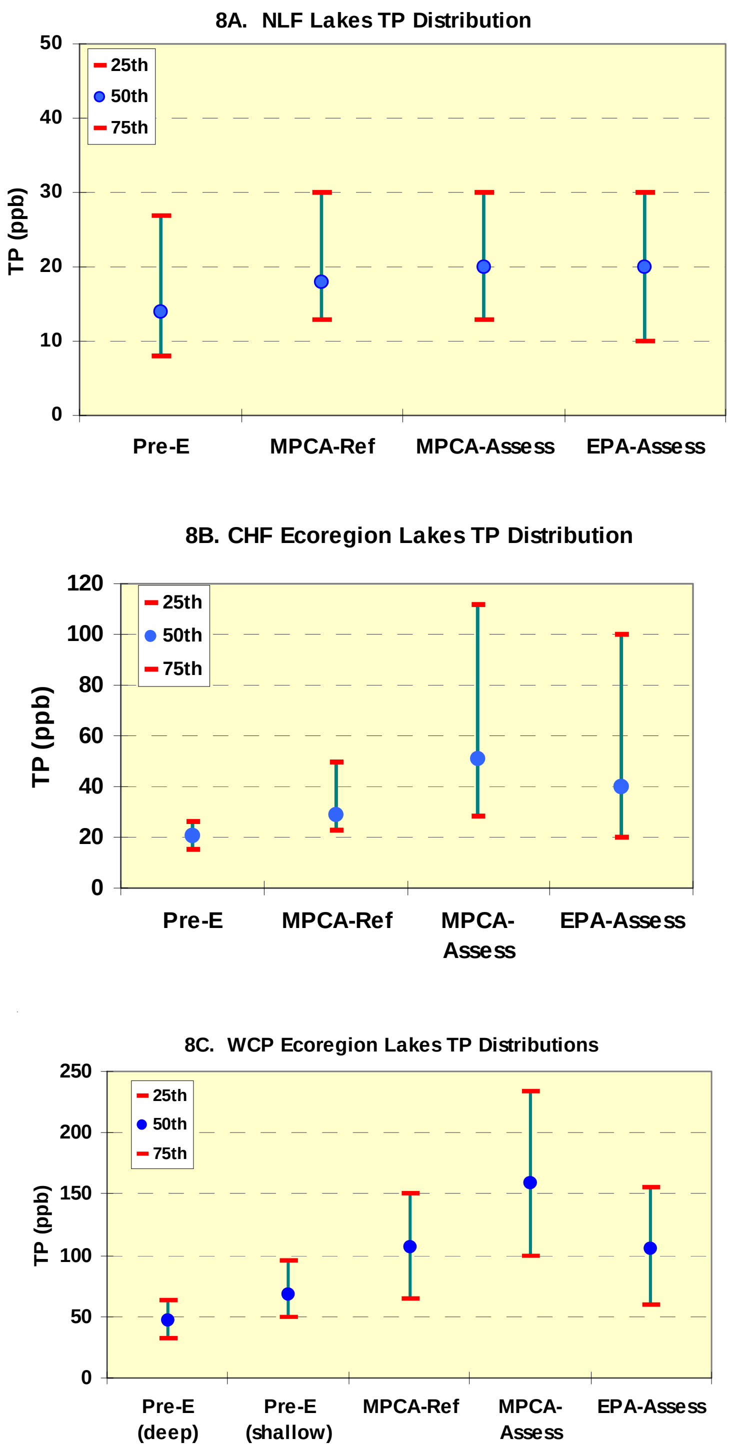


Diatom reconstruction and water-quality standards development

Historical TP inferred from fossil diatoms can place modern-day TP data in perspective, provide insights into background P concentrations and assist with water quality standard-setting efforts. While the study lakes were not randomly selected, they are generally representative of lakes in the NLF and CHF ecoregions in terms of area, depth, and land-use characteristics. For the NLF, the interquartile range (25^{th}-75^{th} percentiles) of the pre-European TP values compares favorably with modern-day reference and overall data and suggests that many lakes may be near their "background" concentration (Figure 8A.) In the CHF ecoregion, the pre-European diatom-inferred phosphorus (DI-P) values are near the 25^{th} percentile of the reference lakes but are below the 25^{th} percentile of the assessed lakes, which suggests that the majority of lakes in the CHF ecoregion are well above background TP concentrations (Figure 8B). Although the study lakes were quite representative in terms of area and depth, the study lakes had a higher percentage of land in urban uses as compared to the CHF reference lakes because of an emphasis on Metro lakes.

Pre-European DI-P values for the five deeper WCP lakes rank well below the 25^{th} percentile for both the reference and assessed data (Figure 8C). This suggests that either these five lakes may not be representative of the larger population or that modern-day condition is substantially changed from pre-European. Modern-day land use in the watersheds of these lakes is typical of lakes in the WCP; however, these five lakes tend to be much deeper and surface areas slightly smaller than the norm for this region. Greater depth and small surface area allow all five of the lakes to thermally stratify through much of the summer, which may minimize internal recycling of P and result in

Figure 8: TP distribution by ecoregion



lower TP in the upper mixed layer of the lakes. Based on an earlier assessment of ecoregion patterns (Heiskary et al., 1987), very few lakes (ten percent or less) in the WCP or NGP are deep enough to stratify; hence from this standpoint these lakes cannot be deemed "typical" of the larger population. Based on these observations it is likely that these five lakes may be among the least eutrophic both in modern-day and in pre-European times and hence the diatom-inferred values might be viewed as a "best case" for lakes in the WCP ecoregion.

These observations led to our subsequent collection of additional sediment cores from more "typical" WCP and NGP lakes. These additional six lakes exhibit a wide range in pre-European TP concentration but average about 70 ppb, which is near the 10th percentile for these two ecoregions based on modern-day data. This suggests that a reasonable region-wide nutrient criteria value for the shallow (predominate lake-type in these regions) WCP and NGP lakes is likely greater than this apparent background range of 60-70 ppb. Further analysis of this and other information will help us to arrive at reasonable nutrient criteria values for these ecoregions.

Summary

Diatom reconstruction is a valuable technique for evaluating environmental changes over time. The performance of the diatom inference model developed for this study is comparable to, or better than, that of similar studies conducted elsewhere in the world (in terms of RMSEP and R^2). The model was strengthened by the addition of the more eutrophic southwestern Minnesota lakes. Also, independent validation of model predictions for c. 1970 with observed TP data for 1970-1980 demonstrates good correspondence between observed and diatom-inferred values, which provides further support for this technique. Further improvement in the model is anticipated with the addition of data from the west-central Minnesota lakes (Figure 2).

A comparison of pre-European diatom-inferred TP concentrations among ecoregions demonstrates that regional patterns evident in modern-day TP concentrations existed prior to European influence. Within-region comparisons showed varying degrees of change over time. The ecoregion NLF lakes, as a group, do not show any significant difference between pre-European and modern-day TP. These lakes, with the possible exception of the five lakes studied near Grand Rapids, have experienced minimal change in land use as compared to lakes in the other ecoregions. However, in the CHF ecoregion, significant increases in TP from pre-European to modern-day are evident for several of the lakes. For lakes in the rural portion of the ecoregion, increased TP is correlated with the percent of the watershed in agricultural uses and for lakes in the metro portion of the region increased TP is significantly correlated with the percent of the watershed in urbanized uses. The lakes of the WCP ecoregion presented a mixed picture of change over time. For example, the five "deep" lakes in the WCP did not exhibit a significant change over time. However the shallow lakes of the WCP and NGP, as a group, exhibited a significant increase in TP from pre-European to modern day. Our data do not allow us to pinpoint the exact timing of the increase but it was most

likely related to the advent of intensive agriculture in the watersheds of these lakes.

These historical data are also part of the database being used to set water quality goals and standards in Minnesota. While this article has focused on analysis of eutrophication trends, sediment cores can also be used to assess environmental changes for issues including acid rain, mercury, PCBs, dioxin, climate and others. Further studies of lake-sediment core collections in Minnesota will undoubtedly provide valuable information that can be used to protect and improve the environment.

This work was funded by the Minnesota Legislature as recommended by the Legislative Commission on Minnesota Resources and the United States Environmental Protection Agency through grants to the MPCA.

References

1. Anderson, N. and B. Rippey. 1994. Monitoring lake recovery from point source eutrophication: the use of diatom-inferred epilimnetic total phosphorus and sediment chemistry. Freshwater Biology 32: 625-637.

2. Birks, H. J. B., J. M. Line, S. Juggins, A.C. Stevenson and C. J. F. ter Braak. 1990. Diatoms and pH reconstruction. Philosophical Transactions Royal Society London, Biological Sciences 327: 263-278.

3. Brugam, R.B., and B.J. Speziale. 1983. Human disturbance and paleolimnological record of change in the zooplankton community of Lake Harriet, Minnesota. Ecology 64: 578-591.

4. Derby, E., D. Pilger, and J. Lee. 1997. Minneapolis Lakes and Parks: Proceedings of a Symposium Special Session. 16th Annual NALMS Intl. Symposium. Minneapolis, MN. 1996.

5. Dixit, S., J. Smol, J. Kingston, and D. Charles. 1992. Diatoms: powerful indicators of environmental change. Environmental Science and Technology 26: 23-33.

6. Garrison, P. and R. Wakeman. 2001. Use of paleolimnology to document the effect of lake shoreland development on water quality. Journal of Paleolimnology 24: 369-393.

7. Hall, R. and J. Smol. 1992. A weighted average regression and distribution model for inferring phosphorus concentration from diatoms in British Columbia lakes. Freshwater Biology 27: 417-434.

8. Heiskary, S., C.B. Wilson and D. P. Larsen. 1987. Analysis of regional patterns in lake water quality: using ecoregions for lake management in Minnesota. Lake and Reservoir Management 3: 337-344

9. Heiskary, S. A. and E. B. Swain. 2002. Water quality reconstruction from fossil diatoms: Applications for trend assessment, model verification, and development of nutrient criteria for lakes in Minnesota, USA. Minnesota Pollution Control Agency, Environmental Outcomes Division, St. Paul, Minnesota. 103 pp.

10. Laird, K. and B. Cumming. 2001. A regional paleolimnological assessment of the impact of clear-cutting on lakes from the central interior of British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 58: 492-505.

11. Laird, K., B. Cumming and R. Nordin. 2001. A regional paleolimnological assessment of the impact of clear-cutting on lakes from the west coast of Vancouver Island, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 58: 479-491.

12. Ramstack, J. M., S. C. Fritz, D. R. Engstrom and S.A. Heiskary. 2003. The application of a diatom-based transfer function to evaluate regional water-quality trends in Minnesota since 1970. Journal of Paleolimnology 29: 79-94.

13. Ramstack, J. M., S. C. Fritz and D. R. Engstrom. 2004. Twentieth-century water-quality trends in Minnesota lakes compared with pre-settlement variability. Canadian Journal of Fisheries and Aquatic Sciences 61: 561-576.

14. Reavie, E., J. Smol and B. Carmichael. 1995. Post-settlement eutrophication histories of six British Columbia (Canada) lakes. Canadian Journal of Fisheries and Aquatic Sciences 52: 2388-2401.

15. Siver, P., A. Lott, E. Cash, J. Moss and L. Marsicano. 1999. Century changes in Connecticut, U.S.A., lakes as inferred from siliceous algal remains and their relationship to land-use change. Limnology and Oceanography 44: 1928-1935.

The MPCA's Environmental Bulletin Series is designed to highlight environmental outcomes and results of scientific studies the MPCA conducts in air, water and waste management. The bulletin is available electronically on the MPCA's web site at: http://www.pca.state.mn.us.

Correspondence with the author about this bulletin can be directed to Steven Heiskary at (651) 296-7217 or steven.heiskary@pca.state.mn.us.

For more information about the Environmental Bulletin, contact either of the following MPCA staff of the Environmental Information and Reporting Unit.

Patricia Engelking	(651) 297-3847
Tom Clark	(651) 296-8580