REPORT ON PALEOECOLOGICAL STUDY OF

BEULAH LAKE, WALWORTH COUNTY

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Introduction

Questions often arise concerning how a lake's water quality has changed through time as a result of watershed disturbances. In most cases there is little or no reliable long-term data. Questions often asked are if the condition of the lake has changed, when did this occur, what were the causes, and what were the historical condition of the lake? Paleoecology offers a way to address these issues. The paleoecological approach depends upon the fact that lakes act as partial sediment traps for particles that are created within the lake or delivered from the watershed. The sediments of the lake entomb a selection of fossil remains that are more or less resistant to bacterial decay or chemical dissolution. These remains include diatom frustules, cell walls of certain algal species, and subfossils from aquatic plants. The chemical composition of the sediments may indicate the composition of particles entering the lake as well as the past chemical environment of the lake itself. Using the fossil remains found in the sediment, one can reconstruct changes in the lake ecosystem over any period of time since the establishment of the lake.

The purpose of this study was to reconstruct the water quality of Beulah Lake since European settlement in the mid-1800's. Analyzing a sediment core taken from the deepest area in the south basin did this. The major interest of this study was changes in nutrient levels within the lake and the likely sources of these increased nutrients.

Site Description

The southeastern part of Wisconsin was one of the first to be settled following the Black Hawk War and the ceding of land by the Indian tribes in 1833 (Stark, 1984). At the time of settlement, the land around Beulah Lake was largely oak savanna with prairie vegetation. With the arrival of settlers, much of the land was converted from prairie to subsistence type farming. Beginning around 1850, farming practices shifted to cultivation of wheat and later corn, hay, and oats but lack of tractors limited the amount of land that was in production. From the 1940's to the 1960's, there was a large increase in the population, especially around lakes in this region. Lake shorelines that were once farmed were sold for seasonal homes (Langill & Loerke, 1984).

Methods

A sediment core was extracted from near the middle of the south basin (Figure 1) on 14 October 1998. The water depth at the site was 16.8 meters (55 feet). The core was collected

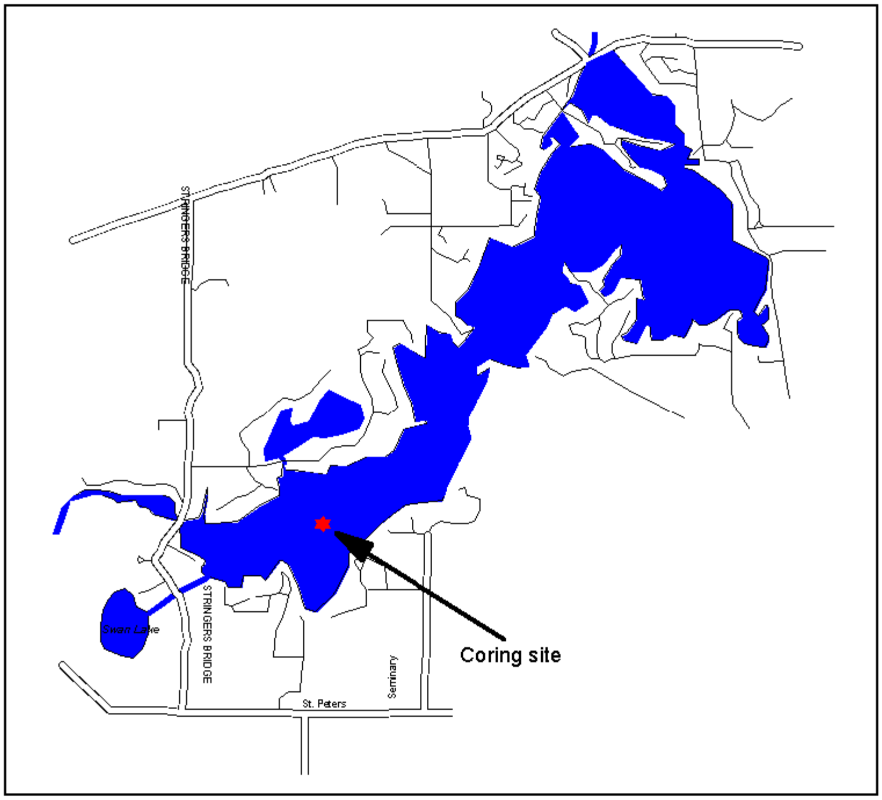

Figure 1. Map of Beulah Lake showing coring site.

with a gravity corer containing with a 6.5-cm plastic liner. The entire core, 24 cm in length, was sectioned into 1 cm slices to 20 cm and then 2 cm slices for the remainder of the core. The sediment was placed in plastic bags and frozen until analysis.

Samples were freeze dried for one week prior to radiometric analyses. The top 19 cm was analyzed to determine age and the sediment accumulation rate. Isotopic activities (^{210}Pb, ^{226}Ra, and ^{137}Cs) were measured by direct gamma counting (Schelske et al., 1994). The core was analyzed at the Wisconsin State Laboratory of Hygiene. Unsupported ^{210}Pb activity was calculated by subtracting ^{226}Ra activity from the total ^{210}Pb activity (Appleby et al., 1990). ^{137}Cs activity as measured in an effort to identify the period of maximum fallout from atmospheric nuclear weapons (Krishnaswami & Lal, 1978) testing and corroborate ^{210}Pb dates.

Sediment age for the various depths of sediment were determined by the constant rate of supply (CRS) model (Appleby & Oldfield, 1978), with dating errors calculated by first-order propagation of counting uncertainty (Binford, 1990). Bulk sediment accumulation rates (g cm^{-2}

yr^{-1}) were calculated from output of the CRS model (Appleby & Oldfield, 1978). Accumulation rates of geochemical variables and diatoms were computed for each sediment depth by multiplying the bulk sediment accumulation rate (g cm^{-2} yr^{-1}) by the corresponding concentration (mg g^{-1}) of each constituent in the bulk sediment.

Percentage dry weight was determined by measuring weight loss after 24 hours at 105°C. Organic matter content was measured by weight loss after ashing at 550°C for one hour and calcium carbonate content was determined by weight loss after combustion at 900°C for one hour (Dean, 1974). The amount of clastic material and biogenic silica was determined by subtracting the sum of organic matter and calcium carbonate percentages from 100. Sediment bulk density was determined by placing a known volume of sediment into a preweighed crucible, reweighed to obtain wet mass, dried at 105°C for 24 hours, and reweighed to obtain the dry mass per unit wet volume of sediment.

The University of Wisconsin Soil & Plant Laboratory performed geochemical analyses of the upper 16 depths. Following digestion, total titanium, arsenic, cadmium, lead, and uranium were analyzed using ICP-MS procedures. The rest of the geochemical variables were analyzed using ICP-OES procedures following digestion.

Samples for diatom analysis were cleaned with hydrogen peroxide and potassium dichromate (van der Werff, 1956). A portion of the diatom suspension was dried on a coverslip and samples were mounted in Naphrax®. Specimens were identified and counted under oil immersion objective (1400X). Two slides from each sample were examined until at least 100 frustules were examined on each slide. A known amount of glass microspheres was added to each sample following the procedure of Battarbee & Keen (1982) in order to determine absolute concentrations. Common nationally and internationally recognized keys were used including Patrick & Reimer (1966, 1975), Dodd (1987), and Krammer & Lange-Bertalot (1986, 1988, 1991a,b).

Results and Discussion

Dating

In order to determine when the various sediment layers were deposited, the samples were analyzed for lead-210 (^{210}Pb). Lead-210 is a naturally occurring radionuclide. It is the result of natural decay of uranium-238 to radium-226 to radon-222. Since radon-222 is a gas (that is why is sometimes is found in high levels in basements) it moves into the atmosphere where it decays to lead-210. The ^{210}Pb is deposited on the lake during precipitation and with dust particles. In the lake sediments it slowly decays. The half-life of ^{210}Pb is 22.26 years (time it takes to lose one half of the concentration of ^{210}Pb) which means that it can be detected for about 130-150 years. This makes ^{210}Pb a good choice to determine the age of the sediment since European settlement began in the mid-1800's.

There can be problems with this dating technique. For example, if sediment has moved after it was deposited, large changes in sediment deposition over the last 150 years, and errors associated with lab analysis with sediments that are over 100 years old. For these reasons the accuracy of the ^{210}Pb dates are verified by other methods. These methods usually involve measuring parameters that are known to have been deposited at a certain time and comparing stratigraphic changes in the core in Beulah Lake with other lakes in the region.

Cesium-137 (Cs^{137}) can be used to identify the period of maximum atmospheric nuclear testing (Krishnaswami and Lal, 1978). The peak testing occurred by the USSR in 1963 and thus the

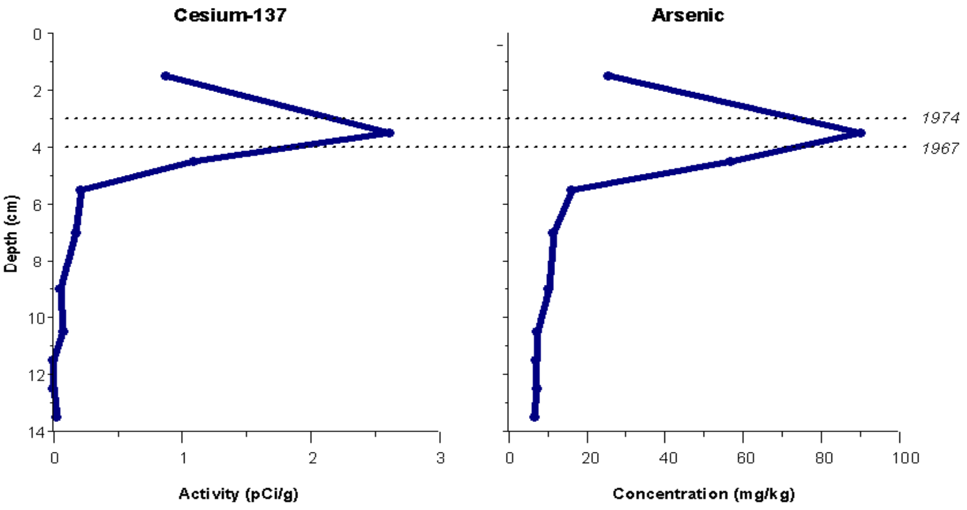

Figure 2. Profiles of cesium-137 and arsenic in the sediment core. Cesium-137 is a byproduct of atmospheric nuclear testing while arsenic was used for aquatic plant control in the 1950-60's. The peak deposition of both of these elements was 1963 for cesium and 1962 for arsenic.

^{137}Cs peak in the sediment core should represent a date of 1963. Another sediment marker that can be used in Beulah Lake is arsenic. Sodium arsenite was used for aquatic plant control during the 1950-60's before its use was banned. The peak application of sodium arsenite in Beulah Lake was in 1962 (Lueschow, 1972). Therefore, the peak arsenic concentration should indicate this date. Figure 2 shows the peak concentrations of ^{137}Cs and arsenic. Both of the peaks occur at the same depth (3-4 cm). This depth is bracketed by the ^{210}Pb dates of 1974 and 1967. These dates are somewhat more recent than they should be. This means that the dates for the last 50 years probably are in error by around 5 years. In other words, a ^{210}Pb date of 1970 may actually be closer to an actual date of 1965.

Sedimentation Rate

The mean sedimentation rate of 0.019 g cm^{-2} yr^{-1} in Beulah Lake is one of the lowest rates found in hard water lakes in Wisconsin (Figure 3). Only Big Green Lake had a lower sedimentation rate. The sedimentation rate during European settlement (1840 to the present) has only changed a relatively small amount (Figure 4). The maximal rate at 0.038 g cm^{-2} yr^{-1} is 3 times the presettlement rate. In many southern Wisconsin lakes, the sedimentation rate has increased at least 10 times over that of the presettlement rate in the last 50 years. The peak sedimentation rate in Beulah Lake occurred around 1920 and since the 1940's the and the lack of a significant increase in the last 150 years is an indication that sediment infilling in the lake is occurring at a moderate rate. While the rate is faster than occurred prior to European settlement, it is slower than most other lakes in the region.

Geochemistry

Organic matter was unchanged until the mid-1800's when it began to increase (Figure 5). This increase was the result of land clearance that occurred with the initial European settlement. At about this time the percentage of calcium carbonate ($CaCO_3$) declined as clastic materials and biogenic silica increased. As the surrounding prairie was plowed, soil erosion increased bringing clastic material into the lake. This increased erosion diluted the $CaCO_3$ in the sediments. In a hardwater lake like Beulah Lake, calcium carbonate is produced within the lake during the summer as a result of the growth of algae and aquatic plants. When $CaCO_3$ concentrations become high enough, the $CaCO_3$ precipitates and is deposited in the lake sediments as marl. Organic matter remained elevated from the mid-1800's until the present

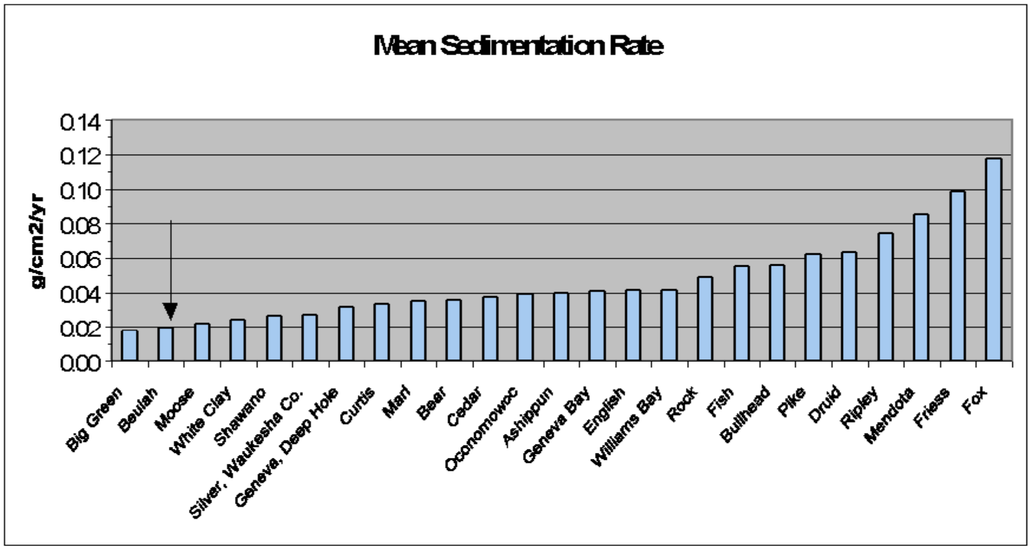

Figure 3. Mean sedimentation rate for some Wisconsin hard water lakes. The arrow indicates Beulah Lake.

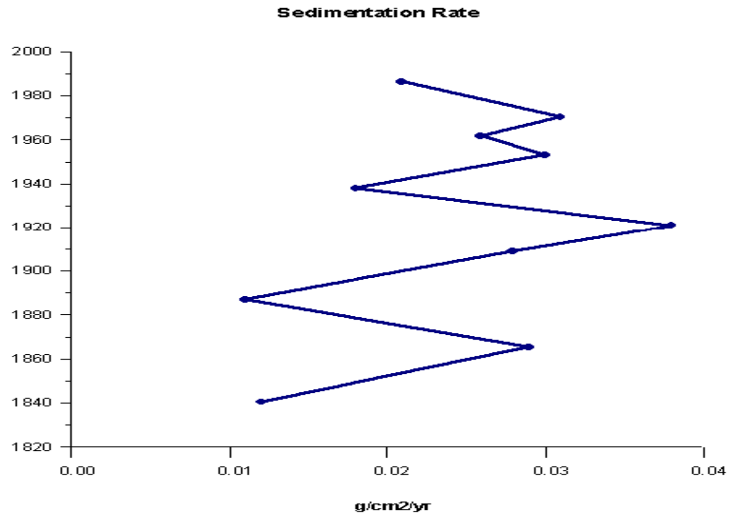

Figure 4. Sedimentation rate at core site in Beulah Lake for the last 160 years.

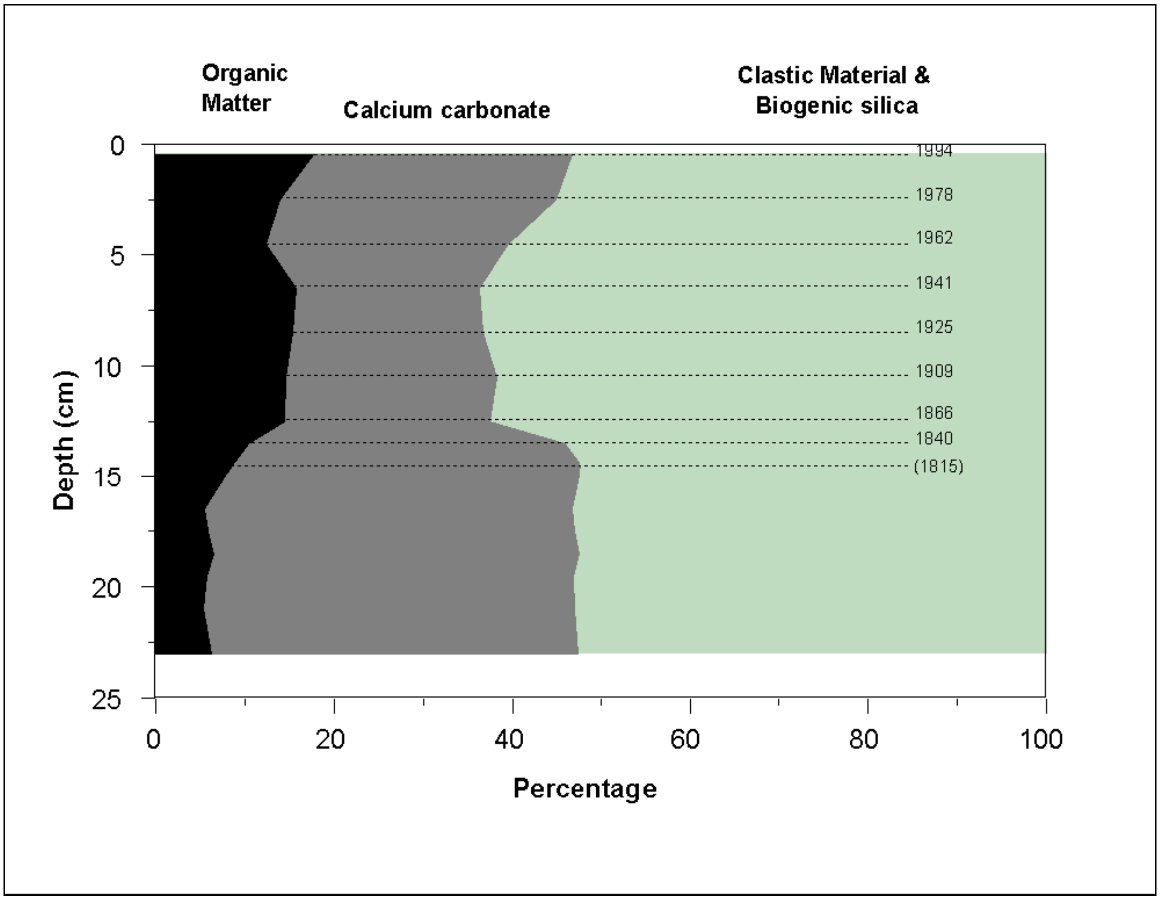

Figure 5. Profile of organic matter, calcium carbonate, and clastic materials and biogenic silica.

time with a decline during the 1960's. The percentage of $CaCO_3$ began to increase during the 1950's and at the present time the concentrations are similar to historical levels. This rise is likely the result of decreased input of clastic materials from soil erosion combined with increased marl deposition associated with increased algal productivity in recent years.

Figure 6 shows the concentration profiles of the geochemical variables that were analyzed in this study. Materials derived from soil erosion such as aluminum, potassium, and titanium all first increase around 1840 and remain elevated until the 1950's. This indicates the highest rates of soil erosion in the watershed occurred during this period and since the 1960's the rate has declined. The decline in soil erosion coincides with the period of reduced agricultural activity as the watershed was being converted to residential use.

Iron and sulfur reach peak concentrations in the 1930's and phosphorus also exhibited elevated levels at this time. Unlike the first two parameters, the highest phosphorus levels occurred in the most recent sediments. Since this core was collected in the fall, the elevated P concentration at the top of the core may be an artifact. Phosphorus is released from the deep sediments during summer stratification. However, during fall turnover, some of this phosphorus is precipitated onto the surface sediments. This results in high P levels on the sediment surface, which does not reflect the true phosphorus levels in the lake.

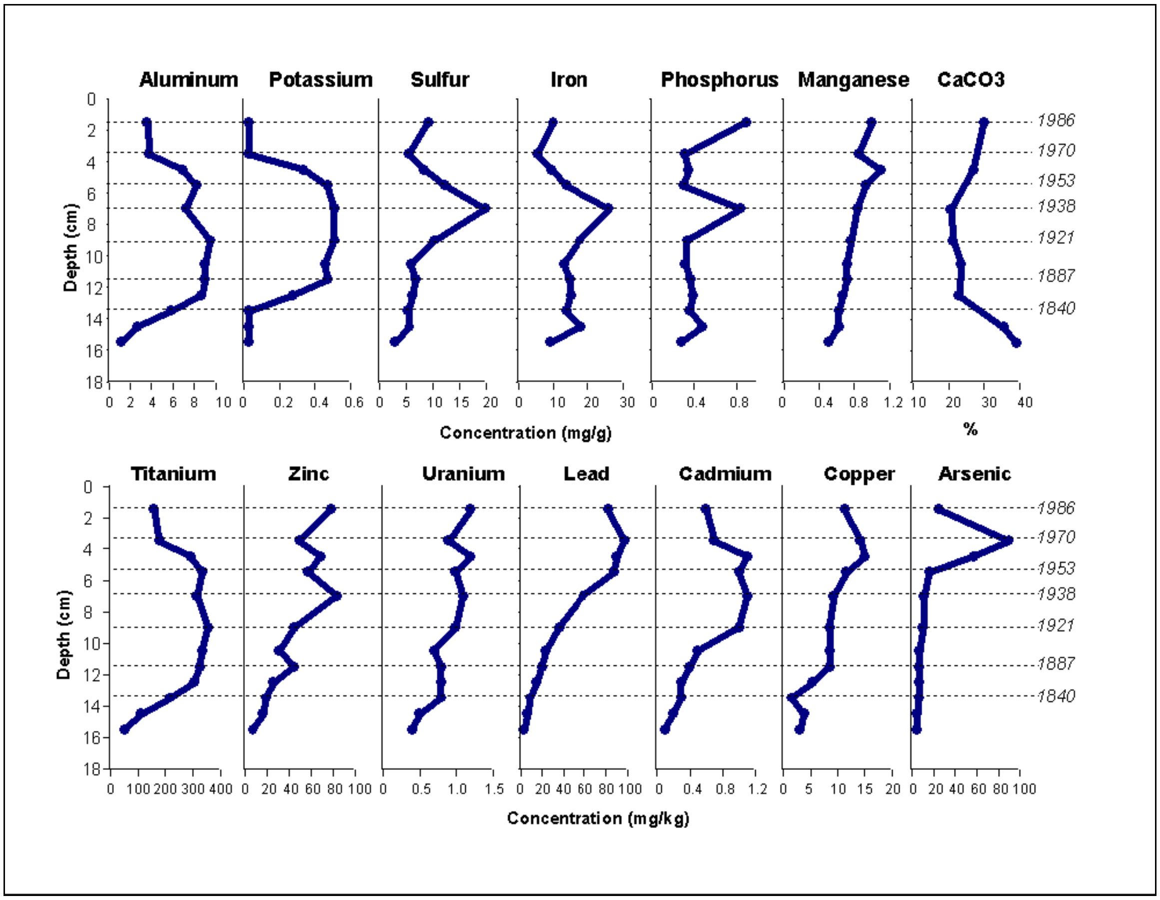

Figure 6. Profiles of selected chemical variables.

Manganese shows at steady increase from the bottom to the top of the core. Since this chemical is sensitive to oxygen levels in the bottoms waters, its increase likely indicates a slow but steady decline in oxygen in the deeper waters of the lake.

Zinc concentrations increased in the 1930's and have remained elevated until the present time. Zinc is generally a good surrogate for urbanization since zinc is a significant contributor to storm water runoff from urban sources (Bannerman et al. 1993; Steuer et al. 1997). Significant sources of zinc in an urban setting are corrosion of vehicles, tires, and roofs, both commercial and residential (Bannerman et al. 1993; Good 1993; Steuer et al. 1997). The increased concentration of zinc since the 1930's is likely an indication of the urbanization of the watershed.

Lead concentration peaks around 1970 (Figure 6). Much of the lead that enters the lake likely comes from atmospheric deposition. Much of the lead in the atmosphere was derived from automobile exhaust. With the mandated use of lead free gasoline in new cars in the early 1970's lead production declined and this reduced emission of lead is reflected in the lake sediments.

In order to understand what the significant sources of phosphorus are to the lake chemical ratios were examined. The ratio of titanium to phosphorus (Ti:P) indicates the importance of soil erosion as a source of phosphorus. The ratio of zinc to phosphorus (Zn:P) indicates the importance of urban sources as a contributor of phosphorus. Between the period of the late 1800's until the 1950's soil erosion was an important source of phosphorus as the Ti:P was at its highest (Figure 7). However, for the last 3 decades, this ratio declined indicating soil erosion was less important as a source of phosphorus. Although the ratio is lowest in the surface sample this is an artifact of the phosphorus precipitation occurring during fall turnover as discussed earlier. The Zn:P ratio steadily increased from the mid-1800's until around 1960 indicating that urban runoff was an increasingly important contributor as a phosphorus source

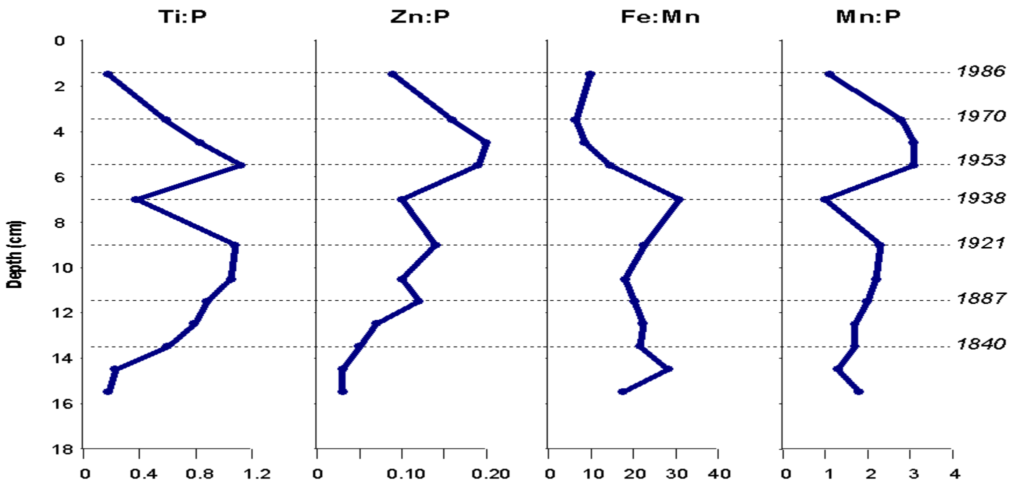

Figure 7. Profiles of ratios of selected chemical variables. Titanium is derived from soil erosion while zinc comes from urban runoff. The ratio of iron to manganese indicates changes in oxygen levels in the deep waters. The ratio of Mn:P indicates the contribution of phosphorus released from the sediments during periods of low oxygen in the bottom waters.

to the lake. Unlike Ti:P, the ratio of zinc to phosphorus has remained elevated indicating the importance of urban runoff as a source of phosphorus to the lake.

The ratio of iron to manganese (Fe:Mn) is an indication of changes in oxygen levels in the deep waters of the lake. As the bottom waters become increasing devoid of oxygen, manganese is preferentially mobilized from the sediments compared with iron (Engstrom et al., 1985). This manganese then moves into the deepest waters resulting in enrichment of manganese with respect to iron. The Fe:Mn is relatively stable from the early 1800's until the 1940's when it declines (Figure 7). Since the 1940's this ratio has remained low indicating the oxygen levels have been reduced in the deepest waters for the last 50 years. When the bottom waters become anoxic, phosphorus is released from the sediments (Mortimer, 1941,1942; Kamp-Nielson, 1974). During turnover in the fall and to a lesser extent in the spring, some of this phosphorus becomes available for algal growth. This internal loading of phosphorus is an indication of declining water quality in the lake. Further evidence of this internal loading is the ratio of manganese to phosphorus. This ratio was highest from the 1950's until the top sample. Again the decline in the ratio at the sediment surface is because of the precipitation of P during fall turnover.

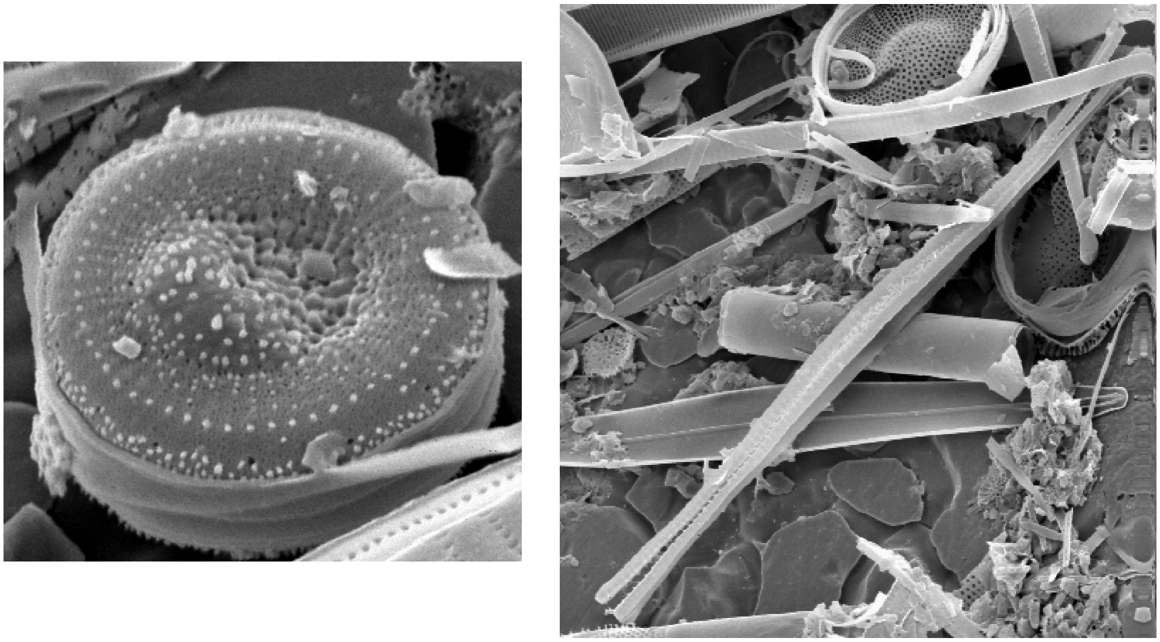

Figure 8. Electron micrographs of diatoms Cyclotella michiganiana *(left) and* Fragilaria crotonensis *(right).*

Diatom Community

Aquatic organisms are good indicators of water chemistry because they are in direct contact with the water and they are strongly affected by the chemical composition of their surroundings. Most indicator groups grow rapidly and are short lived so the community composition responds rapidly to changing environmental conditions. One of the most useful organisms for paleolimnological analysis are diatoms. These are a type of alga, which possess siliceous cell walls and are usually abundant, diverse, and well preserved in sediments. They are especially useful as they are ecologically diverse and their ecological optima and tolerances can be quantified. Certain taxa are usually found under nutrient poor conditions while others are more common under elevated nutrient levels. They also live under a variety of habitats, which enables us to reconstruct changes in nutrient levels in the open water as well as changes in benthic environments such as aquatic plant communities. Figure 8 shows photographs of two diatom species that were common in the sediment core.

The diatom *Cyclotella michiganiana* (Figure 9) dominated the bottom of the core. Since this diatom grows in the metalimnion, it indicates good water clarity and low nutrient levels (Garrison & Wakeman, 2000). The other common diatom at the bottom of the core was *Cyclotella* sp. 1. Both of these species were often important components of the diatom community in southern Wisconsin lakes prior to European settlement (Garrison, unpublished data). The two *Cyclotella* species decline in the early 1800's while the diatoms *Asterionella formosa* and *Fragilaria crotonensis* increase. The latter two species are indicative of increased nutrient levels (Ennis et al., 1983, Engstrom et al., 1985, Christie & Smol, 1993, Stager et al., 1997). Unlike *C. michiganiana*, *A. formosa* and *F. crotonensis* inhabit the surface waters of the lake and do not need as good of water clarity for survival. The increase in nutrient levels during the early 1800's occurred prior to the arrival of European settlers and before agricultural practices intensified. Increased soil erosion did not occur until around 1840 (titanium, Figure 6). This shift from a diatom community dominated by the *Cyclotella* species to one dominated by *A. formosa* and *F. crotonensis*, typically happens later in the nineteenth century of other southern Wisconsin lakes (Garrison & Wakeman, 2000; Garrison, unpublished data). It is unclear why this shift occurred earlier in Beulah Lake than was experienced in other lakes. *A. formosa* and *F. crotonensis* remained the dominant diatom from the early 1800's until the present time. The concentration of diatoms increased during the early part of the twientith century indicating increased productivity.

The increase in the diatom *Stephanodiscus minutulus* during the 1860's is an indication of further increases in phosphorus in the lake since this diatom is found in elevated nutrient levels

(Bradbury, 1975; Carney, 1982; Fritz et al., 1993). This diatom continues to be present in relatively low levels until the early 1960's when is declines. This is an indication that nutrient levels in the lake declined around this time. *F. crotonensis* increased significantly in the most recent sediments indicating a further increase in nutrients in recent years. Further evidence of increased nutrients during the last 15 years is the increase in the percentage of planktonic diatoms (Figure 9). These diatoms which inhabit the open water of the lake, typically become more common with higher nutrient levels (Bradbury & Winter, 1976; Battarbee, 1978).

Achnanthidium minutissima typically grows attached to aquatic plants. Increases in this diatom are an indication of an increase in density or coverage of plant beds. *A. minutissima* was found in very low levels at the very bottom of the core. However, in the early 1800's the abundance increases somewhat. This occurs at the same time that the rest of the diatom community indicates an increase in nutrients in the lake. The plant community increased further during the 1870's probably in response increased agricultural activity. The increase in plant beds with early European settlement has been found in nearly all lakes in Wisconsin where sediment cores have been analyzed. It appears that the littoral zone responds very early to the increased input of nutrients from the watershed.

Diatom assemblages historically have been used as indicators of trophic changes in a qualitative way (Bradbury, 1975; Anderson et al., 1990; Carney, 1982). In recent years, ecologically relevant statistical methods have been developed to infer environmental conditions from diatom assemblages. These methods are based on multivariate ordination and weighted averaging regression and calibration (Birks et al., 1990). Ecological preferences of diatom species are determined by relating modern limnological variables to surface sediment diatom assemblages. The species-environment relationships are then used to infer environmental conditions from fossil diatom assemblages found in the sediment core.

In the Beulah Lake core the diatom community was used to estimate summer phosphorus concentrations throughout the core. Phosphorus concentrations were at their lowest at the bottom of the core. Historical P levels are estimated to be less than 5 $\mu g\ L^{-1}$ (Figure 9). Phosphorus levels increased in the mid-1800's soon after the arrival of European settlers. The increased nutrients were the result of the plowing of the prairie for agriculture. Phosphorus concentrations appear to have declined during the 1960-70's to around 5 $\mu g\ L^{-1}$ which corresponds to a decline in the organic matter during the same time period (Figure 5). Phosphorus levels have increased in the last 15 years and currently are at their highest levels.

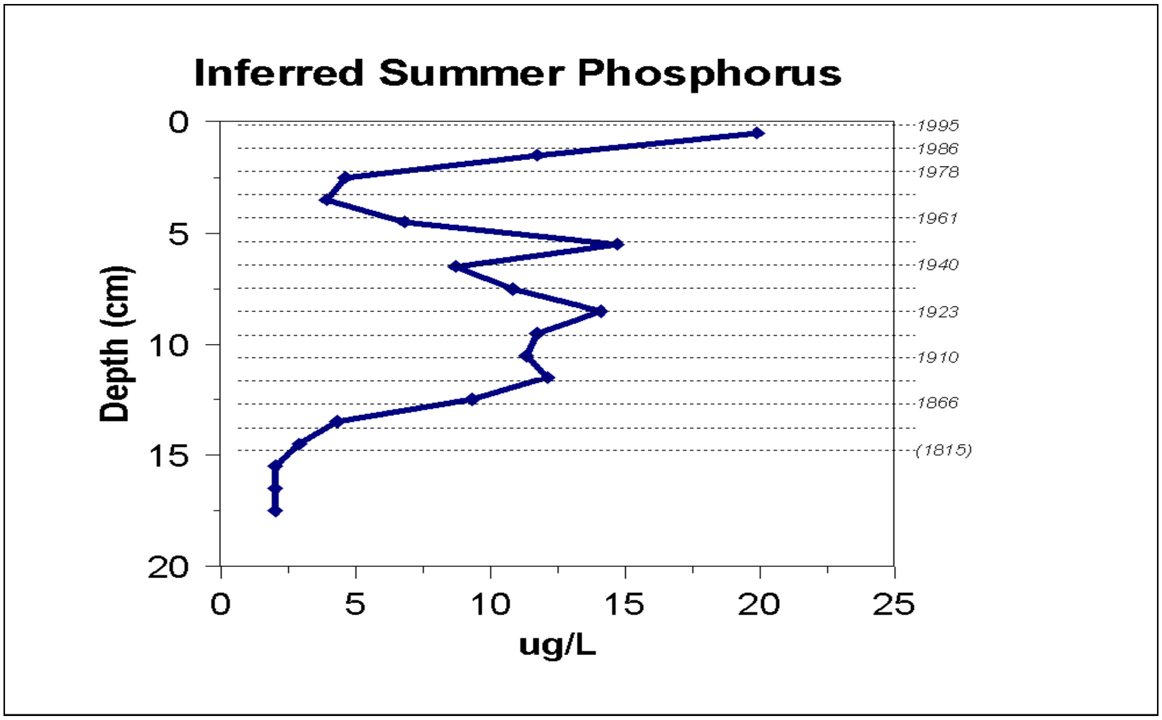

Figure 10. Diatom inferred changes in summer phosphorus in Beulah Lake.

Summary

Beulah Lake has undergone water quality changes in the last two centuries as a result of European settlement and increased development in the watershed. However, the nutrient increase is much less than experienced in many other lakes in the southeastern part of Wisconsin. While present day phosphorus levels are good for this part of the state they are higher compared with presettlement levels.

Some key findings of this paleoecological study are:

- The mean sedimentation rate of Beulah Lake for the last 180 years is one of the lowest measured in hard water lakes in Wisconsin.
- The sedimentation rate has been relatively stable for the last 200 years despite increased watershed activities such as agriculture and urban development. Many other lakes have experienced a significant increase in their sedimentation rate in the last 50 years.
- Input from soil erosion has declined since the 1960's as agricultural land has been converted to home lots

- The bottom waters have experienced a decline in oxygen during the last 50 years. This has resulted in an increase in internal loading of phosphorus, which probably is contributing towards increased algal growth in the lake.
- The diatom community indicated that there was a slight increase in nutrients in the lake around 1800 prior to the arrival of European settlers. Although a similar change has been observed in other nearby lakes, it generally occurred in the mid-1800's.
- During the early 1800's there was an increase in the macrophyte community. The plant community further increased in the latter part of the 1800's and appears to have remained stable for the last 100 years.
- The diatom community indicates that the present day phosphorus concentration in the lake is higher than at any other time in the last 200 years. Phosphorus levels first increased in the mid-1800's with the arrival of European settlers. Phosphorus levels the lake appeared to decline during the 1960-70's.

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