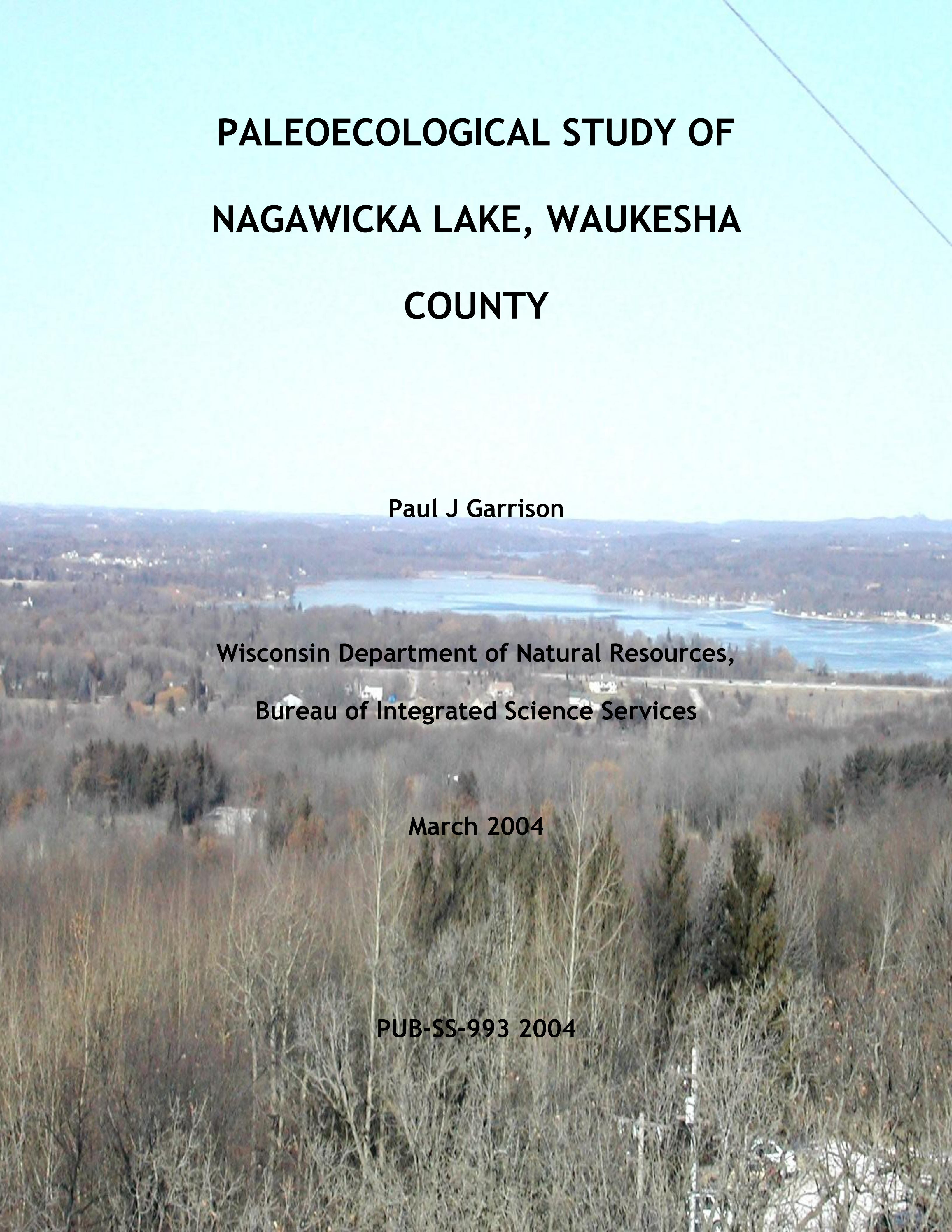

PALEOECOLOGICAL STUDY OF NAGAWICKA LAKE, WAUKESHA COUNTY

Paul J Garrison

Wisconsin Department of Natural Resources,
Bureau of Integrated Science Services

March 2004

PUB-SS-993 2004

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.

Two sediment cores was collected from Nagawicka Lakeon 2 November 2003. The cores were collected with a gravity corer with a 6.5 cm plastic liner. Both cores were collected from the deep area of the lake. The location of the coring site was 43° 04.096' north, 88° 23.172' west in a water depth of 26.5 meters (87 ft). Both cores were sectioned into 2 cm intervals for the upper 40 cm and at 1 cm intervals for the remainder of the cores. The first core was 51 cm long and the other core was 53 cm in length. The second core was used for analysis and the first core was archived. The cores were dated by the ^{210}Pb method and the CRS model used to estimate dates and sedimentation rate. The cores were analyzed for diatoms to assess changes in nutrient levels and geochemical variables in order to determine the causes of changes in the water quality and changes in oxygen conditions in the bottom waters.

Site Description

Nagawicka Lake is a 957 acre lake located in Waukesha County near the city of Delafield. The maximum depth is 90 feet with a mean depth of 48 feet. The major tributary entering the lake is the Bark River and this river also exits the lake. The river provides about 89% of water entering the lake (SEWRPC, 1999). The drainage area contributing to the lake is 28,952 acres. In 1990 nearly 22 percent of the landuse in the watershed was urban, largely residential, while agricultural use was 44 percent, wetlands 10 percent and woodlands 10 percent. The rest of the landuse is water and miscellaneous landuses (SEWRPC, 1999).

Prior to the arrival of Europeans during the 1830s the landscape around Nagawicka Lakewas largely oak savanna with scattered wetlands. Early settlers removed many of the trees and used the land for subsistence farming. Later in the 19th century, especially after the development of the moldboard plow, a larger part of the lake's watershed was plowed. The original land surveys were done in this township during 1836. Land grants had already been granted around these lakes although no structures were shown in the survey (Figure 1). The northern portion of the lake possessed fringing wetlands. These are still there at the present time although some dredging and filling has occurred. Throughout the last half of the 19th century farming became increasingly efficient with the improvement of equipment. During the twentieth century farming practices became increasingly mechanized which enabled the farming of more land. In many other areas of the state this resulted in an increase in the sedimentation rate of lakes as well as increased productivity. The watershed of Nagawicka Lakehas undergone significant changes during the last 100 years with land being converted from agricultural use to urban landuses. Figure 2 shows the cumulative urban area for the direct drainage area (4763 ac) and total drainage area (28,952 ac). In the watershed, urban development has been greatest since 1960.

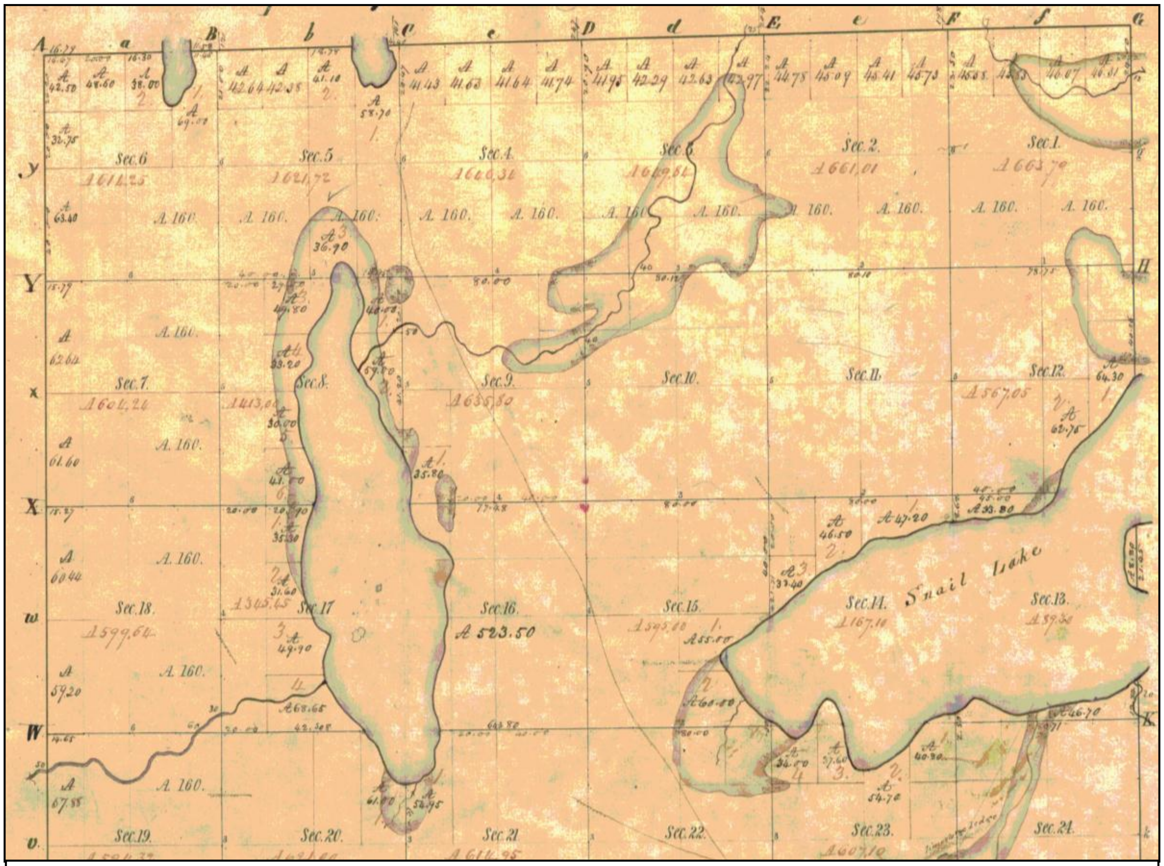

Figure 1. Map of original land survey performed in 1836. Pewaukee Lake was known as Snail Lake at that time.

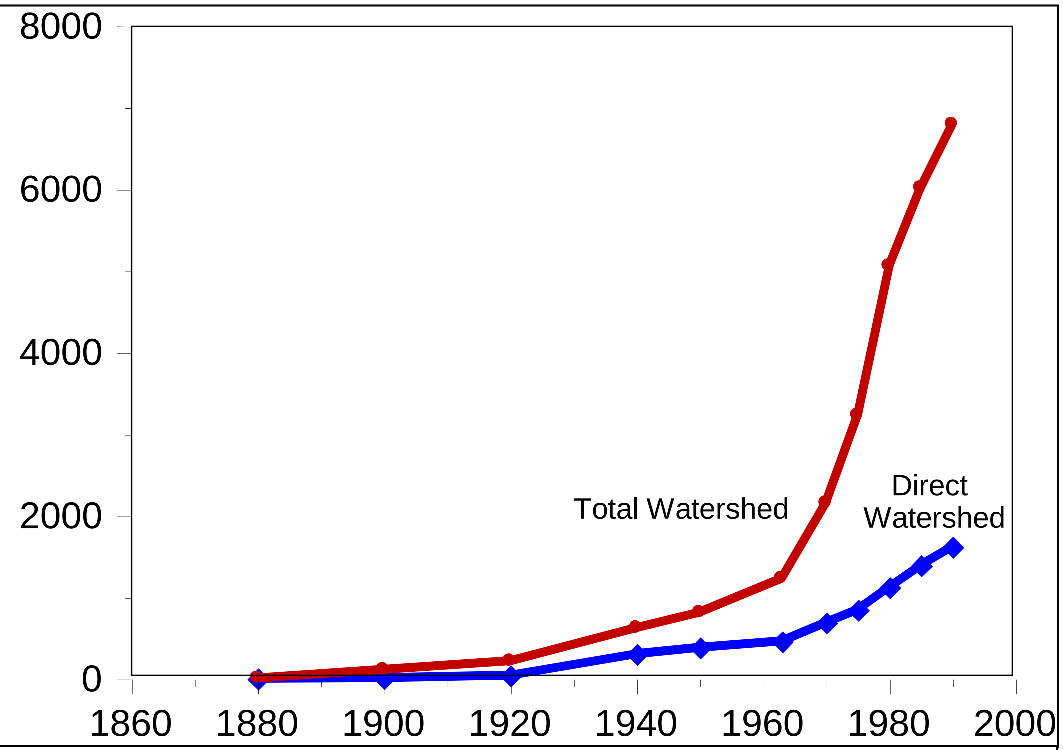

Figure 2. Cumulative area of urban development in Nagawicka Lake watersheds.

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. After it enters the lake and it is 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. Dates and the sedimentation rates were determined using the CRS model (Appleby and Oldfield, 1978).

There can be problems with this dating technique. For example, when 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 is 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 Nagawicka Lake with other lakes in the region.

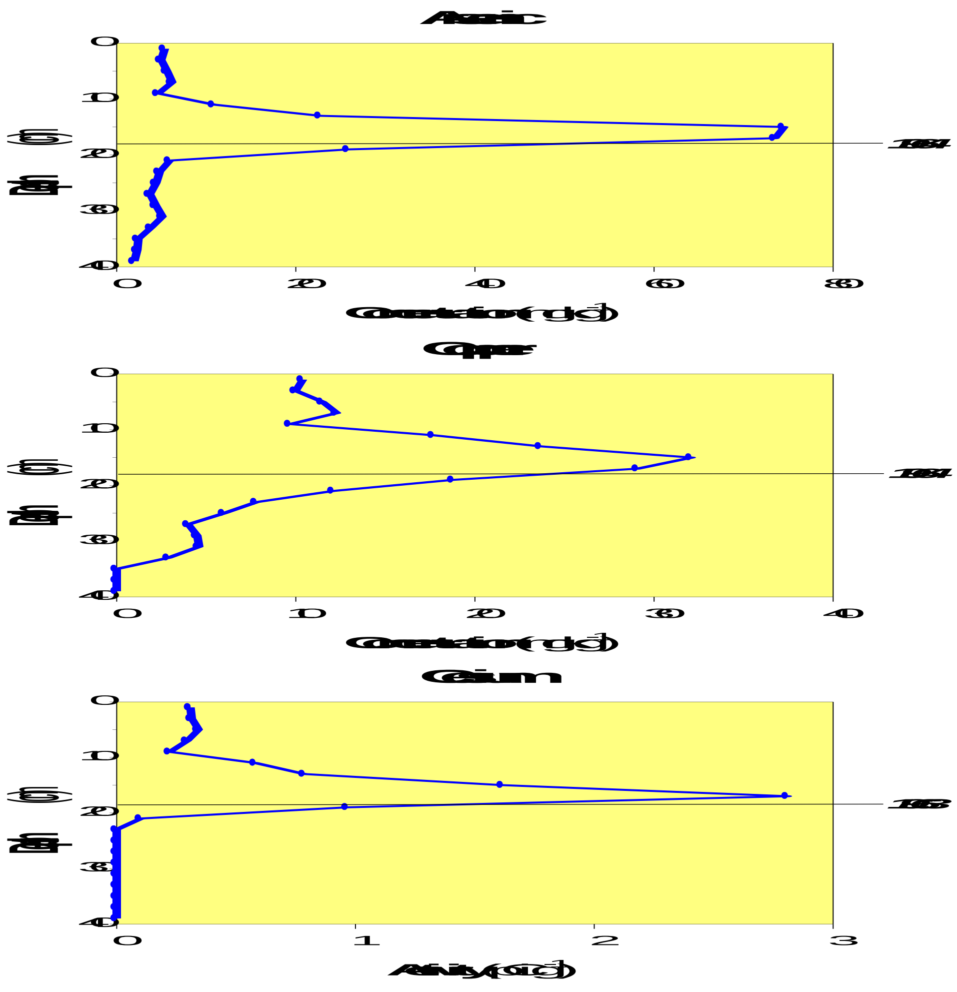

Figure 3. Profiles of arsenic, copper and cesium-137. Arsenic was applied for aquatic plant control and copper was used as a control for algal blooms. The peak applications of these chemicals was in 1964. Cesium-137 is a byproduct of atmospheric nuclear testing. The peak deposition was in 1963.

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

^{137}Cs peak in the sediment core should represent a date of 1963. Another sediment marker that can be used in Nagawicka Lakeis 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 Nagawicka Lakewas in 1963-65 (Lueschow, 1972). Therefore, the peak arsenic concentration should indicate this date. Copper sulfate was also applied to the lake for algal control. The peak application of $CuSO_4$ was in 1964 (Lueschow, 1972). Figure 3 shows the peak concentrations of ^{137}Cs, copper, and arsenic. All of these elements can move somewhat after their deposition so the fact they are slightly offset is not a concern. The depth of these peaks is very close to the date of 1963 calculated by the ^{210}Pb model indicating that the model results are very good.

Sedimentation Rate

The mean sedimentation rate for the last 150 years was 0.067 g cm^{-2} yr^{-1}. This is one of the higher rates found in Wisconsin lakes (Figure 4). This elevated rate is likely because the lake type is drainage. This means that the Bark River brings in sediment and nutrients which contribute to the sedimentation rate. Typically, lakes without surface inflows (seepage lakes) have lower mean sedimentation rates.

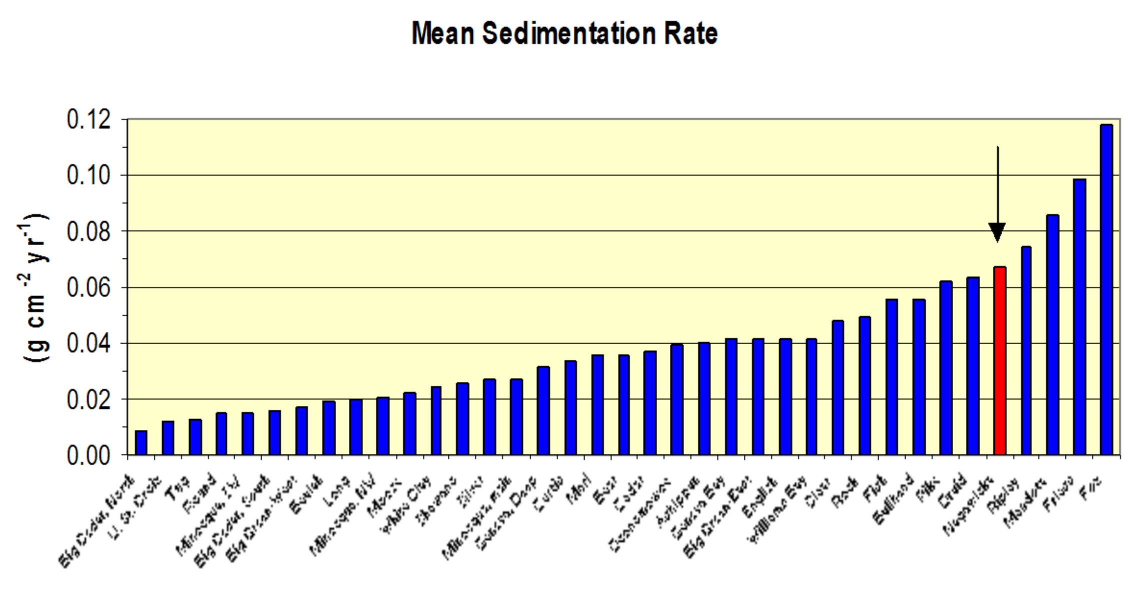

Figure 4. Mean sedimentation rate for the last 150 years for 32 Wisconsin lakes. The arrow indicates Nagawicka Lake.

More important than the mean sedimentation rate is the trend in this rate during the last 150 years. The sedimentation rate during the late 1800s was about 0.030 g cm^{-2} yr^{-1} which is relatively low for a drainage lake. With the increase in the development in the watershed during the twentieth century, the sedimentation rate steadily increased with peak rates occurring during the last 2 decades (Figure 5). As will be detailed later, most of this increase was not the product of soil erosion but instead calcium carbonate that was produced in the lake.

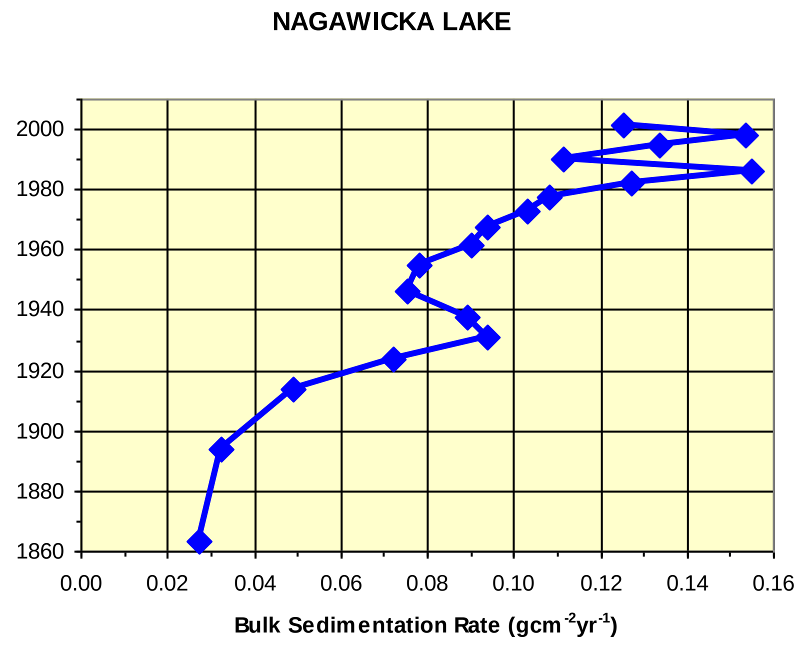

Figure 5. Sedimentation rate for the lake.

Geochemistry

Geochemical variables are analyzed in order to estimate changes in the delivery of soil and nutrients from the watershed (Table 1). The chemical titanium (Ti) is found in soil particles, especially clays. Changes in Ti are an indication of changes in soil erosional rates throughout the lake's history. Zinc (Zn) is associated with urban runoff because it is a component of tires and galvanized roofs and downspouts. Nutrients like phosphorus and nitrogen are important for plant growth, especially algae and aquatic plants. Calcium carbonate is often the most common chemical in hardwater lakes like Lake Nagawicka. These lakes are also known as marl lakes because they precipitate calcium carbonate, which is also known as marl. Marl is very common in Nagawicka Lakeand is the reason for the light gray color of the sediment throughout much of the lake. Organic matter is deposited in the lake as a result of algal and aquatic plant production in the lake. Increases in organic matter are an indication of increased productivity of the lake.

Table 1. Selected chemical indicators of watershed or inlake processes.

Process	**Chemical Variable**
Productivity	calcium carbonate, organic matter
Soil erosion	aluminum, titantium
Urban	zinc, copper
Anoxia	manganese
Nutrients	phosphorus, nitrogen

Calcium, largely, in form of calcium carbonate was the dominant element in the lake sediments. In fact the formation of marl is the driving factor in the sedimentation rate and influences phosphorus chemistry. As shown in Figure 6, the principal reason for the increase in the sedimentation rate during the last century was the precipitation of calcium carbonate ($CaCO_3$). The increase in sediment deposition closely mirrors the accumulation of $CaCO_3$, especially since 1960. The reason for the increase in $CaCO_3$ precipitation is the increase in algal and vascular plant activity in the lake. With the increase in photosynthesis, the pH of the water is elevated and this leads to the over saturation of $CaCO_3$ and thus its precipitation

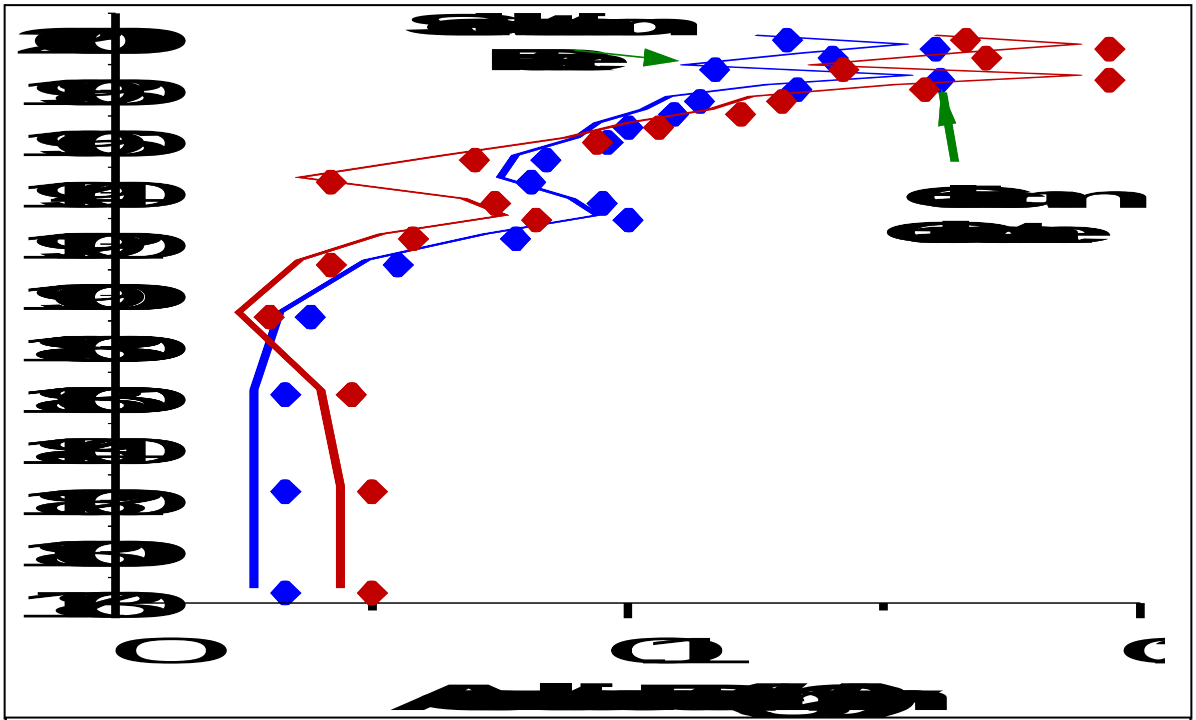

Figure 6. Accumulation of sediment and calcium carbonate for the last 200 years. Most of the lake's infilling is the result of calcium carbonate precipitation. This marl production is the result of increased productivity of the lake.

(Otsuki and Wetzel, 1972). This increased in productivity is a direct result of increased nutrients entering the lake.

There was a significant reduction in the calcium carbonate in the core around 1880 (Figure 7). This reduction has been found in many hardwater lakes and is associated with early agricultural activity (Engstrom et al., 1985; Garrison, 2000a,b; Garrison, 2003; Garrison and Wakeman, 2000). As more land is cleared for farming, the soil erosion materials from around the lake dilute the calcium carbonate. In fact when the $CaCO_3$ declines there is a near mirror increase in inorganic materials which are largely products of soil erosion. With the reduction of soil erosion around 1950 (Figure 7), $CaCO_3$ begins to increase.

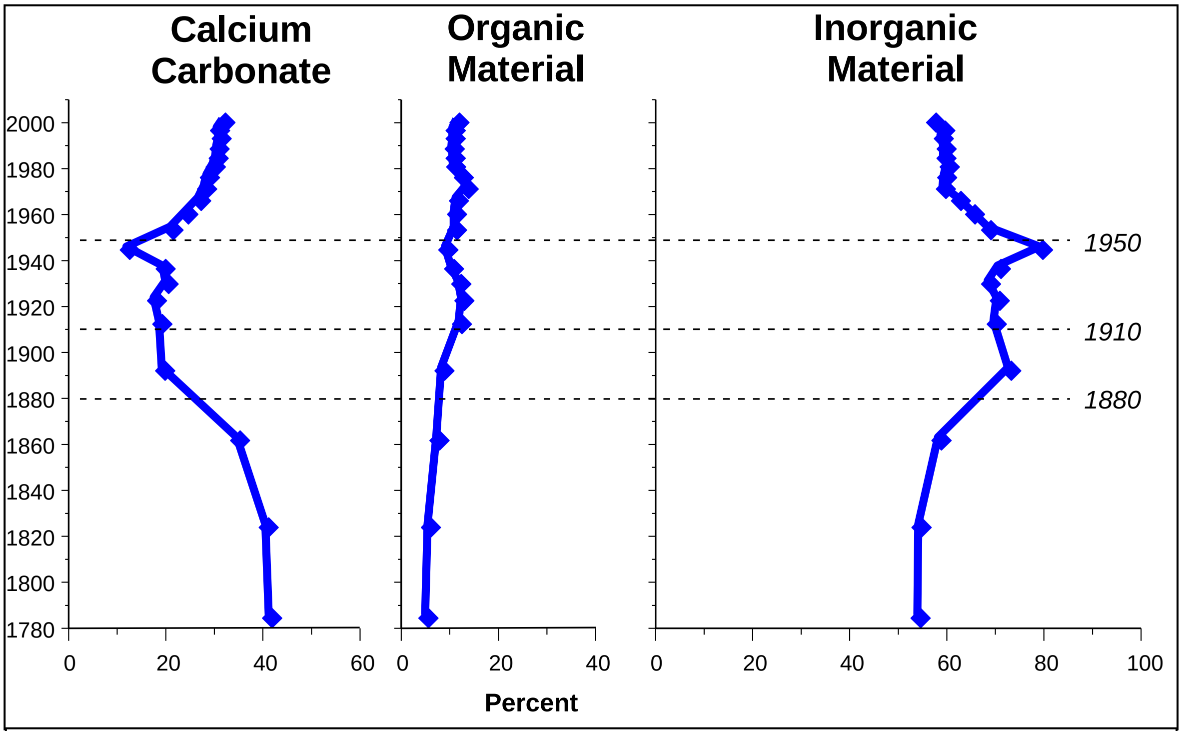

Figure 7. Profiles of the 3 major sediment components. $CaCO_3$ declines between 1880-1950 as a result of dilution of soil (inorganic material) with agricultural activities.

Organic matter began to increase around 1910 and generally continued to increase throughout the twentieth century (Figure 7). This indication of increased biological productivity in the lake as a response to increased nutrient input. The increased productivity indicated by the trend in organic matter agrees well with the increase in marl formation during the last 100 years.

Titanium concentrations first began to increase around the mid-1800s (Figure 8). This reflects the initial farming activities near the lakeshore with the arrival of European settlers. The greatest titanium concentrations occurred between the period 1910-1950. This was the period of the greatest soil erosion around the lake. Soil erosional rates steadily declined between 1950 and 1970 and have remained steady or increased slightly during the last 30 years. This lower soil erosion reflects improved agricultural practices as well as increased urbanization of the watershed.

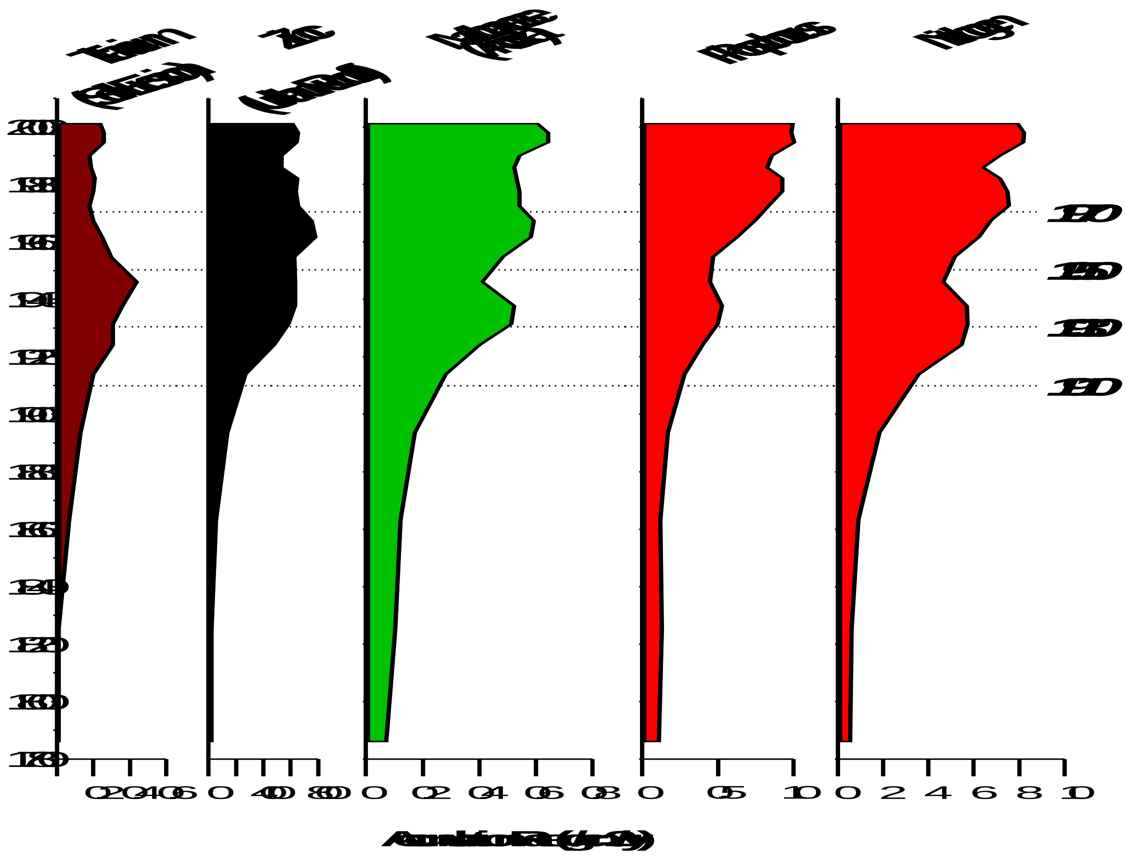

Figure 8. Profiles of selected chemical variables. Soil erosion and urban runoff first increased about 1910. Soil erosion declined after 1950 but urban runoff remains high. With the increase in nutrients from the watershed, the bottom waters became more anoxic after 1910.

Zinc concentrations began to significantly increase after 1910 (Figure 8) which is an indication of the increased urbanization of the watershed. Peak levels were reached about 1960. Unlike titanium, zinc concentrations have remained high, reflecting the fact that 30 percent of the watershed is urbanized.

As the bottom waters become increasing devoid of oxygen, manganese (Mn) is mobilized from the sediments (Engstrom et al., 1985). This manganese then moves into the deepest waters resulting in enrichment of manganese in the sediments of the deeper waters in Lake Nagawicka. The increase in Mn began about 1910 around the same time that soil erosion and urban runoff significantly increased (Figure 8). Manganese first peaked around 1930 and remained near this level until 1990. During the last ten years the concentration has been higher than any other time during the last 200 years. This trend in Mn indicates that the bottom waters became significantly more anoxic about 100 years ago but the amount of bottom waters that are devoid of oxygen has increased since 1990.

Levels of both nutrients, phosphorus and nitrogen, appear to begin to increase around 1910, which is when many other chemicals increased. While the historical trends of these nutrients is very important for determining the history of eutrophication history of the lake, the deposition trends shown in Figure 8 are not indicative of historical nutrient inputs from the watershed. This is especially true for phosphorus. Calcium carbonate has a chemical affinity for many elements, especially phosphorus. With the increase in precipitation of $CaCO_3$ during the last 70 years there has also been an increased deposition of phosphorus. The close association of P with $CaCO_3$ is evident from the trend in the ratio of Ca:P since 1900 (Figure 9). The ratio was nearly constant throughout the twentieth century, although it increased slightly

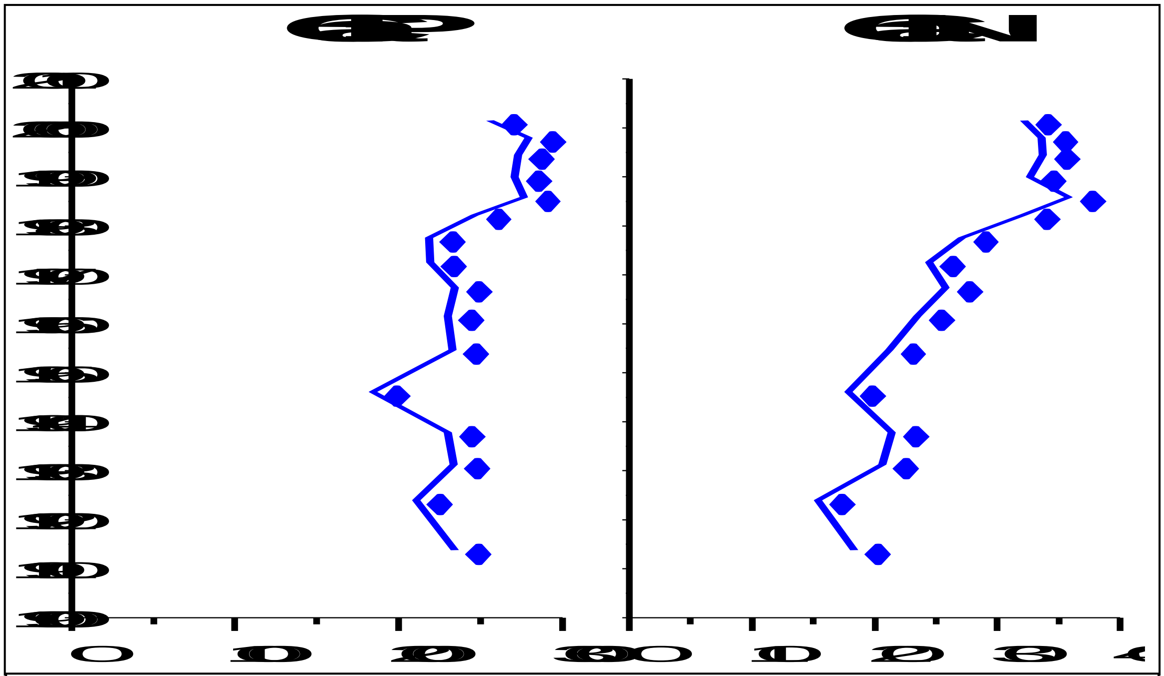

Figure 9. Ratios of Ca:P and Ca:N. Phosphorus deposition is closely related to calcium carbonate deposition while nitrogen is not.

during the 1990s. It is possible that P loading has decreased somewhat during the last decade. Undoubtedly some of this increased P deposition indicates an increase in phosphorus entering the lake from the watershed. However, as has been found in other marl lakes (Engstrom and Wright, 1984; Schelske et al., 1988; Anderson et al., 1993; Fitzpatrick et al., 2003), the increased deposition of P is not necessarily a true indication of historical P loading to Lake Nagawicka.

In contrast to the ratio of Ca:P, the ratio of Ca:N steadily increased after 1940 (Figure 9). Nitrogen deposition is not as tightly controlled by $CaCO_3$ precipitation as P. This likely means that nitrogen deposition more closely reflects historical N loading. If this is the case, there has been a steady increase in N since 1910. Since titanium (soil erosion) has declined since the peak around 1950 while zinc (urban runoff) has remained elevated, it is likely that urban runoff and not soil erosion is the primary source for this nitrogen.

Diatom Community

Aquatic organisms are good indicators of water chemistry because they are in direct contact with the water and 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 is diatoms. They 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 10 shows photographs of two diatom species that were common in the sediment cores.

The diatom community at the bottom of the core was relatively diverse with diatoms typically found in oligo-mesotrophic conditions. *Cyclotella michiganiana Cyclotella* sp. 1, *Asterionella formosa*, *Fragilaria crotonensis*, and *F. crotonensis* var. *oregona* (Figure 11) dominated the community. The first diatom grows in the metalimnion, indicating good water clarity and low nutrient levels (Garrison & Wakeman, 2000). The second diatom has been found in other marl lakes in southern Wisconsin. Both of these species were often important components of the diatom community in southern Wisconsin lakes prior to European settlement (Garrison, unpublished data). The latter three species are indicative moderate nutrient levels (Ennis et

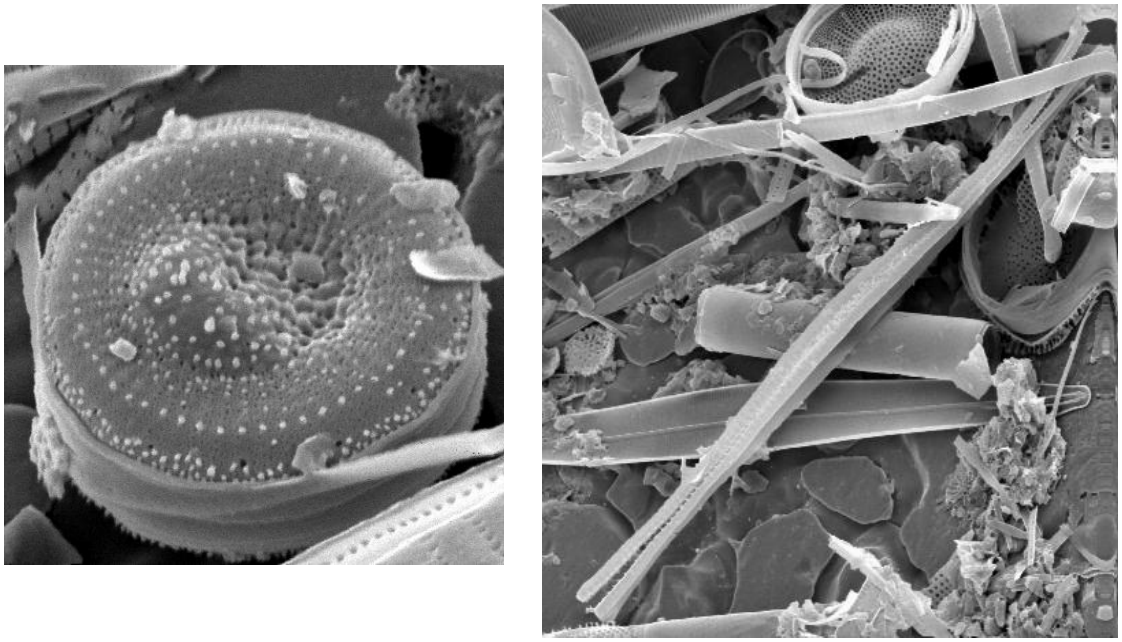

Figure 10. Electron micrographs of the diatoms *Cyclotella michiganiana* (left) and *Fragilaria crotonensis* (right) which were found in the cores from Nagawicka Lake.

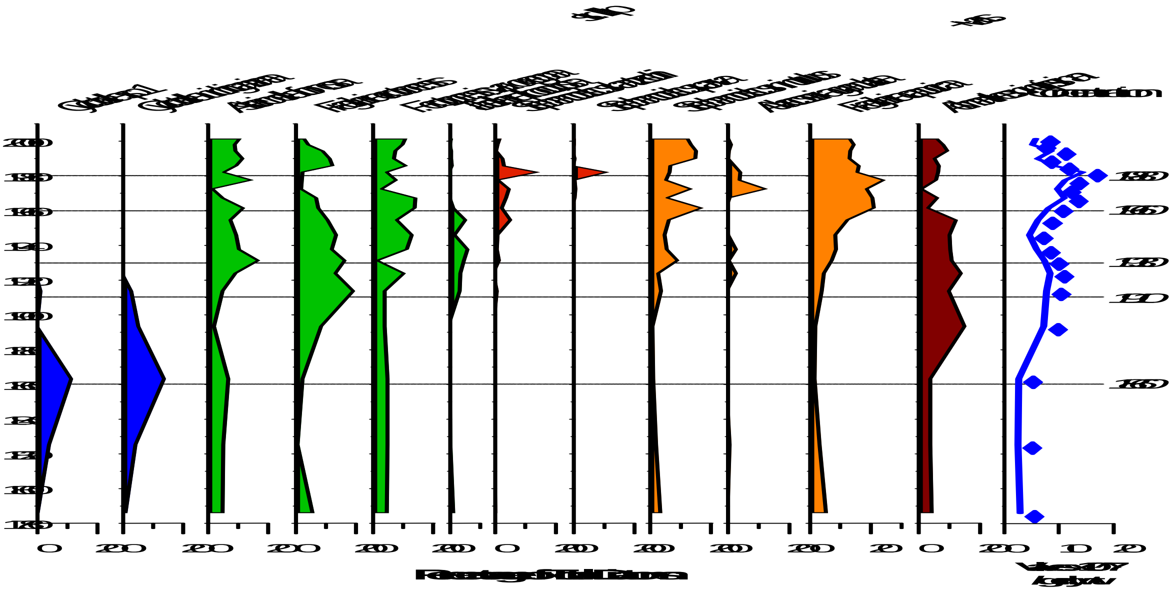

Figure 11. Diatom diagram of selected taxa. Diatoms in blue are indicative of low nutrients, green-moderate nutrients, orange-higher nutrients, and red-highest nutrients.

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 their growth. The increase in abundance of the diatoms *A. formosa*, *F. crotonensis* + vars. around 1910 indicates an increase in nutrient levels. This increase coincides with the disappearance of both *Cyclotella* species indicating a decline in water clarity. This increase in nutrients and decline in water clarity was occurring as soil erosion was increasing (titanium, Figure 8) and was the result of agricultural practices. This shift from a diatom community dominated by the *Cyclotella* species to one dominated by *A. formosa* and *F. crotonensis*, typically happened during the later part of the nineteenth century of other southern Wisconsin lakes (Garrison, 2000a,b; Garrison, 2003; Garrison & Wakeman, 2000). These two diatoms, which indicate moderate nutrient levels, were the dominant component of the diatom community until 1930.

After 1930 there was a small increase in *Stephanodiscus minutulus* and *Fragilaria capucina* + vars. (Figure 11). Both of these taxa typically are found at higher nutrient levels (Bradbury, 1975; Carney, 1982; Fritz et al., 1993; Garrison and Wakeman, 2000). These species increased further around 1960 and there was an increase in the eutrophic diatom *Stephanodiscus hantzschii*. These changes indicate a further increase in the phosphorus level in the lake. The highest phosphorus levels occurred around 1980 with peaks in the *S. hantzschii* and *S. parva*. These two taxa are common in eutrophic, hardwater lakes (Bradbury, 1975; Anderson et al., 1990; Hall and Smol, 1992; Bennion 1994, 1995). Since 1985 there has been a decline in these diatoms indicating a reduction in phosphorus levels.

The concentration profile of the total diatom community supports other indicators of increased productivity during the twentieth century. Diatom productivity increased around 1900 and remained elevated compared with historical levels until about 1940. The highest productivity was around 1980 when the high nutrient diatoms, *S. parvus* and *S. hantzschii* were at their highest levels (Figure 11).

Achnanthidium minutissima typically grows attached to aquatic plants (Reavie and Smol, 1997; Garrison and Wakeman, 2000). Increases in this diatom are an indication of an increase in density or coverage of plant beds. *A. minutissima* was found in low levels at the bottom of the core. However, around 1880 the abundance increased (Figure 11). This occurred at the same time that the rest of the diatom community indicated phosphorus levels were beginning to increase, albeit slightly. The increase in plant beds with early European settlement has been found in nearly all lakes in Wisconsin where sediment cores have been analyzed (Garrison, 2000a,b; Garrison, 2003, Garrison and Wakeman, 2000). It appears that the littoral zone responds very early to the increased input of nutrients from the watershed. The plant community remained at elevated levels compared with pre-settlement times until the 1950s when they declined and remained depressed until recent times. The decline in macrophytes coincide with the use of sodium arsenite for macrophyte control.

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.

The diatom community was used to estimate changes in the summer phosphorus levels throughout the core. Historical P levels were low, being about 13-15 µg L^{-1} (Figure 12). The P levels increased slightly starting in 1930 but increased significantly after 1960. Peak P levels occurred around 1970 through the early 1980s. During the last two decades the P levels have significantly declined and the diatom community estimates a summer phosphorus level of about 21-22 µg L^{-1} (Figure 12). This is somewhat higher than the measured values; 11-13 µg L^{-1} in recent years. The error in estimating the P concentration is not uncommon and should not negate the P trends indicated by the model. While this level is about one half the peak concentration of 50 µg L^{-1}, it is still higher than pre-settlement levels. The increase in P

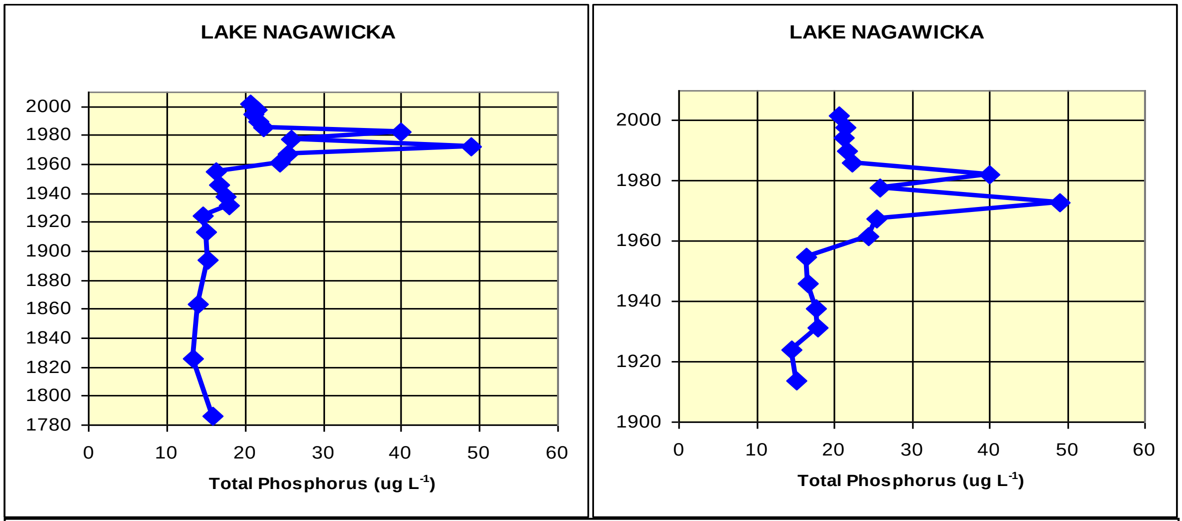

Figure 12. Estimated summer phosphorus concentrations based upon the diatom community. The figure on the right covers the time period 1900 to 2003.

around 1930 coincides with an increase in the sedimentation rate as well as increased urban runoff (zinc, Figure 8). The peak P levels during the period 1970-80, occurred following a decline in soil erosion (titanium, Figure 8) and urban runoff had stabilized. Prior to 1980 The Hartland sewage treatment plant discharged into the Bark River above the lake. With the diversion of this discharge to a point downstream of Lake Nagawicka, the phosphorus levels in the lake declined within five years to the present concentration. Such a large reduction in P was observed in Geneva Lake following the removal of sewage discharge into the lake (Garrison, 2000b).

Summary

- The past use of copper sulfate for algal control and sodium arsenite for weed control was evident in the core.
- The mean sedimentation rate was higher than many other lakes in Wisconsin. This is partly the result of the sediment brought in by the Bark River but is also because it is a marl lake.
- The lake's sedimentation rate first began to increase around 1910. Sedimentation has continued to increase with the highest rates occurring during the last two decades. The increased sedimentation rate is largely the result of calcium carbonate deposition.
- The peak input of soil occurred during the 1940s. This was likely because of agricultural activities in the watershed. As agricultural practices improved and the landuse became urbanized, soil delivery declined. The rate has begun to increase again during the last decade.
- Urban runoff significantly increased around 1920. Although soil erosion declined after 1950, urban runoff has remained high.
- The oxygen levels of the lake began to decline around 1910 and reached present levels around 1930. The decline in oxygen levels was in response to increased productivity in the lake because of agricultural activities and urban runoff. Even though agriculture has declined, urbanization of the watershed has maintained the low oxygen levels in the bottom waters.
- Phosphorus concentrations in the lake during the 1800s were about 13-15 µg L^{-1}. The diatom community estimates the current levels at 21-22 µg L^{-1}.
- In response to agricultural activities and urbanization, summer phosphorus levels first increased during the 1930s. Phosphorus levels increased much more around 1960 and peak concentrations occurred during the 1970s and early 1980s. When the discharge from the Hartford sewage treatment plant was moved to below the lake, P levels declined to about one half of peak levels.
- Prior to the arrival of European settlers in the early 1800s, Nagawicka Lakeexperienced clear water and a moderate aquatic plant community. With the increase in agriculture and urbanization during the first half of the twentieth century, phosphorus levels increased resulting in a decline in water clarity and decreased oxygen levels in the bottom waters. Although the delivery of soil from the watershed was reduced after 1950, nutrients from urban runoff continued at elevated rates. The greatest increase in P levels were the result of the Hartford sewage treatment plant. With the removal of the discharge from this plant, summer P levels were reduced by about one half. Oxygen levels remain depleted in the bottom waters and the macrophyte community maintains a moderate level.
- Although the lake has a relatively large watershed, it is somewhat protected from P input because of the high amount of calcium carbonate ($CaCO_3$) naturally found in the lake. The high rate of $CaCO_3$ deposition at the present time indicates the elevated productivity of the lake and natural buffering of $CaCO_3$.

References

Anderson, N.J., B. Rippey, and C.E. Gibson, 1993. A comparison of sedimentary and diatom-inferred phosphorus profiles: implications for defining pre-disturbance nutrient conditions. Hydrobiol. 253:357-366.

Anderson, N.J., B. Rippey, & A.C. Stevenson, 1990. Diatom assemblage changes in a eutrophic lake following point source nutrient re-direction: a palaeolimnological approach. Freshwat. Biol. 23:205-217.

Appleby, P.G., & F. Oldfield, 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena. 5:1-8.

Bennion, H., 1994. A diatom-phosphorus transfer function for shallow, eutrophic ponds in southeast England. Hydrobiol. 275/276: 391-410.

Bennion, H., 1995. Surface-sediment diatom assemblages in shallow, artificial, enriched ponds, and implications for reconstructing trophic status. Diatom Res. 10:1-19.

Birks, H.J.B., J.M. Line, S. Juggins, A.C. Stevenson, & C.J.F. ter Braak, 1990. Diatoms and pH reconstruction. Phil. Trans. R. Soc., Lond., series B 327:263-278.

Bradbury, J.P., 1975. Diatom stratigraphy and human settlement in Minnesota. Geol. Soc. America Spec. Paper. 171:1-74.

Carney, H.J., 1982. Algal dynamics and trophic interactions in the recent history of Frains Lake, Michigan. Ecology. 63:1814-1826.

Christie, C.E. & J.P. Smol, 1993. Limnological effects of 19th century canal construction and other disturbances on the trophic state history of Upper Rideau Lake, Ontario. Lake and Reserv. Manage. 12:448-454.

Engstrom, D.R., E.B. Swain, & J.C. Kingston, 1985. A paleolimnological record of human disturbance from Harvey's Lake, Vermont: geochemistry, pigments, and diatoms. Freshwat. Biol. 15:261-288.

Engstrom, D.R., and H.E. Wright, Jr., 1984. Chemical stratigraphy of lake sediments as a record of environmental change. In E.Y. Haworth, and J.W.G. Lund (eds.) Lake sediments and Environmental History. U. of Minnesota Press. Minneapolis. 11-68.

Fitzpatrick, F.A., P.J. Garrison, S.A. Fitzgerald, and J.F. Elder, 2003. Nutrient, trace-element, and ecological history of Musky Bay, Lac Courte Oreilles, Wisconsin, as inferred from sediment cores. U.S. Geological Survey Water-Resources Investigation Report 02-4225. 141p.

Ennis, G. L., G. Northcote, & J.G. Stockner, 1983. Recent trophic changes in Kootenay Lake, British Columbia as recorded by fossil diatoms. Can. J. Bot. 61:1983-1992.

Fritz, S.C., J.C. Kingston, and D.R. Engstrom. 1993. Quantitative trophic reconstruction from sedimentary diatom assemblages: a cautionary tale. Freshwat. Biol. 30:1-23.

Garrison, P.J. 2000a. Paleoecological Study of Beulah Lake, Walworth County. Wisconsin Department of Natural Resources. PUB-SS-950 2000. 18p.

Garrison, P.J. 2000b. Paleoecological Study of Geneva Lake, Walworth County. Wisconsin Department of Natural Resources. PUB-SS-952 2000. 25p.

Garrison, P.J. 2003. Paleoecological Study of Big Cedar Lake, Washington County. Wisconsin Department of Natural Resources. PUB-SS-984 2003. 15p.

Garrison, P.J. & R.S. Wakeman. 2000. Use of paleolimnology to document the effect of lake shoreland development on water quality. J. Paleolimn. 24:369-393.

Hall, R.I. and J.P. Smol, 1992. A weighted-averaging regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes. Freshwater Biol. 27:417-434.

Krishnaswami, S. & D. Lal. 1978. Radionuclide limnochronology. In: Lerman, A. (ed.), Lakes: Chemistry, Geology, Physics. Springer-Verlag, NY: 153-177.

Lueschow, L.A. 1972. Biology and Control of Selected Aquatic Nuisances in Recreational Waters. Technical Bulletin No. 57. WI. Dept. of Natural Resources. pp36.

Otsuki, A. and R.G. Wetzel. 1972. Coprecipitation of phosphate with carbonates in a marl lake. Limnol. Oceanogr. 17:763-767.

Reavie, E.D. and J.P. Smol. 1997. Diatom-based model to infer past littoral habitat characteristics in the St. Lawrence River. J. Great Lakes Res. 23:339-348.

Schelske C.L., Robbins J.A., Gardner W.S., Conley D.J., and Bourbonniere R.A. 1988. Sediment record of biogeochemical response to anthropogenic perturbations of nutrient cycles in Lake Ontario. Can. J. of Fish. and Aquat. Sci. 45(7):1291-1303.

SEWRPC. 1999. A Lake and Watershed Inventory for Nagawicka Lake Wauksha County, Wisconsin. Southeastern Wisconsin Regional Planning Commission. Memorandum Report No. 130. Waukesha County. 117p.

Stager, J.C., P.R. Leavitt, & S.S. Dixit, 1997. Assessing impacts of past human activity on the water quality of Upper Saranac Lake, New York. Lake and Reserv. Manage. 13:175-184.

GLOSSARY

Diatoms – Type of algae that possesses shells made of silica. This allows them to remain in the sediments for many years. Many diatoms live under unique environmental conditions including varying nutrient levels.

Managanese – A chemical that is found in elevated levels in the bottom waters of a lake when oxygen is absent. Changes in its levels in the sediment core indicate past oxygen levels in the lake's bottom waters.

Marl – A type of sediment made of calcium carbonate that is deposited in hardwater lakes found in central and southern Wisconsin. Its color is often light gray.

Nitrogen - A major nutrient responsible for plant fertilization. While it is often not as important as phosphorus for plant growth, when present in excessive levels can help cause algal blooms

Paleoecology – The study of a lake's history using fossils preserved in the sediments.

Phosphorus – A major nutrient responsible for plant fertilization. It is usually the nutrient that causes excessive algal growth.

Sediment dating – The use of scientific techniques to determine the age of a sediment slice.

Sedimentation rate – The rate at which sediment is deposited at the bottom of the lake.

Titanium – A chemical that is generally found only in soils. Changes in its deposition is an indication of the watershed.

Zinc – The most common heavy metal present in runoff from urban sites. Changes in its deposition is an indication of past urban development.

Funding for this project was provided by the the City of Delafield and the Wisconsin Department of Natural Resources. Heidi Bunk and Phil Schuman assisted with collection of the sediment cores. Radiochemical analysis was provided by the Lynn West at the Wisconsin Laboratory of Hygiene. Geochemical analyses was provided by University of Wisconsin, Soil Testing Laboratory.