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 Geneva Lake since European settlement. This was done by examining cores from three locations in the lake. One location was the deepest area of the lake. This core represents changes in the water quality of the main body of the lake. The other sites were at Geneva and Williams bays. These sites assess the impact of development on the shores of these bays. The major interest of this study was changes in nutrient levels within the lake and the likely sources of these 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). Prior to the arrival of Europeans, about 500 Native Americans of the Potawatomie Tribe of which Chief Big Foot was their leader inhabited the Geneva lakeshore. There were three major settlements, on the west end of the lake, on the west shore of Williams Bay and at the present site of the city of Lake Geneva. They called the lake "Kish-wauketo" which means clear water. John Brink who named the water Geneva Lake since he was from Seneca Lake, Geneva, New York, surveyed the area around the lake. Christopher Payne built the first cabin on the lake in 1836 near the outlet of the lake. He established a mill on the outlet by building a dam which raised the water level 6 feet (Jenkins, 1922). The village of Lake Geneva was platted in 1844 and in 1847 the population was 1238. By 1856 the population had increased to 1500 and it was 1700 in 1870. The village became a city in 1886 and the population was 2300. The population increased slowly and by 1920 it was 2600. The lake was very attractive to tourists from

Chicago. After the Chicago & North Western Railway Company completed a railway to the City of Lake Geneva in 1871, the area experienced a large influx of visitors. The railway was extended to Williams Bay in 1888. The size of the lake and the wealthy class of people who established summer homes around the lake resulted in extensive use of steamboats on the lake. The first steamboat arrived on the lake in 1858. Many resorts and large homes were built on the lakeshore. The first lakeshore estate, "Maple Lawn" was built on Geneva Bay in 1870. This development resulted in limited agriculture around Geneva Bay.

In 1837 the first European, Captain Israel Williams, settled on the shore of Williams Bay. The Native Americans called the bay "Ke-nago-mak-nebis" which means eel water. Apparently eels inhabited the shallow waters of the bay (Fogle, 1986). Williams Bay was known as Geneva Bay until the 1890's when the name was changed. By 1880 there were few homes on the bay but many were built between 1880 and 1910. The village was platted in 1897 and construction of the Yerkes Observatory was started in 1895 and it opened two years later. Many summer camps were established around the bay beginning in 1886 and some are still operating.

At the time of settlement, the land around Geneva Lake was largely oak savanna with the exception of the northeast side of the lake which was maple/basswood forest (Finley, 1976). With the arrival of settlers, much of the land was converted from prairie to subsistence type farming. In fact the first plowing occurred on Big Foote Prairie when 500 acres were turned over in 1837. 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 (Langill & Loerke, 1984).

Methods

Sediment coring

Cores were collected from Geneva Lake on 22 October 1995 using a gravity corer with a 6.5-cm plastic liner. Cores were extracted from the deepest area of the lake in about 40 meters of water, at the mouth of Williams Bay in 29 meters of water, in Geneva Bay in 14 meters of water, and off Big Foot Beach State Park in 7.5 meters of water (Figure 1). An attempt was made to extract a core from the narrows in 27 meters of water. The substrate was largely cobble and gravel and a core was not retrieved. Apparently this area experiences significant deep-water currents and is not a depositional zone despite its water depth. Cores were stored upright with a stopper in the bottom until returned to the laboratory. In the laboratory, cores were hydraulically pushed up from the bottom and sectioned into 1 cm slices in the Deep Hole core. The other three cores were sliced into 1 cm intervals for the top 10 cms and the

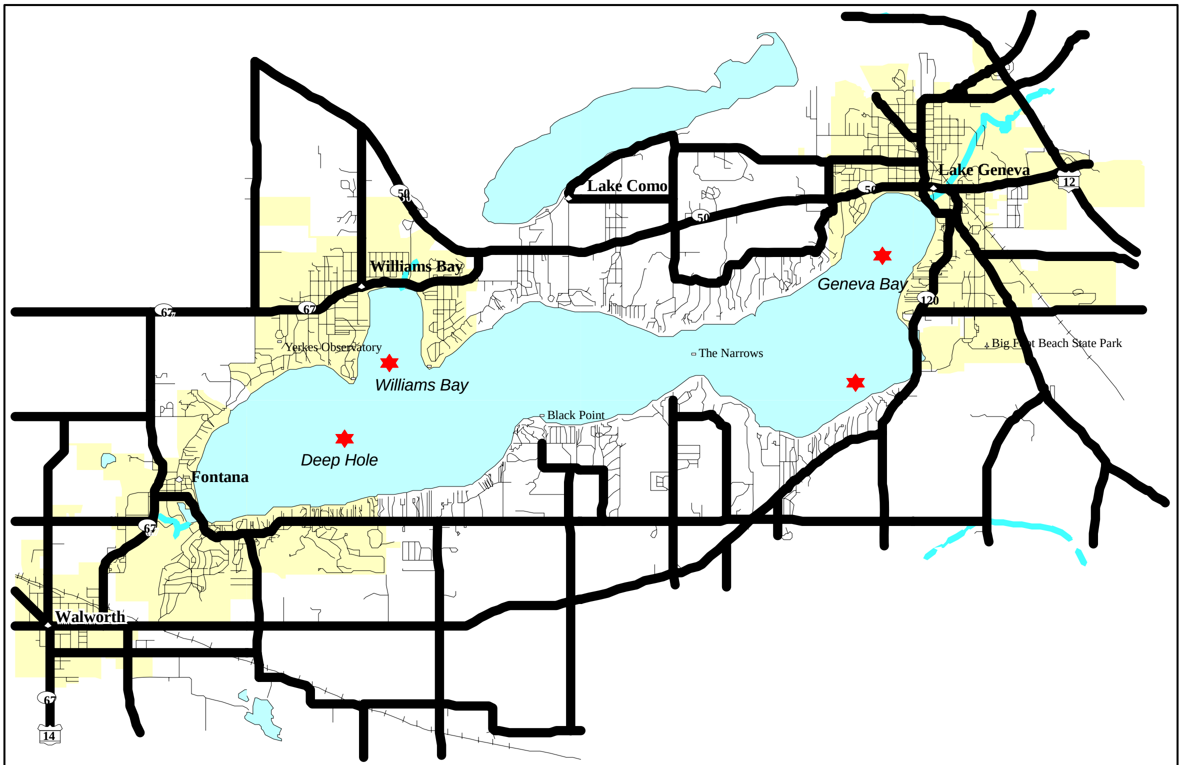

Figure 1. Map of Geneva Lake showing coring sites.

remainder of the cores were sliced into 2 cm sections. No further work was done with the core taken near the Big Foot Beach State Park. The core from the deep hole was 45 cm long, the core from Williams Bay was 52 cm long, and the core from Geneva Bay was 40 cm in length. Samples were placed into clean, labeled plastic bags and stored in a freezer analyzed.

Sediment dating

Samples were freeze dried for one week prior to radiometric analyses. All depths in the cores from Williams and Geneva bays from the surface to 22 cm were analyzed to determine age and sediment accumulation rates. All but 2 depths (13-14, 19-20 cm) in the top 22 cm were analyzed from the Deep Hole core. Isotopic activities (^{210}Pb, ^{226}Ra, and ^{137}Cs) were measured by direct gamma counting (Schelske et al., 1994). The cores were analyzed at the radiochemistry laboratory of 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).

Physical and chemical analyses

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 (Dean, 1974). 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 Wisconsin State Laboratory of Hygiene performed geochemical analyses. Eighteen depths in cores from Williams and Geneva bays and 24 depths in the Deep Hole core were analyzed. Total aluminum, calcium, potassium, iron, manganese, titanium, copper, zinc, and arsenic were analyzed using ICP-MS procedures following digestion of the sediment with $KClO_4$ (Wisconsin State Laboratory of Hygiene, 1993). Sediment samples for phosphorus and nitrogen analyses were digested with sulfuric acid as well as $CuSO_4$ and K_2SO_4 and the digestate measured using a technicon autoanalyzer. All of these parameters were analyzed from the Deep Hole core except titanium. The other 2 cores were analyzed for Al, As, Ti, Zn, N, and P. More variables were analyzed in the Deep Hole core than in the cores from the bays. This was because of different funding sources for these cores. In the Deep Hole core, additional variables included iron and manganese, which can give an indication of changes in dissolved oxygen in the deep water. It was thought that this would not be a concern in the shallower bay sites.

Sediment enrichment factors (SEF) were calculated as

$$SEF = (C_h - C_s / C_s)$$

Where C_h is the pre-settlement concentration and C_s is the concentration at the sediment surface.

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 either Hyrax® or Naphrax®. Specimens were identified and counted under oil immersion objective (1400X) until at least 250 frustules were examined in the Deep Hole core and at least 150 frustules in the other cores. Common nationally and internationally recognized keys were used including Patrick & Reimer (1966, 1975), Dodd (1987), and Krammer & Lange-Bertalot (1986, 1988, 1991a,b).

Results

Sediment dating

The mean annual ^{210}Pb fluxes were between 0.40 and 0.50 pCi cm^{2} yr^{-1} for all three cores (Table 1). These are within the usually cited global range for atmospheric flux of 0.2 to 1.1 pCi cm^{-2} yr^{-1} (Krishnaswamy & Lal, 1978). This means that little sediment focusing is occurring at any of these sites. There may be a slight amount of sediment focusing in the deep hole as the flux was the highest at this site and unsupported ^{210}Pb at the surface was highest.

Table 1. Lead-210 parameters and sediment accumulation rates for cores from Geneva Lake.

	Cumulative Unsupported ^{210}Pb (pCi cm^{-2})	Unsupported ^{210}Pb at surface (pCi g^{-1})	Mean Sedimentation rate (g cm^{-2} yr^{-1})	Mean ^{210}Pb flux (pCi cm^{-2} yr^{-1})
Deep Hole	15.90	12.86	0.032	0.50
Williams Bay	13.66	5.01	0.042	0.43
Geneva Bay	14.89	9.38	0.041	0.46

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 attached to 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 following its deposition for about 130-150 years. This makes ^{210}Pb a good choice to determine the age of the sediment since European settlement which 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 accumulation 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 variables that are known to have been deposited during a specific time span.

Cesium-137 (^{137}Cs) can be used to identify the period of maximum atmospheric nuclear testing (Krishnaswami and Lal, 1978). The most production of ^{137}Cs occurred in 1963 during testing by USSR and thus the ^{137}Cs peak in the sediment core should represent a date of 1963. Figure 2 shows the peak concentrations of ^{137}Cs. In the cores from the Deep Hole and Williams Bay the ^{137}Cs peak occurs at depth that is one depth shallower than it should be. In the Geneva Bay core, the cesium peak is at a depth bracketed by the ^{210}Pb dates of 1956 and 1964.

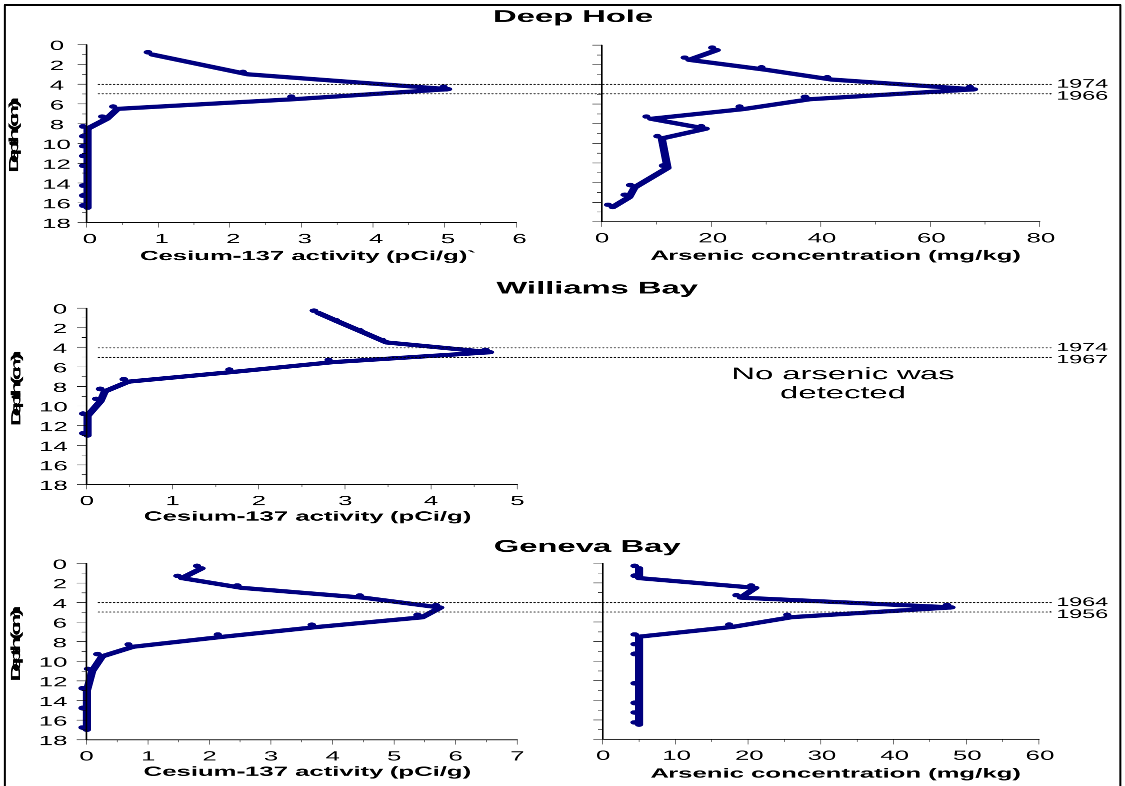

Figure 2. Profiles of cesium-137 and arsenic. Cesium-137 is a byproduct of atmospheric nuclear testing while arsenic was used for aquatic plant control in the 1950-60's. The peak deposition of these elements was 1963 for cesium and 1962-65 for arsenic.

Another sediment marker that can be used in Geneva 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 Geneva Lake was 1962-65 (Lueschow, 1972). Therefore, the peak arsenic concentration should indicate the mid-1960's. In the cores from the Deep Hole and Geneva Bay, the peak arsenic concentrations occurred at the same depths as the cesium-137 peak (Figure 2). Arsenic was undetectable in the core from Williams Bay. This likely means that little or no sodium arsenite was applied in this bay. The sharp peaks of both the arsenic and cesium profiles indicate that there has been little post-depositional movement of sediment. Even though the dating is not perfect for the cores from the Deep Hole and Williams

Bay, they should not be in error by more than 5 years for the last 50 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 rates for the portion of the cores that could be dated (150-185 years) were similar in the cores from the sites in Williams Bay and Geneva Bay, 0.042 and 0.041 g cm^{-2} yr^{-1} respectively. The rate in the Deep Hole was less at 0.032 g cm^{-2} yr^{-1} (Table 1). The higher rates in the bays are most likely because these sites are located closer to areas that would contribute sediment from the watershed. It is to be expected that much of this material be deposited in the lake before it reaches deepest part of the lake. The mean sedimentation rates from cores taken in the bays are near the average for other southern Wisconsin lakes (Figure 3). The mean sedimentation rate for the Deep Hole is at the lower end of sedimentation rates for other southern Wisconsin lakes. This reflects the relatively low ratio of watershed area to lake area of 2.4.

The sedimentation rate for the Deep Hole has changed little for the last 170 years (Figure 4). The highest rates occurred around 1920 and 1940. These rates are only slightly higher than pre-settlement rates. The current sedimentation rate is very similar to historical rates. This indicates that in the main body of the lake the sediment infilling at the present time has not increased from pre-settlement rates.

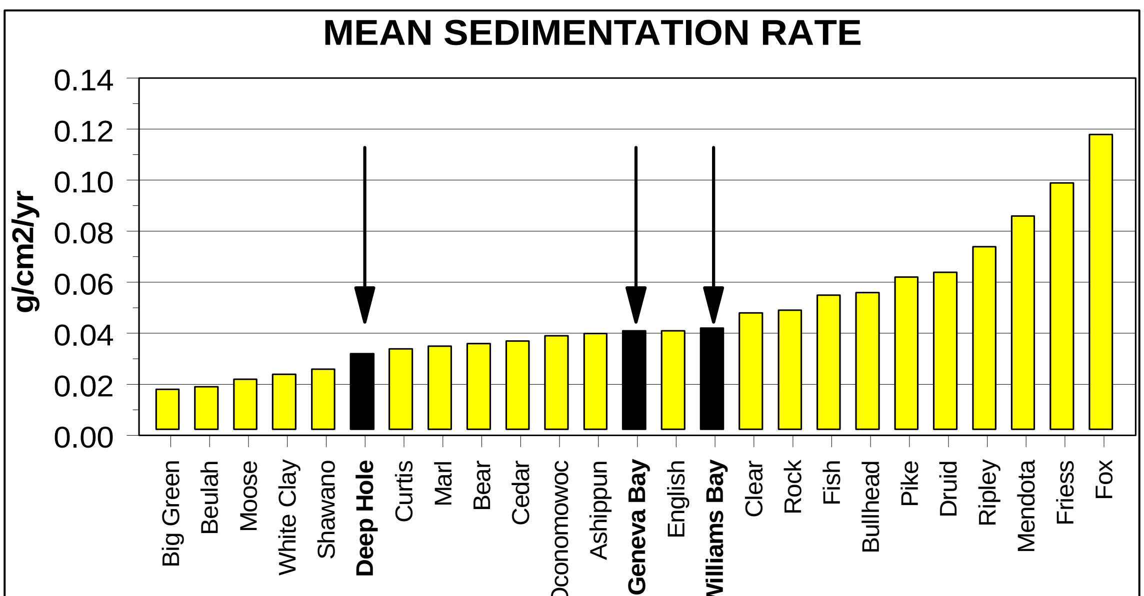

Figure 3. Mean sedimentation rate for some Wisconsin hardwater lakes. The arrows indicate the cores from this study.

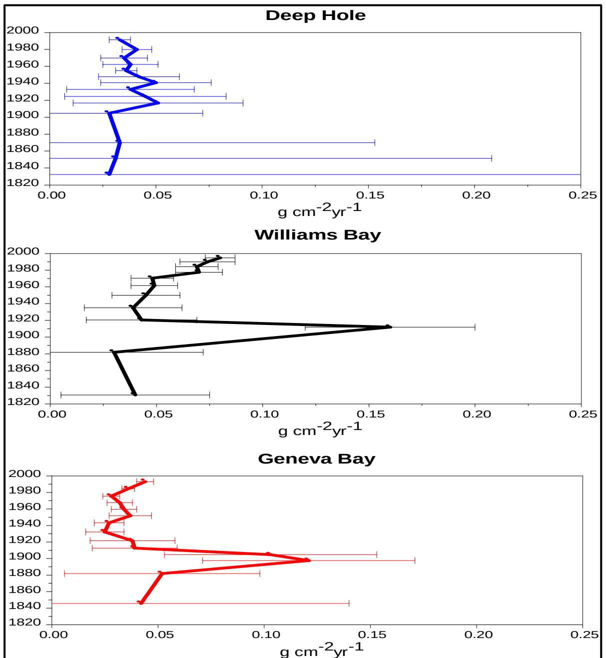

Figure 4. Sedimentation rates for the 3 core sites.

Compared with the Deep Hole, the sedimentation rates in Geneva and Williams bays have been much more variable over the last 170 years. The peak rate in both bays occurred around 1900 (Figure 4). This likely reflects early construction of the towns of Lake Geneva and Williams Bay. During the construction it is likely that considerable sediment was washed into these bays. The high sedimentation rates in these bays did not occur in the deep hole. This indicates that much of this sediment from construction was deposited soon after it entered the lake. Following the construction, the sedimentation rate returned to historical levels. Even though the sedimentation rate in Geneva Bay appears in Figure 4 to be less than the historical rate, this likely is the result of high error associated with the historical rate. Because lead-210 concentrations are difficult to measure at the very low historical levels, it is likely the sedimentation rates historically and most of the twentieth century are similar. In Geneva Bay the sedimentation rate appears to increase slightly during the last decade. The increase is greater in Williams Bay with rate increasing in 1970 from 0.048 g cm^{-2} yr^{-1} to 0.080 g cm^{-2} yr^{-1} in the mid 1990's. This may indicate that increased development in Williams Bay has caused an increased infilling rate in this bay.

Geochemistry

The geochemical profiles can be used to understand watershed processes that have affected the lake's water quality. A summary of processes that can be inferred from changes in geochemical elements can be found in Table 2. For example, since titanium and aluminum are derived from clay particles in the soil, an increase in their concentration is an indication in soil

Table 2. Selected chemical indicators of watershed or inlake processes.

Process	Chemical Variable
Soil erosion	aluminum, titantium, iron
Urban	zinc, copper
Anoxia	manganese
Nutrients	phosphorus, nitrogen

erosion. 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). Other variables also can give an indication of changes of nutrients within the lake as well as an indication of the change in algal productivity in the lake. In a hardwater lake like Geneva 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. That is why the predominant color of the sediment is gray.

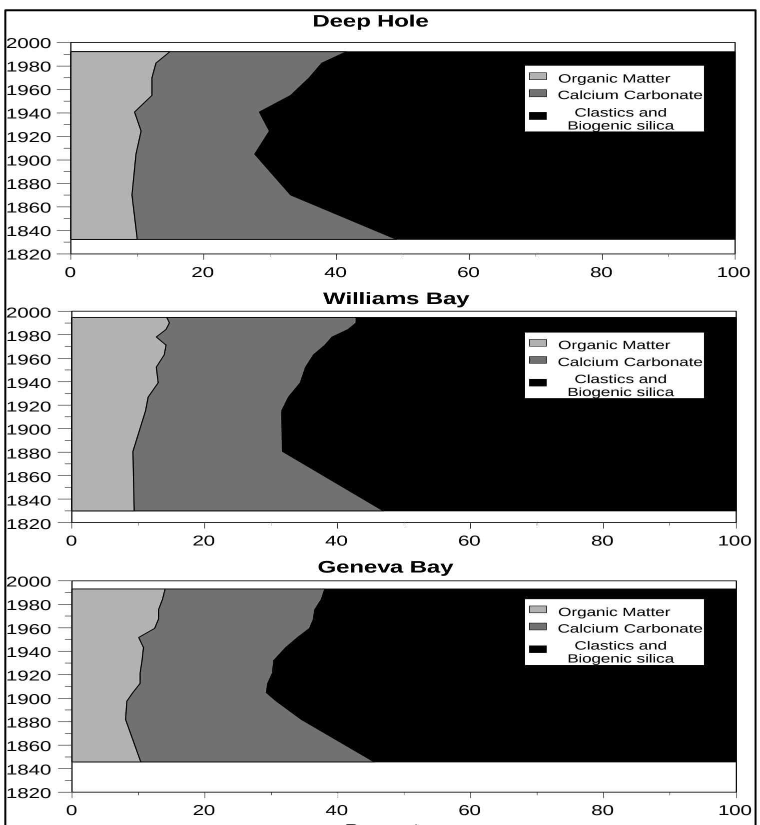

Figure 5. Profiles of organic matter, calcium carbonate, and clastic materials + biogenic silica.

In the cores from all three sites there was a dramatic decline in calcium carbonate and increase in clastic materials and biogenic silica around the mid-1800's (Figure 5). As the surrounding prairie was plowed during early European settlement, soil erosion increased bringing increased amounts of clastic materials into the lake. This increased erosion diluted the $CaCO_3$ in the sediments. This decline of $CaCO_3$ during initial settlement has been found in other southern Wisconsin lakes (Garrison and Wakeman, 2000) as well as other hardwater lakes (Engstrom et al., 1985). During the twentieth century, it appears that soil erosion declined, as there was a reduction in clastic material in cores from all three sites and an increase in organic matter and calcium carbonate.

Deep Hole

In the Deep Hole, materials derived from soil erosion such as aluminum (Al), iron (Fe), and potassium (K) increase soon after 1850 (Figure 6). This likely is the result of the initial plowing of the prairie following the arrival of European settlers. The concentrations of these variables remained high and peaked around 1940. Aluminum and to a lesser extent, potassium declined and concentrations currently are at levels higher than pre-settlement levels but less than concentrations found during the early part of the twentieth century. The sediment enrichment factor (SEF) for Al and K was about 1, which indicates a doubling of the concentration in the recent sediments compared with pre-settlement levels. In contrast,

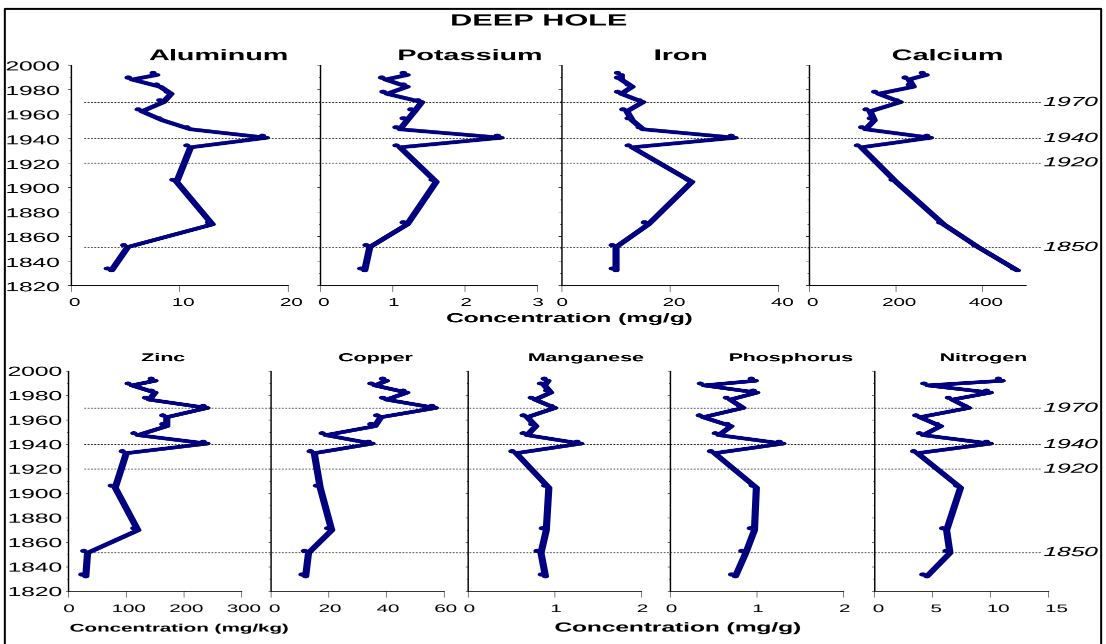

Figure 6. Profiles of selected chemical variables in the Deep Hole Core. Table 2 lists the processes that each element reflects.

calcium concentrations declined during the nineteenth century. The majority of the calcium is derived from within the lake as a consequence of calcium carbonate precipitation as was discussed previously. Since 1980 calcium has increased, probably indicating a small increase in calcium carbonate precipitation as a result of increased algal productivity.

Table 3. Selected sediment enrichment factors from the Geneva Lake cores. A SEF of 1 means the surface concentration is double the pre-settlement concentration.

Variable	Deep Hole	Williams Bay	Geneva Bay
Aluminum (soil erosion)	1.1	4.1	4.6
Titanium (soil erosion)		4.6	5.0
Zinc (urban)	4.0	10.6	9.9
Copper (urban)	2.2		
Nitrogen (nutrient)	1.4	2.4	1.8
Phosphorus (nutrient	0.3	1.7	1.8
Manganese (anoxia)	0.03		

Zinc and copper concentrations initially increased around 1870 but increased further around 1940 (Figure 6). Zinc remained high until 1970 and is present in lower concentrations the last 30 years. Copper levels increased from 1-40-70 and remain elevated at the present time. The increased concentration of zinc since the 1930's is likely an indication of the urbanization of the watershed.

As the bottom waters become increasing devoid of oxygen, manganese 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 Geneva Lake. Although manganese concentrations peaked like the other variables around 1940, the levels generally are unchanged throughout the core. In fact the SEF is 0.03 which means there has been no change in the surface concentration, compared with the concentration in the early 1800's. This indicates that oxygen levels in the bottom waters have not changed much in the last 170 years. This does not mean that oxygen levels have not declined higher up in the water column. It would not be unusual for oxygen levels to decline in the upper part of the hypolimnion with moderate increases in algal productivity without the deep waters being affected. However, if algal levels remain elevated or increase eventually oxygen levels will decline throughout the hypolimnion. The SEWRPC report (1985) indicates a short-lived period of anoxia during the fall of 1976. Changes in manganese in the core likely would not be sensitive enough to detect this amount of change.

Nutrients of concern in most lakes are phosphorus and nitrogen. Although phosphorus is the nutrient of most concern, nitrogen can also be important. Phosphorus levels in the Deep Hole core have remained largely unchanged throughout the last 170 years (Figure 6). The SEF is 0.3 reflecting a similar concentration at the top of the core compared with pre-settlement levels. This is not true for nitrogen. Nitrogen levels have nearly since 1970. This is also illustrated by the increase in the SEF of 1.4 (Table 3).

In order to understand what the significant sources of phosphorus are to the lake, chemical ratios were examined. The ratio of aluminum or titanium to phosphorus (Al:P, 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.

In the Deep Hole, between the period of the mid-1800's until the 1940 soil erosion was an important source of phosphorus as the Al:P was at its highest (Figure 8). However, for the last 5 decades, this ratio declined indicating soil erosion was less important as a source of phosphorus. The Zn:P ratio steadily increased from the mid-1800's until it peaked around 1960 indicating that urban runoff was an increasingly important contributor as a phosphorus source to the lake. Although the ratio declined after 1940, it still remains much higher than pre-settlement levels. In the Deep Hole, at the top of the core it appears that both soil and urban runoff are still important sources of phosphorus although soil erosion is less important than urban runoff.

Williams Bay

In the Williams Bay core, there was a moderate increase in the soil erosional variables aluminum and titantium around 1880, which are indicative of soil erosion (Figure 7). Concentrations of these variables have remained moderately higher compared with pre-settlement levels. Since 1970, titantium has increased further with the peak concentration occurring at the top of the core. The SEF for Al and Ti is over 4 indicating a five-fold increase in soil erosion. Zinc, which is indicative of urban runoff, has generally increased throughout the core. The peak levels also occur at the top of the core as does aluminum and titantium. This indicates that the source of the soil erosion is likely sites associated with urban construction. Both nitrogen and phosphorus levels increased throughout the core. Levels of both nutrients have significantly increased since 1970. The source of these nutrients is likely urban runoff since zinc levels also are elevated in the last 30 years.

In Williams Bay, the Ti:P ratio generally declined from 1880 until the top segment of the core (Figure 8). This indicates that soil erosion was a decreasing source of phosphorus at this site.

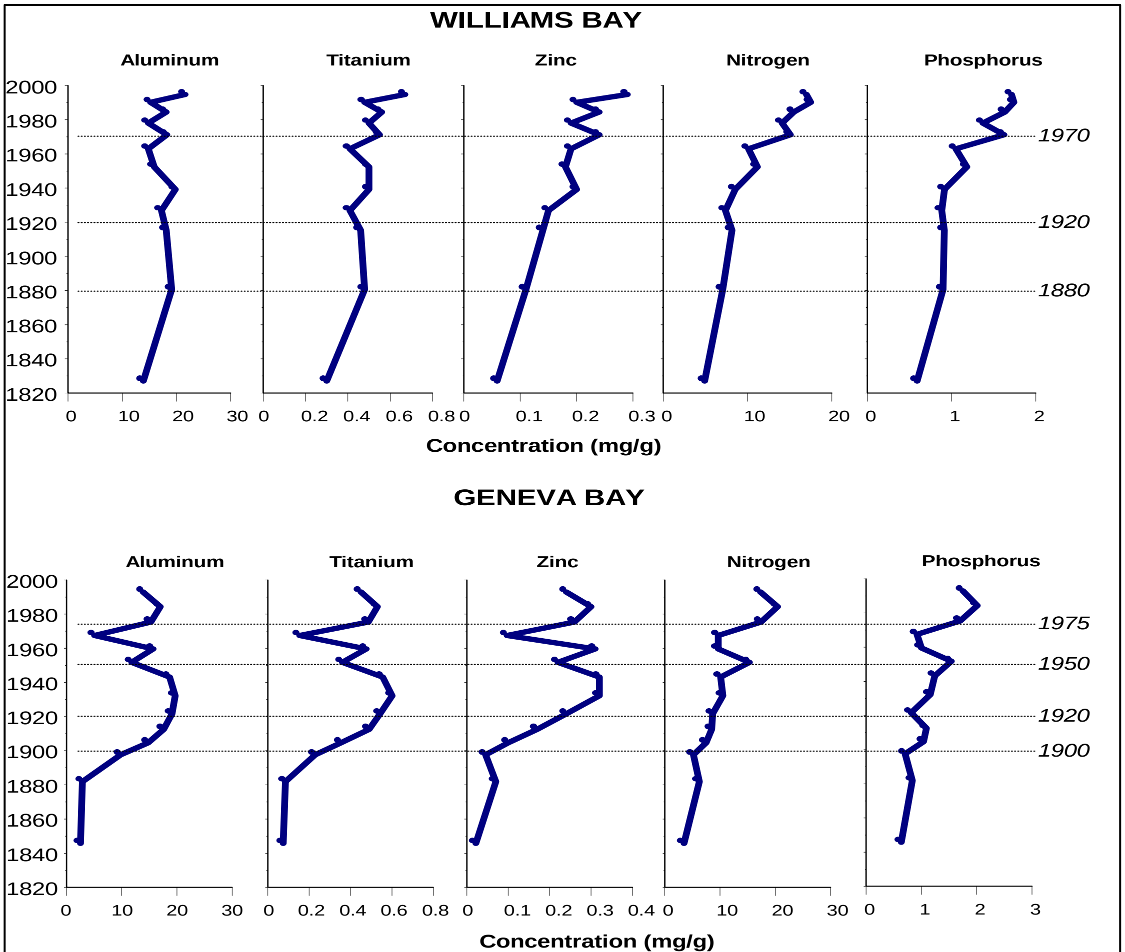

Figure 7. Profiles of selected chemical variables in the cores from the bays. In Williams Bay, the greatest increases have occurred during the last 30 years. In contrast, in Geneva Bay, the highest levels occurred during the period 1920-40. In both bays, the greatest increase in nutrients has occurred during the last 25-30 years.

In contrast, the Zn:P ratio increased after 1880 and remained elevated until the present time. This is further evidence of the importance of urban runoff as a phosphorus source in this bay.

Geneva Bay

In Geneva Bay, the increase in soil erosion during the last 160 years was greater than at the other 2 core sites. Both aluminum and titantium increased by a sediment enrichment factor of 4.6-5.0 (Figure 7, Table 3). In contrast to the cores from the Deep Hole and Williams Bay, in Geneva Bay there was little increase in soil erosion during the 1800's. This likely implies that there was limited agriculture around the bay. However, starting around 1900, with the intensification of development following the arrival of the railway, the development of resorts, estates, and urbanization, there was a significant impact on Geneva Bay. Both soil erosional

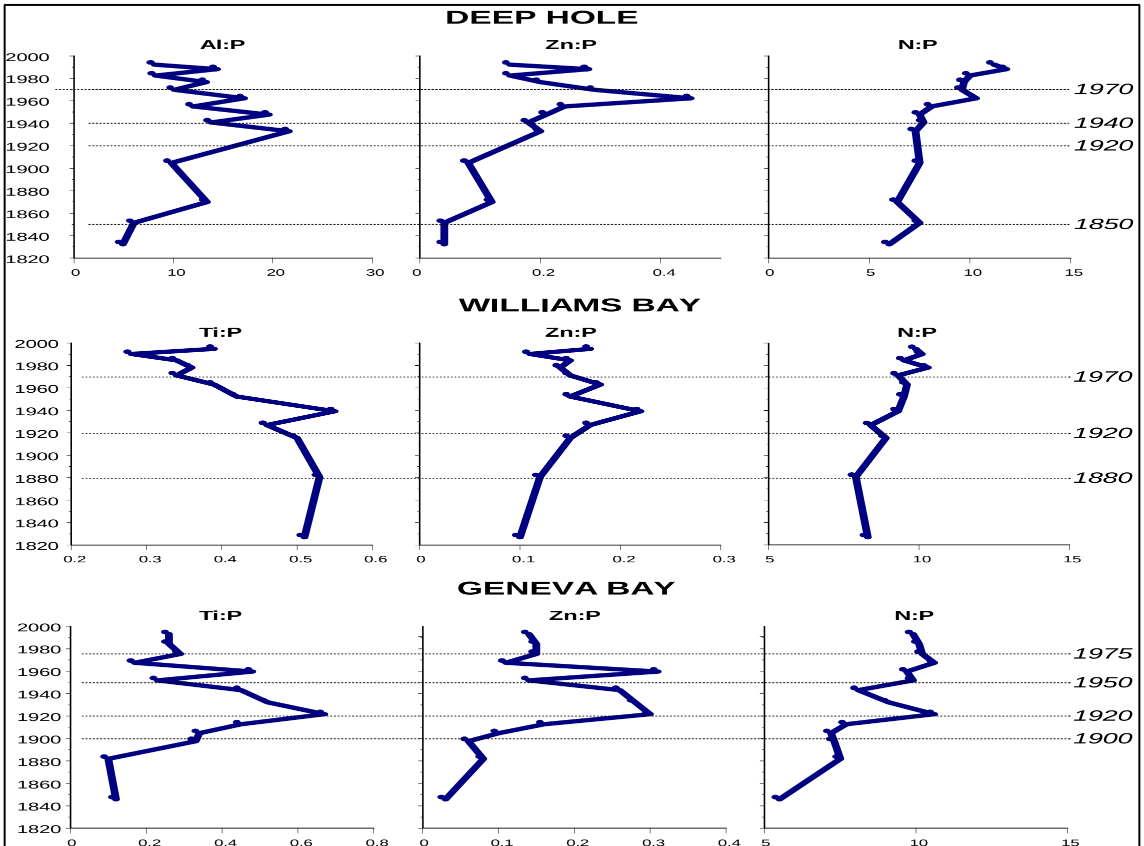

Figure 8. Profiles of ratios of selected chemical variables. These ratios indicate the importance of soil erosion (Al, Ti) and urban runoff (Zn) as sources of phosphorus.

factors significantly increased and peaked around 1930. Zinc concentrations also increased after 1900, reflecting the impact of urbanization. The peak concentrations of the erosional elements (Al, Ti) occurred from the period 1920-1945. Concentrations of these elements declined from 1945 until about 1970. However, since 1975 these levels have again increased. A similar trend occurred with zinc although the decline between 1945-1970 was not quite as great. As with Williams Bay, nutrients steadily increased throughout the core, with the highest concentrations occurring near the top of the core. Both of the nutrients have shown significant increases since 1975 and the SEF is nearly 2 reflecting a tripling of nutrient levels since the early 1800's. It appears that both Geneva and Williams bays have experienced a significant increase in nutrient deposition in the last 25-30 years as a result of urban runoff.

In Geneva Bay, soil erosion was a more important source of phosphorus compared with Williams Bay. The Ti:P ratio increased from 1900 until it peaked around 1920 (Figure 8). The ratio has generally declined for the last 80 years but the ratio remains higher than the pre-settlement level. The ratio of Zn:P increased significantly from 1900 until 1920. It remained elevated until 1960 and has declined somewhat since then. Like Williams Bay, urban runoff remains an important source of phosphorus in Geneva Bay. In contrast to Williams Bay, it appears that soil is a more important source of phosphorus in Geneva Bay.

The cores from both of the bays indicate the importance of urban runoff as a source of phosphorus. This is not surprising given the urban development on the shores of both of these bays. The core from the Deep Hole is indicative of the impact of the entire watershed on the lake not just localized sources. It appears that both urban runoff and soil are important sources of phosphorus. In the main lake basin urban runoff was the greatest source of phosphorus during the 1960's. Although its importance has declined somewhat since then, it still remains an important source of phosphorus.

The ratio of nitrogen to phosphorus steadily increased at all three core sites. This is especially true since the 1960's in the Deep Hole site. This means that while both phosphorus and nitrogen levels have increased during the last 170 years (see SEF in Table 3), there has been a preferential increase in nitrogen.

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 9 shows photographs of two diatom species that were common in the sediment cores.

Deep Hole

The diatoms *Cyclotella sp. 1* and cf. *Cyclostephanos dubius* (Fricke) Round (pictured in Figure 9) dominated the bottom of the core (Figure 10). *Cyclotella sp. 1* has been found in a number of lakes in southern Wisconsin prior to and only soon after European settlement (Garrison,

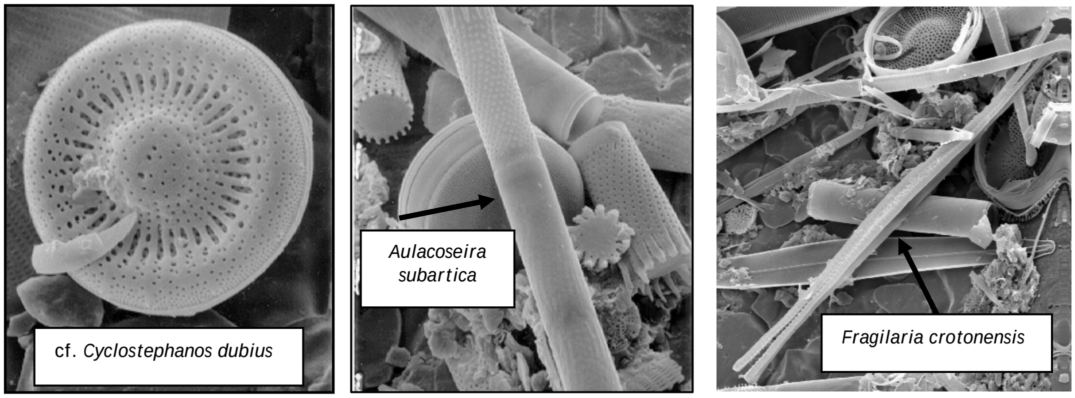

Figure 9. Electron micrographs of three common diatoms from Geneva Lake.

unpublished data). Apparently this diatom is present under low nutrient conditions. The diatom identified as *C. dubius* has not been reported from any other lakes in the Upper Midwest. Its identification is tentative but apparently this taxa is indicative of low P levels. Around 1900, these two species were replaced by *Aulacoseira subarctica* (O. Müller) Haworth (pictured in Figure 9). The dominance of this diatom indicates an increase in P. During the 1920's the epilimnetic diatoms *Fragilaria crotonensis* Kitton (pictured in Figure 9) and *Asterionella formosa* Hasall became important components of the diatom community (Figure 10). These two species are often found in nutrient enriched waters (Bradbury, 1975, Carney, 1982, Fritz et al., 1993). Nutrient levels increased further around 1950 with the dramatic decline in Aulacoseira spp. and the appearance of *Stephanodiscus parvus* Stormer & Håkansson and *Stephanodiscus* sp. 1. *S. parvus* is indicative of elevated P levels (Anderson et al., 1990) and *Stephanodiscus* sp. 1 became an important part of the diatom community in Green Lake, Wisconsin under elevated nutrient levels (Garrison, unpublished data). Phosphorus levels apparently declined somewhat after 1970, as both *Stephanodiscus* species declined and *F. crotonensis* became more important. These reduced nutrient levels have continued until the present time.

Williams Bay

As with the diatom community in the Deep Hole core, water quality was good in Williams Bay during the 1800's as indicated by cf. *C. dubius* (Figure 11). The nutrient levels likely were not as good in the bay as they were in the main part of the lake since *Aulacoseira* spp. was an important part of the diatom community during this time. Soon after 1900, P levels appear to have increased as cf. *C. dubius* disappeared. Nutrient levels increased further around 1920 as *F. crotonensis* increased in abundance. By 1950 the P levels in the bay were likely similar to the main basin as *Aulacoseira* spp. was gone, being replaced by *F. crotonensis*. During the

period of 1950-90 there was also an increase in benthic *Fragilaria*, especially *Pseudostaurosira brevistrata* Grunow (Figure 11). This species generally grows on substrates such as macrophytes and their presence likely means that the abundance of macrophytes was higher during this time. During the last decade the water quality of the bay has declined. The abundance of the benthic *Fragilaria* declined indicating reduced water clarity while both *F. crotonensis* and *Stephanodiscus* sp. 1 increased. In contrast to the diatom community in the Deep Hole core, planktonic diatoms were not always the dominant form of the diatoms. Prior to European settlement, nonplanktonic species dominated. This implies that the waters of the bay during this period were highly transparent and unproductive. This is also supported by anecdotal evidence. The name given to the lake by the Potawatomie's was "Kish-wauketo" which means clear water. This scenario is common in other marl lakes in southeastern Wisconsin (Garrison and Wakeman, 2000). A similar result was reported from the Bay of Quinte, Lake Ontario (Stormer et al., 1985). With land modifications following settlement, transparency declined and planktonic diatoms dominated the community. Between 1930-70 nonplanktonic diatoms were again an important component of the diatom community. Since the P loving *F. crotonensis* was common during this time, it is likely that the increase in nonplanktonic diatoms indicates increased grow of macrophytes.

Geneva Bay

In Geneva Bay the benthic *Fragilaria* were an important component of the diatom community during much of the 1800's (Figure 12). As with Williams Bay, this implies water clarity was exceptional. Since Cyclotella sp. 1 and cf. C. dubius dominated the planktonic community, this also indicates low nutrients. As at the other core sites, around 1900, nutrient levels increased since *Cyclotella* sp. 1 and cf. *C. dubius*, nearly disappeared, as did the benthic *Fragilaria*. Historically, Geneva Bay may have had lower nutrients than Williams Bay since *Aulacoseira* spp. were only present in low numbers in Geneva Bay. Nutrient levels further increased around 1920 as *A. subarctica* declined and *F. crotonensis* increased. This occurred earlier than at the other core sites. Unlike in Williams Bay, benthic *Fragilaria* did not increase during the period 1940-70 but instead the planktonic diatom *Stephanodiscus* sp. 1 increased. This difference in the diatom community may be a result of the application of sodium arsenite. Elevated levels of arsenic were found in the Geneva Bay core during this time indicating treatment of the bay for macrophyte control. Benthic *Fragilaria* would not be present in the Geneva Bay core since plants were not available to provide a substrate for their growth. Since *Stephanodiscus* sp. 1 is believed to be present under elevated nutrient levels it appears that spraying the plants caused the nutrients to be channeled towards planktonic diatoms instead of benthic species. The increased presence of these species also could be a reflection of the taxa residing in the main basin of the lake. Since the prevailing winds are southwesterly, their presence in the

main basin could cause their deposition in Geneva Bay. Since 1970, it appears that nutrient levels have declined as indicated by the reduced presence of *Stephanodiscus* sp. 1.

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 e.g. phosphorus, 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 Geneva Lake cores the diatom community was used to estimate historical spring phosphorus concentrations. The inferred P concentrations in the surface sediments are 20 µg L^{-1} in the Deep Hole and 25 µg L^{-1} in both bays. Dr. Dale Robertson of the U.S. Geological Survey reports spring P concentrations of about 15 µg L^{-1} (Robertson, personal communication). The diatom community infers higher levels than have been measured. This may be because this technique slightly overestimates P concentrations when they are below 20 µg L^{-1}. Therefore, the inferred values should be largely used as an indication of changes in historical levels with the understanding they may be high by about 5-10 µg L^{-1}.

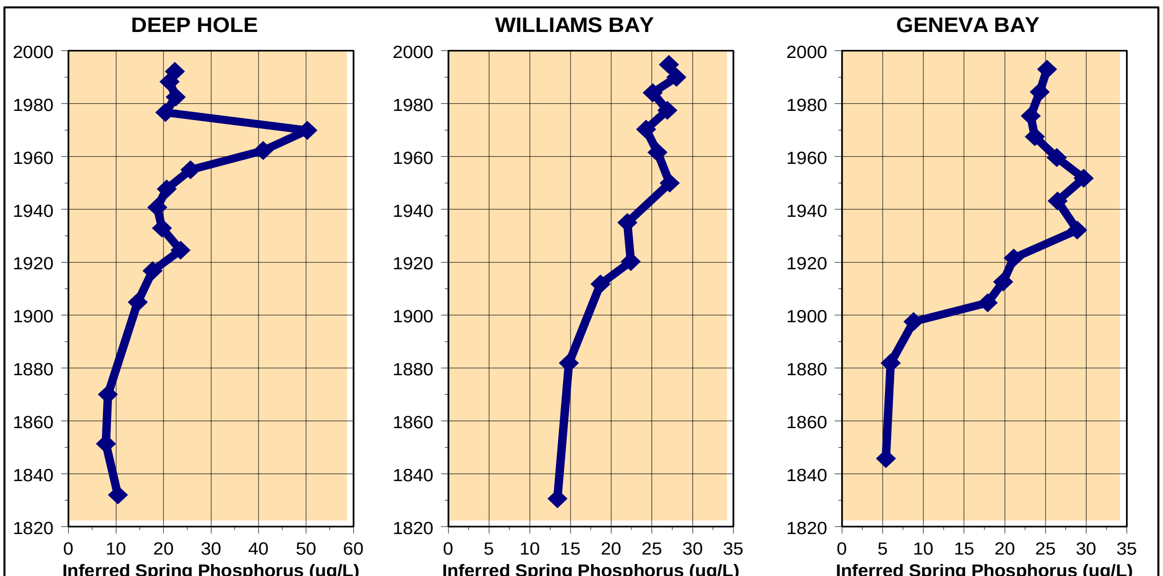

Figure 13. Diatom inferred spring phosphorus concentrations. The inferred levels may be higher than the true concentrations. However, the trends should be a true reflection of changes in P levels during the last two centuries.

Phosphorus concentrations were at their lowest at the bottom of all three cores (Figure 13). Historical spring P levels are estimated to be around 10 µg L^{-1} in Geneva Bay and the Deep Hole. In contrast, the historical levels in Williams Bay were higher at 10-15 µg L^{-1}. The lower concentration in Geneva Bay compared with Williams Bay, likely reflects the fact that it receives more water exchange with the main lake basin, which would enhance flushing of the bay and allow deposition of diatoms produced in the main basin in Geneva Bay. Since Williams Bay is not as open to the main basin, water exchange may not be as great and diatom production in the bay may have naturally been higher as they were able to intercept nutrients delivered from the watershed. Another contributing factor to slightly higher nutrient levels in Williams Bay may be the presence of an Native American village on the west side of the bay (Jenkins, 1922). In the Deep Hole, phosphorus levels began to increase after 1900, and were highest during 1960-75. This trend is largely driven by *S. parvus* and *Stephanodiscus* sp. 1, which composed a large portion of the diatom community. While these species typically are found in eutrophic waters (Anderson et al., 1990) they also are sensitive to the a high ratio of dissolved silica to phosphorus (Si:P). It seems unlikely that P levels in the main basin of Geneva Lake approached 50 µg L^{-1}. Instead it is more likely that the ratio of Si:P was low as increased diatom productivity depleted silica. As Si:P ratios declined, increasing silica limitation would have placed diatoms at a competitive disadvantage relative to non-siliceous algae (Tilman et al., 1986). Consistent with this hypothesis, the diatom community became dominated by lightly silicified diatoms (small *Stephanodiscus* species) which are better competitors at low Si availability (Lund, 1950; Tilman et al., 1982). In contrast, in Williams and Geneva bays, their location closer to nutrient inputs from the watershed, would allow the diatom community access to more silica and thus small *Stephanodiscus* species were not as common.

In Williams Bay, P levels steadily increased from around 1910 to 1950 when levels reached inferred concentrations between 25-30 µg L^{-1} (Figure 13). This P level has been maintained until the present time. In Geneva Bay, P levels increased very rapidly after 1900 (Figure 13). Inferred concentrations increased to about 30 µg L^{-1} by 1930. This elevated concentration was maintained until 1950 when it began to decline. The earlier increase in P compared with Williams Bay likely reflects the earlier and more intense urban development around Geneva Bay. For the last 40 years inferred P levels in Geneva Bay has been about 25 µg L^{-1}. The diatom inferred phosphorus concentration is currently the same at about 25 µg L^{-1} in the both bays but is lower at 20 µg L^{-1} in the main basin.

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