

**PALEOECOLOGICAL STUDY OF
SHELL LAKE, WASHBURN
COUNTY**

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**Wisconsin Department of Natural Resources,
Bureau of Science Services**

February 2012

PUB-SS-1088 2011



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. People often wonder about how a lake has changed, when the changes occurred and what the lake was like before the transformations began. 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 microfossils 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.

It is unclear when the lake became known as Shell Lake as in the mid to late 1800s it was first known as Frog Lake and later as Summit Lake. In the book *The Story of Shell Lake*, the author relates that government surveyors gave the lake the name Frog Lake but by the time the railroad arrived and the town was established it was commonly called Summit Lake because of its location high in the landscape (Stouffer 1961). In the publication *Fifty Years in the Northwest* published in 1888 the lake was known as Summit Lake (Folsom 1888) even though the Shell Lake Lumber Co. was incorporated in 1880 and the village at this time was known as Shell Lake. A large sawmill was built on the northwest shore of the lake in 1881 and this continued in operation until 1899. Along with the sawmill many homes were built in the village of Shell Lake and a thriving community was established. By the mid 1890s most of the timber had been harvested and farming began in the cutover lands.

Because Shell Lake is located high in the landscape, it experiences large fluctuations in its water level. Although records are available for most of the time since 1936, anecdotal records indicate problems with changing lake levels in the late 1880s. When the village was established water levels were high enough that the Shell Lake Lumber Company received permission to dig a canal north of the sawmill to direct water from the lake into Sawyer Creek to the west. Water levels remained high until around 1911 (Stouffer 1961). After this time water levels apparently declined through the 1930s when an engineer who studied the lake indicated that water levels had dropped 17¾ feet in the last 29 years, although this amount seems extreme. Water levels were so low that instead of diverting water from the lake, a ditch was dug to divert water from the headwaters of the Clam River in 1942. This diversion continued until the 1990s when high water levels and concern about nutrient input resulted

in the closure of the ditch. In the late 1990s water levels had again become high enough to cause problems so that since 2003 water has been diverted into the Yellow River as needed.

Anecdotal reports indicate that the water quality of Shell Lake in the late 1800s and later was very good. The water is described as cold and clear with little algae, even in the hot months (Stouffer 1961). In fact the water quality was so good that the lake was used as a source of untreated drinking water with the placement of pipes which extended 150 feet into the lake. In 1930 it was necessary to drill a deep well to be used as a water source because the lake level had declined to a point where the lake water could not longer be used for drinking. There is a hint that the water quality may have been declining at that time as dead cattle were found in the lake. The high quality of the water in the late 1800s and first few decades of the twentieth century is evidenced by the large ice harvesting operations that occurred. The ice was highly sought after since it was clear and tasteless (Stouffer 1961). Ice harvesting continued until it was replaced by chemical refrigeration.

This sediment core study was conducted to better determine the water quality history of Shell Lake, especially how it has been affected by cultural development and fluctuating water levels since the mid 1800s. At the present time, the lake experiences occasional algal blooms and it is unclear if this is a recent occurrence or normal for the lake.

Shell Lake, Washburn County, is a 2153 acre seepage lake with a maximum depth of 36 feet. A sediment core was collected from the deepest area of the lake on 5 October 2010. The location of the coring site was 45.73941° north and -91.90208° west in 36 feet of water (Figure 1). The core was collected with a piston corer with an inside diameter of 8.8 cm. The core was sectioned into 1 cm intervals for the top 40 cm and then at 2 cm intervals to the bottom of the core which was 92 cm in length. The core was dated by the ^{210}Pb method and the CRS was model used to estimate dates and sedimentation rate. The diatom community and blue-green fossils were analyzed to assess changes in nutrient levels and geochemical elements were examined to determine the causes of changes in the water quality.

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 it is sometimes 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 is in

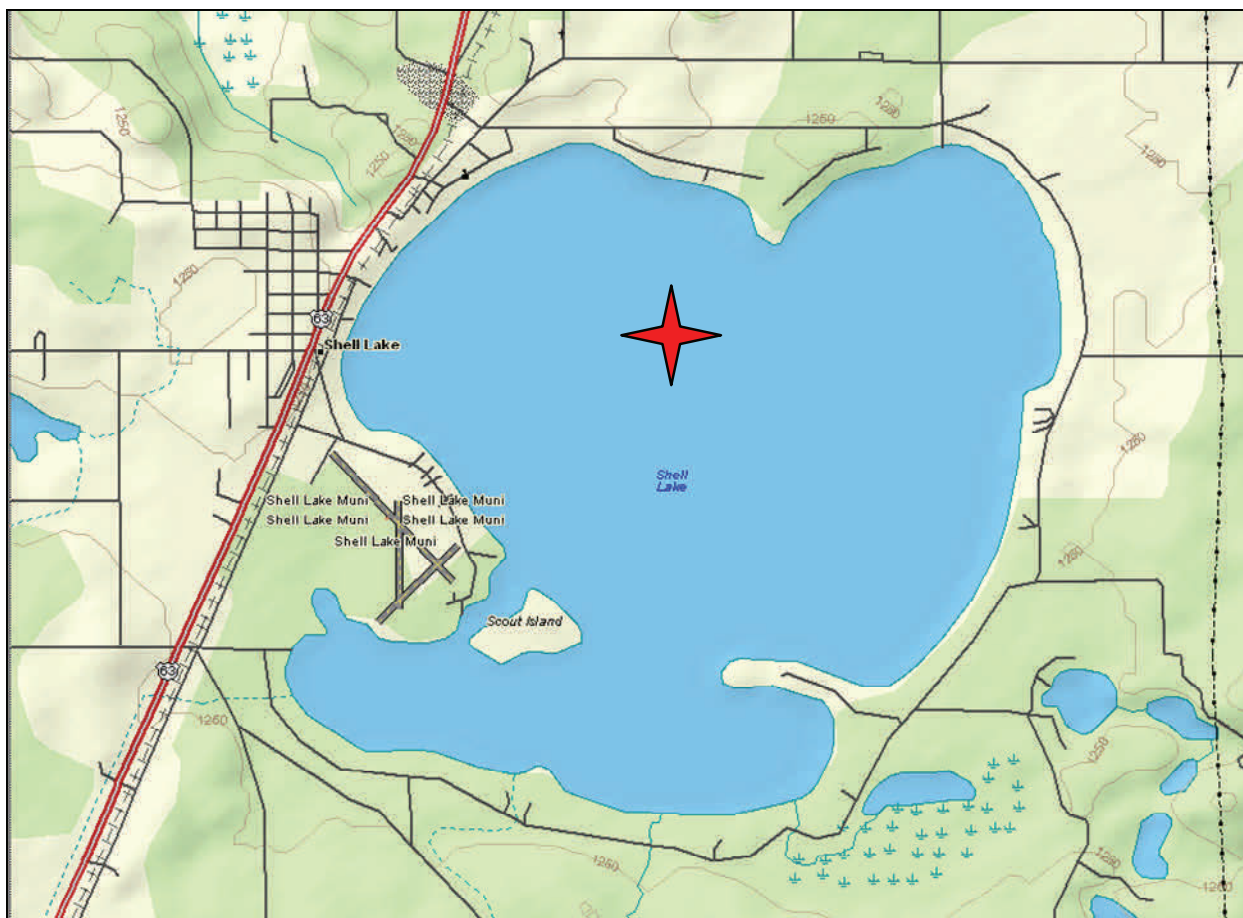


Figure 1. Map of Shell Lake showing the coring site. The water depth at the site was 36 feet.

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 1800s. Sediment age for the various depths of sediment were determined by constant rate of supply (CRS) model (Appleby and Oldfield 1978). Bulk sediment accumulation rates ($\text{g cm}^{-2} \text{yr}^{-1}$) were calculated from output of the CRS model.

The ^{226}Ra levels were generally steady throughout the core (Figure 2) with the mean concentration of 1.09 pCi g^{-1} which is somewhat higher than concentrations measured in other Wisconsin lakes (Garrison and Wakeman 2000, Garrison and Fitzgerald 2005, Garrison and LaLiberte 2010). Assuming that supported ^{210}Pb is in radioactive equilibrium with the ^{226}Ra , background levels were achieved around 22 cm (Figure 2). Total ^{210}Pb activity shows multiple zones of roughly monotonic decline with sediment depth: 17-7 cm, 7-4 cm and the top 4 cm (Figure 2). This suggests changes in the sedimentation rate at these depths. Unsupported ^{210}Pb activity in the surface sediment was 21.31 pCi g^{-1} which implies little dilution of atmospheric inputs. Cumulative unsupported activity was $20.04 \text{ pCi cm}^{-2}$ rep-

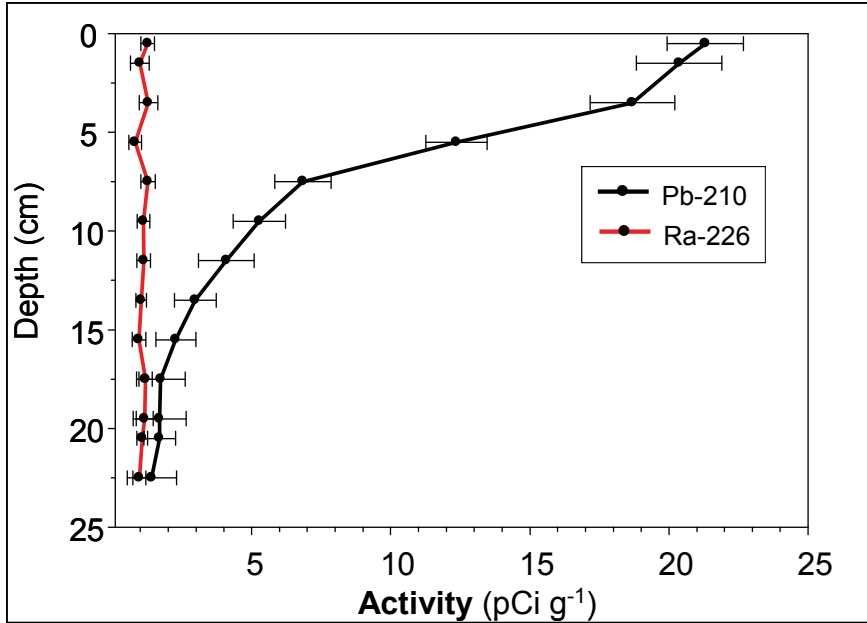


Figure 2. Activity profiles of ^{210}Pb and ^{226}Ra for the core. Background levels were reached at about 22 cm when lead and radium levels are similar. Error bars represent \pm_{SD} .

representing a mean unsupported ^{210}Pb flux of $0.387 \text{ pCi cm}^{-2} \text{ yr}^{-1}$ in the lake. This value is similar to regional values (Urban et al. 1990, Binford et al., 1993) and suggests that little sediment focusing is occurring. The lack of sediment focusing is typical in lakes like Shell Lake with broad deep basins. They lack of focusing means that the sedimentation rate measured at the coring site is likely similar throughout all but the shallowest portion of the lake basin. Error

rates of the CRS modeled dates are relatively small (Figure 2). Often the bottom of the datable portion of the core has large error rates but this is not the case in this core. This implies that estimated dates from the 1800s are fairly accurate. Below 22 cm dates were assigned using linear interpolation.

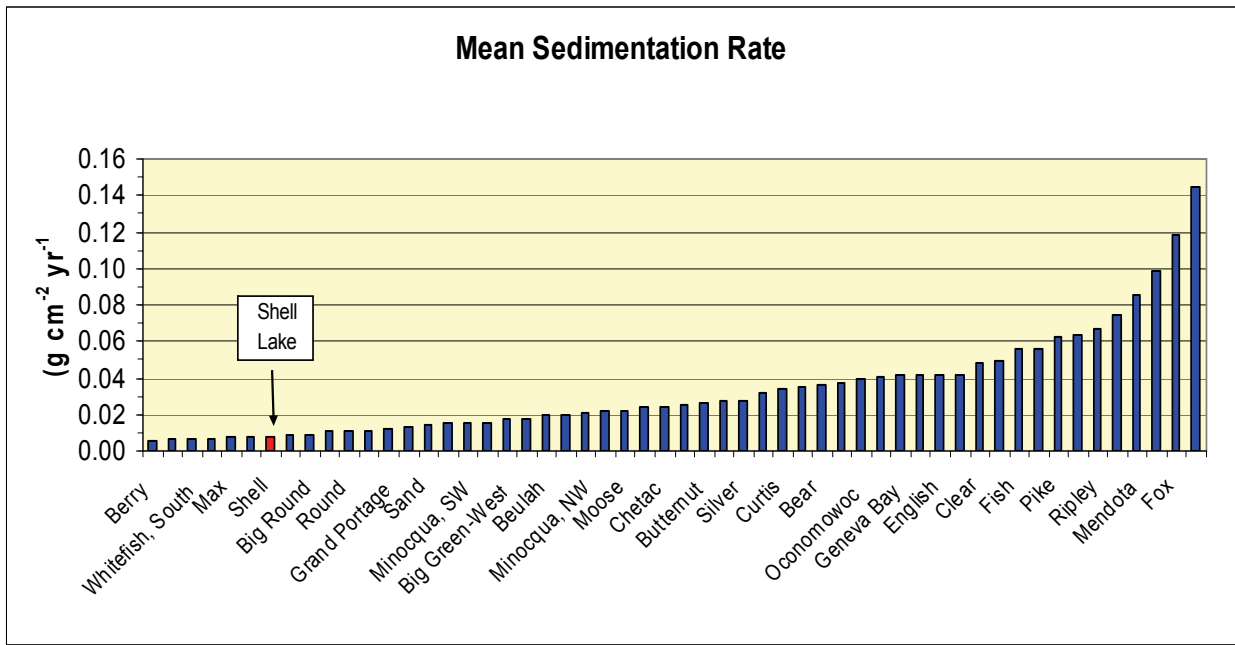


Figure 3. Mean sedimentation rate for the last 150 years for 52 Wisconsin lakes. The arrow indicates Shell Lake. The rate is low because the lake has moderately softwater, has a broad deep basin which reduces sediment focusing, and is a seepage lake.

Sedimentation Rate

The mean mass sedimentation rate for the last 170 years was $0.013 \text{ cm}^{-2} \text{ yr}^{-1}$. This is one of the lowest rates measured in 52 Wisconsin lakes (Figure 3). The rate is low partially because the lake is a moderately softwater lake so there is not a significant amount of precipitation of calcium carbonate. The rate is also lower because the deep area of the lake is large so sediment focusing is reduced. Because the lake is a seepage lake there is reduced sediment input from the watershed compared with a lake with a significant inflowing stream. The average linear rate for the same time period is 0.13 cm yr^{-1} , which equates to 0.05 inches per year.

To account for sediment compaction and to interpret past patterns of sediment accumulation, the dry sediment accumulation rate was calculated. The historical sedimentation rate was about $0.005 \text{ cm}^{-2} \text{ yr}^{-1}$ but the rate increased in the 1880s and 90s with the establishment of the sawmill and the establishment of the village of Shell Lake (Figure 4). Stouffer (1961) notes in his book that while the sawmill was in operation the west side of the lake was choked with logs. With the closing of the mill in 1899, the sedimentation rate quickly declined, although it did not reach the rate of presettlement. During the first 6 decades of the twentieth century the sedimentation rate continued to steadily increase and peaked during the 1960s

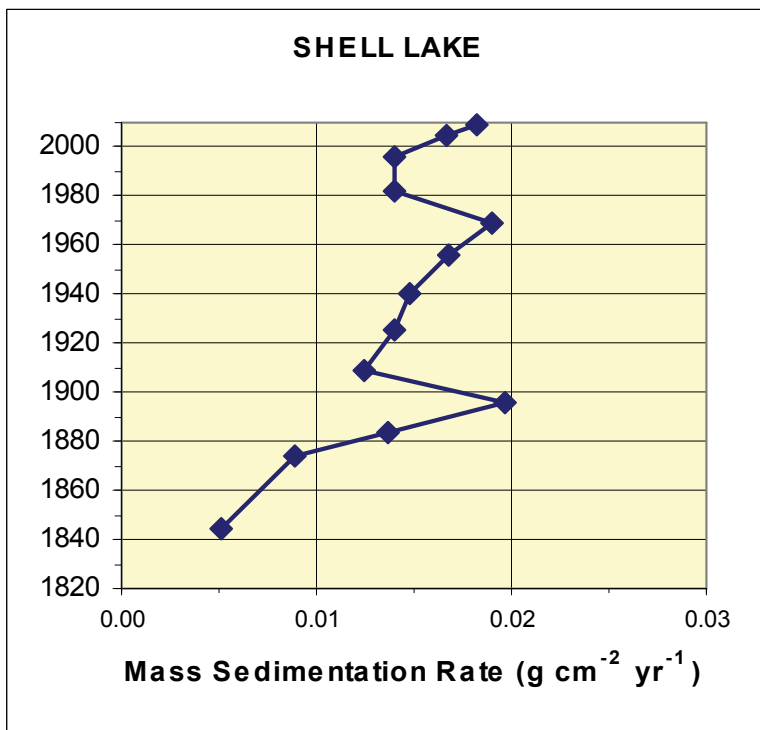


Figure 4. Sediment accumulation rate in Shell Lake. The rate first began to increase in the 1880s after the railroad reached the lakeshore. During the first 6 decades of the twentieth century the rate increased but then declined. During the last ten years the rate has again increased.

increase and peaked during the 1960s (Figure 4). During the 1980s and 1990s the rate declined, although it was still about 3 times higher than presettlement levels. During the last 10 years the rate has again increased and at the present time it is nearly 4 times the historical sedimentation rate.

Although the sediment infilling of the lake has fluctuated depending on cultural activities around the lake, at the present time it is nearly 4 times higher than it was in the mid-1800s.

Sediment Geochemistry

Geochemical variables are analyzed to estimate which watershed activities are having the greatest impact on the lake (Table 1). The chemicals aluminum and titanium are surrogates of detrital aluminosilicate materials and thus changes in their profiles are an indication of changes in soil erosion. Potassium is found in both soils and synthetic fertilizers. Therefore its profile will reflect changes both from soil erosion and the addition of commercial fertilizers in the watershed. Uranium is found in synthetic fertilizer as it is a contaminant in the soils where the fertilizer is mined. Nutrients like phosphorus and nitrogen are important for plant growth, especially algae and aquatic plants. General lake productivity is reflected in the profiles of organic matter. The organic matter determination in-

Table 1. Selected chemical indicators of watershed or in lake processes.

Process	Chemical Variable
Soil erosion	aluminum, potassium, titanium
Soil amendment	calcium
Synthetic fertilizer	potassium, uranium
Nutrients	phosphorus, nitrogen
Lake productivity	organic matter

cludes a number of elements, especially carbon.

The accumulation rate of selected geochemical elements was calculated by combining the elemental concentrations with the sedimentation rate. The accumulation rate gives an indication of how the deposition of the elements changed through time. This provides an indication of what watershed and inlake processes have occurred that consequently affected the lake ecosystem.

The accumulation rate of aluminum, which indicates soil erosion, began to increase in the late 1800s (Figure 5). This was the result of the settlement on the lake, especially the village of Shell Lake and associated businesses, e.g. sawmill. After the peak in the 1890s the rate declined but it remained higher than the presettlement rate. The rate again peaked in the 1960s but declined during the 1980s and 1990s. It is likely the increased erosion during the 1950s and 60s was the result of agricultural activities around the lake. After World War II, tractors became larger making it easier to farm larger tracts and also requiring intensification of farming to support the increased mechanization. During this time period it is likely that some of the wetlands on the east side of the lake were ditched so that

more sediment entered reached the lake. During the last 10 years the rate again increased and at the present time is at its highest rate and over 4 times the historical rate. This indicates that soil erosion in the watershed is having a significant impact on the lake. In other Wisconsin lakes the input of products from soil erosion has declined since the 1960s and 1970s as a result of conservation practices (Garrison 2003, Garrison 2006a) including nearby Whitefish Lake, Douglas County (Garrison 2006b).

Calcium, phosphorus, and nitrogen exhibited similar accumulation profiles as did aluminum (Figure 5). This indicates that these elements are closely associated with soil erosion from the watershed. The nutrient concentrations at the top of the core are at the highest levels observed in the core for phosphorus and only the episodic event that occurred in the 1890s has a higher value for nitrogen.

Uranium is often present in synthetic fertilizers because it is a contaminant in the ore body where phosphate is obtained. Therefore it can be used as a surrogate for the use of synthetic fertilizers in a

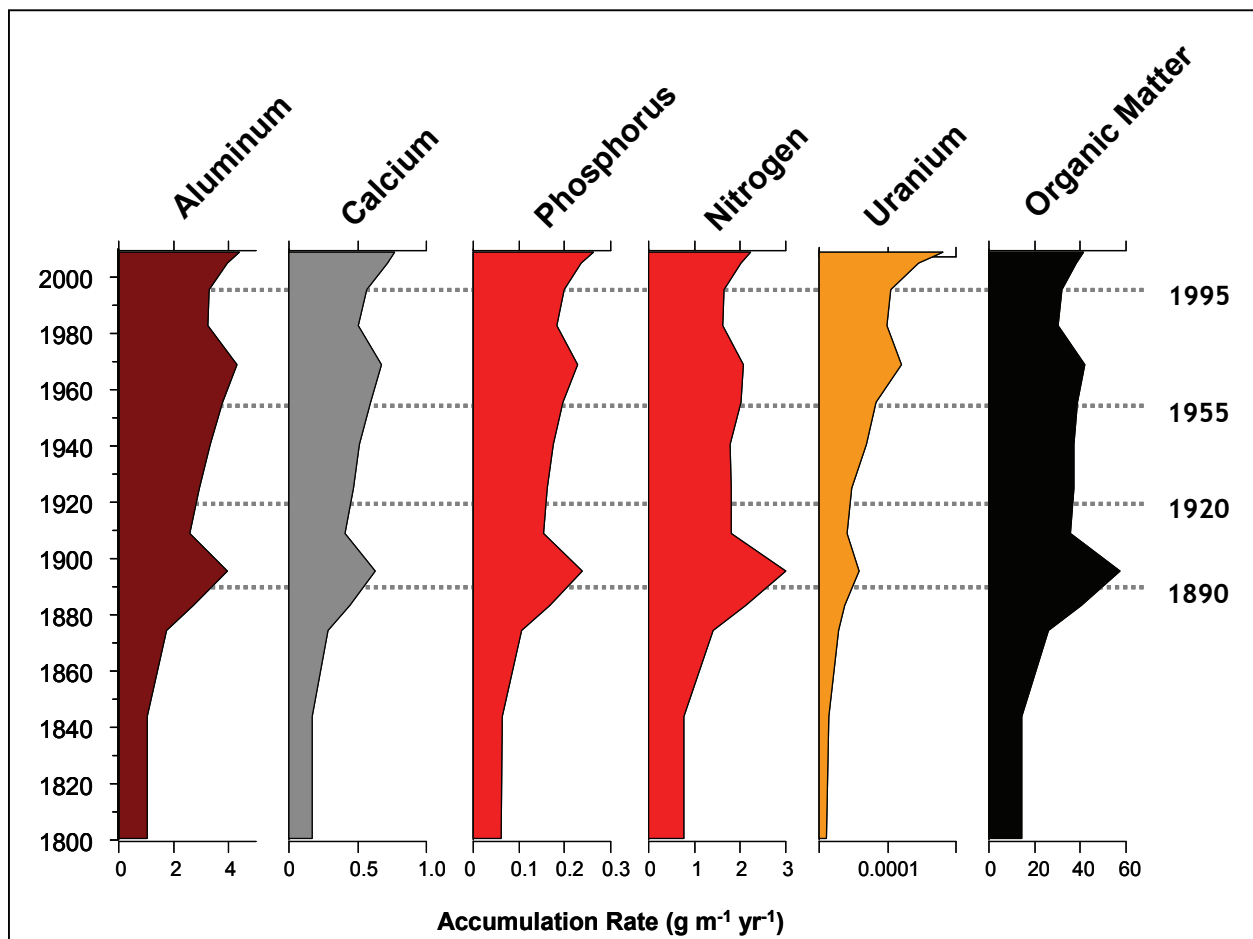


Figure 5. Profiles of the accumulation rate of selected geochemical elements. The aluminum profile is indicative of soil erosional rates in the watershed. Calcium is often used as a soil amendment. Nitrogen and phosphorus profiles reflect changes in nutrient deposition rates. Uranium is found in trace amounts in synthetic fertilizers. Organic matter indicates the general productivity of the lake.

lake's watershed. In the Shell Lake core uranium steadily increased since the 1950s and reached a peak at the top of the core. This indicates that some of the fertilizer applied to lawns and perhaps agricultural lands around the lake is reaching the lake.

The highest value for organic matter occurred during the episodic event in the 1890s (Figure 5). Since that time values have been fairly constant except for lower rates during the 1980-90s.

The elevated concentration of phosphorus, nitrogen and organic matter at the top of the core possibly reflects the fact that post depositional diagenesis of organic matter and nitrogen was not complete when the core was collected. Diagenesis is the conversion of organic forms of a given element to its inorganic form through bacterial action. This often happens with nitrogen and carbon and is common in shallow lake systems and wetlands (Fitzpatrick et al. 2003, Garrison 2011). However, the elevated rates of aluminum and uranium imply that the high rates of C, N, and P are most likely indicative of higher deposition rates.

In order to better understand changes in deposition of geochemical elements in the core some elements are examined using ratios. For example, to understand the importance of different sources of potassium, the ratio of aluminum to potassium (Al:K) is used to separate sources of potassium such as soil particles and the use of potassium in synthetic fertilizers. Since both potassium and aluminum are delivered to the lake in the form of soil particles, their deposition rates should be similar when soils are the only source of potassium. Any decrease in the ratio of Al:K indicates a source of potassium other than solid particles. After 1980, the ratio decreases (Figure 6) which likely indicates that synthetic fertilizers were being used in the lake's watershed and some of this fertilizer was running off into the lake. Calcium is often used as a soil amendment on agricultural fields and lawns. While it is present naturally in soils the increase in the ratio of Ca:Al indicates that calcium is entering the lake from a source other than soil particles. This is the case in the Shell Lake core after 1980 which is about the same time frame for synthetic fertilizer is running off the watershed and into the lake as indicated by the Al:K ratio. An example in the lake's history which demonstrates the input of calcium from land application is that although there was a peak in calcium deposition in the 1890s, the ratio of Ca:Al was unchanged indicating that source of the calcium was the native soils.

The ratio of N:P and C:P decline in the upper part of the core indicating that phosphorus is being deposited at a higher rate than carbon or nitrogen. This likely means that excess amounts of phosphorus are entering the lake. Increased amounts of phosphorus is a problem as this is the element that limits the lake's productivity. This means that with increases in phosphorus it is highly likely that algal growth will increase resulting in declining water clarity and an increased chance of nuisance algal blooms.

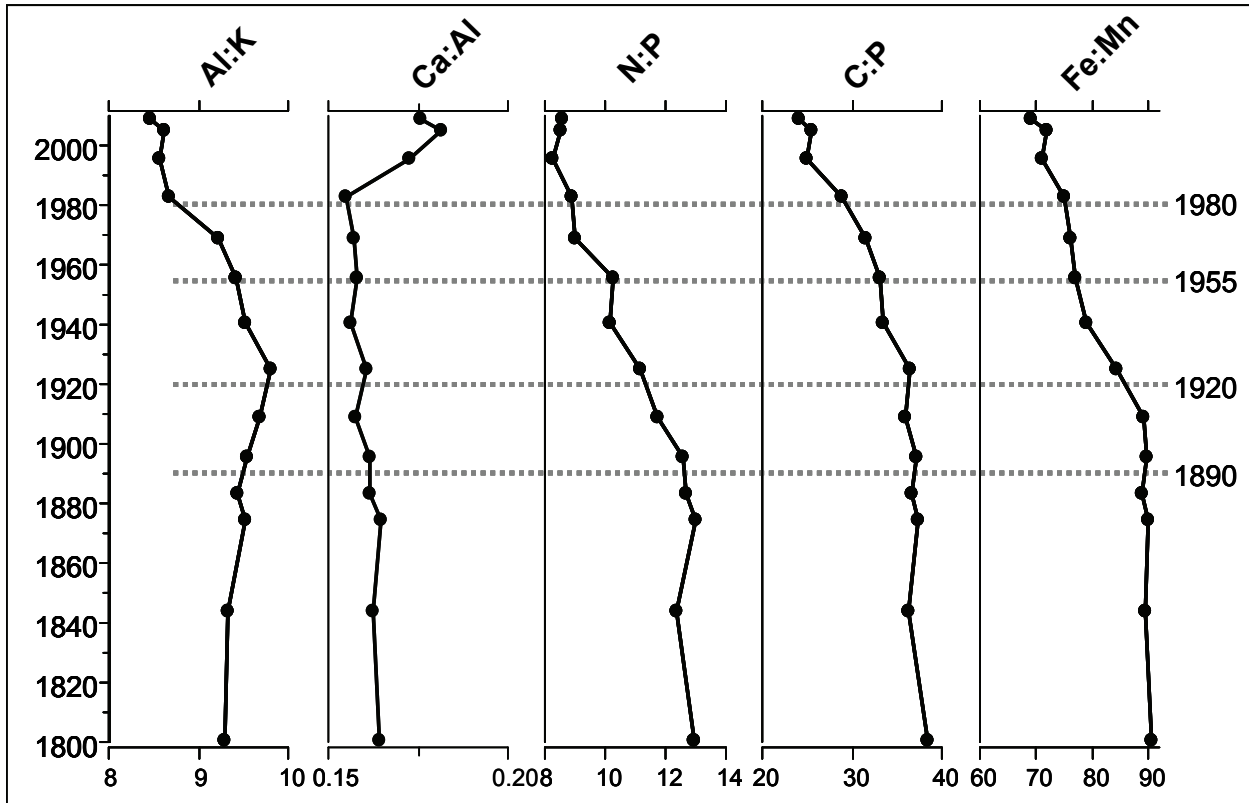


Figure 6. Profiles of various ratios of the geochemical variables. Ratios are used to better understand the impact of watershed activities on the lake. For example, The decline in the Al:K after 1980 indicates that much of the potassium (K) is coming from synthetic fertilizers. The increase in Ca:Al since 1980 indicates the use of lime as a soil amendment on lawns.

As the bottom waters become increasingly devoid of oxygen, manganese (Mn) is mobilized from the sediments. This manganese then moves into the deepest waters resulting in enrichment of manganese in the sediments of the deeper waters. While this also occurs with iron, it happens sooner with manganese and manganese tends to stay in solution longer (Jones and Bowser 1978). Therefore as the bottom waters lose oxygen, manganese is preferentially moved with respect to iron (Engstrom et al. 1985). The result is that with the loss of oxygen, the ratio of iron to manganese (Fe:Mn) declines (Mn increases). Figure 6 shows the profiles of Fe:Mn in the core. The ratio has been steadily declining since the 1920s. This indicates that since the 1920s, the bottom waters are losing oxygen. The decline in hypolimnetic oxygen is a classic sign of increased eutrophication of a lake. Although oxygen is often measured in the bottom waters, it appears that there is a loss of oxygen very near the sediment water interface for at least part of the year. A similar trend was found in the sediment core from nearby Whitefish Lake, Douglas County (Garrison 2006b) even though the lake is still an oligotrophic lake.

In summary, the geochemical analysis indicates that watershed activities began adversely impacting the lake soon after the railroad arrived in the area and the town of Shell Lake was established. Sediment input from soil erosion around the lake is about 4 times higher at the present time compared

with the early 1800s. Amendments to facilitate lawn maintenance in the form of synthetic fertilizer and lime are detectable in the core since 1980. This has resulted in the increased delivery of phosphorus to the lake.

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 are 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 in 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 7 shows photographs of five diatom species that were found in the sediment core.

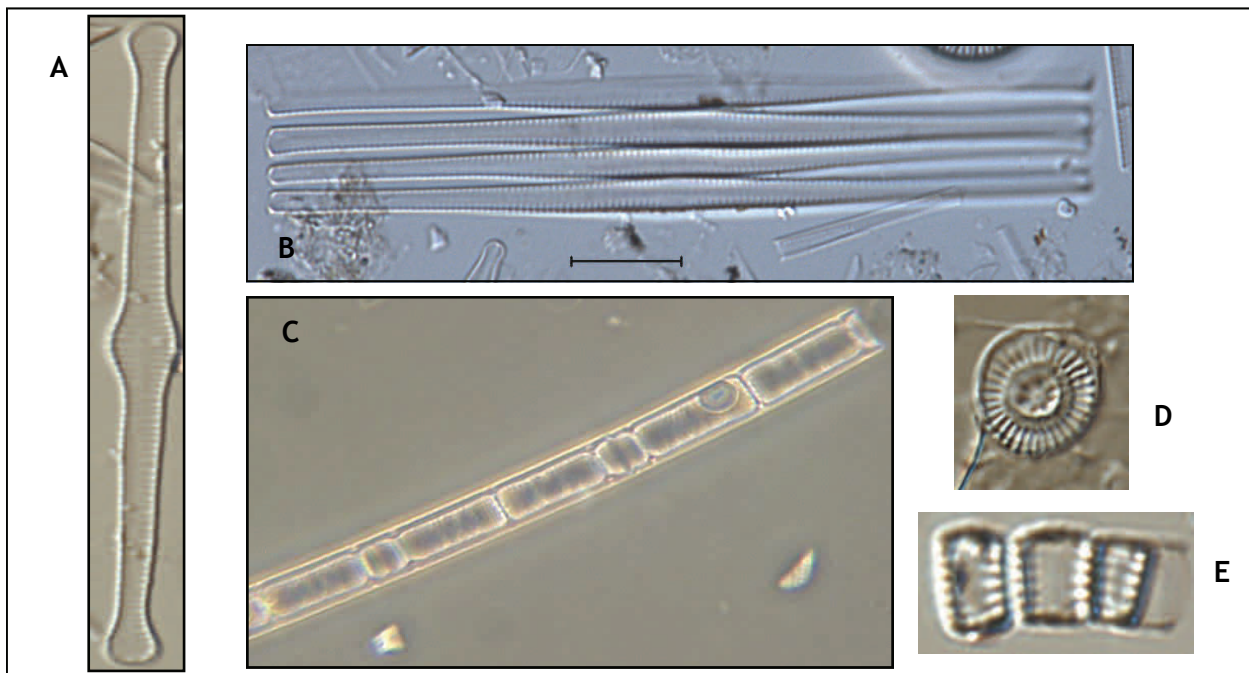


Figure 7. Photomicrographs of diatoms found in the sediment core. The first four diatoms (A) *Tabellaria flocculosa*, (B) *Fragilaria crotonensis*, (C) *Aulacoseira ambigua*, and *Discotella stelligera* are typically found in open water environments. *Staurosira construens* var. *venter* (E) is commonly found attached to substrates such as aquatic plants in lakes or grow on the sediments.

The diatom community is dominated by taxa that are found floating in the open water of the lake. Many lakes like Shell Lake which are relatively shallow have a significant portion of their lake bottom in the littoral area and the diatom community has a strong component of taxa that grow attached to plants and on the lake bottom. Even prior to European settlement, this was not the case in Shell Lake. Historically, the dominant diatom was *Tabellaria flocculosa* (pictured in Figure 7a) which is a common component of softwater seepage lakes like Shell Lake and Whitefish and Silver lakes in northwest WI (Garrison 2006b). The dominant benthic diatoms were small diatoms in the group Fragilariaceae, e.g. *Staurosira construens* var. *venter* (Figure 8).

The diatom community first begins to change in composition around 1920 with the increase in *Asterionella formosa* and *Fragilaria crotonensis*. These taxa usually indicate an increase in nutrients. This increase is not large and these diatoms are typically found in mesotrophic lakes with moderate phosphorus levels. In the early part of the twentieth century *T. flocculosa* declines and again around 1970. This is an indication of further increased nutrient levels, especially with the increase of *A. formosa*

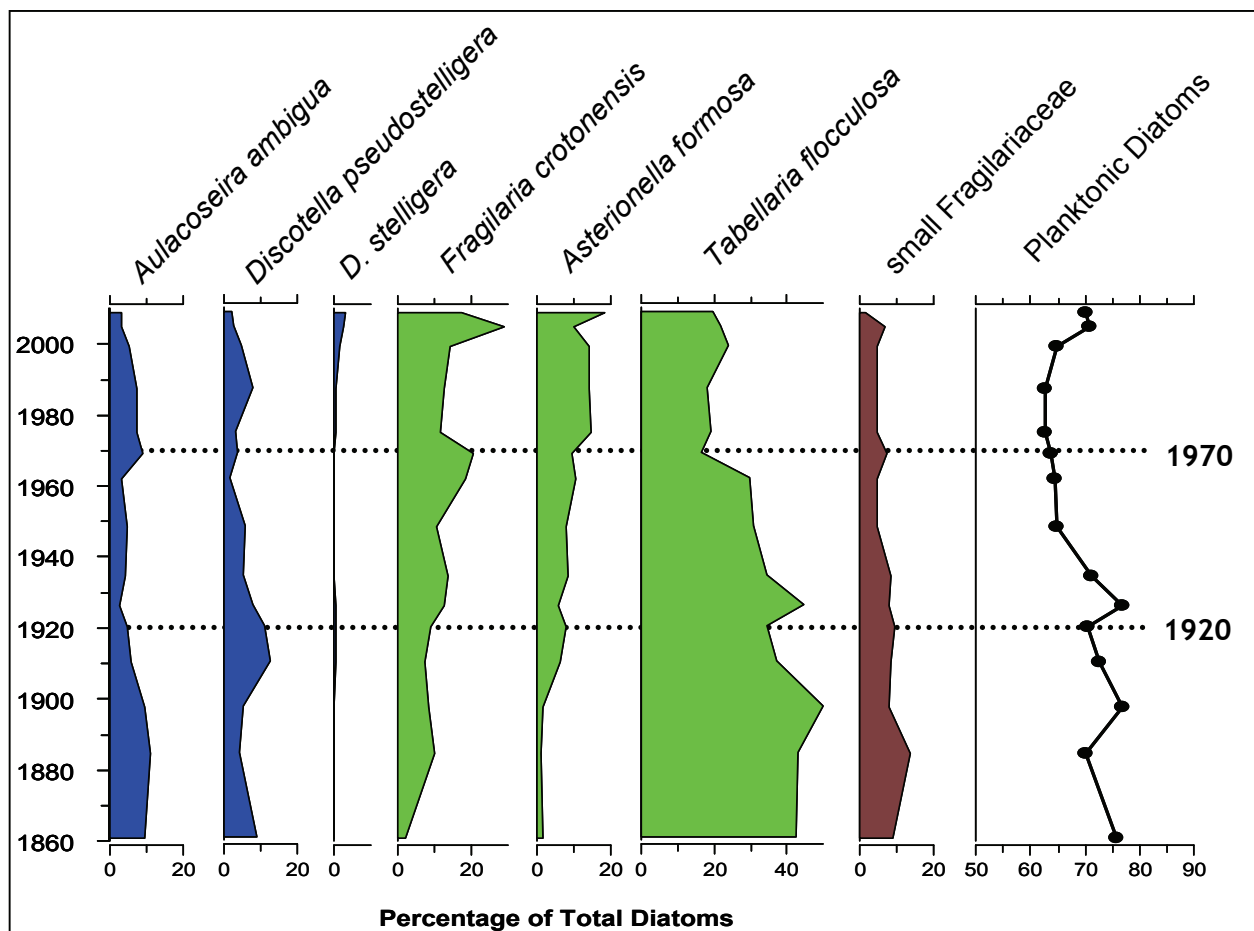


Figure 8. Profiles of common diatoms found in the core. The diatoms in blue are indicative of low nutrients while those in green are indicative of moderate nutrient levels. The brown colored diatoms grow attached to plants and on the sediments.

occurring around 1970.

Benthic diatoms those associated with submerged aquatic vegetation were a minor part of the diatom community. Borman (2007) found that in northwestern Wisconsin the macrophyte community often changed in seepage lakes, from one dominated by low growing plants to a community dominated by larger macrophytes, as a result of shoreline development. The structure of the macrophyte community changes because the increased runoff of sediment during construction on the shoreline enables the establishment of the larger plants. With the larger plants there is much more surface area available on which diatoms and other periphytic algae are able to grow. If this occurred in Shell Lake it was localized and is not evident in the core taken in the deep area of the lake.

Diatom assemblages have been used as indicators of trophic changes in a qualitative way (Bradbury 1975, Carney 1982, Anderson et al. 1990) but quantitative analytical methods exist. 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.

Weighted averaging calibration and reconstruction (Birks et al., 1990) were used to infer historical water column summer average phosphorus in the sediment core. A training set was developed from 59 deep Wisconsin lakes. Training set species and environmental data were analyzed using weighted average regression software (C2; Juggins 2003). The resulting transfer functions (bootstrapped 999 cycles $r^2 = 0.71$, $P < 0.05$) were subsequently applied with weighted averaging calibration to the fossil diatom assemblages (Birks et al., 1990, Juggins, 2003). Initial TP estimates from weighted averaging regression were corrected using inverse deshinking. Bootstrapped error estimates are based on initial log transformed data with the TP log error being 0.2061.

The diatom inferred summer phosphorus concentration prior to the arrival of European settlers was $12 \mu\text{g L}^{-1}$ (Figure 9). With the building of the sawmill in 1881 and the establishment of the village of Shell Lake, the phosphorus levels increased to $14\text{-}15 \mu\text{g L}^{-1}$. Even the sawmill and associated activities significantly increased the sedimentation rate, they had a much smaller impact on the phosphorus concentration of the lake. Land use changes beginning in the 1920s, likely in part from agriculture had a greater impact on the phosphorus levels in the lake. This may have been partially worsened by the low lake levels in the 1930s. An anecdotal account of dead cattle in the lake around this time (Stouffer 1961) may be further indication of deteriorating water quality. Phosphorus levels peaked

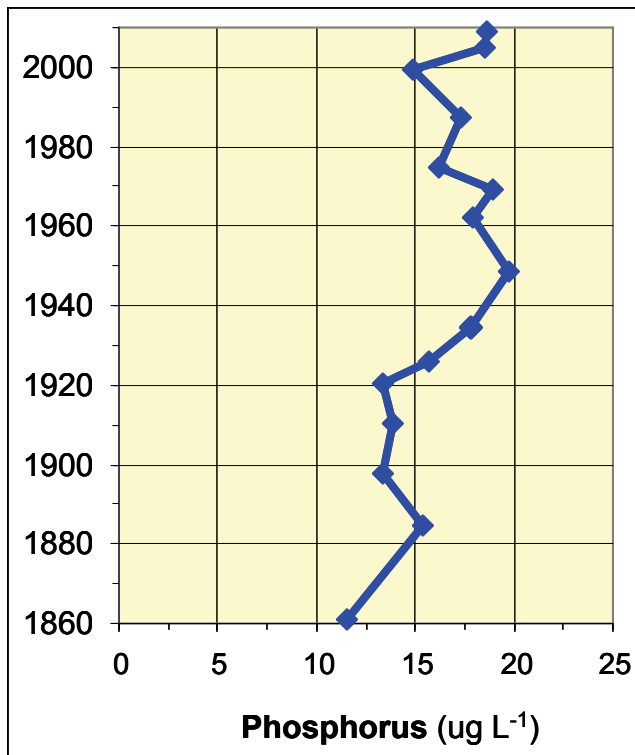


Figure 9. Diatom inferred summer phosphorus concentrations. The historical phosphorus levels were 14-15 $\mu\text{g L}^{-1}$. Concentrations first increased during the 1920s and reached a peak in the 1950s. Although levels declined until about 2000 they have increased within the last decade.

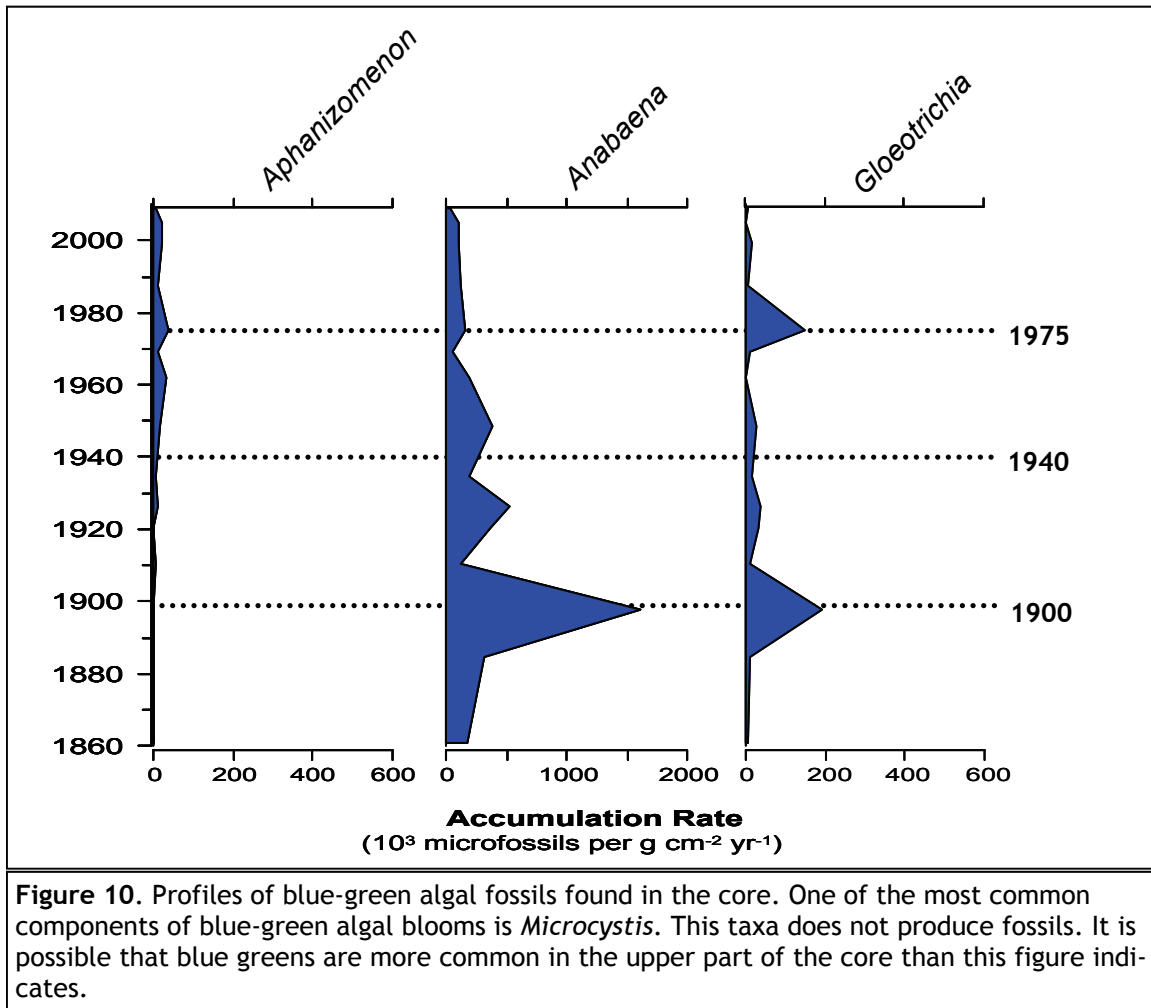
around 1950 with concentrations of 20 $\mu\text{g L}^{-1}$. Phosphorus concentrations declined slightly during the period 1960-2000 to about 17 $\mu\text{g L}^{-1}$. During the last decade, summer phosphorus levels have again increased and they are presently near 20 $\mu\text{g L}^{-1}$.

Blue-green Algal Fossils

Other algae besides diatoms are sometimes preserved in the sediments. These groups include blue-green algae, green algae, and chrysophytes. While nearly all diatom taxa are preserved, in the other groups only certain taxa are fossilized. In blue-green algae only the genera *Aphanizomenon*, *Anabaena*, and *Gloeotrichia* fossils are found in sediments. For chrysophytes only taxa which produce cysts are preserved. These cysts can be very diagnostic where they are abundant (Zeeb and Smol 2001). Unfortunately, in the Upper Midwest, chrysophyte cysts

are generally not preserved in much abundance. Green algae that produce coenobia are also found in the sediments. Since only some taxa are preserved in each of these algal groups, interpretation of the results is more limited than with the diatom community. However, since blue-green algae are currently present in Shell Lake, remains of these non-diatom groups, including blue-green algae, were examined in the core.

The blue-green algae that most frequently dominate algal blooms are *Aphanizomenon*, *Anabaena*, and *Microcystis*. The first two genera produce fossils while *Microcystis* does not. Blue-green algae were present throughout the core (Figure 10). The most common were *Anabaena* and *Gloeotrichia* while *Aphanizomenon* were only present in low numbers. It is clear that blue green algae have been present in the lake for a long time. There was an episodic peak of blue-green fossils in the 1890s which was likely associated with the sawmill operation. Although anecdotal reports suggest that the water quality was very good, there were apparently occasional blue green algal blooms. With the closure of the mill blue-green fossils declined. *Aphanizomenon* became more common around 1940 although their numbers are lower than the other two taxa. Both *Anabaena* and *Gloeotrichia* numbers were lower af-



ter 1975. Because *Microcystis* does not produce fossils, it is not possible to be certain if blue green numbers are lower because *Microcystis* may have replaced other blue greens.

Water Levels

Shell Lake historically has undergone large changes in water levels. Records for the lake available for most years since 1936 (P. Juckem, personal comm.). During this time the lake level has fluctuated over 8 feet from its lowest to its highest level. Prior to the keeping of records, anecdotal reports suggest that water levels were high in the 1880s through 1911 and then a large decrease in lake level occurred through the 1930s (Stouffer 1961) when records are available. One of the purposes of analyzing the sediment core was to estimate the impact of these water level changes on phosphorus inputs to the lake. One hypothesis of the effect of changing water levels is that as the level rises, the vegetation that is flooded along the shoreline will provide a significant amount of phosphorus to the lake thus stimulating algal blooms. Another hypothesis is that the lower volume of water when water levels are low will result in a concentration of the phosphorus, thus making more available for algal blooms.

A comparison of changes in lake level since 1880 and phosphorus concentrations in the lake shows that there is little apparent relationship (Figure 11). Phosphorus levels were lowest in the late 1800s even though water levels were high. Although phosphorus levels were lower during the period 1970-2000, lake levels were at moderate levels at the beginning of this period and did not become high until the mid 1980s. Although phosphorus levels were increasing when lake levels were declining in the 1920s and 2000s they were at their highest level around 1950 when lake levels were low for a short period of time. It is much more likely that activities in the watershed have a much larger impact on the lake's phosphorus concentrations.

It is interesting to note that the early development around the lake in the late 1800s significantly increased the lake's sedimentation rate but had a reduced impact on the phosphorus levels. While phosphorus concentrations did increase, it was only a relatively small amount. Agricultural activities and other shoreland development had a much greater impact in the middle part of the twentieth century. Although phosphorus levels declined during the period 1970 to 2000, with increased application of soil amendments, e.g. lime and fertilizer, phosphorus levels again increased so that at the present time they are at levels experienced in the 1950s and almost twice as high as presettlement concentrations.

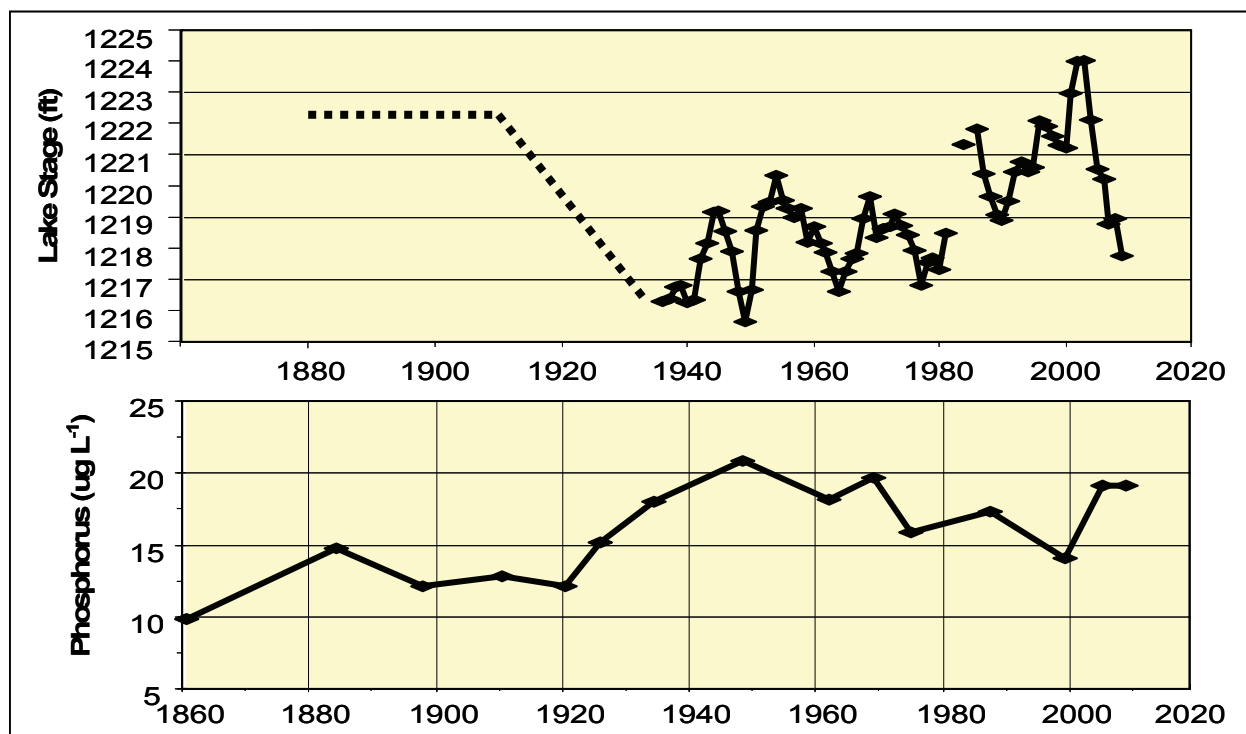


Figure 11. Lake levels and diatom inferred phosphorus concentrations in Shell Lake. The lake levels from 1936 to the present time was provided by P. Juckem, USGS. The dotted line from 1880-1936 is estimated from anecdotal records. This only indicates when lake levels were high or low but not how the extent.

The lack of influence of water levels on the phosphorus concentration has been found in other lakes, including Whitefish Lake, Douglas County (Garrison 2006b) and Berry Lake in Shawano County (Garrison and LaLiberte 2010). Berry Lake is smaller (200 ac) and has a shallower mean depth (7 vs 23 ft) than Shell Lake but has experienced lake level changes of over 8 feet between the time period 1934-2009. In this lake shoreline development had a greater effect than water level changes in contributing phosphorus to the lake. Because of the small surface area and shallow depth, it was expected that if changing water levels had a significant impact on phosphorus concentrations, it would occur in this lake.

The greater importance of land use compared with water level fluctuations on nutrient concentrations in Shell Lake is reflected in results from other paleolimnological studies. A study encompassing 3000 years on a small eutrophic lake in Sweden found that lake processes were impacted by climate induced lake level fluctuations until about AD 800. With the increased anthropogenic impact after this time, land use controlled most of the lake's development processes (Gaillard et al., 1991). A study on a marginal lake in the Lake Michigan basin that covered the late Holocene (last 5000 years) found that climate variability controlled lake processes during pre-Columbian times. Following the arrival of European settlers, anthropogenic effects dominated the lake processes (Wolin, 1996). Even relatively large increases in water level resulting from dam construction had minimal impact on a shallow Canadian lake (Karst and Smol, 2000) but nutrient enrichment occurred from agricultural and residential/recreational activities.

The results of this study are significant because of the potential of lake level fluctuations from climate change. Global climate models for the Upper Midwest, U.S.A. indicate a warmer and drier climate with more intensive precipitation events (Magnuson et al., 1997) are likely to occur in the future in Wisconsin. This climate change likely will result in lower lake levels in seepage lakes like Shell Lake. This study indicates that lower lake water levels may not result in higher nutrient levels. Instead anthropogenic land use around the lake and in the watershed will have a much larger impact on the nutrient levels in the lakes.

SUMMARY

- The mean sedimentation rate for the last 170 years in Shell Lake was near the lower rate measured in 52 Wisconsin lakes. This was partially because it is a moderately softwater, seepage lake and because the deep area is a broad plain.
- The historical sedimentation rate was about $0.005 \text{ cm}^{-2} \text{ yr}^{-1}$ but the rate began to increase soon after the arrival of the railroad. The rate continued to increase during much of the twentieth century. At the present time it is 4 times the rate of the mid-1800s.
- Early activities in the watershed associated with the lumber industry and development of the village increased the delivery of soil particles to the lake, resulting in an increase in deposition of most geochemical variables.
- The increased sediment material had a small impact on the lake's phosphorus status until the 1920s.
- In response to activities near the shoreline, phosphorus concentrations began to increase in the lake after 1920 and peaked around 1950. Phosphorus levels declined until the early 2000s and at the present time are near their highest levels.
- Presettlement phosphorus concentration in the lake was about $12 \mu\text{g L}^{-1}$ while it is nearly $20 \mu\text{g L}^{-1}$ at the present time.
- Although early input of sediment and nutrients to the lake had minimal impact on the phosphorus concentration in the lake, during the last 90 years within lake phosphorus concentrations have generally reflected watershed inputs. This includes reduced input of materials during the 1980s and 90s and increased inputs in the last 10 years.
- Some of the increased phosphorus levels since 1980 are the result of the use of soil amendments for lawn maintenance, e.g. lime, fertilizer. This is indicated by increased deposition of calcium and potassium.
- Although Shell Lake has exhibited large water level changes during the last 75 years, this has had minimal impact on the phosphorus levels in the lake. Watershed activities have had a much larger impact.
- The sediment core study clearly shows that shoreline development and agriculture has adversely affected the water quality of the lake. At the present time the sedimentation rate is 4 times higher than the rate during the mid-1800s and lake phosphorus concentrations are nearly double the historical levels. Although the lake would be classified as mesotrophic, nutrient input from the watershed should be reduced to maintain or improve the lake's water quality.

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Funding for this study was provided by The City of Shell Lake and Wisconsin Department of Natural Resources. Field work help was provided by John Haack and Dave Vold. Radiochemical analysis was provided by the Gary Krinke and Lynn West at the Wisconsin Laboratory of Hygiene. Geochemical analysis was provided by the University of Wisconsin Soil and Plant Analysis Laboratory.

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