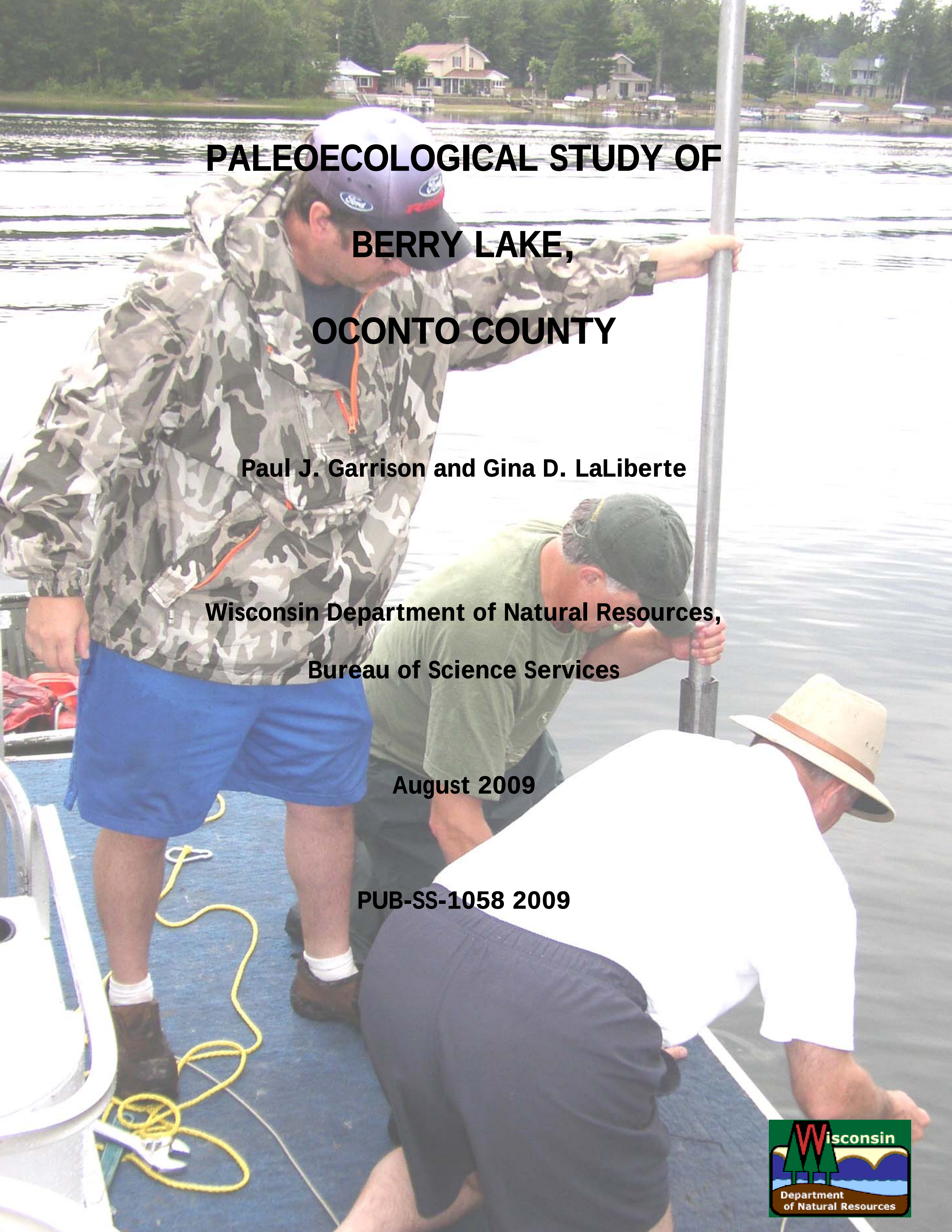

# PALEOECOLOGICAL STUDY OF

# BERRY LAKE,

# OCONTO COUNTY


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## Introduction

Questions often arise concerning how a lake's water quality has changed through time as a result of watershed disturbances. In most cases there is little or no reliable long-term data. People want to know 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 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.

Berry Lake, Oconto County, is a 201 acre lake according to the Wisconsin Department of Natural Resources but it is often less due to low water levels. The maximum depth is 27 feet with a mean depth of 7 feet. A sediment core was collected from the west basin on 4 July 2007. The location of the coring site was 44.88898° north and 88.48521° west in 15 feet of water (Figure 1). Although the east basin is deeper, the core was not taken there because the sediment may have been disturbed by boat anchors. Instead the core was taken in the western basin. The core was sectioned into 1 cm intervals in the top 40 cm and 2 cm intervals from 40 to 92 cm. The core was collected with a piston corer with an inside diameter of 8.8 cm. The core was dated by the $^{210}$Pb method and the CRS model used to estimate dates and sedimentation rate. The diatom community was analyzed to assess changes in nutrient levels and changes in the macrophyte community. Geochemical elements were examined to determine the causes of changes in the water quality and changes in oxygen conditions in the bottom waters.

*Site History*

Berry Lake was formed at the end of the last glacial period over 11,000 years ago. A core collected by Dr. Samantha Kaplan found that underneath the lake's mucky sediments is a layer of sand and clay. More recent sediments are mostly muck with some sand lenses. Her analysis indicates that for much of the last 11,000 years little or no sediment was permanently deposited until about 3500 years ago. This means the amount of lake sediments is much less than many lakes. In the East Basin she measured about 1 meter of mucky sediments.

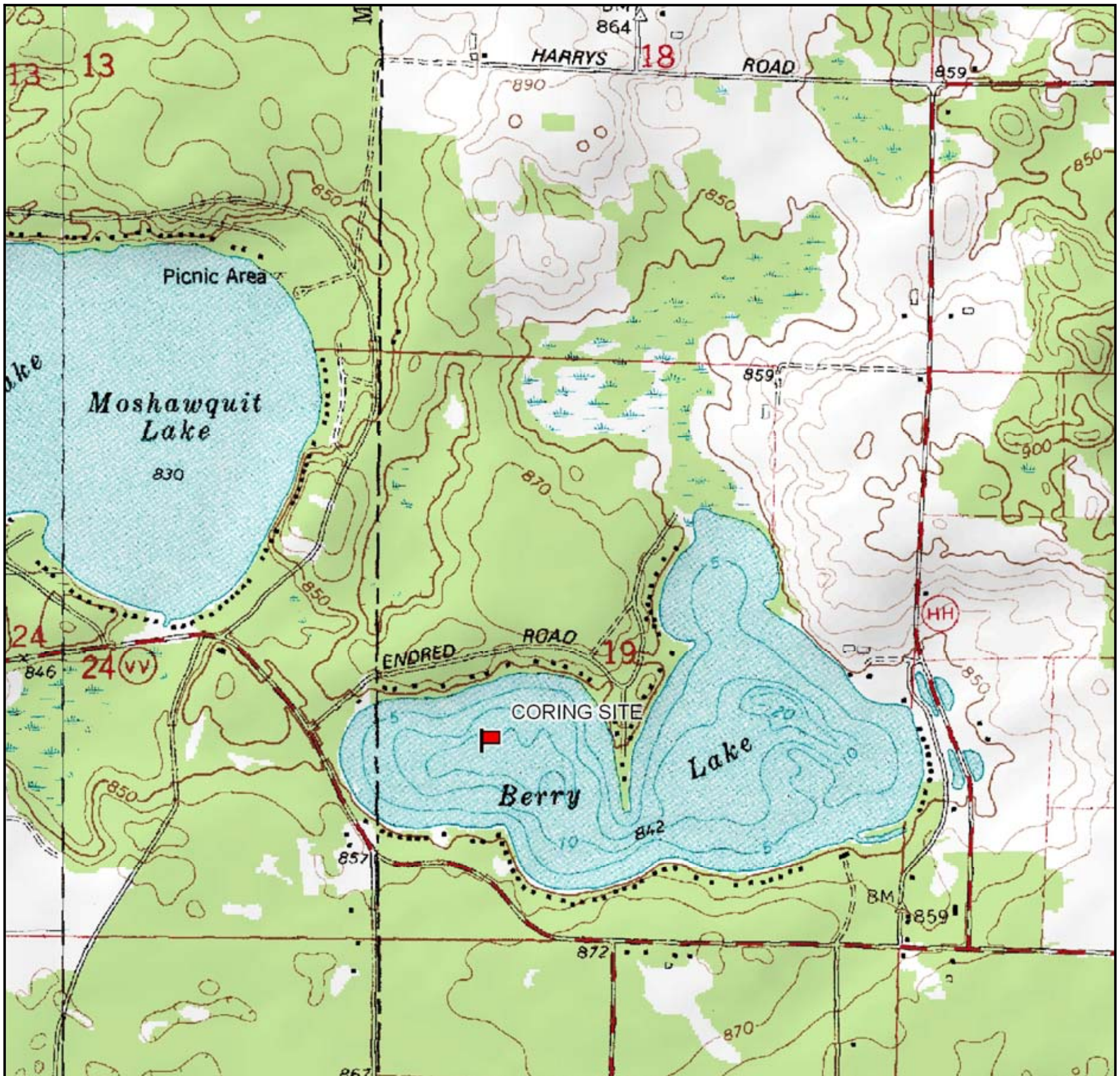


**Figure 1.** Map of Berry Lake showing the coring site in the west basin. The water depth at the site was 15 feet.

The area around Berry Lake was surveyed by the General Land Office in December 1845. A sketch map of the township where the lake is located is shown in Figure 2. The map shows an Indian Trail that traverses about 1/2 mile south of the lake. When the township was surveyed in 1845, there were already 10 lots around the lake (Figure 3).

The area around Berry Lake has experienced forest fires. One such fire occurred in 1914, especially on the north shore of the west basin. The north side of the lake was platted for development in 1917 but cottages were not built until the 1920s. Other cottages were built around the lake during this same period. Some photos from this period seem to show that there was considerable vegetation between the cottages and the lake shore. The density of cottages increased in the late 1930s, especially along

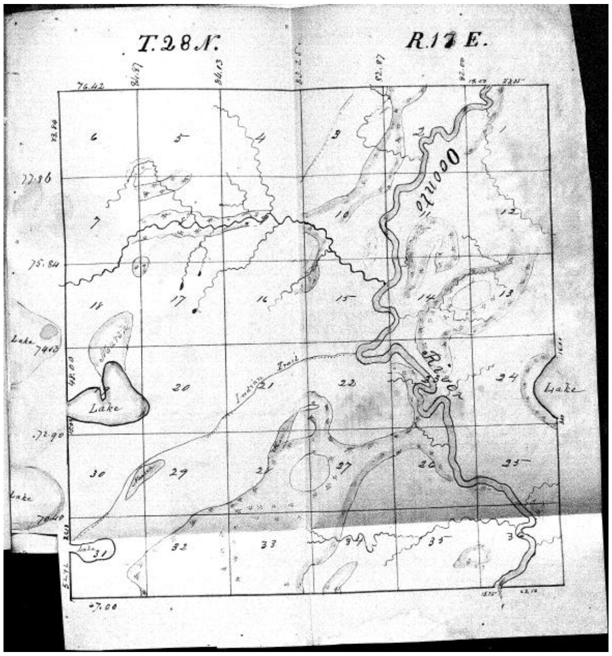


**Figure 2.** Sketch map of Underhill Township made by original land surveyor in 1845. Berry Lake is shown in the left hand side of the map.


**Figure 3.** Plat map of Underhill Township drawn from survey notes taken in 1845. At this time there are 10 lots platted around Berry Lake.

the south shore of the west basin. Photos from this time indicate the amount of the vegetation in this area is sparse and the trees are small suggesting that either burns had occurred recently or a cut-over had occurred.

Although the density of cottages probably increased after 1940, more important was the increase in size of the cottages and longer periods of habitation. During the last few decades the footprints of these homes has increased resulting in a larger amount of impervious area and suburbanization of the landscape. This has likely resulted in more runoff of sediment and nutrients into the lake. the density of dwellings around the lake is fairly high. There are 35 homes per mile which is a density more similar to southern WI lakes than the northern part of the state (Garrison and Wakeman 2000).

## 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 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-1800s. Sediment ages for the various depths of sediment were determined by

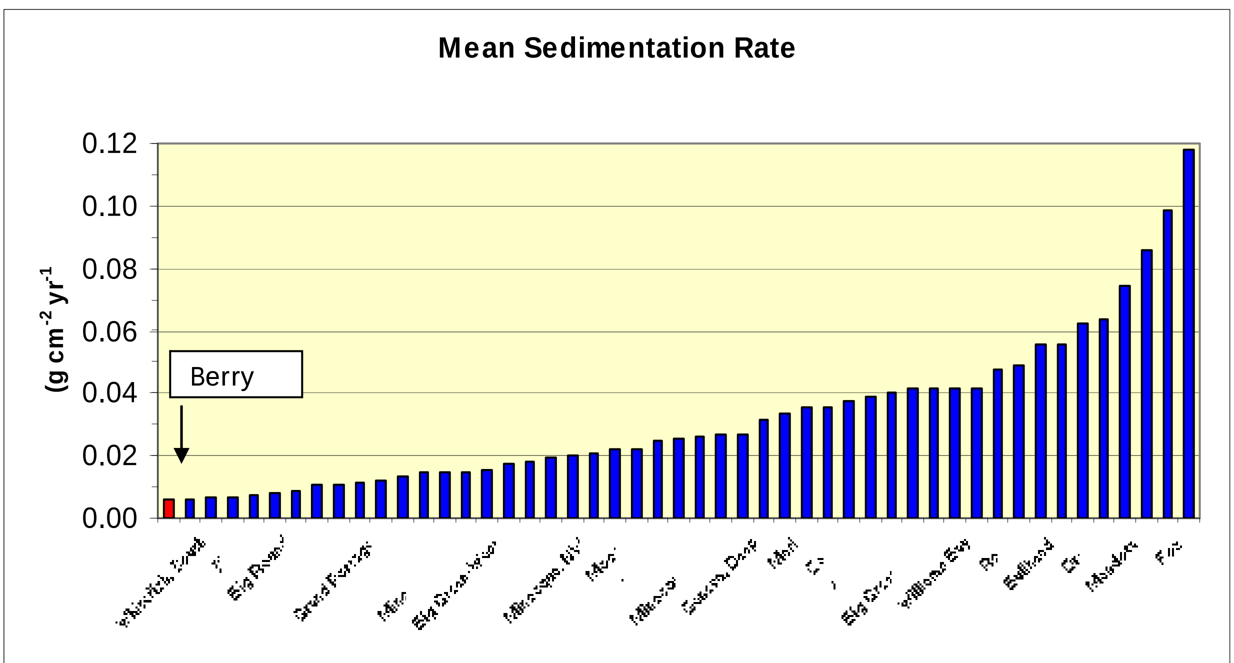


**Figure 4.** Mean sedimentation rate for the last 150 years for 52 Wisconsin lakes. The arrow indicates Berry Lake. This lake has the lowest measured rate. This is partially because the lake is relatively shallow and a seepage lake.

constant rate of supply (CRS) model (Appleby and Oldfield, 1978). Bulk sediment accumulation rates (g $cm^{-2}$ $yr^{-1}$) were calculated from output of the CRS model.

*Sedimentation Rate*

In Berry Lake the mean mass sedimentation rate for the last 200 years was 0.006 $cm^{-2}$ $yr^{-1}$ (Figure 4). This is the lowest rate that has been measured in 52 Wisconsin lakes. One of the contributing factors for the low rate is the lake's hydrology which is seepage. Without an inflowing stream, less material is delivered from the watershed. Another factor is the relative shallow depth of the lake. Deeper lakes often experience more sediment focusing, which increases their sedimentation rate. In fact there does not appear to be any sediment focusing at the coring site. Other shallow seepage lakes, however, show higher rates of sedimentation. The low mean rate is indicative that the rate of sediment entering the lake is lower than most other lakes.

To account for sediment compaction and to interpret past patterns of sediment accumulation, the dry sediment accumulation rate was calculated. The sedimentation rate was very low in the first half of the nineteenth century being 0.003 $cm^{-2}$ $yr^{-1}$ and increased a small amount in the last half of that century. The rate was still low until the 1940s when it began to increase dramatically and peaked during

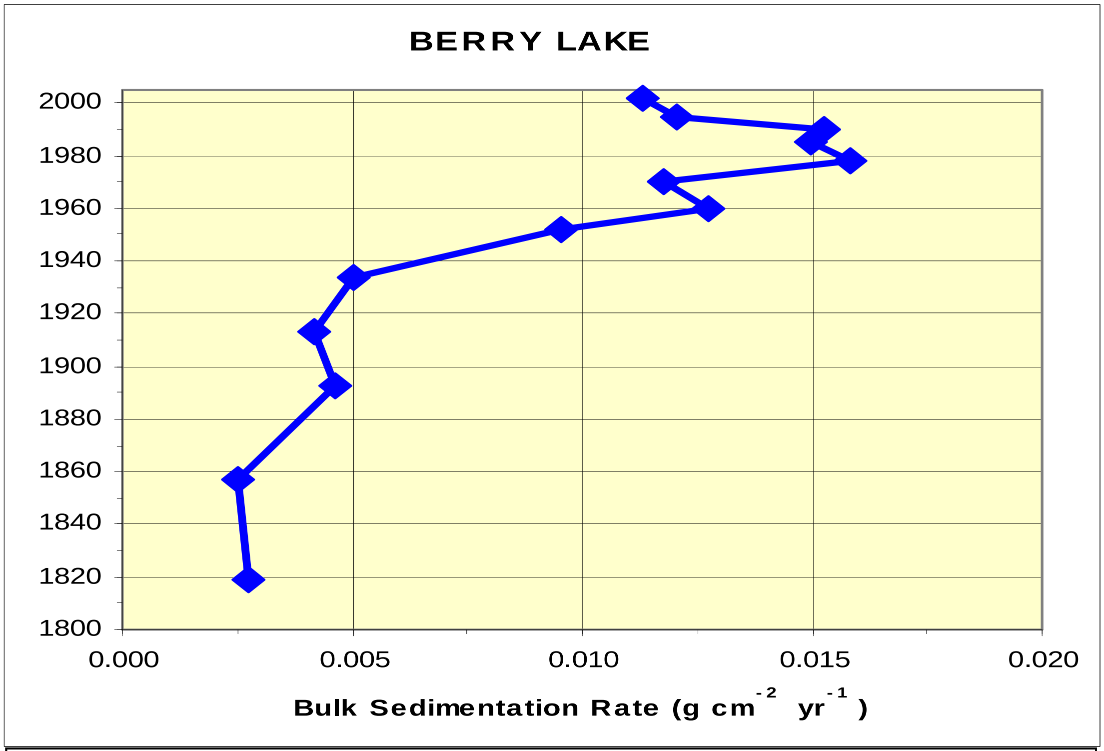


**Figure 5.** Sediment accumulation rate in Berry Lake. The historical rate was very low. The large increase after 1940 was likely the result of shoreline development.

the 1970-80s at 0.015 $cm^{-2}$ $yr^{-1}$ (Figure 5). During the last 15 years the sedimentation rate is slightly lower but it is still much higher than the historical rate. It is likely that this increase in the rate is largely the result of shoreline development. Beginning in the late 1930s there was an increase in cottage construction. Along with construction site erosion there may have been changes in the groundcover near the lakeshore. Prior to development, there would have been substantial native vegetation in the form of shrubs and trees along the shoreline. With development this land surface would have undergone more frequent anthropogenic use resulting in compaction of the soil and likely removal some of the shrubs and trees. Increased soil erosion during this construction phase has been observed in other Wisconsin lakes (Garrison and Wakeman 2000). Studies have documented that more sediment enters the lake with home development (Dennis 1986, Graczyk et al. 2003) compared with shorelines with undisturbed vegetation.

*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.

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

| **Process** | **Chemical Variable** |
|---|---|
| Soil erosion | aluminum, potassium, titanium |
| Synthetic fertilizer | potassium |
| Urban | zinc, copper, aluminum |
| Ore smelting | zinc, cadmium, copper |
| Nutrients | phosphorus, nitrogen |
| Lake productivity | Organic matter |

Zinc is associated with urban runoff because it is a component of tires and galvanized roofs and downspouts. Potassium is found in soils as well as synthetic fertilizers. Therefore, its profile will reflect changes both from soil erosion and the addition of commercial fertilizers in the watershed. 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 includes a number of elements, especially carbon.

The concentration of titanium, which indicates soil erosion, was stable from 1800 until the second half of the twentieth century (Figure 6). In the 1940s there was a slight increase in soil erosion but the largest increase began around 1960 and peaked in the mid-1980s. This increase in soil erosion was likely the result of increased suburbanization of the homes around the lake. Such an increase in soil erosion from shoreline development has been observed in other Wisconsin lakes during this time period (Garrison and Wakeman 2000, Garrison 2008). Although there may not have been a large increase in the number of dwellings during this time period, frequently what occurs is an increase in the size of the homes. This, along with associated activities, e.g. larger driveways and patios, results in a greater amount of impervious area leading to more water runoff and associated sediment into the lake. The decline in the concentration of titanium during the last 15 years indicates a decline in the soil erosion but the titanium concentration is still much higher than historical levels.

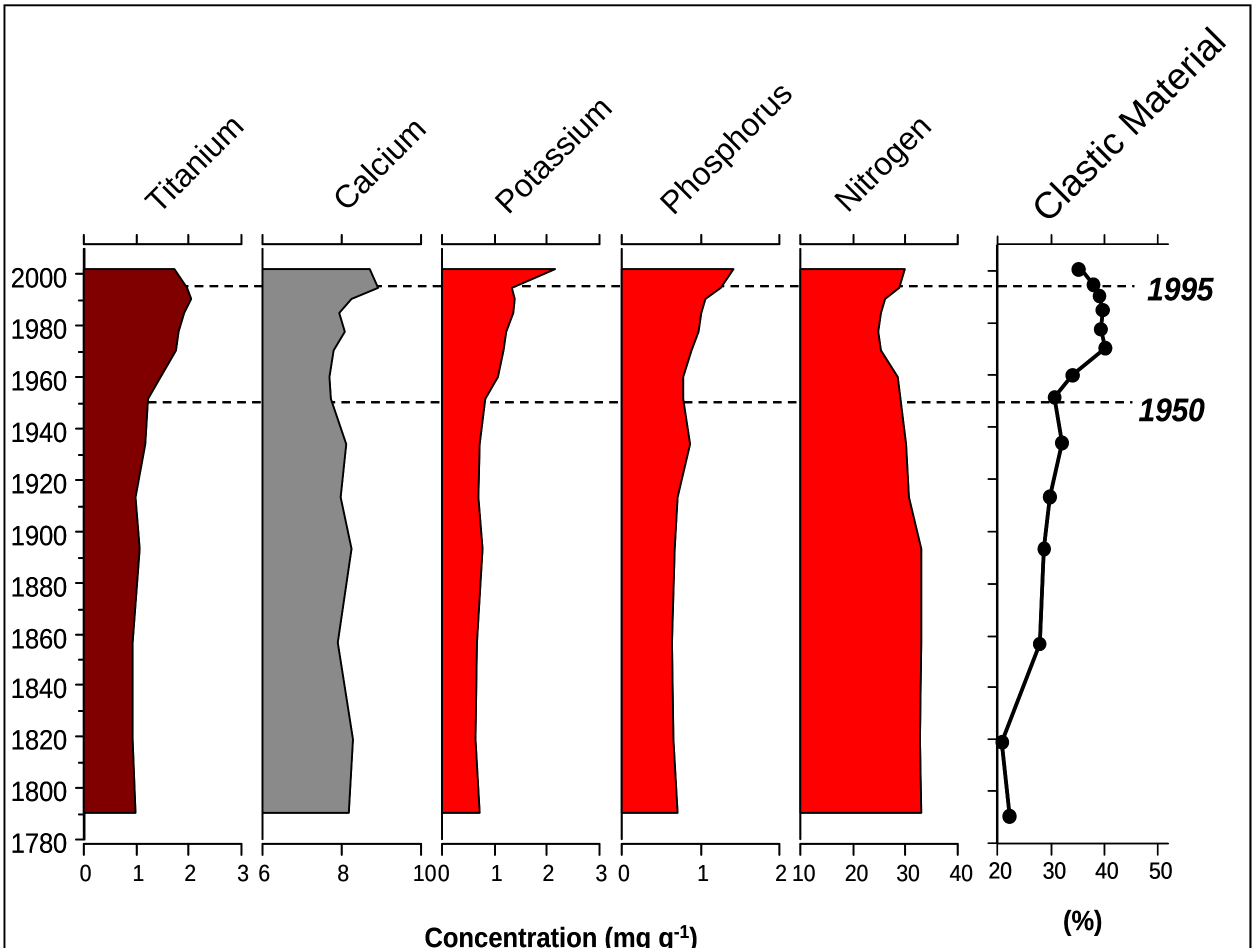


**Figure 6.** Profiles of the concentration of selected geochemical elements. Titanium profiles are indicative of soil erosional rates. Calcium is often applied as a soil amendment in lawns. Phosphorus and nitrogen are essential nutrients for plant growth. Potassium can indicate either soil erosion or fertilizer use. At the top of the core it likely indicates fertilizer usage. Clastic materials are inorganic materials that often are indicative of soil erosion.

Clastic material is nonorganic substances found in the sediments. These materials are often the result of sediment washing into the lake. Although the level of this material increased somewhat after the mid-1800s, the highest amounts were between the period 1965-1990. This peak is likely another indication of increased soil erosion during this period. As with titanium, the levels have dropped some at the top of the core but they remain much higher than historical concentrations.

Calcium is often used as a soil amendment in poor soils like those around Berry Lake. Calcium levels are highest at the top of the core during the last decade. This is likely an indication of increased lawn care and suburbanization of the shoreline properties.

Potassium is found both in synthetic fertilizer, along with nitrogen and phosphorus, as well as clay particles associated with soils. Concentrations were constant and low from the late eighteenth century until about 1960 when levels began to rise. Soil erosional rates also increased around 1960 indicating the potassium increase may have been the result of increased sediment runoff into the lake. Even though soil erosional rates began to decline around 1990, potassium continued to increase. In fact, the highest concentrations occurred at the top of the core. It appears that since 1990 much of

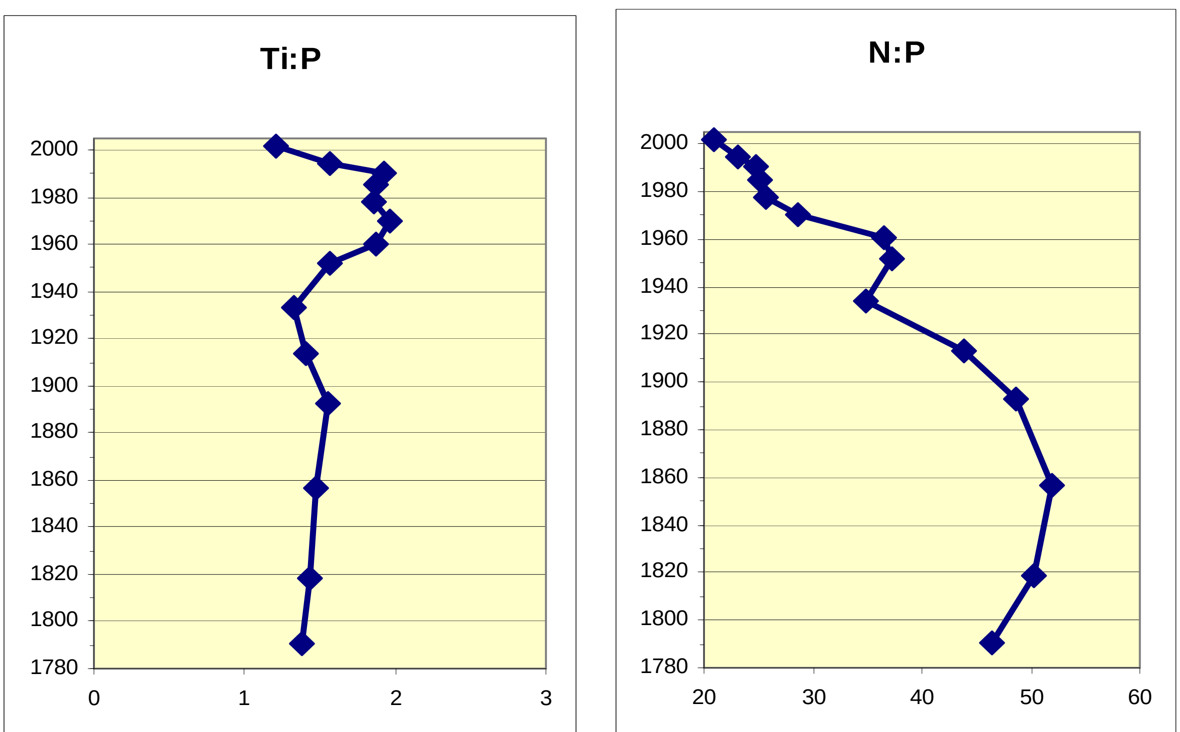


**Figure 7.** Profiles of the ratio of titanium to phosphorus and nitrogen to phosphorus in the sediment core. Titanium is an indication of soil erosion. The decline in the ratio since 1990 indicates that phosphorus is entering the lake from other sources than sediment particles. Both nitrogen and phosphorus are found in macrophytes which were common at the coring site. The preferential increase in phosphorus over nitrogen indicate the increased phosphorus levels are not the result of macrophyte growth.

the increase was the result of the application of synthetic fertilizers to lawns on the lake shore. This agrees with the increase in calcium at the same time.

Phosphorus is the limiting nutrient for algal growth in the lake and thus is the most important nutrient to control. Phosphorus levels were stable during the 1800s but increased slightly in the 1930s with early cottage construction. Since 1960, the concentrations have continually increased and their highest levels are at the top of the core. Some of the phosphorus input is likely associated with soil particles. The ratio of titanium to phosphorus can be used to estimate the amount of phosphorus from this source. This ratio is shown in Figure 7. The decline in the ratio during the 1930s indicates that sources of phosphorus other than soil particles contributed to the phosphorus deposition. During the period 1960-1990 much of the phosphorus entered the lake attached to soil particles. During the last decade other sources likely contributed much of the phosphorus since the ratio declined.

Although nitrogen is an important nutrient, its profile is much different than phosphorus (Figure 6). Most of the nitrogen in the sediment is probably associated with deposited material from the macrophytes which were common at the coring site. The decline in nitrogen in the first half of the twentieth century probably reflects dilution of the nitrogen by clastic materials deposited in the lake from shoreline sediment input. The increase of nitrogen levels at the top of the core also likely reflects a decline in the amount of soil erosion entering the lake.

Part of the increase in phosphorus and nitrogen at the top of the core may reflect post-depositional diagenesis. Diagenesis is the conversion of organic material, to other forms. These other forms may be volatile so that the element leaves the system. For example, as nitrogen in its organic form is degraded, one form is a gas which may escape into the atmosphere. Other authors have noted that phosphorus and nitrogen profiles may not reflect the lake's eutrophication history because of diagenesis (Schelske et al. 1988, Anderson and Rippey 1994, Fitzpatrick et al. 2003). Over the course of a few years some organic fractions of P and N breakdown into the inorganic components. Some of this material then may be recycled into the water column and out of the sediments. An estimate of the degree of diagenesis in sediments can be derived from the ratio of nitrogen to phosphorus (N:P). The large decline in this ratio during the twentieth century and especially near the top of the core likely indicates that diagenesis is not a significant factor affecting the increase in the phosphorus concentrations at the top of the core. Both nitrogen and phosphorus are subject to diagenesis but the greater relative increase in P compared with N indicates increased deposition of phosphorus in the last decade. This increase in phosphorus is likely from activities associated with shoreland development.

*Diatom Community*

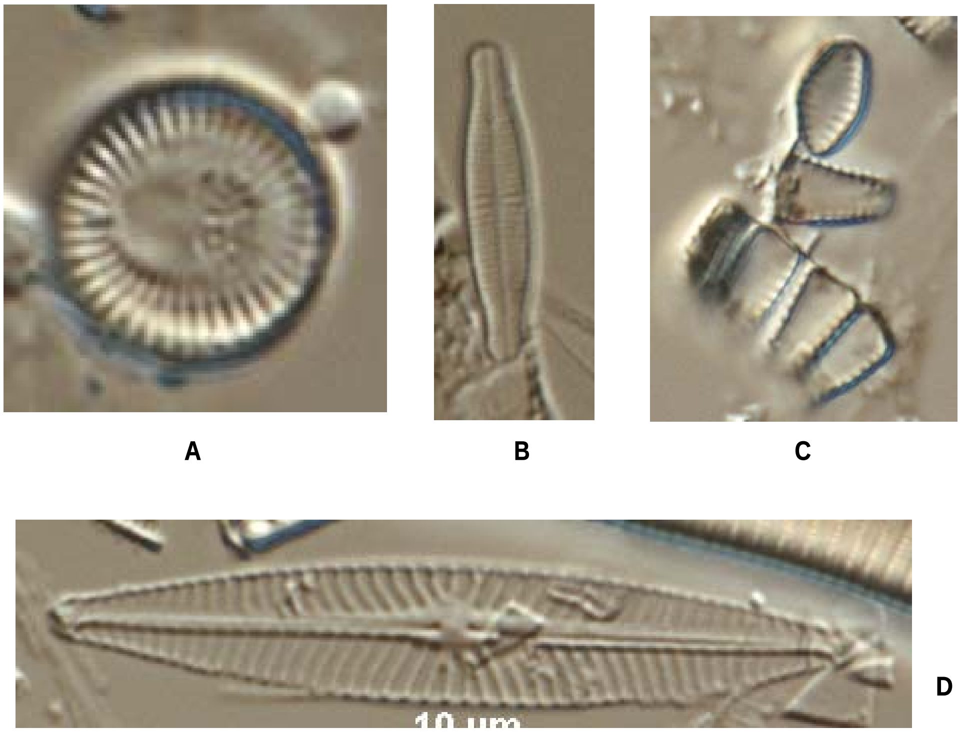


**Figure 8.** Photomicrographs of common diatoms found in the Berry Lake core. The diatom at the top left (A) is *Cyclotella michiganiana*, a common species found in the open water. The other diatoms grow in submerged aquatic vegetation beds. *Achanthidium minutissima* (B) is a pioneering species that is most common during early watershed disturbance. *Staurosirella pinnata* (C) becomes common at higher nutrient levels than *A. minutissima*. The *Navicula* shown in D may be a new diatom in the literature. It is very common throughout the core from the lake.

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. Some 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 under a variety of habitats, which enables us to reconstruct changes in nutrient levels in the open water as well as changes in benthic environments such as aquatic plant communities. Figure 8 shows photographs of four diatom species that were found in the sediment core.

The only open water diatom species that was common in the core was *Cyclotella michiganiana* (pictured in Figure 8A). This diatom is commonly found in lakes with low to moderate phosphorus concentrations (Garrison and Wakeman 2000). Most of the diatoms were species that grow attached to

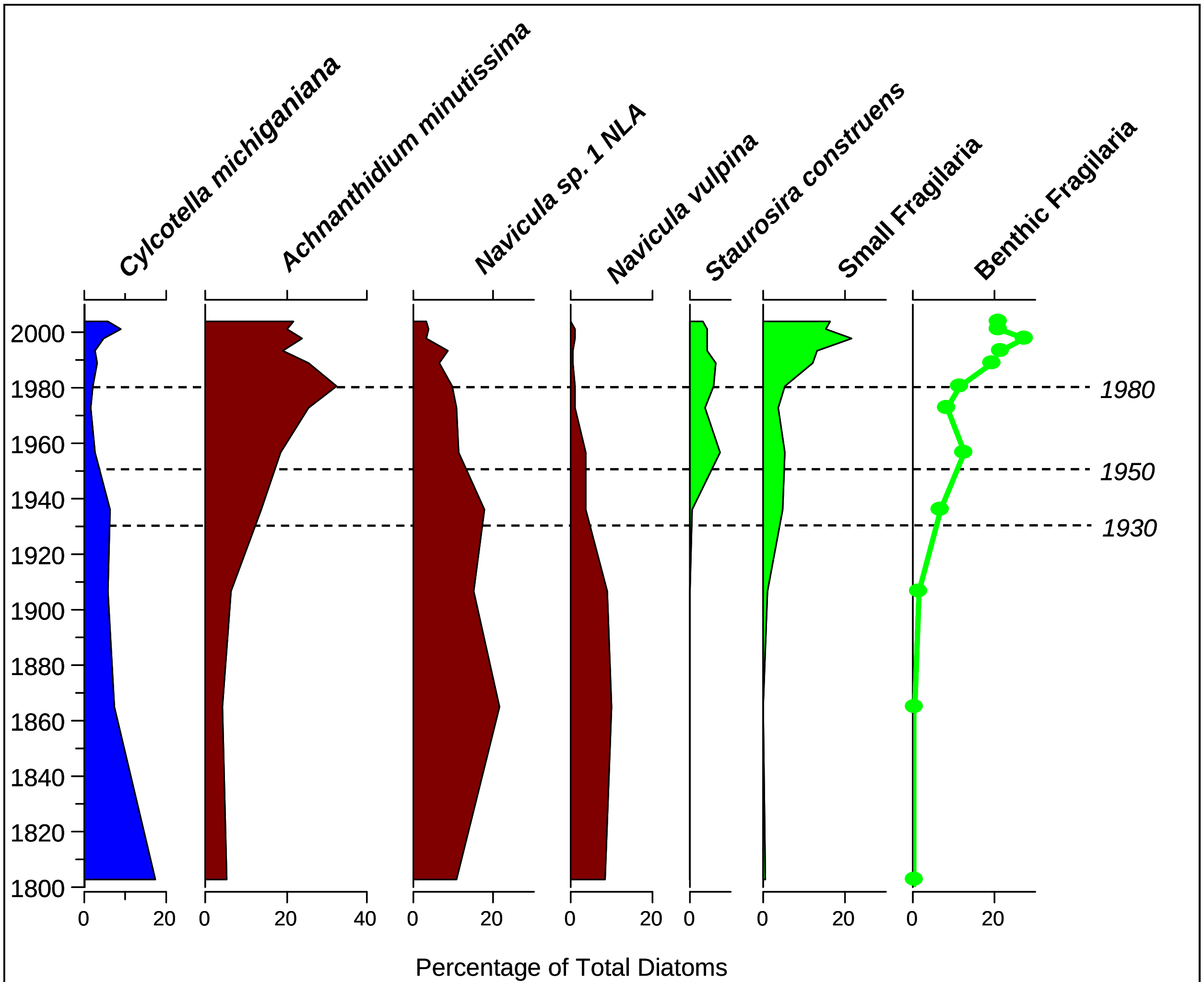


**Figure 9.** Profiles of common diatoms found in the core. The blue taxa (*C. michiganiana*) is the only species found floating in the open water. The other species grow attached to substrates like macrophytes. The species colored green are indicative of higher phosphorus levels.

substrates, e.g. macrophytes. This is not surprising since Berry Lake is relatively shallow. The relatively low numbers of open water diatoms at the bottom of the core indicates that the lake has had a substantial macrophyte community at least for the last 200 years.

During the nineteenth century the dominant diatoms were large species of the genera *Navicula* (Figure 9). These taxa usually are associated with macrophytes and relatively low nutrient levels (Lange-Bertalot 2001). The dominant species, *Navicula* sp. 1 NLA (Figure 8D) has not been described in the scientific literature. Its appearance in Berry Lake is the first recorded in Wisconsin.

These *Navicula* species began to decline around 1930 and were replaced by smaller benthic species. One important replacement taxa was *Achanthidium minutissima* (pictured in Figure 8B). This species is one of the first to appear when nutrient levels begin to increase (Garrison and Wakeman 2000). As nutrient levels continue to increase, benthic Fragilariaceae increase in numbers and may replace *A. minutissima* (Karst and Smol 2000; Garrison and Fitzgerald 2005). While these benthic Fragilariaceae first appeared in significant numbers around 1930, they become more important after 1980 and partially replace *A. minutissima* (Figure 9). This change in the diatom community indicates that nutrient levels began to increase around 1930 but further increased during the 1980s.

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 lim-

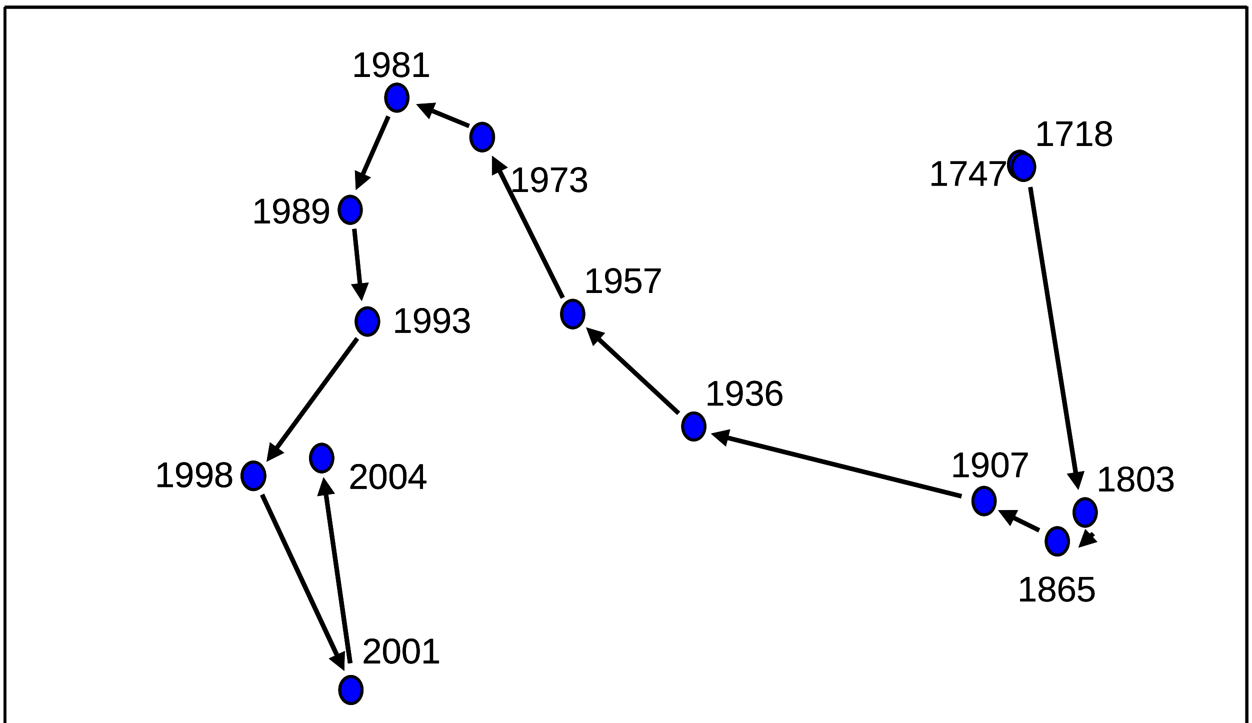


**Figure 10**. Plot of a DCA analysis of the diatom community in the sediment core. This analysis does not determine what ecological factors have caused the change in the diatom community only that the community is different.

nological 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.

A detrended correspondence analysis (DCA) was performed on the diatom community in the sediment core (Figure 10). This analysis separates the samples on differences in the diatom community. It does not determine what ecological factors have caused the changes in the community. The analysis shows that the samples from the 1700s were very similar but the community was different in the 1800s and early part of the twentieth century. With the beginning of shoreland development during the 1920s the diatom community continually changed. These changes are not necessarily phosphorus related but this analysis does show that lake's ecology has been impacted by development. This analysis indicated the diatom community may have stabilized somewhat during the last decade as the plots for the samples during this period are somewhat similar.

A weighted average model of the historical phosphorus levels was performed with the diatom community. This model indicates that pre-settlement phosphorus levels were 12-13 µg $L^{-1}$ (Figure 11) and they first increased in the early twentieth century, although by only a small amount. The model indicates a decline in phosphorus levels between 1940 and 1980 but this is likely not a correct assumption. This decline is largely driven by the increase in *A. minutissima* which is often found in other lakes at lower phosphorus levels then experienced in Berry Lake. The model indicates that the highest phosphorus levels occurred after 1990 and the present concentrations are the highest throughout the last 200 years (Figure 11).

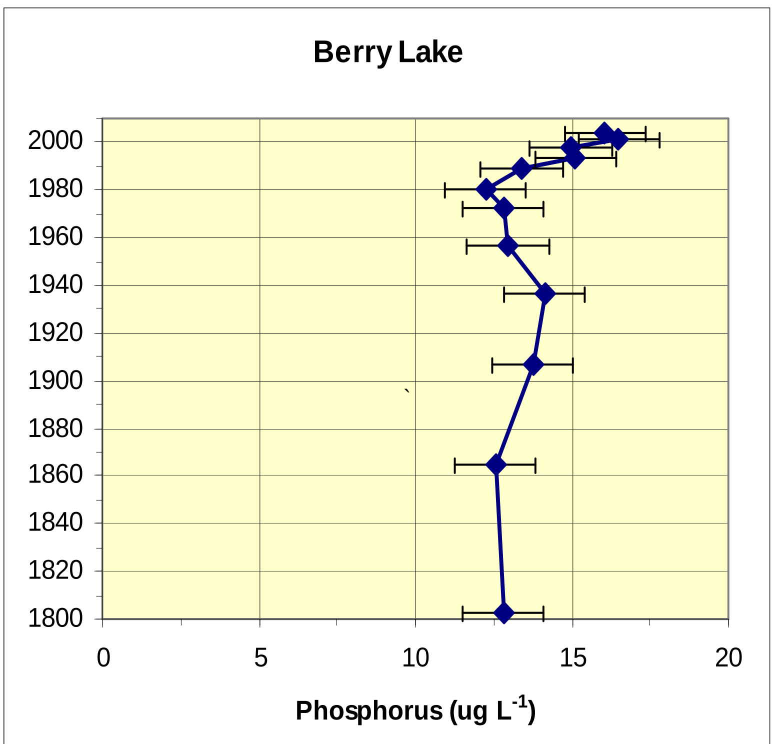


**Figure 11.** Estimated summer phosphorus levels in the core. These values were inferred from the diatom community using weighted averaging modeling.

The diatom community indicates that Berry Lake has had a substantial macrophyte community at least for the last 200 years. During the 1800s phosphorus levels were relatively low. The beginning of cottage development in the 1920-30s, resulted in increased nutrient levels. This was likely the result of runoff from the near shore area. Phosphorus levels remained low, probably around 13-14 µg $L^{-1}$. Phosphorus levels increased much more beginning in the late 1980s and this was likely because of increased development around the lake. During this time period, redevelopment occurred with the result that structures became larger with more impervious area allowing a greater amount of water to be washed into the lake. The increased input of water also brought more phosphorus into the lake. A study conducted in northern WI found that developed sites when compared with undeveloped sites, contribute higher amounts of phosphorus primarily because of increased water flow (Graczk et al. 2003). If more of the water remains on the land it percolates into the soil and the phosphorus does not wash into the lake. Sediment cores from other lakes in northern Wisconsin have shown that one of the most common impacts of shoreline development has been an increase in macrophyte growth with little increase in the phosphorus levels. (Fitzpatrick et al. 2003; Garrison 2005a, b; Garrison 2006; Garrison 2008). Berry Lake appears to have experienced a greater increase in phosphorus as a result of shoreline development. This may be because of its relatively small size and shallow depth. It also may be because the housing density is greater than in the other studies. This indicates that Berry Lake is more sensitive than some other lakes and therefore a strong effort should be made to restrict shoreline runoff.

Berry Lake undergoes large changes in water levels, primarily because the lake is a seepage lake and it is relatively high in the groundwater landscape. One of the possible sources of phosphorus is the reflooding of the lake shore as water levels rise following a drought. Detailed water levels have been continuously measured at Berry Lake since 1942 by the Notbohm's by measuring the distance from their bottom step to the water's edge.

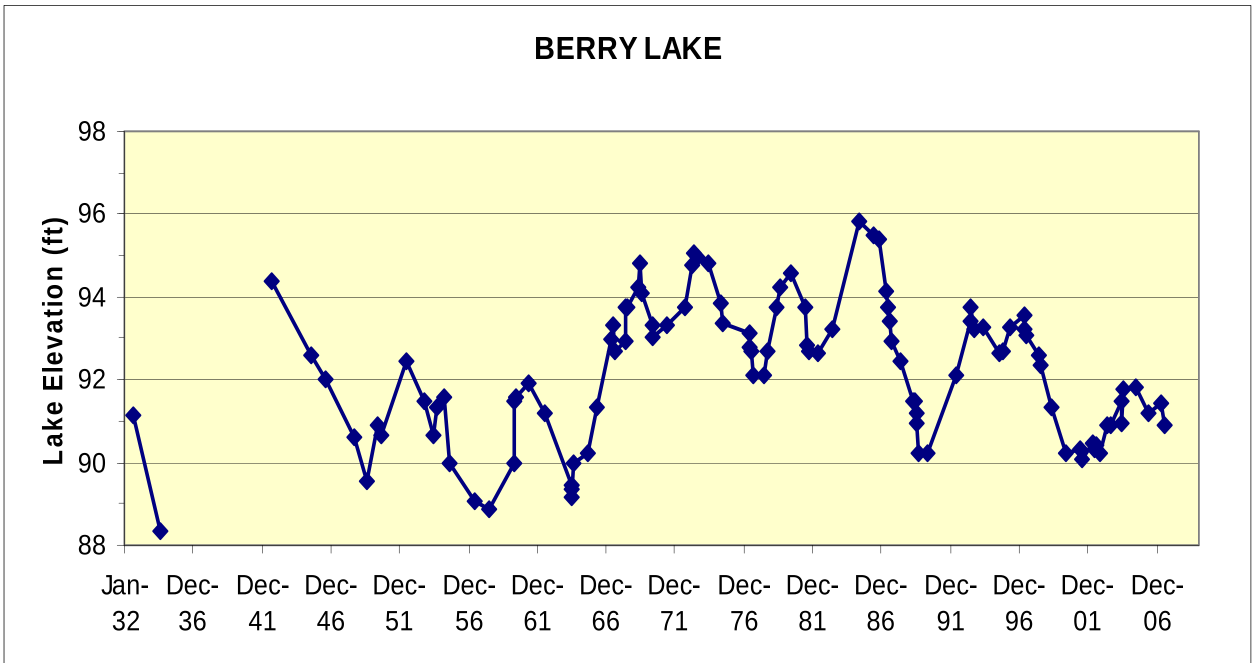


**Figure 12.** Lake levels for Berry Lake. Levels were measured at least annually from 1948-2009. Additional measurements were made intermittently from 1932 to 1946. Originally the width of the beach was measured from the steps of the Notbohm residence to the water's edge. A survey taken in 2008 by Tom Milheiser and Brian Ewart allows conversion of these measurements to lake elevation. The value in Sept. 1932 was recorded by Walter Kirchhoff while the 1934 value was recorded on the Stiles boathouse.

Since records have been maintained starting in the 1930s, Berry Lake has experienced water level fluctuations of nearly 7.5 feet (Figure 12). Lake levels were the lowest during the early 1930s as well as late 1940s, late 1950s, mid 1960s, 1990, and 2002. High levels have occurred in 1942, early and mid-1970s, and the highest recorded level was in 1985.

Figure 13 is a comparison of phosphorus concentrations estimated from the diatom community and lake levels. It is clear that changing lake levels contribute only small amounts of phosphorus to the lake. Instead the greatest increases occurred when the shoreland development increased during the last 25 years. While changing lake levels may pose an access problem for the lake, it does not appear that changing lake levels are a significant source of nutrients to the lake.

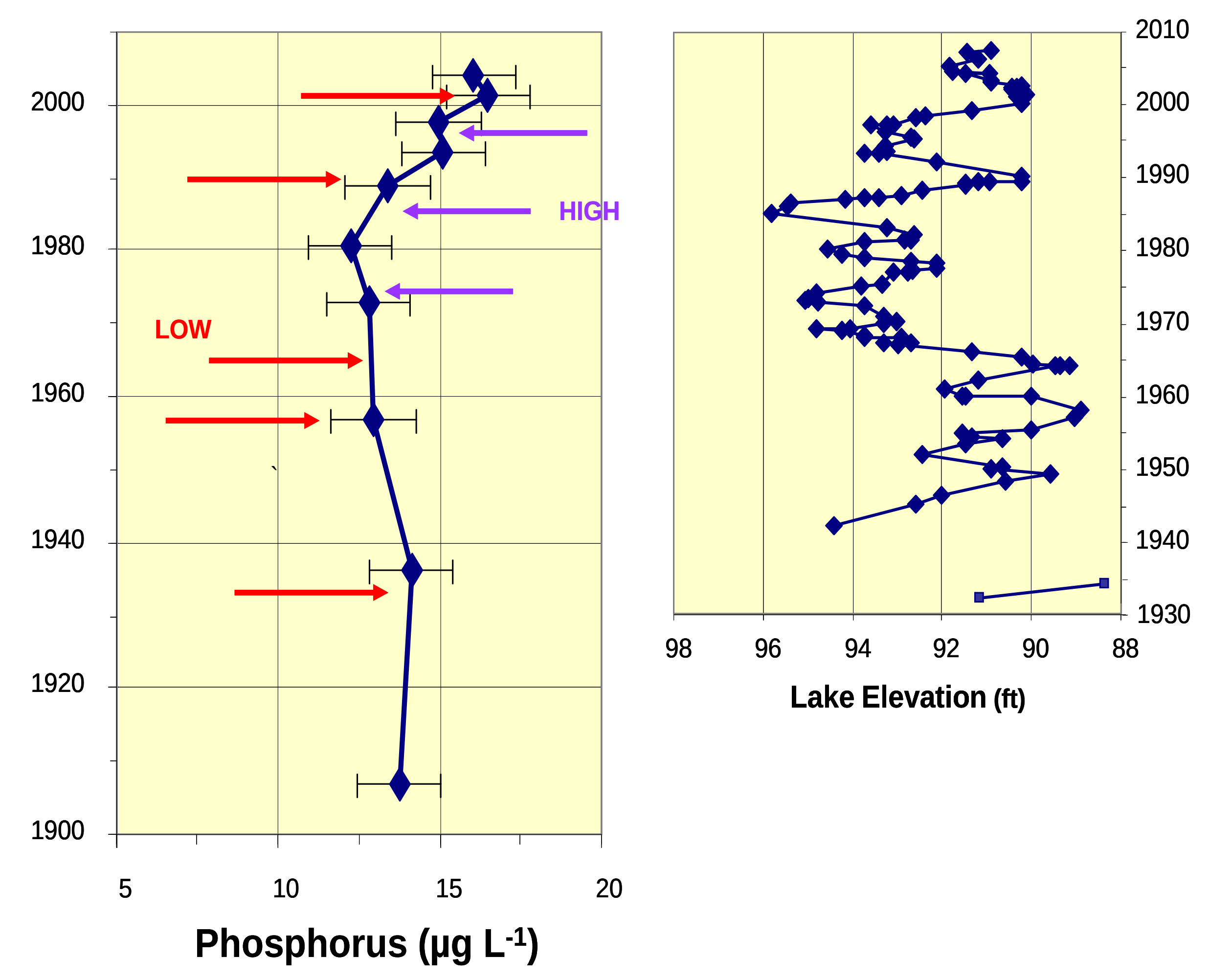


**Figure 13.** Comparison of phosphorus concentrations estimated from the diatom community during the last 100 years and lake levels. In the graph on the left, "low and high" indicate lake level low and high points. It is clear that changing water levels are not contributing significant amounts of phosphorus to the lake. It is more likely that the increased phosphorus during the last decade is the result of runoff from shoreland development.

- The mean sedimentation rate for the last 150 years in Berry Lake was the lowest measured in 52 Wisconsin lakes.
- The sedimentation rate first began to increase around 1900, but a much more significant increase began in the 1950s and peaked in the 1980s. This was most likely the result of cottage development.
- The increased sedimentation rate during the period 1950-1990 was largely the result of increased soil erosion.
- The rate of soil erosion has declined since 1990 but the input of material from lawn maintenance has increased during this time period.
- The increase in concentrations of calcium and potassium during the last 20 years indicates there has been increased application of soil amendments to promote lawn growth.
- The increased shoreland development during the last 20 years has resulted in an increase in the deposition of the nutrients phosphorus and nitrogen.
- Phosphorus deposition has increased at a faster rate than nitrogen.
- The diatom community indicated that nutrient levels increased slightly with the initial cottage development in the 1920-30s but the largest increase occurred during the last 20 years. This is the same time period that geochemical parameters indicate increased suburbanization of the lakeshore homes.
- Berry Lake seems to be particularly sensitive to nutrient input from shoreland development. This is likely a result of the lake's relatively small size and shallow depth.
- Great effort should be made to reduce the impact of shoreland development. One of the ways to do this is installation of buffers between the lawns and lake to reduce runoff. Another effective way to reduce runoff is to redirect water from impervious surfaces away from the lake. Any fertilizer added to lawns and plantings should not contain phosphorus.

## References


Anderson. N.J. and B. Rippey. 1994. Monitoring lake recovery from point-source eutrophication—the use of diatom-inferred epilimnetic total phosphorus and sediment chemistry. Freshwater Biol. 32:625-639.

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., and 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.

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.

Dennis, J. 1986. Phosphorus export from a low-density residential watershed and an adjacent forested watershed. in Fifth Annual Conference and International Symposium on Applied Lake and Watershed Management, 1986: Proceedings of the North American Lake Management Society, Lake Geneva, Wisconsin. Lakes and Reservoir Management. 2:401-407.

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. 141 pp.

Garrison, P.J. 2005a. Paleoecological Study of Round Lake, Sawyer County. Wisconsin Department of Natural Resources. PUB-SS-1011 2005

Garrison, P.J. 2005b. Assessment of water quality in Lake Owen, Bayfield County, Wisconsin by the use of fossil diatoms. Wisconsin Department of Natural Resources. PUB-SS-1014 2005.

Garrison, P.J. 2006. Paleoecological Study of Butternut Lake, Price/Ashland Counties. Wisconsin Department of Natural Resources. PUB-SS-1020 2006.

Garrison, P.J. 2008. Paleoecological Study of Grindstone Lake, Sawyer County. Wisconsin Department of Natural Resources. PUB-SS-1042 2008.

Garrison, P.J. and S.A. Fitzgerald. 2005. The role of shoreland development and commercial cranberry farming in a lake in Wisconsin, USA. J. Paleolimnol. 33:169-188.

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

Graczyk, D.J., R.J. Hunt, S.R. Greb, C.A. Buchwald, and J.T. Krohelski. 2003. Hydrology, nutrient concentrations, and nutrient yields in nearshore areas of four lakes in northern Wisconsin, 1999-2001. U.S. Geological Survey Water-Resources Investigation Report 03-4144. 64 pp.

Karst, T.L. and J.P. Smol. 2000. Paleolimnological evidence of limnetic nutrient concentration equilibrium in a shallow, macrophyte-dominated lake. Aquat. Sci. 62:20-38.

Lange-Bertalot, H. 2001. Diatoms of Europe, Volume 2, Navicula sensu stricto 10 Genera Separated from Navicula sensu lato Frustulia. A.R.G. Ganter Verlag K.G.526 pp.

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

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