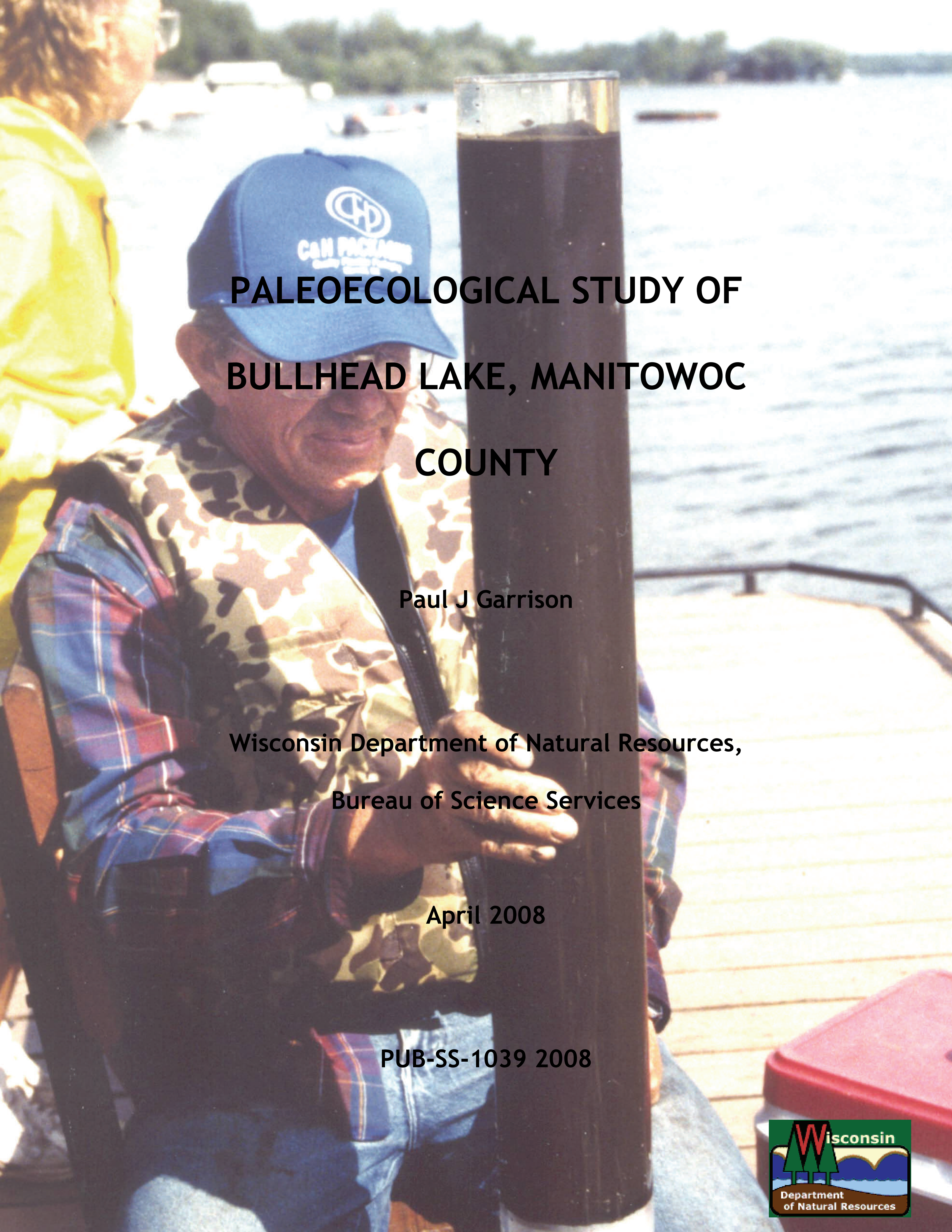

PALEOECOLOGICAL STUDY OF BULLHEAD LAKE, MANITOWOC COUNTY

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Introduction

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

Bullhead Lake is a 67 acre lake located in Manitowoc County. The maximum depth is 40 feet with a mean depth of 13 feet. A sediment core was collected from the deepest area of the lake on 30 September 1991. The core was collected with a piston core with a plastic tube having an inside diameter of 8.8 cm. The core was sectioned into 1 cm intervals for the first 20 cm and 2 cm intervals to the bottom of the core which was 70 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 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 is sometimes is found in high levels in basements) it moves into the atmosphere where it decays to lead-210. The ^{210}Pb is deposited on the lake during precipitation and with dust particles. After it enters the lake and it is in the lake sediments, it slowly decays. The half-life of ^{210}Pb is 22.26 years (time it takes to lose one half of the concentration of ^{210}Pb) which means that it can be detected for about 130-150 years. This makes ^{210}Pb a good choice to determine the age of the sediment since European settlement began in the mid-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 (g cm^{-2} yr^{-1}) were calculated from output of the CRS model (Appleby and Oldfield, 1978). Accumulation rates of geochemical variables were computed for each sediment depth by multiplying the bulk sediment accumulation rate (g cm^{-2} yr^{-1}) by the corresponding concentration (mg g^{-1}) of each constituent in the bulk sediment.

Sedimentation Rate

The mean mass sedimentation rate for Bullhead Lake the last 150 years was 0.056 cm^{-2} yr^{-1} (Figure 1). This is one of the higher rates I have measured for 48 Wisconsin Lakes. This is above the average sedimentation rate of 0.027 cm^{-2} yr^{-1} of these same lakes. The average linear rate in Bullhead Lake for the last 150 years was 0.53 cm yr^{-1} which equates to about 0.21 inch of sediment per year.

To account for sediment compaction and to interpret past patterns of sediment accumulation, dry sediment accumulation rates were calculated. The lowest sedimentation rate occurred in the deepest sediment slice that was dated. This corresponds with a date in the late 1880s which would have been after European settlers had arrived. It is likely the pre-settlement rate would have been slightly less but probably not a lot. It appears this lake has a moderately high historical sediment infilling rate.

By the early twentieth century the sedimentation rate had increased to the highest rate seen in the core (Figure 2). This may be the result of agricultural activity in the watershed. After 1920 the rate declined and remained lower until the mid-1970s. The rate steadily increased after that to the top of the core.

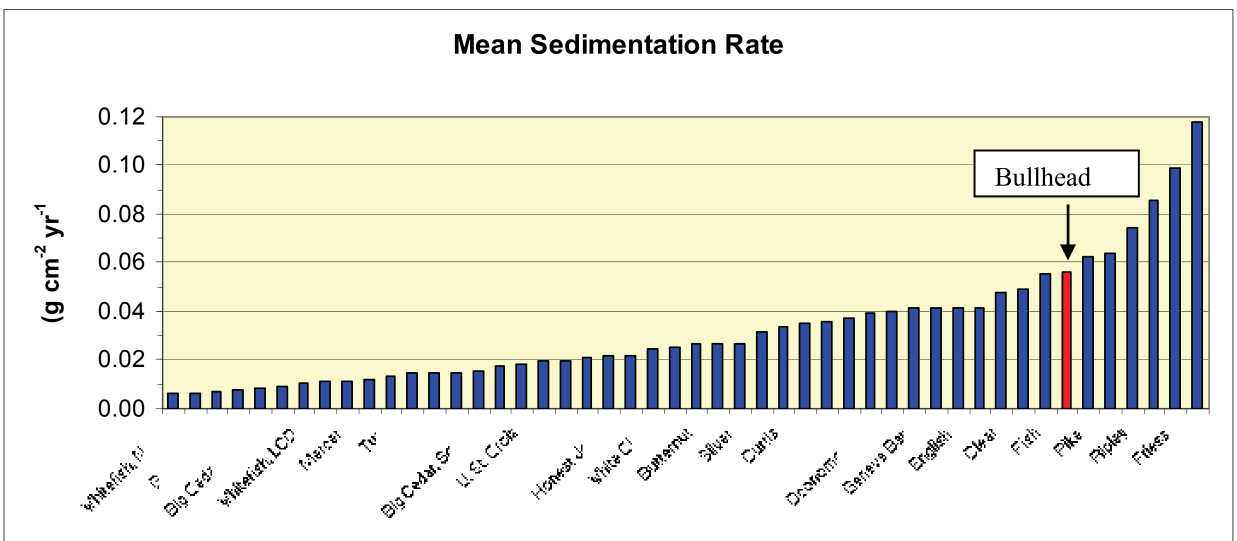

Figure 1. Mean sedimentation rate for the last 150 years for 46 Wisconsin lakes. The arrow indicates Bullhead Lake.

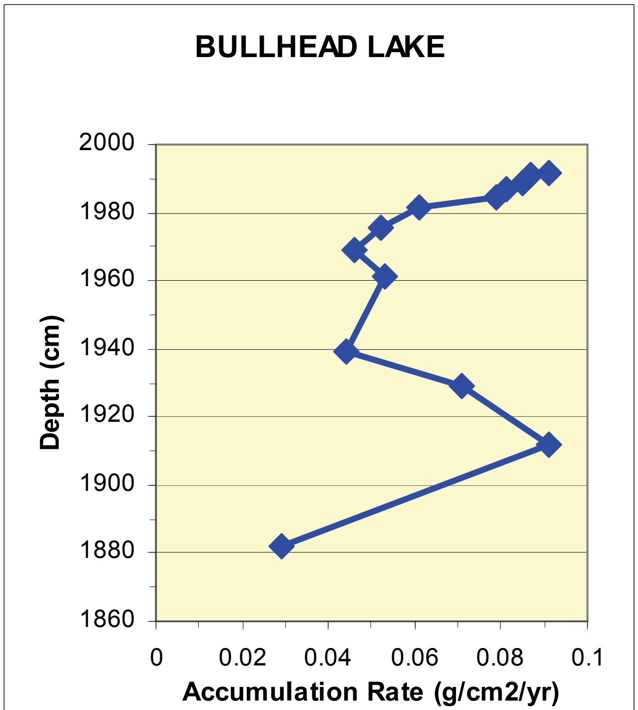

Figure 2. Sediment accumulation rate in Bullhead Lake since 1880. The higher rate near the bottom of the core is likely the result of agricultural activity in the watershed. The increased rate near the top of the core is also likely from agricultural activity in the watershed.

Sediment Geochemistry

Geochemical variables are analyzed to estimate which watershed activities are having the greatest impact on the lake. The chemical alumiinum (Al) is found in soil particles, especially clays. Changes in Al are an indication of changes in soil erosional rates throughout the lake's history. Nutrients like phosphorus and nitrogen are important for plant growth, especially algae and aquatic plants. Calcium carbonate is a common chemical in hardwater lakes like Bullhead Lake. These lakes are also known as marl lakes because they precipitate calcium carbonate. Organic matter is deposited in the lake as a result of algal and aquatic plant production in the lake.

At the bottom of the core, the accumulation rate of all the measured chemicals was elevated (Figure 3). This is not surprising since the sedimentation rate was also high in the early part of the twentieth century. The elevated levels of aluminum indicate the soil erosional rate was high. The nutrients entering the lake as a result of the sediment resulted in increased productivity in the lake. The increase in productivity raises the pH causing increased deposition of marl. The relative increase of calcium was greater than aluminum. This indicates that some of the increased calcium deposition is coming from within the lake, and not just from soil washing into the lake.

As with the sedimentation rate, the depositional rate of all the chemical declined after 1930 until the 1960s. Soil erosion increased again starting in the late 1960s but the greatest increase occurred after the mid-1980s (Figure 3).

In the late 1970s the Bullhead Lake was treated with alum to reduce the internal loading of phosphorus. The episodic input of alum is reflected a temporary reduction of the deposition of rate of most of the chemicals. Alum is largely aluminum sulfate so its deposition dilutes the other variables. The exception is organic matter. As the alum settles to the bottom of the lake it traps large amounts of organic matter in the water column which are then carried to the sediments. It appears surprising that

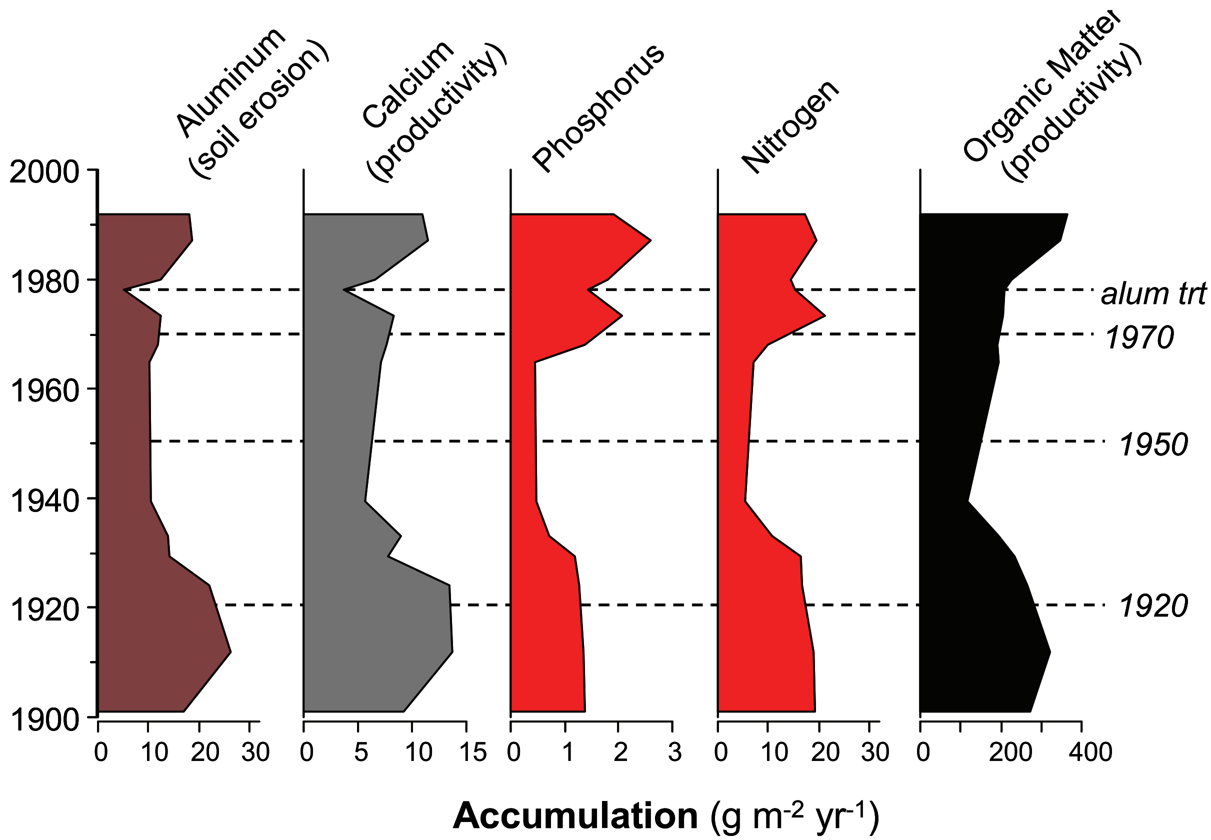

Figure 3. Profiles of selected chemical variables. Some of the highest soil erosion rates occurred during the early twentieth century. Although soil erosion again increased around 1980, the deposition of the nutrients phosphorus and nitrogen increased at a greater rate.

the Al profile as reflects a decline during the alum treatment but this is because the form of Al measured is different than the form of Al in alum.

Both phosphorus and nitrogen were deposited at reduced rates during the period 1930-1965 (Figure 3). During the mid-1960s their deposition rate significantly increased and it remained high to the top of the core. The increased rate is greater than the increase in aluminum so all of the increased nutrients is not from soil erosion. It is likely that the increase is because of application of synthetic fertilizer in the watershed. Following World War II many plants used to make ammunition were converted to make fertilizer. The increased production of fertilizer as well as improvements in farm machinery resulted in large increases in agricultural products. Unfortunately not all of the applied fertilizer remains on the land. Many lakes have seen significant increases the input of nitrogen and phosphorus as the result of fertilizer usage in their watersheds.

Diatom Community

Aquatic organisms are good indicators of water chemistry because they are in direct contact with the

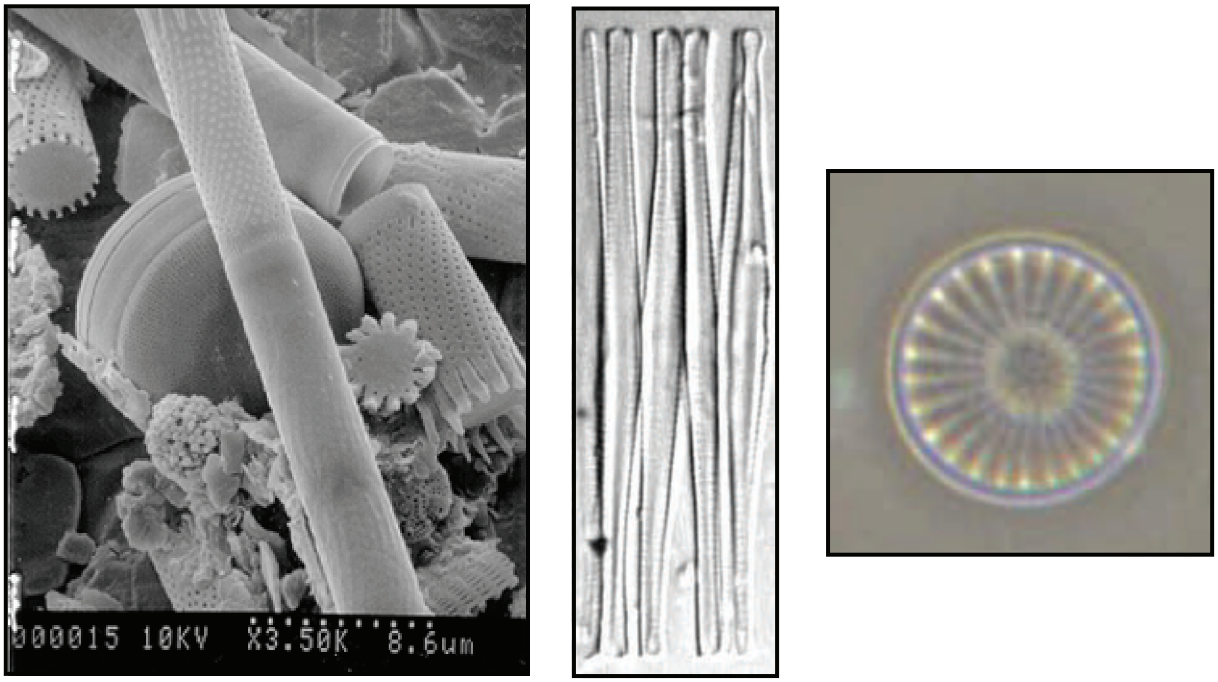

Figure 4. Micrographs of the diatoms *Aulacoseira* (left), *Fragilaria crotonensis* (middle), and *Stephanodiscus minutulus*. All of these diatoms are typically found floating in the open water. The *Aulacoseira* pictured is commonly found in low nutrient waters, *F. crotonensis* is usually found in waters with moderate levels of nutrients, while *S. minutulus* is more common in higher nutrient waters.

water and are strongly affected by the chemical composition of their surroundings. Most indicator groups grow rapidly and are short lived so the community composition responds rapidly to changing environmental conditions. One of the most useful organisms for paleolimnological analysis is diatoms. They are a type of alga which possess siliceous cell walls and are usually abundant, diverse, and well preserved in sediments. They are especially useful as they are ecologically diverse and their ecological optima and tolerances can be quantified. Certain taxa are usually found under nutrient poor conditions while others are more common under elevated nutrient levels. They also live under a variety of habitats, which enables us to reconstruct changes in nutrient levels in the open water as well as changes in benthic environments such as aquatic plant communities. Figure 4 shows photographs of three diatom species that were common in the sediment core.

The presettlement diatom community was composed of a diverse taxa with about half of the diatoms being species that live in the open water of the lake while the rest were diatoms that grow attached to substrates, e.g. submerged aquatic plants. The dominant planktonic diatoms where those belonging to the genera *Aulacoseira* (Figure 5). These species generally prefer lower nutrients. Some of the other important diatoms in the deeper part of the core are the planktonic diatoms *Asterionella formosa* and *Fragilaria crotonensis* (Figure 4). These prefer moderate amounts of nutrients and indicate

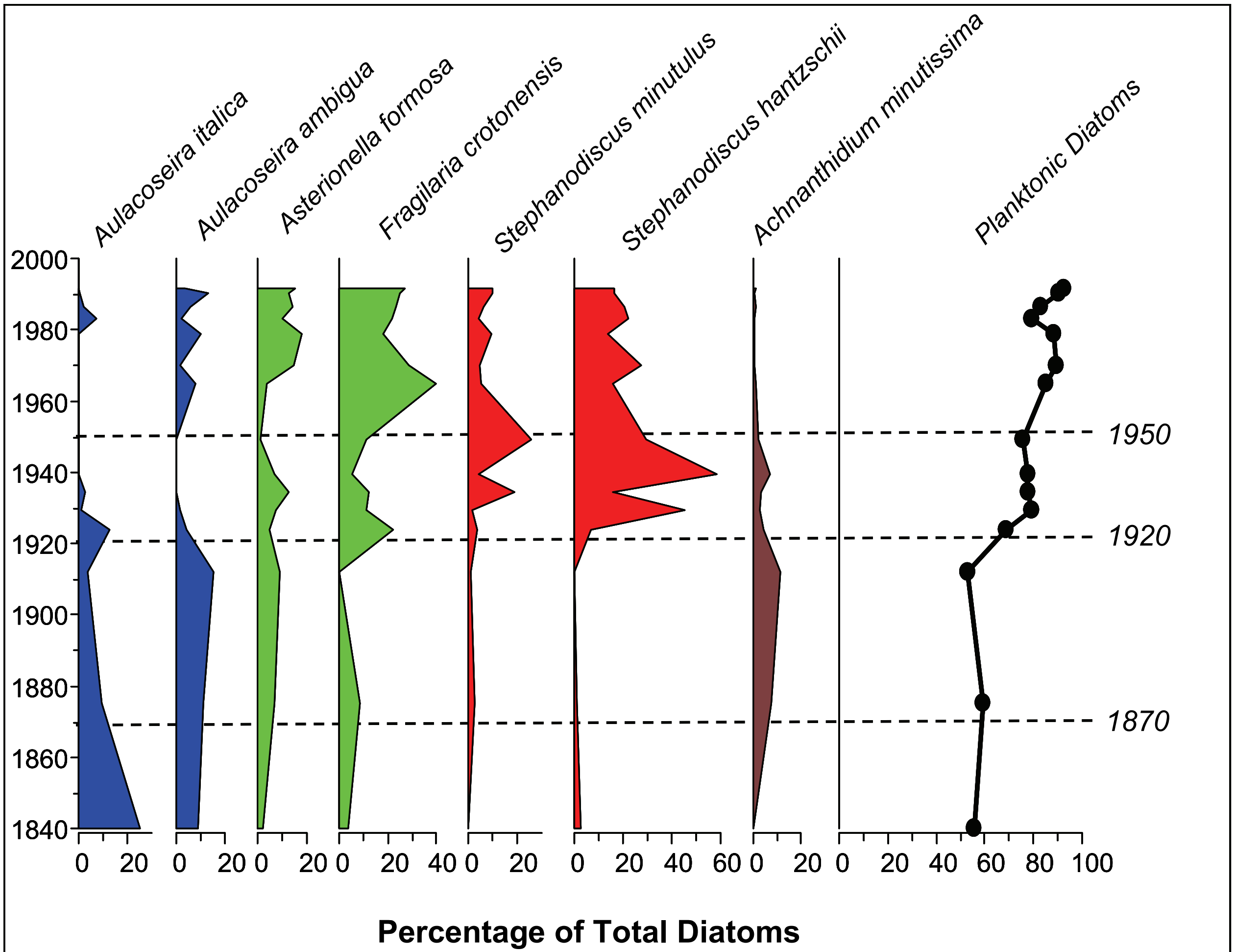

Figure 5. Profiles of selected diatom taxa. The taxa in blue are indicative of low nutrient levels while taxa in green are indicative of moderate nutrient levels. Those taxa colored in red generally indicate higher nutrient levels. The taxa in brown grow on substrates such as aquatic plants.

the lake historically was a mesotrophic lake. Around 1930 the *Aulacoseira* was replaced by *F. crotonensis* and two diatoms in the genus *Stephanodiscus* (Figure 5). The *Stephanodiscus* species are typically found in nutrient enriched waters (Bradbury 1975, Carney 1982, Fritz et al. 1993, Garrison and Wakeman 2000). Although *Stephanodiscus hantzschii* and *Stephanodiscus minutulus* were an important part of the diatom community during the time period after 1950, their numbers were reduced and *F. crotonensis* and *A. formosa* became more important. This indicates there was a reduction in nutrients but they remained higher than prior to 1920.

Achnanthidium minutissima typically grows attached to aquatic plants (Reavie and Smol 1997; Garrison and Wakeman 2000). Increases in this diatom are an indication of an increase in density or coverage of plant beds. *A. minutissima* was found in low levels at the bottom of the core. However, by 1870 the abundance increased (Figure 5). The increase in plant beds with early European settlement has been found in nearly all lakes in Wisconsin where sediment cores have been analyzed (Garrison 2000a,b; Garrison 2003, Garrison 2004, Garrison and Wakeman 2000). It appears that the littoral zone responds very early to the increased input of nutrients from the watershed. The plant community remained at elevated levels compared from pre-settlement times until the 1920s when they declined and remained depressed until recent times.

The highest deposition of calcium carbonate (marl) occurred during the early part of the twentieth century (Figure 3). This occurred before there was a large increase in nutrients which was reflected in the shift in the diatom assemblage to *Stephanodiscus*. Instead this is when the diatom assemblage indicated there were more macrophytes. Apparently the higher marl deposition was caused by denser macrophyte growth and not higher algal levels in the open water.

Diatom assemblages historically have been used as indicators of trophic changes in a qualitative way (Bradbury 1975; Anderson et al. 1990; Carney 1982, Garrison and Wakeman 2000). In recent years, ecologically relevant statistical methods have been developed to infer environmental conditions from diatom assemblages. These methods are based on multivariate ordination and weighted averaging regression and calibration (Birks et al. 1990). Ecological preferences of diatom species are determined by relating modern limnological variables to surface sediment diatom assemblages. The species-environment relationships are then used to infer environmental conditions from fossil diatom assemblages found in the sediment core.

The presettlement summer phosphorus levels were about 15 µg L^{-1} (Figure 6). Phosphorus levels first began to increase in the 1920s and reached their highest levels around 1940. The model indicates that phosphorus levels at this time were about 100 µg L^{-1}. It may be that this is higher than what was actually present in the lake but it does accuratelyindicate a dramatic increase in phosphorus levels. By 1960 the phosphorus levels had declined to about 30 µg L^{-1} and they remained near this level through the top of the core (Figure 6). The diatom community indicates that summer phosphorus levels remained steady during the period 1960-90 despite the addition of alum to reduce internal loading of phosphorus.

The diatom community profile, from the aspect of species assemblage and diatom inferred phosphorus, does not agree with phosphorus profile of deposition rates. Although phosphorus and nitrogen profiles have been used to reconstruct changes in historical loading of these elements, this can be misleading. As Engstrom and Wright (1984) summarize, there are many problems with using phosphorus profiles to reconstruct changes in loading. For example, P retention in sediments is strongly controlled by sorption onto iron oxides, and so variations in iron content and redox conditions may change phosphorus accumulation in sediments independent of changes in phosphorus loading. Anderson et al. (1993) showed that P concentration profiles did not accurately portray known changes in P loading in two small lakes in northern Ireland and Fitzpatrick et al. (2003), clearly show this is especially true in a bay from Lac Courte Oreilles, Sawyer County, Wisconsin. Although the P profiles may not accurately portray changes in loading rates, the increased deposition during the last 2 decades does indicate that there is a potential for increased P in the lake as a result of internal loading.

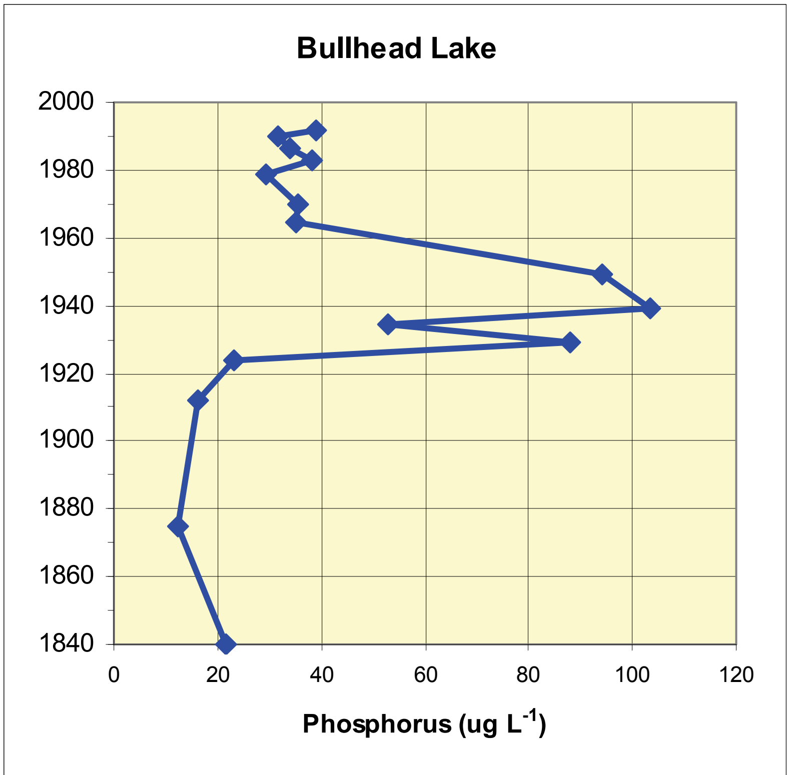

Figure 6. Mean summer phosphorus estimated from the diatom community using weighted averaging modeling.

SUMMARY

Bullhead Lake prior to the arrival of European settlers would have been classified as a mesotrophic lake with phosphorus levels around 15 µg L^{-1}. During the late 1800s and the first part of the twentieth century the rate of sediment infilling dramatically increased. This was likely the result of agricultural activity near the lake. During the middle part of the twentieth century, the sediment infilling rate was reduced but it increased again beginning in the late 1970 and continued to increase until the when the core taken in 1991.

The diatom community indicates the lake's water quality was not greatly affected by this influx of sediment until about 1920. During the 1920s there was a dramatic increase in phosphorus levels in the lake. It is not known what caused this large increase in nutrients but there may have been a farm near the lake that contributed as significant amount of nutrients. Water quality of the lake improved beginning around 1960 as phosphorus levels declined to about 30 µg L^{-1}. The diatom community indicates the summer phosphorus levels remained around 30 µg L^{-1} until the early 1990s when the core was taken. This lake was treated with alum in 1978 but no evidence of its success was seen in the diatom community. The geochemistry profiles did reflect a temporary decline in the concentrations of some of the parameters because of their dilution by the alum.

The highest deposition of marl occurred during the early part of the twentieth century. Marl deposition increases in response to increased primary productivity. With increased plant production, the pH increases as carbon dioxide is removed from the water and calcium carbonate becomes less soluble. The diatom assemblage indicates that the highest productivity occurred in the form of vascular plants (macrophytes) and not algal blooms in the open water. This increase in macrophyte growth in response to early disturbance in the watershed is a common feature in Wisconsin lakes.

Bullhead Lake has undergone significant shifts in water quality during the last 150 years. It appears that phosphorus levels were highest during the period 1930-60. Historical phosphorus levels were about 15 µg L^{-1} which is about half of the concentration during the time when the core was collected in the early 1990s.The sediment infilling rate in the early 1990s was about three times higher than it was in the late 1800s.

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