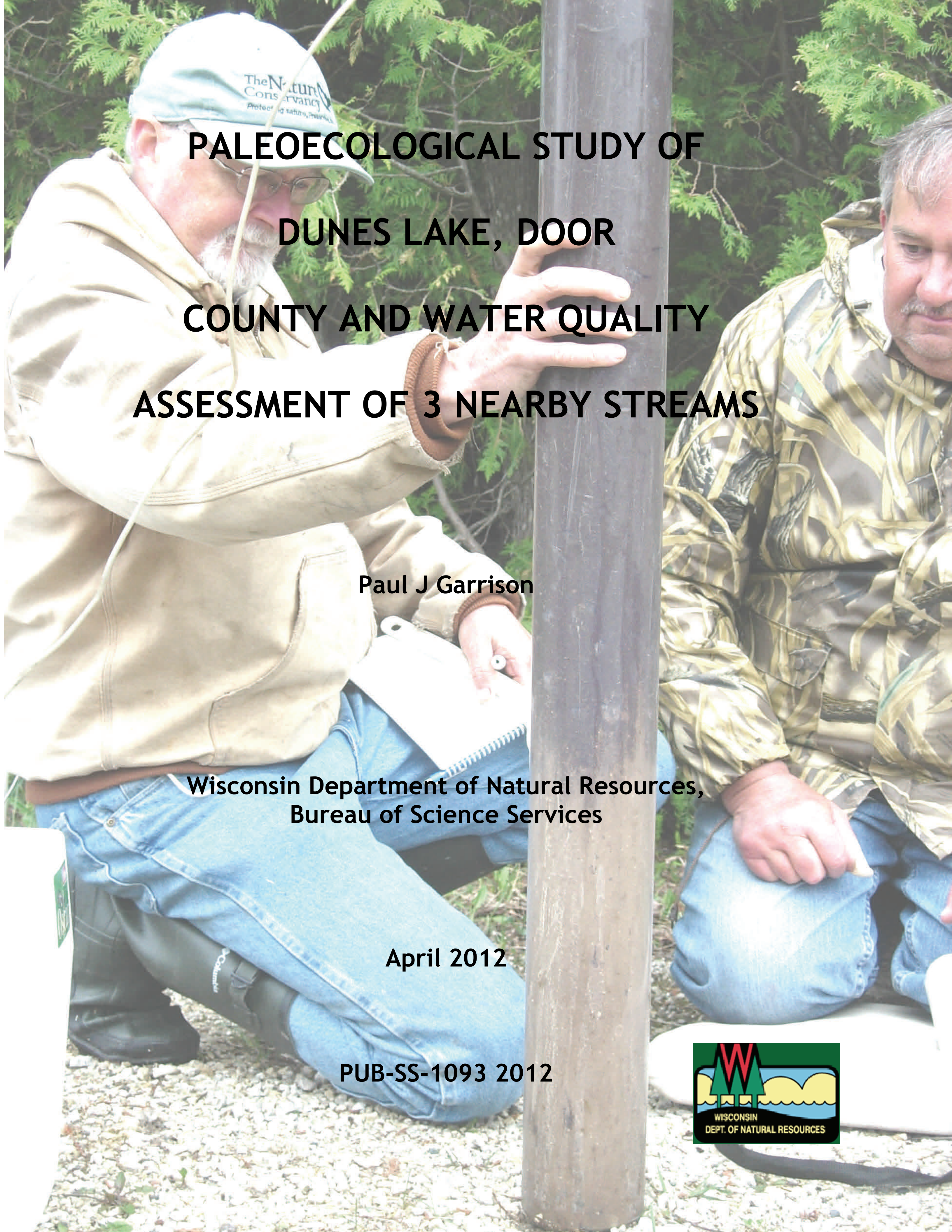

PALEOECOLOGICAL STUDY OF DUNES LAKE, DOOR COUNTY AND WATER QUALITY ASSESSMENT OF 3 NEARBY STREAMS

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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 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 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.

This sediment core study was conducted to better determine the water quality history of Dunes Lake. Dunes Lake, Door County, is a 80 acre lake with a maximum depth of 1 foot. A sediment core was collected on 25 May 2011. The location of the coring site was 44.86709° north and –87.25838° west in 1 foot of water (Figure 1). The core was collected with a piston corer having an inside diameter of 8.8 cm. The core was sectioned into 1 cm intervals for the top 50 cm and then at 2 cm intervals to the bottom of the core which was 96 cm in length. The core was dated by the ^{210}Pb method and the CRS model was used to estimate dates and sedimentation rate. The diatom community was 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 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 sup-

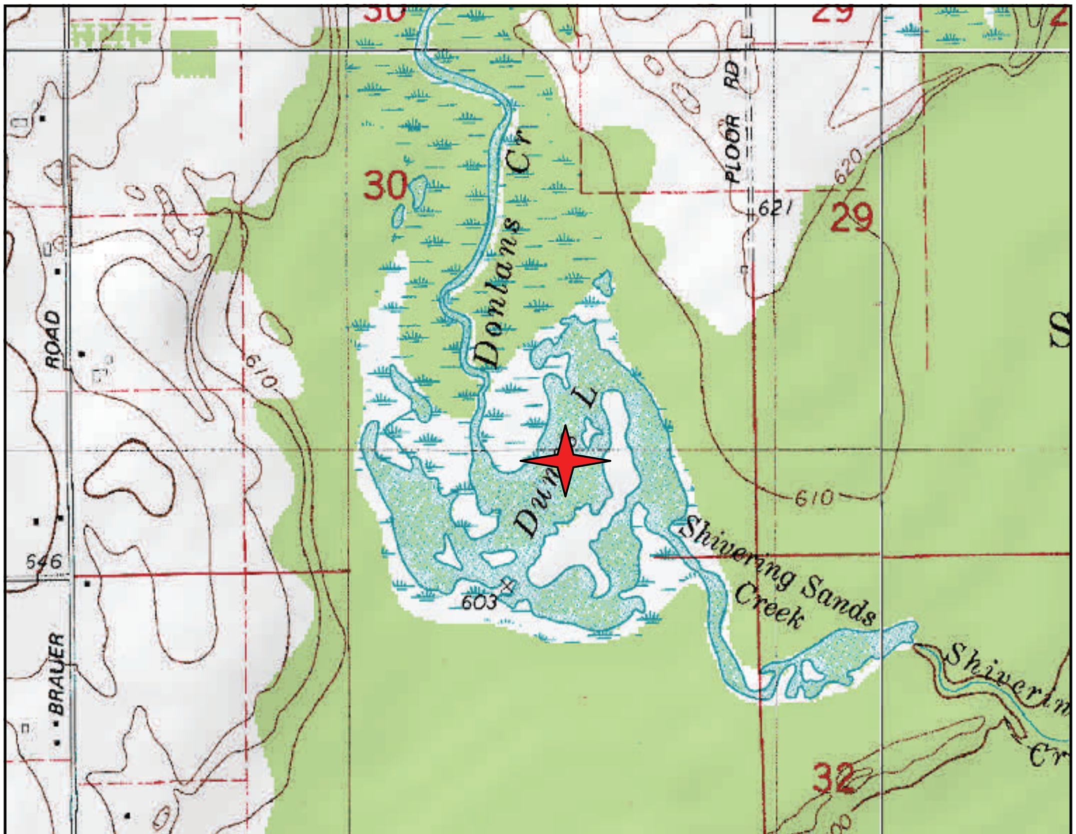

Figure 1. Map of Dunes Lake showing the coring site. The water depth at the site was 1 foot. The name of the creek which flows into the lake is more commonly called Geisal Creek.

ply (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

The mean mass sedimentation rate for the last 190 years was 0.033 cm-^{2} yr^{-1}. This rate is near the average rate for 53 Wisconsin lakes but above the median. The rate is higher than many lakes because Dunes Lake is a hardwater lake which experiences calcium carbonate deposition. Softwater lakes do not have enough calcium for this precipitation so their sedimentation rates are naturally lower. The rate in Dunes is not higher because it is a very shallow lake which means sediment retention is reduced. The average linear rate for the same time period is 0.31 cm yr^{-1}, which equates to 0.12 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 cm^{-2} yr^{-1} but the rate increased slightly in the 1800s with the arrival of early European settlers who started

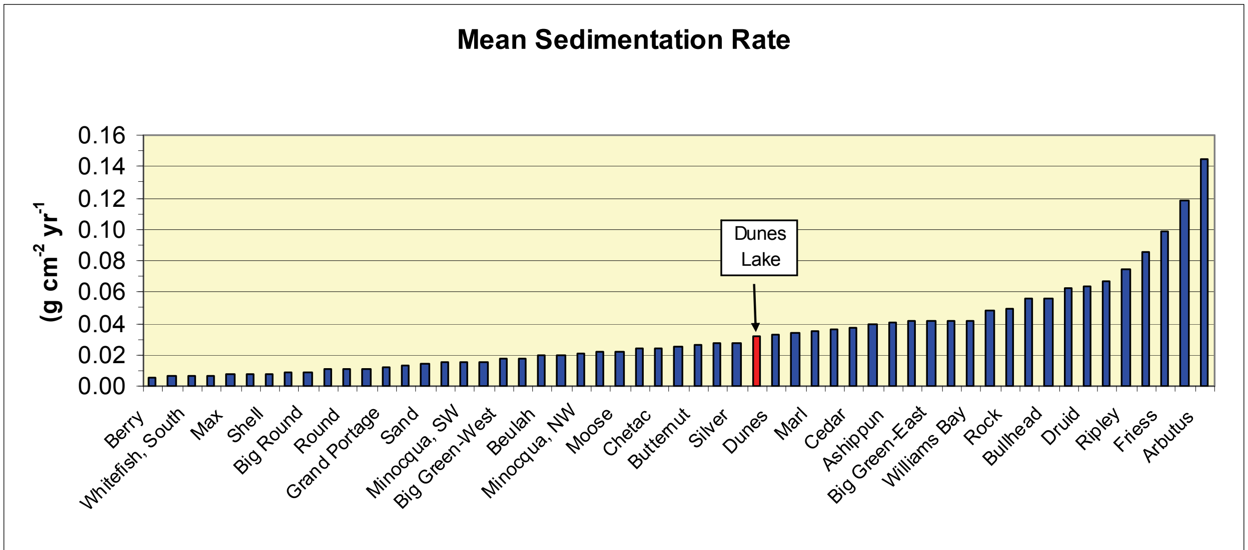

Figure 2. Mean sedimentation rate for the last 150 years for 53 Wisconsin lakes. The rate for Dunes Lake is moderate because the lake is a hardwater lake which results in calcium carbonate precipitation. Another factor is that the lake is very shallow which likely reduces sediment retention in the lake.

farming in the lake's watershed. The rate declined around the beginning of the twentieth century probably reflecting less soil erosion that resulted from the initial clearing of the land for farming. The rate again increased in the 1950s. This likely is the result of agricultural activity. A similar increase in the rate during the time period has been observed in other lakes that have agriculture in their watersheds (Garrison 2002, Garrison 2008, Garrison and Pillsbury 2009). Following World War II, agriculture expanded as tractors became larger and more powerful and farmers were able to farm greater amounts of land. This often meant farming marginal land.

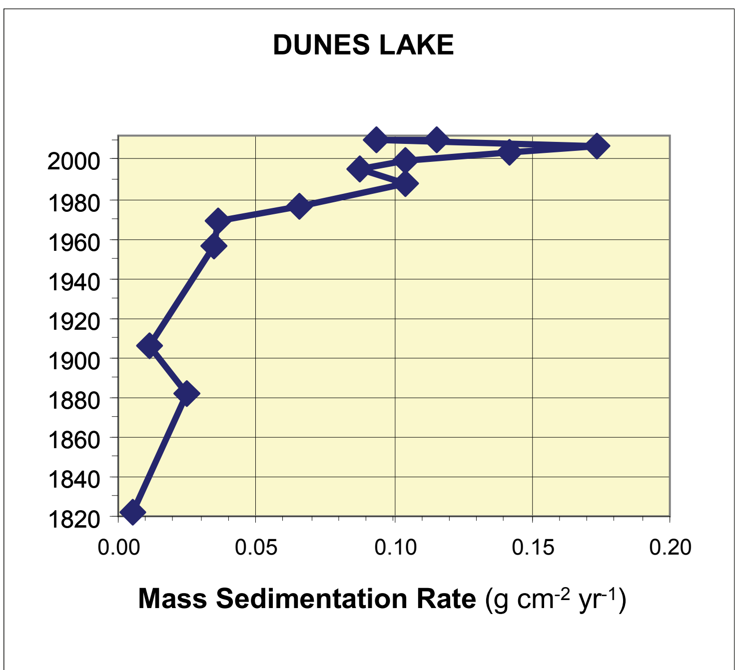

Figure 3. Sediment accumulation rate in Dunes Lake. The rate increased in the 1800s as a result of farming by early settlers but the greatest increase occurred after 1970. Since 1980 the rate has remained high, being over 25 times higher than presettlement rates.

The sedimentation rate greatly began to during the 1970s and peaked in the last few years. The timing of the increased sedimentation rate coincides with the construction of the sewage treatment ponds near Valmy which are near Geisal Creek which enters Dunes Lake. It is likely that nutrients are leaching from these ponds into the creek which results in increased biological production in the creek and the lake with the result being a large increase in the infilling rate of the lake. The average sedimentation rate during the last decade is over 0.13 cm^{-2} yr^{-1} which more than 25 times greater than the presettlement rate.

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 includes a number of elements, especially carbon.

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

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 rates of all the geochemical elements measured in the core increase dramatically in the 1970s (Figure 4). For many elements the accumulation rate during the last 30 years is at least 6 times greater than the rate in the mid-1800s. The increase in phosphorus deposition is even greater at

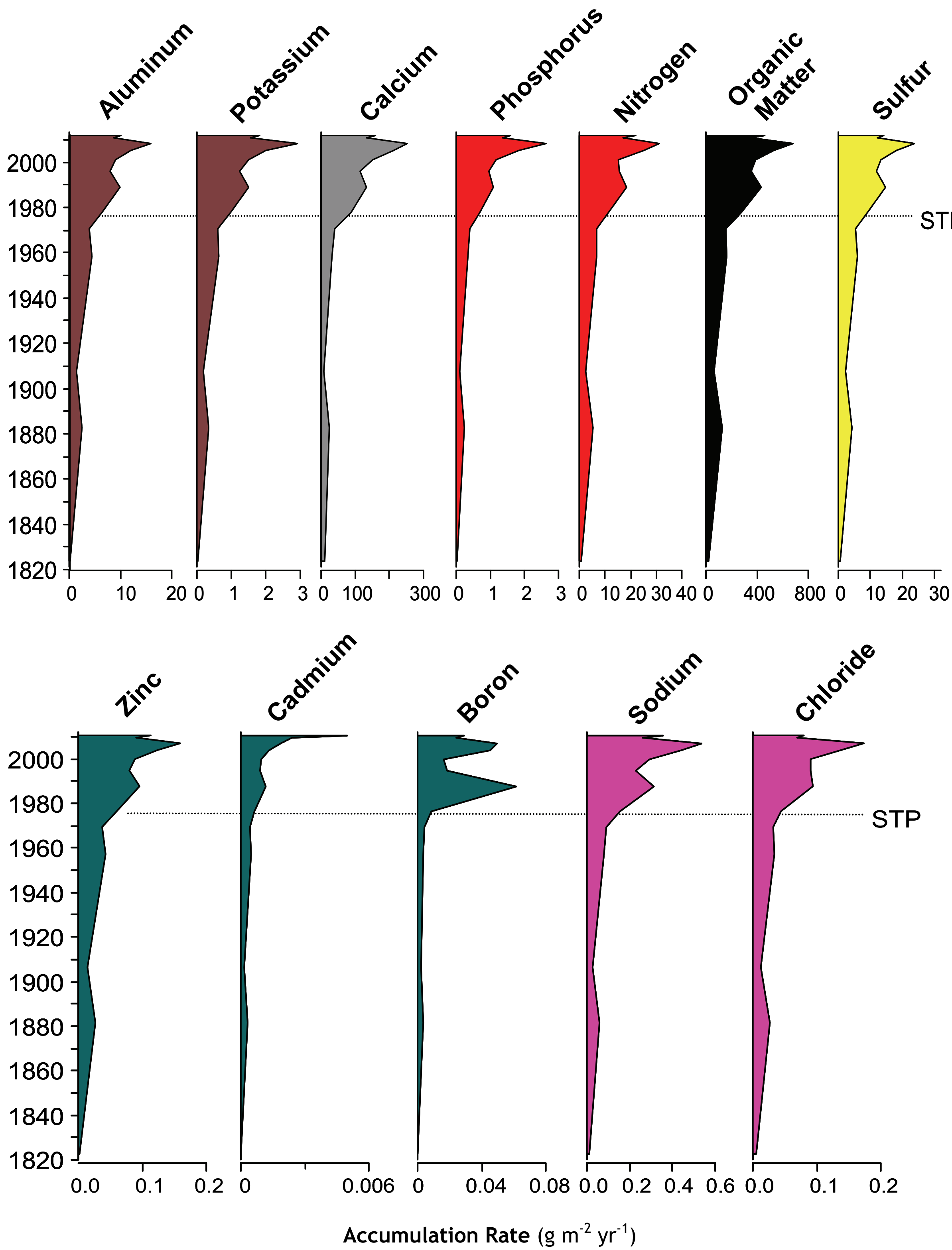

Figure 4. Profiles of the accumulation rate of selected geochemical elements. The accumulation rate for all of the elements increased dramatically during the 1970s. STP represents when the sewage treatment ponds where installed along Geisal Creek near Valmy.

nearly 9 times the historical rate. The source for the increased these elements could be from land runoff because of agricultural activities and the sewage treatment ponds. Other paleolimnological studies in Wisconsin have noted the increase in the deposition rates as a result of agricultural activity (Garrison 2002, Garrison 2004, Garrison and Fitzgerald 2005, Garrison 2006, Garrison 2008, Garrison and Pillsbury 2009). In these studies agricultural activities resulted in increased soil erosion which was indicated by increased deposition rates of aluminum, potassium, phosphorus and nitrogen. In these other studies, the impact from agriculture was first noted in the 1940-50s and in many cases, soil erosional rates began to decline in the 1970s as a result of soil conservation practices.

In Dunes Lake, the increased depositional rates began in the 1970s. This coincides with the installation of the ponds for the sewage treatment plant near Valmy. These ponds are located very near Geisal Creek which discharges into Dunes Lake. A sediment core from Nagawicka Lake, Waukesha County, documented the large impact that the discharge from a sewage treatment plant had upon the lake's water quality. When the sewage treatment plant discharge was diverted away from the lake, the lake's phosphorus concentration was reduced by one half from 40 to 20 $\mu g\ L^{-1}$ (Garrison 2004). It seems likely that much of the increased deposition of most of the elements in Dunes Lake is a result of the discharge from the sewage ponds.

The increased input of nutrients either from agricultural activities or the sewage ponds has resulted in a large increase in the productivity of Dunes Lake. This is reflected in the increased deposition of organic matter (Figure 4). As the nutrient levels increased in the stream and lake, there was an increase in the production of plant material and most of this was deposited in the lake.

There was also an increase in the deposition of sodium and chloride starting in the 1970s (Figure 4). This increase could be from road salt or discharge from the sewage ponds because of the use of water softeners. Although the increased deposition rate appears similar, the ratio of sodium (Na) to chloride (Cl) clearly shows that sodium increased at a faster rate. This implicates discharge from water softeners as the source of the added chemicals. Since much of this increased deposition is not from road salt it likely is from the sewage ponds.

There are two likely sources for the increased deposition of these elements. One is the agricultural practices in the watershed and the other is drainage from the sewage treatment ponds. If more than one activity is the source for an element, the use of ratios can help elucidate the major sources. For example, although aluminum (Al) and potassium (K) are found in clay particles in soils, K is also a component of synthetic fertilizers. The decline in the Al:K after 1960 (Figure 5) indicates fertilizer usage in the watershed. The decline in the K:P indicates that there is also another source of phosphorus besides agricultural runoff. The decline in the nitrogen (N) to phosphorus (P) ratio after the sewage ponds were installed in the 1970s indicates that phosphorus increased faster than nitrogen. Since P is usually the most limiting nutrient for plant growth, its increase likely results in increased algal growth in the lake. The decline in the carbon (C) to nitrogen (N) ratio likely indicates a change in the floral community in Dunes Lake. The C:N is higher in vascular plants compared with algae because of cellulose in the former plants (Meyers and Teranes 2001). It appears that the algal community has expanded in the last decade. There was a large amount of filamentous algae present when the core was collected in May 2011 and a subsequent visit in July 2011. The decline of the C:N after 1990 (Figure 5) indicates that this community has expanded in the last decade.

There is a noticeable increase in the sodium (Na) to chloride (Cl) ratio after the sewage ponds were installed. Although both of these elements are found in salt that is used for clearing snow and ice from roadways, the increase in the ratio indicates that discharge from the sewage ponds is the major source of these elements. The likely source of Na is from its usage in water softeners.

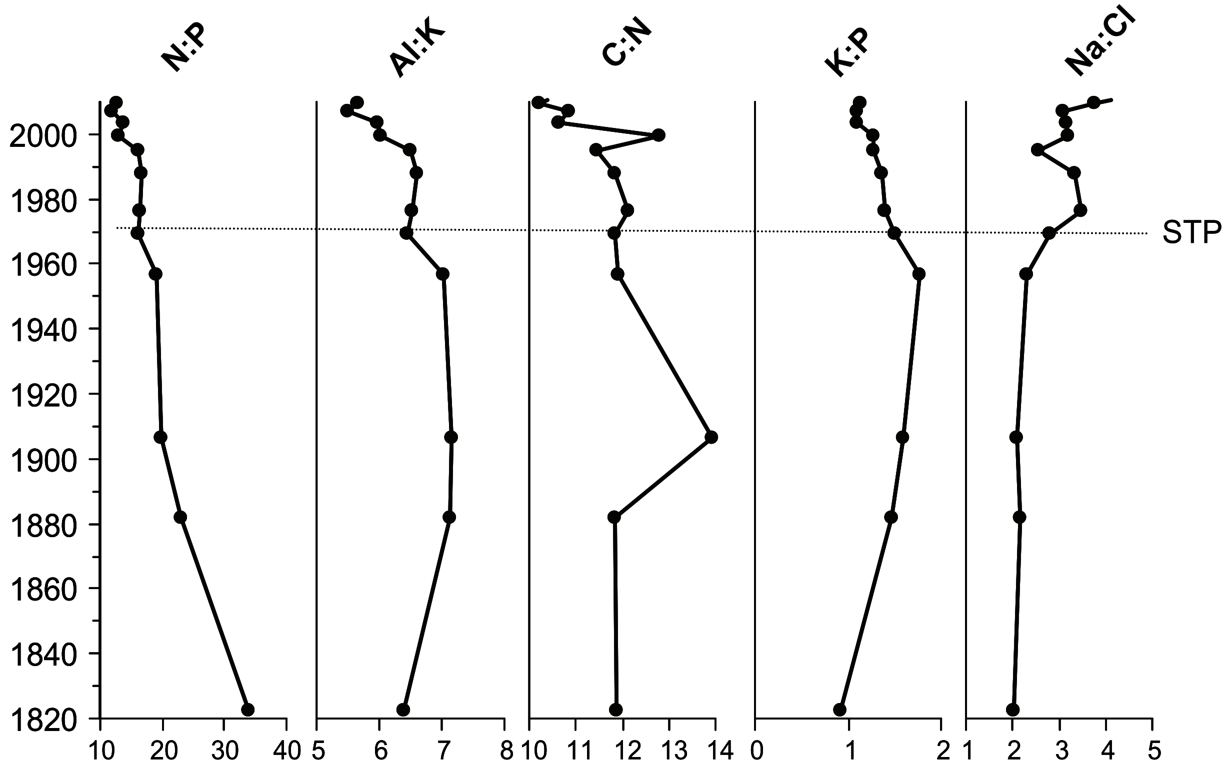

Figure 5. Profiles of various ratios of the geochemical elements. Rations are used to better understand the impact of watershed activities on the lake and changes in the lake's ecology. For example, the decline in the Al:K after 1990 indicates that much of the potassium (K) is coming from synthetic fertilizer but the decline in K:P after the ponds were installed indicates there is additional phosphorus source.

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.

The diatom community throughout the core was composed almost entirely of taxa that grow attached to substrates, e.g. vascular plants, filamentous algae, sediments. This is not surprising as this lake is very shallow. There is a dramatic contrast in the community between the lower part and the upper part of the core (Figures 6, 7). The community prior to the mid 1800s is composed largely of large diatoms that are found in hard water systems with low nutrient levels. During the period prior to the

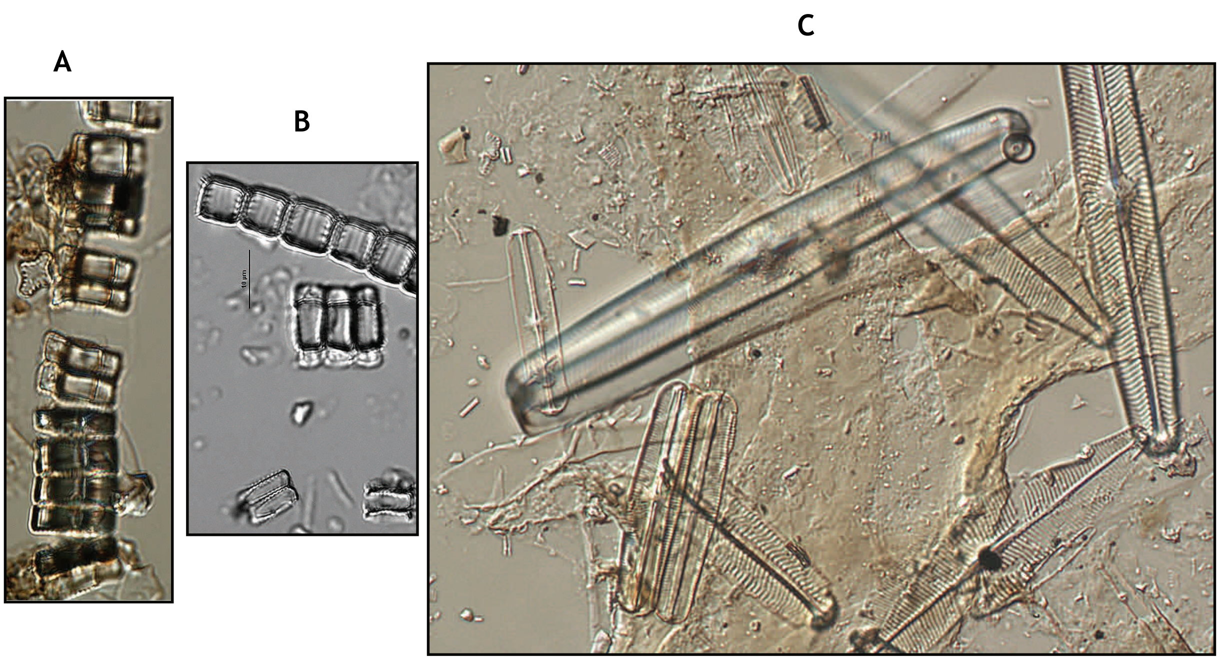

Figure 6. Photomicrographs of diatoms found in the sediment core. The chain forming taxa shown on the left (A, B) were most common in the upper part of the core while the bottom of the core was dominated by large diatoms shown on the right (C).

mid-1800s, there are some subtle floristic changes but all of these taxa are indicative of low nutrients. During the first half of the nineteenth century there was an undescribed diatom in the genus *Pinnularia*. This diatom (*Pinnularia* sp. 1 DUNES) has not been previously reported in the literature.

Around 1840 there was a dramatic change in the diatom community from one composed of generally large diatoms to a community composed of much smaller filamentous taxa (Figure 6). The diatom community in the upper part of the core is very common in higher nutrient shallow water systems.

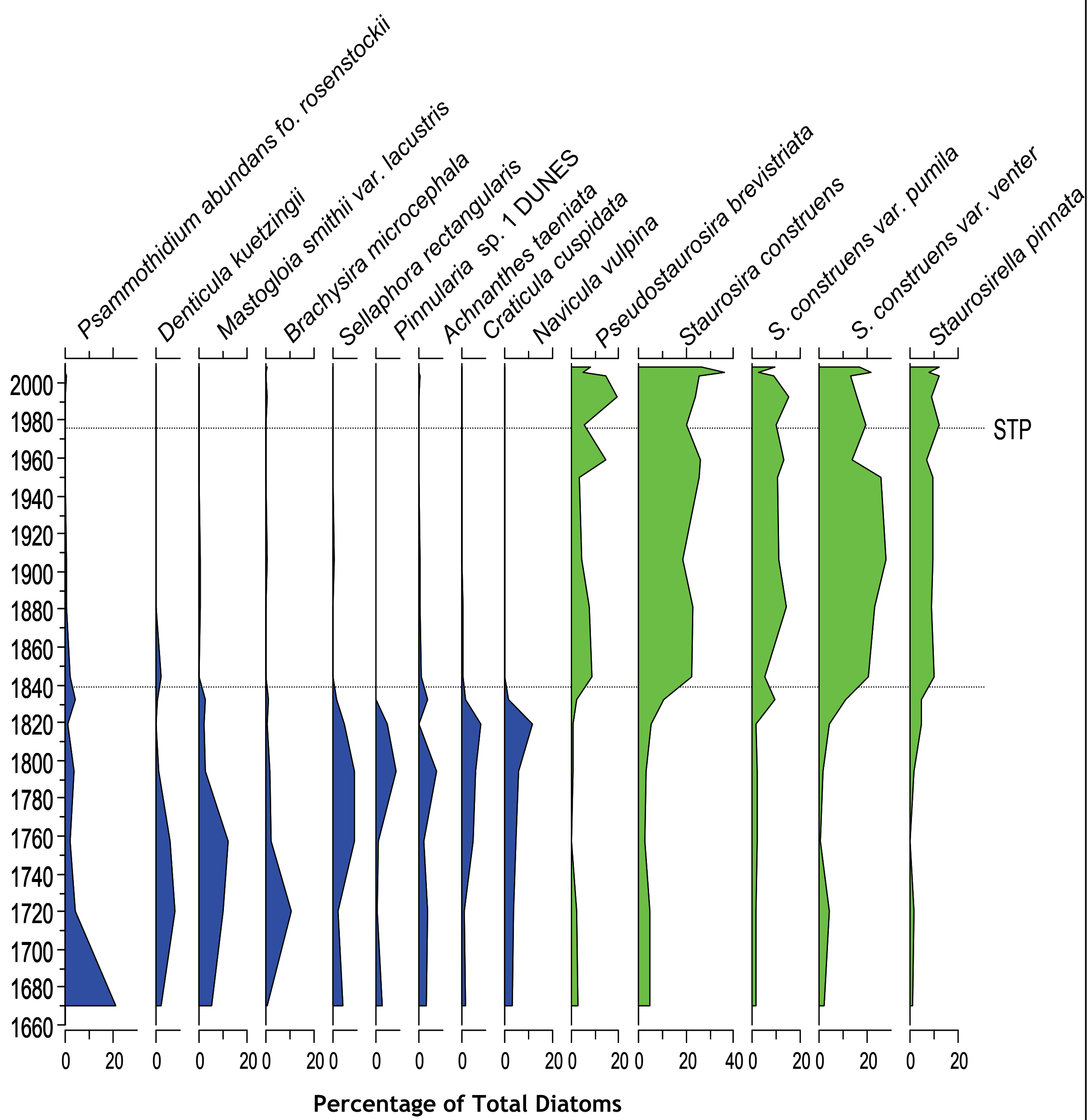

Figure 7. Profiles of common diatoms found in the core. The diatoms in blue are indicative of low nutrients while those in green are indicative of higher nutrient levels.

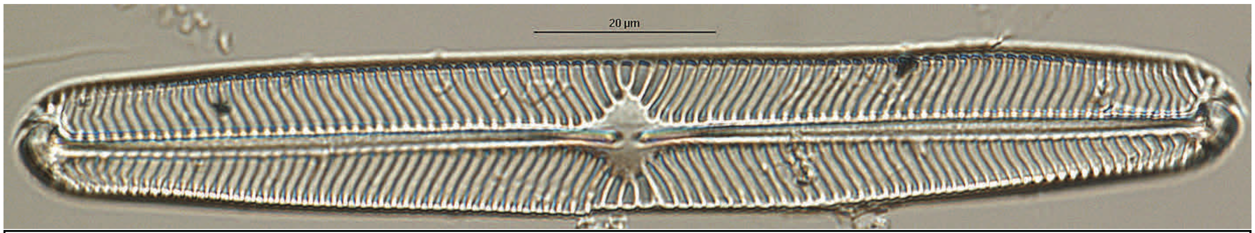

Figure 8. *Pinnularia* sp. 1 DUNES was found in the deeper part of the core. This taxa has not been reported in the literature.

These diatoms tolerate a wide range of phosphorus levels (Wilson et al. 1997, Bennion et al. 2001). These taxa can be found in epiphytic, epipelic, epilithic, or episammic communities (Round 1981; Sayer 2001) and have been observed in a wide range of aquatic environments including high latitude lakes (Douglas and Smol 1995; Jones and Juggins 1995) and subtropical lakes (Stoermer et al. 1992). Often these diatoms respond more to changes in substratum and algal mat chemistry than directly to changes in water column chemistry (Hansson 1988, 1992; Cattaneo 1987). Although these diatoms tolerate a wide range of phosphorus levels, Garrison and Fitzgerald (2005) have shown them to increase in response to higher nutrient concentrations.

This change in the diatom community likely occurred in response to early agricultural activity with the arrival of European settlers. The sedimentation rate and geochemistry only changed slightly with this early development but the diatom community demonstrates how sensitive these shallow lake/ wetland systems are to watershed perturbations.

Even though the geochemical elements did not show much change as a result of the early settlement, along with a change in the diatom community the appearance of the sediments also changed. The color below this depth was light gray but it quickly changed to dark brown which can be seen in the sediment samples in Figure 9.

The sedimentation rate and geochemical elements showed a large change in the 1970s which was at least partially attributed to the installation of the sewage ponds along Geisal Creek near Valmy. The composition of the diatom community did not change during this time period. This likely reflects the wide tolerance of small benthic diatoms which dominate the community. Although the composition of

Table 2. Diatom accumulation rates at three depths in the sediment core.

Depth (cm)	Pb 210 Date	Diatom Accumulation Rate ($mm^3\ m^{-2}\ yr^{-1}$)
7-8	2006	3.13
62-64	1834	0.22
88-90	1670	0.13

Figure 9. Sediment samples from 50-60 cm on the left and 60-80 cm on the right. The darker colored sediment began in the mid-1800s as a result of land disturbance from early settlers. This dark color occurred throughout the upper part of the core.

the community did not change, its productivity did increase. Diatom production was only measured at 3 depths (7-8, 62-64, 88-90 cm). The deposition rate was much higher near the top of the core compared the rates measured closer to the bottom (Table 2). This demonstrates that the increased nutrients entering Dunes Lake since the 1970s has increased algal production even though the composition of the community is largely unchanged.

Summary

The results of this study clearly show that watershed activities have impacted the lake, especially beginning in the 1970s. At this time there was a large increase in the lakes sediment accumulation rate with the rate increasing over 3 times. The geochemical elements also experienced a similar increase, including phosphorus and nitrogen. There are two likely sources for these increases– agriculture and discharge from sewage ponds along Geisal Creek near Valmy. While agriculture likely contributes some of the material, evidence indicates that the ponds are the major source. This is indicated by a greater increase in sodium compared with chloride (Na:Cl increases) and the decline of the potassium to phosphorus ratio which indicates that there is another source of the phosphorus other than synthetic fertilizer addition to fields.

The diatom community was very sensitive to watershed disturbance with a major shift in the community composition occurring in the mid-1800s as a result of early farming. Although the taxonomic composition did not change in the 1970s in response to increased inputs of nutrients, the productivity increased nearly 10 times over historical levels.

Water quality assessment of three Door County Streams

The diatom community was used to assess the nutrient status of three streams in the vicinity of Dunes Lake. These streams were Geisal Creek, upstream of Dunes Lake, Hibberts Creek where County Road A crosses north of Jacksonport, and Logan Creek where Highway 57 crosses the creek (Figure 10). The watersheds of all of these creeks have a large amount of the landuse in their watersheds in agriculture. Geisal Creek also has sewage ponds along the creek. The diatom community was sampled by scraping 5 rocks at each site. Later, the composition of the diatom community was determined much like the diatoms in the Dunes Lake sediment core.

The trophic status of the stream is determined with the Diatom Nutrient Index (DNI). This index assigns tolerance values to individual taxa. The values ranged from 1 to 6 with 1 being the lowest nutrients (oligotrophic) to 6 being hypereutrophic. Nutrient values for Wisconsin diatoms were generated largely from Van Dam et al. (1994) but values were also assigned based upon experience with the diatom community in Wisconsin. If no autecological data was known, the taxa were not assigned a value and were not included in the DNI calculation. Because the index is based upon relative abundance, rare species will have little effect on the final index value. The index value for each of the diatom taxa is presented in Robertson et al. (2006). The formula used to calculate DNI is:

$$DNI = \frac{\sum n_i x t_I}{N}$$

where n_I = number of individuals in species i

t_I = nutrient value of species I

N = total number of individuals

The scale for this index ranges from 1 to 6 with lower values indicating lower nutrient concentrations.

The DNI for the three streams are presented in Table 3. Hibberts and Logan creeks had the lowest values, meaning that had lower nutrient levels. In contrast, the DNI for Geisal Creek was higher. This indicates that much higher nutrients are being exported from the Geisal Creek watershed compared with the other two. A study of 240 wadable streams throughout Wisconsin found that the median DNI value for reference streams was 3.4 (Robertson et al. 2006). The values for Hibberts and Logan creeks were much better than this value while the DNI for Geisal Creek was higher than the value. Since all three watersheds have a significant amount of agriculture in their watersheds there must be an additional source in Geisal Creek. This most likely is the sewage ponds near Valmy. This data supports the implication in the sediment core that the sewage ponds are the largest source of nutrients and other geochemicals to the lake.

Table 3. Diatom Nutrient Index (DNI) values for three streams in the area of Dunes Lake. The lower the value the lower the nutrient levels.

Stream	Location	DNI
Hibberts	County A	1.30
Logan	Highway 57	1.42
Geisal	Haberle Rd.	4.11

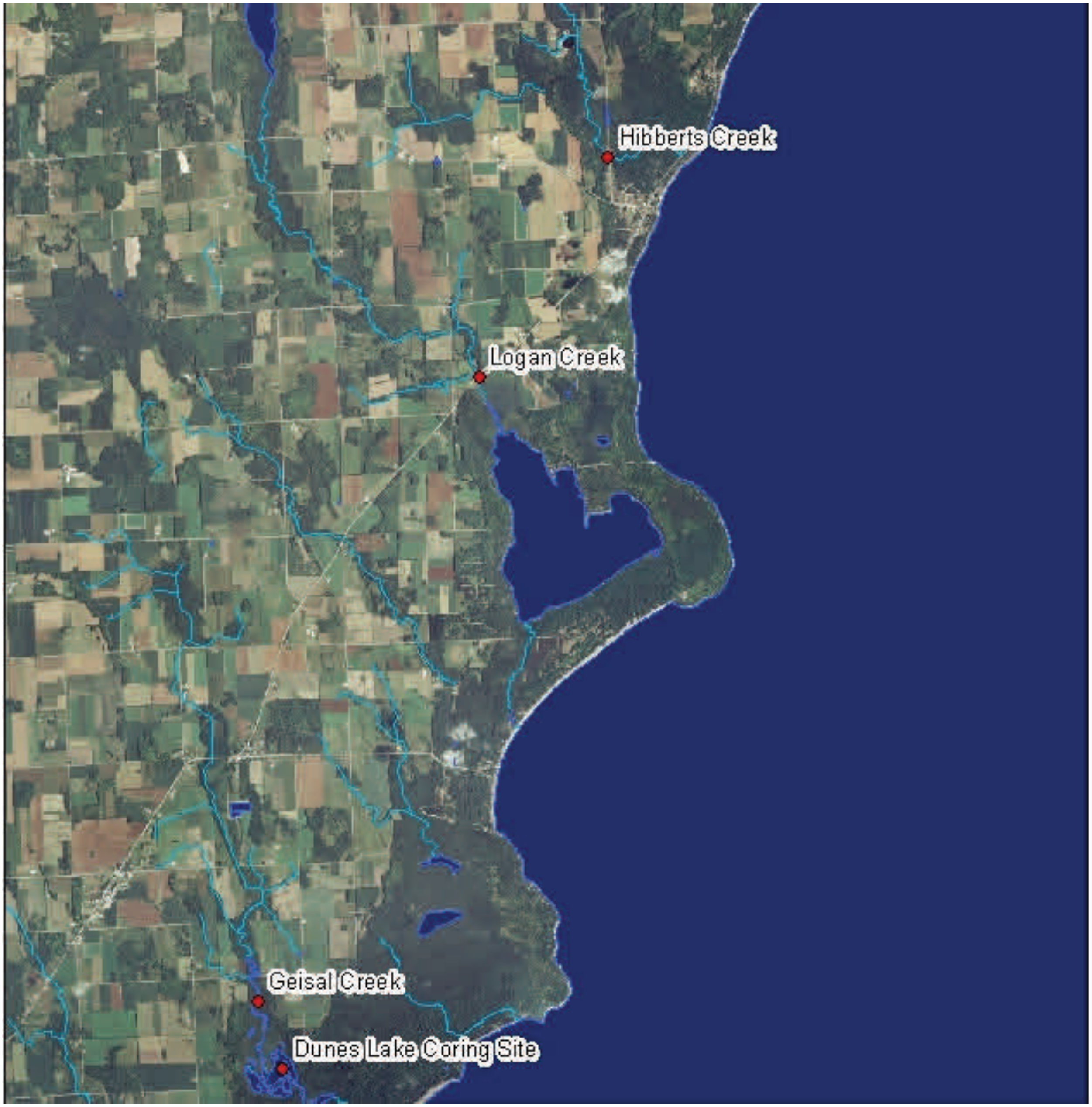

Figure 10. Location of stream sites where the diatom community was collected to determine the nutrient status of the streams.

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