PALEOLIMNOLOGICAL STUDY OF

TAINTER LAKE, DUNN

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 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.

In order to understand water quality changes in Tainter Lake, three sediment cores were taken from different areas in the lake. The core from the main basin was used to estimate changes that have occurred in the general lake basin. Cores were also collected near the inlets of the Red Cedar and Hay rivers to estimate the contribution from each of the rivers. Since the cores were collected in 1995 and 1997, their information does not include any changes that have occurred in the last 13 years.

Methods

Coring

Three sediment cores were collected from Tainter Lake. The first core (TL-1), which was 112 cm in length was retrieved on 19 October 1995 in the deepest area of the lake (Figure 1), The water depth was 9 meters. The core was collected with a piston corer with an inside diameter of 8.8 cm. Immediately upon returning to shore the core was vertically extruded from the top of the core tube and sliced into 2 cm sections. Two other cores were collected on 29 April 1997 in the basins closest to the inlets of Red Cedar River (TL-2) and the Hay River (TL-3). The water depth at TL-2 was 3.0 meters and it was 2.7 meters at TL-3. The total core length of core TL-2 was 110 cm and 66 cm for core TL-3.

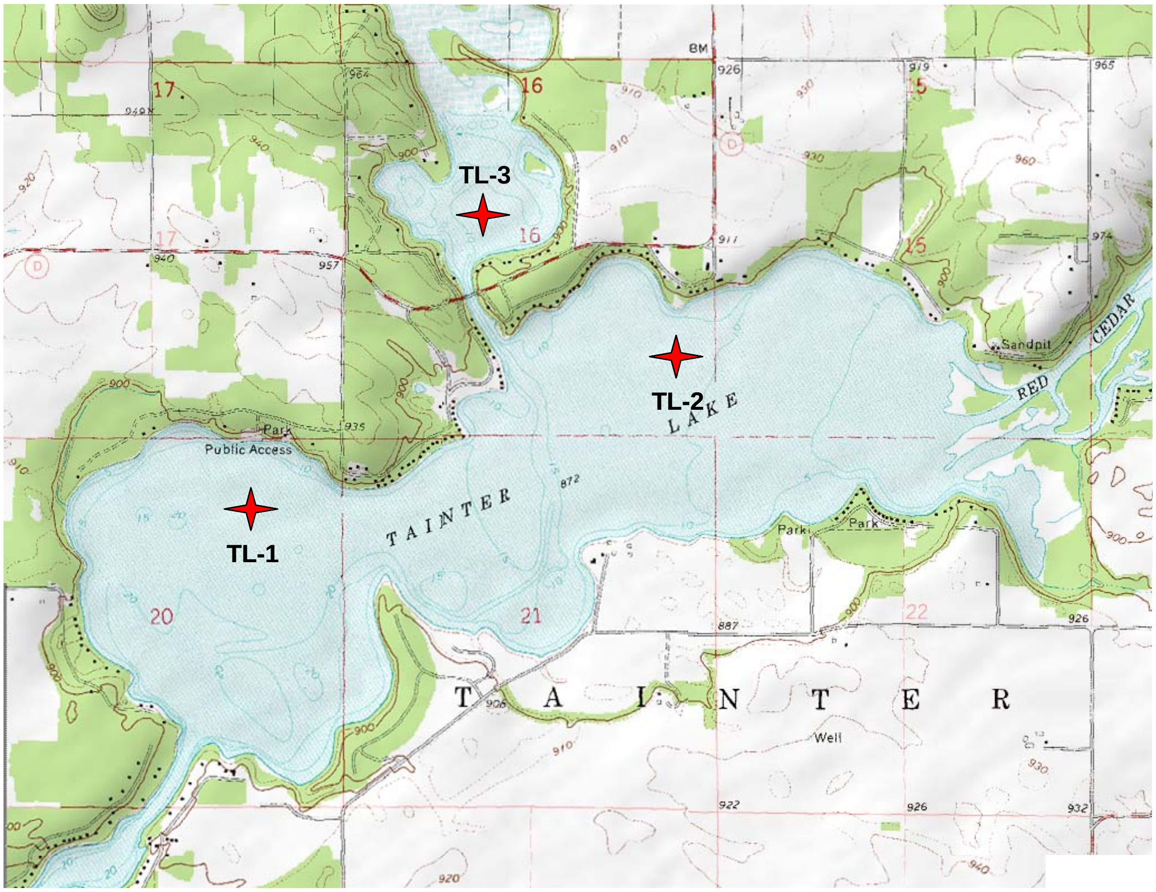


Figure 1. Location of the three coring sites. Core TL-1 was collected in 1995 and the other two cores were collected in 1997.

Radioisotopes

Radioactive cesium (^{137}Cs) was measured in the core from the main basin (TL-1) at the State Laboratory of Hygiene in Madison. Sediment samples were analyzed by gamma radiation emitted from the samples. The cesium profile is used to determine the date 1954 when atmospheric testing of nuclear weapons began and 1963 when the atmospheric testing peaked (Ritchie and McHenry 1990).

Diatoms

Diatoms were analyzed from 17 depths throughout the core from the deep area (TL-1). Depths analyzed were generally evenly distributed throughout the core. Additional samples were analyzed at depths of specific interest, e.g. sediments deposited around flood events. Samples were cleaned with hydrogen peroxide and potassium dichromate (van der Werff 1956). The sample residue was centrifuged and washed at least four times with distilled water to remove the catalyst. A portion of the diatom suspension was dried on a coverslip and samples were mounted in Naphrax@. Diatoms were identified and counted under oil immersion objectives (1400X) under phase contrast illumination until at least 100 frustules had been counted. Common, nationally and internationally recognized keys were used including: Patrick and Reimer (1966, 1975) and Krammer and Lange-Bertalot (1986, 1988, 1991a,b).

Geochemistry

Samples were analyzed for per cent water and loss on ignition (LOI) by determining weight loss after drying at 105°C and 550°C respectively. Dry weight was determined after drying for at least 24 hours and LOI after combustion for one hour. LOI was assumed to be analogous with organic matter. Porosity was calculated from the fraction of dry sediment using the following formula:

$$\text{porosity} = \text{wet weight}/(\text{wet weight} + (\text{dry weight}/2.45))$$

Algal pigments

Algal pigments were measured using high performance liquid chromatography (HPLC). Sediment was extracted with 90% acetone. Ion pairing agent (0.5 M tetrabutyl ammonium acetate in ammonium acetate buffer) was added to filtered extracts and the initial solvent to aid in separation of polar derivatives. Pigment separations were made using Waters solvent delivery and detector systems. Separations were performed on a 15 cm Waters NOVA-PAK C-18 column, protected by a C-18 guard column. Pigment standards were obtained either commercially or from algal cultures. Additional details of these procedures can be found in Hurley and Garrison (1993). This analysis separated chlorophyll *a* into its degradation products and also separated the carotenoids. Carotenoids can be specific for particular algal groups. For example, zeaxanthin is only found in blue-green algae.

Results

Lithology

Core TL-1: The total length of the core was about 140 cm but the bottom 30 cm was lost during retrieval of the core. This lost portion of the core appeared to be very course grained (sand?) sediment and may have represented the pre-lake sediment. The top 40 cm of the core was mostly brown in color with scattered areas of black colored sediment. The rest of the core was generally of a medium gray color. This color change occurred at the depth which other evidence indicates that the delivery of erosional material from the watershed was significantly reduced. A zone between about 55 to 65 cm contained some sand particles and coincided with flood events.

Core TL-2: The total length of this core was 110 cm. The top 45 was generally uniform in color and rather flocculent. From 45 to 90 cm the sediment appeared to possess a higher clay content. Between 90-99 cm there was an abundance of sticks and terrestrial leaf fragments. From 99-110 cm there was little terrestrial debris and there was sand mixed with the mud.

Core TL-3: This core was shorter than the other sites being 66 cm in length. From 0-63 cm the sediment was dark gray in color. The bottom 3 cm of the core contained significant amounts of sand.

It appeared that the cores from all three sites penetrated the entire amount of sediment that has been deposited since the lake was formed. At the bottom of the cores there was a fair amount of sand which likely indicates this was deposited when there was a riverine environment.

Dating

Because the time period of the core did not exceed 130 years, it was not possible to calculate dates or instantaneous sedimentation rates for each core segment of the core from the main basin (TL-1). Instead dates for the core were derived two ways. Radioactive cesium (^{137}CS) was measured in order to estimate the dates 1963 and 1954. Cesium-137 was released during atmospheric testing of nuclear weapons from 1954 through the mid-1960's. The peak production occurred in 1963 when the U.S.S.R. was conducting many of their tests. (Richtie and McHenry 1990). The onset of measurable quantities of ^{137}CS indicates the year 1954 when the USA began atmospheric testing.
Dates were also estimated by comparing flow records compiled by the USGS for the Red Cedar River just below the dam at Menomonie. Flood events would be expected to deliver a large amount of course grained sediment that would be evident in sediment record.

Figure 2 shows the peak annual discharge in the river for the period early in the twentieth century through 1995. Significant flood events occurred in 1934, 1938, 1942, 1965, and 1967. In fact the

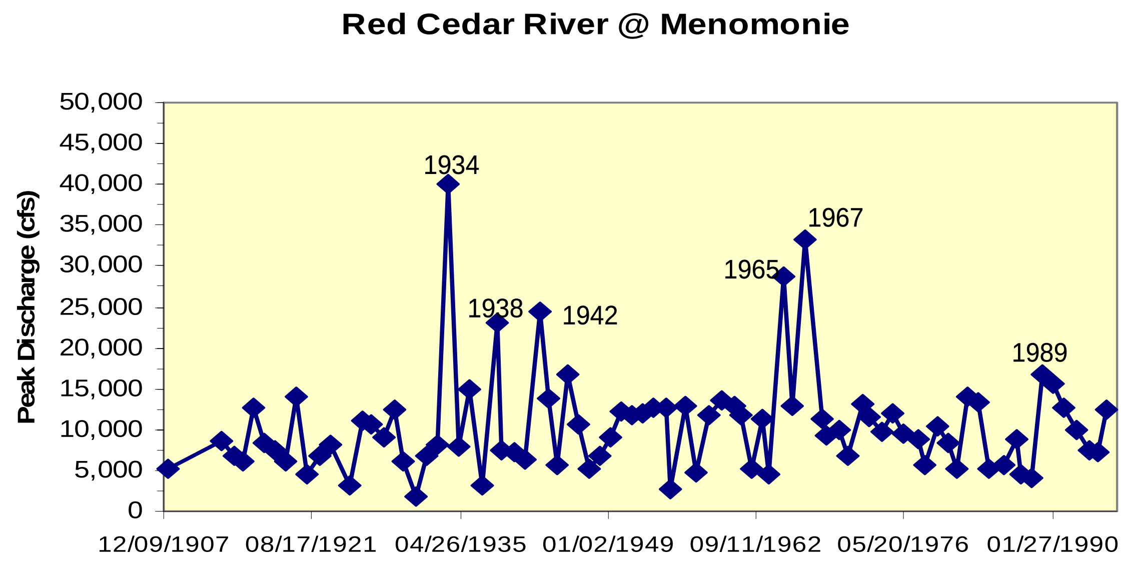


Figure 2. Peak discharge for the Red Cedar River at Menomonie between 1908 and 1995.

floods of 1934 and 1967 were 100 year events and the other floods were 50 year events. Sediment porosity was used to estimate the grain size of the soil particles. A relative low value reflects a greater amount of courser material. There appear to have been three flood events recorded in the sediment core (Figure 3). These events correspond to the floods of l934, 1938-42, and 1965-67. The floods of 1938 and 1942 as well as 1965 and 1967 were not separated because they occurred so close

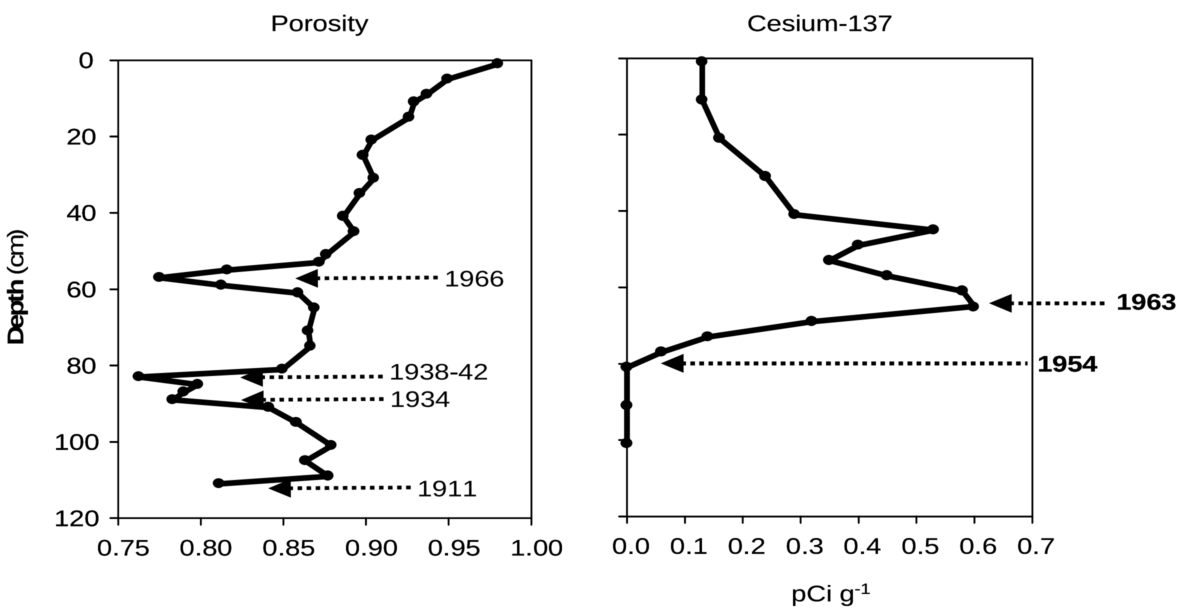


Figure 3. The porosity and cesium-137 profiles for the core from the main basin (TL-1). The lower values in the porosity profile is the result of course grained sediment delivered during flood events. The peak cesium value represents the peak emission of cesium 137 during atmospheric nuclear testing.

together and material from both events likely would be found in the same core segment. The bottom portion of the core that was recovered was assumed to represent a date of 1911 which was the date when the dam height was raised. The 30 cm of sediment below this that was lost during the coring operation was sandy and likely was deposited when the site was a river.

The use of porosity and flood events to date the core segments was confirmed by the cesium profile. The cesium is first measurable at a depth shallower than the estimated 1942 flood and the cesium peak is 1 core section below the 1965-67 flood event (Figure 3). The cesium profile in a sediment core normally does not have a double peak as exhibited in the Tainter Lake core. This core contains a double peak because the sediment delivered to the lake during the floods of 1965-67 diluted the cesium in the core.

The porosity profiles for the cores taken near where the Red Cedar River enters Tainter Lake and where the Hay River enters the lake are shown in Figure 4. The flood events are not as evident in these two cores compared with core TL-1 but the floods of 1965 and 1967 are probably represented by minimum values in each core. The floods of the mid-1960s in core TL-2 is at about the same depth as in core TL-1 indicating the sedimentation rate at these two sites has been similar since the mid-1960s.

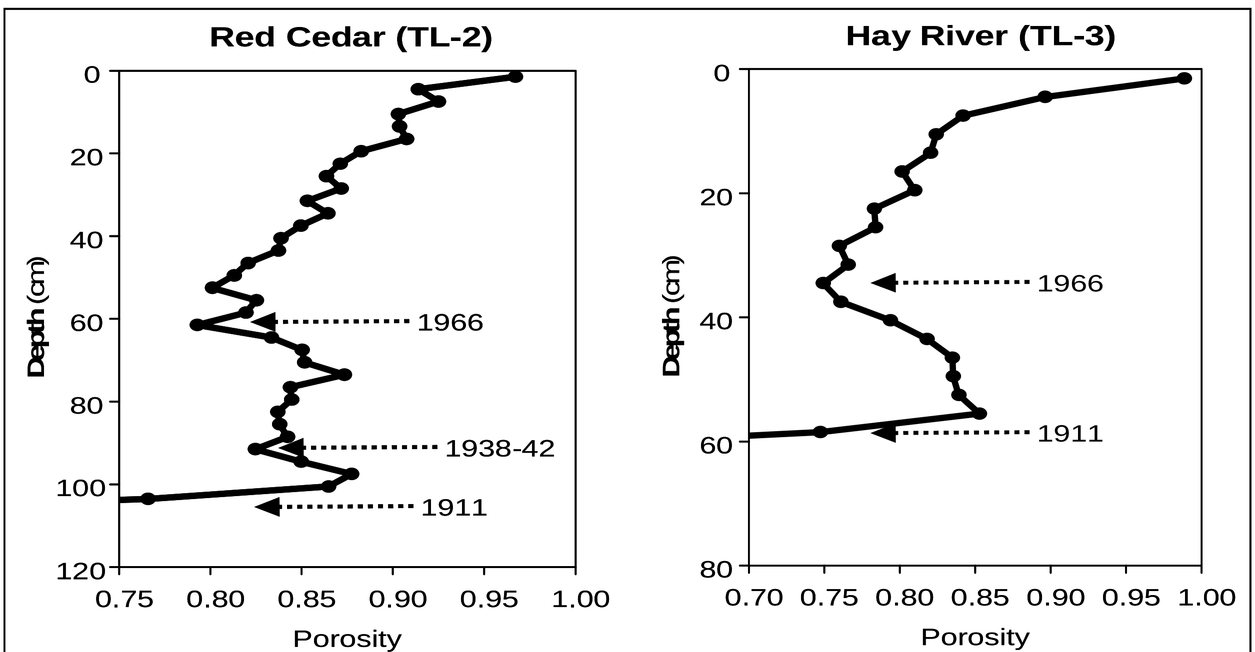


Figure 4. The porosity profiles for the cores from the basin near where the Red Cedar River enters the lake and the basin where the Hay River enters Tainter Lake. The porosity is very low at the bottom of the core because high sand content represents riverine conditions before the lake was formed. The flood events evident in the TL-1 core are not as visible in these cores.

The sedimentation rate at the Hay River site was slower as the floods of the mid-1960s is found at about 35 cm compared with 58 cm in core TL-1 and 62 cm in core TL-2 (Figures 3 and 4).

The porosity values were very low at the bottom of cores Tl-2 and TL-3. This likely is because the sediments at the bottom of the cores was deposited prior to the installation of the dam which formed the lake. This is also indicated by the high sand content in these sediments.

For the core from the main basin (TL-1) the sedimentation rates were estimated for the time period between each estimated date in the core (Table 1). Values were calculated both as mass depth and linear depth. Mass depth is more accurate since it corrects for sediment compaction that occurs as sediment is buried by more recent material. As the thickness of the sediment builds up with successive sedimentation, the water content of deeper sediment decreases normally in an exponential fashion with a net movement of water upwards towards the sediment-water interface. Thus, as time goes on the depth of sediment associated with one year of sedimentation decreases, or the sedimentation rate measured in centimeters appears to decrease. This change in water content does not affect the mass of sediment particles transferred to the sediments in any one year and the build-up of the mass of these particles provides a linear depth scale that is independent of the overall water content. Normally porosity should decrease exponentially with increasing depth in the core.

Table 1. Sediment accumulation rates for time periods throughout the Tainter Lake core. Mass depth rates correct for sediment compaction and are more accurate to compare rates between time periods.

Time Period	Mass Depth	Linear Depth
	(g cm^{-2} yr^{-1})	(cm yr^{-1})
1966-1995	0.46	2.0
1954-1966	0.63	1.8
1940-1954	0.26	0.7
1934-1940	1.11	1.0
1911-1934	0.53	1.0

It should be cautioned that these rates only represent those found at this site and are not necessarily representative of other sites in the lake. Nor should these rates be construed as an average sedimentation rate for the entire lake. These rates should only be used for comparative purposes at this site to determine changes in relative sedimentation rates through time.

The highest sedimentation rate occurred during the period 1934-40, while the slowest sedimentation rate occurred during the period 1940-1954. The sedimentation rate since 1966 has been lower than during much of the time period represented by the core but this is also the longest period. Undoubtedly the sedimentation rate has fluctuated during the last 30 years. Dates for the last 30 years where significant events were calculated using the average sedimentation rate since 1966. These dates are not as accurate as those determined from chronostratigraphic markers such as ^{137}Cs or flood events.

Geochemistry

The loss on ignition (LOI) profiles for the three cores are shown in Figure 5. Loss on ignition is a surrogate for organic matter. The LOI profile from the main basin (TL-1) core, partially reflects past flood events, but not as faithfully as the porosity profile. This likely is because spring floods (1934, 1965-67) possess less organic matter than do fall floods (1938, 1942) which have crop residue in the flood wa-

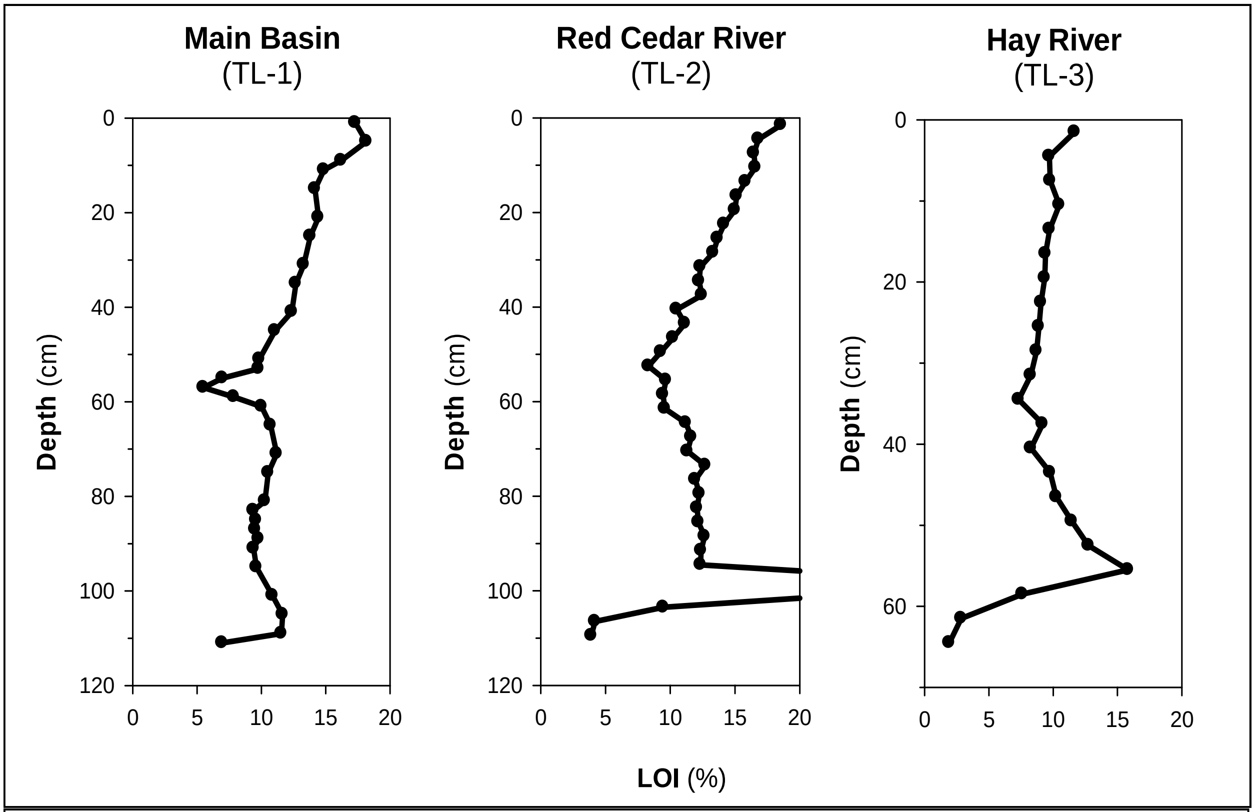


Figure 5. Loss on ignition (LOI) profiles for the 3 cores. This is a surrogate for organic matter. The floods of 1965 and 1967 are evident in the reduced values in core TL-1 but not as evident in the other cores.

ters. Both of the cores taken near the inlets of the rivers (TL-2, TL-3) have elevated LOI values near the bottom of the cores. This reflects the organic matter that was at these sites when the lake was formed. The flooding buried this terrestrially derived material which is reflected in the higher LOI values. Loss on ignition values were the lowest at the very bottom of the core which reflects the high sand content of this sediment because is was deposited in the river channels prior to the installation of the dam which formed Tainter Lake.

Sediment phosphorus concentrations were determined in the cores from all three sites. At all three sites, the highest concentrations occurred at the top of the cores (Figure 6). At the Hay River site (TL-3) concentrations were similar after the bottom sample (pre-lake) until near the top of the core. At the other two sites, phosphorus levels steadily increased from near the bottom of the core until near the top when they dramatically increased (Figure 6). The steady increase in the Red Cedar River site (TL-2) compared with the Hay River site (TL-3) indicates that the Red Cedar River watershed is a higher source of phosphorus, especially since the mid-1960s compared with the Hay River watershed.

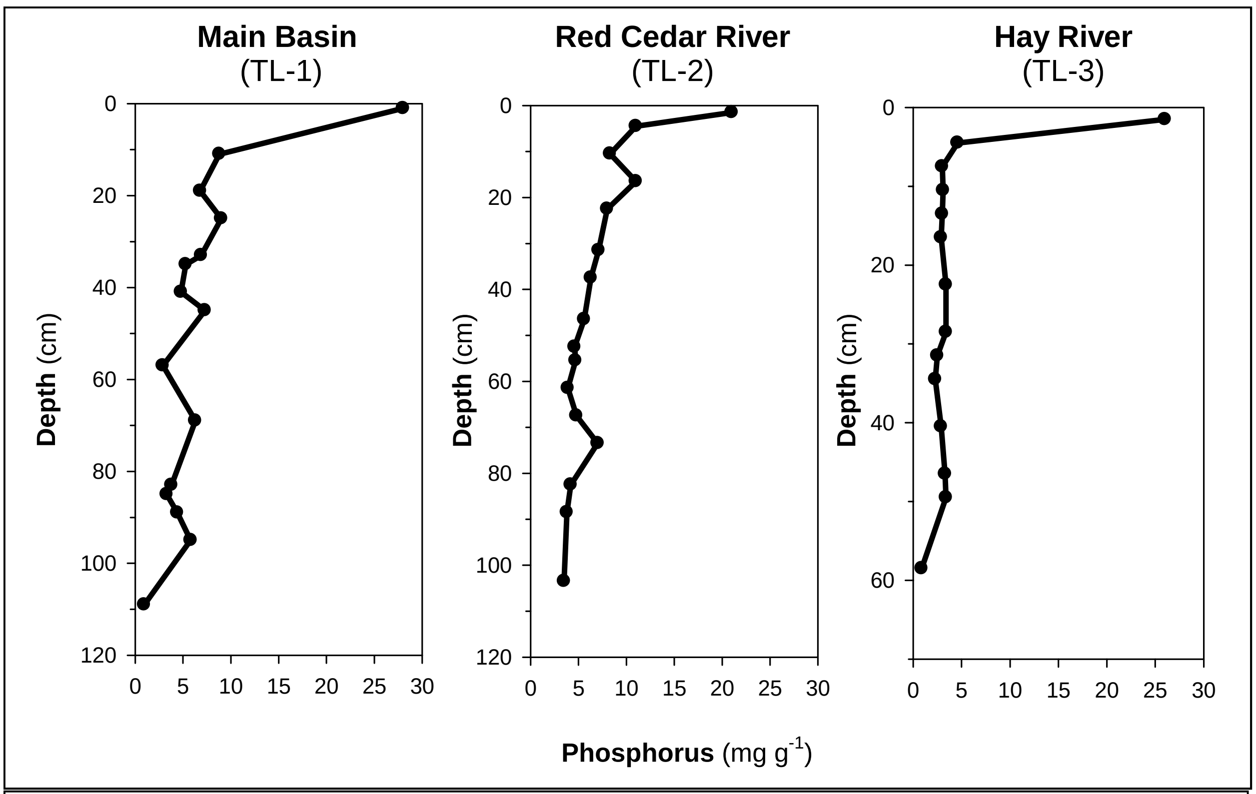
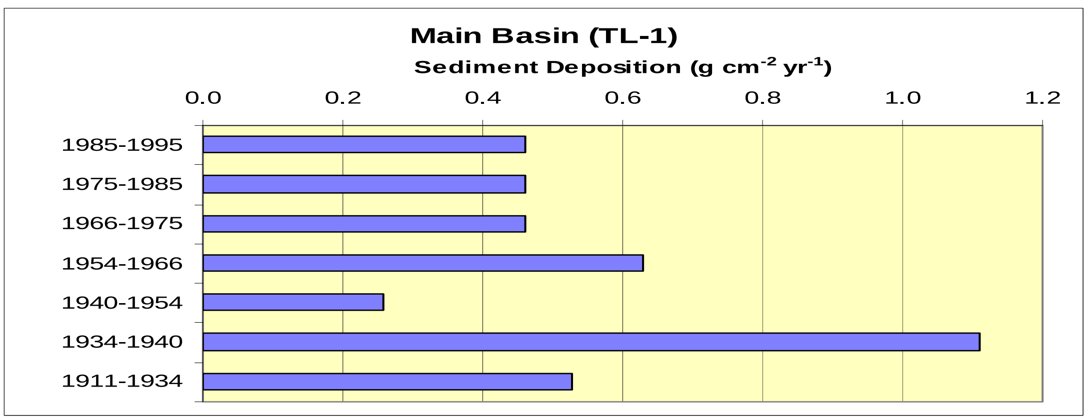


Figure 6. Phosphorus profiles for the 3 cores. The highest phosphorus levels were at the top of all of the cores indicating enhanced phosphorus delivery from the watershed in recent years.

Because it is likely that the sedimentation rate has changed over time in the lake, a better way to determine changes in sediment and phosphorus delivery from the watershed is by accumulation instead of concentration. While concentration changes give a general indication of watershed delivery rates, accumulation provides a more accurate picture. For the core from the main basin (TL-1) it is possible to breakdown the accumulation rate into discrete time periods when there are date constraints from flooding events and the cesium-137 analysis.

The highest sediment accumulation rate occurred during the period 1934-40 (Figure 7). The rate is probably so high because at this time there mass wasting of soils since soil conservation was not practiced. Also two flood events occurred during the period and these events would be expected to deliver more sediment to the lake. The lowest period of sediment deposition was the period 1940-54 when there were no flood events. Since 1966 sediment deposition has been relatively constant and lower than earlier periods probably reflecting the efficiency of soil conservation practices in the watershed. Because cesium-137 was not measured in the cores from the Red Cedar River site (TL-2) or



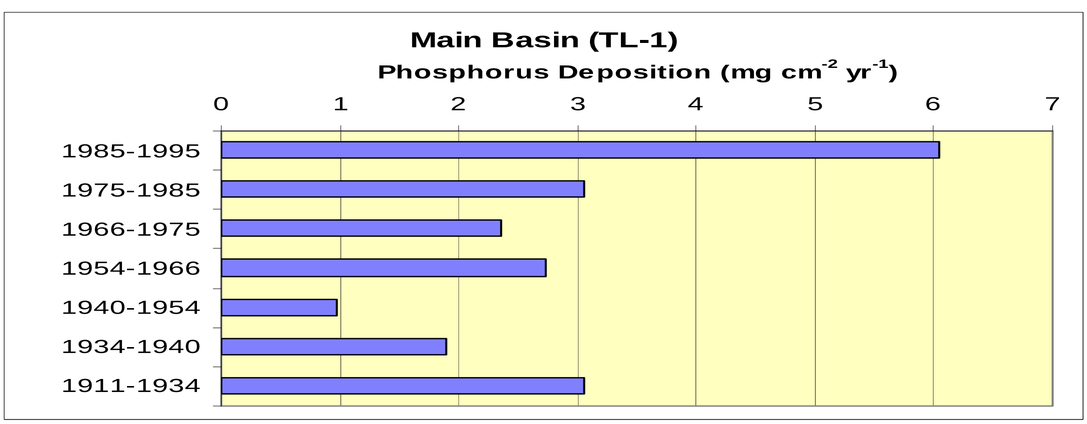


Figure 7. Accumulation rates of sediment and phosphorus in the Main Basin core (TL-1). While the highest rates for sediment occurred during the 1930s the highest phosphorus rate was during the period 1985-95.

the Hay River site (TL-3) it is not possible to do a similar comparison of sediment deposition. However, because the porosity profile reflects the flood events of 1938-42 and 1965-67, we can assume that the sediment deposition rate would be similar at the Red Cedar River site as it is in the main site but the rate would be much lower at the Hay River site.

The highest phosphorus deposition rate was during the most recent period 1985-1995 (Figure 7). This is contrary to when sediment deposition was highest. Even though sediment deposition is reduced during the decade of 1985-95, the use of commercial fertilizers and deposition of poultry waste in the watershed results in elevated phosphorus delivery to the lake. This trend of high phosphorus deposition since the 1970-80s along with declining sediment deposition is common in other Wisconsin lakes where agriculture is a significant part of the landuse in the watershed. Even though cropping has intensified, soil conservation practices have effectively reduced soil erosion. In contrast, phosphorus delivery from the watershed has increased as more commercial fertilizer is applied to landscape. Also there has been increasing use of livestock feed additives which also causes increased phosphorus runoff from the landscape.

Even though changes in phosphorus deposition were not determined in the cores taken near the inlets of the rivers, we can estimate the relative contribution of phosphorus from these sources from the phosphorus concentration profiles. Phosphorus concentrations are highest in both cores at the top. The increase is greater in the Hay River core indicating that phosphorus delivery from this watershed has increased by a greater amount. The increase in phosphorus concentration in the main basin core (TL-1) is greater than in the Red Cedar River core (TL-2) indicating that the Hay River watershed is a larger contributor of phosphorus to the lake than the Red Cedar River is.

Diatoms

Diatoms can be useful in interpreting past environmental changes because many of the taxa are found under narrow environmental conditions. For example, changes in nutrients can be inferred from changes in the relative abundance of the taxa as well as their overall production. The diatom community at the bottom of the core was dominated by *Stephanodiscus minutulus, Cyclostephanos invisitatus,* and *Aulacoseira granulata* (Figure 8). Although knowledge of the ecology of C. *invisitatus* is limited, the other two taxa are common in eutrophic systems. Their dominance indicates that nutrients in the lake were high in the 1930's. The decrease in *A granulata* and *Stephanodiscus hantzschii* after 1938 are indicative of declining nutrient levels. Nutrient levels appear to have again increased around 1960 and these elevated levels were maintained until about 1980. The diatom *Aulacoseira italica* is usually found in lakes with lower phosphorus concentrations than *A. granulata.* The increase in *A. italica* and decline of *A. granulata* since 1980 indicate that nutrient levels may have declined in the last 15 years compared with the period 1960 through 1980. Because S. *minutulus* is still an important component of the diatom community in the upper sediments this indicates that phosphorus levels while probably lower than during the period 1960-1980, are still relatively high.

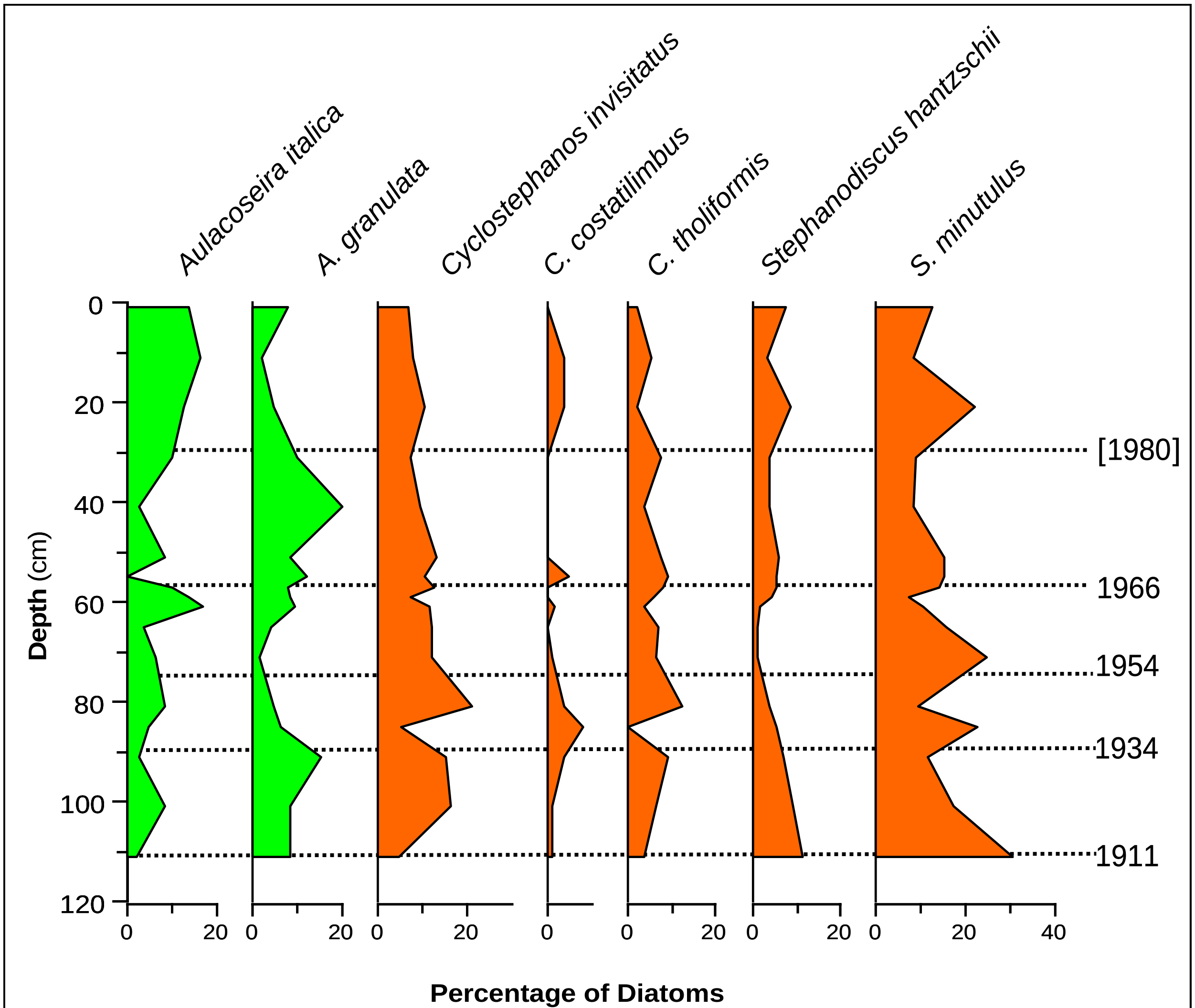


Figure 8. Profiles of common diatoms found in the Main Basin Core (TL-1). The diatoms in green are indicative of moderate nutrient levels and the orange-higher nutrient levels.

Diatom assemblages historically have been used as indicators of nutrient changes in a qualitative way. 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. 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.

Such a model was applied to the diatom community in the core from Tainter Lake. Wisconsin lakes were not used to construct the model since there was not enough data from Wisconsin lakes with phosphorus values in the range of Tainter Lake. Instead data collected from during the National Lake Assessment of 2007 from Dakota lakes was used to construct a model. The model indicates that the highest phosphorus concentrations occurred during the period 1966-80 (Figure 9). The phosphorus concentrations during the period 1966-80 were about 25 µg L^{-1} higher than other time periods.

These results somewhat contradict the sediment phosphorus profiles which indicate higher concentrations in the upper sediments. It is likely that the increase in phosphorus resulted in a decline in summer diatoms such as *A. granulata* because the high frequency of blue-green algal blooms out compete the diatoms. Thus diatoms that are more common in the spring, e.g. *A. italica*, appear more common in the upper sediments of the core.

Algal Pigments

Other evidence of historical water quality that is preserved in the lake sediments are algal pigments. Some pigments such as chlorophyll *a,* are present in all algae whereas many carotenoids are specific for certain algal groups. For example, lutein is only found in green algae whereas zeaxanthin is only found in blue-green algae. Because pigments are highly susceptible to degradation both within the water column and once they have been deposited within the sediments, it is not possible to compare levels between lakes. However other studies have found that changes in algal biomass can be made within a sediment core using residual sediment pigments (Hurley and Armstrong 1991, Hurley et al. 1992, Leavitt 1993, Leavitt and Findlay 1994). Because differential degradation of carotenoids occurs in the water column and the sediments, comparisons can not be made about the relative abundance between algal groups. For example, higher fossil concentrations of carotenoids of green algae (lutein)

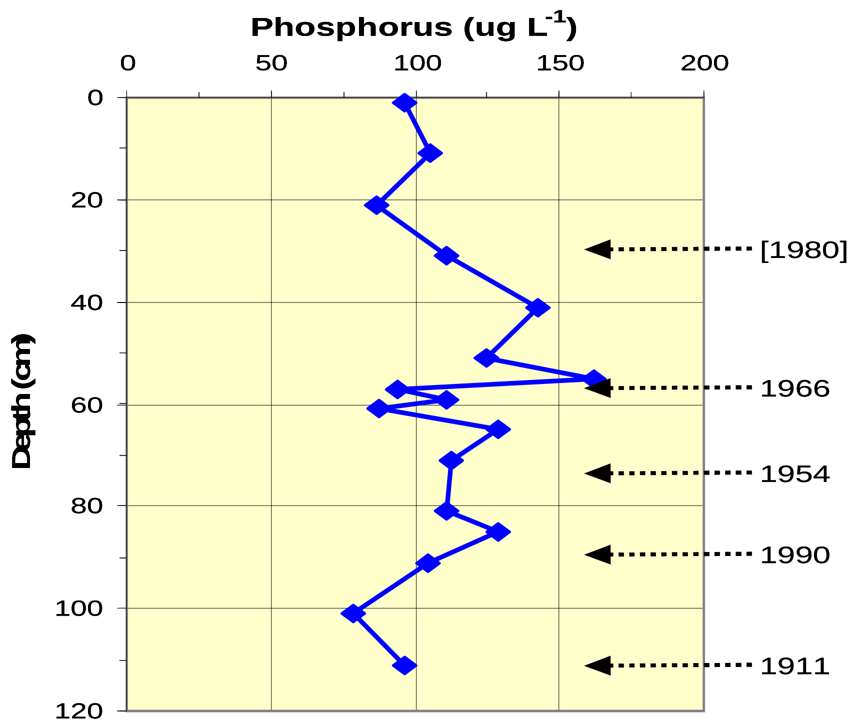


Figure 9. Diatom inferred summer mean phosphorus concentrations in the core from the main basin of Tainter Lake (TL-1). The highest concentrations occurred during the period 1966-1980.

compared with blue-green algae (zeaxanthin) do not securely indicate higher levels of green algae were present in the lake.

Algal pigments have been analyzed in the core from Tainter Lake representing the time period 1954 to the present. Total phorbin, which is the sum of chlorophyll *a* and its degradation products, are highest between the period 1966 through 1980 (Figure 10). This indicates that the algal biomass in the lake was highest at this time. This agrees with evidence for increased nutrients during this time period that were found with the diatom community. The predominant algal group that increased during this time period was greens (lutein), although blue greens (zeaxanthin) also showed elevated levels. During the first half of the 1980's, the algal biomass declined to levels lower than any other time since 1954. Beginning about 1985, phorbin increased although not to levels present in the 1960's and 1970's. All pigments and carotenoids indicated high levels near the top of the core. This elevated peak is likely a combination of two factors. Pigments continue to degrade following deposition in the sediments (Leavitt and Carpenter 1990a, 1990b; Hurley and Armstrong 1991). Incomplete decomposition leads to elevated fossil abundance of pigments in the near surface sediments. This is likely the case in this core as the carotenoid fucoxanthin shows elevated levels in the surface of the core. This pigment is very labile and usually is only present in low levels. This is illustrated by the low levels between

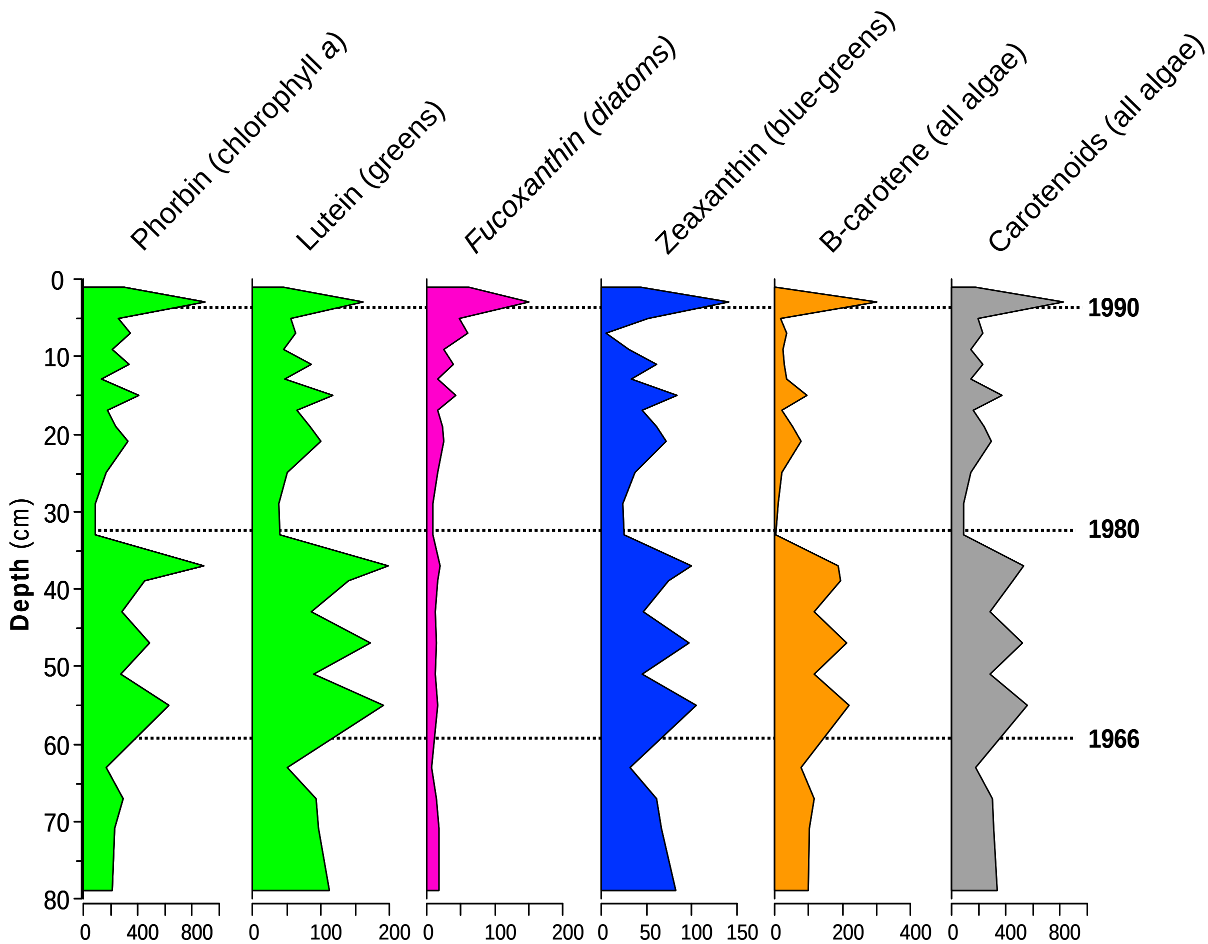


Figure 10. Profiles of important algal pigments. Only the upper of the core was analyzed for pigments. Note that the scale differs between pigment profiles.

1966 and 1980 even though phorbin and carotene levels indicated that algal levels were high. Because all pigment levels were lower in the surface sediments compared to the next deeper section, it seems reasonable that the subsurface peak may indicate some degree of accelerated levels of algal biomass.

Conclusion

Since the cores discussed in this report were collected in 1995 and 1997, any changes that have occurred in the lake since then are not reflected in this report. When discussing results from the top of the core it must be kept in mind that recent changes represent the 1990s.

The sediments of Tainter Lake provide a good record of historical floods that have occurred in the Red Cedar River since the mid-1930's. These events were recorded by a decline in the porosity values. The highest sedimentation rates occurred during the 1930s as a result of mass wasting of soils that occurred since soil conservation practices were not used. The elevated sedimentation deposition rate was also the result of floods which occurred during this time period. The sedimentation rate has been relatively constant since 1966 even though cropping practices have increased. The sedimentation rate at the Red Cedar River site (TL-2) was higher than at the Hay River site (TL-3) indicating that the Red Cedar River is the more important sediment source for the lake.

Unlike sediment deposition, the highest phosphorus deposition rates occurred during the most recent period of the sediment core (1985-1995). This likely is the result of the increased use of commercial fertilizer and food additives to livestock. The Hay River watershed appears to more important source of phosphorus compared with the Red Cedar River.

Both fossil diatoms and algal pigments were used to reconstruct the lake's water quality. Because of the presence of high blue-green algae levels, pigments probably give a better indication of changes in the nutrient levels. Although diatoms and pigments indicated similar trophic changes, they were more subtle in the diatoms. Nutrient levels appear to have been highest during the period 1966 through 1980. Algal levels appear to have been significantly lower during the early 1980's but have increased since then. Pigments indicate that a significant algal bloom may have occurred in the last five years. The likely increase in blue-green algal levels during the last decade is not evident in the diatom community because diatom more common in the summer, e.g. *A. granulata*, are not as common and thus their fossils are found in the core in lower abundance.

The biological fossils indicate that the highest phosphorus concentrations in the lake occurred during the period 1966-1980. This differs from when the highest phosphorus deposition occurred which was during the decade before the core was collected. Other studies have found that phosphorus concentrations in the sediment do not accurately reflect phosphorus levels in the water column (Engstrom and Wright 1984, Schelske et al. 1988, Anderson et al. 1993, Fitzpatrick et al. 2003). Often organic matter continues to decompose after it is deposited in the lake and as the organic phosphorus decomposes and becomes an inorganic form, it is released into the water column (internal loading) and is removed from the lake through the outlet. Another reason for the discrepancy between the highest sediment phosphorus deposition and when the biota indicates the highest phosphorus concentration (1966-80) could be the timing of when much of the phosphorus enters the lake. If this occurs during the spring or fall, algal growth is limited during this period and much of the phosphorus may go to the sediments before it can be utilized.

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