Lake and Reservoir Management 24:349-360, 2008

Sedimentary and historical context of eutrophication and remediation in urban Lake McCarrons (Roseville, Minnesota)

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Abstract

Myrbo, A. 2008. Sedimentary and historical context of eutrophication and remediation in urban Lake McCarrons (Roseville, Minnesota). Lake Reserv. Manage. 24:349-360.

Geochemical analysis of the varved (annually laminated) sediments of a small, deep urban lake in east-central Minnesota shows that some water-quality and watershed indicators are approaching prehistoric (pre-1850s) values after an excursion to anomalous levels during the 1920s through 1950s. This high-resolution paleolimnological information (annually resolved for most of the 20th century), including varve thickness measurements on a digital image, carbon stable isotopic composition of organic matter, and sedimentary component quantification, provides historical perspective to lake managers planning remedial measures with reference to the "natural" state of the lake, especially in regard to the perception that water quality has declined only in recent decades (*i.e.*, in the late 20th century). The lake is at present eutrophic and oligomictic, with oxygen-depleted bottom waters enriched in dissolved solids relative to surface waters; an alum treatment has contributed to the problem of persistent stratification at the same time as it has reduced phosphorus and increased transparency in lake surface waters. The sedimentary record shows the lake's strong response to agricultural, recreational, and urban development in the watershed, gradual improvement beginning at the time of sanitary sewer installation in the 1960s, and only a minor additional response to a concerted remediation effort in the mid-1980s to 1990s. Indices of terrestrial inputs and algal productivity show evidence of a lake that was at its most heavily impacted during the mid-20th century, and which has improved in some respects since the 1960s.

Key words: alum treatment, bathing beach, carbon stable isotopes, detention pond, dissolved sulfate, paleolimnology, urban lake, varved sediments

Lakes in urban settings are recreational and aesthetic focal points for their surrounding communities. City lakes are subject to a special set of problems including nutrient loading, salt inputs, shoreline erosion, and hypolimnetic anoxia (Hollander *et al.* 1992, Engstrom *et al.* 1999, James *et al.* 2002). These human impacts are not solely recent, but date from the very beginning of European settlement in North America, and in some lakes even to prehistoric times (Ekdahl *et al.* 2004). Water quality suffers as a consequence of agriculture and logging, followed by residential, commercial, and civil development in the watershed, as well as use of the lake itself for subsistence and recreation. As a result, urban lakes are also frequently focal points of management efforts to correct the ill effects of the land-use changes listed above.

Remediation goals frequently include returning lakes to their "natural states," and managing lake water quality (Oberts and Osgood 1988, Oberts 1997, Osgood 2003). Unfortunately, the natural state, typically pre-instrumental, is altered before its characteristics can be measured and thus is poorly characterized; impacted systems characteristically show high interannual variability and thus poor predictability (Cottingham *et al.* 2000), complicating management decisions. Paleolimnological analysis of lake sediment cores can provide a picture not only of the prehuman-impact state, but of trends over the intervening period between initial impact and the present day, providing perspective on system variability, as well as correlations between proxy indicators of water quality parameters and events (beneficial and detrimental) in the lake watershed.

This paper presents the results of a sediment core-based study of Lake McCarrons, a small, deep urban lake in Roseville, Minnesota (a first-ring suburb of the capital, Saint Paul). The lake has been the subject of monitoring at times from 1980 to the present and of a remediation attempt in the form of a detention-pond complex intended to reduce nutrient inputs. Following a period of agricultural use of the lake's watershed beginning in the 1850s, one of the first metropolitan-area public bathing beaches was established in 1926. Recreational management included algaecide treatment, addition of tons of beach sand, lake-level manipulation, and construction of buildings, roads, and parking lots. A comparison of the lake's history with the high-resolution sedimentary record of geochemical and sedimentological changes constrains the timing of various impacts, and permits an assessment of their relative importance in contributing to the modern state of the lake.

Materials and methods

Study site

Lake McCarrons (Fig. 1) is a small urban lake in Roseville, Minnesota (Ramsey County). The lake has a surface area of 33 ha and a watershed of about 300 ha. Its maximum depth is 17.3 m, and its mean depth is 7.6 m. The lake has a calcium-

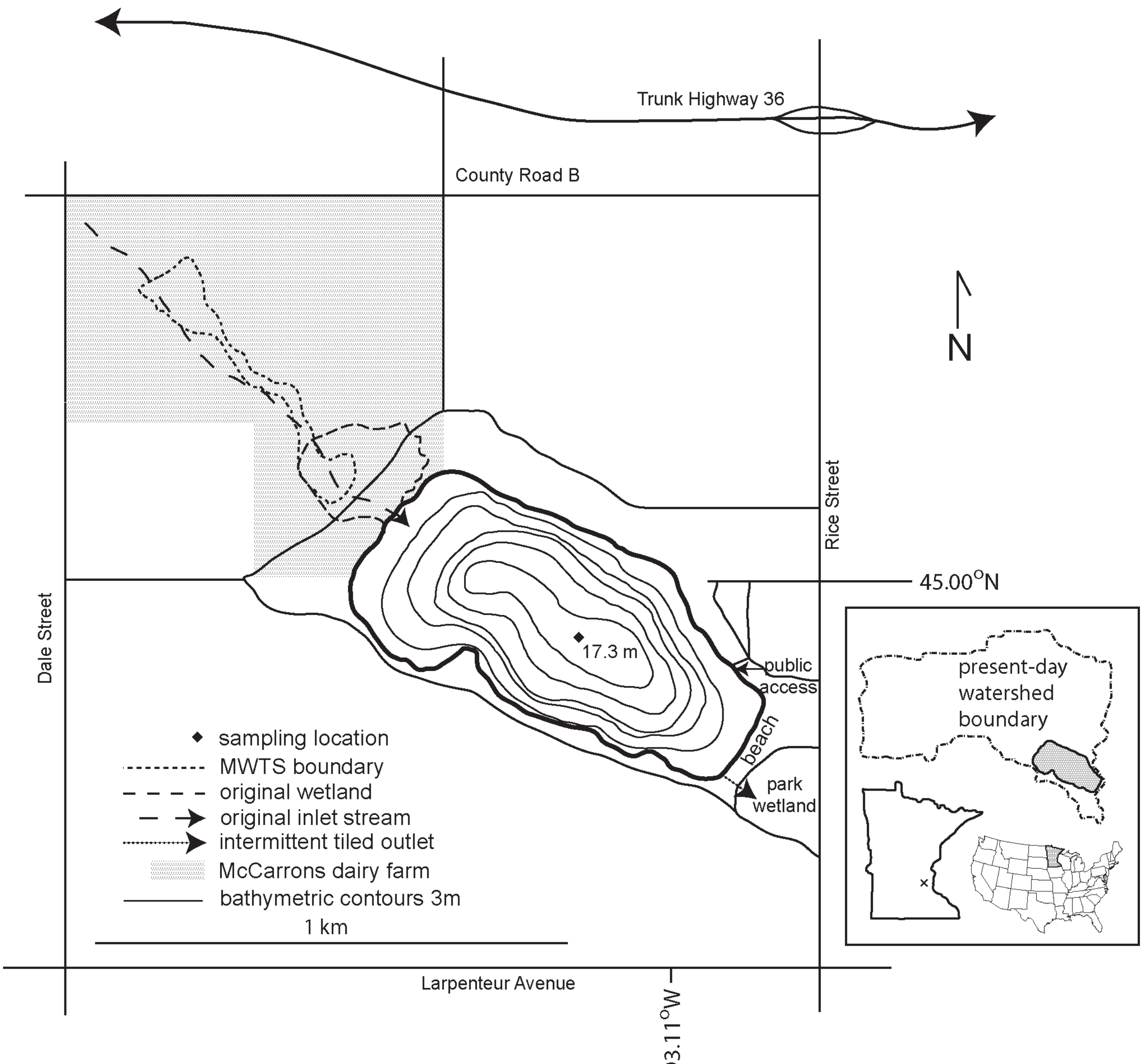

Figure1.-Location and bathymetric map of Lake McCarrons. MWTS is the McCarrons Wetland Treatment System, constructed in the mid-1980s to reduce nutrient loading to the lake.

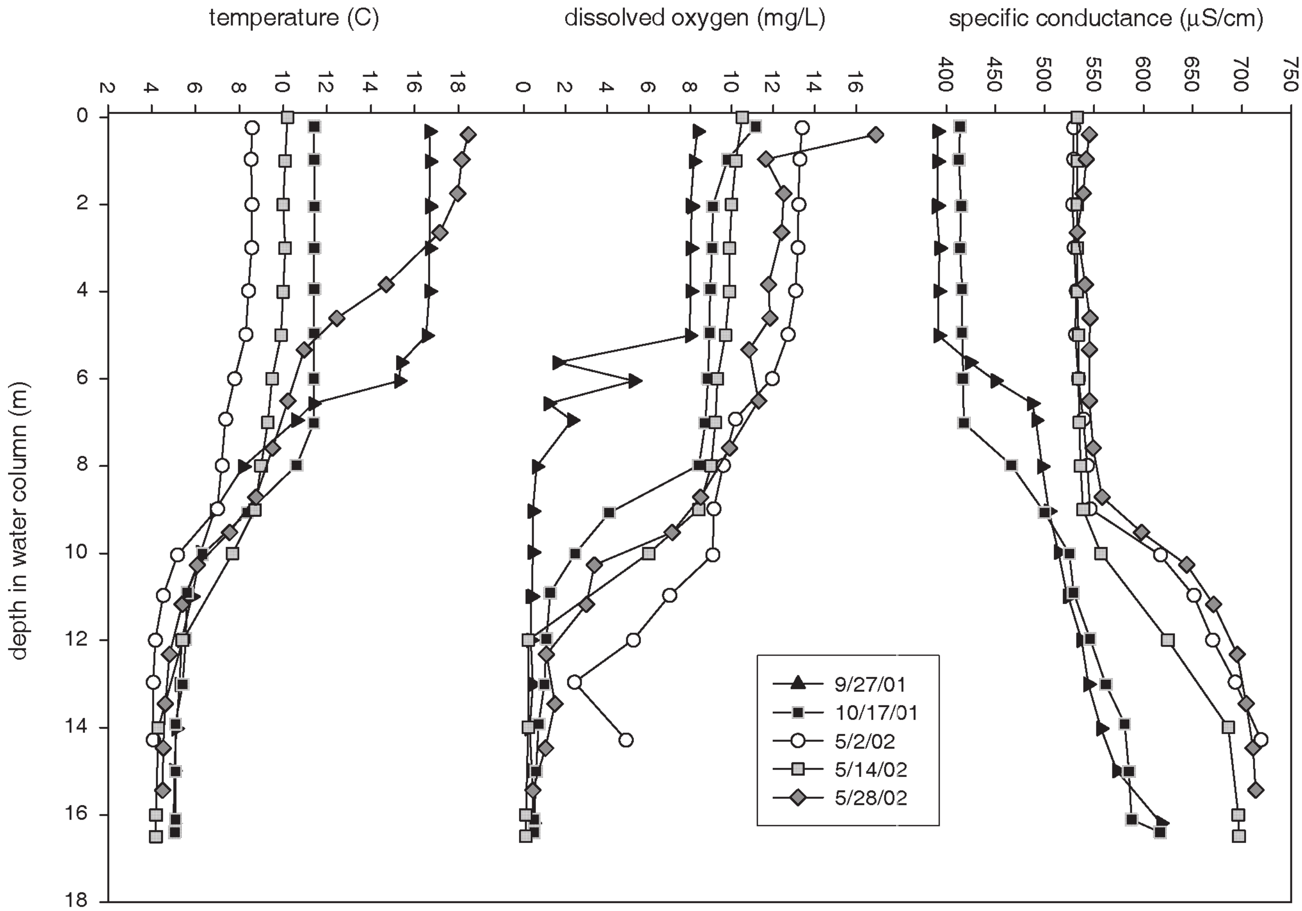

Figure 2.-Late fall and early spring temperature, dissolved oxygen, and specific conductance profiles from Lake McCarrons showing persistence of stratification and incomplete mixis. Additional data available from Minnesota Pollution Control Agency Electronic Data Access suggest that the lake completely overturns only in some years. Lake ice cover in this region typically lasts from late November to mid-April (Johnson and Stefan 2006).

bicarbonate chemistry (200–450 mg/L total dissolved solids [TDS], alkalinity ~2 meq/L), and has 50–100 times higher concentration of some major ions (Cl^-, K^+, and Na^+) than rural lakes in the area, especially in the hypolimnion, (*cf.* Gorham *et al.* 1983). Due to the high bottom water TDS, the lake is evidently persistently stratified and does not overturn every fall (Osgood 2003). Representative late fall and early spring profiles of temperature, specific conductance, and dissolved oxygen concentration (Fig. 2) indicate incomplete mixing (data from Minnesota Pollution Control Agency Electronic Data Access); profiles from the ice-covered period are not available. Lake McCarrons is moderately eutrophic, with a Carlson's Trophic State Index average of 55, chlorophyll *a* (Chl-*a*) of 18 ± 1 ppb, total phosphorus (TP) of 41 ± 2 ppb, and a mean Secchi disk depth of 1.9 m (data from Minnesota Department of Natural Resources; standard errors are reported).

The lake is situated in a pre-Holocene channel of the Mississippi River in glacial material that comprises mixed carbonate-rich Des Moines lobe and iron-rich Superior lobe tills plus outwash sand (Wright 1972). Wetlands occur immediately northwest and southeast of the lake, along the axis of the channel. A small stream flows in from the northwest, and an intermittent tiled outflow exits the lake at the southeastern end. The lake basin is relatively steep-sided, rising ~12 m over 0.1 km toward Larpenteur Avenue to the south and ~27 m over ~1 km to state Highway 36 to the north. Land-use in the watershed is predominantly commercial, industrial, and residential, with some wooded and undeveloped areas; land cover is 25% impervious surfaces (Oberts 1997). The lake's present-day watershed has been estimated to be three times the size it was before late 19th-century ditching and wetland drainage (Minnesota Department of Natural Resources 1997, Osgood 2003).

Historical context

Dairy farming provided the first major human impact to the lake. The McCarrons family settled on 45 ha at the northwestern end of the lake around 1855. Expansion of dairy, hog, poultry, and beef farming, as well as commercial ice harvesting, continued on and around the lake through the 19th century (Roseville Historical Society 1998, and plat maps in the collection of the Minnesota Historical Society [MNHS]), and growth of Rose Township (later Roseville) brought residential and commercial development. By 1931 housing subdivisions existed around about half the lake. In 1926 Ramsey County established a public bathing beach, which still exists today, at the southeastern end of the lake. Minutes of the Ramsey County Recreation Board meetings from 1924 to 1944 (MNHS collection) provide an unusually detailed record of beach attendance, lakeshore modification, and urbanization of the lake basin, including an ongoing effort to maintain a sand beach, to expose more beach area by lowering lake level, and to fill low-lying and swampy areas. By 1928 water quality had deteriorated enough to warrant an expensive treatment of the lake water with copper sulfate as an algaecide (reports of the Minnesota Department of Health, Division of Sanitation, MNHS collection). Additional construction of homes and commercial properties in the lake basin occurred in the 1940s and 1950s, and development continues to the present day. A sanitary sewer system for Roseville was constructed in the mid-1960s, after sewage, nitrates, and detergent were found in water supply wells (St. Paul Suburban Life 1960).

In 1985, following a water quality study by the Metropolitan Council of the Twin Cities, a detention-pond complex designed to trap sediment and nutrients was constructed within the lake's inflow. This complex, the McCarrons Wetland Treatment System (MWTS), consists of two sedimentation basins and a sequence of six wetlands. It was planted with a diverse array of plant species in an attempt to reduce external loading of nutrients, especially phosphorus, which is the limiting nutrient in the lake (West-Mack and Stefan 2000a). Results of the remediation effort are detailed in Metropolitan Council reports (Oberts and Osgood 1988, Oberts 1997), in a series of monitoring/modeling studies (West-Mack and Stefan 2000a, 2000b) and in a project review by Schueler (1999).

Core retrieval

A sediment core 234 cm long, designated MCC01-1MP, was collected from the ice surface in 16 m water depth in February 2001 using a piston surface corer (similar to a square-rod piston corer; Wright 1967, 1991) with a 7-cm diameter clear polycarbonate plastic barrel. The upper 134 cm of the core was used for this study.

Sediment analyses

Initial core description

Initial core description (ICD) follows Schnurrenberger *et al.* (2003) and was conducted in the Limnological Research Center (LRC) LacCore Facility, University of Minnesota, Minneapolis. The core was split lengthwise, and the two halves were wrapped in plastic film, stored in capped D-tubes at 4 °C, and left to oxidize for several days to expose sedimentary structures to view. The upper sediments proved to be laminated, as described below.

A high-resolution (10 pixels/mm) digital scan of the entire core was taken with a GFZ CoreScan digital line scanner, using polarizers to eliminate glare. Light-dark couplet thickness was measured on the digital image using NIH Image®, and these data, along with water content measured on samples of individual couplets and comparison with an earlier ^{210}Pb-dated core from the lake (Fig. 3), were used to calculate sedimentation rate.

The laminated portion of the core (the top ~43 cm) was sectioned into 84 increments along the contacts between the dark (below) and light (above) layers for geochemical analyses. The massive (*i.e.*, not laminated or poorly laminated) sediments below 43 cm were cut into 0.5-cm sections to a depth of 122 cm, and every other sample was analyzed (*e.g.*, 61.0–61.5 cm and 62.0–62.5 cm but not 61.5–62.0 cm). Smear slides (Kelts 2003, Schnurrenberger *et al.* 2003) were examined microscopically for initial estimates of abundance of sediment components.

Geochemical analyses

Sediment analyses included carbon coulometry (Engleman *et al.* 1985) to determine weight percent total inorganic (carbonate) carbon (% TIC), elemental analysis to determine weight percent total carbon and nitrogen (% TC, % TN), biogenic silica measurement (% $BSiO_2$; Mortlock and Froelich 1989) to determine weight percent diatom frustules, stable-isotopic analysis to determine $\delta^{13}C$ of organic matter ($\delta^{13}C_{om}$), X-ray diffraction to determine mineralogy, and analysis of petrographic thin sections. All analyses, except where noted, were made at the LRC LacCore Facility.

All geochemical analyses were performed on freeze-dried sediments. Percent TIC is converted to % calcite, the only carbonate mineral present as determined by X-ray diffraction, by dividing by 0.12, the fraction of C in calcite. Total C and TN were determined by combustion on a Costech Analytical Technologies ECS 4010 gas chromatograph at the Large Lakes Observatory, University of Minnesota, Duluth. Percent total organic carbon (% TOC) was calculated by subtracting % TIC from % TC, and converted to % organic matter (OM) by multiplying by 2 (Dean 1974; Dean and Schwalb

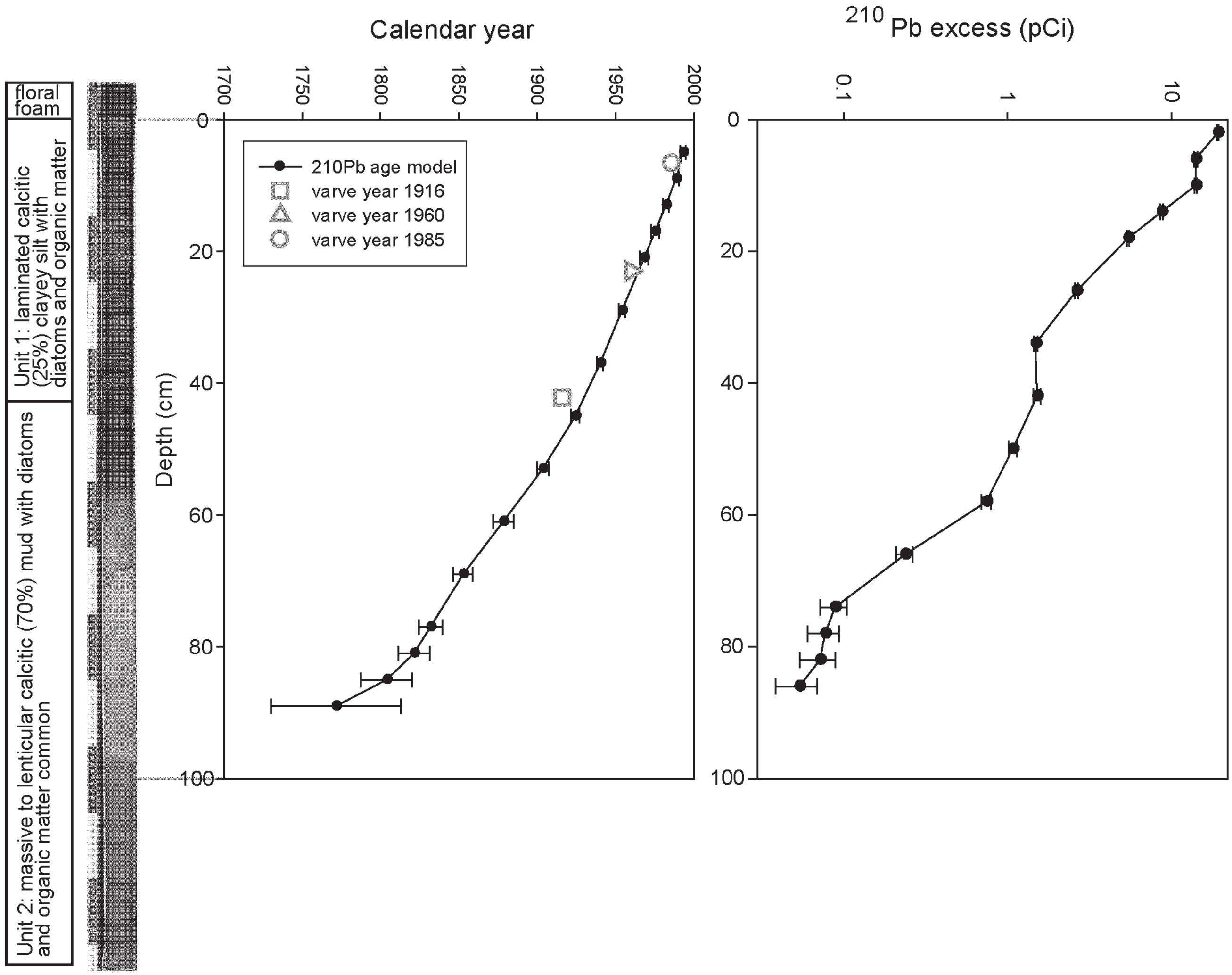

Figure 3.-Lead-210 dating results from an earlier core recovered from Lake McCarrons (Engstrom *et al.* 1999, Engstrom *et al.* 2007) and comparison of age models determined by ^{210}Pb in the earlier core vs. varve counting in core MCC01-1MP. Core image uses same depth scale as time-depth plots.

2000). This ratio was confirmed by a comparison of % TOC from coulometry and % OM from loss-on-ignition (data not shown). Percent siliciclastic material (sand, silt, and clay) was calculated as (100% – % calcite – % OM – % $BSiO_2$). Slurry-mount slides were prepared for X-ray diffraction on a Siemens D500 diffractometer at the Characterization Facility, University of Minnesota, Minneapolis.

Samples for organic carbon isotopic analysis were soaked in 1N HCl for 24 h, centrifuged, rinsed repeatedly with deionized water, and freeze-dried. These samples were ground and analyzed on a VG PRISM (Series II) mass spectrometer (SIRMS) at the Center for Isotope Geoscience, University of Florida, Gainesville. Isotopic values are expressed in standard delta notation relative to the Vienna Peedee Belemnite (VPDB) carbonate standard. Thin sections were prepared by National Petrographic Service, Houston, Texas, from slab-shaped core subsamples shock-frozen in liquid nitrogen, freeze dried, and embedded with Spurr's-type epoxy (summarized in Lotter and Lemcke 1999).

Results and discussion

Initial core description

Core MCC01-1MP contains two sedimentary units (Fig. 3): Unit 1 (0–43 cm core depth) is a laminated (0.5 cm-scale) calcitic (25%) clayey silt with abundant diatoms and organic matter. Each couplet comprises a light-colored layer consisting mainly of authigenic calcite and diatom frustules produced in the lake surface waters in the spring and summer, plus some silt and clay, and a dark-colored layer consisting mainly of organic matter and fine-grained clastic material that settle out in still-water conditions under ice cover. Unit 2 (43–128 cm core depth) is a massive-to-lenticular calcitic (70%) mud with diatoms and organic matter common. The contact between the two units at ~43 cm is diffuse, and the lower unit grades into a darker color in the top ~15 cm.

Dating

Comparison of varve counts and color changes in the massive section of the core (discussed below) with an earlier core dated by ^{210}Pb (Engstrom *et al.* 1999, Engstrom *et al.* 2007; using the constant rate of supply model; Appleby and Oldfield 1978) supports the interpretation of the light-dark couplets as annual layers. According to the ^{210}Pb profile, the 1916 horizon is 47.1 cm below the sediment surface in the Engstrom core; by varve counts it occurs at 42.2 cm in core MCC01-1MP. It is well known that sedimentation rates vary across lake basins (*e.g.*, Baker *et al.* 1992). The ^{210}Pb core was taken some 100–200 m east of core MCC01-1MP, in water ~2 m shallower, and a comparison of the two age models (Fig. 3) suggests that the sedimentation rate at the MCC01-1MP coring site is somewhat lower than at the ^{210}Pb coring site.

The presence of a nearly monospecific layer of large centric diatoms near the base of each light layer is consistent with the timing of annual spring diatom blooms and further supports the interpretation of the laminations as varves. In spite of all attempts to verify the annual nature of each lamination, uncertainties persist in the visual macro- and microscopic counting of varves (see Lotter and Lemcke 1999 for a discussion of differential uncertainties between counting methods), especially in varves such as these, whose composition and appearance are variable from one to another. It is possible, then, that some of the difference between the two age models is the result of varve overcounting, and that some small error term (*e.g.*, ± 5 years) should be applied to the varve chronology.

Sediment composition

Calcite was the dominant sedimentary component by weight (>70%) before about 1870 (Fig. 4). Clastic material (sand, silt, and clay) increased dramatically around 1870 and was the largest component thereafter (35–50%). Percent organic matter was not highly variable: it was roughly constant at ~15% before 1870, had a broad peak between 1870 and 1960, and then rose gradually thereafter to about 20% of the total dry sediment mass. Biogenic silica was stable at ~8% before about 1700, increased two-fold between 1700 and 1870, and then decreased again to around 8% after 1940.

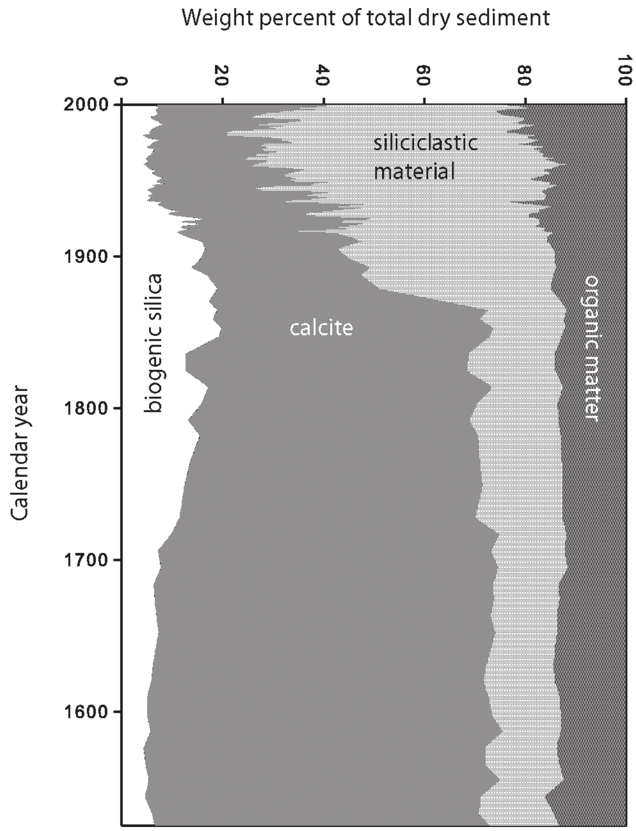

Figure 4.-Composition of core MCC01-1MP. The ~1865 horizon and rise of siliciclastic material (sand, silt, and clay) as a percentage of total sediment correspond to the development of agriculture adjacent to the lake. Note that overall sediment flux increases at this time (Fig. 5), and thus that the apparent decrease in accumulation rate of other components is simply due to dilution of those components by siliciclastic material.

Mass accumulation rates

Weight-percent changes in sedimentary composition over time may be caused simply by dilution of one component by another. Sedimentation expressed in terms of mass accumulation rate (MAR) of individual components provides a more realistic picture of changing inputs and accommodates large increases and decreases in sedimentation rate such as are seen here. Using MAR can introduce error from interpolation because the sampling resolution of dated horizons is sometimes lower than that of geochemically analyzed horizons (Boyle 2001); nevertheless, this approach is necessary and beneficial when sedimentation rate and composition change dramatically. In the case of the laminated unit, the sampling resolution for dating and geochemical analyses is identical.

As noted above, linear sedimentation rate (LSR) was calculated based on varve measurements (for the varved unit) and ^{210}Pb dating (for the massive unit). Mass accumulation rate was determined by the equation:

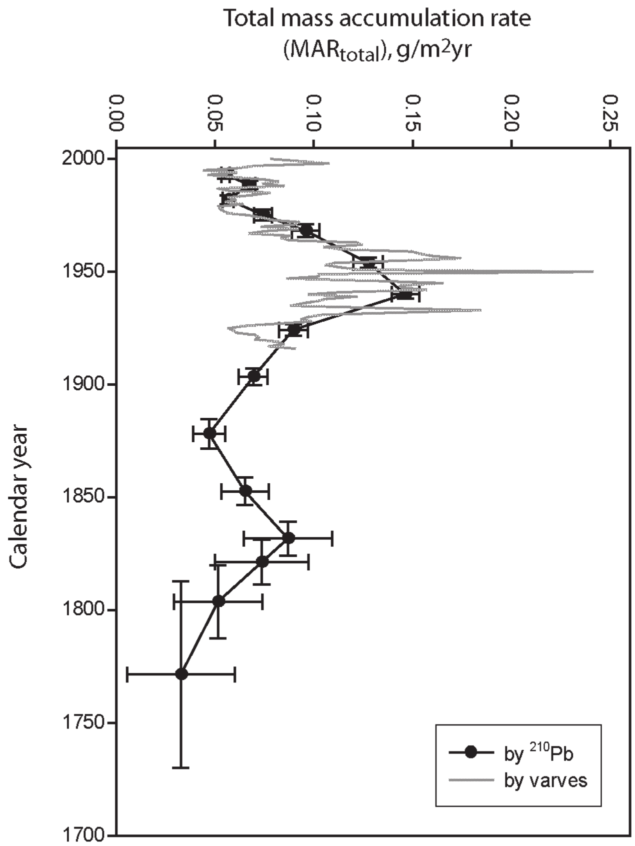

Figure 5.-Comparison of the records of bulk sediment mass accumulation rate (MAR, g/cm²·yr) determined by ^{210}Pb dating vs. calculations based on thickness and composition of individual laminations.

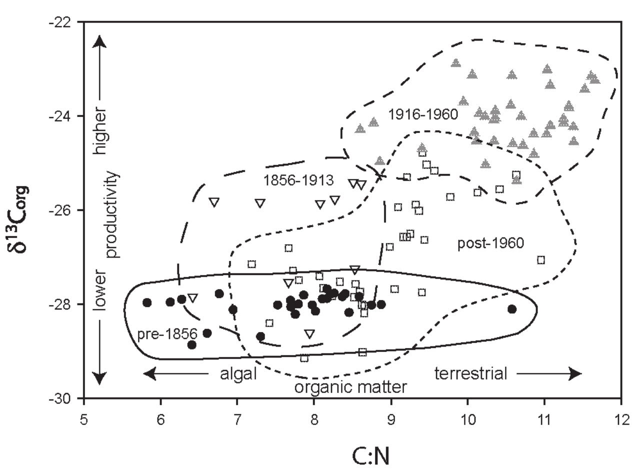

Figure 6.-Organic carbon:total nitrogen mass ratio (C:N) vs. δ^{13}C of organic matter ($\delta^{13}C_{org}$). Mid-20th century values are most anomalous compared to prehistorical values, while recent (post-1960) sediments are more similar to those deposited before human impact. See text for further discussion.

$$MAR_{total} = LSR * (1 - \phi) * \rho_{sed} \quad (1)$$

where ρ_{sed} is the sediment dry bulk density, calculated as:

$$\rho_{sed} = (\%OM/100) * 1 + (1 - \%OM/100) * 2.6 \quad (2)$$

MAR of each sedimentary component is calculated by multiplying the weight percent of that component by MAR_{total}, which is based on varve-calculated MAR_{total} for the varved section of the core and ^{210}Pb-calculated MAR_{total} for the massive section. The MAR_{total} for core MCC01-1MP compares well with that for the ^{210}Pb dated core (Fig. 5) and captures the detail of interannual variability that is necessarily smoothed over by lower sampling resolution in the ^{210}Pb method. Because the two MAR_{total} calculations disagree at the very base of the varved section (*i.e.*, around 1916–1917), the average of the two is used over that interval.

Agricultural development and urbanization

The Lake McCarrons record may be separated into four periods based on inflection points in the isotopic record: pre-1856, 1856–1913, 1916–1960, and post-1960. The trend from each period to the next provides information about changes in the state of the lake. The cross-plot (Fig. 6) of organic carbon:total nitrogen mass ratio (C:N) versus the isotopic value of organic matter ($\delta^{13}C_{om}$) provides information on the source and character of organic matter sedimenting in the lake system over time. High C:N values (typically >10) in sedimentary organic matter indicate a source comprised of terrestrial plants that have a greater component of structural tissue than planktonic algae, which typically have C:N <10 as preserved in sediments (Meyers 1997, Meyers and Teranes 2001). Values of $\delta^{13}C_{om}$ reflect both the organisms that produced the organic matter (in lakes, a combination of aquatic and terrestrial material) and the availability of dissolved CO_2 (Meyers 1997, Hodell and Schelske 1998, Meyers and Teranes 2001). Higher values of are $\delta^{13}C_{om}$ are typically associated with higher algal productivity.

Before about 1856, the source of organic matter was aquatic, with a relatively constant isotopic ratio indicating stable conditions with little CO_2 stress. Between 1856 and 1916, the initial period of European habitation, C:N continues to indicate primarily an algal source of OM, with little or no terrestrial (soil/erosional) inputs, but the $\delta^{13}C_{om}$ value is shifted positively by up to 3‰. This suggests increased photosynthetic utilization of $^{13}CO_2$ (*i.e.*, decreased isotopic discrimination) due to higher algal productivity in the lake, possibly the result of an increased nutrient flux from livestock farming in the area of the (ditching-enlarged) catchment through which the surface inlet flows.

The transition from massive to laminated sediments indicates a major shift in the behavior of the lake system. The presence of fine laminations indicates that during the entire time represented by the varved section of the core, the lake bottom waters were anoxic, thus suppressing bioturbation by benthic invertebrates. The higher level of productivity caused by anthropogenic nutrient fluxes led to the inception of hypolimnetic oxygen depletion and persistent anoxia no later than 1916, the base of the varved section of the core. The sheltered position of the lake in the landscape, its small surface area compared to its depth, and salinization of lake bottom waters by runoff bearing dissolved road salt (since salting began, around 1964; Swain 1984) may all have contributed to the retardation of spring and fall overturn and the lack of entrainment and annual reoxygenation of lake bottom waters.

After 1916, when laminations appear in the record, data fall between this low-C:N and ^{13}C-depleted endmember and some higher-C:N and ^{13}C-enriched component. This trend may indicate a somewhat increased flux of terrestrial organic material from a cultivated C4 (higher $\delta^{13}C_{om}$) plant like *Zea* (maize); however, neither values of C:N nor $\delta^{13}C_{om}$ are outside the ranges of aquatic organic matter, especially that produced under high-productivity, probably N-limited conditions (Meyers and Teranes 2001). The period between 1916 and 1960 stands out as the highest in the record in both C:N and $\delta^{13}C$. It was the time of the most intense construction and development in the lake basin, when year-round lakeshore and lakeview homes were established, along with businesses, roads, and the swimming beach. Both in-lake productivity and delivery of terrestrial-derived organic matter were probably highest during this mid-20th century period. After 1960 C:N values and $\delta^{13}C$ trended back toward the presettlement algal, lower-productivity endmember as the watershed soil stabilized and nutrient inputs decreased.

Effects of the public beach at Lake McCarrons

A major spike in the accumulation rate of clastic material begins in the sedimentary record in 1927, and continues until the peak year of 1931 (Fig. 7). This coincides with the establishment of the bathing beach on Lake McCarrons that opened in June 1926 as one of the metropolitan area's first public beaches (Ramsey County Recreation Board meeting minutes; MNHS collection). The lakeshore is not naturally sandy, so sand was brought in from elsewhere; minutes of the Ramsey County Recreation Board indicate that more sand was added several times each summer, and that clay and crushed rock were used to fill low-lying spots and washouts and to pave parking lots and pathways. Beginning in 1927, at the Board's behest, the County Engineer lowered the lake level to create more beach area; this may have increased offshore sediment transport by exposing littoral sediments to erosion.

Large-scale use of the beach also added nutrients to the lake water. In order to estimate how much nitrogen and phosphorus a given number of swimmers could have contributed, it is necessary to estimate the number of people who used the beach. A calculation of beach use over the first several years of its existence, based on seasonal receipts (not including the food concession) and prices charged for rental of towels, suits, and other items gives a minimum estimate of over 26,500 visits for the summer of 1929 (an average of ~300 visits per day of the beach season), and a minimum of 14,000-21,000 visits for other years between 1926 and 1932. Given a conservative estimate of excreted nutrients per bather per day based on prior studies (Schultz 1981; Caraco *et al.* 1992), this number of bathers would have added at least 0.1 mg P/m^2·d and 0.7 mg N/m^2·d during the summer season (10 mg P/m^2·yr, 70 mg N/m^2·yr), and very likely several times this estimate.

To put this nutrient flux in context, an estimate of other sources of dissolved P to the lake was prepared based on the literature and on records of the proportion of the original watershed devoted to different land uses in the late 19th century. The effect of erosion from a watershed tripled in size was also considered, especially as drying wetland soils may have been rich in P. Dairy farming (Ryden *et al.* 1973, Wang *et al.* 1999) and unfertilized cropping (Newman 1997) are each estimated to have contributed between 50 and 200 mg P/m^2·yr. Sewage inputs (Dillon *et al.* 1993) could have contributed 30-80 mg P/m^2·yr, although this flux is difficult to estimate without more detailed knowledge of sewage disposal systems employed in local housing at the time. Similarly, eroded beach sand and fill sediments would have contributed P to the lake water; sand was likely mined from the nearby extensive glacial outwash deposits, which are relatively nutrient-poor. Without knowledge of the specific source areas of the exotic sediments, however, estimates of their P content are speculative. The minimum estimate of swimmer P input could thus have added an additional 2 to 6% to the combined anthropogenic inputs. For comparison, total external dissolved P loads to Lake McCarrons were about 84 mg P/m^2·yr in the early 1980s before installation of the detention pond complex and about 48 mg P/m^2·yr in the years immediately after installation (Osgood 2003).

Soranno *et al.* (1997) calculated rates of internal P loading in Lake Mendota based on hypolimnetic P concentrations and entrainment of hypolimnetic waters by deepening of the thermocline; these rates can be as high as 400-600 mg P/m^2·yr. Rates this high are unlikely for Lake McCarrons, which has a relatively smaller hypolimnetic volume, and is more sheltered than Lake Mendota, and thus less subject to wind-induced deepening of the thermocline. However, P flux from the permanently anoxic sediments and hypolimnion after 1916 was probably a significant part of the P budget of the lake, and has been identified as a significant P source in the lake today (Oberts and Osgood 1988; Osgood 2003). Vollenweider (1970) suggests a threshold of 200 mg P/m^2·yr for a lake of about 20m depth to be "in danger" of

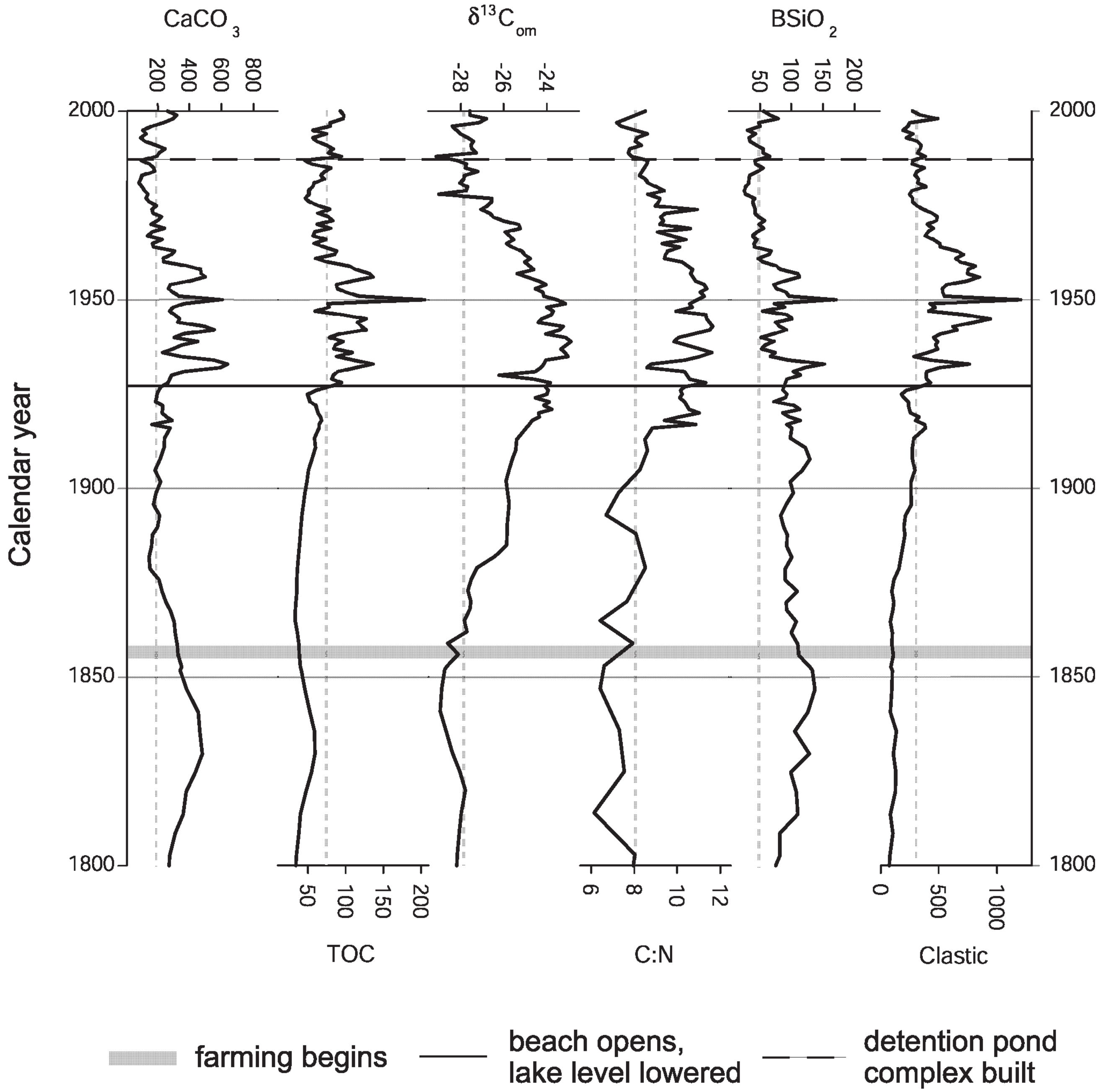

Figure 7.-Complete record from core MCC01-1MP expressed in terms of MAR (g/m²·yr) of individual components and including reference lines (vertical dashed lines) approximating typical modern (1990-2000) values of each parameter as well as timing of historical events (horizontal lines). The period corresponding to Euroamerican occupation of the lake basin (post-1850) shows a considerable increase in variability and a major excursion to anomalous values in all parameters. A striking feature of these records is the number of these parameters that have in recent decades begun to return to their predisturbance values. For visual clarity, MAR error bars (see Fig. 4) are not shown.

eutrophication; if average estimated anthropogenic inputs of the late 19th and early 20th centuries are combined with some small flux from internal P loading, this threshold is readily exceeded. The record of copper sulfate algaecide treatment in 1928 indicates that nutrient levels were probably already high before the public beach opened, and that swimming use was impaired by cyanobacterial blooms by this time.

Response to remediation

Installation in 1985-86 of the detention-pond complex intended to trap inflowing nutrients does not appear as a significant horizon in the sedimentary record. Most of the parameters are relatively constant around this time, and OM and bSi MAR actually show subdued spikes in the years following MWTS completion (Fig. 7). Water sampling data (Oberts 1997) indicate that the detention pond was successful in reducing external nutrient loads for a few years after construction. However, because of channelization of flow, infilling of the detention ponds, and anoxia and increased temperatures under standing-water conditions in the ponds, treatment efficiency then decreased significantly (from 69.9% removal of total P in 1986–1988 to 4.0% in 1995–1996; Oberts 1997), and may have even contributed to "unintended fertilization" of the surface waters when warm, low-density, P-rich water entered the lake from the MWTS (West-Mack and Stefan 2000a, 2000b). Even with the early reduced external P flux, the overall state of the lake ("lake quality report card" and trophic state index; Oberts 1997) remained the same after the MWTS installation as before. The lack of a major MWTS impact on lake water quality is supported by the sediment data.

Internal loading has been identified as the major remaining source of P supporting algal productivity in Lake McCarrons, and in October 2004 an alum (aluminum sulfate) treatment was applied to the entire lake as an internal-phosphate control measure. Water sample analyses from 2006 (Ioan Lascu, LRC, unpubl. data) show that dissolved sulfate levels in the hypolimnion are 5–10 times higher than before the alum treatment (from 3–5 mg/L to 25–40 mg/L), increasing the differential in dissolved solids, and thus density, between the surface and bottom waters. Oligomixis exacerbates the continuing eutrophication problems by providing a persistently anoxic zone conducive to P remobilization; this situation will endure until the issues of road salt inputs and lake circulation are addressed.

The mid-20th century is anomalous

The Lake McCarrons record clearly shows the effects of human impacts, but contrary to expectations, the trends were not entirely monotonic. The public and institutional perception is that the lake is "worse" now than it has ever been (Osgood 2003), that is, that the negative effects of development in the basin are additive and one-way (see discussion of this effect in Stedman 2003). By contrast, the sedimentary record suggests that the lake response to human impacts was strongest in the middle of the 20th century (about 1920–1975) and has since moderated. The MAR profile observed is a common pattern in Minnesota lakes that share with Lake McCarrons the chronology of basin settlement and development (Engstrom *et al.* 1999, 2007). The timing of the reversal in many of the eutrophication indicators coincides with the implementation of water treatment controls and environmental awareness that in Minnesota predated by several years the national-scale mandates of the Federal Water Pollution Control Act Amendments (Clean Water Act). Local factors including the mid-1960s construction of a sanitary sewer system in Roseville, and a decrease in the pace of new development in the watershed certainly contributed to reductions in nutrient and sediment loading as well.

Lake McCarrons has not returned to its natural state – clearly, stratification is stronger due to salt inputs, the phytoplankton community composition is different (Ramstack *et al.* 2004, Stoermer *et al.* 1996), fish stocking from 1908 to the present (Minnesota Department of Natural Resources unpubl. data) and angling pressures have undoubtedly altered the trophic structure of the lake (Schindler 1997, Eilers *et al.* 2001), and other parameters have changed irreversibly as the lake suffers the persistent aftereffects of 20th century eutrophication. The logistical and financial barriers to solving the lake's fundamental management problem – persistent stratification – will continue to hinder improvement efforts. In a study by Hausmann *et al.* (2002) of a Swiss alpine lake eutrophied by animal pasturing in the 14th and 15th centuries and then abandoned, the process of "re-oligotrophication" took about 88 years to return the lake to its pre-impact conditions. Recovery of systems still inhabited will likely take much longer.

Many of the sedimentary parameters measured in Lake McCarrons are approaching their presettlement values (Fig. 7; vertical dashed lines indicate average 1990–2000 values): this historical perspective suggests that the ongoing remediation effort may not easily effect the desired changes in lake-water quality beyond those already achieved. The perceived need for further improvement will undoubtedly drive additional remediation measures nonetheless.

Acknowledgments

This study was supported by a USGS-Water Resources Research Institute (WRRI) grant to the author and Emi Ito. Dan Engstrom provided ^{210}Pb dating results and interpretation. NSF-REU summer intern Aimee Wendt assisted with field and laboratory work. The Minnesota Historical Society, the Roseville Historical Society, and the Metropolitan Council of the Twin Cities provided considerable background information. Water chemistry data were drawn from Minnesota

Pollution Control Agency Electronic Data Access. The Lake McCarrons Neighborhood Association and its members, and the Capitol Region Watershed District have been supportive and informative, and helped to focus my presentation of this material. Jason Curtis performed the organic carbon isotopic measurements. Herb Wright, Tom Johnson, Walt Dean, Dan Engstrom, and Paul Glaser provided helpful comments on an earlier draft. This research would have been impossible without the infrastructure of the Limnological Research Center LacCore Facility (funded by NSF and the University of Minnesota) and the inspiration of Kerry Kelts. This is LRC Contribution #08-01.

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