RECENT SEDIMENTARY HISTORY OF LAKE MONONA, WISCONSIN

GILBERT C. BORTLESON
USGS, Tacoma, Wash., U.S.A.
and
G. FRED LEE
Institute for Environmental Sciences, University of Texas at Dallas, Dallas, Tex., U.S.A.
Currently, G. Fred Lee & Associates, El Macero, CA www.gfredlee.com

(Received 10 August, 1974)

Abstract. Chemical analyses from two short cores in Lake Monona show that pronounced changes in chemical stratigraphy have occurred since white man moved into Madison and southern Wisconsin and began modifying the area. Since the mid to late 1800's, there has been an appreciable increase in P, Fe, Mn, Al, and K in the uppermost sediments. Maximum concentrations of P were observed near the turn of the century and in the most recent sediment layers.

1. Introduction

On a geological time scale lakes are relatively unstable and impermanent features of the landscape since they tend to fill in. Lake Monona was formed by glacial action roughly ten to twelve thousand years ago. Only in very recent decades have various human activities contributed to the accelerated rate of sediment deposition and nutrient enrichment of lakes. The measurements which best describe eutrophication are diverse and often complex. A body of water is a 'dynamic ecosystem' and to study it effectively an investigator must sample frequently and analyze data for many years. This has not been generally possible with the resources available to investigators in the past. Therefore, the information needed to trace changing lake and watershed conditions must come from a record preserved in lake sediments. Although several chemical studies have been performed on Pleistocene sediments and interpreted on the basis of long-term historical trends (Gorham, 1961; Hutchinson and Wollack, 1940; Mackereth, 1966; Kendall, 1969; Livingstone and Boykin, 1962; Pennak, 1963), few investigators have given sustained study to the most recent changes in lake history (Stockner and Benson, 1967; Shapiro *et al.*, 1971). Thus, attention has been directed in this study to examining the recent historical changes of Lake Monona* through the interpretation of chemical profiles and *Ambrosia* (ragweed) pollen of lake sediment cores.

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[*] Lake Monona is a hard-water eutrophic lake formed by morainic damming of the preglacial Yahara River near Madison, Wisconsin (Twenhofel, 1933). The Lake currently receives drainage from agricultural lands, urban runoff, and until 2 yr ago, small amounts of municipal and industrial waste effluents contained in entering streams.

Water, Air, and Soil Pollution 4 (1975) 89–98. *All Rights Reserved*

2. Experimental Procedures

In 1966, core WC-46, and in 1969, core WC-101, were taken from Lake Monona in 52 and 69 ft of water, respectively, from the locations shown in Figure 1. The sample drive through 1 m of sediment was accomplished by a piston coring device (3.5 in. in diameter) which was described in detail by Wentz (1967) and Bortleson (1968). The sediment samples were extruded and fractionated into 5 cm intervals and stored frozen at $-20\,^{\circ}$C until commencement of analysis.

Sediment sample aliquots (0.500 g sample, 100 mesh, dried 105 °C) were heated in the presence of 48% HF for 8 to 12 h. The predigest step with HF was omitted for core WC-46 samples. The solid residue (or sediment sample) was transferred to a 100-ml Kjeldahl flask and digested for 2 h in the presence of 5 ml of concentrated HNO_3 and 60% $HClO_4$. After this digestion, the sample was cooled, passed through a pre-rinsed Whatman No. 2 filter, and drained directly into a 100-ml volumetric flask. This solution, or an appropriate aliquot thereof, was used for total P, Fe, Mn, Mg, K, Ca, and Al determinations.

Iron was determined by the orthophenanthroline method (Olson, 1965) and P by the vanadomolybdophosphoric (VM) yellow colorimetric procedure (Jackson, 1958). Analyses for Mn, Al, Mg, K, and Ca were made by direct aspiration of the digest solution, or diluted aliquots, into a Perkin-Elmer Model 303 atomic absorption spec-

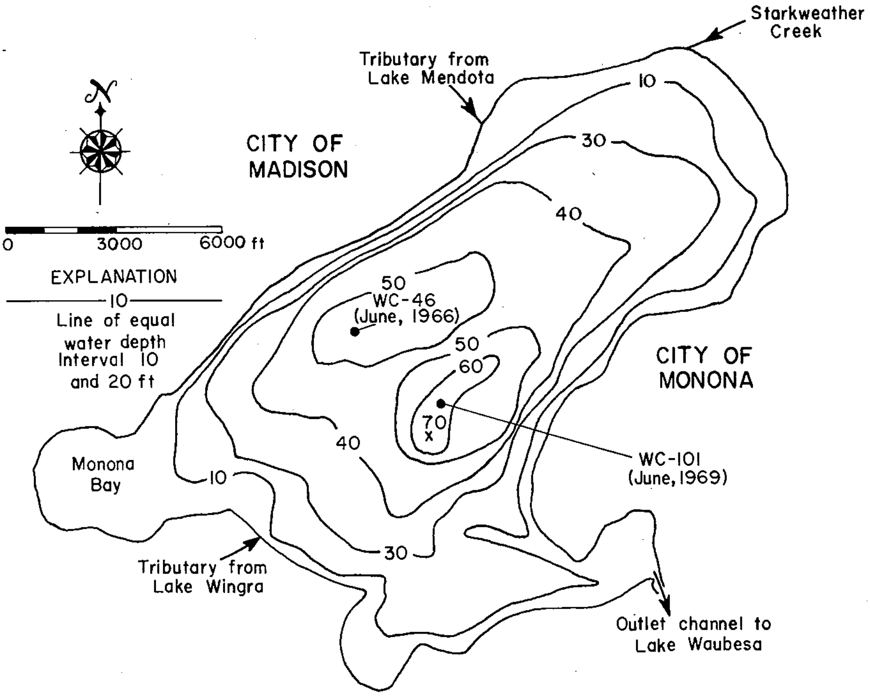

Fig. 1. Lake Monona bathymetry and coring locations.

trophotometer. Organic N was determined by semimicro Kjeldahl technique outlined by Bremner (1965). Exchangeable ammonium was determined by steam distilling a wet sample of sediment in the presence of 2N KCl and MgO and titrating the distilled NH_3 (Bremner, 1965). Total C was determined by a dry combustion technique using a LECO (Laboratory Equipment Corporation) low carbon analyzer (Model 589–400) and LECO induction furnace. The Ca dissolved by $HF–HNO_3–HClO_4$ or $HNO_3–HClO_4$ acid system was converted to carbonate C equivalents; this value was subtracted from total C to obtain organic C.

Sediment sample aliquots (0.200 g sample, 100-mesh, dried 105 °C) for *Ambrosia* pollen analyses were processed by standard palynological procedures (Faegri and Iverson, 1964; Andersen, 1960) which remove most of the unwanted sediments and leave a concentrate rich in pollen. Since a total pollen assemblage (e.g. oak, pine, hickory, grass pollen) was not counted and identified to obtain a percentage of ragweed pollen, it was necessary to add an internal standard before the sediment was processed. A well-stirred suspension volume of 0.20 ml of internal standard (1 g of pure *Eucalyptus* pollen in 500 ml of tertiary butyl alcohol) was pipetted at constant temperature (25.5 °C to 0.5 °C) and transferred to the sediment aliquot. The *Eucalyptus* pollen, which are exotic pollen, were easily identifiable triangular-shaped grains. Identification of '*Ambrosia*-type' pollen was made with high power magnification using a Bausch & Lomb microscope. No reference was given to a particular species of ragweed. Continuous sweeps were made across the entire width of the preparation; in each sample 100 to 200 grains were counted. The abundance of ragweed found in the sediment cores was based on the average ragweed to *Eucalyptus* pollen ratio of duplicate or triplicate samples.

The results presented for the chemical analyses of each core are mean values of two or five replicate determinations. Duplicate pollen counts were made from each processed sample. In the transition zone (high to low ragweed) triplicate counts were made.

3. Results and Discussion

The sediments laid down from the precultural period to the present can be subdivided into four zones according to changes in chemical distribution and ragweed pollen patterns shown in Figures 2 and 3 for Monona cores WC-46 and WC-101, respectively. However, it is apparent that core WC-101 which was taken in the deepest part of the lake is represented only by two upper zones even though the cores were approximately the same length. This is best explained by differences in rates of sediment deposition in various parts of the lake. The main physical and historical features of the Lake Monona cores are shown in Table I. No evidence of laminations or lenses, which could be used for dating purposes, was observed in the cores. In order to identify pre- and postcultural periods of deposition in the sedimentary column, *Ambrosia* pollen counts were performed; the appearance of these pollen grains provided a stratigraphic horizon which could be dated from historical records showing when man moved into the Madison and southern Wisconsin region and began modifying the ecology.

TABLE I

Main features of Lake Monona cores and corresponding historical events

Core no.	Sediment depth and thickness of zones (cm)	Chemical zone	Type of deposit	Period	Relevant historical events
WC-46 WC-101	0–35 0–85	IV	black gyttja	late cultural (1910–1969)	Rapid urbanization in Madison (pop. 26000 to 158000, 1910–65. Lake Monona received large amounts of sewage from 1898 to 1936 (partial diversion after 1928); received sewage from reactivated treatment plant during WW II. Large systematic doses of $CuSO_4$ 1925–44; irregular doses of $CuSO_4$ 1918–25; some doses of $CuSO_4$ 1953–62. 'Detergent era' after 1940.
WC-46 WC-101	35–65 85–95	III	gray-colored gyttja-marl	mid cultural (1860–1910)	Rapid settlement in Lake Monona basin and early urbanization of Madison (pop. 6600 to 26000, 1860–1910) Dredging of Murphy Creek channel (inflow), 1905–08. Privies, cesspools, and direct drains to lake to dispose sewage.
WC-46 WC-101	64–95 no sediment penetration	II	buff marl	early cultural (1820–1860)	Early settlement in southern Wisconsin and Lake Monona basin
WC-46 WC-101	95–105 no sediment penetration	I	buff marl	precultural (before 1820)	Presettlement of Madison and southern Wisconsin.

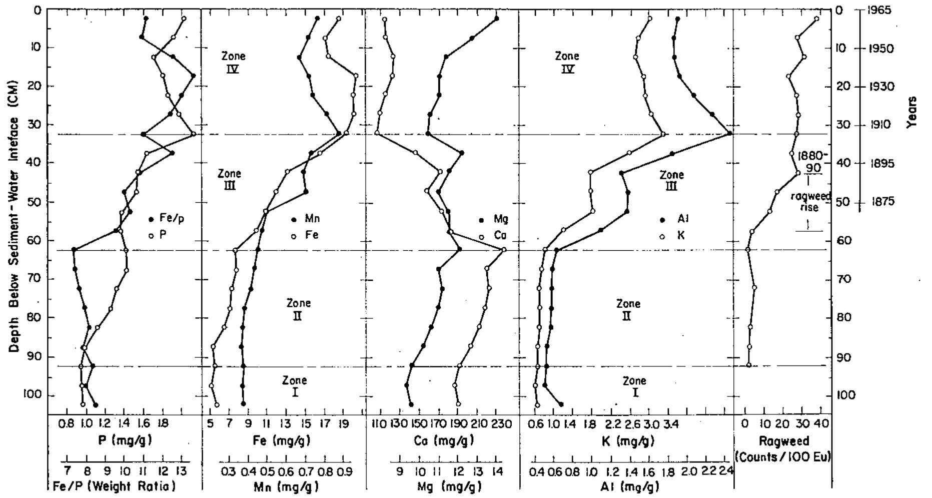

Fig. 2. Chemical and Ambrosia pollen stratigraphy of Lake Monona core WC-46.

Ragweed pollen occurs in relatively high percentages (5 to 40%) in surface sediment samples from the deciduous forest region of the northeastern and northcentral U.S.A.; the plant seems to have increased as a result of disturbance and creation of open habitats through forest clearance by European settlers (Webb, 1973; Davis, 1967; Wright, 1968).

3.1. ZONE I

The lowermost sediments in Zone I (core WC-46) consist of a compacted buff marl containing 190 mg g^{-1} Ca of 47% $CaCO_3$. In Lake Monona, the Ca deposition is

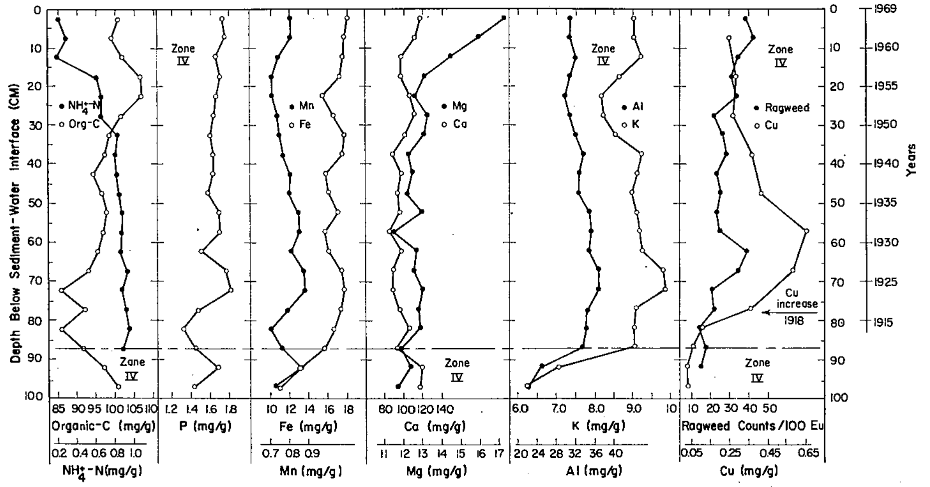

Fig. 3. Chemical and *Ambrosia* pollen stratigraphy of Lake Monona core WC-101.

mainly controlled by chemical or biological precipitation of $CaCO_3$. The sedimentary concentrations of P, Fe, Mn, K, Ca, and Mg showed little or no change with depth in the lowermost buff marl. The distribution of Al, K, and Mg may depend primarily on the rate of supply of dissolved and particulate mineral matter, the precipitation of carbonates, and the variation in the accumulation of the whole sediment.

3.2. ZONE II

The sediments in Zone II (core WC-46) consist of a buff marl which is slightly modified in chemical composition from that of Zone I. The concentration of Ca increased upward throughout Zone II from 190 mg g^{-1}. In the early cultural period, concentrations of Al, K, Mg, P, Fe, and Mn increased upward slightly. Aluminum, Mg, and K may occur in a large variety of mineral structures such as feldspars, clay minerals, and amorphous aluminosilicate gels. Mackereth (1966) noted that Na, K, and Mg were associated with the mineral fraction of the sediment of English lakes and a direct relationship existed between these elements in the sediments and the erosional intensity of the drainage basin.

The sediments in Zone II consisted of minimum ragweed pollen counts. This interval probably corresponds to the initial period of active settlement in the Madison and southern Wisconsin region during the first few decades following 1820 (Smith, 1929). The time period for Zone II is estimated to have occurred from 1820 to 1860. The erosional activity, as exemplified by only slight changes in Al and K concentrations, was probably not intense during the early cultural period. But with the advent of clearing and cultivation of areas around the lake, the erosion of cultivated lands resulted in a direct contribution of mineral matter to the lake. The increase in sedimentary Fe may be associated with an increased Fe supply to the lakes from land runoff. Carroll (1958) found that the association of Fe with clay minerals is an important means whereby Fe is transported by streams to lakes. According to Carroll, Fe is associated with clay minerals as an essential constituent, as a minor constituent within the crystal lattice, and as FeO on the surface of mineral platelets. Analyses of the clay fractions of soils show that Fe is mainly associated with the finest fractions (the clay and silt grades), which have extremely large surface areas (Carroll, 1958). The P concentration increased slightly in Zone II, which is well before the time of detergents or fertilizer use. It is possible that runoff and leaching from land clearing and burned-over areas may have caused an increase in P during this early period.

3.3. ZONE III

The sediments in Zone III consist of gray-colored gyttjamarl which represents the transition zone between buff marl and black gyttja. Zone III is scarcely discernable in core WC-101 due to insufficient core length. The ragweed rise occurred at the 45 to 55 cm level (Zone III) in core WC-46. A pronounced rate of population increase in Wisconsin occurred between 1830 and 1890 (Smith, 1929). During the period 1850 to 1880 the movement of population into Wisconsin completed the agricultural settlement in the southern part of the state. By 1920, the southern half of the state had over

80% of the land area in farms (Smith, 1929). Since the distribution of land as farms is closely related to the distribution of the rural population, the rate of land settlement probably reached a peak about 1890, the same time the rate of population increased. The sediment deposition at the 40 to 45 cm level, where the ragweed pollen counts reached a maximum before leveling off, is estimated at 1890. Using 40 to 45 cm stratum and the year 1890 as a reference base, the mean sedimentation rate for the upper 45 cm of sediment of core WC-46 is approximately 5.6 mm yr^{-1}. This rate of sedimentation corresponds closely to that of nearby Lake Mendota (Bortleson and Lee, 1972). The time period for the midcultural interval is estimated to span the period 1850–60 to 1905–10. Early urbanization in Madison and further settlement in the Lake Monona basin occurred during the period represented by Zone III. The population of Madison increased from 6600 in 1860 to 13000 in 1890 to 26000 by 1910.

During the period represented by Zone III, the Fe, Mn, Al, and K concentrations increased sharply upward. Domestic drainage from urban and rural areas may have provided for increased influx of Fe and Mn compounds, clay minerals, and oxides of Al, causing a pronounced change in the sediment profiles. The P concentration steadily increased in Zone III. Throughout this interval the Fe increased faster than the P concentration as shown by the increase in the Fe/P ratio. Amorphous hydroxo ferric-ferrous compounds have a strong tendency to form a complex with P; these compounds ultimately lead to the formation of insoluble precipitates which could have a remarkable effect on removal of P from solution. Phosphate ions in solution may also precipitate with carbonates by simple coprecipitation in lakes marked by high bicarbonate alkalinity and Ca concentration (Otsuki and Wetzel, 1972). The carbonate profile (WC-46) of the Lake Monona core indicates uniform deposition had occurred in the precultural period followed by a slight rise in the early cultural period. The constant or slight increase in $CaCO_3$ concentration is interrupted during the cultural period to depress the carbonate C concentration. Calcium carbonate precipitation initiated by planktonic photosynthesis or chemical precipitation has probably not decreased in recent times (Zone III) as inferred directly by the concentration profile of Ca. If photosynthetic uptake of CO_2 is the dominant mechanism for carbonate precipitation, then an increase in $CaCO_3$ precipitation in recent times might be slightly favored with increased productivity. However, increased biological respiration, bacterial activity, and chemical oxidation serve to decrease $CaCO_3$ precipitation. Furthermore, Megard (1969) noted that it is unlikely the productivity during the history of lakes can be inferred from the concentration of carbonate in the sediment because a large proportion of the carbonate formed in the epilimnion of productive lakes is dissolved in deep water during periods of stratification. It appears that the most likely explanation for the postcultural decrease in carbonate C concentration is the masking of a somewhat constant (or increasing) carbonate deposition by the increased inorganic sedimentation.

3.4. ZONE IV

The sediments in Zone IV (core WC-46 and WC-101) consist of a black gyttja. High ragweed counts were observed throughout Zone IV in both cores. The time period for Zone IV is estimated to have occurred from 1910 to 1966–69. The time period for core WC-101 was estimated from the marked sedimentary increase in total Cu concentration at the 75 to 80 cm stratum. In 1884 the Madison population of 12000 people had 18 separate sewage districts discharging raw sewage into either Lake Mendota or Lake Monona (Lord, 1950). From 1898 (first unified sewage system for Madison) to 1936 Lake Monona received large amounts of treated sewage effluent (Stewart and Rohlich, 1967). The exceptionally heavy algal bloom in Lake Monona in 1918 stimulated community action to the extent that Lake Monona was treated with $CuSO_4$ for the first time. From 1918 to 1925 $CuSO_4$ was applied to Lake Monona in a rather irregular manner to control odor nuisance due to excessive algal growth (Stewart and Rohlich, 1967). Thereafter and continuing for 29 yr through 1953, $CuSO_4$ was applied systematically to the lake at the dosage levels indicated in Figure 4 (Edmondson, 1968; Nichols *et al.*, 1946). The Cu concentration increased from a background concentration of 0.05 mg l^{-1} in Zone III to 0.65 mg l^{-1} at the 55–60 cm stratum in Zone IV (Sanchez, 1971). A mean sedimentary rate of approximately 15 mm yr^{-1} was estab-

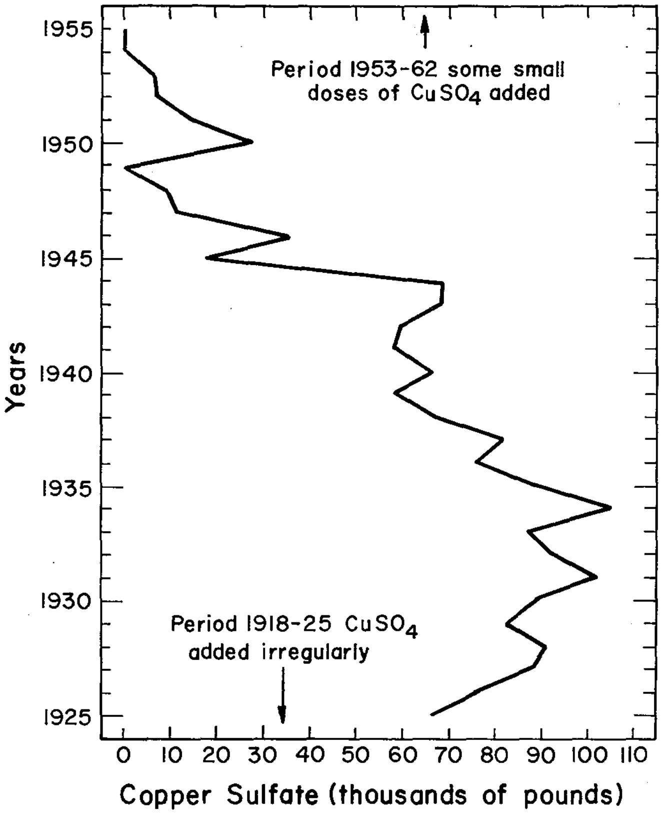

Fig. 4. Amount of $CuSO_4$ applied each year to Lake Monona to control algae (data from Nichols *et al.*, 1946 and Edmondson, 1968).

lished for core WC-101 using the 75 to 80 cm horizon and 1918 as a reference base for the first application of $CuSO_4$ to the lake. A comparison of the Cu observed in Lake Monona sedimentary column (Figure 3) with the amount of $CuSO_4$ applied yearly (Figure 4) corresponds rather closely.

Since the sedimentation rate in the center of Lake Monona is high (15 mm yr^{-1}), a long sedimentary column represents a relatively short historical period in core WC-101. The chemical composition of the core WC-101 (Zone IV) varied only slightly with sediment depth. In Zone IV, organic C increased from 86 mg g^{-1} at the 70 to 75 cm level (ca. 1920–25) to 107 mg g^{-1} at the 15 to 20 cm level (ca. 1955–60). In the same interval mentioned above P, Fe, and Mg remained nearly constant while Al, K, Mn, and $NH_4 \pm N$ decreased slightly. Lake Monona received large amounts of treated sewage from 1898 to 1936. Especially, from 1906 to 1914, Lake Monona was polluted with poorly treated effluent from an overloaded treatment plant. The highest concentration of P observed in both cores corresponds to the period 1905–20 which is close to the historical record of known high input of P. In core WC-46, the P concentration decreased slightly throughout most of Zone IV to reach a minimum at the 10 to 15 cm level (ca. 1945–50). Phosphorus then increased upward to the sediment-water interface. In core WC-101, the P concentration decreased slightly to reach a minimum at the 40 to 50 cm level (ca. 1935–40). Thus the data from two cores with vastly different sedimentation rates and respective time scales do not agree precisely but are within 5 to 10 yr of each other. Among the domestic changes taking place during this period in the Lake Monona basin were the rapid urbanization of Madison, rapid growth of towns and suburban areas in the drainage basin which contribute effluent to the Lake Monona tributaries, and emergence of the "detergent era" as an additional source of P.

Acknowledgments

This investigation was supported by Grants from the U.S. Environmental Protection Agency, No. 16010 EHR and No. 5-TO2-WP-00184. In addition, support was given this investigation by the Department of Civil Engineering at the University of Wisconsin, U.S. Office of Research, the University of Wisconsin Experiment Station, and the Institute for Environmental Sciences, the University of Texas at Dallas.

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