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A land-use and water-quality history of White Rock Lake reservoir, Dallas, Texas, based on paleolimnological analyses

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Abstract

White Rock Lake reservoir in Dallas, Texas contains a 150-cm sediment record of silty clay that documents land-use changes since its construction in 1912. Pollen analysis corroborates historical evidence that between 1912 and 1950 the watershed was primarily agricultural. Land disturbance by plowing coupled with strong and variable spring precipitation caused large amounts of sediment to enter the lake during this period. Diatoms were not preserved at this time probably because of low productivity compared to diatom dissolution by warm, alkaline water prior to burial in the sediments. After 1956, the watershed became progressively urbanized. Erosion decreased, land stabilized, and pollen of riparian trees increased as the lake water became somewhat less turbid. By 1986 the sediment record indicates that diatom productivity had increased beyond rates of diatom destruction. Neither increased nutrients nor reduced pesticides can account for increased diatom productivity, but grain size studies imply that before 1986 diatoms were light limited by high levels of turbidity. This study documents how reservoirs may relate to land-use practices and how watershed management could extend reservoir life and improve water quality.

Introduction

Documentation of trends in historical surface-water quality for trace metals, pesticides and nutrient levels is an important facet of the National Water Quality Assessment (NAWQA) program of the U.S. Geological Survey. Understanding of the relation between water quality and the kind and intensity of land-use practices, both agricultural and urban, will enable planners and municipalities to avoid destructive practices that jeopardize the quality of water resources. Because relevant historical data (monitored water analyses) for many lakes, reservoirs and streams are lacking, or confined to comparatively recent time, paleolimnological and paleoecological analyses of sediment cores can help track changes in water quality and land-use practices over the life of a reservoir or lake. The sediment core/paleo-environmental approach for documenting both natural and anthropogenic changes in lake basins, their drainages, and regional (climatic) influences on water quality has a long history and an active future (Davis, 1990).

This paper presents pollen, diatom and grain-size analyses on a 1.5-m core from White Rock Lake, a reservoir first filled in 1912 on White Rock Creek when the drainage was largely agricultural (Figure 1). Presently the creek and reservoir are surrounded by suburban expansion of Dallas, Texas. In the core from White Rock Lake, pollen stratigraphy tracks changing land-use practices. Diatoms are only present in the upper 15 cm of the core, apparently reflecting increased water clarity as a result of urbanization and integrated storm sewerage as well as decreasing agricultural activity in the drainage. With increased transparency, diatom productivity in White Rock Lake could exceed rates of diatom destruction by solution during and after sedimentation.

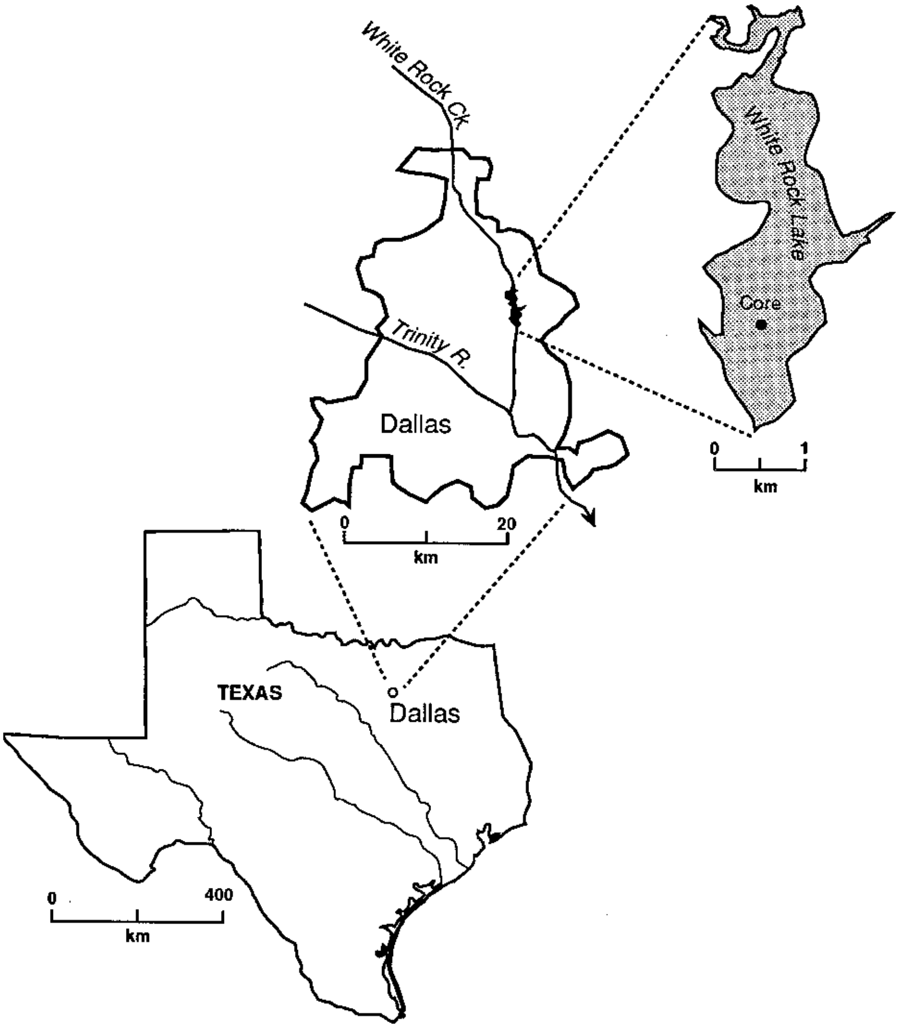

Figure 1. Index map of White Rock Lake and its urban drainage basin.

Setting

Climate

The climate of northeastern Texas is temperate with short and usually mild winters. Mean winter temperatures are above freezing, although in exceptionally cold years reservoirs in the area freeze for short periods (Cole, 1963; Harris & Silvey, 1940). Mean summer temperatures exceed 28 °C and account for stratification of deeper reservoir lakes.

Most precipitation falls as rain, chiefly in the spring, but the mean for any season is above 15 cm. Precipitation of wet and dry years varied by a factor of three over a 49-year period. Intense precipitation of >15 cm in 24 h may characterize thunderstorms in the spring or fall.

Land use and vegetation

Native vegetation of the region is 'blackland' tall-grass prairie with woody vegetation, characterized by *Carya* [pecan], *Salix* [willow] and *Ulmus* [elm] growing principally along streams and drainages with many other taxa. On shallow soils of the uplands, where damage from erosion (post cultivation) has been severe, *Juniperus virginiana* [eastern redcedar] and annual and perennial weeds (chiefly plant families of Asteraceae and Chenopodiaceae + Amaranthaceae) become common (Marshall & Brown, 1939).

Agriculture dominated land use when the reservoir was constructed in 1912. Cotton and grass crops prevailed and the rich soils required no fertilization. Nevertheless, soil conservation practices were uncommon, and accelerated soil erosion had affected 93% of the land in the watershed by 1939. Catastrophic sheet flooding and soil erosion through croplands after high intensity rain storms are photographically documented by Marshall & Brown (1939).

Intensive urban development of the White Rock Creek area followed World War II (1945). In 1956 14% of the drainage was urban (Zodin et al., 1971). By the 1960s much of the lower drainage to the reservoir was urban and by 1990, 72% of the 259 km^2 creek drainage had been urbanized (Samuel Brush, North Central Texas Council of Governments, written communication, 1992).

Limnology

White Rock Lake is located in the suburban community of Highland Park within the metropolitan area of Dallas, Texas. The reservoir was filled in 1912 after a 12-m dam was constructed across White Rock Creek, a tributary of the Trinity River presumably named for its course across the white Austin Chalk Formation (Cretaceous) that outcrops along its drainage. The reservoir had an area of 465 ha in 1935 after silt deposition and delta formation upstream had reduced the original (1912) area by about 7%. In the first 25 years, silt had reduced the reservoir capacity by nearly 1% per year (Marshall & Brown, 1939). Its maximum depth in 1939 was about 10 m (Patterson, 1942), while today the deepest part of the lake is about 6 m. Clearly sediment accumulation rates for the basin are high.

Today, White Rock Lake is shallow, turbid and probably polymictic, completely circulating at intervals throughout the year when winds are sufficient to mix the lake. Earlier in its history when the lake was deeper, however, limnological observations indicate transient stratification and hypolimnetic oxygen depletion in summer beneath a 4 to 9-m thick thermocline (Patterson, 1942). At that time, surface water temperature ranged from 8.8 °C in February to 28.5 °C in July. pH (determined colorimetrically with a Hellige comparometer) varied between 8.3 and 7.2 with an average of 8.1 for the winter and spring months. Current (1973–1993) mean pH (determined by calibrated pH meter) is 7.72 (range 6.7–9) suggesting little change in this variable for the past 50 years. Occasional measurements of nutrients, suspended solids and chloride since 1973 show considerable variability (Figure 2), but only suspended solids and nitrate have consistently fallen to comparatively low values since the early 1980s.

In April, 1939, the diatom *Melosira* (= *Aulacoseira*) was recorded as the most abundant phytoplankter (1741 cells L^{-1}). Nevertheless, these population numbers were quite low in comparison to counts of the same genus from nearby reservoirs (Patterson, 1942). A sample of reservoir water taken during coring in early July, 1994 contained several diatom species, chiefly *Cyclotella stelligera*, and smaller numbers of *Synedra acus*, *S. tenera*, *Aulacoseira alpigena*, *A. granulata*, and *A. ambigua*.

Materials and methods

Coring and sampling

A 6.3-cm diameter gravity core was taken from a pontoon boat/coring platform anchored in about 5 m water depth in the southern third of White Rock Lake in July, 1994 (Figure 1). The core was extruded and scraped clean, and samples were extracted and sealed in airtight plastic bags in the field.

Pollen analyses

Pollen samples were prepared by removal of carbonates with 10% HCl, silicates with 48% HF and labile organic matter with hot, 5% KOH and acetolysis (Faegri & Iversen, 1964). Pollen types enumerated are presented as percentages based on the count sum (usually $\geq$ 200) except in two cases (81 and 142 cm) where insufficient pollen was recovered to calculate statistically reliable percentages. In these cases, an artificial divisor of 200 was used to under-weight these pollen spectra values graphically relative to the other samples. The 'percentages' of these two samples do not, therefore sum to 100%.

Diatom analyses

Samples prepared for diatoms were digested in concentrated HNO_3 at 100 °C for 0.5 h and cleaned of remaining acid and solutes by centrifugation and decantation. Equal aliquots of the residues were settled onto coverslips (Battarbee, 1973) and mounted in refractive resin (n = 1.6). Diatom concentrations were determined by enumeration of diatom valves along measured traverses across the microscope slide. Enumeration con-

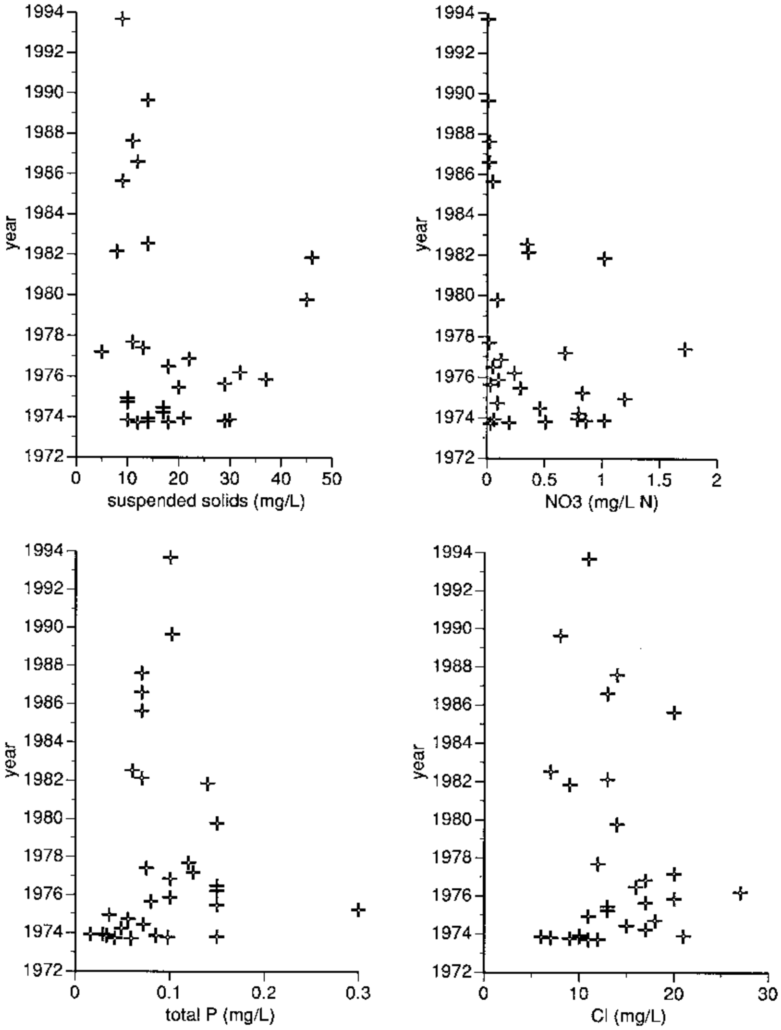

Figure 2. Plots of selected limnological variables at White Rock Lake from 1972 to 1994. Data from Texas Natural Resources Conservation Comission, Austin, Texas.

tinued until a count of 400 valves was recorded or until two full traverses (36 mm total length) were examined. The diatom concentrations are presented in number of valves/mm of traverse. Diatom identifications were based on comparisons to standard references, particularly by Krammer & Lange-Bertalot (1986–1991).

Age control

An age model for the White Rock Lake core was constructed based on the reservoir filling date (1912) at the depth of the pre-reservoir surface (136 cm); the top of the core reckoned at 1994, the year the core was taken; a date of 1963 at a depth of 49.5 cm based on the peak of atomic bomb-produced cesium (^{137}Cs) and a date of 1952 (61.5 cm) when ^{137}Cs first began to increase (see Pennington et al., 1973). Samples between these levels have been dated by linear interpolation. It is recognized that the assumption of constant sedimentation rates is unlikely to strictly apply to deposition in White Rock Lake. Nevertheless, this age model (Figure 3a) provides a reasonable method for evaluating land-use changes in the White Rock drainage basin. An alternative age model, based on sediment mass accumulation rates and the same chronological ties, presents a very similar, nearly linear record of sedimentation in White Rock Lake (Figure 3b). Sediment mass accumulation rates were 0.82, 0.50, and 1.13 g cm^{-2} yr^{-1} for the time periods, ca. 1963–1994, 1956–1963, and 1912–1952, respectively. Because the history of White Rock Lake is so intimately tied to the chronology of land-use changes, the results are presented according to the mass accumulation rate chronology.

Results and discussion

Core lithology

The core was 156 cm long, and penetrated pre-reservoir clayey soil with plant rootlets and a crumbly texture at a depth of 136 cm. The reservoir sediments are characterized by uniform, fine textured, olive grey (5Y 4/1) and olive black (5Y 2/1) silty clay that oxidizes to a dark yellowish brown (10YR 4/2) on exposure. The clay is slightly calcareous by virtue of a detrital component derived from the Austin Chalk (individual coccoliths can be seen in sediment smears) and occasional lenticular cells of the calcareous green alga, *Phacotus*. Clay-sized material ($< 4\ \mu$m diameter) is typically 80–95% throughout most of the core although clay-poor silt layers occur at discrete intervals (Figure 4) that may represent flood events and other disturbances in the drainage area or reservoir basin such as nearshore dredging. For example, the pronounced drop in clay-sized material centered on 1938 may document silt influx that relates to shallow water dredging operations between 1936 and 1941 in the northern part of the basin (Dallas Morning News, 7 VIII 1994). Percentages of clay are smaller and less variable after the mid-1950s than before, and decrease further above a depth of 15 cm (1986), apparently as a result of land stabilization related to urbanization.

Pollen

The pollen record of White Rock Lake divides naturally into three zones based on the percentages of dominant pollen types (Figure 5). The basal sample (142 cm with an extrapolated age of AD. 1908) represents the pre-reservoir surface, in this case probably a clay-rich alluvial soil associated with overbank deposition from White Rock Creek. The basal sample has low pollen concentration, perhaps because of the harsh depositional environment represented by alternately wetting and drying of soils in such environments. The only pollen present in significant numbers is of the herbaceous Chenopodiaceae + *Amaranthus* type. Weeds of this group commonly occupy disturbed habitats along seasonally-fluctuating stream courses, and they may have been the source of pollen in this sample. In addition, the drainage of White Rock Creek was under heavy cultivation at the time the reservoir was constructed, and the same plants are common agricultural weeds.

The pollen record between 1912–1936 is characterized by large percentages of agricultural weeds: Chenopodiaceae + *Amaranthus*, *Ambrosia* [ragweed], and

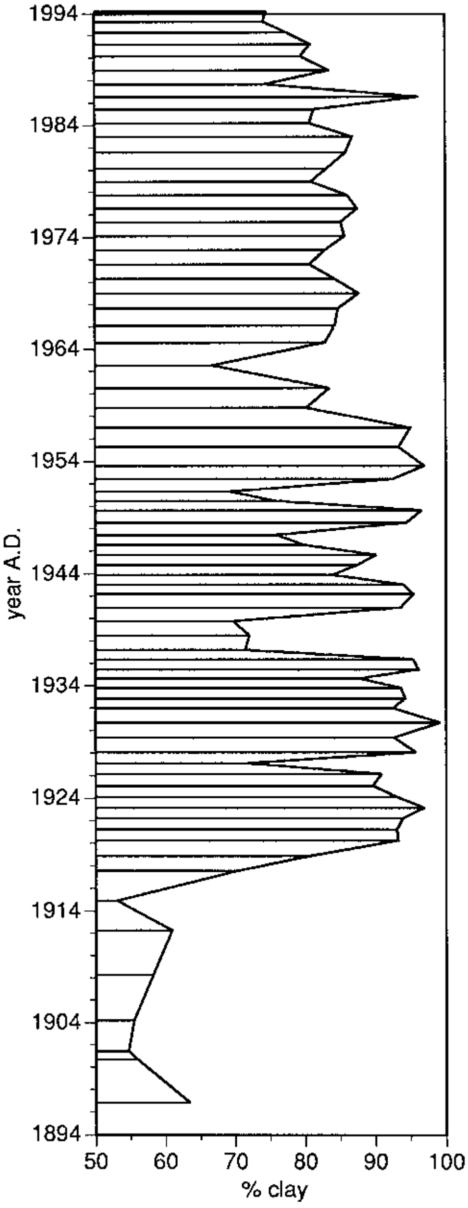

Figure 4. Percent clay-sized particles plotted against core chronology (see Figure3b).

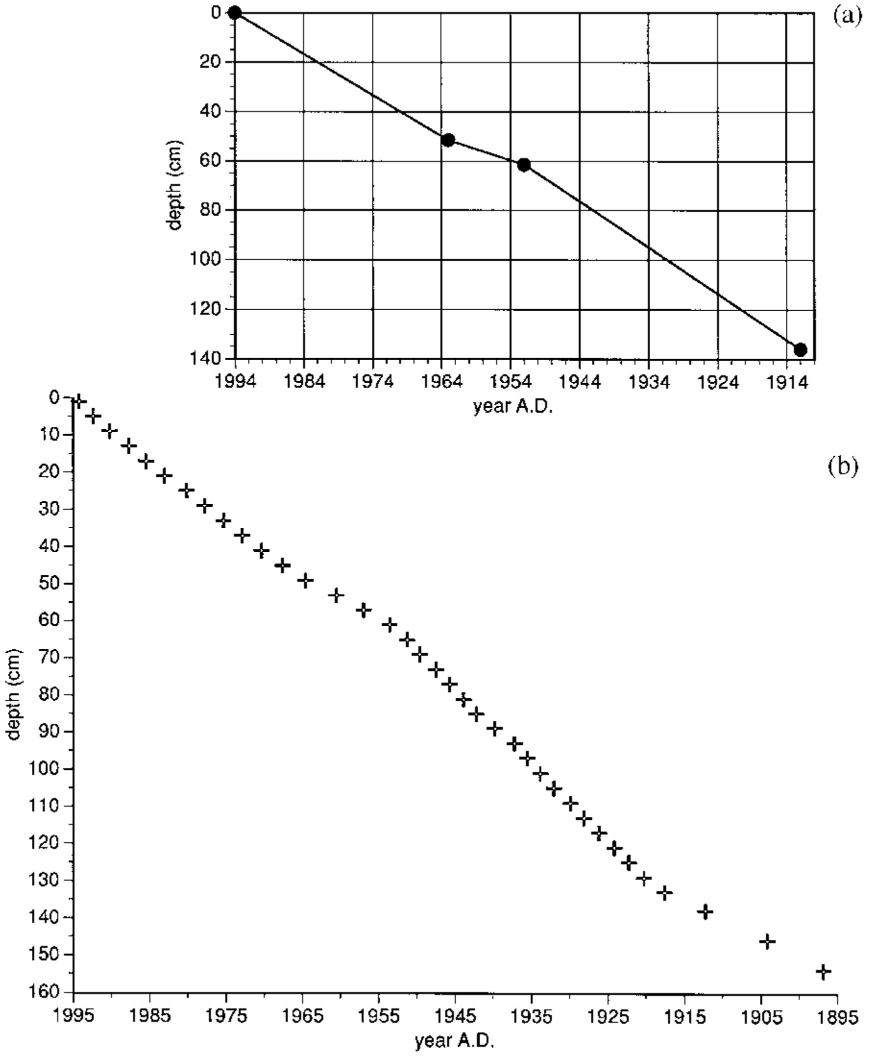

Figure 3. (a) Age model for White Rock Lake core based on straight line extrapolation of depth from levels dated by the ^{137}Cs profile and the top and bottom of the core. Data from Van Metre & Callender (1997). (b) Age model of White Rock Lake core based on mass accumulation rates tied to the chronology of the figure at the top.

assorted weeds of the subfamily Tubuliflorae (Asteraceae). The pollen category 'degraded Tubuliflorae' contains decomposed and corroded but still recognizable pollen grains of this group. Such pollen is commonly found in soils, and may represent increases in the extent and intensity of soil erosion within the drainage basin in the 1930s (Marshall & Brown, 1939).

One sample at 81-cm (ca. 1944) is essentially barren of pollen and may represent a drought and very low water levels in the reservoir. The overlying sample (71-cm, ca. 1948) is dominated (65%) by Poaceae (grass) pollen clumped together in anther fragments. The percentage representation (Figure 5) does not account for all the Poaceae pollen in this sample because after 130 grass pollen were counted (1/2 slide) the remainder were excluded from the count in order to obtain a more reasonable estimation of other pollen taxa in the sample. Fifty-four additional anther clumps packed with grass pollen were encountered in the remaining half of the slide. Many of the Poaceae pollen in this sample had large diameters, some exceeding 60 μm, suggesting that the origin of the anther clumps may have been from cereal crop plants in the White Rock drainage.

The grass-rich, ca. 1948 sample at 71 cm overlies a silty layer in the core at 73 cm, perhaps indicating that the grass anther fragments washed into White Rock Lake during an intense sheetwash flood passing through cultivated cropland in the drainage. In fact, plate 2A in Marshall & Brown (1939) illustrates such a flood after a high intensity rainstorm.

After ca. 1952 (61 cm), the pollen of the White Rock Lake core is characterized by reduced percentages of agricultural weeds and increased percentages of mesic, mostly riparian tree taxa such as *Celtis* [hackberry], *Ulmus* [elm], *Carya* [pecan], *Fraxinus* [ash], and *Salix* [willow] and some species of *Quercus* [oak] (Figure 5). This part of the core postdates World War II and records the reduction of agricultural land use in the White Rock Creek drainage and increased urbanization. The increase in juniper pollen (probably *Juniperus virginiana*) may reflect the expansion of this species on abandoned and severely eroded farm land (Marshall & Brown, 1939). Major element concentrations in the core indicate a change from eroded, weathered soils prior to about 1982 to progressively less-weathered parent material after ca. 1982 (Van Metre & Callender, 1997). Moraceae pollen, perhaps representing domestic mulberry at least in part, may document urban plantings of this species in the last two decades.

Diatoms

Diatoms are preserved in significant numbers only in sediment dated post ca. 1989 (Figure 6). It is clear from the work of Patterson (1942) that diatoms were an important part of the phytoplankton in the spring of 1939 along with smaller numbers of *Ceratium* and *Dinobryon*. A species of *Melosira* (*Aulacoseira*) was dominant at that time, yet diatoms were completely absent in the approximately equivalent sediment sample (91 cm).

Preservation of diatoms in lake sediments reflects the difference between diatom production and diatom destruction by breakage and dissolution. The opaline silica of diatom valves is susceptible to dissolution (Schleske, 1985), especially in warm, alkaline water (Lawson et al., 1978). In all probability, the lack of diatoms below 15 cm (ca. 1986) in the White Rock Lake core reflects the corrosive action of warm, turbulent and alkaline lake water on the frustules sedimenting on the relatively shallow bottom. Patterson's observation that numbers of *Melosira* per liter in White Rock Lake (1939) were significantly lower (by a factor of nearly 30) than in an earlier analysis at nearby Bridgeport Reservoir (Harris & Silvey, 1938) may indicate that White Rock Lake was comparatively unproductive, at least with respect to diatoms, when agriculture was the principal land-use strategy in the drainage basin.

Diatom productivity apparently increased above rates of diatom dissolution a decade ago when large numbers of *Aulacoseira alpigena* and small *Stephanodiscus* species (*S. medius*? and *S. minutulus*) appeared with other planktic diatoms (*Aulacoseira granulata*, *A. ambigua*, *Cyclotella meneghiniana*, *C. stelligera*, *C. pseudostelligera*, *Cyclostephanos tholiformis*, *Stephanodiscus parvus*, *Synedra acus*) and assorted benthic species in small percentages (Figure 6).

Small *Stephanodiscus* species probably thrive in low light conditions during the winter or early spring when nutrients, especially phosphorus, become abundant and winds are sufficient to transport and suspend the cells in the photic zone (Kilham & Kilham, 1978; Kilham et al., 1986). *Aulacoseira alpigena* (formerly *A. distans v. alpigena*) is a common diatom at some stations in the Savannah River (Patrick et al., 1967) and in shallow, moderately alkaline lakes (for example Gasse et al., 1983; Tolonen, 1978). Analysis of varved sediments in a Finnish meromictic lake (Simola, 1984) indicate that *Aulacoseira alpigena* blooms during periods of lake turnover, often in the fall when turbulence brings nutrients from the hypolimnion and suspends these diatoms in the photic zone. In shallow lakes, like the northeast Texas reservoirs, the required nutrient and turbulence combinations are more likely to occur throughout the year, and *Aulacoseira* apparently blooms in the spring when illumination levels increase (Patterson, 1942).

General discussion

The pollen stratigraphy of White Rock Lake documents the rather abrupt transition between agricultural and urban land-use practices, and possibly the effect of well known drought conditions of the 1930s. As agricultural activities in the White Rock Creek drainage declined, native riparian plant communities began to reoccupy drainage channels to contribute pollen of mesic, arboreal taxa to the lake sediments. Probably urban tree plantings are also sources of some tree pollen in the record.

The principal question relating to the diatom stratigraphy is why are diatoms only preserved in the last decade of the reservoir's history? It is conceivable that pesticides applied to croplands had a deleterious effect on algal growth in White Rock Lake (e.g., Boyle, 1984), but the pesticide stratigraphy (Van Metre &

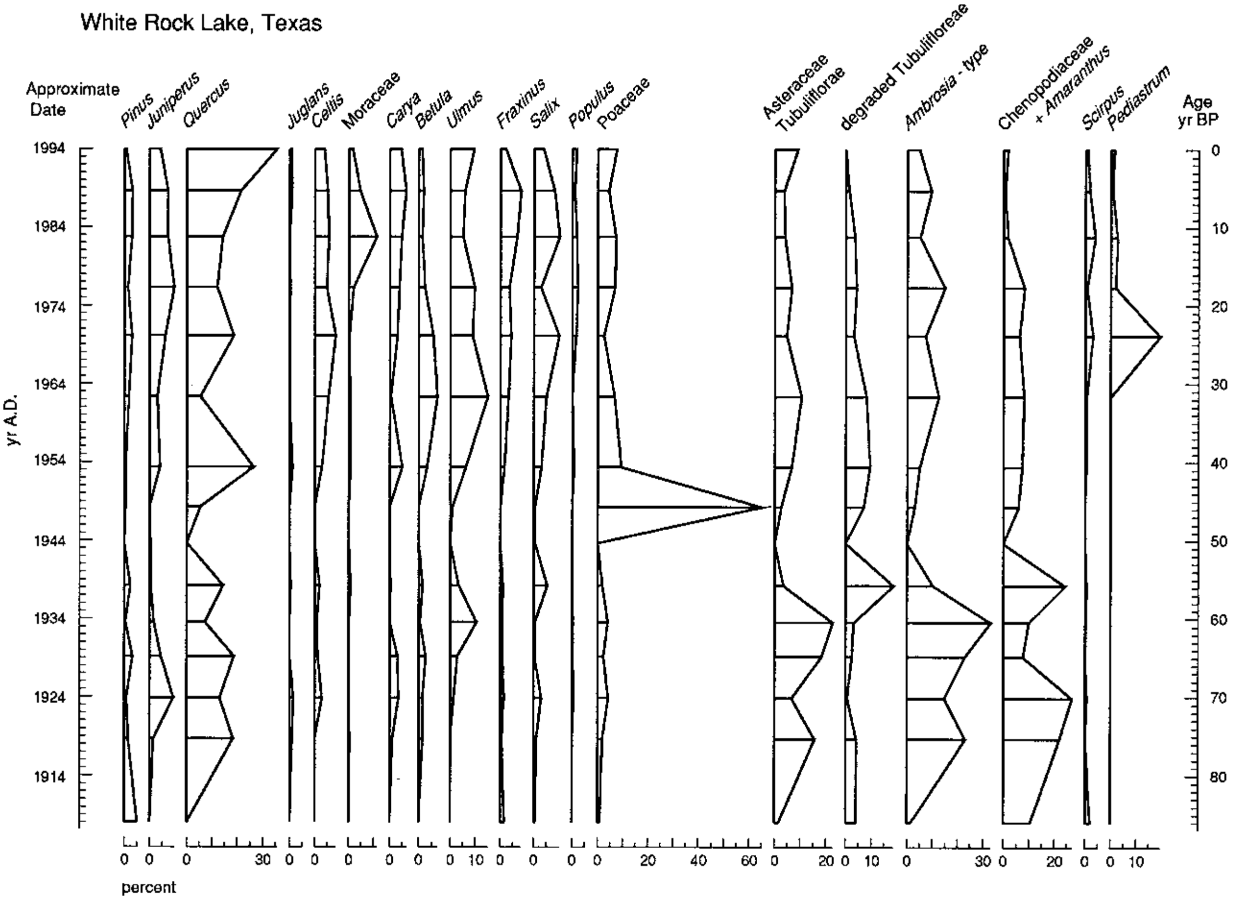

Figure 5. Pollen profiles of White Rock Lake core plotted against core chronology (see Figure 3b).

Callender, 1997, Figure 6) indicates pesticide application only after the mid-1940s, and therefore could not account for lack of diatoms or algae before that time. In addition, with the exception of chlordane and dieldrin, pesticide use declined after 1970, before diatoms became abundant. Higher levels of chlordane and dieldrin coincide with the increase in diatom production in the 1980s and so are unlikely to have adversely affected diatom growth in this case. The brief increase in *Pediastrum* ca. 1970 (Figure 5), when all pesticides were at low values, may, however, document an algal response to pesticide toxicity.

Increased nutrient levels entering urban lakes from integrated storm drainage has been invoked to account for increased algal productivity (e.g., Brugam & Speziale, 1983), but water column analyses of nutrients in White Rock Lake have actually fallen since 1975 (Figure 2), presumably as a result of drainage area stabilization and reduced soil erosion. However, stabilization of the White Rock Lake watershed by integrated storm drainage and urban planting (lawns, trees, etc.) has resulted in a sharp decrease in the total suspended solids in the water column since 1983 (Figure 2). Textural analysis of the core sediments documents reduced sedimentation of clay since ca. 1954 and especially since ca. 1986 (Figure 3) that probably also reflects urbanization with lower sediment loads to White Rock Creek. Additionally, sediment mass accumulation rates have decreased 35% since the shift from agricultural to urban land use took place.

Abiotic turbidity is often sufficient to limit the photosynthetic activity of algae in reservoirs (Osborne, 1972; Marzolf & Osborne, 1971). In a summary of phytoplankton productivity estimates for reservoirs, Kimmel et al. (1990) noted 'that in the most 'oligotrophic' reservoir (Turtle Creek Reservoir, Kansas) phytoplankton productivity is severely light limited by high levels of abiogenic turbidity'. Because abiotic tur-

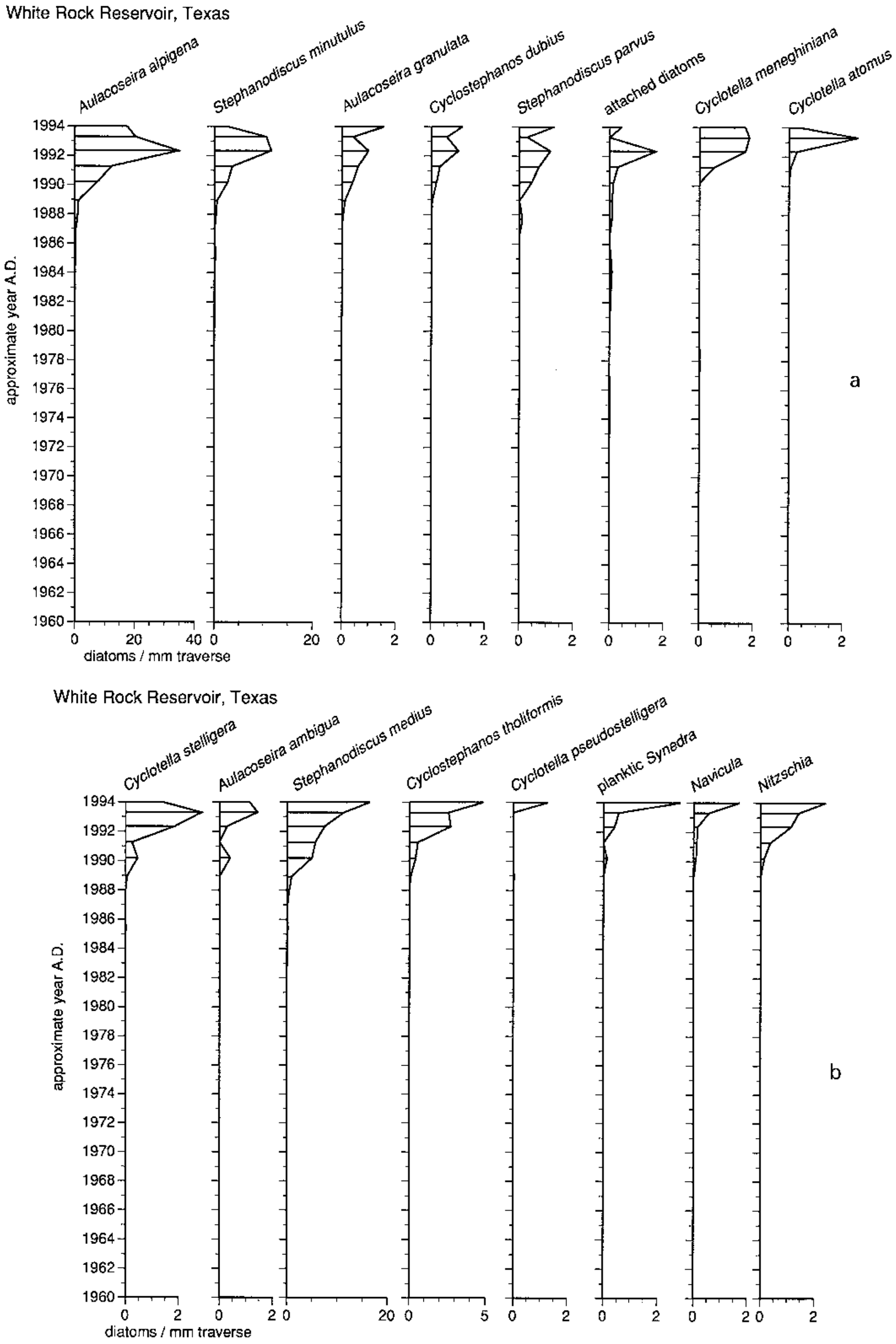

Figure 6. (a,b) Diatom profiles of White Rock Lake core plotted against core chronology (see Figure 3b).

bidity is enhanced by easily suspended clay-size sediment, the decrease in clay-sized particles in the core and decreased concentrations of total suspended solids probably reflects a decrease in turbidity in White Rock Lake. The increase of phytoplankton productivity as suggested by increased preservation and numbers of diatoms after ca. 1989 could record increased effective illumination in White Rock Lake. Increased productivity of periphytic algae was documented by Grubaugh & Wallace (1995) in a comparative study of benthic community structure of a piedmont river in Georgia after sediment loads decreased with the reduction of agriculture in the drainage. In this instance, higher levels of the ecosystem all responded (and improved) as the trophic base increased. It is not unreasonable to expect that White Rock Lake would behave in a similar fashion if sedimentation and turbidity can be effectively reduced.

Conclusions and recommendations

Because reservoirs are, by definition, unnatural impoundments, their water quality would unlikely resemble that of natural lacustrine systems. As lakes, reservoirs must fill with sediment over time; as rivers, reservoirs will be dominated by sediment transport processes. It is natural that reservoirs tend toward turbidity and fill rapidly with sediment. Were White Rock Lake built in an unmodified, natural drainage basin of White Rock Creek before human settlement, it still would have been short-lived, although probably less turbid.

Land-use changes in the drainage basin of White Rock Creek are recorded in the sediments deposited in White Rock Lake. Pollen in the sediments documents the shift from agricultural to urban land use and diatoms indicate an apparent increase in algal productivity that correlates with a recent decrease in lake turbidity. The large amounts of clastic sediment entering the basin, first from erosion related to poor agricultural practices (Marshall & Brown, 1939) and later possibly by home and road construction in the drainage basin continue to rapidly fill the basin although at a somewhat slower rate in recent decades. Some dredging (Patterson, 1942; Dallas Morning News, 7 VIII, 1994) has maintained useful nearshore depths, but it is clear that further reduction of sediment loads or extensive dredging will be required to maintain the reservoir into the future. Storm drains, lawns, and trees related to urbanization have apparently reduced sedimentation of clay-sized material relative to land use under past agricultural strategies and have resulted in biologically improved water quality.

A more detailed interpretation of land-use and water quality changes could be made for White Rock Lake, or other reservoirs, by utilizing sediment traps and lake monitoring protocols that can directly tie the seasonal autecological dynamics of diatoms and other algae to the stratigraphic record and to anthropogenic and climatic events in the drainage basin. Such studies, coupled with a systematic investigation of historical economic and planning records in state and county archives, could provide exceptionally useful insights into the relations among water quality, land use, and climate change.

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