Paleolimnology of Onondaga Lake: the History of Anthropogenic Impacts on Water Quality

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ABSTRACT

Rowell, H. C. 1996. Paleolimnology of Onondaga Lake: the history of anthropogenic impacts on water quality. Lake and Reserv. Manage. 12(1):35-45.

New York State's Onondaga Lake is a polluted, hypereutrophic, saline lake with a remarkable paleolimnological record. The chemical and diatom stratigraphy of two sediment cores was used to document past anthropogenic impacts on the lake's water quality. Onondaga Lake's pre-historic and pre-industrial water quality conditions are clarified and subsequent major pollution events identified. Pre-1800s Onondaga Lake was mesotrophic and considerably less saline (around 230 mgL^{-1} Cl^-) than at present (around 450 mgL^{-1} Cl^-). Factors that most affected lake water quality were: 1) increasing settlement in the watershed which increased lake sedimentation and nutrient levels, 2) development of the salt industry during the 1800s which contributed to a rise in lake salinity, 3) the soda-ash industry in the late 1800s through 1900s which added major amounts of $CaCO_3$ and salt to the lake, and 4) post-World War II urban and industrial development which contributed to very high nutrient, Hg, and other heavy metal loadings.

Introduction

Diatom and geochemical analyses have been used widely in paleolimnology to document anthropogenic impacts on lake water quality (Dixit et al. 1992, Engstrom and Wright 1984). Stratigraphic analysis of multiple sediment variables provides a mutually-supportive record of human-induced paleoenvironmental change (e.g., Engstrom et al. 1985). This multidisciplinary approach was used to demonstrate the link between specific anthropogenic impacts in the Onondaga Lake watershed and changes in lake water quality.

Site Description

Onondaga Lake is a polluted, saline (450-500 mgL^{-1} Cl^-), carbonate-rich, hypereutrophic (up to 100 ugL^{-1} Chl *a*) waterbody (Effler 1996, 1987) located in a highly urbanized area immediately north of Syracuse in upstate New York (Figure 1). Formed as a geological remnant of a proglacial lake system that existed following glacial retreat from the area around 14,000 years ago (Muller 1977, Mullins and Hinchey 1989), it is morphologically similar to the New York Finger Lakes that stretch across central New York State (Mullins and Hinchey 1989). It is 7.2 km long, 1.6 km wide, has a surface area of 11.7 km^2, a maximum depth of 20.5 m, and a mean depth of 12 m (Effler 1987). The lake's watershed drains approximately 642 km^2 of carbonate-rich rocks and soils (Winkley 1989).

Onondaga Lake has been described as one of the most polluted lakes in the United States (Hennigan 1990). It is in violation of several water quality standards developed by the State of New York in response to the "fishable and swimmable" criteria of the 1972 Federal Clean Water Act (Effler 1996). Toxic contaminants include mercury, chlorobenzenes, and PCBs. It also experiences high rates of calcium carbonate deposition (Driscoll et al. 1994). The lake's pre-cultural condition and subsequent historical changes in its nutrient levels, salinity, overall degree of pollution, and rate of sedimentation have been points of debate since at least the 1950s (Effler and Harnett 1996, Hennigan 1990). This study uses sedimentology, geochemistry, and fossil diatom analysis to resolve these issues.

History

A number of historical events in the Onondaga Lake watershed (Table 1) are potentially reflected in the lacustrine sediment record. Colonial settlement and riparian land clearance occurred during the late 1700s. Salt production was the primary impetus for population growth in the area throughout the 1800s, peaking during the American Civil War when Syracuse provided the bulk of the nation's salt supply (Onondaga County 1971). During the late 1800s industrial waste containing salt started to be discharged to the Lake. Over the next hundred years solid waste from soda ash

Table 1.–*Selected anthropogenic impacts on the Onondaga Lake watershed.

Date	Event
1988	Closure of mercury process, end of permitted Hg loading to Onondaga Lake
1986	Closure of soda ash production facilities
1981-86	Rise in Hg levels in fish flesh
1981	METRO Sewage Treatment Plant tertiary treatment starts, removes P
1979	METRO Sewage Treatment Plant upgrade to secondary treatment completed
1978	Further reductions of Hg loading
1976	85% - 90% reduction in metal loadings to the lake from Crucible Steel
1971	Onondaga County ban on high phosphate detergents
1970-79	Drop in Hg levels in fish flesh
1970	95% reduction in Hg loading to lake
1953	Doubling of Hg loading to lake (to 10 kg/day)
1946	Start of Hg loading to lake (5 kg/day)
1940s	Solvay waste deposited along Nine Mile Creek
1928	METRO Sewage Treatment Plant primary treatment started
1920s	Oil City established, Solvay waste deposited at Saddle Point
1920	Lake closed to public swimming
1901	Ice cutting banned due to water impurities
1900-10	Commercial salt production ends, industrial development (e.g., Crucible Steel) begins
1898	Whitefish disappear, ending Lake's commercial fishery
1890s	Solvay waste deposited at south end of Onondaga Lake
1880s	Heyday of lakeside recreational resorts
1884	Start of Solvay Process Company soda ash production
1822	Lake lowered to drain Syracuse swamps, lake surface reduced by 20%
1794	First commercial salt production near Onondaga Lake
1786	Ephraim Webster, first white settler, settles near lake on Onondaga Creek
1779	Indian crops and villages within the Onondaga Lake watershed burned by Sullivan Military Expedition

* from Blasland and Bouck (1990), DEC (1990), Effler (1987), Effler et al. (1981), Hennigan (1990), Onondaga County (1971), Saroff (1990).

production (the Solvay process), composed largely of calcium carbonate, was deposited along much of the shoreline of the lake and several of its tributaries. Additionally, steel manufacture and other industries discharged metal waste to the lake, the city of Syracuse continued to grow on the lake's southern end, and a chlor-alkali facility contributed an estimated 75,000 kg of mercury to the lake sediments (DEC 1990). Hypereutrophic conditions characterized the lake by the late 1960s (Effler 1987).

Since 1970 the lake's water quality has improved, apparently in response to a decline in pollution due to various remediation efforts (Effler 1987). Today the lake's phosphorus level ranges around 60 ugL^{-1} TP (Effler et al. 1996). Persisting problems stem from continued sewage discharge to the lake, residual industrial wastebed inputs, leachate from a number of hazardous waste sites near the lake and its tributaries, and recycling of contaminants from the lake-bottom sediments.

Methods

In August 1988 sediment profiles were recovered from the north and south basins of Onondaga Lake (Fig. 1) with a gravity corer and analyzed for ^{137}Cs, $CaCO_3$, and metals (Hg, Cr, Zn, Pb). The south basin core (located at the site of lake water quality monitoring since 1969) was also analyzed for total organic carbon (TOC), total phosphorus (TP), and diatom stratigraphy (Rowell 1992). Cesium-137 analysis followed the procedures of Ritchie and McHenry (1973). Analytical

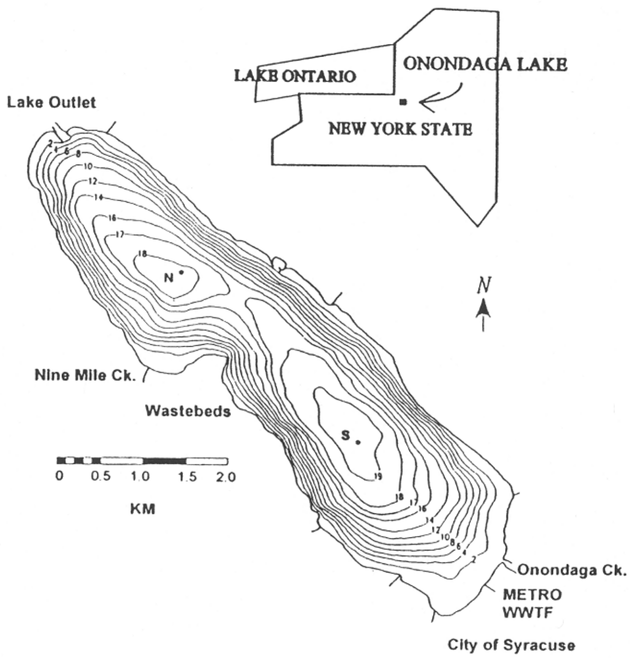

Figure 1.–Location and Bathymetry of Onondaga Lake (taken from Effler 1996). Location of the north (N) and south (S) basin sediment cores used in this study. Contours are in meters. METRO WWTF = Syracuse metropolitan waste water treatment facility.

methods for TOC, TP and metals are described in Krishnamurty and Reddy (1975) as modified from Standard Methods (1971). Calcium carbonate content was determined by the loss on ignition procedure (Dean 1974, Johnson 1989). Loss on ignition carbonate values at 1000°C were multiplied by 2.27 (the molar ratio of $CaCO_3$ to CO_2) to convert to calcium carbonate (Johnson 1989). Diatom samples were prepared according to Battarbee (1979). The assemblages were identified by the author. The Shannon-Weaver diversity index was calculated as given in Cole (1983).

Results

Sediment Stratigraphy and Pollen

Profundal sediments of Onondaga Lake consist of a black, gaseous (sulphide-rich), micro-laminated, silty clay overlying a dark grey clay. The black clay is typical of sediments from anaerobic lake bottoms, often found in eutrophic systems (Wetzel 1983, Cole 1983, Reineck and Singh 1980). The underlying dark grey clay, containing evenly-spaced laminations and occasional gastropod shells, appears characteristic of less productive lakes.

The transition between the two sediment types occurs coincident with an increase in ragweed (*Ambrosia*) pollen (Rowell 1992), an opportunistic open-space genus indicative of forest clearance by colonial settlers (Faegri and Iversen 1989). European settlement near Onondaga Lake started at the end of the 1700s and the *Ambrosia* horizon is taken to represent the period around 1800. Based on the above stratigraphic relationships, the lake's transition to higher levels of productivity is correlated with post-settlement cultural activity.

Sediment Chronology and Rate of Accumulation

A ^{137}Cs activity peak, associated with the period of maximum atmospheric fallout in 1963 and 1964 (Ritchie and McHenry 1990), is apparent in the Onondaga Lake sediments (Fig. 2). Based on the cesium-137 and *Ambrosia* horizons, average linear sediment accumulation rates in the southern basin core are .4 cm yr^{-1} from 1800 to 1963 and .8 cm yr^{-1} from 1963 to 1988. From 1963 to 1988 the rate in the northern basin core is also .8 cm yr^{-1}, but earlier data are not available. Radiocarbon dates from older sediment in the southern basin (Rowell 1992) indicate a pre-1800 linear accumulation rate of .04 cm yr^{-1} in Onondaga Lake. These linear rates do not account for sediment compaction.

Average dry mass accumulation rates compensate for sediment compaction. In the southern basin core these rates are .195 g $cm^{-2}yr^{-1}$ from 1822-1884, .235 g $cm^{-2}yr^{-1}$ from 1884-1963, and .665 g $cm^{-2}yr^{-1}$ from 1963-1988. In the northern basin core the average dry mass rates are .196 g $cm^{-2}yr^{-1}$ from 1884-1963 and .317 g $cm^{-2}yr^{-1}$ from 1963-1988. The 1822 and 1884 age horizons are derived from diatom and calcium carbonate data presented below. Both the linear and dry mass accumulation rates increase upward.

A pattern of upward increase in sediment accumulation rates is commonly observed in anthropogenically impacted lakes (e.g., Oldfield and Appleby 1984, Appleby and Oldfield 1978, Oldfield et al. 1978). In Onondaga Lake the dry mass accumulation rates also vary considerably between the north and south basins. An even thicker black-clay sequence, indicative of higher cultural sediment accumulation rates, has been reported for a number of sites in Onondaga Lake (Effler 1975, EPA 1973, DEC 1990). These findings suggest considerable localized variation in sediment accumulation rates in Onondaga Lake. This report emphasizes the interpretation of stratigraphic relationships rather than quantification of sediment accumulation.

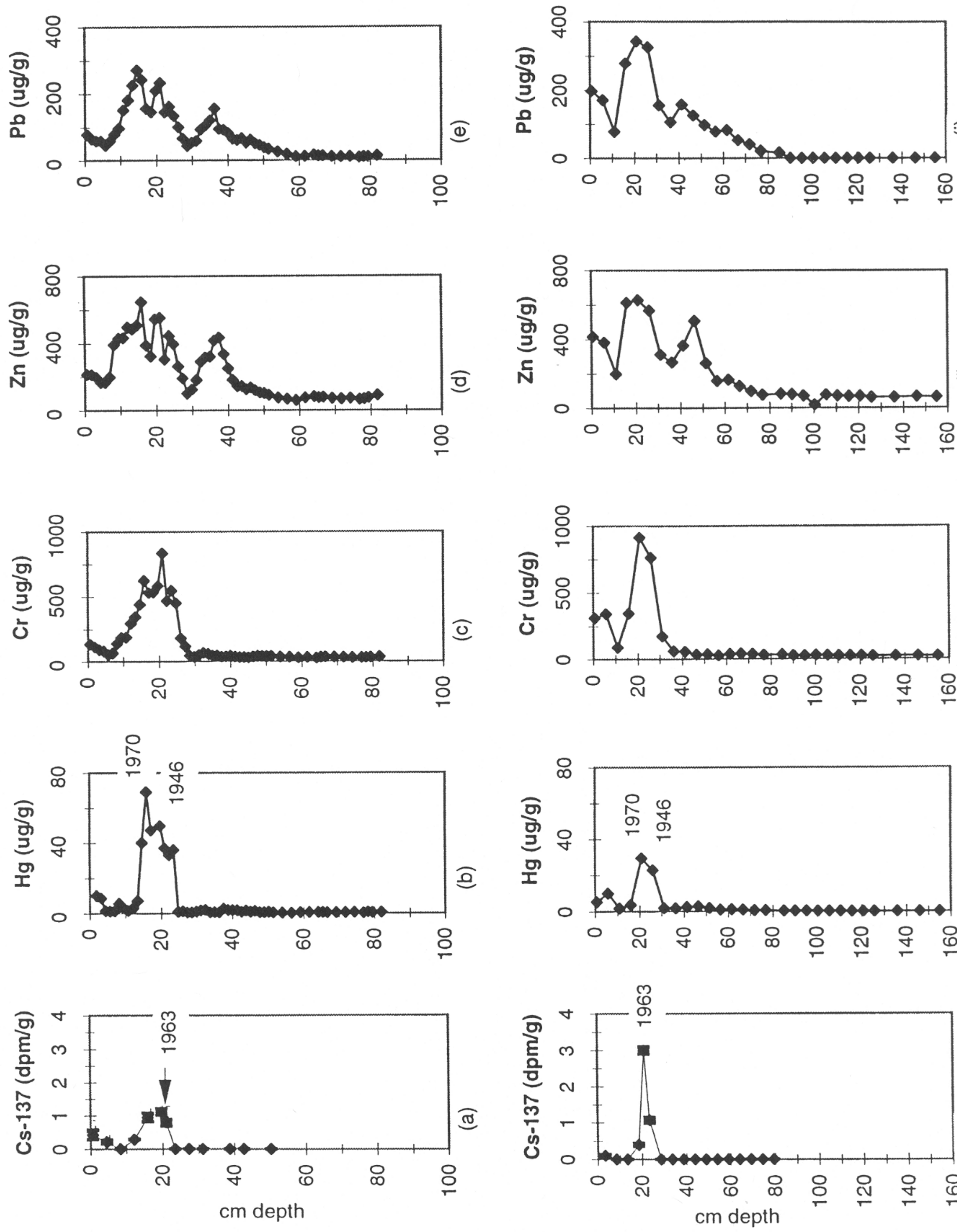

Figure 2.–Stratigraphic profiles of cesium-137 and selected metals in sediment cores from the north basin (a-e) and south basin (f-j) of Onondaga Lake; north basin samples taken at 1.27 cm (.5 inch) intervals, south basin samples taken at 5.08 cm (2 inch) intervals.

Sediment Constituent Profiles

Increase in industrial and municipal activity in the Onondaga Lake watershed accompanied post-World War II economic growth (Effler and Harnett 1996). The stratigraphy of heavy metals (Zn, Pb, Cr, Hg) in the sediments of Onondaga Lake shows this trend (Figure 2). The greatest concentrations occur around the 1963/64 ^{137}Cs peak. The rise in mercury concentration represents loadings no older than 1946 (Table 1) and the overall decline in element concentrations is attributable to controls placed upon anthropogenic loadings during the early to mid 1970s (Effler 1987). The Hg concentrations in this interval are comparable to those found elsewhere in the United States for highly Hg-enriched sites (e.g., Saroff 1990, Golterman et al. 1983) contaminated by direct loadings from local industrial sources.

Since World War II, stratigraphic concentrations of total organic carbon and total phosphorus (Fig. 3, a and b) follow the same pattern as metals. TOC and TP peaks are attributable to increased residential development and waste discharge (Effler 1987) followed by controls on the use of phosphorus detergents and improvements in sewage treatment instituted in the 1970s. Both TP and TOC in sediments can reflect lake productivity (Kemp et al. 1976) and may well be tied to hypereutrophic conditions in Onondaga Lake.

Above the *Ambrosia* horizon (i.e., 1800) increases occur in concentrations of TP, Zn, and Pb. Peaks in these elements and TOC occur higher in the stratigraphic column. Watershed clearing and increased settlement activity account for the former increases. Loading from early industrial development (post-1900) probably caused the latter peaks. This interpretation is supported by the stratigraphic position of the calcium carbonate loading event discussed below. Calcium carbonate deposition is a major factor in Onondaga Lake (Driscoll et al. 1994) and its effect on these stratigraphic profiles is therefore examined.

A three-fold increase in calcium carbonate concentration occurs at 60 cm depth in the Lake's southern basin (Fig. 3c; 45 to 35 cm depth in Fig. 3d). High levels (up to 70%) of calcium carbonate are also found deeper (5 m) within the sediment section (Rowell 1992), indicating that Onondaga Lake was characterized

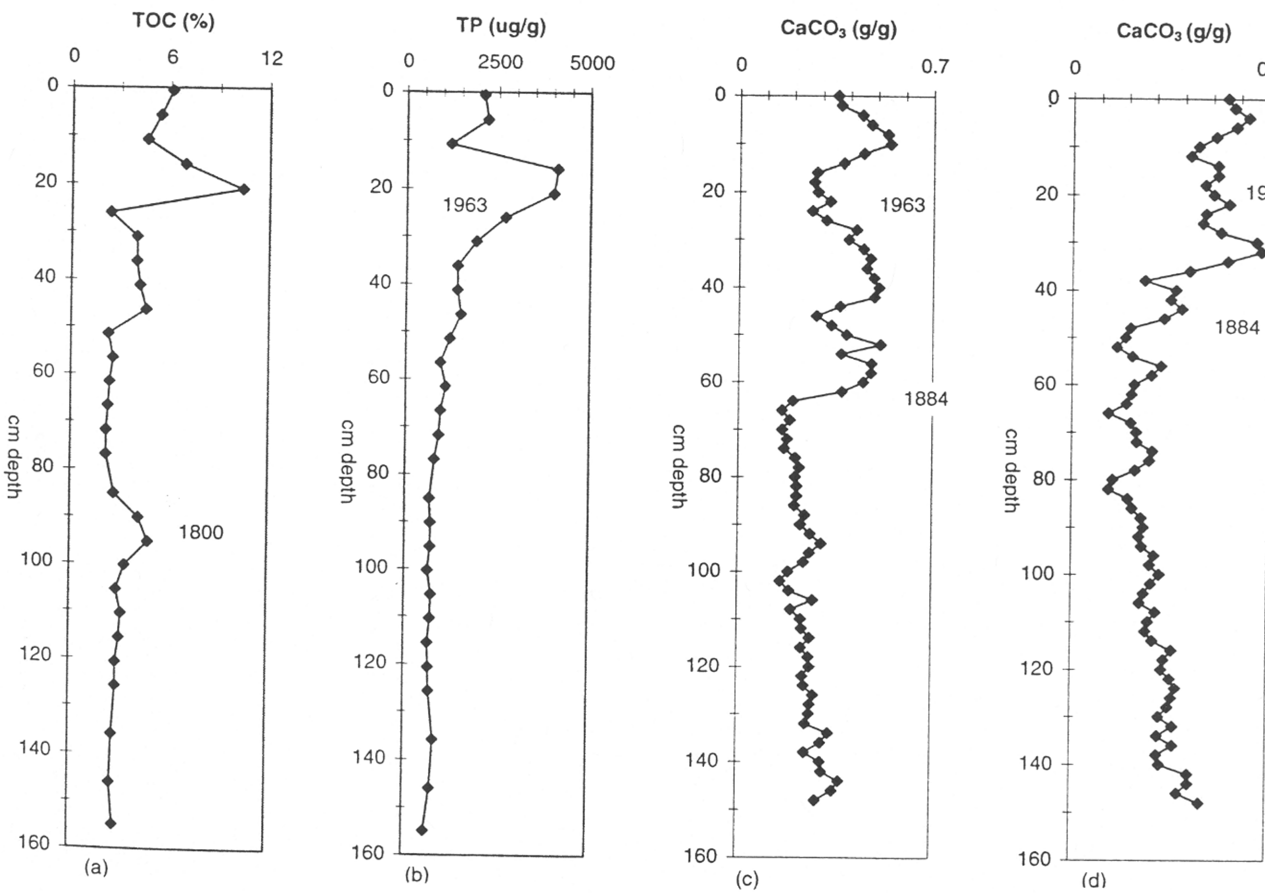

Figure 3.–Stratigraphic profiles of Total Organic Carbon (a), Total Phosphorus (b), and calcium carbonate (c) in sediment cores from south basin of Onondaga Lake and calcium carbonate in a core from the north basin (d).

by carbonate deposition prior to anthropogenic alteration of the watershed. Nevertheless, slower prehistoric linear sediment accumulation rates suggest that predisturbance bulk calcium carbonate loadings to the lake sediment were probably much lower than rates measured in recent years.

High carbonate sedimentation can be caused by high phytoplankton productivity in calcareous lakes (Kelts and Hsu 1978). The calcium carbonate rise in Onondaga Lake sediments, and subsequent short-term fluctuations in concentration (Fig. 3, c and d), may, in part, be the result of shifts in biological productivity. However, the abruptness of the $CaCO_3$ change strongly suggests another contributing cause.

A recent study showed that major reductions in calcium carbonate deposition in Onondaga Lake coincided with reductions in lake calcium concentrations that accompanied the 1986 closure of the soda ash/chlor-alkali facility (Driscoll et al. 1994). Conversely, it is likely that the onset of discharges from the facility in the late 1800s triggered a rise in sediment carbonate content. Added calcium ions would have combined with available dissolved inorganic carbon from the carbonate-rich watershed to increase calcite formation in a system already supersaturated with calcite (e.g., Driscoll et al. 1994). That the soda ash industrial process was a cause of increased $CaCO_3$ deposition in the lake is further supported by paleoecological indications of associated salt loadings.

The water quality history (trophic level, salinity, and relative degree of pollution) of Onondaga Lake is reflected in the stratigraphy of its diatom associations. The taxa were grouped (Table 2; e.g., Haworth 1969, Duthie and Sreenivasa 1971) by environmental association (cf. Patrick and Reimer 1966, Beaver 1981).

The plot of benthic-epiphytic/planktonic taxa versus depth (Fig. 4) reveals a decrease in attached species around 80 cm depth probably caused by 1) increases in planktonic diatom productivity and 2) the 1822 lowering of the lake level by an estimated .6 meters (Effler and Harnett 1996) that significantly decreased the area of the littoral zone (Onondaga County 1971). A further decline in benthic-epiphytic vs. planktonic diatom species around 55 cm depth may be a response to the elimination of submerged macrophyte surfaces in response to increased $CaCO_3$ deposition (Dean and Eggleston 1984).

Prior to the early 1800s, oligo-mesotrophic assemblages existed in Onondaga Lake (Fig. 5). Eutrophic associations increased and mesotrophic

Table 2. –Summary of environmental associations and key diatom species used in the Onondaga Lake sediment study.

Environmental Association	# of Species	Selected Key Taxa
total assemblage	216	inclu. chrysophyte cysts
widely tolerant or undefined	76	e.g., *Surirella* spp. *Mastogloia* spp.
oligotrophic	7	chrysophyte cysts
mesotrophic	18	*Cyclotella comta* *Fragilaria crotonensis*
eutrophic	47	*Asterionella formosa* *Cyclotella meneghiniana* *Melosira granulata* *Nitzschia palea* *Stephanodiscus hantzschii* *S. niagarae* *Synedra pulchella* *Tabellaria fenestrata*
salt tolerant	126	*Cyclotella atomus* *Diatoma tenue*
halophilic	4	*Diatoma tenue elongata*
halophobic	13	*Stephanodiscus niagarae* *Tabellaria fenestrata*
pollution indicators	7	*Navicula integra* *Nitzschia palea*

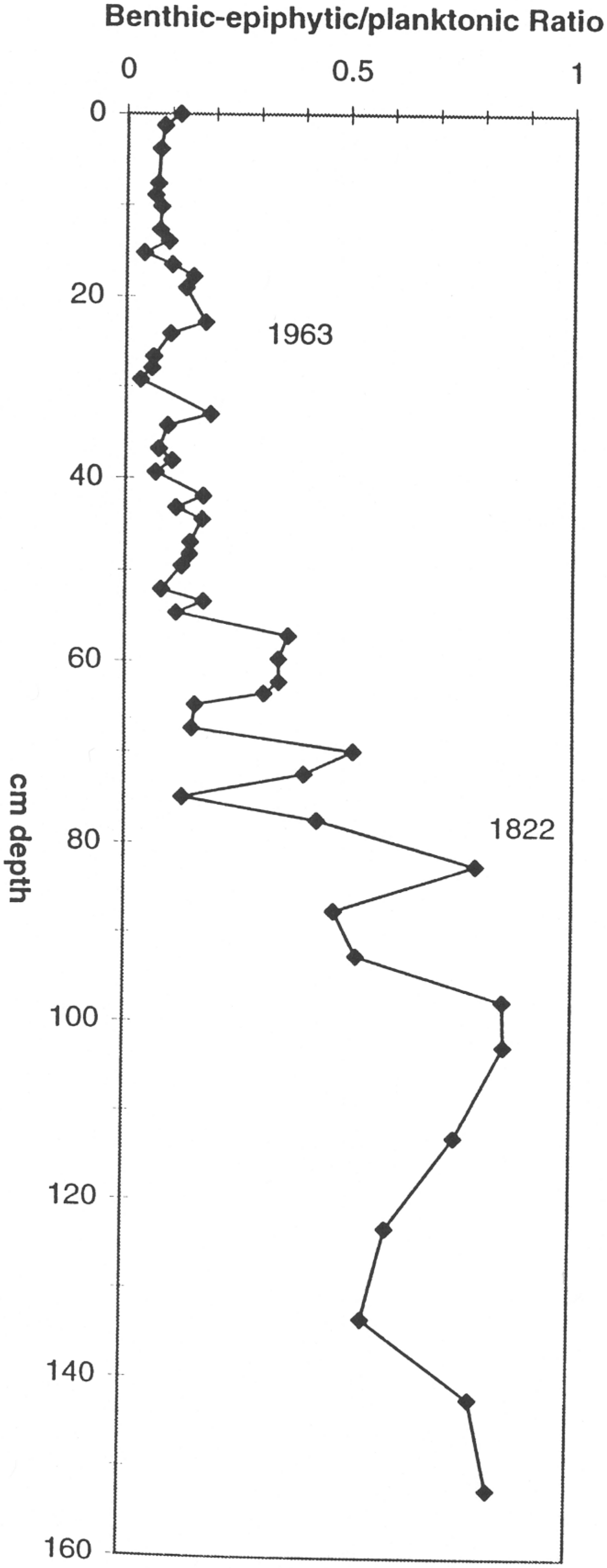

Figure 4.–Stratigraphic profile of benthic-epiphytic/planktonic diatom species ratio in sediment core from southern basin of Onondaga Lake.

associations declined during the 1800s. Considering how cultural impacts affected sediment characteristics above the *Ambrosia* horizon, it is probable that the rise in eutrophic indicator species during the mid-1800s reflects the lake's change to eutrophic conditions. The eutrophic diatom assemblage that predominates from World War II to present reflects the recent hypereutrophic condition of the lake. Several of the species that dominate this interval (e.g., *Cyclotella meneghiniana* and *C. cryptica*) are indicators of perturbed (saline, nutrient-rich) conditions (Stoermer 1984). A slight increase in oligotrophic forms at the top of the stratigraphic column may reflect recent water quality improvements.

Two significant historical increases in lake salinity are apparent in the profile of saline tolerant diatom species shown in Fig. 6. The first occurred after 1800 following settlement of the watershed. Undocumented loadings to the lake of various elements may have occurred during the 1800s and, in particular, early salt production probably caused a combination of increased watershed erosion and dumping of salt waste into the Lake (Effler and Harnett 1996). Lake lowering in 1822 could also have contributed to the salinity increase by reducing the lake volume, but most of the area lost was swamp and shallow littoral habitat (Onondaga County 1971).

The second major salinity increase occurred in conjunction with the large increase in sediment calcium carbonate concentrations at about 60 cm. Salt tolerant and halophilic species increase as a component of the diatom assemblage (Fig. 6) and a drop in assemblage diversity also occurs at this stratigraphic level (Fig. 7). A similar stratigraphic pattern has been reported

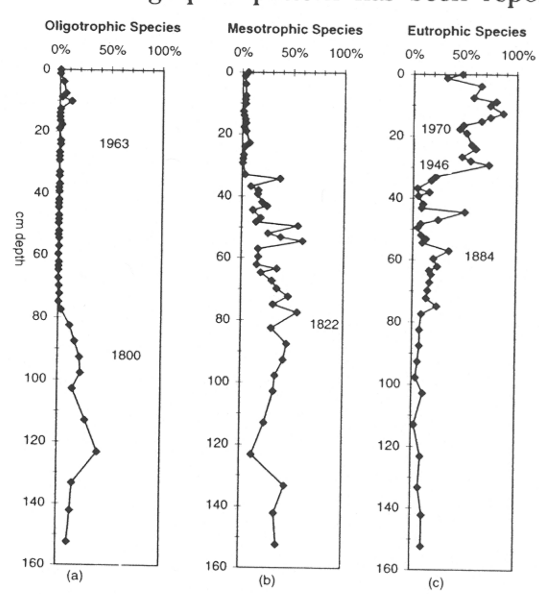

Figure 5.–Stratigraphic profile of diatom taxa trophic level associations in sediment core from southern basin of Onondaga Lake.

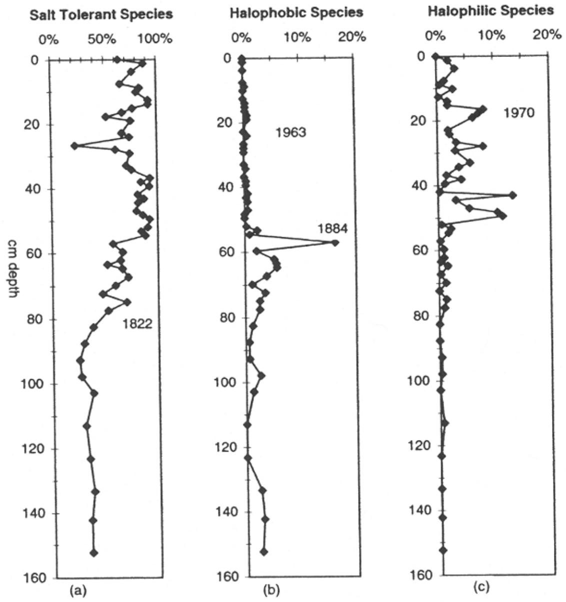

Figure 6.–Stratigraphic profiles of diatom taxa salinity indicator associations in sediment core from southern basin of Onondaga Lake.

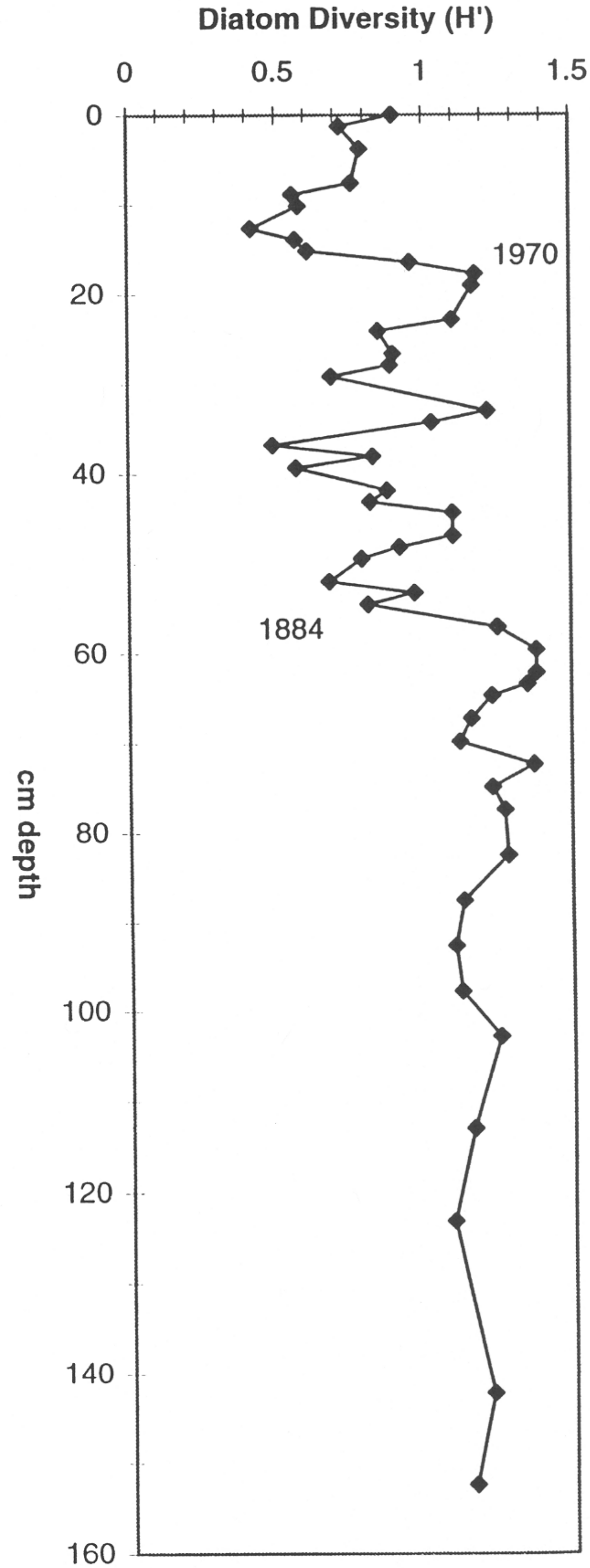

Figure 7.–Stratigraphic profile of Shannon-Weaver diversity index for diatom assemblages in sediment core from southern basin of Onondaga Lake.

elsewhere for both halophilic/halophobic diatom associations and diatom diversity indices related to salt loading (Tuchman et al. 1984). The drop in diversity indicates a shift towards an assemblage dominated by a few, in this case, salt-tolerant species, an ecologic response to stress (Wetzel 1983, Patrick 1977, Cooper and Brush 1991).

In conclusion, a significant portion of the modern stress on the lake's biotic system stems from a century of industrial salt and $CaCO_3$ discharge to the lake. Doerr et al. (1994) estimated that, without the influence of industrial wastes, the lake's salinity would be around 230 mgL^{-1} Cl^-. This conclusion is based on the observation that the closing of the chlor-alkali facility in 1986 reduced salinity levels in Onondaga Lake from over 2000 mgL^{-1} Cl^- to around 450-500 mgL^{-1} Cl^- and that residuals from that industry's waste beds continue to release ionic salts to the lake (Effler and Whitehead 1996).

Discussion

Reconstruction of Onondaga Lake's water quality history is based on stratigraphic changes in sediment variables and assumes a direct relationship between anthropogenic impacts and sediment response. This relationship may be confounded by several factors. For instance, the bulk sediment chemical analysis employed here can lead to erroneous interpretations of element stratigraphic distributions (Engstrom and Wright 1984).

Some investigators have used selective chemical extraction techniques to separate allogenic and authigenic components, thereby distinguishing external loading impacts from in-lake chemical processes (Engstrom and Wright 1984, Bengtsson and Enell 1986). A number of authors have mathematically compensated for diluting influences of dominant constituents (e.g., Engstrom and Wright 1984, Kemp et al. 1976, Forstner 1990, Cowgill and Hutchinson 1966).

Calcium carbonate "dilution factor" adjustments to the Onondaga Lake data did not substantially alter the stratigraphic patterns presented here (H. C. Rowell unpubl.), probably because the magnitude of pollutant loading was sufficient to overcome dilution effects. Rowell and Effler (1996) used correlation factors based on linear regression to compare the Onondaga Lake sediment profiles. Significant (at 95% confidence interval) positive r values are reported between calcium (as a surrogate for $CaCO_3$) and Hg, Pb, Cr, and Zn profiles from the northern basin. Correlations between Ca and TOC ($r = 0.07$) and, for the southern basin, Ca and TP ($r = 0.37$) are not significant at 95%. When the regression is restricted to the 1946-1988 portion of the profiles, the correlations are negative (except for Ca vs. TP which remains positive) but only Ca vs. Pb ($r = -0.69$) and Ca vs. Zn ($r = -0.51$) are significant at the 95% confidence level. It is evident that the profiles are responding, in part, to changes in calcium carbonate concentrations, but the correlations can not be attributed entirely to $CaCO_3$ dilution. It is concluded that, while the stratigraphic profiles have integrity as indicators of watershed events, because the profiles reflect both the depositional rate of calcium carbonate and changes in depositional rates of individual elements, stratigraphic interpretation must be limited to a non-quantitative assessment of pollutant impacts.

A number of biogeochemical processes also influence stratigraphic profiles of elemental concentrations. Metal concentrations in lake sediments can be influenced by organic matter concentrations (Kemp et al. 1976) because many elements adsorb or absorb to, and chemically complex with, organic material (Sly 1977). For Onondaga Lake, the histories of organic and inorganic contaminant loadings coincide and the stratigraphic pattern of metals correlates closely with the stratigraphic pattern of TOC (Rowell 1992). In Onondaga Lake's sediment, the stratigraphic profiles of heavy metals are probably due both to $CaCO_3$ dilution and a combination of the loading history of metals and organic carbon to Onondaga Lake sediments. Again, the shear magnitude and coincidence of lake contamination produced a record of loadings that can be correlated with watershed events.

Phosphorus stratigraphy is also subject to chemical alteration. It is known that TP concentration in lake sediments can be affected by redox, temperature, and pH conditions (Engstrom et al. 1985), and in particular by P release in lakes with anoxia hypolimnia and low redox conditions (Mortimer 1941, 1942). Phosphorus in sediments can also be influenced by iron oxides and organic compounds in the lake to which P may bind chemically (Engstrom et al. 1985). Onondaga Lake experiences lengthy summer periods of hypolimnetic anoxia and post-depositional cycling of phosphorus has been well documented in Onondaga Lake (Effler et al. 1996). However, the stratigraphic profile of TP in Onondaga Lake correlates strongly with that of TOC ($r = 0.79$, significant at the 99% confidence level) (Rowell and Effler 1996), suggesting that the TP stratigraphy reflects phosphorus loading and lake productivity rather than the effects of post-depositional recycling. Increases in TP concentrations within lake sediments have been directly correlated elsewhere to increases in anthropogenic P loadings (Kemp et al. 1976, Engstrom et al. 1985, Schelske et al. 1986). Effler et al. (1996) attribute immobilization of P in the Onondaga Lake sediments to either precipitation of $Ca\text{-}PO_4$ minerals or absorption of PO_4 to sediment surfaces. The close TP/TOC relationship supports the latter explanation, with P bound to organic carbon by absorption or as a component of refractory organic matter.

Conclusion

This paleoliminological study has elucidated Onondaga Lake's pre-historic and pre-industrial trophic state and salinity. High levels of productivity that prevailed in Onondaga Lake after the mid-1800s are correlated with cultural activity. Prior to about 1800, Onondaga Lake was mesotrophic and fresh to slightly saline. The lake became eutrophic during the early to middle 1800s and hypereutrophic shortly after World War II. Prehistoric Onondaga Lake was less salty than its present 450-500 mgL^{-1} Cl^-. Lake salinity started to increase around 1800 when the local salt industry developed. An abrupt increase in lake salinity and reduction in diatom diversity in the late 1800s is associated with waste discharges from a soda ash facility.

Much of the modern stress upon the lake's biota stems from the soda ash industrial process. Waste discharge from this process probably triggered the sharp rise in carbonate content within the top meter of Onondaga Lake sediment and accounts for the high concentrations of calcium carbonate in recent Onondaga Lake sediments. The greatest concentration of contaminants in the sediments of Onondaga Lake is attributable to post-World War II industrial and municipal growth in the lake's watershed. It is the magnitude and co-occurrence of pollution-associated material loadings (i.e., metals, phosphorus, organic carbon) to Onondaga Lake sediments that have produced a remarkably preserved sediment record that can be closely correlated with watershed events.

ACKNOWLEDGEMENTS: Support for this study was provided by the New York State Department of Environmental Conservation, the Upstate Freshwater Institute in Syracuse, NY, the Syracuse University Geology Department, and the SUNY College of Environmental Science and Forestry in Syracuse, NY. Special thanks are expressed to Drs. Steven Effler and Jay Bloomfield for advice with the manuscript and to Dr. Martin Auer and members of the Upstate Freshwater Institute for help with the field program. This is contribution #95-1 of the New York State Freshwater Institute.

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