ANSWERING LAKE MANAGEMENT QUESTIONS WITH PALEOLIMNOLOGY

ERIC SMELTZER
Agency of Environmental Conservation
State of Vermont
Montpelier, Vermont

EDWARD B. SWAIN
Gray Freshwater Biological Institute
University of Minnesota
Navarre, Minnesota

ABSTRACT

When historical limnological data are lacking on a lake, paleolimnology offers a means to evaluate the magnitude and timing of recent changes in water quality. Paleolimnological studies have proven valuable in developing lake management strategies for two Vermont lakes. In Harvey's Lake, it was uncertain whether the dominance of the phytoplankton by *Oscillatoria* was natural or culturally induced, and therefore uncertain whether restoration efforts were even appropriate. Analysis of a sediment core revealed that *Oscillatoria* became dominant shortly after 1945, in association with other major water quality changes such as increased rates of primary production, hypolimnetic oxygen depletion, and sediment accumulation. Thus, water quality had indeed declined, and Harvey's Lake was given high priority for restoration. Paleolimnological studies on Lake Morey indicated that a period of intense residential and commercial development of the lakeshore culminating around 1920 caused a severe deterioration in lake water quality that has since been perpetuated by mechanisms of hypolimnetic anoxia and internal phosphorus recycling, even in the absence of continued excessive nutrient loading from the watershed. These findings supported the recommendation that alum treatment be used as a restoration method for Lake Morey, with the expectation that long-term water quality benefits would result from the treatment. The Harvey's Lake and Lake Morey cases demonstrate that paleolimnological work is a valuable tool in lake diagnostic studies.

INTRODUCTION

Questions arise during a lake diagnostic study that are very difficult to address adequately: Has there been a change in water quality? If so, what water quality factors have changed? When did the change occur? What would the lake be like if all human influences were removed? (that is, what is the best water quality status realistically attainable?) Even if historical data are available (which is unusual), long-term trends may be difficult to document because of changes in analytical technique over the long term (Shapiro and Swain, 1983).

Paleolimnology offers a way to address each of these issues, especially in North America where humans have had significant effects on lakes only since settlement by Europeans. A single core of surface sediments about a meter long (a "surface core") can document the effects of humans over the past several hundred years, and indicate what the lake was like under undisturbed conditions (e.g. Bradbury and Megard, 1972; Brugam, 1978a; Engstrom et al. (in press); Smol et al. 1983).

The purpose of this paper is to give an overview of paleolimnological techniques for documenting the water quality history of a lake, and to describe how paleolimnological studies of two Vermont lakes contributed to decisionmaking regarding their management. This discussion is limited to the problem of nutrient enrichment, and the resulting eutrophication. Other practical applications of paleolimnology include (1) quantifying the impact of acid rain (Battarbee, 1984), (2) documenting pollution by heavy metals (Davis et al. 1983), and (3) quantifying erosion rates within a watershed (O'Sullivan et al. 1982).

PALEOLIMNOLOGICAL INDICATORS OF PAST WATER QUALITY

Accumulation Rate Versus Concentration

The usual way to express the results of paleolimnological analysis is as concentration in the sediment (e.g., phosphorus concentration as mg P per g dry matter). However, such data are highly vulnerable to the effects of dilution of the sediment matrix. For example, the phosphorus concentration of the sediment would go down if nutrient-poor subsoils were eroded into the lake. This dilution effect (which can be caused by the introduction of any diluting substance including the precipitation of marl) can be misleading if one is attempting to relate the concentration to past trophic state.

The problem of sediment matrix dilution can be avoided through expressing data as accumulation rate instead of as concentration. The effect of dilution is removed by calculating the parameter as accumulation per unit area per year (e.g., mg P cm^{-2} yr^{-1}). Expression of data as accumulation has great

advantages over concentration, but is heavily dependent upon the availability of detailed information about changes in the sediment accumulation rate. Sediment accumulation rate is calculated from loss-on-ignition data and dating.

Calculation of ratios of materials measured in lake sediments (for example, Fe/Mn or Fe/P) can also help avoid the pitfalls of concentration expressions. Common fossils are usually expressed as the percentage that a taxon makes up of the sum of that taxonomic group (for example, diatoms, pollen, cladocerans). A percentage is, of course, a type of ratio that is immune to dilution effects.

Loss-On-Ignition

After a core is obtained and split into discrete samples, the first analysis should be a loss-on-ignition series. Loss-on-ignition can be measured at 100°, 500°, and 1000°C to quantify the water, organic, and carbonate content of a sediment sample (Dean, 1974). Not only are all subsequent analyses dependent upon these data, but the stratigraphy usually reveals the stratum corresponding to the first activity by white settlers in the watershed. Settlement is usually marked by a decrease in the concentration of organic matter in the sediment, caused purely by dilution through erosion of soils. The accumulation rate of organic matter would reveal an increase at that time, caused not only by the introduction of the eroded soils but also by increased primary productivity.

Dating Indicators

The dating of the sediments is necessary in paleolimnology (1) to calculate accumulation rates, and (2) to assign dates to limnological changes documented in the core. It is best to use several dating methods, because each has its weaknesses, and agreement among several methods greatly strengthens the final conclusions of a study.

Lead-210. Lead-210 is unquestionably the most valuable tool for dating recent lake sediments (less than 150 years old). When the constant-rate-of-supply (c.r.s.) calculation model is used (Appleby and Oldfield, 1983), variations in the sediment accumulation rate can be detected and quantified. Other calculation models may assume a constant rate of sediment accumulation, which is a weak assumption if agriculture, road-building, or any construction project has occurred in the watershed.

Stable lead. A combination of factors (especially the 1973 oil embargo and decreased lead content of gasoline) produced a 1970–73 peak in lead consumed in gasoline in the United Sates (Fig. 1). This peak should be a useful dating horizon for lakes receiving highway runoff throughout the United States.

Cesium-137. Cesium-137 is introduced into the atmosphere only through atmospheric testing of nuclear weapons (it does not occur naturally). Because a worldwide peak in atmospheric testing occurred in 1963 (Pennington, 1981), many paleolimnologists have tried to use this horizon to obtain a sediment date. The technique, however, appears to have problems including (1) that cesium-137 may diffuse through lake sediments (Davis et al. 1983), (2) the identification of the cesium-137 peak is subjective, and (3) cesium-137 deposition was apparently very uneven geographically, and in fact was seldom measured (graphics portraying cesium-137 deposition are all estimated from measurements of strontium-90 deposition).

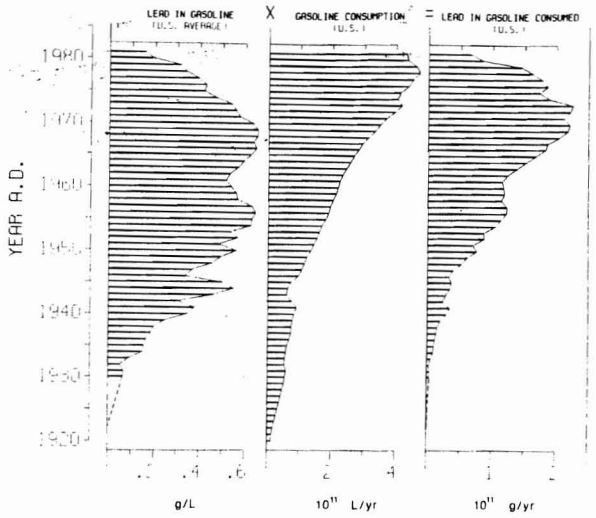

Figure 1.—Lead consumed in gasoline on U.S. highways, average by year (from Swain, 1984).

Carbon-14. Carbon-14 dating should be used only for sediment estimated to be at least 200 years old, not only because of confounding inputs of old carbon from fossil-fuel consumption since the industrial revolution, but also because the usual error associated with measurement is about 100 years. Therefore, an appropriate use of carbon-14 dating is to date the base of a surface core in order to estimate the sediment accumulation rate before human disturbance.

Pollen analysis. Analysis of the pollen preserved in lake sediments can identify sediment horizons associated with known vegetational changes, and thereby allow one to assign a date. Those changes that have proven useful in the paleolimnological analysis of recent lake sediments are: (1) The increase in ragweed pollen associated with settlement (1700's in the eastern United States and about 1800's in the Midwest), (2) the decline in chestnut pollen on the east coast after 1900, (3) increases in pollen associated with agricultural crops, and (4) declines in pollen resulting from known logging of a watershed (see Brugam, 1978b for examples).

Indicators unique to a given lake. Any known event documented in the lake sediment is valuable for dating, and there may be events unique to a given lake that prove useful. Such unique events might be (1) a landslide that carried large amounts of mineral soil into the lake (Staub, 1977), (2) a construction project within the watershed (Culver et al. 1981), or (3) unusual and identifiable materials that were added to the lake for some reason (Allott, 1978; Bradbury and Megard, 1972).

Productivity Indicators

In studies where the primary concern is reconstructing the history of the lake's trophic state, indicators of primary productivity are of obvious interest.

Diatom analysis. This is the most unambiguous way to reconstruct primary productivity. The silicaceous cell walls of diatoms usually preserve well in lake sediments, and are identifiable to species. The occurrence of certain diatom species can be indicative of water quality conditions. An experienced diatom analyst can reconstruct the trophic state his-

tory of a lake in qualitative terms quite easily from a stratigraphic diagram of diatom species. A major drawback is that the preparation of a diatom diagram is extremely time consuming.

A crude alternative to diatom analysis is the measurement of biogenic silica in a core. The silica produced by diatoms is chemically extracted as a measure of past diatom productivity (Engstrom and Wright, 1984). Biogenic silica data are vulnerable to dilution effects unless calculated as accumulation rate, whereas diatom identifications reveal a qualitative history of productivity regardless of dilution effects.

Algal pigments. Stratigraphic shifts in the concentration of chlorophyll and carotenoids have often been interpreted as representing shifts in primary productivity (e.g., Wetzel, 1970; Sanger and Gorham, 1972). Pigments are particularly susceptible to dilution effects, and are most meaningful when expressed as accumulation rates (Swain, in press). Algal pigments are better preserved under low oxygen conditions, so increased pigment accumulation may reflect increased primary productivity, increased hypolimnetic oxygen depletion, or both. Analysis of pigments unique to blue-green algae (e.g., oscillaxanthin is a pigment unique to the Oscillatoriaceae) can detect the shift to dominance by blue-green algae that usually occurs during the eutrophication process (Swain, in press).

Phosphorus. Sedimentary phosphorus is difficult to correlate with past productivity because phosphorus is mobile in sediments under some conditions (notably anoxic conditions). Because sediments become anoxic as they are buried by additional sediment, phosphorus can migrate continuously upward, yielding a misleading peak at the mud–water interface (Engstrom and Wright, 1984). However, lakes that experience gross changes in phosphorus loading may preserve that qualitative history in the sediment stratigraphy (e.g., Shapiro et al. 1970).

Zooplankton. Zooplankton remains can be used to reconstruct the history of the cladoceran community in a lake. Two phenomena are associated with eutrophication: (1) an increase in the percentage of *Chydorus sphaericus* and (2) a shift from large to small-bodied cladocerans during eutrophication. Although extremely common in the littoral zone, most chydorid cladocerans are not common in cores from the center of lakes. *Chydorus sphaericus* is thought to increase with eutrophication because of rafting on blue-green algal colonies from its littoral habitat. The shift from large to small-bodied cladocerans with eutrophication probably occurs because of the loss of a hypolimnetic refuge from zooplanktivorous fish (but see Porter and McDonough, 1984). This size shift may therefore actually indicate shifts in the hypolimnetic oxygen regime, albeit indirectly.

Hypolimnetic Oxygen Indicators

In a given lake, hypolimnetic oxygen concentration is proportional to primary productivity unless organic substances with biological oxygen demand (BOD) are introduced into the lake. In addition, the onset of sedimentary anoxia allows internal loading of phosphorus, a major component of the eutrophication process. For these reasons, paleolimnological reconstruction of the history of a lake's hypolimnetic oxygen regime is extremely valuable.

Larval midge remains. Midge larvae are among the few organisms that live in the profundal zone whose taxonomy can reveal a history of hypolimnetic oxygen concentrations. However, analysis is laborious and interpretation is not straightforward (see Brugam, 1983a).

Redox-sensitive metals: iron and manganese. Mackereth (1966) first proposed a scheme to reconstruct the profundal oxygen concentration from the sediment stratigraphy of iron and manganese, which are both more mobile under low oxygen conditions. Generally, one assumes that both iron and manganese concentrations are lower in strata laid down during periods of low profundal oxygen concentration because of mobilization out of the sediments. However, interpretation is complicated (Engstrom and Wright, 1984) and in some cases may be opposite to that proposed by Mackereth (Engstrom et al. in press).

Sulfide. The major source of hydrogen sulfide in a lake is the reduction of sulfate in an anoxic hypolimnion. A portion of this sulfide will be preserved in the sediments as iron sulfide. There is no other major pathway for sulfur to precipitate except in saline lakes where gypsum ($CaSO_4$) can precipitate. Sulfide (or just total sulfur) should therefore be an excellent indicator of past anoxic conditions in a lake (e.g., Culver et al. 1981).

Algal pigments. Because algal pigments preserve much better under anoxic conditions, they have the potential to be excellent indicators of past oxygen conditions. Currently, the best index of pigment preservation is "percent native chlorophyll," the percentage of chlorophyll that has not degraded to pheopigments (Swain, in press).

PALEOLIMNOLOGICAL STUDIES ON TWO VERMONT LAKES

The paleolimnological techniques previously described can be used to provide information useful in lake diagnostic studies. Studies on two Vermont lakes illustrate the value of paleolimnology in lake management.

Harvey's Lake

Harvey's Lake is a large, deep lake with a surface area of 156 ha and a maximum depth of 44 m, located in northeastern Vermont (see Fig. 2). Most (71 percent) of the 2,024 ha drainage basin is forested, but a significant portion (20 percent) of the watershed is devoted to agricultural use. The lake itself is used primarily for recreation, with about 100 private cottages located along the lakeshore and an additional 120 campsites available at two private campgrounds. The lake supports a coldwater fishery composed of lake trout and rainbow trout.

Harvey's Lake is a mesotrophic lake. Spring phosphorus levels averaged 14 mg/m^3 during 1977–83 (Warren, 1984). Summer chlorophyll *a* levels averaged 4.6 mg/m^3, and Secchi disk transparency averaged 5.9 m. A significant hypolimnetic oxygen deficit develops in the lake during summer stratification, but anoxic conditions have never been observed. Oxygen concentrations in the upper portion of the hypolimnion remain high enough to provide adequate coldwater habitat for trout.

Concern over possible water quality deterioration in Harvey's Lake began in the mid-1970's with the discovery of a metalimnetic population of the blue-green alga *Oscillatoria rubescens*. Subsequent studies showed that the phytoplankton community in Harvey's Lake is overwhelmingly dominated by

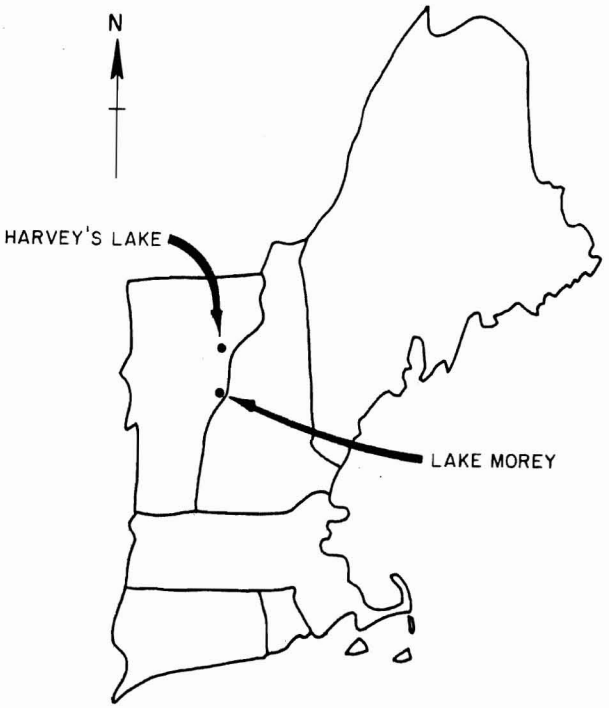

Figure 2.—Location map showing Harvey's Lake and Lake Morey, Vermont.

Oscillatoria, which composes more than 90 percent of the total algal biomass during the summer. The presence of *Oscillatoria rubescens* is often characteristic of a lake in transition from an oligotrophic to a eutrophic state as a result of excessive nutrient enrichment. Numerous examples exist in Europe and North America of deep, clear lakes in which nutrient input from sewage discharges, agricultural runoff, and other sources have resulted in the appearance of this alga, later followed by serious water quality problems (Edmondson, 1966; Ravera and Vollenweider, 1968; Jaag, 1973; Fricker, 1980; Skulberg, 1980).

The implications of the *Oscillatoria* presence in Harvey's Lake prompted the State of Vermont to undertake a diagnostic-feasibility study of the lake under the Federal Clean Lakes Program (Enright and Smeltzer, 1983). In the process of conducting this study, however, questions arose as to whether the *Oscillatoria* presence in Harvey's Lake did, in fact, indicate that the lake was in transition to a more eutrophic state. The lack of long-term historical water quality data on the lake made it difficult to determine whether the *Oscillatoria* presence was the result of recent nutrient enrichment and changing water quality, or whether the lake has had a naturally-occurring *Oscillatoria* population for centuries. The desire to avoid unnecessary lake restoration activities prompted a paleolimnological study on Harvey's Lake to resolve this issue.

The results of the Harvey's Lake paleolimnological study are described in detail in Engstrom et al. (in press). A sediment core approximately 70 cm in length was obtained from the deepest portion of the lake. Sediment chronology was determined primarily by the lead-210 and carbon-14 techniques, with corroboration of the lead-210 results by stratigraphic analysis of cesium-137, pollen, and sawmill wastes. The core was also analyzed by Engstrom et al. for a variety of water quality indicators, and their results are summarized in Figure 3.

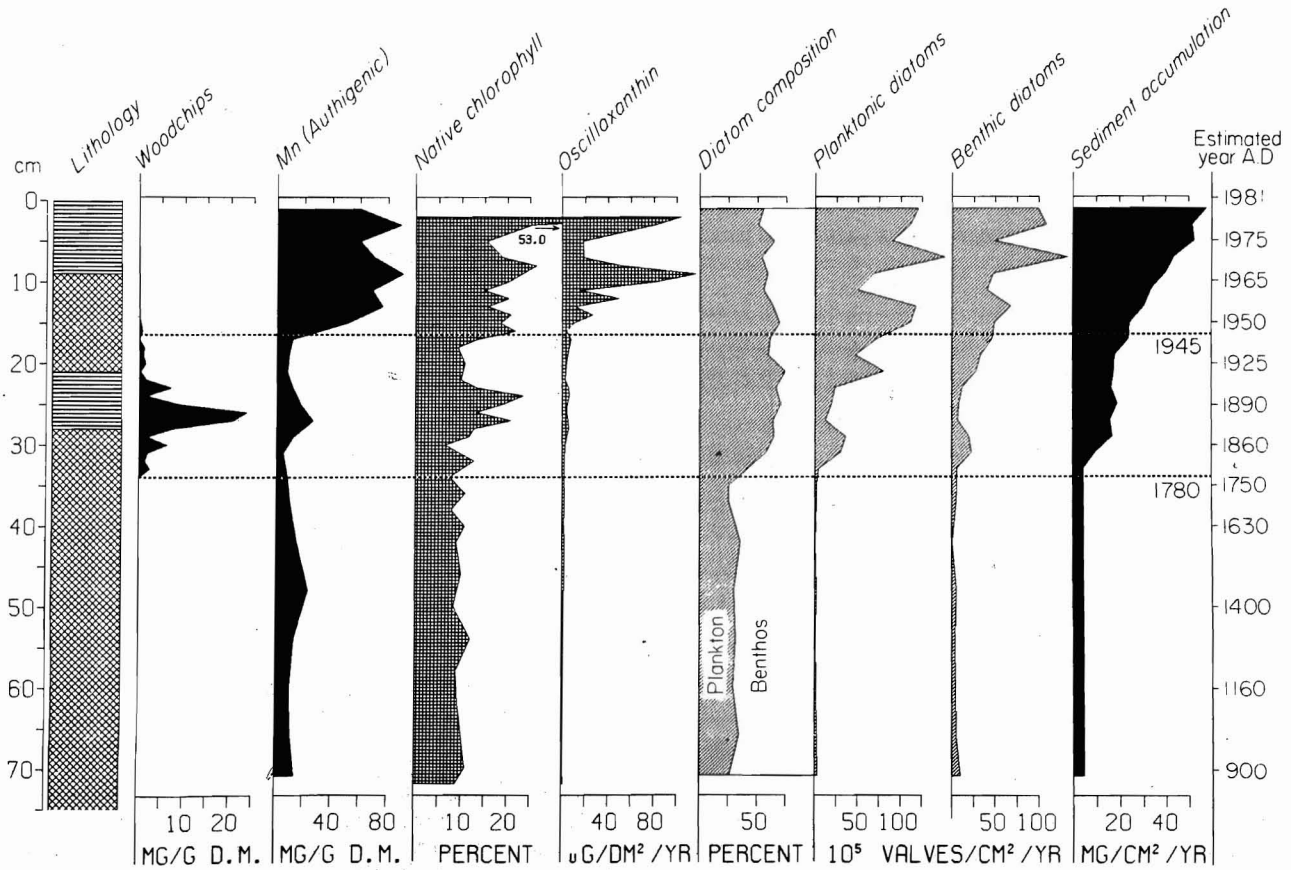

Figure 3.—Paleolimnological results for Harvey's Lake (from Engstrom et al. in press).

Figure 3 shows that water quality conditions in Harvey's Lake during the pre-settlement period were highly stable, and characterized by relatively low accumulation rates of sediment, diatom frustules, and algal pigments. Engstrom et al. (in press) attributed the sharp increases in the accumulation rates of these materials observed around 1780 to the arrival of the first colonial settlers and the erosion and nutrient runoff associated with land clearing. An increase in lake productivity apparently occurred at this time, as indicated by higher rates of diatom and algal pigment accumulation, and by a shift toward planktonic diatom species.

The discharge of oxygen-demanding sawmill waste into the lake during the period of about 1780–1920 was associated with increased hypolimnetic oxygen depletion, as indicated by the appearance of laminated sediments, greater maganese deposition, and an increased percentage of native chlorophyll preserved in the sediments (see Fig. 3). However, the primary productivity indicators were unaffected by the sawdust discharge.

The most striking feature of the results obtained by Engstrom et al. (in press) was the sudden appearance, after about 1945, of large concentrations of the pigment oscillaxanthin. Their results strongly indicate that a significant shift towards greater eutrophication has occurred in Harvey's Lake since 1945. Not only did *Oscillatoria* first appear in abundance at this time, but sediment accumulation also accelerated, primary productivity increased (as indicated by greater diatom and algal pigment accumulation), and hypolimnetic oxygen depletion became more severe (as indicated by increased manganese deposition, greater native chlorophyll preservation, the reappearance of laminated sediments, and historical water quality data.

The major cause for these water quality changes in Harvey's Lake since 1945 is probably nutrient runoff from agricultural activities. The diagnostic studies on the lake (Enright and Smeltzer, 1983) showed that the chief cultural source of phosphorus to the lake is runoff from dairy farms within the lake's watershed and from an adjacent watershed intermittently directed into Harvey's Lake by the dam controlling the lake's outlet. While the amount of agricultural land in these two watersheds has not increased since 1945, the methods of farming have changed significantly. Greater mechanization on the farms has permitted more efficient tillage and manure spreading, and larger herd sizes. Inorganic chemical fertilizers have been used widely in the watershed only in recent decades. These changes in the intensity of farmland use probably account for the water quality degradation in the lake observed since 1945.

Convinced by the historical and paleolimnological evidence that water quality in Harvey's Lake has deteriorated substantially in recent years, the State of Vermont is actively pursuing a restoration project on the lake. The project will involve diversion of nutrient-enriched runoff and improved farm management practices.

Lake Morey

Lake Morey is a large, relatively shallow lake with a surface area of 220 ha and a maximum depth of 13.1 m, located in eastern Vermont (see Fig. 2). Almost the entire drainage basin (92 percent) is forested, but the immediate shoreline is heavily developed with about 120 lakeshore homes, three resort inns, two summer children's camps, and one outdoor recreation center. The lake supports a warmwater fishery composed primarily of largemouth and smallmouth bass.

Lake Morey is a fairly eutrophic lake. Spring phosphorus levels averaged 38 mg/m^3 during 1977–1983 (Warren, 1984). Summer chlorophyll *a* concentrations averaged about 10 mg/m^3, and average Secchi disk transparency was 4.2 m. Severe hypolimnetic oxygen depletion occurs during the summer, usually to the point of anoxia.

The recreational use of Lake Morey is periodically impaired by extensive algal blooms, composed of blue-green algae such as *Anabaena* and *Aphanizomenon*, or the dinoflagellate *Ceratium*. Planning efforts by local citizens to construct a sewer line and treatment plant serving the lake prompted the State of Vermont to undertake a diagnostic-feasibility study of Lake Morey under the Federal Clean Lakes Program. The results of the diagnostic work (Morgan et al. 1984) indicate that internal phosphorus loading from the hypolimnetic sediments, rather than nutrient inputs from septic systems, is the major cause of the algae blooms.

A variety of factors contribute to the extensive internal phosphorus recycling in Lake Morey, as discussed by Walker (1983). Two-thirds of the lake area is deeper than 8 m, the depth of the hypolimnion surface. Thus, extensive areas of sediment are exposed to oxygen-deficient water and reducing conditions at the sediment–water interface. Phosphorus released from the sediments under these reducing conditions during the summer tends to remain in the water column through fall overturn and the following winter, probably as a result of low iron concentrations in Lake Morey and the lack of an effective phosphorus reprecipitation mechanism. The low iron levels may be related to a high sulfate concentration in the lake and the resulting precipitation of iron sulfide.

It was clear from the diagnostic work on Lake Morey that elimination of the algal blooms would require control of the internal phosphorus loading. Quantitative evaluation of external phosphorus inputs from surface inflows and from shoreline septic systems via groundwater showed that the phosphorus loading rate from external sources was low enough to preclude serious algal blooms in the absence of extensive internal phosphorus recycling. Feasibility studies conducted by Booker Associates (1983) indicated that treatment of the lake with aluminum sulfate (alum) would be the most cost-effective means to limit the internal loading.

It was not obvious, however, whether the internal phosphorus recycling situation in Lake Morey was a natural one, or whether it was related to some past period of pollution. The morphological and chemical factors of extensive hypolimnetic sediment area and low iron levels could have naturally predisposed the lake to an internal phosphorus recycling problem. On the other hand, there was a period in the lake's history beginning around 1880, and culminating around 1920, in which nearly all of the existing shoreline development took place. It was possible that the lake directly received much of the sewage generated by the numerous private homes and large resort inns during this period before proper septic systems were the rule.

The question of whether the internal phosphorus loading in Lake Morey was naturally or culturally induced was an important one in evaluating the effectiveness of an alum treatment. Post-treatment evaluations of alum applications (Cooke and Kennedy, 1981; Garrison and Knauer, 1984) have shown that long-

term success has been possible when external phosphorus sources were adequately controlled. Treatment failures have occurred, however, when watershed sources were not reduced, or when other lake characteristics contributing to internal recycling were not considered. There was no historical limnological data available on Lake Morey to assess water quality conditions prior to the 1880–1920 period of shoreline development. Consequently, a paleolimnological study offered the only means to determine the historical cause of the internal phosphorus loading situation in the lake.

As part of the diagnostic study of Lake Morey, a sediment core about 80 cm in length was obtained from the deepest portion of the lake. Sediment chronology was determined by Brugam (1983b) using lead-210 dating. Samples from 25 levels in the core were analyzed for several water quality indicators. Sediment geochemistry was analyzed by D. Engstrom. The results of the paleolimnological study on Lake Morey are described in detail in Morgan et al. (1984) and summarized in Figure 4.

Figure 4 shows that limnological conditions in Lake Morey were quite stable prior to about 1900. During the next few decades, however, major changes occurred, corresponding with the period of intense residential and commercial development of the lakeshore. The sediment accumulation rate rose to a sharp peak about 1920–1925, while the sediment organic content dropped, suggesting that extensive erosion of mineral soils was taking place. The chlorophyll accumulation rate also peaked about 1920–1925, indicating increased algal production, better pigment preservation conditions, or both. Hypolimnetic oxygen indicators also showed changes at this time. Concentrations of iron and manganese in the sediments increased, possibly as a result of oxygen depletion and changing redox conditions leading to mobilization and redeposition of these metals in the deeper sediments, as hypothesized by Engstrom et al. (in press). Chlorophyll preservation, indicated by percent native chlorophyll, increased after 1920, also suggesting that hypolimnetic oxygen depletion became more severe following the development of the lakeshore.

Water quality indicators in the sediments showed improvements after 1925, presumably as a result of revegetation of disturbed shoreland soils and better means of waste disposal. However, conditions have never returned to the pre-1900 baseline levels. The recent increase in sediment and chlorophyll accumulation rates since 1970 may be attributable to the construction of Interstate Highway 91 within the watershed during 1970–1972. Erosion of nutrients from excavated areas, and leaching of sulfate from the rock fill may have accelerated phosphorus recycling and eutrophication in the lake once again.

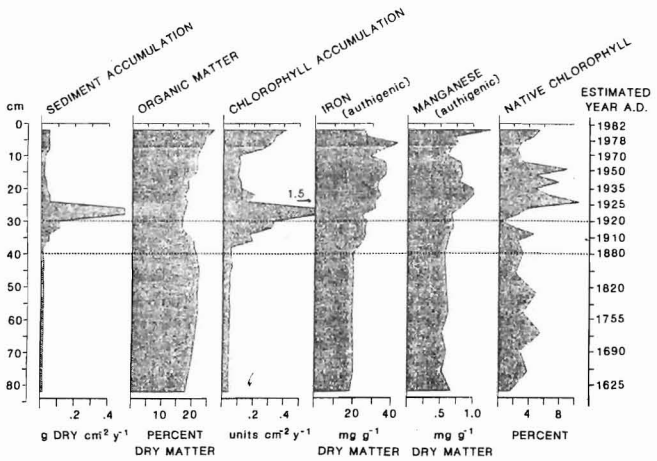

Figure 4.—Paleolimnological results for Lake Morey.

The paleolimnological results on Lake Morey suggest that the eutrophication problem in the lake began with the brief but intense period of development in the early 1900's. It is reasonable to suppose that erosion from uncontrolled land clearing, combined with the discharge of poorly treated wastewater, enriched the lake and its sediments with phosphorus that has been recycled internally ever since. This extensive internal recycling has been maintained even in the absence of continued excessive phosphorus loading from the watershed.

These results supported the proposal to treat the hypolimnetic sediments with alum in an effort to deactivate the historical phosphorus load, and allow the lake to attain a new trophic state more closely related to present day phosphorus loading rates from the watershed. The paleolimnological results were influential in the decision by the State of Vermont to actively pursue an alum treatment project for Lake Morey, with the expectation that long-term water quality benefits would result from the treatment.

CONCLUSIONS

The Harvey's Lake and Lake Morey cases demonstrate that paleolimnology can be a valuable tool in lake management. In both cases, a long-term historical water quality perspective was needed to assist in decision-making regarding the choice of appropriate lake restoration measures. Historical limnological data were lacking, and paleolimnological study offered the only means to address important lake management questions. While the specific management questions will vary from lake to lake, we believe that the paleolimnological techniques illustrated here will prove useful in a variety of applications.

REFERENCES

Allott, N. 1978. Recent paleolimnology of Twin Lake near St. Paul, Minnesota, based on a transect of cores. Master's Thesis. Univ. Minnesota, Minneapolis.

Appleby, P. G., and F. Oldfield. 1983. The assessment of 210 Pb data from sites with varying sediment accumulation rates. Hydrobiologia 103:29–35.

Battarbee, R. W. 1984. Diatom analysis and the acidification of lakes. Phil. Trans. R. Soc. Lond. B. 305:451–77.

Booker Associates. 1983. Lake Morey feasibility study of hypolimnetic aeration and alum treatment. Prep. for Vt. Dep. Water Resour. Environ. Eng.

Bradbury, J. P., and R. O. Megard. 1972. The stratigraphic record of pollution in Shagawa Lake, northeastern Minnesota. Geol. Soc. Am. Bull. 83:2639–48.

Brugam, R. B. 1978a. Human disturbance and the historical development of Linsley Pond. Ecology 59:19–36.

———. 1978b. Pollen indicators of land-use change in Southern Connecticut. Quarternary Res. 9:349–62.

———. 1983a. Holocene Paleolimnology. *In* H. E. Wright, Jr., ed. Late-Quarternary Environments of the United States. Vol. II. University of Minnesota Press, Minneapolis.

———. 1983b. Lead-210 analysis of Lake Morey sediment. Prep. for Vt. Dept. Water Resour. Environ. Eng.

Cooke, G. D., and R. H. Kennedy. 1981. Precipitation and inactivation of phosphorus as a lake restoration technique. EPA-600/3-81-012. U.S. Environ. Prot. Agency. Washington, D.C.

Culver, D. A., R. M. Vaga, C. S. Munch, and S. M. Harris. 1981. Paleoecology of Hall Lake, Wash.: A history of meromixis and disturbance. Ecology 62:848–63.

Davis, R. B., S. A. Norton, C. T. Hess, and D. F. Brakke. 1983. Paleolimnological reconstruction of the effects of atmospheric deposition of acids and heavy metals on the chemistry and biology of lakes in New England and Norway. Hydrobiologia 103:113–23.

Dean, W. E. Jr. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods. J. Sediment. Petrol. 44:242–48.

Edmondson, W. T. 1966. Changes in the oxygen deficit of Lake Washington. Verh. Int. Ver. Limnol. 16:153–58.

Engstrom, D. R., and H. E. Wright, Jr. 1984. Chemical stratigraphy of Lake sediments as a record of environmental change. *In* E. Y. Haworth and J. W. G. Lund, eds., Lake Sediments and Environmental History. Leicester University Press.

Engstrom, D. R., E. B. Swain, and J. C. Kingston. In press. A paleolimnological record of human disturbance from Harvey's Lake, Vermont: Diatoms, pigments, and geochemistry. Freshw. Biol.

Enright, K., and E. Smeltzer. 1983. Harvey's Lake diagnostic-feasibility study final report. Vt. Dept. Water Resour. Environ. Eng.

Fricker, Hj. 1980. OECD Eutrophication Program. Regional Project. Alpine Lakes. Swiss Fed. Board Environ. Prot. Bern.

Garrison, P.J., and D. R. Knauer. 1984. Long-term evaluation of three alum-treated lakes. Pages 513-8. *In* Lake and Reservoir Management. Proc. Third Annu. Conf. N. Am. Lake Manage. Soc. EPA-44/5-84-001. U.S. Environ. Prot. Agency. Washington, D.C.

Jaag, O. 1973. *Oscillatoria rubescens* D.C. Pages 296-9 *in* T.V. Desikachary, ed. Proc. Symp. Taxon. Bio. Blue-Green Algae. Univ. of Madras Press.

Mackereth, F. J. H. 1966. Some chemical observations on post-glacial lake sediments. Phil. Trans. R. Soc. London B. 250:165–213.

Morgan, J., T. Moye, E. Smeltzer, and V. Garrison. 1984. Lake Morey diagnostic-feasibility study final report. Vt. Dept. Water Resour. Environ. Eng.

O'Sullivan, P. E., M. A. Coard, and D. A. Pickering. 1982. The use of laminated lake sediments in the estimation and calibration of erosion rates. Pages 385–96 *in* Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield. IAHS Publ. 137. Proc. Exeter Sym., 1982.

Pennington, W. 1981. Records of a lake's life in time: The sediments. Hydrobiologia 79:197–219.

Porter, K. G., and R. McDonough. 1984. The energetic cost of response to blue-green algal filaments by cladocerans. Limnol. Oceanogr. 29:365–69.

Ravera, O., and R. A. Vollenweider. 1968. *Oscillatoria rubescens* D.C. as an indicator of Lago Maggiore eutrophication. Schweiz. Z. Hydrol. 30:374–80.

Sanger, J. E., and E. Gorham. 1972. Stratigraphy of fossil pigments as a guide to the postglacial history of Kirchner Marsh, Minnesota. Limnol. Oceanogr. 17:840–54.

Shapiro, J., W. T. Edmondson, and D. E. Allison. 1970. Changes in the chemical composition of sediment of Lake Washington 1958–1970. Limnol. Oceanogr. 16:437–52.

Shapiro, J., and E. B. Swain. 1983. Lessons from the silica "decline" in Lake Michigan. Science 221:457–59.

Skulberg, O. M. 1980. Blue-green algae in Lake Mjosa and other Norwegian lakes. Prog. Water Tech. 12:121–40.

Smol, J. P., S. R. Brown, and R. N. McNeely. 1983. Cultural disturbances and trophic history of a small meromictic lake from central Canada. Hydrobiologia 103:125–30.

Staub, E. 1977. Stratigraphy of diatoms and chlorophyll derivatives in the uppermost sediments of a Swiss lake. Pages 161–164 *in* H. L. Golterman, ed. Interactions between Sediments and Freshwaters. Junk and Pudoc, The Hague.

Swain, E. B. 1984. The paucity of blue-green algae in meromictic Brownie Lake: Iron limitation or heavy metal toxicity? Ph.D. Thesis. Univ. Minnesota, Minneapolis.

———. In press. Measurement and interpretation of sedimentary pigments. Freshw. Biol.

Walker, W. W. 1983. Data analysis and model development for the Lake Morey 314 diagnostic study. Prep. for Vt. Agency Environ. Conserv.

Warren, S. 1984. 1983 Vermont Lay Monitoring Report. Volume II. Water Quality Surveillance Series. Rep. No. 13. Vt. Agency Environ. Conserv.

Wetzel, R. G. 1970. Recent and postglacial production rates of a marl lake. Limnol. Oceanogr. 15:491–503.

LAKE AND RESERVOIR MANAGEMENT: PRACTICAL APPLICATIONS

Proceedings of the

Fourth Annual Conference and International Symposium

October 16–19, 1984
McAfee, New Jersey

North American Lake Management Society

1985