

A Successful Alum/Aluminate Treatment of Lake Morey, Vermont

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ABSTRACT

Lake Morey, Vermont provides a case history of a successful lake restoration effort. Decades of algal blooms and a major summer fish kill preceded a hypolimnetic alum and sodium aluminate treatment in 1986. Earlier diagnostic studies with paleolimnological analyses and a detailed phosphorus budget revealed the cause to be internal phosphorus loading from anoxic hypolimnetic sediments. The aluminum treatment of these sediments resulted in sharp declines in total phosphorus and chlorophyll *a* concentrations, and increased Secchi transparency. The dose rate of 44 g Al/m² appears to have been sufficient to form an effective barrier to sediment phosphorus release, and improved conditions continue to persist after four years. Elevated dissolved aluminum levels and some possible adverse effects on the benthic invertebrates and the yellow perch population were temporarily observed following the treatment. The apparent success of the project in controlling phosphorus concentrations is the result of an accurate diagnosis of sediment release as the dominant source of phosphorus and the appropriate use of aluminum treatment to inhibit release.

Introduction

Treatment of lakes with aluminum salts for phosphorus precipitation or inactivation was recognized in the early 1970s as a potentially useful lake restoration technique (Dunst et al. 1974). Since then, a large variety of lakes have been treated with alum (aluminum sulfate), sometimes in combination with sodium aluminate, and the record includes many successes and some failures (Cooke and Kennedy, 1981). The technique continues to be popular, as evidenced by the fact that 30 percent of all lake restoration projects funded under the federal Clean Lakes Program in fiscal year 1987 used this method (N. Am. Lake Manage. Soc. 1988). Most of the recent projects have been aimed at achieving long-term suppression of internal phosphorus loading from lake sediments by forming an aluminum hydroxide floc layer on the bottom, rather than short-term phosphorus precipitation from the water column.

There have been several critical reviews of the long-term effects of lake aluminum treatments. Cooke and Kennedy (1981) examined a number of well-documented projects and found that the treatment could last for several years at least, if external phosphorus sources were controlled and a dose rate sufficient to form flocs was used. Garrison and Knauer (1984) reported that internal phosphorus loading was suppressed by alum floc layers for up to 12 years in two lakes with stable summer thermal stratification patterns. Long-term treatment effectiveness was compromised in a third lake where frequent mixing redistributed the floc. Welch et al. (1988) found that alum treatments of shallow, unstratified lakes often succeeded for more than one year, apparently because substantial phosphorus release from littoral sediments was suppressed during brief summer episodes of sediment surface anoxia at high temperature and pH.

In spite of the large number of treatments conducted to date and the review efforts cited, Cooke et

al. (1986) noted that major gaps exist in our knowledge about this technique. More lake treatments need to be monitored to determine whether long-term effectiveness can be generally expected. No good basis exists for determining the aluminum dose rate to the sediments required to achieve long-term control of internal phosphorus loading. While few adverse biological effects have been reported to result from these treatments, the potential for long-term toxic effects at a variety of trophic levels needs to be better examined.

This paper presents an evaluation of the alum/aluminate treatment of Lake Morey, Vermont to provide knowledge in these areas. The lake was the subject of intensive studies before and after the 1986 treatment to document water quality and biological effects. Long-term monitoring of eutrophication levels in the lake began in 1977 and has continued through four summer seasons since the treatment. Lake Morey provides a case history of a successful lake restoration effort, at least for the first several years; the limnological reasons for the success will be discussed.

Lake Description and Study Methods

Lake Morey (Fig. 1) is a large, relatively shallow lake with a surface area of 220 ha, a mean depth of 8.4 m, and a maximum depth of 13 m, located in east central Vermont. The mountainous, 1,900 ha drainage basin is predominantly (92 percent) forested, with dense development along the shoreline, including 120 homes, three resort inns, and two summer children's camps. Spring total phosphorus concentrations in Lake Morey prior to the aluminum treatment averaged a eutrophic 37 $\mu\text{g/L}$. Decades of algal blooms involving blue-greens and other algal groups and a major summer fish kill in 1985 seriously impaired the recreational use of the lake.

Public concern for water quality conditions in Lake Morey became evident in the early 1970s. It was initially assumed that phosphorus contributed by shoreline septic systems was causing the algal blooms, and planning began for a \$3 million sewer line and wastewater treatment plant to serve the lake community. Before the sewer planning was completed, however, the community recognized the need for more detailed understanding of the phosphorus dynamics in Lake Morey; a federal Clean Lakes Program diagnostic-feasibility study of the lake was initiated in 1980.

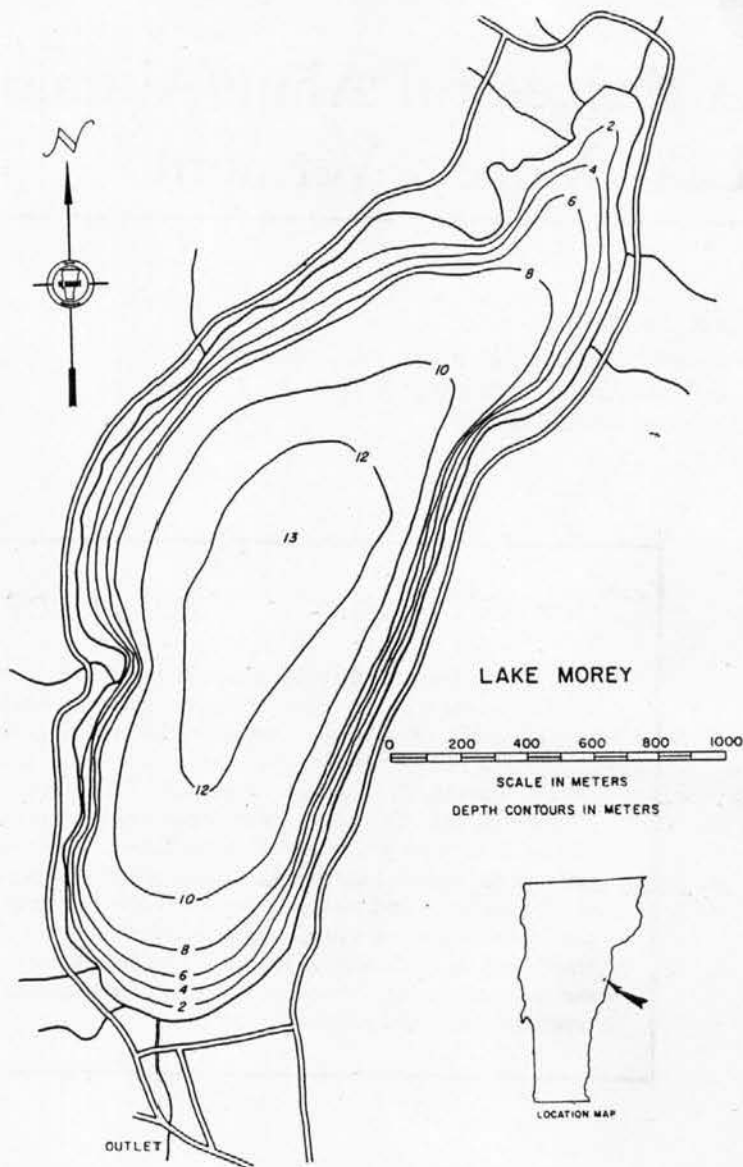


Figure 1.—Bathymetric map of Lake Morey.

The methods used in the diagnostic-feasibility study are described in detail in Morgan et al. (1984). A phosphorus budget was developed for the lake based on direct measurements of tributary loading and phosphorus inputs from groundwater, septic systems, and direct precipitation. Phosphorus loading data were obtained for the nine major tributary streams and the lake's outlet during 1981 and 1982. The necessary hydrologic data were developed from a network of continuous flow gages on four of the tributary streams, covering 55 percent of the total lake drainage area, supplemented with weekly instantaneous flow measurements at the other five inlets. Inter-gage correlations and unit area runoff calculations were used to estimate daily flows at the mouths of all nine tributaries throughout the study period.

Phosphorus loading rates from all nine tributaries were calculated using the flow-interval method (Verhoff et al. 1980; Walker, 1983), based on weekly total phosphorus sampling at each site and more frequent sampling during high flow periods. The individual tributary loading estimates had coefficients of variation ranging from 7 to 25 percent (Walker, 1983).

Groundwater and septic system phosphorus loading estimates were based on field data derived from monitoring wells, seepage meters, and piezometers. Bulk precipitation collectors were used to measure atmospheric phosphorus inputs to the lake surface.

Lake Morey was sampled at a central lake station during 1981-82 for a variety of limnological variables at 1-meter depth intervals throughout the water column. Chemical analyses were conducted according to U.S. Environmental Protection Agency (1983) and Standard Methods (1981). Sampling frequency varied from weekly to monthly, depending on the variable and the time of year. A comparable lake monitoring program was conducted during 1986 and 1987 following the aluminum treatment.

Long-term eutrophication monitoring has also been conducted on Lake Morey every year since 1977 by the state of Vermont. The long-term programs involve spring total phosphorus, summer chlorophyll a , and summer transparency. Spring phosphorus is analyzed on a single date each year during the turnover period on a vertically integrated sample of the entire water column. Summer chlorophyll a and Secchi disk monitoring is conducted weekly during June through August, with chlorophyll a analyses determined on vertically integrated samples obtained to a depth of twice the Secchi depth at the time of sampling.

Diagnostic Study Results

The phosphorus budget for Lake Morey is summarized in Table 1, based on Morgan et al. (1984), Walker (1983), and Wagner, Heindel, and Noyes, Inc. (1983). It was immediately apparent from the phosphorus budget calculations that septic system inputs via groundwater flow were not a significant lakewide source of phosphorus to Lake Morey. Tributary inflow was the major external phosphorus source. However, phosphorus export rates from the nine monitored sub-watersheds were low, in the range of 0.07 - 0.36 kg/ha-yr, with one minor exception. Since these low export rates are characteristic of undeveloped, forested watersheds (Reckhow and Chapra, 1983), it appeared unlikely that excessive phosphorus loading from human influences in the watershed was causing eutrophication problems in Lake Morey.

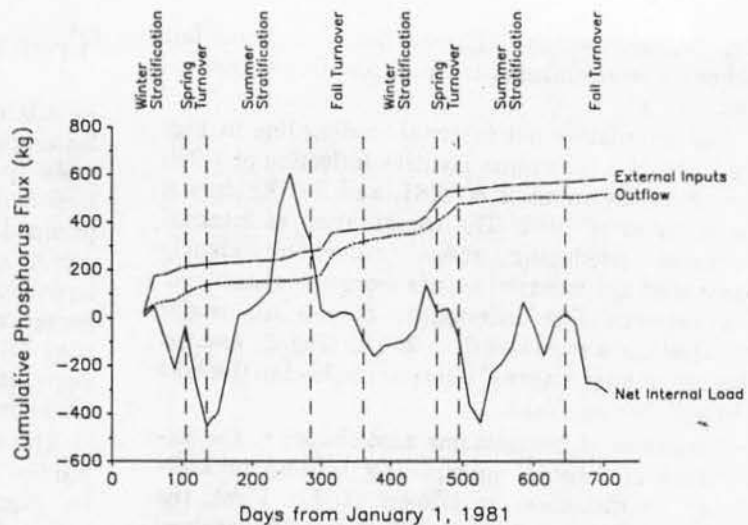


Figure 2.—Cumulative phosphorus flux rates in Lake Morey during 1981-82 (after Walker, 1983).

Table 1.—Total phosphorus budget for Lake Morey showing average flux rates over the period of February 1981 through December 1982. Values in parentheses are percentages of total inputs.

| | KG/YR | PERCENT |
|--|-------|---------|
| INPUTS | | |
| Tributaries | 295 | (87) |
| Groundwater (including septic systems) | 3 | (1) |
| Precipitation | 40 | (12) |
| Total Inputs | 338 | (100) |
| OUTFLOW | | |
| | 291 | (86) |
| NET RETENTION | | |
| | 47 | (14) |

The low phosphorus retention coefficient (14 percent, Table 1) suggested that internal loading was significant. The dominance of internal loading in the lake's phosphorus dynamics was confirmed by transient mass balance calculations (Walker, 1983). Phosphorus inputs, outflow loss, change in lake storage, and net internal load (residual term) were calculated for each 15-day interval. The cumulative phosphorus flux terms over the 1981-82 period are plotted in Figure 2, beginning at an arbitrary starting value of zero on February 14, 1981. Runoff periods with high phosphorus loading from the watershed are indicated by steep positive steps in the external input line. Periods of net internal phosphorus release are indicated by a positive slope of the cumulative net internal loading line. Negative internal loading slopes correspond to periods of net phosphorus sedimentation.

Figure 2 shows that internal processes were of much greater magnitude in Lake Morey than external inputs or outflow losses. There was also a clear seasonal pattern to the internal loading. Internal phosphorus release occurred during the summer

stratification periods, whereas the spring and fall turnovers were times of net phosphorus sedimentation.

The cumulative net internal loading line in Figure 2 shows a maximum positive inflection of 1,060 kg during the summer of 1981, and 507 kg during the summer of 1982. The combination of internal processes producing these inflections clearly dominated the external inputs from the watershed. The external flux increments during the major runoff seasons were less than 200 kg (Fig. 2), and the average annual external phosphorus load to the lake was only 338 kg (Table 1).

A number of mechanisms contributed to the importance of internal phosphorus loading in Lake Morey, as discussed by Walker (1983). First, the stable summer thermal stratification and dissolved oxygen depletion to the point of anoxia throughout the hypolimnion created reducing conditions favorable for phosphorus release from the hypolimnetic sediments. The importance of phosphorus release from anoxic hypolimnetic sediments was magnified by the unusual hypsographic relationship in Lake Morey, with two thirds of the lake's total sediment area occurring below the 8-meter hypolimnion depth (see Fig. 1). Other contributing factors included a low hypolimnetic iron/phosphorus mass ratio, possibly related to high sulfide concentrations and precipitation of iron sulfide. As a consequence, relatively little phosphorus could be removed by the iron phosphate precipitation mechanism during fall turnover. Furthermore, Lake Morey sediments had the highest laboratory anaerobic phosphorus release rates among 57 lakes measured by Ostrofsky et al. (1989).

An important historical perspective on the internal phosphorus loading problem in Lake Morey was gained through paleolimnological studies (Smeltzer and Swain, 1985). A dated sediment core from the lake indicated that accelerated cultural eutrophication occurred at the time the lakeshore was developed for resort inns and private homes in the early 1900s. Erosion from land clearing and poor wastewater disposal practices apparently delivered a phosphorus load from which the lake has never fully recovered. Internal phosphorus recycling has maintained a eutrophic state in Lake Morey in spite of the subsequent abatement of excessive loading from human activities in the watershed. These paleolimnological findings influenced Vermont's decision to pursue a sediment nutrient inactivation treatment, with the expectation that a one-time treatment would chemically seal off the historical phosphorus residue and improve the lake's trophic state to a level more consistent with its present-day phosphorus loading rates.

Treatment

Feasibility studies for control of internal phosphorus loading in Lake Morey evaluated a variety of techniques including nutrient inactivation, *in situ* hypolimnetic aeration, hypolimnetic aeration by pumped withdrawal, and total destratification (Morgan et al. 1984; Booker Assoc. 1983). Although the hypolimnetic aeration techniques were considered to be technically feasible, they were rejected because they carried long-term operation and maintenance requirements with no reliable funding source to continue the operation indefinitely.

The choice of chemicals and dose determination studies for the aluminum treatment were conducted by Aquatic Control Technology and Reitzel Associates (1986). With the moderately low alkalinity in Lake Morey (35-45 mg/L as CaCO₃), it was apparent that it would be necessary to add an alkaline substance with the acidic alum to avoid pH reduction and aluminum toxicity. Several alkaline compounds were considered, including sodium hydroxide (caustic soda), sodium carbonate (soda ash), calcium hydroxide (lime), and sodium aluminate. Sodium aluminate, as originally used in Annabessacook Lake, Maine (Dominie, 1980), was found to be the most economical choice because it supplied additional aluminum ions as well as alkalinity. Much of the alkalinity in commercial liquid sodium aluminate is actually derived from sodium hydroxide present in the product as a result of the production process.

Dose determination procedures were adapted from guidelines presented in Cooke and Kennedy (1981) and Cooke et al. (1986). A maximum aluminum dose was determined within constraints imposed by project funding, treatment logistics, and toxicity considerations. Laboratory jar testing procedures using commercial liquid chemicals were used to establish a sodium aluminate/alum dose ratio that maintained dissolved aluminum concentrations below 50 µg/L and pH above 6.5. The 50 µg/L aluminum toxicity criterion was based on the recommendation of Cooke and Kennedy (1981), and the pH criterion was dictated by Vermont Water Quality Standards. The jar testing results (Fig. 3) indicated that an aluminate/ alum Al ratio of 1.4 (1.4 grams of Al from sodium aluminate per gram of Al from alum) would achieve these criteria.

Project funding and treatment logistics indicated that a total aluminum quantity of 60,000 kg was the maximum feasible dose. Using an aluminate/alum Al ratio of 1.4, the target dose rates were 35,000 kg Al from sodium aluminate (142 dry tons of commercial product) and 25,000 kg Al from alum (305 dry tons of commercial product).

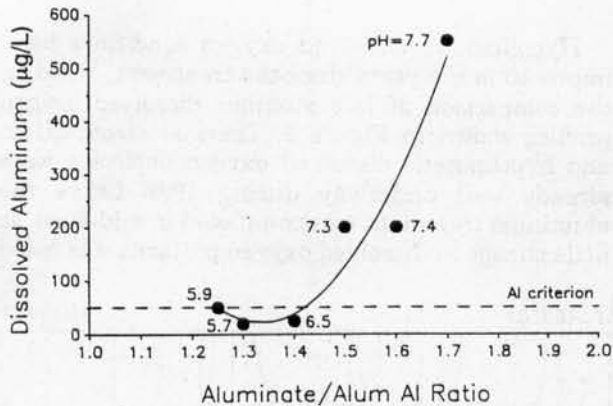


Figure 3.—Dose determination laboratory test results. Testing was done using commercial liquid alum and liquid sodium aluminate added to samples of Lake Morey water having an initial pH of 7.4 and an alkalinity of 33 mg/L. The dissolved aluminum and pH results shown were based on a total aluminum dose of 12 mg/L using various ratios of aluminum supplied from sodium aluminate vs. alum.

The lake was treated from May 23 to June 18, 1986, using a high speed transport barge modified from aquatic plant harvesting operations. The treatment was conducted during the thermal stratification season to minimize the potential for vertical transport of treatment chemicals. Liquid alum and liquid sodium aluminate were pumped separately into a double manifold equipped with brass spray nozzles trailed behind the vessel at the hypolimnion depth of 8 meters. Complete coverage of the 133-ha hypolimnetic sediment area below the 8-meter depth contour was ensured by placing marker buoys along the edge of the treated area during each pass of the vessel across the width of the lake. A summary of the chemical quantities actually applied and the treatment costs is given in Table 2. The quantities of alum and sodium aluminate actually applied were within 4 percent of the target dose rates.

The aluminum dose rate used to treat Lake Morey is compared in Table 3 with the dose rates used in

Table 2.—Summary of actual chemical quantities applied and treatment costs.

| | | |
|--|--------------|------------------|
| Treated Area | 133 ha | |
| Chemical Quantities Applied | | |
| liquid alum | 304 dry tons | 24,918 kg Al |
| liquid sodium aluminate | 137 dry tons | 33,768 kg Al |
| | | 58,686 kg Al |
| Chemical Costs (including freight and other charges) | | |
| liquid alum | | \$ 26,646* |
| liquid sodium aluminate | | 82,877 |
| | | \$109,523 |
| Application Cost (excluding chemicals) | | \$ 67,205 |
| Total Treatment Cost | | \$176,728 |

*The low alum cost resulted from a substantial public service donation of liquid alum from General Chemical Corp.

eight other metalimnetic or hypolimnetic lake aluminum treatments. Since the goal of most such treatments is to create an aluminum hydroxide floc layer covering the bottom sediments, the areal dose rate for the treated area (g Al/m^2) is the most appropriate basis for comparison, rather than a water column aluminum concentration as is often reported. The areal aluminum dose rates used for the lakes reviewed in Table 3 ranged from 18 g Al/m^2 for two treatments in Maine up to 139 g Al/m^2 applied to Irondequoit Bay, New York. The 44 g Al/m^2 applied to Lake Morey was higher than the rates used for most of the other lakes.

All of the treatments listed in Table 3 significantly reduced in-lake phosphorus concentrations, based on the references cited. The duration of effectiveness has been for post-treatment monitoring periods ranging from one to eight years. A possible exception is Kezar Lake, New Hampshire, in which initial phosphorus declines were followed by increasing hypolimnetic phosphorus concentrations and a recent return to pre-treatment chlorophyll *a* levels after four years (Connor and Martin, 1989). In general, however, the aluminum dose rates listed in

Table 3.—Comparison of areal aluminum dose rates used in nine metalimnetic or hypolimnetic lake treatments.

| LAKE | YEAR TREATED | AREA TREATED (HA) | AREAL DOSE RATE (G AL/M ²) | REFERENCE |
|-----------------------|--------------|-------------------|--|---|
| Cochnewagon, Maine | 1986 | 91 | 18 | W. Dennis (pers. comm., Cobbossee Watershed Dist., ME) |
| Annabessacook, Maine | 1978 | 113 | 18–25 | Dominie (1980) and W. Dennis (pers. comm., Cobbossee Watershed Dist., ME) |
| Three Mile, Maine | 1988 | 259 | 25 | R. Bouchard (pers. comm. ME Dept. Env. Prot.) |
| Dollar, Ohio | 1974 | 1.4 | 29 | Cooke and Kennedy (1981) |
| West Twin, Ohio | 1975 | 16 | 32 | Cooke and Kennedy (1981) |
| Kezar, N.H. | 1984 | 48 | 40 | Connor and Martin (1989) |
| Bullhead, Wis. | 1978 | 5.6 | 42 | Narf (1985) |
| Morey, Vt. | 1986 | 133 | 44 | This report |
| Irondequoit Bay, N.Y. | 1986 | 305 | 139 | Monroe County Dept. Health, NY (1986, 1989) |

Table 3 appear to have provided at least several years of phosphorus control in a variety of lakes.

Lake Monitoring Results

Figures 4 through 8 compare the 1986-87 post-treatment water quality results for Lake Morey with the pre-treatment data obtained during the 1981-82 diagnostic study. Figure 4 shows that seasonal patterns of thermal stratification and mixing were essentially the same during each of the study years.

Total phosphorus changes are illustrated in Figure 5. Prior to the treatment, summer epilimnetic phosphorus concentrations were generally in the 10-30 $\mu\text{g/L}$ range, with spring and fall turnover values of 30-40 $\mu\text{g/L}$. Phosphorus accumulated in the hypolimnion to levels as high as 500 $\mu\text{g/L}$. Phosphorus concentrations in Lake Morey declined sharply following the June 1986 aluminum treatment. Epilimnetic values were generally below 10 $\mu\text{g/L}$ after the treatment, as were the spring and fall turnover values. Hypolimnetic total phosphorus concentrations decreased to less than 50 $\mu\text{g/L}$.

Figure 6 compares the seasonal changes in whole-lake phosphorus mass before and after the aluminum treatment. Whole-lake phosphorus mass was calculated by volume-weighting the water column phosphorus concentrations sampled at 1 meter depth intervals. Figure 6 shows that in 1981-82, prior to the treatment, the phosphorus content of Lake Morey increased greatly during the summer months because of internal loading to the hypolimnion, as previously described. This pattern was altered dramatically following the June 1986 aluminum treatment. The whole-lake phosphorus content declined immediately after the treatment and no significant summer increases in lake phosphorus content were observed during 1986 or 1987. The lake's phosphorus mass stabilized after the treatment at a much lower value than previously recorded.

Chlorophyll *a* concentrations showed corresponding reductions, as indicated in Figure 7. Summer epilimnetic chlorophyll *a* concentrations declined from pre-treatment levels of 5-20 $\mu\text{g/L}$ to values generally less than 5 $\mu\text{g/L}$ following the treatment. Metalimnetic or hypolimnetic chlorophyll *a* maxima continued to exist after the treatment, but at lower concentrations and more limited spatial-temporal extent.

Hypolimnetic dissolved oxygen conditions have improved in the years since the treatment, based on the comparison of late summer dissolved oxygen profiles shown in Figure 8. Thermal stratification and hypolimnetic dissolved oxygen depletion were already well underway during 1986 before the aluminum treatment was completed in mid-June, so little change in dissolved oxygen patterns was noted

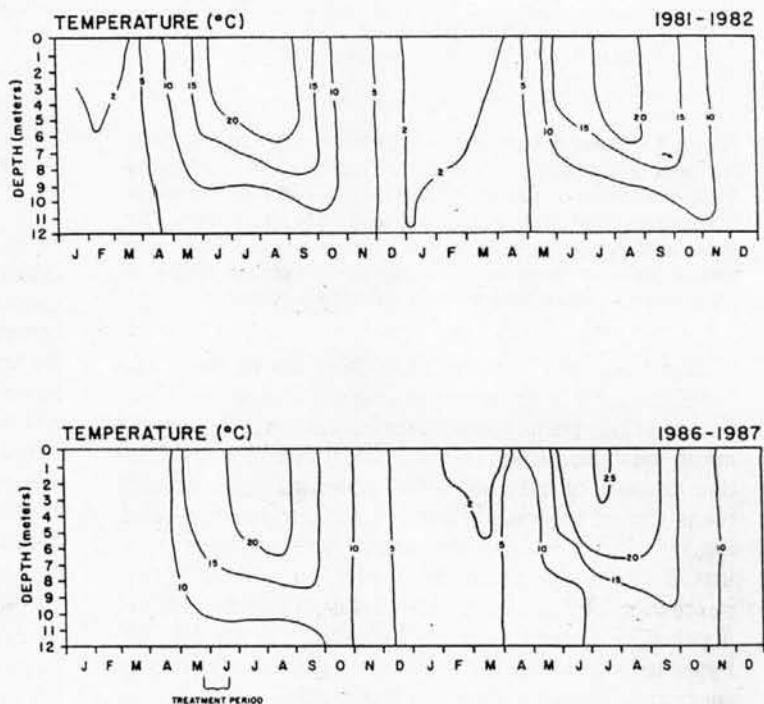


Figure 4.—Depth-time distribution of temperature in Lake Morey before and after the aluminum treatment.

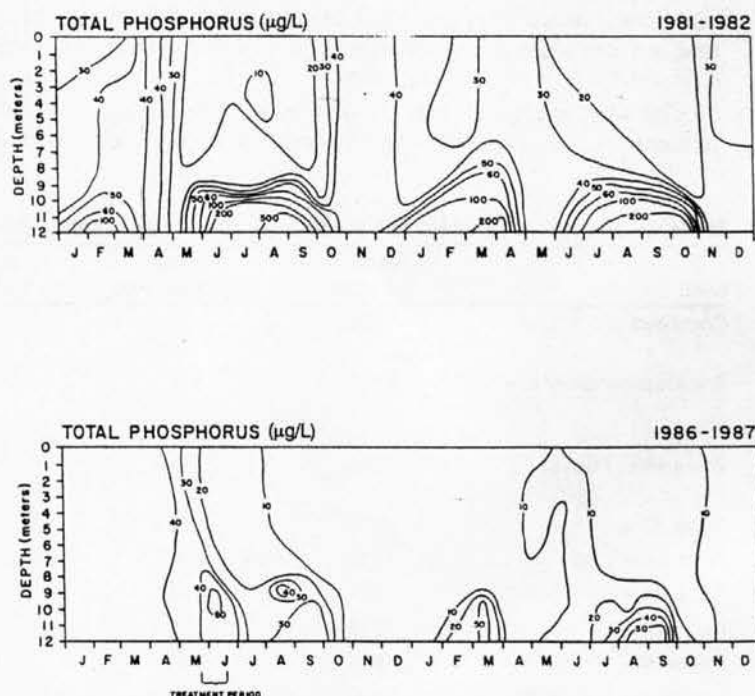


Figure 5.—Depth-time distribution of total phosphorus in Lake Morey before and after the aluminum treatment.

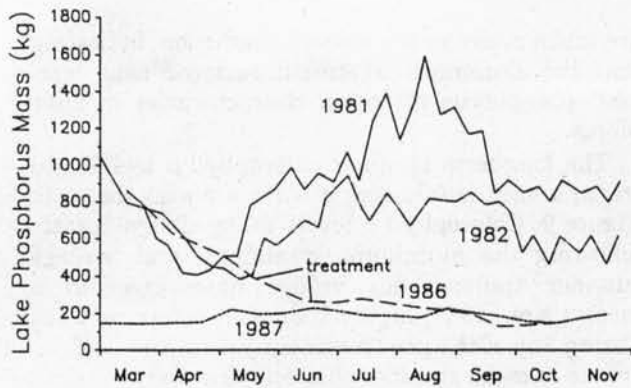


Figure 6.—Seasonal changes in whole-lake phosphorus mass before and after the aluminum treatment.

that year. However, substantially higher dissolved oxygen concentrations were observed deeper in the hypolimnion during 1987, and again on a single late August sampling date during 1989.

The dissolved oxygen maxima in the upper hypolimnion during 1987 and 1989 resulted from photosynthetic activity by algal populations concentrated at that depth (see Fig. 7). Apparently, clearer water in Lake Morey following the aluminum treatment allowed enough light into the hypolimnion to produce photosynthetic oxygen. This effect could help in establishing long-term control over internal phosphorus loading in Lake Morey by reducing the area of sediment exposed to anoxic conditions.

Long-term monitoring programs on Lake Morey have provided additional perspective on the water quality improvement following the aluminum treat-

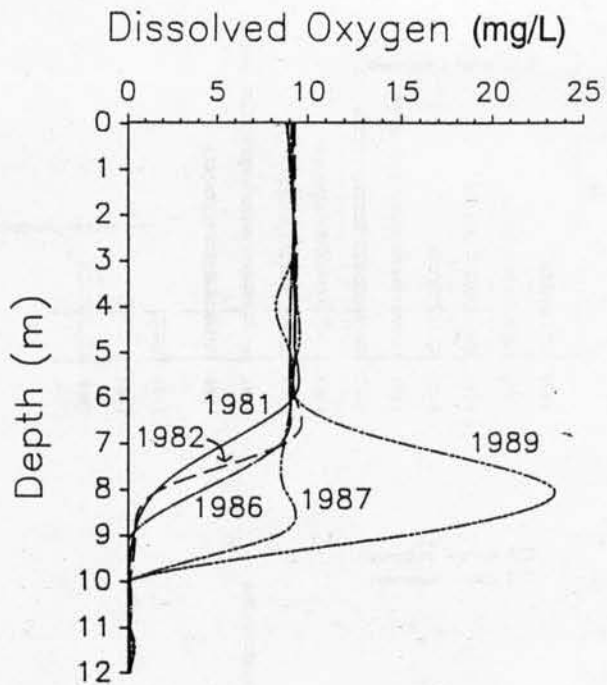


Figure 8.—Late August to early September dissolved oxygen profiles in Lake Morey before and after the aluminum treatment.

ment. The results of springtime total phosphorus sampling conducted annually since 1977 (Fig. 9) show that the post-treatment values have been substantially lower than the pre-treatment levels. Spring phosphorus levels have increased since the record low value of 9 µg/L observed in 1987 immediately after the treatment, but the post-treatment levels have not approached the pre-treatment mean of 37 µg/L.

Figure 9 also compares the spring phosphorus data with the phosphorus concentration predicted for Lake Morey from a simple lake phosphorus model modified from Dillon and Rigler (1974).

$$P = W(1-R) / Q \quad (1)$$

- Where
- P = predicted lake phosphorus concentration
 - W = external phosphorus loading rate
 - R = phosphorus retention coefficient
 - Q = water inflow rate

Equation 1 was applied to Lake Morey using a phosphorus loading rate of 338 kg/yr (Table 1) and an inflow rate of $11.5 \times 10^6 \text{ m}^3/\text{yr}$ (Morgan et al., 1984). A phosphorus retention value of 0.71 was predicted from an empirical model (Ostrosky, 1978) derived from 53 Canadian Shield lakes having low areal water loading rates similar to Lake Morey (5.2 m/yr).

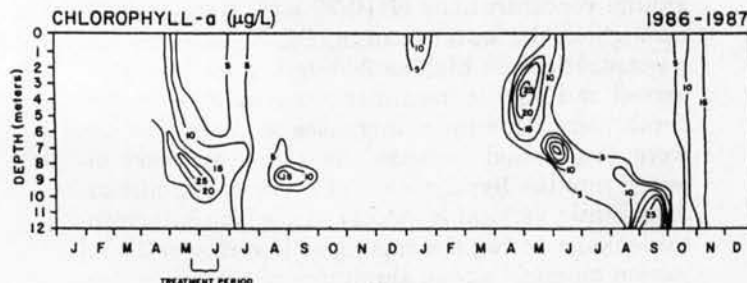
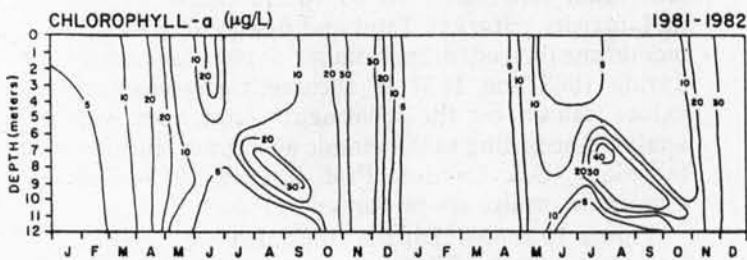


Figure 7.—Depth-time distribution of chlorophyll a in Lake Morey before and after the aluminum treatment.

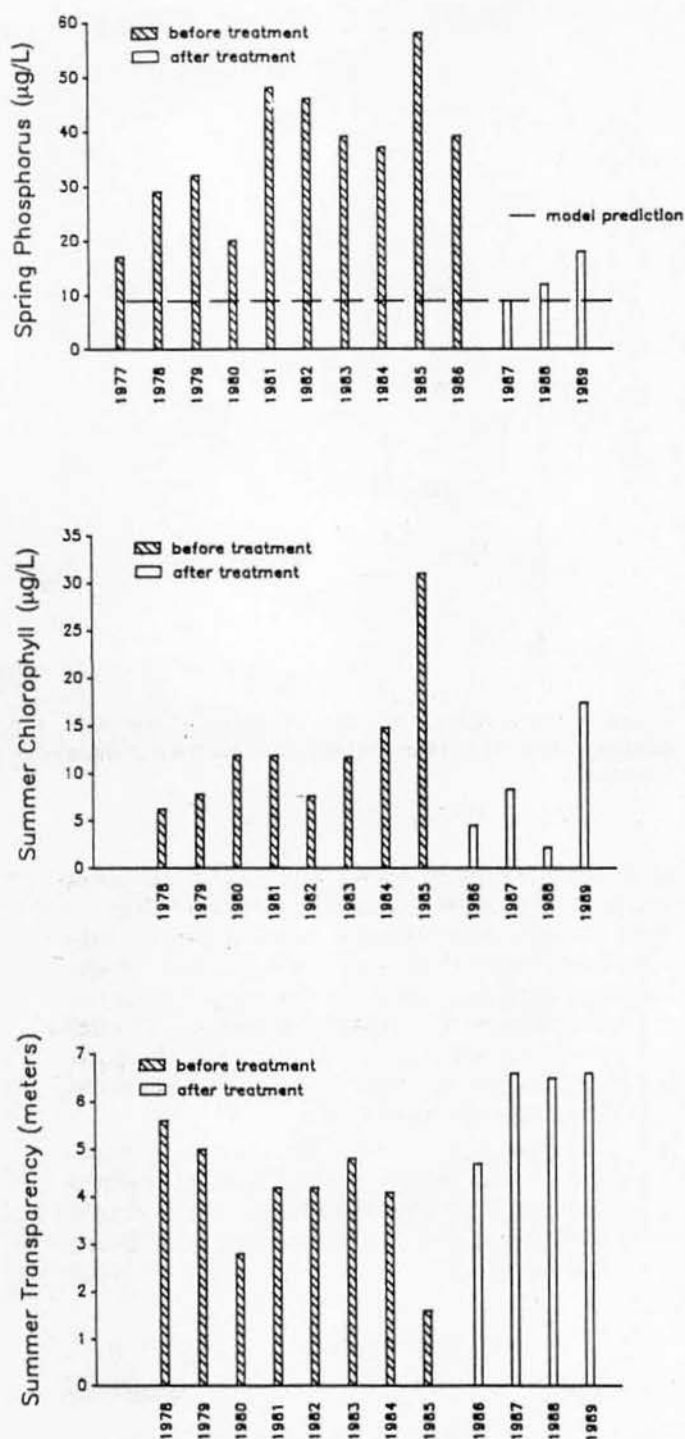


Figure 9.—Long-term monitoring results for spring total phosphorus, mean summer chlorophyll *a*, and mean summer Secchi transparency.

Equation 1 predicts a phosphorus concentration of 9 µg/L for Lake Morey. This value is much lower than the observed pre-treatment values because Ostrofsky's model greatly over-estimated phosphorus retention when the lake's phosphorus dynamics were dominated by internal loading. However, the post-treatment spring phosphorus values

are much closer to the model's prediction, indicating that the aluminum treatment restored near "normal" phosphorus retention characteristics in Lake Morey.

The long-term summer chlorophyll *a* and Secchi transparency monitoring results are also shown in Figure 9. Chlorophyll *a* levels dropped significantly following the aluminum treatment, and average summer transparency values have exceeded 6 meters since 1987, higher than ever before recorded during any of the pre-treatment years. The 1989 increase in mean summer chlorophyll *a* was the result of the inclusion of a concentrated hypolimnetic algal layer in the vertically-integrated samples. The integrated samples were obtained to a depth of twice the Secchi value, so the increased transparency led to deeper sampling and the inclusion of the hypolimnetic algal population.

It is unclear whether the deep algal layer and the increases in spring phosphorus and summer chlorophyll *a* seen during 1989 should be a cause for concern. The permanence of the water quality improvements observed in Lake Morey following the aluminum treatment will be assessed by continuing monitoring efforts.

Adverse Effects

Aluminum

As discussed previously, the alum/aluminate treatment was designed to limit water column dissolved aluminum concentrations to values below the 50 µg/L toxicity criterion. Total and dissolved (0.45 µm membrane filtered) aluminum levels were monitored during 1986 and 1987 to document any elevated values caused by the treatment. Aluminum was analyzed according to the atomic absorption, furnace technique (U.S. Environ. Prot. Agency, 1983). The aluminum results are presented in Figure 10.

Figure 10 shows that the treatment beginning in late May 1986 caused dissolved aluminum levels in the epilimnion of Lake Morey to rise above the 50 µg/L criterion. Dissolved aluminum concentrations in the epilimnion were generally in the 50-100 µg/L range until the fall turnover, at which time background concentrations of 10-20 µg/L were restored throughout the water column. Dissolved aluminum concentrations as high as 200 µg/L were briefly observed during the treatment period in a limited depth zone. Aluminum increases in the epilimnion were unexpected because the chemicals were injected into the hypolimnion at a depth of 8 meters. Apparently, vertical transport in the lake or incidental leakage during the raising or lowering of the injection manifold added aluminum to the epilimnion. Here, the ambient pH values of 8.0 or higher (Fig. 11) created conditions that enhanced aluminum

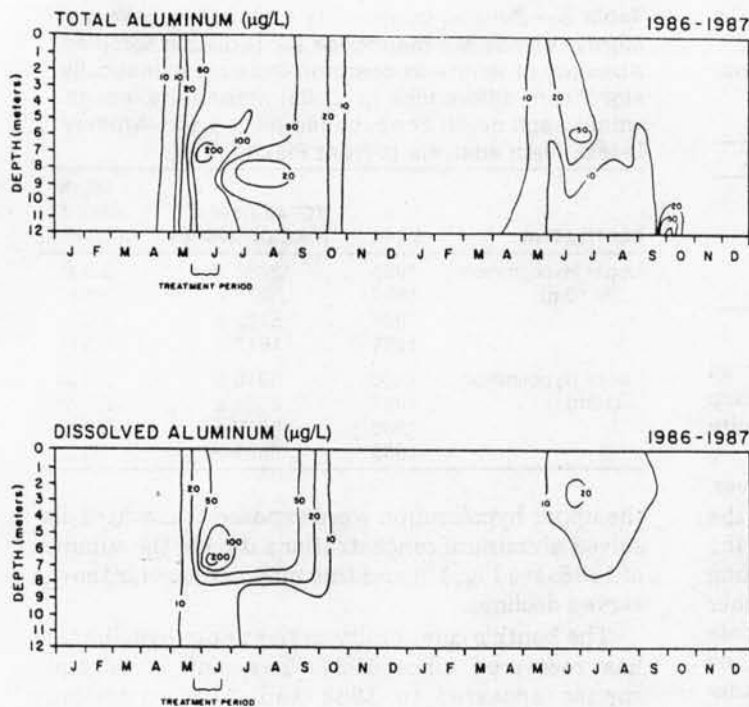


Figure 10.—Depth-time distributions of total and dissolved aluminum in Lake Morey during 1986 and 1987.

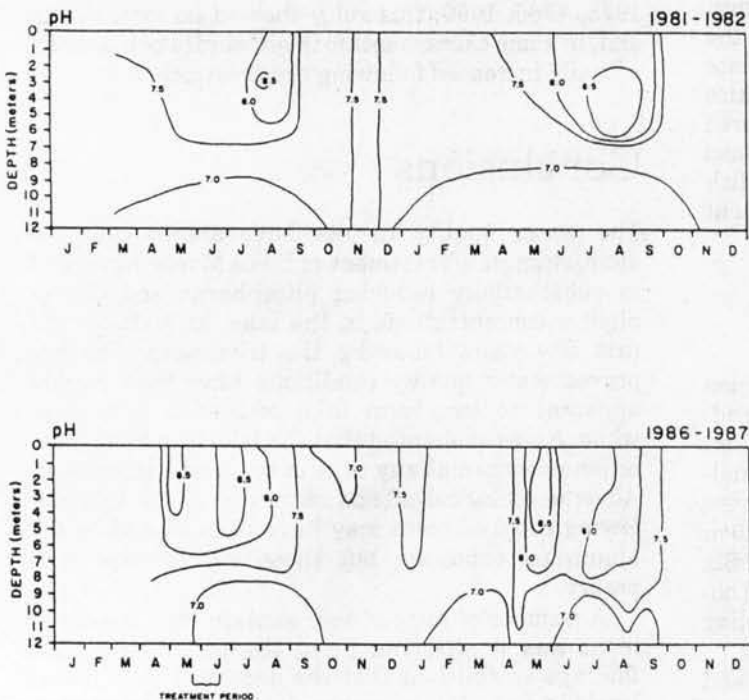


Figure 11.—Depth-time distribution of pH in Lake Morey before and after the aluminum treatment.

solubility. In the hypolimnion where the vast majority of the chemicals were applied, the pH remained in the safe range near 7.0, and dissolved aluminum concentrations stayed below 20 µg/L.

Figure 11 shows that pH conditions in the lake were not altered by the treatment, confirming that the proper mixture of chemicals was applied. The elevated epilimnetic pH values were normal for Lake Morey during the summer, probably as a result of photosynthetic uptake of CO₂ by the phytoplankton. Since elevated pH values are common during the summer in many eutrophic lakes (Wetzel, 1975), future phosphorus inactivation treatments should be designed with greater care to avoid adding aluminum to either high or low pH environments.

Fish

No direct mortality of fish in Lake Morey was observed as a result of the aluminum treatment. However, analysis of experimental gillnet data routinely collected by the Vermont Department of Fish and Wildlife each fall since 1984 (Kirn, in press) indicated that the condition of adult yellow perch (*Perca flavescens*) declined significantly following the treatment.

Kirn (in press) calculated condition factors (K), where $K = (\text{weight-g}) \times 10^5 / (\text{length-mm})^3$, for yellow perch in the 203-279 mm length range from 1984 to 1988 (Table 4). An improvement in yellow perch condition from 1984 to 1985 was apparently the result of reduced intraspecific competition following a major fish kill of yellow perch caused by the collapse of an algae bloom during the summer of 1985. Following the 1986 aluminum treatment, significant reductions in the condition of the perch were observed in the fall gillnet samples from 1986, 1987, and 1988. These reductions represented an average weight loss of 17-21 percent relative to the 1985 values (Kirn, in press).

Kirn noted that aluminum toxicity experiments conducted at high pH on rainbow trout by Freeman and Everhart (1971) yielded sub-lethal effects, including reduced feeding activity and weight loss, at aluminum concentrations of 520 µg/L and higher. The maximum dissolved aluminum concentrations observed in Lake Morey were below the lowest value reported in the literature as causing sub-lethal effects at high pH for rainbow trout, a more sensitive species than yellow perch (U.S. Environ. Prot. Agency, 1988). However, Kirn (in press) concluded that the decline in yellow perch condition in Lake Morey resulted directly from exposure to the elevated aluminum concentrations.

Table 4.—Condition factors for adult yellow perch in Lake Morey. Different letters indicate statistically significant differences ($p < .05$) between the means, based on a Mann-Whitney U-test. Data analysis is from Kirn (in prep.).

| YEAR | MEAN CONDITION FACTOR |
|------|-----------------------|
| 1984 | 1.11 a |
| 1985 | 1.17 b |
| 1986 | 0.97 c |
| 1987 | 0.92 d |
| 1988 | 0.92 d |

An alternative explanation for the observed weight loss in Lake Morey perch might be the sharp reduction in phosphorus and primary productivity following the treatment and, consequently, a reduced food base for higher trophic levels. However, this explanation appears unlikely because the weight loss effect was more pronounced for the larger size classes of perch that were feeding primarily on fish and macroinvertebrates, rather than plankton (Kirn, in press). Such an immediate weight loss response would not be expected at the upper trophic levels. Another alternative explanation is that 1984 and 1985 were unusually good growth years not representative of the long-term mean pre-treatment condition of yellow perch in Lake Morey.

The condition of yellow perch in Lake Morey is expected to return to "normal" as the affected adult fish gradually succumb to natural mortality and the relatively unaffected younger fish are recruited into the adult population. In spite of the uncertainties regarding the mechanism for the observed perch condition decline, Kirn's findings indicate the need for greater concern about the protection of lake fish populations from exposure to aluminum treatment chemicals at high pH conditions.

Benthos

Benthic invertebrate populations in the hypolimnion of Lake Morey were monitored to detect possible adverse effects from the aluminum treatment. Sampling was conducted on one late winter date annually during 1986 through 1989. Two depth zones were sampled, including the upper hypolimnion at 8-10 m depth and the lower hypolimnion at 12 m depth. Six replicate Ekman dredge samples (232 cm²) were obtained within each depth zone on each sampling date.

The results were analyzed by Fiske (1989) and summarized in Table 5. Species richness was very low throughout the monitoring period and the benthic community was dominated by *Chaoborus* spp. Benthos density in the upper hypolimnion decreased significantly in 1987. Mean species richness also declined. These declines may have been related to the 1986 aluminum treatment, although no significant changes in density or species richness were observed in the lower hypolimnion. The organisms in

Table 5.—Benthic community changes in Lake Morey. Values are means for six replicate samples. Absence of letters in common indicate statistically significant differences ($p < .05$) among the means within each depth zone, based on a Mann-Whitney U-test. Data analysis is from Fiske (1989).

| DEPTH ZONE | YEAR | TOTAL DENSITY (ORGANISMS/M ²) | MEAN SPECIES RICHNESS |
|---------------------------|------|---|-----------------------|
| Upper Hypolimnion (8-10m) | 1986 | 2783 ab | 5.3 a |
| | 1987 | 275 c | 3.5 b |
| | 1988 | 5125 a | 6.0 a |
| | 1989 | 1617 b | 5.3 a |
| Lower Hypolimnion (12m) | 1986 | 3216 a | 2.5 ab |
| | 1987 | 2891 a | 2.3 ab |
| | 1988 | 10633 a | 2.0 a |
| | 1989 | 5891 a | 3.0 b |

the upper hypolimnion were exposed to elevated dissolved aluminum concentrations during the summer of 1986 (see Fig. 10) and this may account for the observed declines.

The benthic community in the upper hypolimnion has recovered since 1987. Two new chironomid species appeared in 1988 and have successfully colonized the hypolimnetic sediments, possibly benefitting from the reduced lake productivity levels and less severe hypolimnetic anoxia since the treatment (Fiske, 1989). Similarly, post-treatment monitoring of alum-treated lakes in Wisconsin (Narf, 1978, 1985, 1990 (this vol.)) showed no toxic effects and, in some cases, benthic invertebrate populations actually increased following the treatments.

Conclusions

The water quality results have shown that the alum/aluminate treatment of Lake Morey succeeded in substantially reducing phosphorus and chlorophyll *a* concentrations in the lake, at least for the first few years following the treatment. The improved water quality conditions have been readily apparent to long-term lake residents, several of whom have commented that the lake is in better condition now than at any time in the past half century. Adverse biological effects observed in the lake following the treatment may have been caused by the aluminum exposure, but these effects were temporary.

A number of factors help explain why the treatment was so effective. First, the paleolimnological findings established that the excessive phosphorus levels in Lake Morey were related to pollution sources that occurred in the past and from which the lake has never fully recovered. The paleolimnological data showed that the lake was far less productive during the pre-development period, indicating that morphometric or geologic factors did not necessarily predispose Lake Morey to a eutrophic condition. Restoration of near-oligotrophic conditions was therefore a realistically attainable goal.

The detailed phosphorus budget measurements made as part of the diagnostic study demonstrated that the phosphorus dynamics in Lake Morey were dominated by a single clearly identified source — the hypolimnetic sediments. External phosphorus loadings from the watershed were low and typical of relatively undisturbed forestland. The land use characteristics, measured tributary loadings, and phosphorus modeling calculations all suggested that the lake would be in a near-oligotrophic condition if internal phosphorus loading were adequately controlled.

Finally, the aluminum dose rate for Lake Morey was apparently adequate, although the treatment's ultimate longevity is undetermined. The aluminum areal dose rate of 44 g Al/m² used to treat Lake Morey was well within the range of rates used for the other successful hypolimnetic lake aluminum treatments reviewed. Although aluminum dose rates for Lake Morey and other lakes have been determined primarily from cost and toxicity considerations rather than from known dose versus effectiveness relationships, rates in the 18-139 g Al/m² range appear to be generally successful in forming a stable phosphorus barrier on lake sediments.

The goal of the Lake Morey Restoration Project was to achieve long-term or permanent control over internal phosphorus loading in the lake. The ultimate success of the project must therefore be judged by monitoring over a period of many years. However, the results to date indicate that the prospects for long-term success are good.

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