# REVIEW OF LAKE MANAGEMENT IN MINNESOTA

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# Forward

Lakes are an important component of Minnesota's water resources and are a major economic and recreational asset to the state. Management of them is an important concern because of their impact on recreation and aesthetics, and the demand for their increased use.

Lake management and restoration has been practiced in Minnesota for over 20 years, but heretofore little information has been assembled concerning the effectiveness of various restoration practices and programs. In 1988 the WRRC commissioned the authors of this report to review lake management and restoration projects undertaken in the state since the beginning of the federally-funded Clean Lakes Program in the early 1970s. The study examined these projects in terms of success and failure (to achieve intended goals) and adequacy of existing information on which to base such conclusions. Where possible, the effectiveness of individual management/restoration techniques was evaluated. Based on the review and analysis of past restoration projects, the authors have developed several useful recommendations regarding technical and institutional changes that should be considered to improve the state's lake restoration programs.

This report describes the findings of the lake restoration review study. The text of the report was published in *Lake and Reservoir Management*, Vol. 5, pp 1-10, 1989.

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# Review of Lake Management in Minnesota

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## ABSTRACT

Lake management practices in Minnesota have included holistic Clean Lakes Projects, extensive remedial methods to control excessive phytoplankton and macrophyte growth, and fisheries improvement projects. Clean Lakes projects have had varying degrees of success, but there has been no systematic evaluation of the overall success of the program. Remedial methods and fisheries management have narrow objectives, and the broader water quality impacts of these management practices have generally not been considered. Future lake management activities in Minnesota include developing better predictive and assessment capabilities, using innovative management techniques such as biomanipulation and community management of macrophytes, and renewing emphasis on controlling nonpoint source inputs to lakes.

## Introduction

Lake management is an important concern in Minnesota because lakes are extremely numerous (12,000 lakes larger than 10 acres) and highly valued for recreation and aesthetics. Many cities and towns have at least one lake, and over half (2.3 million) of all Minnesotans fish. Furthermore, the potential for degradation is increasing with the demand for lake-based recreation: between 1967 and 1982, the number of lakeshore dwellings increased by 74 percent (5 percent per year) to over 125,000 (Cohen and Stinchfield, 1984).

Accordingly, lake management has a long history in Minnesota, both through the Clean Lakes Program and through other state and local government programs (Mulloy, 1987). The objectives of this paper are to (1) review lake management practices currently used in Minnesota; (2) critically review the successes and failures of lake management projects as well as individual management techniques, given the constraints of limited documentation of individual case studies; and (3) examine changes in technical and institutional approaches to lake management and make specific recommendations regarding future programs.

## Minnesota's Clean Lakes Program

This discussion of restoration techniques used in Minnesota focuses primarily on the Clean Lakes Program; however, many restoration efforts have occurred outside this program (Larsen et al. 1981; Peterson et al. 1974; Hanson and Stefan, 1985). The authors' classification of restoration techniques is somewhat arbitrary, since significant differences occur during implementation of projects listed for a given technique (Table 1). In most cases insufficient data exist to judge the efficacy of a technique in a particular lake, but successes or failures have been summarized where published documentation exists.

■ **Inflow treatment:** Reducing nutrient inputs has been the most common strategy for controlling eutrophication in Minnesota lakes. Inflow treatment by wetlands, sedimentation basins, or filtration beds were used in 12 of the 14 Clean Lakes projects reaching the implementation phase (Table 1). Wetlands and sedimentation basins function primarily by removing particulates, in contrast to filtration beds, which are designed to also remove dissolved phosphorus through adsorption during filtration. However, the distinction is not precise; the wetland at Clear Lake in

Table 1.—Clean Lakes Projects in Minnesota.[a]

| LAKE | PROJECT COSTS (MILLIONS) | PHASE[b] | RESTORATION TECHNIQUE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DIVERSION | TREATMENT[c] BASIN | LAND-USE | DRAW-DOWN | AERATION | MACROINVERTEBRATE HARVEST | CHEMICAL TREATMENT | FISH MANIPULATION | DREDGING | OTHER |
| Fountain & Albert Lea (Freeborn Co.) | 0.6 | DEMO | ☐ | FB | ☐ | | | | | | | |
| Clear Lake (Waseca) | 0.83 | DEMO | ☐ | WL | ☐ | ☐ | ☐ | | ☐ | ☐ | ☐ | Biomanipulation |
| Loon Lake* (Waseca) | | | ☐* | | | | | | | ☐* | | |
| Penn Lake (Bloomington) | 0.18 | DEMO | ☐ | SB | | | ☐ | ☐ | | ☐ | ☐ | Groundwater addition |
| Hyland Lake (Hennepin Co.) | 0.32 | DEMO | ☐ | SB<br>WL | | ☐ | ☐ | | | ☐ | | Groundwater addition |
| Minneapolis Chain of Lakes (Minneapolis) | 0.36 | DEMO | | US | | ☐ | ☐ | | | ☐ | | Flushing |
| Clearwater River Chain of Lakes (Clearwater) | 3.33 | DEMO | | WL | ☐ | | ☐ | | | ☐ | | Wetland Isolation |
| Long Lake Chain of Lakes (Rice Creek) | 3.76 | DEMO | ☐ | | ☐ | | | | | | | |
| Moore Lake (Fridley) | 1.01 | DEMO | ☐ | SB<br>FB | | | ☐ | ☐ | ☐ | ☐ | ☐ | Peat-Sand Filter, Sheeting of Littoral |
| Lake Phalen Chain of Lakes (St. Paul) | 1.15 | DEMO | ☐ | WL | | | | | | | | Groundwater addition |
| Seven Twin Cities Lakes (Minneapolis) | 1.48 | I | | | | | | | | | | |
| Chippewa Tribe Lakes (Becker, Koochiching, St. Louis & Crow Wing Co.) | 0.09 | | | | | | | | | | | |
| Lake Como (St. Paul) | 0.70 | I,II | | SB<br>FB | | | | | | | | Biomanipulation |
| Golden Lake (Circle Pines) | 0.45 | I,II | | | | | | | | | ☐ | Biomanipulation |
| Big Stone Lake (Big Stone Co.) | 1.49 | I,II | ☐ | | | | | | | | | NPS Demonstration Project |
| Lake McCarron (Roseville) | 0.39 | I,II | | SB<br>WL | | | | | | | | |
| Riley Creek Chain of Lakes (Chanhassen & Eden Prairie) | 1.15 | I,II | | | | | | | | ☐ | | NPS Demonstration Project Biomanipulation |

[a] Restoration projects funded locally before or after federal cost-sharing program are noted by asterisk (*).

[b] Phase: DEMO = Demonstration Grant Program; I = Phase I Diagnostic Feasibility Study; II = Phase II Implementation Projects.

[c] Treatment basin types: SB = sedimentation basin; FB = filtration bed; WL = wetland filtration; vs = vacuum sweeping of streets in watershed.

Waseca was designed to remove dissolved phosphorus, but removal of particulates was the dominant phosphorus reduction mechanism (Barten, 1986).

Several of the filtration beds have not functioned as planned. Results from two pilot plant filtration beds at Fountain and Albert Lea Lakes for treatment of agricultural runoff were not encouraging. The first, constructed of native soils, actually added phosphorus, and the second, constructed of crushed limestone, quickly lost adsorptive capacity (Tuveson, 1983). The peat/sand filtration system built for Moore Lake quickly lost hydraulic conductivity (Tomasek et al. 1987).

It is clear that phosphorus has been removed in some of the wetland treatment projects. In 1980, 37 percent of the urban runoff that was flowing directly into Lake Josephine was diverted into a wetland called Little Josephine. Over the next three years the wetland reduced inflow phosphorus concentrations by 62 percent and phosphorus loading by 59 percent (Weidenbacher and Willenbring, 1984; Willenbring 1985). Resulting water quality trends included an increase in mean transparency from 1.0 m to 1.9 m and a concomitant increase in macrophyte abundance (Noonan, 1985). Similar successful results were obtained for the 1981 diversion of a storm sewer into a marsh adjacent to Clear Lake in Waseca. This storm sewer was responsible for 55 percent of the external phosphorus load to Clear Lake, and over the next five years the wetland removed 54 percent of the inflowing total phosphorus (Barten, 1986). In a singular case, a wetland was hydrologically isolated to reduce phosphorus inputs to the Clearwater chain of lakes because it was enriched in phosphorus as a result of having received wastewater effluent from a dairy operation over a period of many years (Erdmann et al. 1985).

Willenbring (1985) compared the performance of five Minnesota wetlands used to treat urban runoff and concluded the more successful ones had high retention times that maximized stormwater contact with soils. Long retention times were achieved by having a high wetland to watershed ratio, a control structure at the wetland outflow, and minimal channelization (short-circuiting) within the wetland.

■ **Land use:** Six projects have included best management practices (BMPs) to reduce nonpoint source nutrient inputs from the lakes' watersheds. Only two of the six projects were in nonagricultural basins. In the only urban project a vacuum street sweeper cleaned the paved watershed around Lake Harriet in Minneapolis 13 times during the summer in 1979 and 1980. Weekly sweeping was projected to remove 38 percent of the phosphorus loading to the lake (Erdmann et al. 1984). In a suburban watershed of the Long Lake chain, erosion control was implemented by stabilizing ditches.

Three recent projects in agricultural watersheds—Big Stone Lake, Clearwater River chain of lakes, and Riley Creek chain of lakes—have all included demonstration projects to reduce erosion. In the Clearwater River chain, for instance, farmers in test watersheds could receive cash payments for modifying their tillage practices to leave more surface residue (Kells, 1988).

■ **Drawdown:** Lake drawdown was used in only one Minnesota Clean Lakes project (Table 1). In Hyland Lake, drawdown was intended to remove the phosphorus-rich hypolimnetic water from the lake, reduce future release of phosphorus from the sediments, and consolidate the sediments. Dewatering was completed in spring 1978, along with two other simultaneous restoration efforts: (1) an augmentation and groundwater recharge system was constructed using a 300-foot deep well, and (2) a stormwater sedimentation basin was constructed along with an artificial wetland. Concurrently, the Minnesota Department of Natural Resources applied rotenone to the lake and restocked it with bass to improve fishing. Four years of post-construction data indicated an 85 percent increase in Secchi depth, an 85 percent decrease in chlorophyll, and a 49 percent decrease in phosphorus concentration (Minn. Pollut. Control Agency, 1982). However, Shapiro (1983) has argued that the observed decrease in chlorophyll was disproportionate to the decrease in phosphorus, and suggested the change in fish communities created greater grazing pressure on phytoplankton by zooplankton (*D. pulex*). It is, therefore, unclear which management technique(s) had the greatest impact on water quality.

■ **Aeration:** Under the Minnesota Clean Lakes Program aeration was used in nine lakes (Table 1). In two projects (Penn and Hyland lakes), winter aeration was used to prevent winterkill. In two other projects, hypolimnetic aeration was used to decrease internal phosphorus loading. The Penn Lake and Golden Lake aeration systems are notable because they used lakeside cascade aerators (Runke, pers. comm.). In several lakes, hypolimnetic aeration did not prevent anoxia throughout the year (Runke, pers. comm.; Erdmann, pers. comm.). No published evidence in the peer-reviewed literature indicates that hypolimnetic aeration has substantially reduced phosphorus release rates in any Minnesota lakes.

■ **Chemical treatments:** Both alum and calcium nitrate (RIPLOX treatment) have been used in Minnesota. Alum was added to two lakes, Moore and Clear (see Table 1), but to the authors' knowledge the success of these treatments has not been documented. Calcium nitrate was applied to the sediments of the south basin of Long Lake in spring 1984. Post-treatment chlorophyll, phosphorus, and Secchi disk measurements were not significantly different from pre-treatment measurements, even though internal loading was reduced by an estimated 50 to 80 percent (Noonan, 1986). Noonan argued that the failure to improve water quality occurred because external phosphorus inputs were much greater than internal inputs.

■ **Fish manipulations:** Rehabilitation of fisheries by killing the existing fish populations with rotenone and stocking with desirable species was included in half the Minnesota Clean Lakes Projects (Table 1). Early in the program, fisheries "rehabilitation" was carried out simply to provide good fishing (e.g., Penn Lake). In later projects rough fish such as carp were removed to reduce recycling of phosphorus from sediments (e.g., Clearwater River chain of lakes). In several recent projects (Como, Golden, and Loon lakes), fish were manipulated to maximize populations of large zooplankton such as *Daphnia* and thereby increase phytoplankton grazing. In Como and Golden lakes, rotenone treatment initially resulted in a large *Daphnia* population, clear water, and enhanced macrophyte growth. However, in Como Lake dense phytoplankton blooms returned when zooplanktivores (panfish) were reestablished (Noonan, pers. comm.).

■ **Dredging:** Sediment dredging was part of three Clean Lakes projects, but in all three cases dredging was a localized effort to improve lake aesthetics rather than reduce internal phosphorus loading. Extensive dredging of three lakes in the Fairmont chain over many years—not part of the Clean Lakes program—did reduce sediment resuspension but also may have increased internal recycling of nutrients (Hanson and Stefan, 1985).

■ **Addition of water:** Adding water as a deliberate lake restoration technique was used only once in Minnesota, although water is sometimes added in an effort to maintain or increase lake water levels. Groundwater was added to Hyland Lake after drawdown to dilute the lake water and decrease phosphorus concentrations. The effort may have been counterproductive because the well water had higher phosphorus concentrations (0.11 to 0.52 mg/L phosphorus) than the lake (Minn. Pollut. Control Agency, 1982).

■ **Macrophyte control:** Only one Clean Lakes project included an attempt to control macrophyte growth. In Moore Lake macrophytes were harvested in the spring and fall 1985 and further growth was discouraged by placing nylon sheeting ("Dartek") on the epilimnetic sediments. Some problems apparently occurred with deterioration of the sheeting and excessive macrophyte growth in the years after installation (Tomasek, pers. comm.).

## Remedial Methods

Remedial methods for lake management include short-term control of algae blooms and macrophytes. Copper sulfate is widely used throughout the state for controlling algae blooms. Total treated acreage increased roughly threefold between 1970 and the mid-1980s, peaking at around 70,000 acres in 1983 and declining to 10,000 acres in 1986 (Fig. 1). Major reasons for the general decrease in treated acreage include failure of anticipated nuisance conditions to develop, poorer compliance with treatment reporting requirements, and modified methods for calculating the area treated for different nuisance conditions (Minn. Dep. Nat. Resour. 1987a).

Several studies in Minnesota lakes and elsewhere show the effects of copper sulfate treatment are short-lived and repeated treatments are needed to maintain control of algae blooms (McKnight, 1981; Gatcher et al. 1978; Swain et al. 1986; Swain et al. in prep.). Furthermore, nuisance algae (particularly *Aphanizomenon flos-aquae*) appear to become resistant to copper sulfate treatments. This was evident when comparing the rapid recovery of *Aphanizomenon* in Vadnais Lake, which received weekly copper sulfate treatments, to slower recovery of the same species in both Lake Minnetonka's Halsted Bay, which was treated only three times a summer (Swain, unpubl. data), and in the Fairmont Lakes, which were treated regularly for 58 years (Hanson and Stefan, 1984). Finally, copper treatments can lead to severe oxygen depletion and did cause fish kills in several Minnesota lakes (Hanson and Stefan, 1984).

Perhaps the most important consideration in using copper treatments is the high cost in relation to the short-term benefit. Hanson and Stefan (1984) estimated that the City of Fairmont spent $1.9 million on copper sulfate treatments from 1921 to 1979 before abandoning in-lake treatments and relying upon treatment within the water treatment plant. Similarly, the St. Paul Water Supply District currently spends over $50,000 per year for copper treatment in the Vadnais chain of lakes, achieving limited success in controlling algae blooms and improving the taste of its drinking water (Walker et al. 1989)

Most macrophyte control treatments in Minnesota are intended to accomplish one purpose: eliminating or reducing dense macrophyte growth. Just over a thousand permits for macrophyte control (84 percent for submerged species; 14 percent for emergent species) were issued in 1986, and 2,470 acres were treated. More permits were issued for chemical application (primarily Endothall compounds) than for

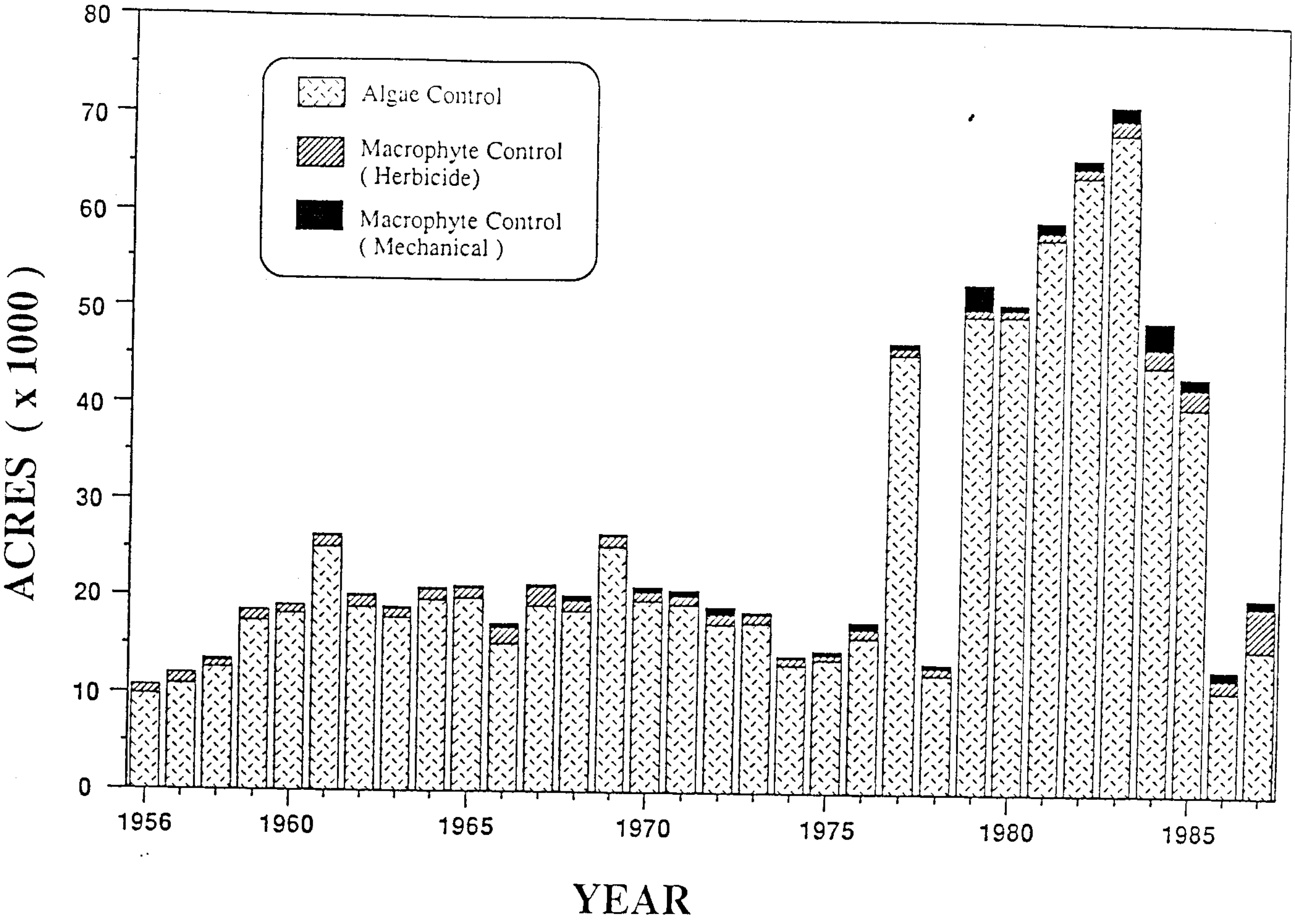

Figure 1.—Remedial treatment for control of macrophytes and phytoplankton blooms through the Minnesota Department of Natural Resources Aquatic Nuisance Control Program. Source: Minn. Dep. Nat. Resour. 1987a.

mechanical harvesting (685 versus 209); however, the total treated acreage for the two methods was nearly identical (Minn. Dep. Nat. Resour. 1987b). Submerged macrophyte control in Minnesota is generally a small-scale operation: the average treatment area was 5.1 acres for mechanical harvesting and 1.5 acres for chemical treatment. Nevertheless, treatment areas were greater than 10 acres for 38 lakes and greater than 50 acres in 8 of these 38. The only documented study of the effects of macrophyte harvesting in removing nutrients was at Lake Sallie, Minnesota. In this study complete harvesting was unsuccessful in reducing algae blooms because large external nutrient inputs were much greater than the mass of nutrients removed by macrophyte harvesting (Peterson et al. 1974).

## Fisheries Management

Undoubtedly the most important lake management activity in Minnesota is associated with fisheries management. The major fisheries management activity is stocking: 955 lakes were stocked with warmwater species and another 174 lakes were stocked with coldwater species during 1987. In addition, the Minnesota Department of Natural Resources regularly "rehabilitates" lakes with rotenone treatment and restocking. From 1983 to 1987, 37 lakes were rehabilitated by the Department of Natural Resources. Of these, 19 were restocked with warmwater species and the remaining 18 were stocked with coldwater species or were not stocked (Groebner, unpubl. data).

Finally, lake aeration is frequently used to prevent winterkill. The number of lakes experiencing winterkill varies each winter, averaging 125 winterkills/year from 1955 to 1982 (Pederson, 1982). The number of winter aeration systems has increased from less than 80/year, from 1978 to 1981, to 149 during the winter of 1986-87. Although most systems were used solely to prevent winterkill, a small number (13 percent of all permits) were intended for winterkill prevention and water quality improvement. A few systems were used solely for water quality improvement, primarily as part of comprehensive Clean Lakes projects or to maintain ice-free areas for waterfowl (Minn. Dep. Nat. Resour. 1987b; Pederson, 1982).

Most winter aeration systems appear to work with at least limited success (Bandow, 1986; Pederson, 1982; Minn. Dep. Nat. Resour. 1987b). For example, of the 53 lakes with functioning winter aeration systems in 1981-82, winterkill occurred in only 5. For three of these lakes, aeration systems were inadequate, and for two others, winterkill probably would have been more severe if aerators had not been used (Pederson, 1982). A major concern with lake aeration systems in Minnesota is that most air injection systems result in open water, which has led to several drowning deaths. Safety concerns have been the impetus for the Minnesota Department of Natural Resources permitting system and sponsorship of aeration workshops.

## Evaluation of Lake Management Practices

No comprehensive review exists on the effectiveness of Clean Lakes projects or other lake management practices in improving water quality in Minnesota lakes. The difficulties in designing and implementing a review program are formidable, but the results of a thorough evaluation would be beneficial for guiding new and ongoing projects. A comprehensive evaluation program should include: (1) an evaluation of project design and implementation, (2) documentation of short-term treatment effects, (3) evaluation of long-term effects, and (4) economic analyses.

Since a requisite for the success of any lake management project is engineering feasibility and proper implementation, the first step of a comprehensive evaluation program should be considering the engineering feasibility and implementation success of each project. For example, the macrophyte harvesting project on Lake Sallie failed to reduce phosphorus levels and algae blooms because the mass of macrophytes removed was too small to significantly affect the lake's overall phosphorus budget (Peterson et al. 1974). Similarly, alum treatment of a lake with large external phosphorus inputs is likely to fail, and installing an aerator to reduce hypolimnetic phosphorus levels is likely to fail if it is unable to prevent anoxia.

For most lake management projects, follow-up monitoring and evaluation is generally of short duration, and reported "successes" are often based on data collected over one or a few seasons. Experimental controls, such as nearby lakes, are almost unheard of in lake management evaluations. Ideally, a monitoring and evaluation program should be continued over a period of many years and include control lakes as well as treatment lakes to evaluate hydrologic and climatic variations and changes in analytical methods (Shapiro and Swain, 1983; Storch, 1986; Preston and Brezonik, 1985; Dierberg et al. 1988). For projects that require continued operation and maintenance (e.g., aerators) or renewal (e.g., continued macrophyte harvesting for phosphorus control), documentation of these operations is essential to evaluate their long-term success. Multi-project evaluations would be greatly facilitated if all data—including design information and operations records as well as monitoring data—were incorporated into a computer data base. For projects that are successful, the final evaluation step would be measuring cost effectiveness.

Evaluation of some projects is complicated by the multiple management techniques used, often simultaneously, making it nearly impossible to determine the relationship between treatment and changes in water quality. Moore Lake, in urban Fridley, Minnesota, clearly illustrates this problem. The present basin of Moore Lake was excavated in 1954 during the construction of a highway. From 1969 to the present management activities have included fish stocking, winter aeration, copper sulfate addition, and construction of a sedimentation basin (prior to 1978). Since 1985, Clean Lakes project restoration activities have included constructing a peat filter to treat inflows, dredging, hypolimnetic aeration, several alum treatments, fisheries rehabilitation, and further macrophyte control.

Despite all this activity, no rigorous evaluation of success has been conducted. This situation, furthermore, is similar to many other lake management programs in Minnesota and elsewhere. Consequently, many Clean Lakes projects result in little or no new knowledge for lake management agencies. One result of this is that failures are likely to be repeated, or at best, moderately successful strategies are unlikely to be optimized. A more insidious problem is that the public may believe that programs fail because of the general inability of scientists to manage lakes, at least in a cost-effective manner.

# Innovative Techniques and Future Directions

Lake management projects in Minnesota have had varying degrees of success, but a variety of new techniques and institutional programs are being developed that should improve management success in the future.

## Development of Predictive Capabilities and Monitoring Methods

■ **Refinement of lake management models.** The anticipated effects of management practices generally are based on prior experience or semi-quantitative empirical relationships. In many cases, this is sufficient: what worked the first time is repeated. However, predictive capability with respect to specific management practices is desirable. Dynamic simulation models clearly have a role in lake management, and one example is the Minnesota Lake Water Quality Model (MINLAKE) (Riley and Stefan, 1987, 1988a,b; Hanson et al. 1987; Zic and Stefan, 1988). MINLAKE is a dynamic process simulation model that represents most of the physical, chemical, and biological parameters (dissolved oxygen, phosphate, chlorophyll a, suspended solids, etc.) that describe lake water quality. MINLAKE has been calibrated for several lakes and then used to select management practices (Riley and Stefan, 1988a,b). However, predictions of management strategies by MINLAKE have not yet been verified. Further model refinements should include: (1) improved representation of "bioavailable" phosphorus, (2) better representation of phosphorus release from sediments, (3) a submodel to represent macrophyte growth and senescence, and (4) a submodel to better represent higher trophic levels such as zooplankton and fish.

■ **Improved assessment methods.** Several new analytical methods are being evaluated that may improve the capability for cost-effective assessment. Paleolimnological analysis has been developed to where it is now routinely used to assess ecological changes in lakes (Engstrom et al. 1985; Smeltzer and Swain, 1985) and has great potential for long-term evaluations of lake management practices (Garrison and Knauer, 1982). Lillesand et al. (1981) found that LANDSAT data were reliable predictors of Secchi depth and moderately good predictors of chlorophyll concentrations in Minnesota lakes. Thus, remote sensing methods appear to have good potential for limnological monitoring.

■ **Biomanipulation.** Biomanipulation generally involves one or more alterations of the fish community (Shapiro et al. 1975, 1982). Most commonly it is directed to specific fish populations. Eliminating benthivorous fish (carp, etc.) may be undertaken to decrease nutrient regeneration from sediments. A second approach is to increase algae grazing by zooplankton. This can be accomplished by reducing populations of planktivorous fish, generally small panfish, either directly—by seining, adding fish toxins, etc.—or indirectly, by adding piscivorous fish such as northern pike. Biomanipulation may also involve physically or chemically altering the environment through whole-lake circulation, metalimnetic aeration (Stefan et al. 1987), or direct alteration of water chemistry to promote desirable algal species (Shapiro et al. 1982). These manipulations have been conducted experimentally with some success (Shapiro et al. 1982; Shapiro and Wright, 1984), but biomanipulation techniques have been intentionally used only occasionally in Clean Lakes projects. As noted earlier, fish rehabilitation has been used in several Clean Lakes projects, and is regularly conducted by the Minnesota Department of Natural Resources outside the Clean Lakes Program. However, with few exceptions (Golden, Como, and Loon lakes), the goal was improved fisheries rather than improved water quality. The potential for achieving water quality improvements by manipulating fish populations is good, but further research is needed to develop ideal stocking densities, to determine the extent of undesirable side effects (e.g., development of *Aphanizomenon* blooms and increased macrophyte growth), and to lengthen the duration of effectiveness, which is now typically only a few years (Shapiro and Wright, 1984).

■ **Improved lake aeration.** Lake aeration has successfully prevented winterkill, but remains expensive and potentially dangerous since it creates patches of open water in the ice. Several techniques have been proposed to improve the efficiency and safety of wintertime aeration. A "bubbleless" aeration technique has been proposed in which air or oxygen is pumped through a bundle of hollow fiber membranes at the lake bottom at sufficient pressure to promote diffusion but not bubble formation. Advantages of this system are enhanced safety, since the ice cover is not disturbed, and greater energy efficiency (Semmens, pers. comm.). A second system, developed at the St. Anthony Falls Hydraulics Laboratory, uses super-fine bubbles to improve oxygen transfer efficiency. Both systems are theoretically sound, but need further development for routine application. Walker et al. (1989) postulated that aeration may not succeed in removing phosphorus in lakes with an inadequate iron supply and found it necessary to add ferric chloride during hypolimnetic aeration in Vandais Lake.

■ **Community management of macrophytes.** Techniques of community management, in which littoral zones are managed to prevent excessive nuisance weed growth, promote desirable macrophyte species growth and improve fisheries, are being developed in Wisconsin (Engel, 1984a,b; 1987a,b; Engel and Nichols, 1984). Given the extent of macrophyte nuisance growths and the strong public interest in warmwater fishing, these techniques appear to have strong potential for application to Minnesota lakes.

### Institutional Changes: The Clean Water Partnership

The Clean Water Partnership is a new cost-sharing program, modelled after the Clean Lakes Program, to "control water pollution associated with land use and land management activities" (Minn. Pollut. Control Agency, 1987). Although the program is not limited to lake water quality improvement—groundwater and stream projects are also eligible—it is likely that the objective of some Clean Water Partnership projects will be lake water quality improvement. The potential for improving water quality in lakes through Clean Water Partnership projects is high because: (1) these projects will focus on controlling nonpoint source loadings; and (2) the project period is sufficiently long (up to eight years) to achieve this goal.

One potential problem is that the Clean Water Partnership, like the Clean Lakes Program, does not require a rigorous evaluation of the effectiveness of each implemented project. For example, the proposed monitoring program (Minn. Pollut. Control Agency, 1988) is unlikely to be sufficiently intensive to determine whether control strategies have actually worked (e.g., resulted in decreased loadings). The guidance document indicates that stream loadings should be calculated with about 20 samples per year, including five storm events (Minn. Pollut. Control Agency, 1988). In view of the published literature on errors in loading estimates (Dolan et al. 1981; Stevens and Smith 1978; Sharpley et al. 1976; Spooner et al. 1988), one might expect errors in annual loadings from roughly 20 to 50 percent with the intensity and methods outlined by the Minnesota Pollution Control Agency (1988). With errors of this magnitude and without control watersheds, it will probably not be possible to determine whether land-use best management practices have been effective. For best management practices that have been thoroughly evaluated, rigorous project analysis may be unnecessary. However, many best management practices have not been closely evaluated or have questionable effectiveness, and the overall success of watershed-scale nonpoint source reduction projects is mixed (Humenik et al. 1987). In this context, rigorous project evaluation for some projects, particularly those employing innovative management techniques, would be sensible. In addition, research to evaluate and further develop best management practices is needed in conjunction with the Clean Water Partnership program.

## Specific Recommendations

Based on this review of lake management in Minnesota, the following recommendations are made:

1. Lake water quality models should be further developed as a lake management tool. Part of this effort should be directed towards detailed limnological "process" studies.
2. Innovative techniques for lake management should be further developed and subjected to rigorous evaluation. These include biomanipulation, high-efficiency aeration systems, and community management of littoral areas.
3. Innovative monitoring approaches such as paleolimnology and remote sensing may be highly cost effective compared to existing monitoring methods and should be further evaluated.
4. Evaluation of the effects of fisheries management on water quality should be continued.
5. Rigorous evaluation of some Clean Water Partnership projects should be conducted, particularly where innovative management strategies are used, in order to determine which best management practices work and are cost effective.

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