UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 249

AN INTRODUCTION TO MATHEMATICAL MODELING OF LAKE PROCESSES FOR MANAGEMENT DECISIONS

by

Mark J. Hanson

Michael J. Riley

and

Heinz G. Stefan

Prepared for

LEGISLATIVE COMMISSION ON MINNESOTA RESOURCES
STATE OF MINNESOTA
St. Paul, Minnesota

February, 1987
Minneapolis, Minnesota

University of Minnesota
St. Anthony Falls Hydraulic Laboratory

Project Report No. 249

AN INTRODUCTION TO MATHEMATICAL MODELING OF LAKE PROCESSES FOR MANAGEMENT DECISIONS

by

Mark J. Hanson

Michael J. Riley

and

Heinz G. Stefan

Prepared for

LEGISLATIVE COMMISSION ON MINNESOTA RESOURCES
STATE OF MINNESOTA
St. Paul, Minnesota

February, 1987

TABLE OF CONTENTS

Page No.

AN INTRODUCTION TO MATHEMATICAL MODELING OF LAKE PROCESSES FOR MANAGEMENT DECISIONS

1. INTRODUCTION

Use of Minnesota Lakes has increased, placing demands on lake managers to maintain or to improve water quality. Although many different management and lake rehabilitation techniques have proven effective, the complex nature of the in-lake processes makes selection of a technique and prediction of effectiveness very difficult. Lake managers are often confronted with expensive projects that must actually be tried to determine their effectiveness.

The Minnesota Lake Water Quality Model, MINLAKE, will be a lake processes simulation model representing some physical, chemical and biological parameters that describe the behavior and quality of a lake, at least in a first approximation. These parameters, including water temperature, dissolved oxygen, phosphate, chlorophyll-a, and suspended solids, will be simulated as a function of depth and time over an entire season. The model will be used with local lake and regional weather data and will require limnological field investigations for calibration and verification. It will be a tool integrating fundamental concepts of physical, chemical, and biological limnology with conservation of mass, energy, and momentum equations as used in engineering analysis. Additions of several possible forms of lake manipulation (lake management and rehabilitation techniques), are planned.

The MINLAKE model will, therefore, offer lake managers a new tool to explore management and rehabilitation techniques by simulation. The primary benefits of modeling are evaluation of management manipulations to a lake for effectiveness, potential problems, and comparison with other options before making large expenditures in the field.

2. COMMON LAKE PROBLEMS AND THEIR POTENTIAL MANAGEMENT SOLUTIONS

2.1. Excessive Algal Growth.

Acceptable water quality is often related to the amount of algae present. There are two basic strategies to reduce an over abundance of algae: (1) prevent or inhibit algal population growth; and (2) kill or eliminate existing algal populations.

Algae need water, light, and nutrients to grow. Management strategies designed to inhibit growth limit the amount of available essential nutrients or limit the amount of light for photosynthesis.

2.1.1. Nutrient Limitation Strategies

Phosphorus has been identified as an essential nutrient for algal growth and is most often the target of nutrient limitation techniques. Nutrient limitation strategies are based on (1) reducing the inflow of nutrients into a lake, (2) decreasing the concentration of nutrients in the lake, and (3) inhibiting recycling of nutrients from the bottom waters and sediments.

Nutrient inflow may be reduced by stopping or reducing the nutrient source, chemical treatment of the inflow water and/or settling out of the nutrients, or use of a biological system to withdraw the nutrients before the inflow reaches the lake. Nonpoint nutrient inflows are very difficult to reduce. Reductions in these nutrient inflows will usually require changes in cultural or agrarian practices.

Concentrations of nutrients within a lake may be reduced by chemical precipitation, biotic harvesting, selective discharge, or dilution (flushing). Descriptions of such techniques can be found, e.g. in "Survey of Lake Rehabilitation Techniques and Experience," Technical Bulletin No. 75, Wisconsin Department of Natural Resources, Madison, Wisconsin, 1974, or in "Lake and Reservoir Restoration," Cooke, G. D. et al., Butterworth Press, Boston, Mass. (1986).

Nutrient recycling from the bottom waters or sediments may be inhibited in a number of ways. Recycling often depends on stratification, hypolimnetic oxygen depletion, nutrient release and/or demineralization of organic matter, and subsequent mixing of the water column.

Strategies to prevent nutrient recycling are:

(1) to suppress stratification by intensified mixing,
(2) to prevent vertical mixing by strengthening the thermal and density gradients, if stratification cannot be stopped.
(3) to oxygenate the hypolimnion, and
(4) to chemically inactivate or physically seal the sediment nutrient source.

2.1.2. Light Limitation Strategies

The second strategy to stop algal growth is to decrease the available light for photosynthesis. This may be done by increasing the time algae will be out of the photogenic zone through intensified mixing, or reducing the photogenic zone by increasing reflectivity or light attenuation.

2.1.3. Other Methods

Other methods of algal control are not aimed at preventing growth but elimination of the standing crop by use of chemical algicides and biological predation (biomanipulation).

2.2. Sediment Turbidity

Aesthetic appearance, as well as biological healthiness, may be harmed by sediment turbidity. The source of the sediment is usually inflow and/or bottom sediment. Inflowing sediment may be reduced by diversion, precipitation, and settling. Bottom sediment may be prevented from entering the water column by physically or chemically sealing the bottom, or increasing the depth of the water column so that surface induced water currents are insufficient to entrain sediment.

2.3. Deficient Fish Habitat

Some lake management goals include providing a better fishery. Particular strategies are highly lake dependent but may include: assurance of adequate dissolved oxygen, development of a greater volume of lower temperature water, or the development of suitable depth for macrophyte growth.

2.4. Poor Potable Water Supply Quality

The problems that affect recreational use are also responsible for many water supply problems.

2.5. Excessive Macrophyte Growth

Many lakes have macrophytes growing in the shallow and shoreline areas. Excessive macrophyte growth diminishes recreational use, especially for boaters accessing the lake from shore and for swimmers. Macrophytes require light and a sufficient nutrient and rooting substrate to grow. Strategies to prevent macrophyte growth include: increasing depth to decrease light and covering sediments with materials (sand, plastic and vinyl sheeting, burlap, etc.) to develop an unsuitable substrate or prevent rooting. Standing crops of macrophytes may be eliminated by chemical treatments, harvesting, shading with light barriers, or introduction of macrophyte predators.

2.6. Summary

Many proven techniques have been developed to solve common lake problems. Any strategy may be of limited effectiveness, and if effective, may have secondary and undesirable effects on other lake processes.

3. PHYSICAL, CHEMICAL, AND BIOLOGICAL CHARACTERISTICS CONSIDERED FOR MODELING OF SHALLOW LAKES

Shallow lakes change more rapidly than large deep lakes, partly because of the stronger influence of weather on a smaller mass of water. The physical dynamics have strong influences and even tend to control biological and chemical processes. Management schemes should consider the shallow lake dynamics and, if possible, use them to aid management methods.

3.1. Physical Characteristics

Heat transfer and water movements, both related to local weather, cause the physical changes occurring in lakes. Most important are thermally induced stratification and mixing.

3.1.1. Temperature

The temperature variation in lakes is related to their heat budget. In temperate climates, from early spring through mid-summer is a period of positive heat input to a lake, primarily by solar radiation and some by heating from the warmer air; midsummer through freeze-up is a period of heat loss. The lake surface is the dominant plane of heat transfer, and the sediments a minor source and sink. Absorption of solar radiation from the lake surface downward and dissipation of heat causes thermal gradients and corresponding density gradients during periods of net heat gain. During the period of heat loss, cooling by evaporation and convection of heat to the atmosphere exceeds solar heat input. Stratification is destroyed by cooler, more dense surface water mixing downward.

A similar periodic cycle of heat input and heat loss also occurs on a daily scale. Solar radiation provides the primary daytime heat input, while evaporation and conduction during the night result in a heat loss.

Heat inputs or losses may also come from water inflows outside of a lake (i.e. cooling water, groundwater, etc.).

3.1.2. Stratification

During the summer, most temperate lakes have many layers, often grouped into three regions: a surface layer mixed down to a depth controlled by nocturnal cooling and wind mixing; the thermocline, a layer where temperature and density change rapidly with depth; and the hypolimnion, or bottom waters below the thermocline. A stratified lake retains a thermocline that prevents the hypolimnion from mixing with the surface waters. The surface waters and hypolimnion develop different physical, chemical, and biological characteristics. The period of stratification depends on the resistance of the thermocline to mixing.

3.1.3. Mixing

Waves, Langmuir currents and surface currents produced by wind and convective currents resulting from cooling provide energy to mix lakes vertically. Surface mixed layers are usually of one to three meters deep. Minnesota lakes that are up to 2 meters deep, therefore, stratify only briefly, and are mixed on an almost daily basis. Lakes with depths in the range from about 3 to 7 meters depth will develop a stronger stratification lasting a few days to several weeks. Lakes deeper than 8 meters will tend to form a season-long stratification. The depths given above are only approximations, and will vary with lake morphometry and weather conditions. In general, three types of mixing are found in shallow lakes: frequent, intermittent, and seasonal. Shallower lakes will mix to the bottom more often and will have higher temperatures at depths below the surface waters.

3.1.4. Lake Inflow and Outflow

Although water inflows to a lake frequently occur at the surface, they will eventually seek levels of similar density in the lake. Significant inflows or outflows can alter lake stratification and mixing.

3.1.5. Turbidity

Sediment turbidity that does not result from inflows is greater in shallower lakes because wind and wave generated currents attenuate with depth. A shallower lake will have more and larger sediments lifted by water currents from the bottom resulting in more sediment being suspended in the water column. The strength of the water currents is related to the fetch of the lake and wind velocity.

Sediment from inflows will remain suspended or settle in response to gravity and lake water currents.

3.1.6. Lake Morphometry

The depth characteristics, surface shape, and orientation of a lake determine how a lake will respond to weather conditions. Water temperature, stratification, and mixing are products of weather inputs into a particular morphometry. A large lake with subbasins may behave similarly to a chain of interconnected lakes.

3.2. Chemical Characteristics

Chemical characteristics of a lake contribute to the basic environment for organisms to live. Concentrations of substances in the water change in response to physical and biological dynamics.

3.2.1. Dissolved Oxygen

Oxygen is needed by most higher aquatic organisms for metabolism. Some oxygen enters a lake by diffusion through the water surface. This slow process can be intensified by waves and mixing. Most oxygen in lake waters is produced by photosynthesis. Oxygen is consumed by respiration of plants and animals and the bacterial and chemical decomposition processes.

Oxygen producing phenomena tend to occur in the surface waters and decomposition processes occur primarily in the hypolimnion. Oxygen concentration tends to be directly related to the temperature distribution. After stratification, the hypolimnion has little or no oxygen input and in productive lakes oxygen will usually become depleted after a certain time.

3.2.2. Nutrients

Nutrient input from snowmelt runoff and other inflows will determine the early spring concentrations in a lake. After the onset of stratification, nutrient recycling may become important. Water current and wave dynamics affect nutrient recycling. Nutrients often accumulate in the hypolimnion due to decomposition of organic matter and release from the sediments. Similarly, algal uptake reduces available nutrients in surface water to small concentrations. When a lake is seasonally stratified, nutrients from decomposition and any nutrients released from the sediments often remain in the bottom waters until fall turn over. Significant nutrient recycling occurs when there is intermittent mixing. Intermittent mixing during the summer transports the nutrient-laden bottom waters to the surface photogenic zone where the nutrients are utilized for algal growth. Sequences of stratification, increase of nutrient concentrations in the bottom waters, and subsequent mixing to the surface waters have the effect of being a "nutrient pump" during the summer.

Nutrient inflow from runoff during the summer is related to precipitation intensity, land use, soil conditions, and watershed topography.

3.3. Biological Characteristics

The two most important biological indicators to lake managers are algal and fish populations. Although a complete chain of lake biota is necessary to sustain fish populations, the essential characteristics to be modeled will be given here.

3.3.1. Algae

Algal growth requires light in addition to nutrients. Algae are predominantly present in the surface waters of lakes where light is sufficient for growth. Algae are distributed throughout the surface mixed layer by wind mixing. In a deeper lake, algae can be circulated out of the photogenic zone reducing the available growth period and total growth. In a shallow lake, algae are kept closer to the source of light, often contributing to excessive growth. Most algae with the exception of some blue-green algae will settle out of a water column if there is no circulation at all.

3.3.2. Fish Habitat

Fish populations will not be modelled, but the important temperature and oxygen characteristics of their habitat will be. Fish require oxygen and anoxic waters are unsuitable for fish. Fish also have preferred temperature ranges. Shallow lakes are generally warmer and more likely to experience summer kill or winter kill from anoxic conditions. Deeper lakes, although cooler, may, if eutrophic and stratified, have only an oxygenated surface mixed zone.

4. MODELING: A LAKE MANAGEMENT TOOL

To use modeling as a lake management tool, a lake manager should be aware of the capabilities and limitations of modeling. The uniqueness and complexity of each lake and lake system require an individualized assessment for lake management and restoration techniques. Indeed, a vendor offering a single solution for all lakes has only a random chance of succeeding. Even when the lake manager has developed a sufficient data base to determine what lake processes cause the lake problems, an assessment must be made of lake management schemes. A given management technique, such as dredging, chemical precipitation, or destratification, affects many interrelated lake processes. Changes in all lake processes must be evaluated to determine the effectiveness of reducing a lake problem and to determine if there are any unwanted side effects. The lake manager must acquire a sufficient data base to determine what dominant lake proceses cause a lake problem, decide which management techniques affect lake processes sufficiently to reduce the problem, and evaluate cost and benefits of management techniques.

The modeling of a lake as described herein utilizes knowledge of known lake processes and their interconnected and interdependent relationships. By inputting individualized lake data, the changes in one process or many lake processes can be simulated. Modeling offers the lake manager a sophisticated evaluation tool at a comparatively low cost to analyze expensive lake management techniques and optimize the money spent on a lake management program.

4.1. Expectation of Modeling

A lake manager would desire a model that can describe all effects of a management technique. A primary limitation of model prediction is the data base with which the model is verified. On a first run basis, a lake manager may simply want to know the feasibility of solving a particular lake problem. If solution of the lake problem is feasible within given constraints, the lake manager will want to know how other lake processes will be affected. Lastly, the lake manager will want to know the best technique to solve the lake problem and how it can be most efficiently administered.

4.2. Minnesota Lake Water Quality Model MINLAKE

4.2.1. Water Temperature Stratification

In the Minnesota Lake Water Quality Model (MINLAKE), a lake is represented as a stack of horizontal layers of variable thickness and of horizontal areas corresponding to the depth-area curve of a lake's morphometry. Each layer is considered to be homogeneously mixed with uniform concentrations and temperature. Temperature and concentrations are considered variable with depth and time. They are computed by the model for specific layers at a particular time. The meteorological variables of air temperature, dew point temperatures, wind direction, wind speed, wind direction, and solar radiation are the input data that drive the physical dynamics of the model.

The turbulence generated in a lake by wind or natural convection mixes the upper layers into a homogeneous surface mixed layer. The mixed layer depth and temperature of the layers within the mixed layer are determined by applying internal (thermal) energy balances and mechanical energy balances. For each time step, the heat energy input and the internal heat energy budget are calculated and applied to give a particular temperature profile. If the water is thermally stratified, lifting work is required to mix a lower layer with the layer above it. The energy required to do the lifting work is derived from wind shear on the water surface (Wu, 1969).

To determine the heat input to the lake, net long wave radiation (mostly atmospheric radiation absorbed at the water surface), net short wave radiation (mostly solar radiation, which is absorbed exponentially with depth with a specified attenuation coefficient), back radiation, heat losses at the water surface by evaporation (condensation), and heat transfer by convection are all considered.

An albedo adjusts the incoming radiation at the water surface for reflection. The cooling which occurs by evaporation at the lake surface is calculated using a relationship similar to that used by Brady et al. (1969).

Solar radiation and wind velocity are the two most important weather variables in the MINLAKE model. Both may vary strongly from day to day and from year to year, and the response in terms of water surface temperature and vertical mixing is, therefore, very dynamic.

4.2.2. Inflow-Outflow Submodel

The inflow-outflow routines simulate the variations in stage through the season. The inflow must be specified in terms of water volume, the temperature of the inflow, and the concentration of all substances simulated by the model (state variables). Measurements or hydrologic models are available to generate the inflow quantity and quality from each source based on meteorological and watershed conditions. A known outflow is more easily handled as only the quantity is required and discharge is often related to stage by a known mathematical relationship.

The inflowing water may flow into any layer depending on the density of the inflow. Inflow with a density less than the density of the surface mixed layer flows into and mixes with the surface layer. If the inflow is of greater density than the mixed layer, it plunges as a density current. The density current entrains water from each layer of lower density until it reaches a layer of equal or greater density and then mixes with that layer.

4.2.3. Suspended Sediment Submodel

An equation representing a relationship among suspended sediment concentration profiles, vertical mixing intensity, rate of deposition, and time is solved over the entire depth. The result is a predicted suspended sediment profile for each time step.

Suspended sediments do not readily react with other substances in the water. Therefore, the suspended sediment concentration is decreased only by settling and increased only by suspended sediment in the inflow and resuspension of sediment from the bottom. Vertical mixing may increase or decrease the suspended sediment concentration in a layer depending on the concentration difference between adjacent layers.

4.2.4 Chlorophyll Submodel

The prediction of algal biomass is the principle objective of a lake eutrophication model. The change in biomass is related to the biological productivity of a lake. Biomass can be expressed in many different ways such as dry weight of algae, carbon content of algae and chlorophyll-a concentration. Of the different representations of biomass, chlorophyll-a concentration is most closely related to productivity. Therefore, the MINLAKE model uses chlorophyll-a concentration as an indicator of biomass.

Fluctuations in algal biomass in a volume of water are due to the combined effects of growth, diffusion, settling, respiration, mortality, and grazing by zooplankton. Most algal cells have a density greater than the density of water and will settle to the bottom over time. Mortality occurs from the natural expriation of cells as well as from grazing by zooplankton. Some types of zooplankton are simulated separately in a zooplankton submodel, but the effect of other, less significant, zooplankton are simulated as a component of algal mortality. Respiration is the reverse process of photosynthesis in which energy is produced by converting organic matter into inorganic matter. Respiration is associated with a release of carbon dioxide and nutrients and utilization of oxygen.

Growth, or more correctly, increase in chlorophyll-a can be simulated in several different ways. Some simple prediction equations are available that compute chlorophyll-a concentration in the surface mixed layer based on nutrient concentrations, mixed layer depth and other parameters. More complex methods predict the growth in each layer individually. In the MINLAKE model, three different methods or model levels are available depending on the level of complexity desired. More complex methods require more field data to adequately calibrate and verify the model.

The first model level for chlorphyll-a concentration is a single equation to predict the chlorophyll-a concentration in the surface mixed layer (Forsberg and Shapiro, 1980). The second and third levels for predicting the chlorophyll-a concentration are more complex. Both simulate growth in each layer individually. The second model level estimates the growth based on the phosphorus concentration in a layer. The third model level simulates an internal pool of nutrients that affect both nutrient uptake from the water and growth separately. Consequently, the increase in chlorophyll-a concentration becomes a two stage process: nutrient uptake and growth. The third model level uses phosphorus as well as nitrate-nitrite and ammonium nitrogen as available nutrients.

All three models include the affect of light as a potential limiting agent to algae growth. The first chlorophyll-a submodel uses the extinction coefficient in the mixed layer to predict the effect of light on algal growth. The two more complex models use a more complex light function in which the light intensity is computed at each layer by computing the attenuation of light through each layer. The effect of light on growth uses a formulation that accounts for growth inhibition at high light intensities and growth limitation at low light intensities (Megard et al., 1984).

4.2.5. The Nutrient Submodel

The modeling of the nutrient cycles is essential to the modeling of phytoplankton growth. The components actually incorporated into the chlorophyll submodel depend on the nutrient being modeled and the relative importance of the component in the overall nutrient budget. Typically a eutrophication model treats phosphorus as the most significant nutrient, but many models also include nitrate-nitrite and ammonium for nitrogen limitation. In the chlorophyll submodel, phosphorus is the only limiting nutrient used in the level one and two models. In the third model level, nitrogen may also be treated as a limiting nutrient.

Phosphorus - Phosphorus available to algae for growth is dissolved in the water and, therefore, fluctuates due to diffusion, biological cycling, and external and internal sources, primarily inflow and sediment release. The biological cycle involves the uptake of phosphorus by algae and subsequent release of phosphorus from algae through respiration and the decay of expired algae. The biological cycling of phosphorus does not in itself make a lake eutrophic. Without external or internal sources, the phosphorus concentration would continually decline due to the settling of algae cells. Consequently, a lake eutrophication model must simulate the biological dynamics of phosphorus to predict chlorophyll-a concentrations as well as simulate additional sources of phosphorus.

The primary external source of phosphorus is from the inflow. Phosphorus is present in the inflow in two forms: dissolved reactive phosphorus that is readily utilized by algae and phosphorus in organic matter (detritus) that is made available as the organic matter decomposes over time. The effect of both sources of phosphorus are simulated in the MINLAKE model. The incoming dissolved reactive phosphorus contributes to an available phosphorus pool and the organic matter contributes to a detrital pool which releases phosphorus as the detritus decays.

The sediment of a lake contains a large store of phosphorus in organic matter, adsorbed to sediment, and complexed with metal ions. The release of phosphorus from the sediments is generally a rather slow, constant rate. However, under anoxic conditions, the complexed portion can be rapidly mobilized causing a significant increase in the release rate. Presently, the release rate in the model is a constant, but there is a need to treat the higher anoxic release rate to more accurately model the phosphorus cycle.

Nitrogen - Nitrogen limitation is modeled only in the case of the first and second algal classes in the Level 3 chlorophyll submodel. The third algal class is assumed to be capable of fixing dissolved nitrogen under nitrogen limitation, and therefore it is phosphorus and light limited only. Nitrogen, like phosphorus, exists in many forms. However, uptake occurs almost exclusively from the nitrate-nitrite fractions and the ammonium fraction. There is also a preference in the uptake of ammonium over the uptake of nitrate-nitrite. Therefore, nitrate-nitrite and ammonium are modeled separately.

Ammonium is modeled in a manner very similar to phosphorus. Respiration, mortality, grazing detrital decay, inflow, and sediment release contribute to ammonium and only sediment release, inflow, and nitrification contribute to the concentration of nitrate-nitrite.

4.2.6. Zooplankton Submodel

The treatment of zooplankton in the model differs from the treatment of all other state variables. Zooplankton movement is not simply a combination of settling and diffusion, but the result of the individual mobility of the zooplankton. In addition, the zooplankton population, effect of grazing, and nutrient recycling are related to the number of zooplankton rather than to the concentration.

The movement of zooplankton (especially large zooplankton) follow a pattern of vertical migration from deep water (day depth) to the surface on a daily time scale. The assumption is made that the retreat to deeper waters during the day provides zooplankton with a refuge from visual predators. At dusk, the zooplankton begin a vertical rise to the surface while grazing and return to deeper layers by dawn. Grazing during vertical migration is assumed to occur in proportion to the chlorophyll-a concentration in a layer compared to the total chlorophyll-a concentration from the day depth to the surface. The effect of the proportion of chlorophyll in each layer is to simulate the time spent in each layer. The day depth of the zooplankton is fixed in the model at the layer where the dissolved oxygen concentration is greater than 0.5 mg/L^{-1} from the layer to the surface. Predation on zooplankton is taken to be a function of light availability at the day depth (Wright et al., 1980). The respiratory and mortality losses contribute to the oxygen and nutrient budgets of the day depth layer in proportion to the length of the daylight period. Grazing at the day depth is not treated in the model.

4.2.7. Dissolved Oxygen and Detritus Submodels

Dissolved oxygen directly affects biological decay processes and phosphorus release from the sediment. In addition, the vertical migration of zooplankton is inhibited by layers of low oxygen concentration. Dissolved oxygen is included as a state variable in the model to aid simulation of the movement of large zooplankton and to simulate some lake management techniques such as hypolimnetic aeration.

In the submodel, dissolved oxygen is increased from two sources. First, at the lake surface, diffusion of oxygen occurs to attain an equilibrium (saturation) dissolved oxygen concentration in the water. Second, the photosynthetic process produces oxygen (Wetzel, 1983). Oxygen is depleted from a layer by the combined actions of respiration, sediment uptake, nitrification, and organic decay of detritus (BOD).

4.3. Data Base Requirements: Weather, Lake and Watershed

The three types of data required to simulate lake conditions with the MINLAKE model are weather data, lake data, and watershed inflow data. It is likely that certain data will not be available for a particular lake site. The following combinations for data availability exist:

1. On-site weather data, on-site lake data, on-site watershed inflow data are available.

2. On-site weather data, on-site lake data, no watershed inflow data are available.

3. On-site weather data, no lake data, no watershed inflow data.

4. No weather data, on-site lake data, no watershed inflow data.

5. No weather data, on-site lake data, no watershed inflow data.

6. No weather data, no lake data, on-site watershed inflow.

7. No weather data, no lake data, no watershed inflow data.

Weather data is the first group of data required to run MINLAKE. Numerous weather data bases are available from which a site specific weather data base can be generated by interpolation.

There are relatively few lake data bases available in the state. However, there is a great deal of data on individual lakes monitored by local, state, and national agencies as well as data collected by private consultants. The lake data is used to specify the morphology of the lake, set initial values of water quality parameters and for verification and calibration of the model. If morphological data is not available transects with a sonar graphic depth finder will supply adequate data to describe the morphology of the lake.

Very little watershed inflow data is available in the state. This data is only necessary if the inflow substantially affects the water quality of the lake to be simulated. In some cases on-site watershed inflow data will not be necessary. Where the data is necessary, a data base of daily values is required. This data base can be generated from inflow measurements or with the aid of hydrologic watershed models (see Hendrickson et al., 1985). Some knowledge of the watershed is required to simulate the amount and quality of inflow resulting from precipitation events.

The MINLAKE Model will simulate the processes of a lake most accurately if lake specific data is available. If the data is not available, the simulation will represent the major lake processes, but is not as accurate. The lake manager is interested in how much the existing lake processes will be affected by a lake improvement method and the MINLAKE model will be able to show major effects.

4.3.1. Weather Data Availability in Minnesota

Weather data that are needed for input to the model are:

1. 24-hr average air temperature
2. 24-hr average wind velocity and direction of the highest wind speed

3. 24-hr incoming solar radiation
4. 24-hr total precipitation
5. 24-hr average dew point temperature, or 24-hr total pan evaporation.
6. percent sunshine

All of the data listed above are recorded at first order weather stations with exception of 24 hour incoming solar radiation. First order weather stations in and near Minnesota are located at:

1. International Falls
2. Duluth Airport
3. St. Cloud Airport
4. Minnesota/St. Paul Airport
5. Rochester Airport
6. Fargo Airport/North Dakota
7. Sioux Falls Airport/South Dakota
8. La Crosse Airport/Wisconsin

Data obtained from the last three stations may be useful if interpolation of data becomes necessary. The locations of the first order weather stations are indicated in Fig. 4.1.

The required weather input data from any weather station can be purchased from:

National Climatic Data Center
NOAA
Asheville, North Carolina 28801
Tel. (704) 257-6682, Ext. 682

The required weather input data from the five first order Minnesota stations can also be obtained through Mr. Earl Keuhnast, Minnesota State Climatologist at Room 284, North Hall on the St. Paul Campus, University of Minnesota as well as from some local and university libraries. The data are presently on microfiche, but not on magnetic media. The data cannot be loaned out, but may be accessed at their location.

The University of Minnesota's Agricultural Extension Service operates nine experiment stations in Minnesota. The stations are located at:

1. Waseca
2. Lamberton
3. Morris
4. St. Paul
5. Crookston
6. Grand Rapids
7. Staples
8. Becker
9. Rosemount

From March 1, 1980, through present, these stations recorded some or all of the following parameters.

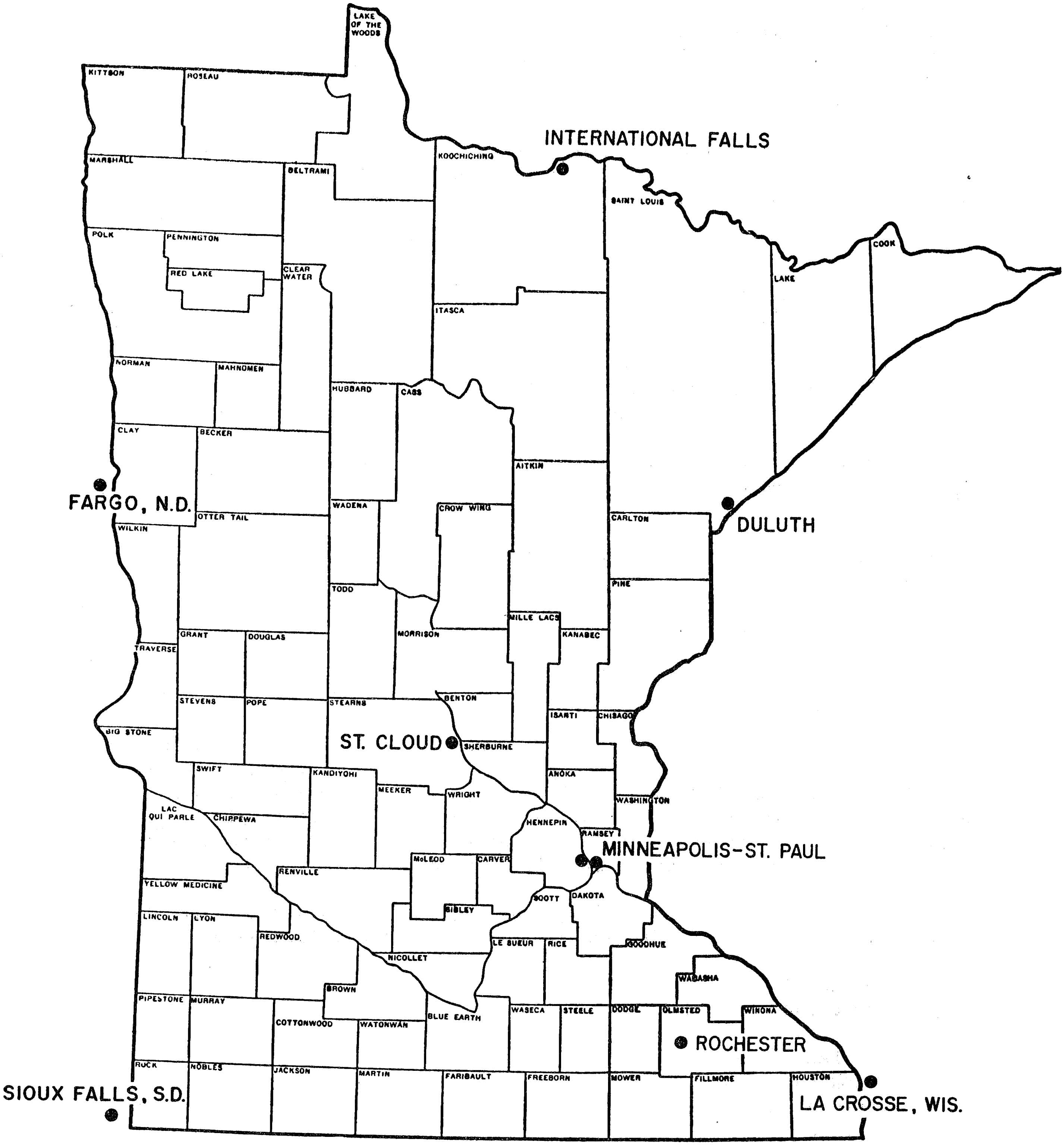

Figure 4.1. Location of first order weather station in and near Minnesota.

1. Daily maximum and minimum air temperature
2. Daily precipitation
3. Daily average wind velocity
4. Daily incoming solar radiation
5. Daily pan evaporation
6. Maximum and minimum soil temperature
7. Solar radiation (Stations 1 through 8).

Complete records of data from all University of Minnesota experiment stations are stored on files by year and by station in the UCC Cyber computer system (Agricultural Extension Service). Additional weather service stations that collect only temperature and precipitation data are operated by the National Oceanic and Atmospheric Administration. Complete tabulated records of air temperatures and precipitation from all weather stations in Minnesota are available in the State Climatologists Office and from the National Climatic Data Center. Precipitation data from other locally maintained observation stations may be available from the state climatologist. Interpolations of the first order weather station data and weather data taken near the simulated lake would be necessary if on-site weather data was not taken. This was done successfully in using an earlier version of the model on the Fairmont Lakes in South Central Minnesota.

The locations of weather stations in Minnesota and the University of Minnesota experiment stations are shown on Fig. 4.2.

4.3.2. Lake Data Availability in Minnesota

Some lake data are probably available on any lake to be simulated as part of assessing the problem in the lake. Lake data are not needed for daily input into the model, but initial lake water quality parameters must be set and the lake morphology must be known. Lake data are necessary for verification and calibration of the model.

The most useful lake data for verification and calibration are:

1. Temperature profile measurements
2. Dissolved oxygen profile measurements
3. Nutrient profile measurements
4. Suspended sediment profile
5. Surface chlorophyll-a measurements in Near Surface Profiles (0 to 4 meters)
6. Profile measurement of BOD

The following agencies have collected various data related to lake modeling.

A. The Pollution Control Agency

   1. Statewide Lake Survey on over 700 lakes
   2. Statewide citizen Secchi Disk Program
   3. Clear Lakes program monitoring

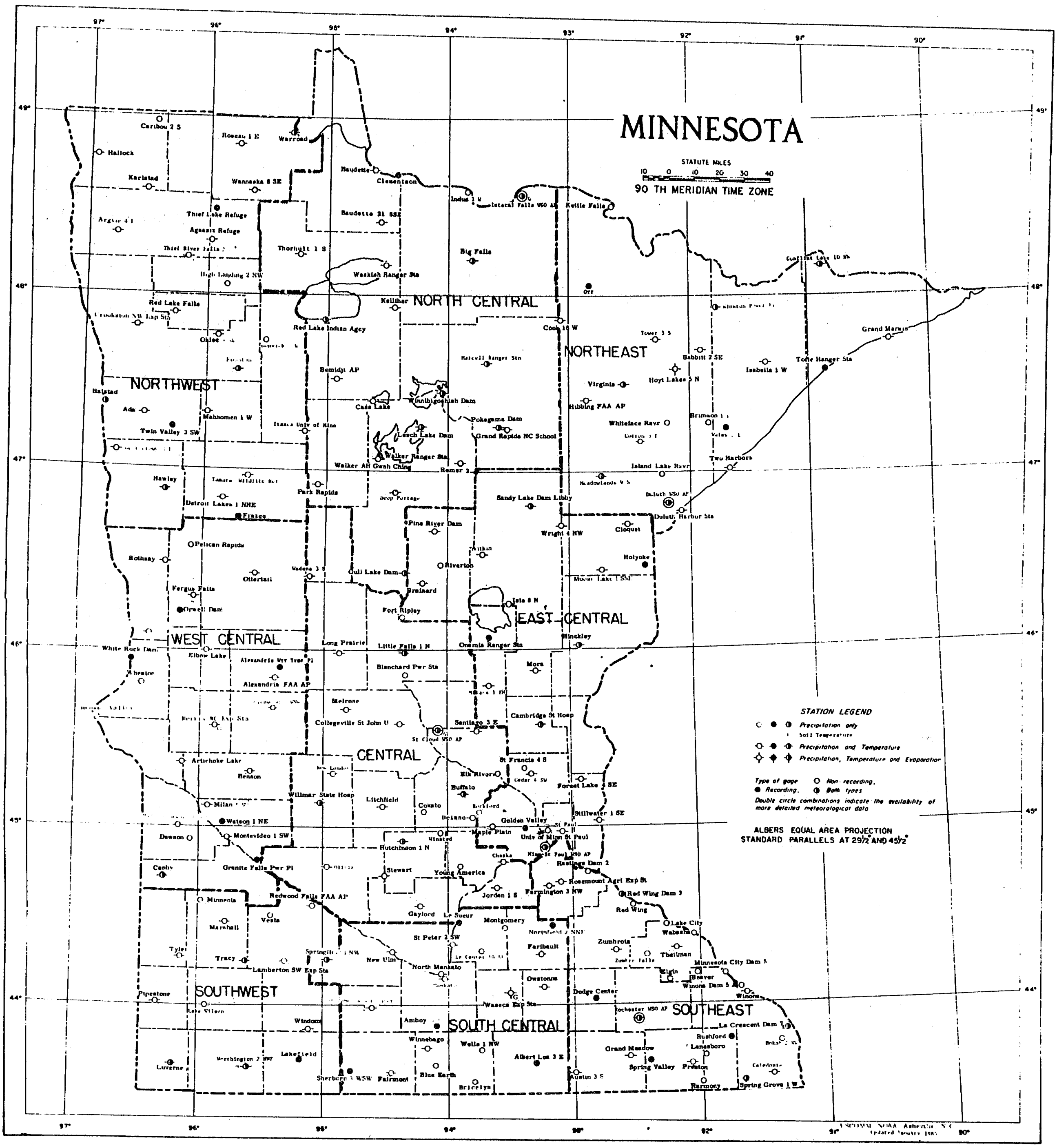

Figure 4.2. Location of all National Weather Service Stations and University of Minnesota experiment stations within Minnesota.

B. Department of Health

   1. Data on lakes and streams for water plants using surface water

C. Water Resources Research Center
   Limnological Research Center
   Freshwater Biological Institute
   University of Minnesota

D. U.S. Geological Survey

   1. Hydrological data
   2. Topographical and watershed data
   3. Research project data

E. Department of Natural Resources

   1. Morphological maps
   2. Water quality data
   3. Fisheries data

F. State Universities

G. Metropolitan Council: Lake surveys and water quality data

The data collected by these agencies varies in intensity and length of record. Before modeling is begun these agencies should be contacted to determine what data is available.

4.3.3. Watershed Inflow Data Availability in Minnesota

Watershed inflow data is required as an input parameter if the inflow has a substantial effect on the lake water quality parameters being modeled. Many lake inflows have only a small effect on lake water quality after spring runoff. For watershed runoff that does affect lake water quality, the effect of precipitation on the quality of the runoff must be analyzed. On-site data is most preferable for watershed inflow data, but generalizations and interpolation from similar watersheds can be made. Inflow quantity and quality data from a watershed are soldom collected on a regular basis except in conjunction with lake and stream improvement programs and wastewater discharge monitoring.

Watershed inflow data is available as follows:

A. Pollution Control Agency

   1. Stream monitoring program
   2. Wastewater treatment discharge monitoring

B. Department of Health

   Stream monitoring related to surface water supplies

C. Department of Natural Resources

Stream flows and hydrological data

D. U.S. Geological Survey

1. Watershed delineation
2. Streamflow

E. Soil Conservation Service

1. Turbidity
2. Streamflow

F. Corps of Engineers

Hydrological data

4.4. Management Technique Submodels

A large number of lake management and improvement techniques have been developed. About 100 lake management and improvement methods have been identified and inventoried from the USEPA lake management proceedings. These methods have been classified into the following categories:

1. Inflow control methods
2. Lake deepening methods
3. Water column mixing methods
4. Nutrient inactivation methods
5. Nutrient outflow acceleration methods
6. Phytoplankton treatment methods
7. Macrophyte treatment methods
8. Fish treatment methods

The manner in which the submodels will simulate each of these categories is addressed in general under section 4.4.2 below. Examples of inflow control, lake deepening, and water column mixing model simulations are presented in 4.4.3.

4.4.1. Inventory of Lake Management Techniques

The lake management and improvement techniques presented in a series of EPA lake management, improvement, and restoration conferences proceedings have been reviewed and listed in Appendix A. The inventory of about 100 lake management techniques in Appendix A contains a brief description of the lake management technique, the objective of the technique, and the reported effectiveness, if stated. Some techniques have reported costs given. Each technique was given an experience rating as follows:

theoretical - observation of method, no reports of method being tried at other sites experimental - experiments have been made using method, but the results are not predictable. Few, if any, actual lake projects

limited experience - method has been applied in a few actual reported cases

moderate experience - method used in a number of areas with supporting documentation

considerable experience - accepted use of method in some geographical areas

extensive experience - method is broadly used and accepted

The techniques are listed in Table 4.1.

4.4.2. Modeling of Lake Management Techniques

Modeling a lake management technique requires that the model can represent the conditions in the lake that the management technique is to control. If this assumption is satisfied, a simplistic approach is to increase or decrease coefficients within the model to reflect the effectiveness of the lake management technique. For example, if the management technique to be modeled was an alum treatment that produced a floc layer on top of the sediment, a simplistic approach to modeling this management technique is to determine the anticipated reduction in sediment nutrient release and to apply it to the sediment release rate function in the model. When using this approach it is necessary to model the sediment release of nutrients in a precise enough manner to predict the effectiveness of the lake improvement technique.

Almost all lake improvement techniques are designed to change one or more of the seven following processes afecting lake productivity:

1. The inflow of water, nutrients, and sediment into a lake;

2. The loss of algal population by settling or grazing;

3. The availability of light to an algal population within a lake;

4. The nutrients in the photogenic or well-mixed surface zone of a lake;

5. The transfer of nutrients from a thermally isolated bottom layer to a surface layer where the nutrients can become available for algal growth;

6. The quantity of nutrients in the bottom layer of water that are thermally isolated from the surface water; and

TABLE 4.1

No.	1 Inflow Input	2 Algal Population	3 Light Availability	4 Mixed Layer Nutrients	5 Nutrient Transfer	6 Hypolimnetic Nutrients	7 Sediment Nutrients	8 Experience Rating	INFLOW CONTROL METHODS
									Biofiltration and Uptake of Nutrients
1.	●	-	-	-	-	-	-	2	1. Detention ponds utilizing macrophytes to remove nutrients
2.	●	-	-	-	-	-	-	3	2. Wetland filtration of nutrients
3.	●	-	-	-	-	-	-	2	3. Seepage trenches
									Chemical Treatments
4.	●	-	-	-	-	-	-	2	4. Aluminum oxide columns
5.	●	-	-	-	-	-	-	1	5. Aluminum sludge treatment
6.	●	-	-	-	-	-	-	2	6. Ferric aluminum blocks
7.	●	-	-	-	-	-	-	2	7. Ferric iron treatment plant
									Sediment Removal
8.	●	-	-	-	-	-	-	6	8. Sediment retention basins
9.	●	-	-	-	-	-	-	2	9. Perimeter road sediment traps
									Stormwater
10.	●	-	-	-	-	-	-	2	10. Aluminum sludge treatment
11.	●	-	-	-	-	-	-	4	11. Detention and storage
12.	●	-	-	-	-	-	-	4	12. Collection system control
13.	●	-	-	-	-	-	-	6	13. Sewage overflow elimination
14.	●	-	-	-	-	-	-	2	14. Underground percolation
15.	●	-	-	-	-	-	-	3	15. Wetland filtration
									Wastewater
16.	●	-	-	-	-	-	-	6	16. Central sewerage
17.	●	-	-	-	-	-	-	3	17. Evapotranspiration bed
18.	●	-	-	-	-	-	-	2	18. Grey water management
19.	●	-	-	-	-	-	-	2	19. Mound systems
20.	●	-	-	-	-	-	-	2	20. Sand filters
21.	●	-	-	-	-	-	-	6	21. Septic tank systems
22.	●	-	-	-	-	-	-	4	22. Tertiary treatment
23.	●	-	-	-	-	-	-	3	23. Wastewater modification
									Watershed Control
									Agricultural
24.	●	-	-	-	-	-	-	2	24. Animal waste containment
25.	●	-	-	-	-	-	-	4	25. Animal waste management
26.	●	-	-	-	-	-	-	5	26. Waste storage ponds
27.	●	-	-	-	-	-	-	6	27. Waste treatment lagoons
28.	●	-	-	-	-	-	-	6	28. Filter strips
29.	●	-	-	-	-	-	-	6	29. Soil conservation management practices
									Urban
30.	●	-	-	-	-	-	-	3	30. Product and use modification to reduce nutrients
31.	●	-	-	-	-	-	-	6	31. Street sweeping
32.	●	-	-	-	-	-	-	2	32. Use of porous concrete
									Lake Watershed
33.	●	-	-	-	-	-	-	3	33. Diversion
34.	●	-	-	-	-	-	-	6	34. Greenbelts
35.	●	-	-	-	-	-	-	2	35. Perimeter road sediment traps
36.	●	-	-	-	-	-	-	4	36. Regrade shore banks
37.	●	-	-	-	-	-	-	6	37. Shore erosion protection and stabilization

TABLE 4.1 (Cont'd)

No.	1 Inflow Input	2 Algal Population	3 Light Availability	4 Mixed Layer Nutrients	5 Nutrient Transfer	6 Hypolimnetic Nutrients	7 Sediment Nutrients	8 Experience Rating	Control
									Regulatory Control
38.	●							6	38. Surface water regulations
39.	●							4	39. Conservation easements
40.	●							3	40. Control of regulation removal
41.	●							4	41. Erosion control ordinance
42.	●							4	42. Improve enforcement of existing regulation
43.	●							6	43. Population density control
44.	●							6	44. Sanitary codes
45.	●							6	45. Shoreland protection ordinance
46.	●							6	46. Subdivision regulations
47.	●							3	47. Wetland conservancy zoning
48.	●							6	48. Zoning controls
									IN-LAKE CONTROLS
									Lake Deepening
									Sediment Removal
49.			●		●	●	●	4	49. Dredging
50.			●		●	●	●	3	50. Excavation
									Physical In Situ consolidation
51.						●	●	2	51. Drawdown and desiccation
52.						●	●	2	52. Aquifer dewatering
									Chemical In Situ Consolidation
53.								1	53. Aeration
54.						●	●	1	54. Nitrogen addition
55.						●	●	1	55. Hydrogen peroxide addition
56.						●	●	1	56. Ozone addition
									Biological In Situ Consolidation
57.						●	●	1	57. Proprietary organism addition
									Sediment Nutrient Inactivation
									Chemical
58.						●		3	58. Hypolimnetic aeration
59.						●		3	59. Hypolimnetic oxygenation
60.						●		2	60. Aluminium injection into sediment
61.						●		3	61. Aluminium floc layering
62.						●		2	62. Ferric chloride
63.						●		2	63. Calcium nitrate
64.						●		2	64. Fly ash layering
65.						●		2	65. Water treatment plant sludge
									Physical sealing
66.						●		3	66. Plastic, vinyl and synthetic liners
67.						●		2	67. Clay-Montmorillite layering
68.						●		2	68. Sand layering
									Water Column Nutrient Inactivation
69.				●		●		3	69. Aluminium treatment
70.								2	70. Potassium aluminium sulfate treatment
71.				●		●		2	71. Ferric chloride treatment
72.				●		●		2	72. Zirconium tetrachloride treatment
73.				●		●		1	73. Lanthanum treatment

TABLE 4.1 (Cont'd)

No.	1 Inflow Input	2 Algal Population	3 Light Availability	4 Mixed Layer Nutrients	5 Nutrient Transfer	6 Hypolimnetic Nutrients	7 Sediment Nutrients	8 Experience Rating	
									Water Column Mixing
74.			●		●	●		6	74. Air injection
75.			●		●	●		3	75. Water jet
									Nutrient Outflow Acceleration
76.		●		●	●		●	4	76. Selective discharge
77.	●	●		●			●	3	77. Flushing/dilution
78.					●	●		3	78. Hypolimnetic withdrawal
									Biological Problem Treatment
									Phytoplankton
									Chemical
79.		●						6	79. Copper sulfate treatment
80.		●						3	80. Cuprose treatment
81.		●						3	81. Cutrine-plus treatment
									Biological
82.		●						1	82. Zooplankton predation
									Macrophytes
83.				●				6	83. Plant harvesting
84.				●				6	84. Macrophyte herbicides
85.				●				3	85. Bottom barriers for macrophyte control
86.				●				2	86. Floating shades for macrophyte control
87.				●				2	87. Dyes for macrophyte control
88.				●				3	88. Fish Predation of macrophytes
89.				●				2	89. Shellfish for macrophyte control
90.				●				2	90. Insects for macrophyte control
91.				●				1	91. Disease organisms for macrophyte control
92.				●				1	92. Competitive plants to displace undesirable macrophytes
93.				●				3	93. Hydraulic dredging for macrophyte control
94.				●				3	94. Diver dredging for macrophyte control
95.				●				3	95. Manual harvesting of small macrophyte plots
96.				●				3	96. Use of a rotovator for macrophyte control
97.				●				3	97. Shallow water tillage for macrophyte control
98.				●				4	98. Drawdown for macrophyte control
									Fish
99.				●				4	99. Piscicides
100.				●				6	100. Rough fish removal

Experience

1 - Theoretical
2 - Experimental
3 - Limited Experience
4 - Moderate Experience
5 - Considerable Experience
6 - Extensive Experience

7. The sediment concentration in the surface layer of a lake.

Figure 4.3 shows schematically the different lake productivity factors that are affected by lake improvement methods.

Inflow control methods, which include biofiltration and uptake of nutrients, watershed control, and regulatory controls, affect the quantity or quality of the inflow. For inflow control methods two factors have to be determined: (1) the change if any in the amount of inflow; and (2) the effect of the inflow control method on the quality of the inflow. Most of th einflow control methods affect the quality of the inflow rather than the quantity. A subroutine can be constructed that modifies the inflow data according to the inflow control method implemented. If the inflow is important, a hydrologic runoff quality model can be used to generate inflow quantity and quality. Submodels can be added to the hydrologic runoff quality model to simulate individual inflow control alternatives.

Diversion of inflow also affects the quantity of the inflows and has to be taken into consideration. Inflow modifications by a wastewater treatment plant or a construction site can generally be well understood in both quantity and quality. These types of inflow control methods are easier to simulate than more complex methods.

Control methods that affect processes within the lake can be simulated by changing certain parameters within the model. Lake deepening through dredging or excavation affects: 1) the photogenic or surface water sediment concentration by reducing resuspension from the bottom; 2) the hypolimnetic nutrient concentration by altering internal recycling; 3) nutrient transfer mechanism by changing the thermostructure of the lake; and 4) light availability by changing the mixing characteristics of the well-mixed area, and the seasonal turnover dynamics.

Lake deepening methods that change lake depths to a small degree are usually intended to reduce resuspension of bottom sediments and to reduce the release of hypolimnetic nutrients. These methods include in situ consolidation of sediment by physical, chemical, and biological methods. Lake deepening methods can be modeled by changing the depth area curves in the model to reflect the new morphology of the lake. The bottom release simulation may have to be altered if lake deepening is accomplished to either a nutrient rich or a nutrient poor layer of sediment.

Sediment nutrient inactivation is intended to reduce hypolimnetic nutrients by either precipitating them during treatment and/or preventing further release of nutrients from the sediments. These methods can be simulated by adjusting the release rate to reflect the effectiveness of a particular method. For methods that precipitate hypolimnetic nutrients, a reduction should be made in the bottom water nutrient concentrations after the treatment.

Water column nutrient inactivation has two objectives: to reduce the nutrients in the photogenic surface waters and to reduce hypolimnetic nutrients. The water column nutrient inactivation methods precipitate nutrients from the entire water column. In addition, some methods build up

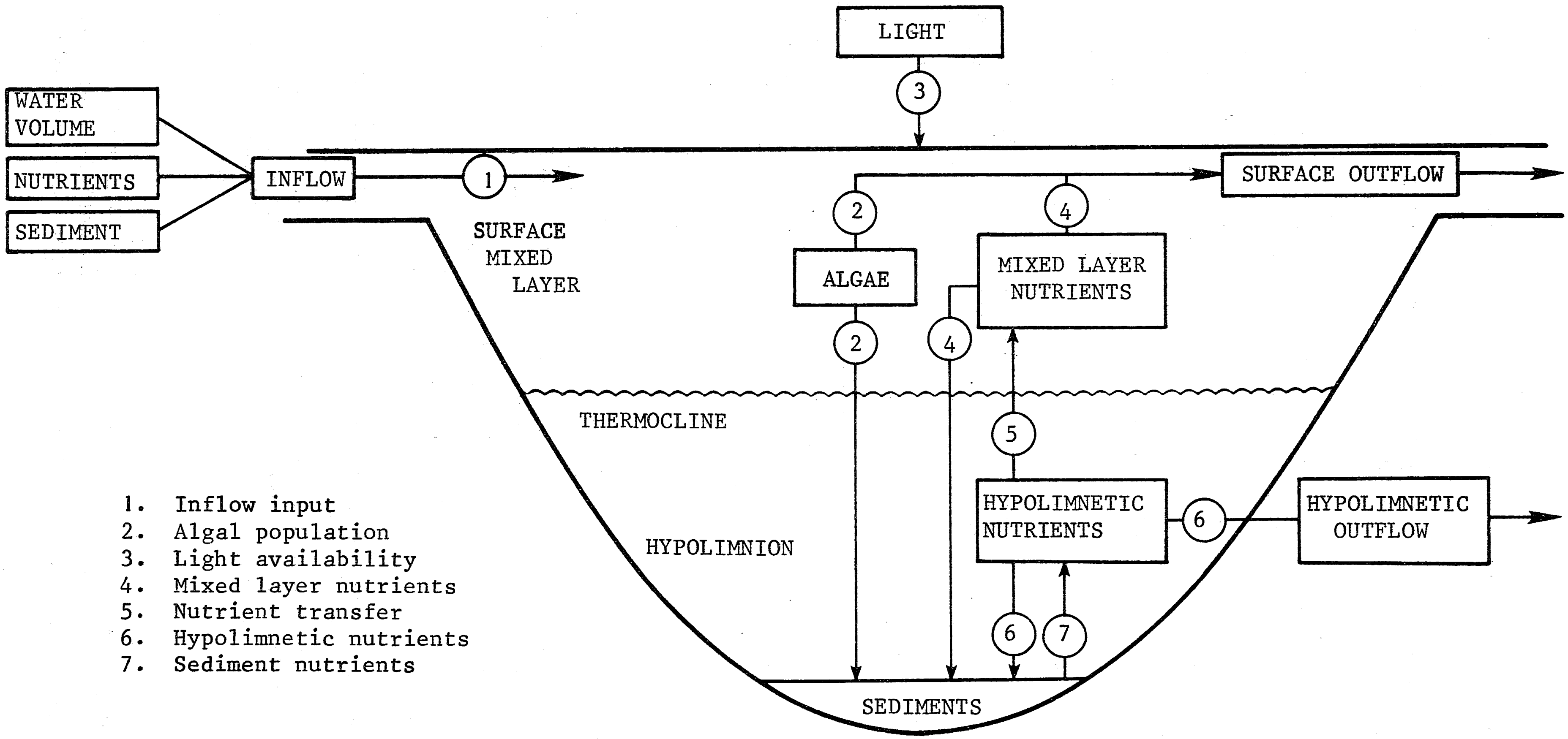

Figure 4.3. Schematic of basic objectives of lake management techniques.

a layer at the sediment-water interface and inhibit further release of nutrients from the sediments. The simplest method of simulating water column nutrient inactivation is by removing a set quantity of the nutrient from each layer as determined from laboratory analysis for the effectiveness of the inactivation technique. The removal would only be applied at one particular timestep. After that, all the biological and nutrient exchange process would continue, but with a reduced supply of nutrients.

Water column mixing methods are usually designed to: 1) reduce the light availability to algae by increasing the mixed-layer depth; 2) restrict nutrient transfer from nutrient laden bottom water to nutrient deficient surface waters by maintaining well mixed conditions throughout the water column at a time when nutrients within the water column are at a low concentration; and 3) maintain aerobic conditions in the bottom waters to prevent or reduce sediment nutrient release.

If the water column mixing method is properly designed and completely mixes the water column it is relatively simple to model. However, mixing techniques have been tried on a large number of lakes with varied results. If compressed air is used, it is difficult to predict (without analysis) what the resulting mixing in the lake will be. The circulation induced by the aeration must be applied to the water column and be separate from the wind-induced circulation and diffusion. If the water column mixing technique does not attain a well-mixed condition, the effects of the artificially induced circulation have to be modeled by subprograms accessed at different times.

Hypolimnetic oxygenation can be simulated by modifying the dissolved oxygen submodeled in the hypolimnion. This can be done by assuming a dissolved oxygen transfer rate from the source and increasing the dissolved oxygen in the hypolimnetic layers. Based on the increased concentration of oxygen in the hypolimnion, the rate of exchange of nutrients between the and water column have to be simulated dependent on the oxygen concentration.

Nutrient outflow acceleration has a number of objectives for altering lake productivity factors. Selective discharge will affect: 1) the algal population by removing some of that population; 2) the photogenic nutrients by removal; 3) nutrient transfer by either removing nutrient laden layers or by decreasing the size of nutrient laden layers; and 4) the photogenic or surface water sediments by removing surface water. Flushing and dilution methods have the same effect but also alter the inflow input. Hypolimnetic withdrawal is designed to affect nutrient transfer and the hypolimnetic sediments.

Biological problem treatments tend to have single control method objectives. Phytoplankton treatment methods are designed to directly reduce algal populations within the lake. Macrophyte control methods affect the population of macrophytes and are usually designed from a water quality perspective to reduce the nutrient recycling from the macrophytes. Fish control methods that are used to improve water quality are usually designed to reduce nutrients in the surface layers by reducing the fish that cause the recycling of nutrients from the sediment, especially bottom feeding fish.

4.4.3. Selected Examples of Modeling for Lake Management

Diversion of sediment-laden inflow to Lake Chicot, Arkansas. Lake Chicot is an oxbow lake adjacent to the Mississipi River in southeastern Arkansas. Before 1920 the lake had a limited drainage area along the Mississippi River and was attractive for recreation. A disasterous flood occurred in 1927 and with the contruction of levies, clearing of land for row crops, and other erosional practices, the main inflow into the lake (Connerly Bayou) has a high concentration of suspended sediment that causes a high turbidity in the lake. To reduce the turbidity and to stabilize the lake level, the U.S. Corps of Engineers has constructed a new outlet structure from the lake and 6,500 cfs pumping stations to divert the inflow from Connerly Bayou to the Mississippi River (Rothwell and Fletcher, 1979; Schiebe et al., 1981).

The objective of the pumping station was to divert enough of the inflow to improve the water quality in the lower part of Lake Chicot and at the same time allow enough water to flow out of the lake to provide a sufficient water supply for rice farmers downstream. Climatological, inflow, and lake data were taken for about four years to assist in the interpretation of the data and ultimately the selection of lake operational management alternatives. An earlier version of the MINLAKE model, a process oriented dynamic model simulating several water quality perimeters including transparency of the lake on a daily time scale,was developed.

Partial destratification of Lake Calhoun, Minneapolis, Minnesota. Lake Calhoun is located in an urban area of Minneapolis, Minnesota. It is approximately one mile in diameter with a mean depth of about 11 meters and a maximum depth of about 20 meters.

On August 3, 1972, a compressed air pumping device was installed at 20 meters depth in Lake Calhoun to test the effects of destratification. The installation was not sufficiently powerful and the lake did not become destratified until mid-September. The rising air bubble plume produced a funnel of water and dissolved materials were transported from the hypolimnion to the mixed layer. The resulting lake temperature structure showed two strong thermoclines, one descending caused by the destratification and one remaining near the surface controlled by air/water interaction.

The artificial mixing was simulated by a vertical advective transport from the deeper to the near surface layers and basin-wide vertical turbulent mixing was considered as only wind and weather controlled before and during the destratification experiment. It was assumed that the rising plume would not change the turbulent diffusion characteristics of the lake as a whole but could be modeled separately as a "chimney effect" e.g., a rising plume which entrains fluid from each layer and transports it to the surface layer. This transport was modeled as a constant flux of a fraction of the phytoplankton and the phosphorus in each layer to the surface mixed layer.

The model was used to predict chlorophyll-a concentration which would have occurred in Lake Calhoun without artificial mid-summer destratification. The simulation indicated that the large mid-summer phytoplankton bloom was due predominantly to the mixed layer fertilization during the first two weeks of the destratification experiment. Six weeks were required to significantly increase the surface mixed layer depth.

The surface phytoplankton population was also predicted under conditions that simulated no sediment phosphorus release. Before the mid-summer destratification experiment the exclusion of internal loading had no effect upon the surface layer phytoplankton population. After the destratification experiment, however, the exclusion of internal loading reduced the surface layer phytoplankton population by approximately 50 percent.

Another simulation was made on conditions that would have existed if the destratification had been initiated during the spring turnover. Under these conditions it would be possible to maintain a mixed layer that is deeper than the naturally occurring one. The effect of this type of destratification on the phytoplankton mass was studied.

Dredging of the Fairmont Lakes, Fairmont, Minnesota. Five shallow lakes in southcentral Minnesota were simulated for conditions before and after dredging. These lakes had problems of excessive resuspension of sediment from the bottom, internal nutrient recycling, and excessive algal blooms. The lakes have maximum depths of 2 to 5-1/2 meters and areas of 34 to 224 hectares. George Lake, Sisseton Lake, and Hall Lake had shallow depths of 2 to 2-1/2 meters maximum depth.

Sisseton, Budd, and Hall Lakes were simulated to determine to what depth these lakes should be dredged, if internal nutrient recycling was to be eliminated. Field measurements had shown that internal nutrient recycling occurred from:

1. Anoxic conditions developing in the bottom waters after weak stratifications;

2. Release of phosphorus from the sediments and increase of concentrations in the bottom waters;

3. Mixing of the water column three to six times during the growth season increased the surface phosphorus concentrations; and

4. Weather conditions that allowed algal populations to utilize the phosphorus received from the bottom waters by the turnover events.

Simulations were run in half-meter increments to determine the depth of dredging so that a season-long stratification would be maintained. The assumption was made that with the season-long stratification, the nutrient-laden bottom waters would be inhibited from mixing to the surface and thus sediment-released nutrients would not be available for mid-summer algal growth. Simulations were run on three different weather years. It was found that the lakes would remain well mixed, essentially to the bottom at maximum lake depths of about 2 to 2-1/2 meters (it should be noted, however, that this also allows resuspension of bottom sediment). By dredging to maximum depths of 2 to 6-1/2 meters the intermittent stratification and subsequent mixing was increased. Season-long stratification could be obtained by dredging to depths of 8 meters or more.

The simulations provided guidelines for persons managing the lakes to determine proper dredging depths.

REFERENCES

1. Bannister, T. T. 1974. "Production equations in terms of chlorophyll concentration, quantum yield, and upper limit to production," and "A general theory of steady-state phytoplankton growth in a nutrient saturated mixed layer," Limnology and Oceanography, Vol. 19, No. 1

2. Bierman, V. J., Jr. 1981. "Modeling phytoplankton-nutrient dynamics in Sagenaw Bay," Jour. of Great Lake Research, Vol. 7, No. 4.

3. Brady, D. K., Groves, W. L. and Geyer, J. C. 1969. "Surface Exchange at Power Plant Cooling Lakes," Report No. 5, Cooling Water Studies for Edison Electric Institute, EEI Publ. No. 69-901, Johns Hopkins Univ., Baltimore, Md., Nov.

4. Cardoni, J. and Stefan, H. 1981. "A model for light and temperature limited productivity in Lake Chicot," Univ. of Minn. St. Anthony Falls Hydraulic Laboratory, External Memorandum 176.

5. DeGroot, W. T. 1983. "Modeling the multiple nutrient limitation of algal growth," Ecological Modeling, Vol. 18, pp. 99-119.

6. DiToro, D. M. and Connolly, J. P. 1980. "Mathematical models of water quality in large lakes, Part II," U.S. Environmental Protection Agency, EPA 600/3-80-65, Gross Ile, Mich.

7. Ford, D. and Stefan, H. 1980. "Thermal Prediction using an integral energy model," ASCE, Jour. of the Hydraulic Div., Vol. 106, HY1, pp. 39-55, Jan.

8. Forsberg, B. and Shapiro, J. 1981. "The effects of artificial destratification on algal populations," in Proc., Symp. on Surface Water Impoundments, June, 1980, Minneapolis,Minn., H. Stefan, ed., published by ASCE, pp. 851-864.

9. Hendrickson, A.C.H. and Stefan, H. G. 1985. "Models for daily quantity and quality of runoff: input to a dynamic lake water quality simulation model, External Memorandum No. 196, St. Anthony Falls Hydraulic Laboratory, Univ. of Minnesota, Oct., 119 pp.

10. Jensen, T. E., Sicko-Groad, L., and Lehman, H. 1976. Aspects of phosphate utilization by blue-green algae," U.S. Env. Protection Agency, EPA 600/3-76-103, Corvallis, Oregon.

11. Jorgensen, S. E. 1981. "Models for Lake Glumso, Denmark," in Models for Water Quality Management, Biswas (ed.)

12. Lehman, J. T., Botkins, D. B., and Likens, G. E. 1975. "The assumptions and rationales of a computer model of phytoplankton population dynamics," Limnology and Oceanography, Vol. 20, No. 3.

13. Mattingly, G. 1977. "Experimental Study of Wind Effects on Reaeration," ASCE, Jour. of Hydraulics Div., Vol. 103, No. HY3, pp. 311-23.

14. Megard, R. O., Tonkyn, D. W., and Senft, III, W. H. 1984. "Kinetics of oxygenic photosynthesis in planktonic algae," Jour. of Plankton Research, Vol. 6(2), pp. 325-337.

15. Monod, J. 1949. "The growth of bactorial cultures," Annual Review of Microbiology, Vol. 3, pp. 371-394.

16. Rothwell, E. D. and Fletcher, B. P. 1979. "Lake Chicot pumping plat outlet structure, Arkansas," U. S. Army Waterways Experiment Station, Tech. Rep. HL-79-10, Vicksburg, Miss., June.

17. Scavia, D. 1980. "An ecological model of Lake Ontario," Ecological Modeling, Vol. 8, pp. 49-78.

18. Schiebe, F. R., Farell, J. O., and Mettenry, J. R. 1981. "Water Quality Improvement of Lake Chicot, Arkansas," in Proc. Symp. on Surface Water Impoundments, June, 1980, Minneapolis, Mn, H. Stefan (ed.), published by ASCE.

19. Schlesinger, D. A. and Shuter, B. J. 1981. "Patterns of growth and cell computation of freshwater algae in light-limited continuous cultures," Jour. of Phycology, Vol. 17, pp. 250-256.

20. Stefan, H. G. and Ford, D. E. 1975. Temperature dynamics in dimictic lakes," ASCE, Jour. of the Hydraulics Div., Vol. 101, No. HY1, pp. 97-114.

21. Stumm, W. and Morgan, J. J. 1981. Aquatic Chemistry, Wiley Interscience Publications, New York, N. Y.

22. Thomann, R. V., DiToro, D. M., Winfield, R. P., and O'Connor, D. J. 1975. "Mathematical modeling of phytoplankton in Lake Ontario," U. S. Environmental Protection Agency, EPA 600/3-75-005, Corvallis, Oregon.

23. Walters, R. A. 1980. "A time and depth-dependent model for physical, chemical, and biological cycles in temperature lakes," Ecological Modeling, Vol. 8, pp. 76-96.

24. Wetzel, R. G. 1983. Limnology. W. B. Saunders Co., Philadelphia, Pa.

25. Wright, D., O'Brien, W. J., and Venyard, G. L. 1980. "Adaptive value of vertical migration: A simulation model argument for the predation hypothesis," in Evolution and Ecology of Zooplankton Communities, C. W. Kerfoot, ed., Univ. Press of New England, pp. 138-147.

26. Wu, J. 1969. "Wind stress and surface roughness at the air-sea interface," Jour. of Geophysical Research, Vol. 74, No. 2, pp. 444-445.

27. Yu, S. L., Tuffey, T. J. and Lee, D. S. 1977. "Atmospheric reaeration in a lake," Water Resources Research Institute, Rutgers University, New Brunswick, N. J., 50 pp.

APPENDIX A

REFERENCES TO LAKE MANAGEMENT TECHNIQUES IN FOUR USEPA AND NALMS LAKE RESTORATION, IMPROVEMENT, AND MANAGEMENT CONFERENCE PROCEEDINGS

I. LAKE RESTORATION

Proceedings of a National Conference August 22-24, 1978.
Minneapolis, Minnesota
U.S.E.P.A. Washington, D.C. 1979

I-63 * Lake renewal techniques

a. Techniques to reduce nutrient in flow

1. wastewater treatment
2. wastewater and stormwater diversion
3. agricultural land treatments
4. treatment of inflow
5. modification of products that contain nutrients

b. Techniques to disrupt internal nutrient cycles

1. dredging
2. destratification - Aeration
3. hypolimnetic Aeration
4. nutrient Inactivation/precipitation
5. bottom sealing

c. Techniques to accelerate nutrient outflow

1. biotic harvesting
2. selective discharge
3. dilution/flushing

I-75 Drainage basin solutions

a. strict zoning and better zoning enforcement
b. sediment basins on tributaries and subsequent removal of sediment
c. greenbelts
d. diversion
e. dilution
f. collection and treatment of stormwater
g. street sweeping
h. use of porous pavement in urban areas

I-96 Alternatives to domestic waste in lakeshore development

a. central sewerage
b. septic tank systems
c. mound system
d. sand filter
e. evapotranspiration bed.
f. waste water modification
g. grey water management

I-105 Summary of dredging

---

*Refers to page number 63 in proceedings. I. LAKE RESTORATION.

I-117	Treatment of lake sediments a. physical liners b. sand c. clay - montmovillite d. fly ash
I-121	Artificial aeration - decision making process - Hypolimnetic oxygenation
I-133	Summary of dilution methods
I-141	Nutrient inactivation a. ferric chloride b. alum (examples) c. zirconium
I-153	Wetlands and organic soils for the control of urban storm water.
I-177	Aquatic plant harvesting - summary of plants harvested - phosphorus loading by macrophytes - costs
I-188	Classification of lake restoration techniques
I-205	Perimeter road sediment traps
I-223	Clean lake programs - draw down - stabilize shoreline - excavate muck - manure shortage facilities - harvest rough fish - sediment control dams - plant macrophytes as a nutrient trap.
I-228	- construct augmentation well - marsh detention ponds - shoreline excavation - introduction of alewives to control zooplankton problem - application of potassium aluminum sulfate
I-230	- use pond containing water hyacinths for premoval of phosphorus - herbicides for macrophytes
I-233	- use of log booms
I-234	- regrade banks to prevent shore erosion - barnyard, feedlot management improvements
I-235	- list of restoration techniques

II. RESTORATION OF LAKES AND INLAND WATERS
International Symposium on Inland Waters and Lake Restoration
September 8-12, 1980. Portland, Maine
U.S.E.P.A. Washington, D.C. 1980

II-7 **	Agricultural waste management
II-116	Alum injected into sediment with a ploughshare
II-124	Review of aeration circulation for lake management
II-140	Reservoir mixing using jet inlet system
II-146	Macrophyte control methods
II-155	Aluminum oxide columns
II-154	Drinking water intake devices
II-158	Weed harvestation
II-198	Shoreland protection ordinances
II-245	Managing macrophytes with fiberglass screens - temporary placement
II-249	Agricultural practices to improve water quality
II-257	Control of animal wastes
II-263	USDA manure management practices
II-272	Treatment of reservoir inflows
II-279	Urban storm water management and cost
II-298	Treatment of wastewater in Sweden and costs
II-304	Stormwater management and costs
II-395	Phosphorus inactivation - dosage requirements
II-400	Control of blue green algae in farm ponds - blocks of ferric-alum
II-405	Alum dose determination and techniques
II-417	Hypolimnetic alum treatment
II-424	Alum treatment
II-429	Detergent modification

** Refers to page 7 in Proceedings, II. RESTORATION OF LAKES AND INLAND WATERS.

III. LAKE RESTORATION, PROTECTION AND MANAGEMENT

Proceedings of the Second Annual Conference of the North American Lake Management Society - October 26-29, 1982. Vancouver, British Columbia
U.S.E.P.A. Washington, D.C. 1983.

III-8*** Dredged sediment for improvement of agricultural lands

III-13 Underground exfiltration of stormwater and treatment of bottom sediment with water plant alum sludge and calcium sludge

III-23 Wetland filtration of stormwater

III-41 In situ lake deepening techniques

a. sediment digestion
  - aeration
  - nitrate
  - hydrogen peroxide
  - ozone
  - proprietary organisms

b. sediment consolidation
  - aquifer dewatering

III-46 Hypolimnetic withdrawal of nutrient laden water

III-70 Importing water from adjacent watershed

III-77 Regulatory tools to protect lakes

- zoning
- subdivision regulations
- sanitary codes
- erosion control ordinance
- boating regulations

III-148 Conservation easements in lake management

- wetland conservancy zoning
- control of regulation removal
- regulation of filling and costs
- grading to reduce shore erosion
- population density control

III-105 Cultivation of macrophyte species to reduce internal loading

III-181 Macrophyte control

- chemical control
- mechanical control by dredging and harvesting
- shades
- dyes
- bottom covering/drawdown
- fish predation
- shellfish
- insects, disease, competitive plants

***Refers to page 8 in Proceedings, III. LAKE RESTORATION, PROTECTION AND MANAGEMENT.

III-202 Macrophyte control costs

III-214 Herbivore insects

III- Blue green algae control by zooplankton grazing

III-257 Lake restoration evaluation and costs

IV. LAKE AND RESERVOIR MANAGEMENT
Proceedings of the Third Annual Conference October 18-20, 1983.
Knoxville, Tennessee
U.S.E.P.A. Washington, D.C. 1984

IV-80 * Agricultural best management practices
- contouring
- strip cropping
- reduced or conservation tillage
- no till
- sod based rotations

IV-82 Effectiveness of agricultural best management practices and the use of sediment control structures

IV-118 Reduction of sediment phosphorus release by ferric chloride and calcium nitrate addition

IV-134 Hypolimnetic aeration
- effects on potable water supplies

IV-151 Biological control of nuisance algae by daphnia

IV-340 Evaluation of alum, aeration, copper sulfate, and water supply treatment to remove taste and odeor problems

IV-395 Tertiary wastewater treatment with alum to remove phosphorus

IV-405 Economic benefits of lake rehabilitation

IV-416 Hydraulic dredging of Shallow Oxbow Lake

IV-423 Regulatory controls to manage water quality

IV-453 Overview of the use of chemicals for aquatic plant control

IV-456 Effects of mechanical harvesting of macrophytes on regrowth and juvenile fish populations

IV-463 Restructuring macrophytes in litteral zones by using screens

IV-467 Use of pigmented nylon film as a macrophyte screen

IV-493 Dilution to reduce nitrogen concentrations

*Refers to page 80 in Proceedings IV. LAKE AND RESERVOIR MANAGEMENT.

IV-498	Multiple phase drawdown for macrophyte control
IV-502	Seasonal flushing to reduce nutrient concentrations
IV-508	Nutrient reduction by street sweeping and stormwater diversion
IV-514	Long term evaluation of alum treatment
IV-525	Method treatment of stormwater
IV-527	Effect of shoreland zoning on macrophytes
IV-531	Prediction of lake response to artificial circulation
IV-537	Selection and design of aeration devices
IV-542	Effects of three years of aeration on water quality
IV-549	Design of hydraulic mixing devices
IV-552	Localized mixing for selective withdrawal
IV-555	Soil and water conservation programs to improve lake watersheds
IV-558	Modifying the project approach in watershed management to reduce nonpoint nutrients
IV-561	Cooperation and compromise in watershed management
IV-564	Screening methodology for urban lake improvement
IV-580	Dredged material disposal and return flow management
IV-586	Dredging techniques for contaminated sediments
IV-592	Dredging loose sediments to control nutrient recycling
IV-599	Dredging and transportation of contaminated sediments

APPENDIX B

DESCRIPTION OF 100 LAKE MANAGEMENT TECHNIQUES

1. INFLOW CONTROL: Biofiltration and Uptake of Nutrients

METHOD: Detention Ponds Utilizing Macrophytes to Remove Nutrients - Inflow water to a lake passes through a detention pond. The pond reduces the flow rate to the lake. Within the pond macrophytes are planted or exist naturally. The macrophytes remove nutrients from the water and utilize them for growth. Increased nutrient removal may be obtained by harvesting the macrophytes. (II-158, II-154)

Objective: Remove nutrients from lake inflows.

Effectiveness: Removal potential: 1,100 kg^{N}/ha/yr; 200 kg^{P}/ha/hr based on growth of 700 g dry wt per year of coontail. (I-177, II-154)

Cost: Dependent on size, control structures, pumping, if necessary.

Experience: Experimental

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentrations in inflow.

2. INFLOW CONTROL: Biofiltration and Uptake of Nutrients

METHOD: Wetland Filtration of Nutrients - Inflow water is percolated through a marsh or wetland area before entering the lake. As water filters through the marsh suspended solids and nutrients are removed. Harvesting of marsh vegetation is recommended to increase long-term efficiency. [See Wetland Filtration of Stormwater.] (III-23)

Objective: Remove nutrients from inflow water.

Effectiveness: 4.2×10^{4} m^{3} water/ha filtered, 24.6 kg P/ha removed (50%)
3.4×10^{4} m^{3} water/ha filtered, 12.1 kg P/ha removed (70%)
(III-25)

Cost: Harvesting, pumping

Experience: Limited

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentrations in inflow.

3. INFLOW CONTROL: Biofiltration and Uptake of Nutrients

METHOD: Seepage Trenches - Seepage trenches can reduce the phosphosus content of small streams that are rich in nutrients. Phosphorus is eliminated when the water passes through the ground. The process is more effective in predominantly finegrained sand and clay. The phosphorus becomes fixed in upper soil layers. (II-154)

Objective: Remove phosphorus from lake inflow water.

Effectiveness: Seepage rate of 55 to 250 m^3/hr reduction was 57 (50 %) (II-154)

Cost: Construction and clean prebasin about every 5 years,

Experience: Experimental

Modeling Method: Inflow input, reduce inflow phosphorus.

Parameters req'd: Phosphorus concentrations in inflow.

4. INFLOW CONTROL: Chemical Treatment

METHOD: Aluminum Oxide Columns - This method removes phosphorus by absorption on aluminum oxide columns. It is mainly effective where the amount of runoff has only slight fluctuations (II-155)

Objective: Remove phosphorus from inflow water.

Effectiveness: Reduction of average P content from 370 mg P/m^3 to 20 mg P/m^3 (II-155)

Experience: Experimental

Modeling Method: Inflow input, reduce inflow phosphorus.

Parameters req'd: Phosphorus concentrations in inflow.

5. INFLOW CONTROL: Chemical Treatment

METHOD: Aluminum Sludge - Aluminum sludge, a waste product of lime-soda ash water softening treatment plants will remove total and ortho-phosphorus when mixed and flocculated. Only laboratory tests have been conducted and parallel efficiencies examined. (III-18)

Objective:	Remove phosphorus from inflow water.
Effectiveness:	Dependent on dosage and contact time.
Experience:	Theoretical
Modeling Method:	Inflow input, reduce phosphorus inflow.
Parameters req'd:	Phosphorus concentrations in inflow.

6. INFLOW CONTROL: Chemical Treatment

METHOD: Ferric Aluminum Blocks - Small ponds or inflows may be treated with aluminum using ferric aluminum blocks to remove phosphorus. The method is inexpensive yet effective for small ponds. (II-402)

Objective:	Remove phosphorus from lake inflows.
Effectiveness:	Dose of 100 mg/L ferric aluminum recommended to eliminate blooms.
Experience:	Experimental
Modeling Method:	Inflow input, reduce inflow phosphorus.
Parameters req'd:	Phosphorus concentrations in inflow.

7. INFLOW CONTROL: Chemical Treatment

METHOD: Ferric Iron Treatment Plant - For large flows of water flocculation or filtration is effective in removing phosphorus. A system called the Wahnbach system has been demonstrated in the Federal Republic of Germany.

Objective: Remove inflowing phosphorus.

Effectiveness: 80 to 90% removal of total phosphorus.

Experience: Experimental

Modeling Method: Inflow input, reduce inflow phosphorus.

Parameters req'd: Phosphorus concentration in inflow.

8. INFLOW CONTROL: Sediment Removal

METHOD: Sediment Retention Basins - Sediment basins slow down the flow rate of inflow water and allow suspended sediment to settle out. Often it is desirable to combine sediment removal with nutrient removal. Detection ponds that use macrophytes to remove nutrients should be considered in conjunction with sediment retention basins.

Objective: Remove sediment by settling in a prelake basin.

Effectiveness: Dependent on flow and basin size.

Cost: Diking, land

Experience: Extensive

Modeling Method: Inflow input, reduction of sediment inflow.

Parameters req'd: Sediment concentrations in inflow.

9. INFLOW CONTROL: Sediment Removal

METHOD: Perimeter Road Sediment Traps - Sediment may be trapped in the watershed by using a perimeter road system. The road serves the purposes of transportation and a dam to hold back sediment laden water. Sediment is retained in the ponding area and the clarified water is discharged to the lake via a drop inlet and discharge tube.

Objective: Remove sediment by settling and filtration.

Effectiveness: 80% removal of sediment entering traps. (I-205)

Cost: Traps alone ~ $20,000: covered cost of 3 traps but did not include cost of road (I-206)

Experience: Experimental

Modeling Method: Inflow input, reduce inflow sediment.

Parameters req'd: Sediment concentrations in inflow.

10. INFLOW CONTROL: Stormwater

METHOD: Aluminum Sludge Treatment - An aluminum based water treatment plant sludge has phosphorus adsorption and retention capabilities. The sludge may have to be mixed with sand to prevent caking. The sludge or sludge-sand mixture is used as a filter media for stormwater to percolate through. (III-13)

Objective: Remove phosphorus from inflowing stormwater.

Effectiveness: Up to 140 g P/m^3 of sludge-sand mixture, 82% total phosphorus removal (382 to 68 mg/m^3) from inflow. (III-13)

Experience: Experimental

Modeling Method: Inflow input, inflow phosphorus reduced.

Parameters req'd: Phosphorus concentration in stormwater inflow.

11. INFLOW CONTROL: Stormwater

METHOD: Detention and Storage - Facilities for detention and storage are designed to equalize flow characteristics for random weather characteristics. Storage facilities include concrete holding tanks, open basins, tunnels, underground and underwater containers, underground "silos," granular packed beds (void space storage), and existing sewer lines. Systems using in-line storage represent promising alternatives in areas where conduits are large, deep, and flat and interceptor capacity is high. In-line storage is reported to cost 10 to 50 percent of similar off-line facilities. Off-line storage is used to attenuate storm flow peaks, reduce storm overflows and capture the first flush or provide treatment in terms of sedimentation. Disadvantages, of storage facilities include their large size, high cost, and dependence on other facilities for processing the retained water and settled solids. (II-285)

Objective: Reduce peak flow and provide opportunities for nutrient and sediment treatment.

Effectiveness: Dependent on particular system.

Cost: In-line: $0.02 to $0.42 per gallon of storage; $31 to $564 per drainage acre. (II-286)

Experience: Moderate

Modeling Method: Inflow input, reduce inflow volume, nutrients, and sediment.

Parameters req'd: Nutrient and sediment concentrations in stormwater.

12. INFLOW CONTROL: Stormwater

METHOD: Collection System Control - Improvement of the collection system will enhance treatment efficiency and direct better quality stormwater to receiving water bodies. Extraneous flows entering the collection system reduce the collection system and plant capacities resulting in unnecessary pollution. Stormwater regulators separate solids from liquids allowing the solids to receive plant treatment and the better quality liquids to flow to water bodies. Catch basins that trap sediment should be used only where necessary, and cleaned more than once a year to limit the sediment build-up to 40 to 50 percent of the sump capacity. Sewers should be flushed frequently to prevent sediment build-up. (II-283)

Objective: Improve collection system efficiency and reduce solids and nutrients to receiving water.

Cost: Infiltration can be reduced at costs of $1 to $15 per gal/min. of inflow rate (II-283).

Experience: Moderate

Modeling Method: Inflow input, reduce water nutrient and sediment inflows.

Parameters req'd: Nutrient and sediment concentrations in stormwater.

13. INFLOW CONTROL: Stormwater

METHOD: Sewage Overflow Elimination - Many wastewater sewer systems have overflow connections that discharge wastewater sewage into stormwater drainage systems at high flows. This results in untreated wastewater sewage being discharged into receiving water bodies. Eliminating the overflow connections is costly because they have to be located, dug up, and sealed. An alternative is to implement better planning and reduce infiltration of extraneous water.

Objective: Prevent untreated wastewater sewage from entering stormwater systems.

Effectiveness: Dependent on number of cross connections and number of periods when wastewater capacity is exceeded.

Experience: Extensive

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentrations in stormwater.

14. INFLOW CONTROL: Stormwater

METHOD: Underground Percolation - Where no land area is available for construction of above ground retention systems, underground percolation may be used. One design used a 1.3 m diameter perforated pipe surrounded by 30 cm of gravel. Much of the first flush stormwater is held in the percolation cylinder until it filters into the surrounding soil.

Objective: Reduce stormwater and nutrient inflow to receiving water body (III-16).

Effectiveness: Total P reduced by 75%; 650 to 158 mgP/m^3.

Cost: $94/hectare - annual - percent removal (III-16)

Experience: Experimental

Modeling Method: Inflow input, reduce stormwater volume and nutrients.

Parameters req'd: Volume of stormwater directed to underground percolation; stormwater nutrient concentration.

15. INFLOW CONTROL: Stormwater

METHOD: Wetland Filtration - Stormwater is diverted to a marsh or wetland area where plants remove nutrients and suspended solids are retained. The wetland area is designed to allow retention and controlled release of filtered stormwater. Harvesting of the wetland vegetation is recommended to increase long-term efficiency. (III-23)

Objective: Remove nutrients from stormwater

Effectiveness: 1.2×10^4 m^3 water filtered, 24.6 kg P/ha removed (51%)
3.4×10^4 m^3 water filtered, 12.1 kg P/ha removed (70%) (III-25)

Cost: Land acquisition; pumping, harvesting.

Experience: Limited

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Stormwater inflow nutrient concentration.

16. INFLOW CONTROL: Wastewater

METHOD: Central Sewerage - Because of the economics of scale, central sewerage is usually more cost effective than individual sewerage in sufficiently populated areas. Central sewerage allows central management and responsibility. Developments must overcome the high capitalization cost to utilize central sewerage.

Objective: Treat wastewater at a central facility and reduce many potential point sources of wastewater pollution. (I-96)

Effectiveness: Dependent on type of system used.

Cost: 65% of annual cost is amortization and maintenance of collection system. (I-96)

Experience: Extensive

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentrations in inflow from existing sewage systems.

17. INFLOW CONTROL: Wastewater

METHOD: Evapotranspiration Bed - This method may provide a means of wastewater disposal in areas where soil absorption of wastewater is precluded. Moisture is evaporated from the soil surface or by transpiration. Ground absorption is minimized if evaporation exceeds precipitation and wastewater application. A typical system consists of 1.5 to 3 feet of selected sand over an impermeable liner. (I-99)

Objective: Evaporate wastewater to prevent any inflow to receiving waters.

Effectiveness: Dependent on site weather conditions.

Experience: Limited

Modeling Method: Inflow input, eliminate or reduce wastewater inflow.

Parameters req'd: Nutrient concentrations in inflow from sewerage systems.

18. INFLOW CONTROL: Wastewater

METHOD: Grey Water Management - Grey water, the domestic wastewater from kitchens, baths, showers, and washers, does not need the treatment that toilet or garbage wastes require. Where central sewerage does not exist grey water may be used after sedimentation and filtration for irrigation and exterior needs. Soil absorption may be sufficient for filtration. After nutrient removal, the water can be discharged to surface waters.

Objective: Remove part of flow from wastewater stream before treatment.

Experience: Experimental

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentrations in inflow from sewerage systems.

19. INFLOW CONTROL: Wastewater

METHOD: Mound Systems - In an area where conventional septic tank soil absorption fields are not suitable, the site can be modified by filling to make a mound absorption field. The mound system provides additional soil for purifying wastewater and the mound reduces the clogging matt that will develop in a conventional system. (I-98)

Objective: Improvement of septic tank drainage field in areas with marginal site characteristics.

Experience: Experimental

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentrations in inflow from sewerage systems.

20. INFLOW CONTROL: Wastewater

METHOD: Sand Filters - At a site where the soil is not suitable for a treatment and disposal medium, an intermittent or recirculating sand filter may prove economically and environmentally acceptable. The filters produce an effluent that meets the BOD and suspended solid standards but the effluent may require further treatment for disinfection and phosphorus.

Objective: Provide alternative medium for treatment and disposal of wastewater where central sewerage is not provided.

Effectiveness: Satisfactory for BOD and suspended solids.

Experience: Experimental

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrite concentrations in inflow from sewerage systems.

21. INFLOW CONTROL: Wastewater

METHOD: Septic Tank Systems - A conventional system consists of a septic tank and soil absorption field. When wastewater is continuously applied to soil a clogging matt that restricts water flow to the soil forms at the infiltrative surface. Soil of more than 3 feet will usually remove bacteria and viruses. A septic system in suitable soil and a separation of at least 50 feet from surface water will usually serve as an adequate disposal system. Nitrates may be a problem, however.

Objective: Provide alternative to control sewerage for wastewater disposal.

Effectiveness: Satisfactory for bacteria, viruses, and phosphorus. Nitrates may be a problem.

Experience: Extensive

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentrations in inflow from sewerage systems.

22. INFLOW CONTROL: Wastewater

METHOD: Tertiary Treatment - Conventional central sewerage involves biological and chemical treatment. Effluents from these processes are frequently high in phosphorus. Aluminum, iron, and lime have been used for precipitating agents. Tertiary treatment is designed to reduce the nutrient load of effluents. (II-300)

Objective: Reduce nutrients in wastewater effluent.

Effectiveness: Precipitation plus filtration effluents 150 to 300 mg^P/m^3 (II-300).

Cost/ Capital: $11 to $30 per capita per year for population of 50,000 to 2,000, respectively.

Cost/ Operating: $9 to $23 per capita per year for population of 50,000 to 2,000, respectively.

Experience: Moderate

Modeling Method: Inflow input, reduce nutrients in inflow.

Parameters req'd: Nutrient concentrations in inflow from sewerage systems.

23. INFLOW CONTROL: Wastewater

METHOD: Wastewater Modification - Where alternatives to central sewerage, especially septic tank systems, are used, modifying the discharged wastewater reduces the dependence on soils for final treatment. Domestic separation of toilet water from garbage and grey water can remove up to 70% of the nitrogen and 30% of the phosphorus in the toilet water to be treated. Use of nonphosphate detergents may reduce nutrients by 65%.

Objective:	Reduce nutrients in wastewater to be treated.
Effectiveness:	Wastewater phosphorus may be reduced by 30 to 65%.
Experience:	Limited
Modeling Method:	Inflow input, reduce inflow nutrients.
Parameters req'd:	Nutrient concentrations in inflow from sewerage systems.

24. WATERSHED CONTROL: Agricultural

METHOD: Animal Waste Containment - Effective containment of animal wastes for a winter period requires a storage capacity of about 6 months. This can reduce phosphorus runoff from animals by as much as 70%. A facility for daily manure storage ranges from 155 m^3 to 1130 m^3. Facilities require transfer systems to move manure to containment areas in the winter and to aid field application in the spring. (II-7)

Objective:	Reduce nutrients from animal wastes.
Effectiveness:	Reduction up to 70%
Cost:	Average cost for 23 major farms was $11,500 per farm. (II-7).
Experience:	Experimental
Modeling Method:	Inflow input, reduce inflow nutrients.
Parameters req'd:	Phosphorus concentrations in inflow from animal wastes.

25. WATERSHED CONTROL: Agricultural

METHOD: Animal Waste Management - There are many ways to use animal wastes in the production of fuel or feed, or as a fertilizer. Fuel or feed production require additional capital and technology. Fertilizer on field is probably the best use. Pasturing animals typically causes wastes to accumulate near watering areas and shaded areas. Trees can be cut from surface water areas and planted near new watering areas away from streams and surface waters. (II-258)

Objective: Reduce nutrients from animal wastes.

Experience: Moderate

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentrations in inflow from animal wastes.

26. WATERSHED CONTROL: Agricultural

METHOD: Waste Storage Ponds - These ponds are used to temporarily store liquid and solid wastes, wastewater, and polluted runoff until it can be safely applied to land or otherwise used. They are constructed of earth and may have paved entrances and bottoms. The ponds tend to seal themselves from seeping as long as liquid wastes are present. Extended drying breaks down the biological seal.

Objective: Storage of farm wastes for later use to reduce pollution.

Experience: Considerable

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentrations in pond inflow.

27. WATERSHED CONTROL: Agricultural

METHOD: Waste Treatment Lagoons - Lagoons are designed to be anaerobic, aerobic, or aerated. Anaerobic lagoons are typically used for livestock wastes, aerobic lagoons are used for relatively weak wastes, and aerated lagoons are used primarily for odor control. The effluent is seldom suitable for discharge to surface waters.

Objective: Reduce nitrogen content of wastes.

Effectiveness: Anaerobic - 3 to 7 Lbs of volatile solids per 1000 ft^3/day
Aerobic - 20 to 60 Lbs BOD5 per acre of surface area per day.

Experience: Extensive

Modeling Method: Inflow input, reduce inflow nitrogen.

Parameters req'd: Nitrogen concentration in inflow from agricultural wastes.

28. WATERSHED CONTROL: Agricultural

METHOD: Filter Strips - While filter strips have been used for years to filter sediment from water flowing from cropland, they can be useful and relatively inexpensive for reducing sediment and pollutants. Filter strips may be used for feeding areas, pasture, waste storage areas, and below feed lots to filter solids.

Objective: Filter solids from waste flows.

Experience: Extensive

Modeling Method: Inflow input, reduce sediment and nutrient inflow.

Parameters req'd: Sediment and nutrient concentrations in inflow from agriculture.

29. WATERSHED CONTROL: Agriculture

METHOD: Soil Conservation Management Practices - Soil erosion and soil loss can be significantly reduced in agricultural watersheds by the use of best management practices. The practices include contour forming, strip cropping, reduced or conservation tillage, and sod base stations. (IV-80, IV-81)

Objective: Reduce soil loss from agricultural watersheds.

Experience: Extensive

Modeling Method: Inflow input, reduce sediment in inflows.

Parameters req'd: Sediment inflow concentrations from agriculture.

30. WATERSHED CONTROL: Urban

METHOD: Product and Use Modification to Reduce Nutrients - Products and the way people use them can be changed to minimize the addition of nutrients in an urban watershed. The use of high phosphate content detergents may be substituted for low phosphaste detergents. Lawn fertilizers and their application may be modified. Other activities that add nutrients to watershed runoff may be changed.

Objective: Reduce nutrients in urban runoff.

Effectiveness: Dependent on amount of modification.

Experience: Limited

Modeling Method: Inflow input, reduce nutrient inflow.

Parameters req'd: Nutrient concentration in stormwater inflow from targeted uses and products.

31. WATERSHED CONTROL: Urban

METHOD: Street Sweeping - Sediment, debris, and other solids that contribute to lake degradation are present on the streets and in gutters. Some studies have shown that more intense street sweeping programs may reduce nutrient inflow to the stormwater system.

Objective: Reduce nutrients and sediments in stormwater inflow.

Experience: Extensive

Modeling Method: Inflow input, reduce nutrients and sediment in stormwater inflow.

Parameters req'd: Nutrient and sediment concentration in stormwater inflow from street runoff.

32. WATERSHED CONTROL: Urban

METHOD: Use of Porous Pavement - Many of the effects of an urban watershed can be minimized by the use of porous pavement. Open graded asphaltic concrete will allow as much as 64 cm/hr of urban runoff to infiltrate through the pavement. The material withstands stability, durability, and freeze-thaw tests. The soil under the pavement should be free draining.

Objective: Reduce urban runoff and utilize soil filtration of nutrients of urban runoff.

Effectiveness: Infiltration rates and storage capacities are good but long term use and clogging has not been measured.

Cost: Comparable to pavement plus drainage.

Experience: Experimental

Modeling Method: Inflow input, reduce inflow nutrients.

Parameters req'd: Nutrient concentration in urban runoff to be filtered.

33. WATERSHED CONTROL: Lake watershed

METHOD: Diversion - Divert runoff from a lake watershed to a point downstream of the lake. Consideration must be given to the amount of water diverted and the quality of that water.

Objective: Reduce the volume of high nutrient runoff.

Effectiveness: Dependent on runoff quality and amount of water diverted.

Experience: Limited

Modeling Method: Inflow input, reduce inflow and nutrient inflow

Parameters req'd: Inflow volume and nutrient concentration.

34. WATERSHED CONTROL: Lake Watershed

METHOD: Greenbelts - The effects of urban surface runoff may be reduced by establishing greenbelts, areas of natural vegetation that are not developed, adjacent to inflow streams and around the lake. The greenbelts allow filtering of nutrients and sediment before surface water flows into the lake.

Objective: Filter sediment and nutrients from surface runoff.

Experience: Extensive

Modeling Method: Inflow input, reduce sediment and nutrient inflow.

Parameters req'd: Inflow sediment and nutrient concentration from area where greenbelts are to be used.

35. WATERSHED CONTROL: Lake watershed

METHOD: Perimeter Road Sediment Traps - For lakes that have high amounts of suspended solids in surface runoff, sediment traps created by a perimeter road may control the rate of runoff to the lake and reduce suspended solids.

Objective: Reduce sediment in surface water runoff.

Effectiveness: Up to 80 percent removal of suspended solids.

Cost: $20,000 per trap in addition to road costs for flood easements; riprap of earthfill area; excavation of core trench; and design changed in the drainage systems.

Experience: Experimental

Modeling Method: Inflow input, reduce inflow of sediment.

Parameters req'd: Inflow sediment concentration from area where sediment traps are used.

36. WATERSHED CONTROL: Lake Watershed

METHOD: Regrade Shorebanks - Steep, sluffing shorebanks can cause increased sediment concentrations in lakes and are more susceptible to erosion. Regrading of shorebanks allows vegetation to develop and increases the stabilization and erosion protection of the shore bank.

Objective: Reduce sediment inflow to lake and sedimentation of lake.

Experience: Moderate

Modeling Method: Inflow input, reduce sediment inflow.

Parameters req'd: Inflow sediment concentration from shore erosion.

37. WATERSHED CONTROL: Lake Watershed

METHOD: Shore Erosion Protection and Stabilization - Shore erosion may be a serious problem for some lakes. Erosion protection reduces sediment input into the lake and may be incorporated with greenbelt and other measured to reduce the nutrient input to a lake.

Objective: Reduce suspended sediment in lake and sedimentation of lake.

Experience: Extensive

Modeling Method: Inflow input, reduce sediment in inflow.

Parameters req'd: Inflow sediment concentration from shore erosion.

38. WATERSHED CONTROL: Regulatory Control

METHOD: Surface Water Regulations - These regulations may restrict specified water uses to designated areas; separate different uses by distances, e.g. swimming, boating; unit uses to time periods or seasons, or exclude some uses completely. In addition to accomplishing recreation arrangement objectives, surface water regulations can be design to prevent erosion (no wake boat speeds), exclude recreational use from spawning and beneficial macrophyte areas.

Objective: Reduce destruction of beneficial habitat and erosion.

Effectiveness: Dependent on compliance with regulation.

Experience: Extensive

Modeling Method: Inflow input, reduce sediment inflow.

Parameters req'd: Inflow sediment concentration from erosion of area to be regulated.

39. WATERSHED CONTROL: Regulatory Control

METHOD: Conservation Easements - provide a mechanism for permanently restricting land use for conservation purposes. The easements can be used by lake management organizations to preserve relatively natural shoreland areas and to provide parcel specific land use management in areas requiring control of non-point sources of water pollution.

Objective: Restrict land use that will degradate lake water quality.

Experience: Moderate

Modeling Method: Inflow input; increase inflow sediment and nutrients for unrestricted development compared to restricted land use in development.

Parameters req'd: Estimated inflow sediment and nutrient concentration from area to be developed.

40. WATERSHED CONTROL: Regulatory Control

METHOD: Control of Regulation Removal - After regulations that protect lake water quality become effective, slight changes in a political base may remove the regulations. A requirement of supermajorities or citizen referendum to remove regulations assures strong support for removal.

Objective: Assume permanency of regulations.

Effectiveness: Dependent on ease of removal.

Experience: Limited

Modeling Method: Estimated inflow sediment and nutrient concentrations under deregulation compared to present use.

41. WATERSHED CONTROL: Regulatory Control

METHOD: Erosion Control Ordinance - Soil loss or erosion control ordinances regulate the amount of erosion or soil loss that may occur from development activities and land use. Soil conservation practices may be necessary to prevent excessive erosion.

Objective: Prevent excessive sediment from entering streams and lakes.

Effectiveness: Dependent upon conservation practices and enforcement.

Experience: Moderate

Modeling Method: Inflow input, reduce sediment inflow.

Parameters req'd: Inflow sediment concentration from area to be regulated.

42. WATERSHED CONTROL: Regulatory Control

METHOD: Improve Enforcement of Existing Regulations - Existence of regulations does not ensure compliance. Existing regulations may be sufficient to meet lake management objectives. The cost and time required to improve enforcement must be considered.

Objective: Achieve compliance of existing regulations that protect lakes.

Experience: Moderate

Modeling Method: Inflow input, reduce sediment and nutrient inflow.

Parameters req'd: Inflow sediment and nutrient concentrations from area to be enforced.

43. WATERSHED CONTROL: Regulatory control

METHOD: Population Density Standards - Dimensional zoning standards for lake areas should take into consideration the size and shape of a lake. Zoning based on surface area of the lake per lot will protect against overcrowding. Water volume, flush potential, and the absorptive capacity of a lake to assimilate nutrients are important considerations.

Objective: Reduce vulnerability to overcrowding and eutrophication by restricting development.

Experience: Extensive

Modeling Method: Inflow input, reduce or maintain nutrient inflow.

Parameters req'd: Inflow nutrient concentrations from area to be zoned.

44. WATERSHED CONTROL: Regulatory Control

METHOD: Sanitary Codes - regulation of the construction and dimensional standards for septic tanks can protect lakes from nutrients derived from sanitary wastes. Percolation and soil boring tests may be required on each lot to determine the location and size of the septic system. Minimum distances between septic systems and from the waters edge should be established.

Objective: Protect lake from septic system nutrients.

Experience: Extensive

Modeling Method: Inflow input, reduce or maintain nutrient inflow.

Parameters req'd: Inflow nutrient concentrations from regulated septic systems.

45. WATERSHED CONTROL: Regulatory control

METHOD: Shoreland Protection Ordinance - Protection of the shoreland area can be very important to preserve a lake from undesirable development and shoreland use. Shoreland use may be restricted to activities that do not degrade lake water quality.

Objective: Protect shoreland area from undesirable use and development.

Experience: Extensive

Modeling Method: Inflow input, reduce or maintain sediment and nutrient flow.

Parameters req'd: Inflow sediment and nutrient concentrations from regulated area.

46. WATERSHED CONTROL: Regulatory Control

METHOD: Subdivision Regulations - To ensure proper and orderly development, subdivision regulations control and division of land into lots. Plots should be reviewed to ensure the adequacy of the street system, proper dimension and layout of lots, sufficient water supply and waste disposal system, proper stormwater arrangement and erosion control, and adequate open space. Planned unit developments can allow a developer to arrange lots in offshore clusters and provide common areas along the shores.

Objective: Provide proper and orderly development.

Experience: Extensive

Modeling Method: Inflow input, reduce or maintain sediment and nutrient inflow.

Parameters req'd: Inflow sediment and nutrient concentrations from regulated area.

47. WATERSHED CONTROL: Regulatory control

METHOD: Wetland Conservancy Zoning - Wetlands may be important to maintaining the long-term health of a lake. Wetlands can be protected by establishing a special wetland conservancy district where alteration of the natural condition of the wetland is prohibited or any changes are made only after the permit is issued that minimizes adverse effects to the wetland.

Objective: Preserve wetlands for spawning grounds and nutrients sinks.

Effectiveness: Sediment traps, and floodwater storage.

Experience: Limited

Modeling Method: Inflow input, reduce or maintain sediment and nutrient inflow.

Parameters req'd: Inflow sediment and nutrient concentrations from the regulated area.

48. WATERSHED CONTROL: Regulatory Control

METHOD: Zoning Controls - Special provisions can be added to existing zoning regulations to adapt them for lake protection purposes. Zoning provisions may include building setback requirements from shore area, retention of shoreland vegetation, regulation of filling and grading to reduce erosion and sedimentation, protection of wetlands, standards to prevent slumping of excavated areas, and standard for construction of lagoons.

Objective: Prevent conflicts between incompatible land use and designate uses beneficial to lakes.

Experience: Extensive

Modeling Method: Inflow input, reduce or maintain sediment inflow.

Parameters req'd: Inflow sediment concentrations from area to be regulated.

49. IN-LAKE CONTROLS: Lake Deepening - Sediment Removal

METHOD: Dredging - Lakes may be deepened or have the morphology changed while the water is present by dredging. The dredging may be done by different methods, but the hydraulic dredge is the most popular. Lake deepening may inhibit nutrient recycling, change seasonal mixing and temperatures, increase water supply, remove undesirable sediment layers, and improve lake water quality.

Objective: Inhibit nutrient recycling, or change mixing and temperature distribution.

Effectiveness: Dependent on particular project.

Cost: $\$1.00$ to $\$15/m^3$

Experience: Moderate for lake improvement.

Modeling Method: Change depth area-curve input, adjust sediment nutrient release rate.

Parameters req'd: Anticipated morphometry; estimated change in sediment nutrient release rate.

50. IN-LAKE CONTROLS: Lake Deepening - Sediment Removal

METHOD: Excavation - Lakes may be deepened and sediment removed by excavation. A dry basin is necessary to excavate the sediment. The costs of digging and transporting large amount of sediment usually exceed the cost of dredging.

Objective: Deepen lake to improve water quality; remove sediment layer.

Effectiveness: Dependent on particular project.

Experience: Limited

Modeling Method: Change depth-area curve input, adjust sediment nutrient release rate, if necessary.

Parameters req'd: Anticipated morphometry; estimated change in sediment nutrient release rate.

51. IN-LAKE CONTROLS: Lake Deepening - Physical In Situ Consolidation

METHOD: Drawdown and Desiccation - A lake that is above the local water table may be deepened by creating an outlet to drain the water out of the lake and allowing the sediments to dry and become more consolidated. Freeze and thaw of the sediments may cause greater consolidation. Dredge material deposition basins have shown consolidation of loose sediment to one-half the original volume.

Objective: Deepen the lake to improve the lake water quality and quantity.

Effectiveness: Dependent on type of sediments, loose sediments that are dried may reduce original volume by one-half.

Experience: Experimental

Modeling Method: Change depth-area curve input, adjust sediment nutrient release rates, if necessary.

Parameters req'd: Anticipated morphometry; estimated change to sediment nutrient release rate.

52. IN-LAKE CONTROLS: Lake Deepening - Physical In Situ Consolication

METHOD: Aquifer Dewatering - A lake that is fed by local groundwater or that has sediments below the local water table may be deepened by dewatering the aquifer until the lake sediments are below the local water table. The sediments should be allowed to dry and go through a freeze-thaw period.

Objective: Deepen an aquifer supplied lake by sediment consolidation.

Cost: Dependent on amount of water to be pumped.

Experience: Experimental

Modeling Method: Change depth-area curve input, adjust sediment nutrient release rates, if necessary.

Parameters req'd: Anticipated morphometry; estimated change in sediment nutrient release rate.

53. IN-LAKE CONTROLS: Lake Deepening - In Situ Consolidation Chemical

METHOD: Aeration - Lake sediments that have high organic contents may be deepened by consolidating the sediment through chemical reactions resulting from aeration. Results have not been substantiated through carefully controlled studies.

Objective: Deepen lake by consolidating sediments.

Effectiveness: Preliminary tests showed little or no reduction in sediment. volume.

Experience: Theoretical - experimental

Modeling Method: Change depth-area curve input, reduce sediment nutrient release rates, if necessary.

Parameters req'd: Anticipated morphometry; estimated change in sediment nutrient release rate.

54. IN-LAKE CONTROLS: Lake Deepening - Chemical In Situ consolidation

METHOD: Nitrogen Addition - It has been reported that nitrate addition has reduced sediment oxygen demand and internal recycling was reduced. Lab experiments have shown a decrease in chemical oxygen demand but an increase in sediment volume.

Objective: Deepen lake or reduce sediment oxygen demand by nitrogen or nitrate addition.

Effectiveness: Chemical oxygen demand was slightly reduced but sediment volume remained the same or increased slightly.

Experience: Theoretical - experimental

Modeling Method: Change depth-area curve input, adjust sediment nutrient release rates and sediment oxygen uptake rate, if necessary.

Parameters req'd: Anticipated morphometry; estimated changes to sediment nutrient release rate and sediment oxygen uptake rate.

55. IN-LAKE CONTROLS: Lake Deepening-Chemical In Situ Consolidation

METHOD: Hydrogen Peroxide Addition - This method appears to have the most promise to reduce lake sediments in situ. Further work is needed to evaluate optimal treatment dosages and the effects of hydrogen peroxide addition on the sediments and the overlying water column

Objective: Deepen lake or reduce sediment oxygen demand by hydrogen peroxide addition.

Effectiveness: Volume of highly organic sediment reduced by over 60%.

Experience: Theoretical- experimental

Modeling Method: Change depth-area curve input, adjust sediment nutrient release rates and sediment oxygen uptake rate, if necessary.

Parameters req'd: Anticipated morphometry; estimated changed to sediment nutrient release rate and sediment oxygen uptake rate.

56. IN-LAKE CONTROLS: Lake Deepening-Chemical In Situ Consolidation

METHOD: Ozone Addition: This method appears to be effective in reducing sediment volume and chemical oxygen demand. Significant pH reductions were noted in tests. More work is needed to determine dosage and adverse effects.

Objective: Deepen lake and reduce highly organic sediments.

Effectiveness: Volume of highly organic sediment reduced over 20%.

Experience: Theoretical - experimental

Modeling Method: Change depth-area curve input, adjust sediment nutrient release rates and sediment oxygen uptake rate, if necessary.

Parameters req'd: Anticipated morphometry; estimated changes to sediment nutrient release rate and sediment oxygen uptake rate.

57. IN-LAKE CONTROLS: Lake Deepening - Biological In Situ Consolidation

METHOD: Proprietary Organism Addition - It has been suggested that the addition of certain organisms to sediments in a lake will accelerate organic decomposition of organic sediment and thereby reduce sediment volume.

Objective: Reduce sediment volume by accelerating biological sediment decomposition.

Experience: Theoretical

Modeling Method: Change depth-area curve input, adjust sediment nutrient release rates, if necessary.

Parameters req'd: Anticipated morphometry; estimated change in sediment nutrient release rate.

58. IN-LAKE CONTROLS: Sediment Nutrient Inactivation - Chemical

METHOD: Hypolimnetic Aeration - This method introduces air into hypolimnetic waters and usually results in waste air and gases being stripped off. The hypolimnetic water is returned back to the hypolimnion after being aerated and destratification does not occur.

Objective: Increase dissolved oxygen in hypolimnetic water to inhibit nutrient release from the sediments.

Effectiveness: Increased oxygen from 0.0 to 5.0 mg/ℓ.

Experience: Limited

Modeling Method: Adjust hypolimnetic dissolved oxygen and nutrient release rate.

Parameters req'd: Nutrient release rate; mass of oxygen added to the hypolimnion.

59. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Chemical

METHOD: Hypolimnetic Oxygenation: This method introduces pure oxygen into hypolimnetic waters while maintaining stratification.

Objective: Inhibit sediment nutrient release by increasing hypolimnetic dissolved oxygen concentration.

Effectiveness: Hypolimnetic oxygen concentration increased from 0.0 to 21.0 mg/ℓ.

Cost:

Capital: Lower than hypolimnatic aeration.

Operating: Higher than hypolimnetic aeration.

Experience: Limited

Modeling Method: Adjust hypolimnetic dissolved oxygen and nutrient release rate.

Parameters req'd: Nutrient release rate; mass of oxygen added to the hypolimnion.

60. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Chemical

METHOD: Aluminum Injection into Sediment - This method injects aluminum with a ploughshare into the upper 15 cm of sediment. The aluminum prevents migration and release of sediment phosphate. The sediment is plowed first without aluminum to release gases. After the aluminum injection a whole lake treatment is applied to precipitate disturbed sediment and phosphate.

Objective: Prevent sediment phosphate release.

Effectiveness: Improved water clarity.

Experience: Experimental

Modeling Method: Reduce water column phosphate and phosphate release rate. Increase secchi depth.

Parameters req'd: Phosphate reduction in water column and sediment release rate.

61. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Chemical

METHOD: Aluminum Floc Layering - This method results in a floc layer on top of the sediments. The floc layer prevents release of phosphate into the water column (II-395, II-405)

Objective: Reduce sediment nutrient release.

Effectiveness: Single treatments have prevented phosphate release for up to five years.

Cost: Varies with treatment method.

Experience: Limited

Modeling Method: Reduce sediment nutrient release.

Parameters req'd: Sediment nutrient release rate.

62. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Chemical

METHOD: Calcium Nitrate - The addition of sufficient amounts of calcium nitrate into the sediment will oxidize the top centimeters of sediment. The oxidation process converts iron in the sediment and water column from a ferrous to a ferric state and ferric hydroxide combines with phosphate and prevents it from being released from the sediments (IV-118)

Objective: Reduce phosphorus recycling from the sediments.

Effectiveness: N/A

Cost: $350,000 for adding calcium nitrate at a rate of 140 g N/m^2.

Experience: Experimental

Modeling Method: Reduce phosphorus release ratios from the sediments.

Parameters req'd: Estimate of the sediment phosphorus release rate after calcium nitrate treatment.

63. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Chemical

METHOD: Ferric Chloride - The application of ferric chloride to sediment has been determined to reduce phosphorus recycling by providing iron that will precipitate ferric phosphate when oxygenated. Comparison has shown that addition of ferric chloride will improve the effectivenss of calcium nitrate addition, but the ferric chloride addition is not as effective as calcium nitrate (IV-118).

Objective: Reduce phosphorus recycling from the sediments.

Effectiveness: Varies with sediment.

Experience: Experimental

Modeling Method: Reduce phosphorus release rates from sediments.

Parameters req'd: Estimate of sediment phosphorus release after ferric chloride treatment.

64. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Chemical

METHOD: Fly-Ash Layering - Fly-ash, a by-product of coal fired power power plants that usually has high lime and aluminum concentrations. Application of a 2-5 cm fly-ash floc layer has reduced the soluable phosphorus in treated sediments. The environmental effects have not been reported (I-118).

Objective: Reduce nutrient release from sediments.

Effectiveness: Significant reduction in interstitial phosphorus concentrations reported and a reduction in summer phosphate release rates (I-118). Fly-ash is a waste product of burning coal. It can usually be obtained at little or not cost.

Experience: Experimental

Modeling Method: Reduce sediment nutrient release rate.

Parameters req'd: Sediment nutrient release rate.

65. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Chemical

METHOD: Water Softening Plant Sludge - Lime-soda ash-alum softening plant sludges have high calcium and aluminum concentrations. These concentrations can combine with sediment phosphate and reduce nutrient release. (III-18)

Objective: Reduce sediment nutrient release.

Cost: Water softening plant sludge is a waste produce of water treatment processes and may be obtained for little or no cost.

Experience: Experimental

Modeling Method: Reduce sediment nutrient release rate.

Parameters req'd: Sediment nutrient release rate.

66. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Physical Sealing

METHOD: Plastic, Vinyl, and Synthetic Liners - Physical synthetic lines have been used more frequntly to prevent seepage of a contained substance into lower strata. Although physical liners have been used for large basins, they are still quite expensive for lake improvement projects. In addition special care must be used to present tearing the liner. Another layer of sand or other material may have to be placed on top of the liner.

Objective: Prevent nutrient release by physical sealing.

Effectiveness:

Experience: Limited

Modeling Method: Reduce sediment nutrient release rate.

Parameters req'd: Sediment nutrient release rate.

67. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Physical

METHOD: Clay-Montmorillite Layering - These materials have had extensive experience for preventing seepage from water bodies. Problems exist in applying the clay layering. In some cases the lake may have to be drawn down and the clay applied directly to the sediments. (I-118)

Objective: Prevent sediment nutrient release.

Experience: Experimental

Modeling Method: Reduce sediment nutrient release rate.

Parameters req'd: Sediment nutrient release rate.

68. IN-LAKE CONTROLS: Sediment Nutrient Inactivation-Physical

METHOD: Sand Layering - If the layering is thick enough, sand may be used as a barrier to prevent sediment nutrient release. The sand tends to compact and may be applied on top of the ice. Sand layering has a low cost but is seldom used in deep water areas by itself because it is not a diffusive barrier and does not appear to have any positive chemical effects.

Objective: Prevent sediment nutrient release.

Experience: Experimental

Modeling Method: Reduce sediment nutrient release rate.

Parameters req'd: Sediment nutrient release rate.

69. IN-LAKE CONTROLS: Water Column Nutrient Inactivation

METHOD: Aluminum Treatment - Aluminum treatment to remove phosphorus is accomplished by coagulation and entrapment of phosphorus laden particulates, precipitation of aluminum phosphorus, and by sorption of phosphorus on the surfaces of aluminum hydrophyde polymers. (II-405)

Objective: Remove available phosphorus from the water column.

Effectiveness: Dependent on water chemistry and dosage.

Experience: Limited

Modeling Method: Reduce phosphorus in the water column.

Parameters req'd: Decrease nutrient concentration immediately after treatment.

70. IN-LAKE CONTROLS: Water Column Nutrient Inactivation

METHOD: Potassium Aluminum Sulfate - Treatment of water column with potassium aluminum sulfate to precipitate phosphorus treatment was used in conjunction with other lake improvement methods so it was not possible to determine results or effectiveness. (I-230)

Objective: Remove available phosphorus from the water column.

Effectiveness: Not reported.

Experience: Experimental

Modeling Method: Reduce phosphorus in the water column.

Parameters req'd: Decrease in the nutrient concentration immediately after treatment.

71. IN-LAKE CONTROLS: Water Column Nutrient Inactivation

METHOD: Ferric Chloride Treatment - Phosphorus will combine quite readily with iron (III) compounds. Experimental application of ferric chloride was made in The Netherlands in 1962 at a dosage of 2 mg/liter. (I-141)

Objective: Remove available phosphorus from the water column.

Effectiveness: Not reported.

Experience: Experimental

Modeling Method: Reduce amount of available phosphorus in the water column.

Parameters req'd: Decrease nutrient concentrations immediately after treatment.

72. IN-LAKE CONTROLS: Water Column Nutrient Inactivation

METHOD: Zirconium Tetrachloride Treatment - Zirconium is effective in removing phosphorus from the water column but may have environmental side effects. A concentration of 5 mg/ℓ was added to a water column with sodium hydroxide to counteract the lowering of pH.

Objective: Remove available phosphorus from the water column.

Effectiveness: Not reported.

Experience: Experimental

Modeling Method: Reduce amount of available phosphorus in the water column.

Parameters req'd: Decrease nutrient concentrations immediately after treatment.

73. IN-LAKE CONTROLS: Water Column Nutrient Inactivation

METHOD: Lanthanum Treatment - Lanthanum has been shown to be effective in removing phosphorus from the water column but more needs to be known about the environmental and health aspects of introducing lanthanum into lakes on a large scale. (I-141)

Objective: Remove available phosphorus from the water column.

Experience: Theoretical

Modeling Method: Reduce phosphorus in the water column.

Parameters req'd: Decrease in nutrient concentration immediately following treatment.

74. IN-LAKE CONTROLS: Water Column Mixing

METHOD: Air Injection - Use of aeration to mix lakes has been one of the most widely used lake improvement methods. Effectiveness of the method has varied widely due to inadequately designed systems. An inadequate system may reduce water quality rather than improve it. (IV-531)(IV-537)(II-124)

Objective: Destratify or maintain deeper surface mixed layer in a lake.

Effectiveness: Reported effectiveness is varied due to inadequately design systems.

Experience: Extensive

Modeling Method: Mixing of layers.

Parameters req'd: Effectiveness of air injection mixing system; Energy added to the water column.

75. IN-LAKE CONTROLS: Water Column Mixing

METHOD: Water Jet - Water jet mixing systems have not been used extensively probably because capitol costs are greater than for air injection systems and a more sophisticated design is required to make them work properly. Water jet mixing systems have been used for reservoir mixing in Great Britain and elsewhere. The water jet system uses input energy quite efficiently.

Objective: Destratify or maintain deeper surface mixed layer in a lake.

Effectiveness: Dependent on system used.

Experience: Limited

Modeling Method: Mixing of layers.

Parameters req'd: Effectiveness of water jet to entrain and mix water layers; energy added to the water column.

76. IN-LAKE CONTROL: Nutrient Outflow Acceleration

METHOD: Selective discharge - total nutrients in a stratified lake can be reduced if water is discharged from stratified layers that have high nutrient concentrations. In most lakes this is typically hypolimnetic waters.

Objective: Discharge nutrient laden water.

Effectiveness: Dependent on amount of nutrients removed.

Cost: Dependent on discharge structure and pumping cost.

Experience: Moderate

Modeling Method: Withdraw modeled nutrient and water mass from discharged layer.

Parameters Req'd: Submodel to determine layers affected by location of the discharge structure.

77. IN-LAKE CONTROL: Nutrient Outflow Acceleration

METHOD: Flushing/Dilution - Flushing/dilution reduce the standing crop of algal cells by replacing lake water with algae-free water.

Objective: Reduce concentration of algal cells and nutrient concentration.

Effectiveness: Dependent on replacement rate, algal concentration and nutrient concentration.

Cost: Cost may be attractive where facilities exist or where dilution water is plentiful and relatively inexpensive to deliver. On the other hand, cost is great where piping is extensive and water is expensive.

Experience: Limited

Modeling Method: Inflow/outflow rates adjusted.

Parameters Req'd: Nutrient and/or algae concentrations in inflow; inflow volume.

78. IN-LAKE CONTROL: Nutrient Outflow Acceleration

METHOD: Hypolimnetic Withdrawal - In a stratified lake the hypolimnion will usually have higher nutrient concentrations than the overlying water column. Hypolimnetic withdrawal removes the nutrient-laden bottom waters to prevent the nutrients from reaching the surface where the nutrients would be available for growth.

Objective: Remove nutrient-laden bottom waters from the lake.

Effectiveness: Dependent on concentration of nutrients in hypolimnion. Volume of hypolimnion removed and contribution of nutrients in bottom water to surface waters.

Cost: Dependent on energy and structures necessary to remove the bottom waters.

Experience: Limited

Modeling Method: Reduce water volume in hypolimnetic waters.

Parameters req'd: Volume of outflow and depth from which water is removed.

79. BIOLOGICAL PROBLEM TREATMENT: Phytoplankton-chemical

METHOD: Copper Sulfate Treatment - Excess concentration of copper ion is toxic to most algae. Treatment is accomplished by dragging mesh bags of copper sulfate through the water or dissolving the copper sulfate in a premixing chamber and then spraying the saturated solution on the water.

Objective: Kill standing crop of algae.

Effectiveness: At proper concentrations complete kill can be achieved in hours.

Cost: $0.85 per lb. applied on an annual basis

Capital: Boat and motor, pumping equipment.

Operating: 20 man hrs/6000 Lbs copper sulfate applied, fuel, cooper sulfate.

Experience: Extensive

Modeling Method: Algae reduction.

Parameters req'd: Rapid short term increase in algal mortality rate.

80. BIOLOGICAL PROBLEM TREATMENT: Phytoplankton-Chemical

METHOD: Cuprose Treatment (Cuprose manufactured by Nalco Chemical Co.) - One of the major limitations of copper sulfate is its ineffectiveness in alkaline waters. The development of a special copper formulation, Cuprose, offers increased effectiveness in alkaline waters. Cuprose is available in granular form and can be applied in the same way as copper sulfate. Cuprose is completely soluble and has greater stability than copper sulfate in water.

Objective: Kill standing crop of algae.

Effectiveness: At proper concentrations complete kill can be achieved in hours. Cuprose dosages have been shown to be 1/5 to 1/2 that of copper sulfate.

Cost: $0.85 per lb. applied on an annual basis.

Capital: Boat and motor; pumping equipment.

Operating: Fuel, Cuprose, labor

Experience: Limited

Modeling Method: Algae reduction.

Parameters req'd: Rapid short term increase in algal mortality rate.

81. BIOLOGICAL PROBLEM TREATMENT: Phytoplankton-chemical

METHOD: Cutrine plus treatment (Cutrine plus manufactured by Applied Biochemists, Inc.) - Cutrine plus is a liquid algicide that contains about 9.0 per cent copper. The recommended dosage is 0.6 gallons per acre of water to be treated for planktonic and filamentous algae. Surface spraying is the most practical method of application.

Objective: Kill standing crop of algae.

Effectiveness: At proper concentration, complete kill in hours.

Cost:

Capital: Boat and motor; pumping equipment.

Operating: Labor, fuel, Cutrine plus.

Experience: Limited

Modeling Method: Reduce algae.

Parameters req'd: Rapid short term increase in algal mortality rate.

82. BIOLOGICAL PROBLEM TREATMENT: Phytoplankton-Biological

METHOD: Zooplankton Predation - It has been observed in many instances that zooplankton predation can control phytoplankton populations. Experiments have been conducted where zooplankton, especially Daphnia, have been introduced into lakes to control phytoplankton populations. It may be possible to decrease zooplankton predation or increase zooplankton populations to control phytoplankton.

Objective: Reduce or control phytoplankton population with zooplankton grazing.

Experience: Theoretical-expeimental

Modeling Method: Reduce algae.

Parameters Req'd: Change in zooplankton predation and/or growth rates.

83. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Plant Harvesting - Most species are soft enough to be cut and will float to the top of the water surface where they can be removed with conventional harvesting equipment. The efficiency of harvesting relates to the biology of individual plant species for which information about potential biomass, regrowth rates, and methods of reproduction are needed to determine the longivity of a harvest treatment.

Objective:	Remove objectionable macrophytes from the water, reduce nutrient input from microphytes.
Effectiveness:	One to two harvests per season; milfoil possibly more
Cost:	$1,200/ha(III-202) - $1,575/ha(III-199), $100-$300 ha(I-183)
Capital:	Harvestor; $55,000(III-202) ~ $50,000(III-198), $70,620(I-183)
Experience:	Extensive
Modeling Method:	Reduce nutrient input attributable to microphytes
Parameters req'd:	Nutrient input attributable to macrophytes

84. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Macrophyte Herbidices - Chemicals available include 2,4-D, Diquat Endothal Simazine, Fenac, dichlobenil, acroaurolein, fluridone and copper compounds. Endothal diquat and 2,4-D are used for control of Eurasian water milfoil, curly leaf pondweed, and elodea. Rapid decomposition may cause adverse effects on aquatic life.

Objective:	Eliminate macrophytes and nutrient input from macrophytes.
Effectiveness:	Weeks to seasonal macrophytes.
Cost:	$700 at 10 ha/dy to $2,500 at 1 ha/dy. (III-202)
Capital:	About $12,000 for applicator unit (III-202)
Operating:	Chemical at 45 kg/ha is about $200/ha (III-202)
Experience:	Extensive; summaries III-181, III-200
Modeling Method:	Reduce nutrient input attributable to macrophytes, expired macrophytes contribute to detrital pool.
Parameters req'd:	Nutrient input attributed to macrophytes; mass of macrophyte detritus contributing to the detrital pool.

85. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Bottom Barriers for Macrophyte Control - Sediment coverings of fly ash, sand, clay, and plastic or rubber sheeting have been used to prevent macrophyte growth. Long term control is thwarted by accumulation of new sediment on top of the covering that supports plant growth. Barriers are effective if cleaned. Polyethylene, windowscreen and aqua screen may be reusable and therefore cost could be amortized over years, (III-184; 185). Sediment amendments of $Cu(OH)_2$, H_2SO_4 and NaCℓ have been tested, but did not kill plants.

Objective:	Prevent macrophyte growth by inhibiting root development and reduce nutrient input from macrophytes.
Effectiveness:	3 weeks to 2 months required to reduce biomass. Must be cleaned seasonally. (III-190)
Cost:	Burlap - $12,000/ha; Polyethylene - $13,000/ha; Window Screen - $20,000/ha; Aqua Screen - $50,000 ha. (III-202).
Capital:	Burlap ($.36/m^2); Typar (DuPont)($.72/m^2); Aqua Screen (Menardi Southern - $2.16/m^2)
Experience:	Limited
Modeling Method:	Reduce nutrient input attributable to macrophytes, reduce sediment nutrient release rate.
Parameters req'd:	Amount of macrophyte reduction and nutrients from macrophytes; sediment nutrient release rate.

86. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Floating Shades for Macrophyte Control - Floating black vinyl sheeting. Water underneath is generally unusable. The shades are relatively fragile and cannot withstand high winds or pounding waves. (III-184)

Objective:	Prevent light from reaching macrophytes, and reduce nutrient input from macrophytes.
Effectiveness:	Varied; 1 to 2 months to kill macrophytes.
Experience:	Experimental
Modeling Method:	Reduce nutrient input from macrophytes.
Parameters req'd:	Amount of macrophyte reduction and nutrients from macrophytes

87. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Dyes for Macrophyte Control - Use of dyes began in 1947 to control macrophytes. Dilution and high sediment turbidity can make dyes ineffective. Caution must be used because dye is toxic to humans. Commercial dye names are "Aqua Shade," "Sierra Blue" (Aquatic Systems). (III-184)

Objective: Reduce macrophytes and nutrients released from macrophytes.

Effectiveness: Varied.

Experience: Experimental

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Amount of macrophyte reduction and nutrients from macrophytes.

88. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Fish Predation of Macrophytes - Various species of carp, roach, rudd, tidapia, silver dollar fish, and white amur have been suggested for macrophyte control. Roach and rudd prefer elodea to milfoil. Silver dollar fish eat curly leaf pondweed and elodea, but eat little below 21°C and die below 16°C. Common Carp root out macrophytes while looking for benthic organisms. They have been reported effective on curly leaf pondweed and elodea. Tilapia have been tested successfully on curly leaf pondweed and elodea. They do not prefer milfoil. Mortality below 10°C. White amur (grass carp) can consume their body weight in a day but eat only 50% of the plants they pull out. They are effective for elodea, milfoil, and curly leaf pondweed but preference for elodea. Considerable experience in Iowa and Arkansas. III-187-88.

Objective: Reduce macrophyte standing crop by fish grazing and nutrients released from macrophytes.

Effectiveness: Varied.

Experience: Limited.

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Amount of macrophyte reduction and nutrients from macrophytes.

89. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Shellfish for Macrophyte Control - Certain species of shellfish (snails and crayfish) feed on macrophytes and may substantially reduce vegetation.

Objective: Reduce macrophyte standing crop and nutrients released from macrophytes.

Effectiveness: Varied.

Experience: Experimental

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Reduction in macrophytes and nutrients from macrophytes.

90. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Insects for Macrophyte Control - Some insects feed specifically on milfoil. These species have potential for controlling milfoil but there has been little research done and no reports of how insects could fit into a management scheme.

Objective: Reduce macrophyte standing crop and nutrients released from macrophytes.

Experience: Experimental.

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Reduction in macrophytes and nutrients for macrophytes.

91. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Disease Organisms for Macrophyte Control - Milfoil appears to be susceptible to diseases. Although the decline in milfoil populations has been reported, the ability to use pathogenic agents for control has not been substantiated. There have not been reports of diseases affecting curly leaf pondweed or elodea. (III-166)

Objective: Reduce, weaken, or kill standing crop of macrophytes, reduce nutrients released from macrophytes.

Experience: Theoretical

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Reduction in macrophytes and nutrients from macrophytes.

92. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Competitive Plants to Displace Undesirable Macrophytes - Three species of spikerush have displaced curlyleaf pondweed and elodea in California waters. The mechanisms that cause displacement are still being researched. No interaction with milfoil was reported. (III-186)

Objective: Displace objectionable macrophytes with tolerable species and reduce nutrients released from macrophytes if possible.

Experience: Theoretical

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Change in nutrient release from displaced macrophytes.

93. **BIOLOGICAL PROBLEM TREATMENT: Macrophytes**

METHOD: Hydraulic Dredging for Macrophyte Control - Depending on the conditions present, dredging deep enough to eliminate macrophytes may be impossible. Water clarity is important. Elodea has been reported to grow to a depth of 12 m.

Objective: Deepen lake bottom until light limits growth or plants are sufficiently below water surface not to cause problem and reduce nutrient release from macrophytes.

Effectiveness: Varied results.

Cost: $5000/ha

Capital: ~ $100,000

Experience: Limited.

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Nutrient release from macrophytes; estimated change in sediment nutrient release rate.

94. **BIOLOGICAL PROBLEM TREATMENT: Macrophytes**

METHOD: Diver Operated Suction Dredge for Macrophyte Control - This technique removes the whole plant, including subsediment structures (i.e. roots and rhizomes). Where there is a ready source of plant material reinvasion may be rapid. (III-183)

Objective: Remove the whole plant from the sediment and reduce nutrient release from macrophytes.

Effectiveness: Dependent source of plant material for reinvasion.

Cost: $2,500 to $19,000/ha (depending on macrophyte density) (III-202).

Capital: ~ $12,000 (III-202)

Operating:

Experience: Limited

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Nutrient release from macrophytes.

95. BIOLOGICAL PROBLEM TREATMENT

METHOD: Manual Harvesting of Small Macrophyte Plots - Macrophytes may be pulled out by hand and disposed of.

Objective:	Remove macrophytes from water and reduce nutrient release from macrophytes.
Effectiveness:	Seasonal (III-184)
Cost:	Dependent on labor rates and type of macrophytes.
Experience:	Limited
Modeling Method:	Reduce nutrient input from macrophytes.
Parameters req'd:	Nutrient release from macrophytes.

96. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Use of a Rotovater for Macrophyte Control - Rotovator removes shoots and roots from the sediment. The cost and rate of harvest are dependent on the degree of difficulty in treating the site and the number of passes necessary to remove most of the root and shoot material.

Objective:	Remove roots and shoots from sediment to prevent regrowth and reduce nutrient release from macrophytes.
Effectiveness:	50% of pretreatment densities by second growing season.
Cost:	\$400 to \$1200/ha (III-202)
Capital:	~ \$60,000 (III-202)
Experience:	Limited
Modeling Method:	Reduce nutrient input from macrophytes.
Parameters req'd:	Nutrient release from macrophytes.

97. BIOLOGICAL PROBLEM TREATMENT

METHOD: Shallow Water Tillage for Macrophyte Control - Cost may increase in soft substrate areas or where obstacles are present.

Objective: Uproot or till over macrophytes to prevent growth and reduce nutrient release from macrophytes.

Cost: $400/ha (III-202)

Capital: $60,000 (III-202)

Experience: Limited

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Nutrient release from macrophytes.

98. BIOLOGICAL PROBLEM TREATMENT: Macrophytes

METHOD: Drawdown for Macrophyte Control - Winter drawdown appears to successfully control milfoil. A three week exposure to freezing temperatures is recommended. The technique is specie specific and those resistant to drawdown will proliferate. The thallus and reproductive structures of the plants must be rigorously exposed to temperature extremes for successful control. (III-185)

Objective: Kill plants by desiccating soil or freezing in winter drawdown and reduce nutrient release from macrophytes.

Effectiveness: Successful for milfoil, other species may proliferate.

Cost: Site dependent.

Experience: Moderate

Modeling Method: Reduce nutrient input from macrophytes.

Parameters req'd: Nutrient release from macrophytes.

99. BIOLOGICAL PROBLEM TREATMENT: Fish

METHOD: Piscicides - A lake that has a large population of rough fish may not respond as well to other lake improvement methods if the population remains. Rough fish have been known to uproot macrophytes and release nutrients through excrement. If the lake habitat is suitable, a piscicide, such as rotenon, may be used to kill the undesirable species before restocking with desirable fish.

Objective: Eliminate undesirable fish populations.

Effectiveness: Dependent on lake size and morphology

Experience: Moderate

Modeling Method: Reduce nutrient input attributable to recycling by fish

Parameters Req'd: Nutrient recycling rates attributed to fish activity.

100. BIOLOGICAL PROBLEM TREATMENT - Fish

METHOD: Rough Fish Removal - If a lake has an unbalanced or high population of rough fish that are causing water quality problems, the rough fish populations may be controlled by netting the rough fish and removing them or establishing fish traps to remove the rough fish. These methods tend to be labor intensive.

Objective: Control rough fish populations

Effectiveness: Dependent on intensity of netting and trapping

Experience: Extensive

Modeling Method: Reduce water quality problems attributable to rough fish.

Parameters Req'd: Nutrient recycling rates attributed to rough fish activity.

APPENDIX C

TABLES OF CONTENTS OF FOUR USEPA AND NALMS LAKE RESTORATION, IMPROVEMENT, AND MANAGEMENT CONFERENCE PROCEEDINGS

LAKE RESTORATION

Proceedings of a National Conference

August 22-24, 1978

Minneapolis, Minnesota

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF WATER PLANNING AND STANDARDS
WASHINGTON, D.C.

MARCH, 1979

CONTENTS

RESTORATION OF LAKES AND INLAND WATERS

International Symposium on Inland Waters and Lake Restoration

September 8-12, 1980
Portland, Maine

U.S.ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF WATER REGULATIONS AND STANDARDS
WASHINGTON, D. C.

December 1980

CONTENTS

PUBLIC BENEFIT AND INSTITUTIONAL PROBLEMS

SPECIAL PROJECTS AND TOPICS FOR ASSESSING THE TROPHIC STATE

RURAL WATERSHED POLLUTION CONTROL

URBAN AND POINT SOURCE POLLUTION CONTROL TECHNOLOGY

MODELING AND ASSESSMENT OF THE TROPHIC STATE

98

LAKE RESTORATION, PROTECTION, AND MANAGEMENT

Proceedings of the

Second Annual Conference

North American Lake Management Society

October 26–29, 1982
Vancouver, British Columbia

U.S. Environmental Protection Agency
Washington, D.C.
1983

CONTENTS

LAKE AND RESERVOIR MANAGEMENT

Proceedings of the
Third Annual Conference

North American Lake Management Society

October 18-20, 1983
Knoxville, Tennessee

U.S. Environmental Protection Agency
Washington, D.C.

1984

CONTENTS

BIOMANIPULATION

MODELING TECHNIQUES AND INNOVATIONS

CASE STUDY: THE BEAR LAKE PROJECT

SEDIMENT ANALYSIS

COMPARATIVE ANALYSIS OF RESERVOIRS

FISHERY MANAGEMENT