State Water Survey Division
SURFACE WATER SECTION
AT THE
UNIVERSITY OF ILLINOIS

ENR
**Illinois Department of
Energy and Natural Resources**

SWS Contract Report 301

LAKE RESTORATION METHODS AND FEASIBILITY OF WATER QUALITY MANAGEMENT IN LAKE OF THE WOODS

by

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Prepared for the
Illinois Environmental Protection Agency

Champaign, Illinois
November 1982

AUG 26TH 1818

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ACKNOWLEDGMENTS

This study was sponsored jointly by the Illinois Environmental Protection Agency and the State Water Survey Division of the Illinois Department of Energy and Natural Resources. Donna F. Sefton of the Illinois Environmental Protection Agency served in a liaison capacity during the course of this study and provided useful information whenever needed.

Ronald N. Pennock, Executive Director of the Forest Preserve District, Champaign County, was very helpful throughout the course of the study. V. Kothandaraman of the Water Quality Section of the State Water Survey provided valuable suggestions. The manuscript was typed by Lynn Weiss, Kathleen Brown, and Pamela Lovett.

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PART 1. LAKE RESTORATION METHODS

INTRODUCTION

An extensive literature search was made to find information on various methods and techniques for lake protection and restoration. The literature contains many discussions of lake water problems and criteria for classifying lakes according to their condition.

Pollutants, Problems, Sources, and Consequences

Most lake pollution problems are caused by nutrients, contaminants, and sediments carried into the lakes. Soil particles carry more than 90 percent of the organic nitrogen and phosphorus originating from upland agricultural practices (Wilkin and Hebel, 1982). Sediments come from all over the land and thus have nonpoint sources, whereas nutrients can have both nonpoint and point sources. In a typical watershed, nutrients may come from sewage, wastewater, agricultural and urban runoff, and atmospheric fallout. In recent years, heavy use of fertilizers and pesticides and high rates of soil erosion have increased the severity of the problem. About 37 million tons of fertilizer is currently consumed in the United States (USEPA, 1973), and it contains 7.3 million tons of nitrogen and 1.9 million tons of phosphorus. About 76 percent of nitrogen and 38 percent of phosphorus are released to surface and ground waters.

High concentrations of nitrogen and phosphorus are the main causes of algal growth, which results in the deterioration of the lake water quality. Algae have a very high growth potential, many times more than any land-based plant system, and respond quickly to nutrient inputs which act as fertilizers. Table 1 shows the minimum nutrient requirements for algal

Table 1.-- *Common forms, minimum requirements, and some sources of elements essential for the growth of algae*

[The minimum nutrient requirements of algae in the aquatic environment are difficult to determine, and this uncertainty is shown by the wide range of concentrations in the table. "Trace" quantities generally refer to concentrations less than 1 mg/l, and more exact concentration requirements for these elements have not been determined. "Quantities always sufficient in surrounding medium" refers to those elements that are never below minimum concentrations so as to limit algal growth]

Element[1]	Symbol	Some common forms in water[1,2]	Minimum requirements[3]	Examples of natural sources[1,4]	Examples of manmade sources[5,6,7]
Aluminum....	Al	Al^{+3}, $AlSO_4$, AlO_2, (salts of aluminum)	Probably trace quantities	Clay minerals, silicate rock minerals	Domestic sewage, industrial wastes, mine drainage.
Boron.......	B	B, H_3BO_3	100 µg/l	Evaporite deposits, igneous rock minerals, springs, volcanic gases	Cleaning aids, detergents, industrial wastes, irrigation, sewage.
Calcium.....	Ca	Ca^{+2}, $CaCO_3$, $CaSO_4$	20 mg/l	Igneous rock minerals, rainwater, sedimentary rocks, soil	Industrial wastes (metallurgy, steelmaking), treatment plant wastes.
Carbon......	C	CO_2, CO_3, HCO_3, H_2CO_3,$CaCO_3$	Quantities always sufficient in surrounding medium	Atmosphere, organic compounds and decay products, rainwater, soil	Industrial wastes (carbonation, metallurgy, pulp and paper, soda, and steclmaking), domestic sewage.
Chlorine.....	Cl	Cl^{-1}, (oxides of chlorine)	Trace quantities	Evaporite deposits, igneous rock minerals, ocean water, rainwater, sedimentary rocks, volcanic gases	Chlorinated hydrocarbon process, cleaning aids, industrial wastes (petroleum and refining), irrigation, salt mining.
Cobalt.......	Co	Co	500 µg/l	Coal ash, soil, ultramafic rocks	Manufacturing wastes (tools and instruments). metallurgy.
Copper......	Cu	Cu^{+2}, Cu, $CuSO_4$	6.0 µg/l	Crustal rocks, ground water, marine animals	Industrial wastes (fabrication of pipes, refining, smelting), manufacturing wastes (electrical, foods), mill tailings, mine wastes, ore dumps, treatment plant wastes.
Hydrogen	H	H^+, H_2S, H_2O, HCO_3, H_2CO_3,OH	Quantities always sufficient in surrounding medium	Atmosphere, oxidation processes, rainwater, volcanic activity	Industrial wastes (hydrocarbon process), oils.
Iron.........	Fe	Fe^{+2}, Fe^{+3}, $FeSO_4$, $Fe(OH)_2$	0.65-6,000 µg/l	Ground water, igneous rock minerals, iron minerals, organic decomposition, soil	Acid drainage from mines, industrial wastes (steelmaking), iron ore mining, manufacturing wastes, oxides of iron metals (car bodies, refigerators).
Magnesium ...	Mg	Mg^{+2},$MgSO_4$	Trace quantities	Igneous rock minerals, ground water, rainwater, sedimentary rocks	Irrigation, manufacturing wastes (transportation vehicles).
Manganese ...	Mn	Mn^{+2},MnO_2	5.0 µg/l	Ground water, plants, rocks, soil, tree leaves	Acid drainage from coal mines, industrial wastes (steclmaking).

Table 1.--*Common forms, minimum requirements, and some sources of elements essential for the growth of algae*--Continued

Element[1]	Symbol	Some common forms in water[1 2]	Minimum requirements[3]	Examples of natural sources[1 4]	Examples of manmade sources[5 6 7]
Molybdenum..	Mo	Mo, MoO_4	Trace quantities	Ground water, rocks, soil	Industrial wastes (electrical devices, metallurgy, steelmaking), manufacturing wastes (alloys).
Nitrogen.	N	N, NO_2, NO_3, organic nitrogen, NH_3	Trace quantities to 5.3 mg/l	Atmosphere, bacterial and plant fixation, limestone, rainwater, soil	Agricultural wastes (feedlots, fertilizers), domestic sewage, industrial wastes, storm drainage.
Oxygen......	O	O_2, H_2O, oxides	Quantities always sufficient in surrounding medium	Atmosphere, oxidation processes, photosynthesis, rainwater	Industry (metallurgy).
Phosphorus...	P	P^{+5}, PO_4, HPO_3, organic phosphorus	0.002-0.09 mg/l	Ground water, igneous and marine sediments, rainwater, soil, waterfowl	Agricultural wastes (feedlots, fertilizers), domestic sewage (detergents), industrial wastes.
Potassium....	K	K^+(salts of potassium)	Trace quantities	Evaporite deposits, igneous rock minerals, plant ash, sedimentary rocks	Agricultural wastes (feedlots, fertilizers), industrial wastes (preservatives, pulp ash).
Silicon.	Si	Si^{+4},SiO_2	0.5-0.8 mg/l	Diatom shells, igneous rock minerals, metamorphic rocks	Domestic sewage, industrial wastes.
Sodium.	Na	Na^+, Na salts (NaCl, $NaCO_3$	5.0 mg/l	Ground water, igneous rock minerals, ocean water, soil	Industrial wastes (paper and pulp, rubber, soda, water softeners), manufacturing wastes (dyes and drugs).
Sulfur.	S	SO_2, HS, H_2S, SO_4	5.0 mg/l	Animal and plant decomposition, igneous rocks, rainwater, sedimentary rocks, springs, volcanic activity	Agricultural wastes (fertilizers), industrial wastes (fuels, paper and pulp).
Vanadium________	V	V^{+2}, V^{+3}, V^{+4}, V^{+5} (salts and oxides of vanadium)	Trace quantities	Ground water, plant ash	Industrial wastes.
Zinc.	Zn	Zn^{+2} (salts of zinc), ZnO_2	10-100 µg/l	Igneous and carbonate rock minerals	Industrial wastes (piping, refining), mine wastes.

1. Mem (1970).
2. McKee and Wolf (1971).
3. Greeson (1971).
4. Reid(1961).
5. Gurnham (1965).
6. Nebergall, Schmidt, and Holtzclaw (1963).
7. Sawyer and McCarty (1967).

Source: Britten et al., 1975

growth and examples of natural and man-made sources of these nutrients, as given by Britten et al. (1975).

Algae affect the quality and appearance of water. They cause taste and odor problems in municipal water supplies and excrete toxins into waters. Blooms of algae adversely affect recreational activities like swimming, boating and fishing. High algal growth leads to large masses of dead plants which settle to the bottom and cause dissolved oxygen deficiencies on decomposition. Fish die along with algae, and anaerobic decomposition releases ammonia, causing more fish kills. High sediment loads are unsuitable for fish because of the increased turbidity of the water. Because of relatively higher and more uniform temperatures in shallow lakes during summer, there is a reduction in the diversity of aquatic life.

Water Quality Standards

Water quality controlling standards are described in terms of either the effluent standards or receiving water standards. Effluent standards deal with the quality of the waste or used water to be discharged at a given location, whereas the receiving water standards are related to the quality desired in the waters into which the wastewater is discharged. The required quality is described in terms of the limiting values of the various constituents or specific properties and depends on the use to which water may be put. The recommended surface water criteria for selected beneficial uses of water (Dougal, 1970) are given in table 2.

Lake Condition Classification

One of the most important aspects of a lake water quality study involves the determination of the status of the lake based on the water

Table 2. Recommended Surface Water Criteria for Selected Beneficial Uses of Water (from M.D. Dougal, 1970)

Constituent or characteristic	Maximum level to be permitted as desirable criterion for designated water use, in mg/l	
	Water supply[d]	Recreation and aquatic life[b]
Arsenic	0.05	
Boron	1.0	
Barium	1.0	
Cadmium	0.01	1/30 96-hr TL_m
Chromium, hexavalent	0.05	0.02
Copper	1.0	1/10 96-hr TL_m
Lead	0.05	
Manganese	0.05	
Mercury		Perform bioassay
Nickel		Perform bioassay
Selenium	0.01	
Silver	0.05	
Uranyl ion	5.0	
Zinc	5.0	1/100 96-hr TL_m
Heavy metals as a group		1/100 96-hr TL_m
Cyanide	0.2	Perform bioassay
Ammonia, as N	0.5	1.20 96-hr TL_m
Chloride	250.	
Fluoride	0.8 - 1.7	
Iron	0.3	
Nitrate, as N	10.	
Sulfide		1/20 96-hr TL_m
Sulfate	250.	
Total dissolved solids	500.	
pH (ion conc., not	mg/l)	6.5 - 8.3 swimming
Desirable range	6.0-8.5	6.0-9.0 other
Maximum range	5.5-9.0	5.0-9.0 other

[a] For public, farmstead, and industrial food processing
[b] All others not listed to be determined on individual bioassays.

quality of that lake. A variety of alternative approaches have been proposed. Models used to estimate the concentration of a single constituent, such as phosphorus, give the lake condition in terms of a single parameter on a continuous scale. Alternatively, discrete classification criteria may be used to reduce the dimensionality of continuous data. One common approach involves classification of the current water quality in the lake in terms of parameter values. Typically, this requires measurements of phosphorus and nitrogen concentrations, chlorophyll a level, secchi depth, and other constituents.

A number of different trophic state criteria, as a function of measured water quality parameters, have been proposed by different authors. Some of these are shown in tables 3a (Wetzel, 1975); 3b (Sakamoto, 1966; NAS and NAE, 1972; Dobson et al, 1974; USEPA, 1974); 3c (USEPA, 1974), and 3d (Jorgensen, 1980). These univariate criteria are based on subjective judgment and possibly limited to specific geographical regions.

Shannon and Brezonik (1972) used principal component analysis to develop a robust multivariate trophic index for Florida lakes. The index was defined as the first principal component which is a linear combination of variables that best describe the "most" common element. The variables considered included primary production, chlorophyll a, total organic nitrogen, total phosphorus, secchi depth transparency, specific conductance, and a cation ratio. Analyses were done separately for the lakes with and without appreciable organic color, and boundaries between various trophic states were delineated.

Carlson (1977) correlated the values of secchi depth, total phosphorus, and chlorophyll <u>a</u> concentration by regression analysis with an arbitrarily assigned trophic state index, TSI, of 0 to 100 such that a

Table 3. Trophic State Criteria

a) Wetzel, 1975

Trophic type	Total organic C (mg/l)	Total P (mg/l)	Total N (mg/l)	Total inorganic solids (mg/l)
Ultra-oligotrophic	-	<.001-.005	<.001-.25	-
Oligotrophic	<1-3	-	-	2-15
Oligo-mesotrophic	-	.005-.010	.25-.60	10-200
Mesotrophic	<1-5			
Mesoeutrophic	-	.010-.030	.50-1.1	100-500
Eutrophic	5-30			
Hypereutrophic	-	.030-5.0	.50-1.5	400-6000

b) Sakamoto, 1976; NAS and NAE, 1972; Dobson et al., 1974; USEPA, 1974

	Chlorophyll a (µg/l)			
Trophic condition	Sakamoto	NAS & NAE	Dobson	USEPA
Oligotrophic	0.3-2.5	0-4	0-4.3	<7
Mesotrophic	1-15	4-10	4.3-8.8	7-12
Eutrophic	5-140	>10	>8.8	>12

c) USEPA, 1974

Trophic state	Chlorophyll a (µg/l)	Total P (µg/l)	Secchi disk depth (m)
Oligotrophic	<7	<10	>3.7
Mesotrophic	7-12	10-12	2.0-3.7
Eutrophic	>12	>20	<2.0

d) Jorgensen, 1980

Trophic state	Chlorophyll (μg/l)	Total organic C (mg/l)	Total P (mg/l)	Total N (mg/l)
Ultra-oligotrophic	0.01-0.5		<.001-.005	<.001-.250
Oligotrophic	0.3-3	<1-3		
Oligo-mesotrophic			.005-0.010	.25-.60
Mesotrophic	2-15	<1-5		
Meso-eutrophic			.010-.030	.50-1.1
Eutrophic	10-500	5-30		
Hypereutrophic			.030-5.0	.50-15

change of 10 units in TSI corresponds to halving of the secchi disk depth and a change in trophic state (table 4).

Table 4. Carlson's Trophic State Index

TSI	Secchi disk (m)	Surface phosphorus (μg/l)	Surface chlorophyll (μg/l)
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.06	768	1183

Illinois Lakes

Lakes in Illinois range from small farm ponds to 26,000-acre Carlyle Lake. There are about 2700 lakes with a surface area of 6 acres or more (IEPA, 1978). Most of these are artificial reservoirs, formed by the impoundment of water courses for a variety of uses such as municipal water supply, recreation, industrial cooling water, flood control, and farm use. Most of these reservoirs start their life with high eutrophication potential because of nutrient-rich soils in the bottomlands. A recent study (Sefton et al., 1980) shows that turbidity and siltation are the main problems in Illinois lakes.

Various parameters for 63 Illinois lakes were studied by Sefton et al. (1980). Conclusions of this report are briefly summarized here.

1. The lakes with a depth of more than 15 to 20 feet show a distinct and stable thermal stratification.

2. The bottom waters have oxygen deficiencies, especially during the summer months. Surface waters are adequately saturated with oxygen.

3. Based on the criteria of Allum et al. (1977), the classification on the basis of secchi depths shows that one lake is oligotrophic, 5 are mesotrophic, and the remaining 57 are eutrophic.

4. The lakes are markedly turbid and the nonvolatile suspended solids are the main cause of the high turbidity.

5. High total suspended solid concentrations were recorded in shallow lakes. Surface volatile solid concentration was higher than in the bottom waters.

6. Most of the lakes are alkaline with pH >7.0, but three lakes have pH values exceeding 9.0, i.e., higher than the water quality standard given in table 2.

7. Nitrate and nitrate nitrogen, ammonia nitrogen, and organic nitrogen were all well below the admissible limits.

8. Mean values of chlorophyll a ranged from 4 to 153 µg/l. On the basis of these values, a few of the lakes are oligotrophic and some are mesotrophic, but the great majority are eutrophic.

9. Parameters such as conductivity, total organic carbon, sulfate, fecal coliform, chloride, heavy metals, and arsenic have low values for all the lakes.

LAKE RESTORATION METHODS

The various lake restoration methods can be considered under two broad categories: 1) preventive or indirect methods, and 2) ameliorative or direct methods. The preventive methods are basically the ones which identify the pollutants, reduce their rate of generation, and/or prevent them from reaching the lake. The ameliorative methods involve either the treatment of the wastes before discharge into the lake (outside-lake methods) or direct intervention in the lake (in-lake methods). Various techniques used under this classification system are shown in figure 1. Frequently, it is necessary to use some of these methods in combination to achieve the desired results.

Preventive Methods

1. Drainage Basin Alterations. This approach is useful primarily for controlling nonpoint sources of pollution which are incidental to the land use of the drainage basin of the lake. Land development activities, logging of forests, and other construction activities increase erosion and, thus, sediment in the runoff. Phosphorous and nitrogen from the fertilizers used in farming operations are transported with the sediments. Sediment has been found to be the most important source of nitrogen and phosphorus to Lake Norrviken in Sweden (D. Ahlgren, 1978).

The drainage basin alterations involve structural and land treatment measures and interception of nutrients and sediments before they reach the lake. The main soil erosion management practices include terracing, contour farming, grassed waterways, conservation cropping systems, crop residue management or increases in the amount of residue left after harvesting, and creation of shelter belts. The Soil Conservation Service

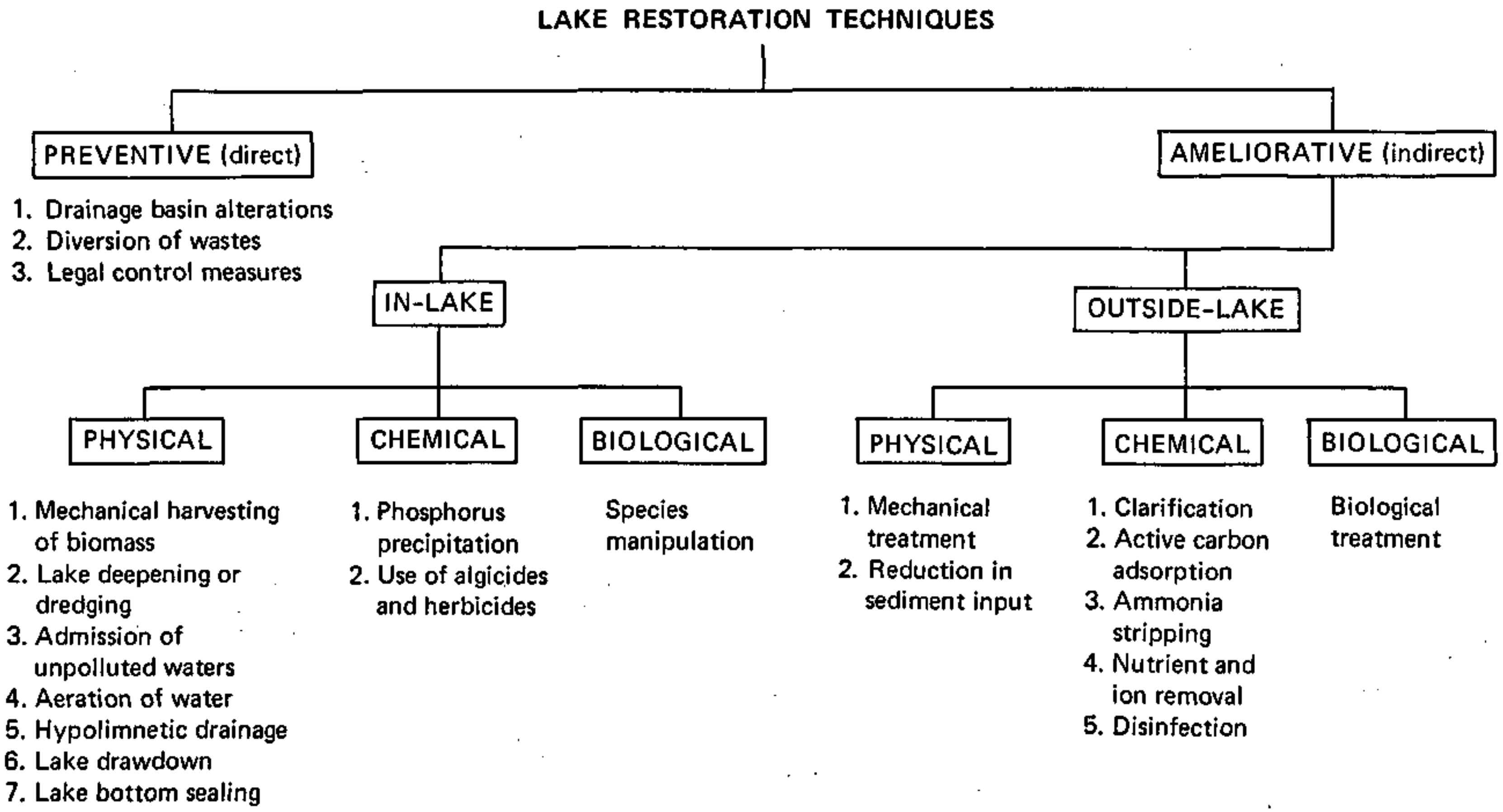

Figure 1. Classification of lake restoration techniques

of the U.S. Department of Agriculture is active in the land use conservation program, largely on rural lands. Alternatively, mechanical measures can be used to intercept, divert, retard, or otherwise control runoff; these include such practices as land grading, bench terracing, construction of diversion structures, and installation of sediment basins.

2. Diversion of Wastes. This is a frequently-used solution for improving the water quality of eutrophic lakes. This method has been successfully tried for Lake Washington in Washington State (Edmondson, 1977), Lake Norrviken in Sweden (I. Ahlgren, 1978), Lake Tegernsee in West Germany (Hamm, 1978), and Lakes Muskegon, Mona, and White in Michigan (Freedman and Canale, 1979). In the cases cited, sewage effluents were the main source of lake eutrophication. Their diversion resulted in a marked improvement in quality as measured by increase in transparency, decrease in phytoplankton biomass, and increase in species diversity. Concentrations of nutrients such as phosphorus, chlorophyll, and nitrogen were reduced and an increase in bottom oxygen was observed.

Before undertaking treatment by this method, it is necessary to account for all the sources of nutrients to the lake so that the impact of diverted nutrient sources can be estimated. Thus, even though Lake Schliersee in West Germany is adjacent to Lake Tegernsee, sewage diversion did not improve eutrophic conditions in Schliersee because of remaining allochthonous nutrient inputs (Hamm, 1978). Similarly, for Lake Chautauqua in New York, the eutrophic conditions could not be improved without controlling both point and nonpoint phosphorus sources in the southern part of the basin (Storch et al., 1978).

The effluents diverted from one watershed can end up in another ecosystem. The diversion is frequently criticized because the pollution is not eliminated but only transferred to another location. This solution is reasonable if the wastewater is mainly of domestic origin, the ecosystem receiving the wastes is able to maintain the balance, and there is enough water in the former ecosystem to bear the loss. Otherwise, the diverted wastewater can be treated. In the case of lakes in Michigan, the diverted wastewater was pretreated in aerated lagoons, disinfected, and sprayed on agricultural land (Freedman and Canale, 1979). Drainage from the sprayed lands was collected and discharged to the tributaries discharging into the lakes. Dunst et al. (1974) give a list of 44 lakes for which diversion was used as a lake restoration technique.

3. Legal Control Measures. Some political jurisdictions can impose legal controls on the land use and discharge of nutrients so as to restrict uses with direct or indirect pollution potential or effects. Legal controls allow certain land-use practices, prohibit others, and control recreational use of water, location of industries, fertilizer use, etc. Many of the states have regulations governing the use of shorelands and other lands in the drainage basin. A summary of some regulatory approaches followed in the midwestern states is given below.

Regulatory Approaches in the Midwest

State	*Control Measures*
Iowa	Mandatory soil conservation if erosion exceeds prescribed limits; farm animal waste regulations aimed at large feedlot installations.

Illinois	Prohibition of the use of certain types of fertilizers in excess of specified amounts.
Indiana	Farm animal waste regulations aimed at large field installations.
Wisconsin	Shoreland protection statute with provisions for shoreland regulation, zoning to prohibit pollution-generating uses, restrictions in vegetation removal, and sanitary codes and subdivision regulations to limit development.
Minnesota	Similar to Wisconsin, but with different zoning standards for each category of lake.

For Lake Balaton in Hungary, continental Europe's largest body of freshwater, a number of strict control measures were used in addition to other techniques (Lang, 1978). These included: a) limiting lake use to drinking water and some recreation, b) prohibiting inflow of all treated or untreated wastewater effluents, c) curtailing use of fertilizers and pesticides in the basin, d) permitting no new industries in the lake catchment, e) modernizing existing industries, and 6) planting trees to reduce erosion.

Ameliorative Methods

In-Lake Physical Methods

There are 7 different techniques cited under this heading in figure 1. These are dealt with in order below.

1. Mechanical Harvesting of Biomass. Harvesting of the biomass may be useful if the rate of removal by existing machinery can be improved,

making it an economical alternative. Some beneficial use of the harvested material is yet to be found as an aid to reduce operating costs.

2. Lake Deepening or Dredging. Sediment removal is resorted to for improving diminished recreational potential, reducing internal cycling of nutrients, removing any toxic sediments, and reducing nuisance aquatic macrophyte growth (Peterson, 1981). Sediment-regenerated phosphorus adds considerably to the phosphorus loading in lakes. Sediment removal for deepening shallow lakes may become necessary for restoring the lake to uses for which it was designed and built. Dredging operations may lead to some short-term environmental problems, such as resuspension of sediment, possible release of toxic substances, and destruction of the bottom benthic community. Lake drawdown and compaction of sediments by natural drying can be a time-consuming process, negating lake use during drawdown periods. The conventional hydraulic dredges are commonly used. The major non-lake impact of sediment removal is associated with disposal site(s). Rose (1977) shows some increase in groundwater inflow after dredging of some small lakes in Wisconsin.

3. Admission of Unpolluted Waters (Dilution/Flushing). Admission of water or dilution results in lowering of nutrient concentration and a washout of algal cells, whereas flushing achieves only a washout of algal cells (Welch, 1981). The effectiveness of this restoration technique increases with an increase in the difference between nutrient concentrations in the inflow and lake waters. The method is economical if an adequate supply of good quality water exists and the costs of facilities and their maintenance for delivering the water to the lake are not high.

Dilution is shown to reduce phosphorus, chlorophyll a, and biomass. It improves secchi disk visibility.

4. Aeration of Water. Dissolved oxygen, DO, is very low in deep waters of stratified lakes during summer. The DO is needed by all the living organisms in the lake for their survival. The DO deficiency occurs mainly because of the decomposition of organic material in the hypolimnion and thermal stratification which restricts movement of cold, dense water in the hypolimnion to the overlying waters in the metalimnion and epilimnion. When the DO levels fall close to zero, more phosphorus is released from the sediments under the prevailing anaerobic conditions. This causes algal blooms, which produce more organic matter, requiring more dissolved oxygen. One ameliorative technique is to pump hypolimnetic water to the surface and allow it to mix with warm epilmnetic water, or force the epilimnetic water to the hypolimnion. The resulting mixing and disruption of the thermal stratification improve the DO in the deeper waters at the expense of the shallower waters. The other technique is to directly aerate the hypolimnetic water.

Destratification by means of artificial aeration of deep eutrophic Lake Starodworskie in northeastern Poland greatly improved the bottom fauna (Sikorowa, 1978). Through an aeration system supplemented by a soluble non-toxic calcium-based product, a phosphate removal (by precipitation) of 70 to 100 percent was achieved in 25 lakes in Minnesota and 8 in Florida (Laing, 1974). After application of clean-flow lake cleanser, all bottom muck was gone, revealing a clean sandy bottom in a trout fishery pond. A guide to aeration/circulation techniques under various conditions and goals is provided by Lorenzen and Past (1977). Various hypolimnetic aeration devices and their applications; effects on planktonic microorganisms, microinvertebrates, and fish; and benefits and adverse impacts are discussed in detail by Pastorok et al. (1981). However, nitrogen-N cannot be removed from hypolimnetic waters by aeration (Fast, 1979).

5. Hypolimnetic Drainage. In a thermally stratified lake, the cool and stagnant bottom layer (hypolimnion) is rich in nutrients and low in dissolved oxygen whereas the upper warmer layer (epilimnion) has fewer nutrients and high dissolved oxygen. By the withdrawal of water from the bottom layers instead of from the top, the nutrients in the lake are reduced and the dissolved oxygen condition is improved. Installation of a hypolimnion siphon on the highly eutrophic Lake Mauensee in Switzerland achieved an increased nutrient export and decreased the diffusion rate from the sediments to the water because of a nutrient reduction in the top sediment layer (Cachter, 1976). Lakes receiving nutrients from non-point sources in Austria were successfully rehabilitated by artificial drainage of the hypolimnetic waters (Pechlander 1975).

6. Lake Drawdown. Lake drawdown involves drainage of a lake through suitable outlet structures or through the use of high capacity pumps (Born et al. , 1973). Because the water content of the sediments is very high, about 90 percent on a volume basis for organic-rich sediments and a lesser value for the inorganic sediments, the drawdown decreases sediment thickness considerably due to expulsion of pore water. This consolidation process, though incomplete, is permanent because of oxidation and shrinkage of the sediment. In some cases the shrinkage of the sediment is significant. Experience shows that the shrinkage is permanent (1 to 2 meters reported), and after refilling with water, an increased water depth

gives improved water quality (Jorgensen, 1980). The mineralization processes are accelerated and it is necessary in each individual case to balance the positive and negative sides. Cooke (1980a) dicusses the positive and negative effects of the lake level drawdown as a macrophyte control technique for a short term of 1 to 2 years. Lake drawdown provides opportunity for shore line improvements such as sediment excavation, sand blanketing, and riprapping by conventional dry land procedures (Dunst et al., 1974).

7. Lake Bottom Sealing. Under anaerobic conditions, lake bottom sediments have been found to release nutrients to the lake water. To reduce or prevent this nutrient release, the sediment can be covered with plastic sheets, fly ash and iron-rich sand or clay (Cooke, 1980b). Each of these materials has some disadvantages. For example, the plastic polyethylene sheets are not good for long-term use due to macrophyte growth on their surfaces. Commonly, a 0.1-mm thick sheet, with perforations for the outflow of gases released by sediments, is anchored to the bottom. Anoxic conditions below the sheet may interrupt fish spawning. Boating activities and wave action may dislodge the material. Recently, some nonbuoyant and permeable materials have been developed but are not effective. The improvement with clay sealing may be temporary, and benthic fauna may be affected. Fly ash has been found to be positively harmful with adverse effects on fish and zooplankton. It also leads to high pH, low dissolved oxygen, and high concentrations of heavy metals (Theis et al., 1979).

In-Lake Chemical Methods

Phosphorus precipitation and the use of algicides and herbicides are included among in-lake chemical methods.

1. Phosphorus Precipitation. This method involves successive applications of aluminum sulfate or alum to disrupt the internal phosphorus cycle. This is especially useful if the high phosphorus loading is not due to allochthonous nutrient inputs. Restoration of Medical Lake (USEPA, 1980) was carried out by sequential applications of liquid alum slurry: two subsurface applications, two surface applications, and two more subsurface applications, followed by one surface and one subsurface application. The monitoring results show that alum application was highly successful in decreasing phosphorus levels, eliminating nuisance algal blooms, and greatly increasing water clarity. The major sources of phosphorus in Medical Lake were dead algae on the bottom sediments, which released nutrients during the summer. The phosphorus was mixed throughout the lake during the fall season. Algae grew very quickly, died, decomposed, and kept the internal phosphorous cycle going. Application of alum broke this cycle.

According to Cooke et al. (1981), many eutrophic lakes respond slowly following nutrient diversion because of long water retention times and the recycling of phosphorus from sediments and other internal sources. Restoration of such lakes with alum treatment is successful, with a few undesirable effects such as reduced planktonic microcrustacea species diversity (Sonnichsen, 1978) and the possibility of an increase in rooted plant biomass. Maximum alum dose is defined as that which reduces pH to 6 to form insoluble aluminum hydroxide. The technique is long-lasting (about

3 years) when properly applied. In some lakes, the littoral phosphorus sources are more important than hypolimnetic sediments. In small lakes, the littoral is probably the most important internal phosphorus source (Cooke and Kennedy, 1978). Alum controls the phosphorus in sediments through the sorptive capacity of the aluminum hydroxide floc formed in alkaline water. The maximum alum should be such that residual dissolved aluminum does not exceed 0.05 mg/l.

2. Use of Algicides and Herbicides. Chemical treatments have been used for control of nuisance algal blooms and dense growth of macrophytes. Copper sulfate has been widely used for control of blue-green algae (Janik et al., 1980). Over 10,000 tons of copper sulfate per year was used for this purpose in the U.S.A. and the concentrations ranged from 0.5 to 1.0 mg/l (Fitzgerald, 1971). The low concentration is applied to water with alkalinity less than 40 mg/l and the higher concentration to water with alkalinity exceeding 40 mg/l. The effectiveness of the copper ion in controlling algae is enhanced by using a chelating agent, such as citric acid (Kothandaraman et al., 1980; Kothandaraman and Evans, 1982a). A follow-up application of potassium permanganate, to oxidize the decaying algae and to reduce the DO-depressing effect of these algae, has been shown to yield excellent results. Any fish kills because of copper sulfate application can generally be traced to improper application and/or excessive dosage rates. Some of the other algicides used, though on a very small scale, are rosin, amines, triazine derivatives, mixture of copper sulfate and silver nitrate, quaternary ammonium compounds, organic acids, aldehydes, and ketones.

Use of herbicides is an effective method of controlling nuisance weed growths. Tests conducted on the effectiveness, toxicity, and residues of herbicides have led to a limited number of very effective products for weed control. These herbicides can be applied easily in areas difficult to reach by mechanical harvesters. Fishery Bulletin No. 4 (Illinois Department of Conservation, 1976) contains a list of various chemicals, dosage rates, and macrophyte responses to chemical applications. Some drawbacks of chemical in-lake control (Kothandaraman and Evans, 1982b) are: the need for different chemicals to control different plant species, water use restrictions after chemical applications, the presence of climatic and other factors that affect the results of applications, some toxicity and residue problems, and unaesthetic appearance of decaying vegatation in the lake.

In-Lake Biological Methods

Species manipulation is the main in-lake biological method for lake restoration. The method considers the introduction or promotion of organisms that are inimical to the target organisms. In nature, predation by zooplankton and fish species keeps a sort of control on algal populations. A decline in the abundance of the crustacean *neomysis mercedis*, caused by changes in fish predation, led to an abundance of the crustacean genus *daphnia* in Lake Washington (Edmondson and Murtaugh, 1980). Biological in-lake control measures are still in their infancy and are not widely used.

Out side-Lake Physical Methods

Two methods can be considered under this heading: mechanical treatment and reduction in sediment inputs.

1. Mechanical Treatment. Such a treatment was patented for removing water soluble substances from the rainwater runoff from mine tailing piles (Dawson and Mercer, 1979). Magnetically attractable collection units containing an ion-exchange or sorbent medium with an affinity for a chosen target substance are distributed in the sediments or tailings. After a period of time has passed sufficient for the particles to bind up the target substances, a magnet drawn through the sediments or across the tailings retrieves the units along with the target substances. In many cases this medium can be regenerated and the units subsequently put back into use. Examples of practical uses of this patent were not found in the literature search.

2. Reduction in Sediment Input. A large part of phosphorus and other nutrients enters the lake with sediments as the carrier. Reduction in sediment inputs to the lake not only leads to a reduction in nutrient inputs but also to a reduction in the amount of storage volume lost to sediments deposited in the lake. The outside-lake methods may involve some low check dams upstream of the reservoir, diversion of sediment-laden bottom water, and use of sediment pools. The low pools created by check dams as well as sediment pools need clearance every 3 to 5 years. This clearance is easier than dredging the lake. The sediment-laden bottom water in the stream during high flow months can be directed to a diversion channel with the help of vane walls (low walls built at an angle across the stream).

Outside-Lake Chemical Methods

There are a number of methods that can be used to improve the quality of inflows to the lake. These methods are described below. The treatments are applied to the sewage or wastewaters before they are discharged to the streams flowing into the lake.

1. Clarification. Chemical clarification, properly conducted, transforms raw wastewater to a fully clarified effluent with substantially reduced concentrations of phosphorus, organic matter and metals (Cohen and Westrick, 1975; Burns and Shell, 1973). The clarifying agents used are $Fe\ Cl_3$, lime, and alum. Clarification typically removes 70-80 percent of organic matter, 90-98 percent of suspended solids, and 80-98 percent of phosphorus. The weight of sludge produced is increased considerably because of the greater removal of suspended solids and because of the presence of precipitated hydroxides, carbonates, and phosphates.

2. Active Carbon Adsorption. Activated carbon is a generic term for a broad range of amorphous carbon-based materials so prepared as to exhibit a high degree of porosity and an extensive associated surface area (Weber, 1975). The concept of applying clarification and sorption processes directly to raw wastewater rather than to secondary effluents is derived from effectiveness and reliability of treatment and from economic considerations when tertiary treatment is indicated (Weber and Kim, 1965). An organic removal of about 95 percent or more is achieved. In the most common type of adsorber system, the effluent is passed through fixed beds of granular carbon. For backwashing, it is advisable to include a surface wash and air scour to be assured of removing suspended solids as well as gelatinous biologic growth.

3. Ammonia Stripping. Ammonia stripping by air was studied by O'Farrell et al.(1973). A high pH is needed for efficient stripping and is achieved by combining the stripping process with lime clarification. However, ammonia is highly soluble in water and its volatility decreases at lower temperatures. Effective stripping by air requires warm temperatures and the use of large volumes of air per gallon of wastewater. Barnes et al. (1972) demonstrated the effectiveness of chlorination followed by dechlorination of the wastewater from a physical-chemical treatment plant after clarification, filtration, and active carbon adsorption. The dechlorination process consisted of passing the chlorinated wastewater through carbon contactors. The pilot facility removed an average of 85 percent of the ammonia-nitrogen, and free and combined chlorine was completely removed from the effluent during the dechlorination stage.

4. Nutrient and Ion Removal. Three standardized techniques (alumina adsorption, capillary membrane dialysis, and alum/polyelectrolyte coagulation) were tested under laboratory conditions (Starkey et al. , 1973) to determine their relative effectiveness in removing a broad spectrum of nutrients, cations, and anions from secondary and tertiary wastewater effluents. Alumina adsorption was highly effective in the removal of phosphorus, inorganic carbon, and most cations. Dialysis matched alumina adsorption in removing inorganic carbon, but cation removal was less efficient. Alum/polyelectrolyte coagulation proved to be effective in removing phosphorus but was inadequate for removal of inorganic carbon and cations. Coagulated samples were shown to contain potassium and sulfate in excess of controls.

5. Disinfection. Chlorine is both efficient and reasonably cheap for disinfecting effluents. Ozone is efficient but relatively expensive. Chlorine inactivates enzymes that are essential to the metabolic process of bacterial cells. Chlorination of sewage can be thought of as a two-stage process (Drehwing et al., 1979): addition of sufficient chlorine for satisfaction of chlorine demand and further addition of chlorine for maintenance of free chlorine. The rate of disinfection is a function of the time of contact, the concentration of the disinfectant, and the temperature of the water. Chlorination for lowering the BOD of wastewater effluents has been practiced to control nuisance conditions in a receiving stream during drought flows (Clark et al., 1971).

Outside-Lake Biological Methods

Primary treatment of sewage is achieved with plain sedimentation. The fresh solids contain most of the settleable solids in the raw wastewater (Fair et al., 1971). An aerobic digestion destroys about 67 percent of the volatile matter, and about a quarter of it is converted to fixed solids. The secondary treatment includes trickling filters and activated sludge. Various removal efficiencies are attained, such as about 85 percent for BOD, 80 percent for suspended solids, 90 percent for bacteria, and 70 percent for COD. Efficiencies drop when treatment plants are overloaded. Advanced waste treatment methods and processes remove more contaminants from wastewater than are usually taken out by conventional secondary treatment plants (Clark et al., 1971). An example is the chemical addition in the activated-sludge biological process to precipitate phosphorus. Some advanced waste-treatment processes are biologic in nature. Phosphates can be reduced by algal photosynthesis. Biological nitrification and denitrification in association with activated sludge treatment (Echelberger et al., 1969) can greatly reduce the water quality problems in the lake receiving the effluents.

PART 2. FEASIBILITY OF WATER QUALITY MANAGEMENT IN LAKE OF THE WOODS

INTRODUCTION

Lake of the Woods (figure 2) lies entirely within the boundaries of Lake of The Woods Park, managed by the Forest Preserve District, Champaign County. The lake is accessible to the public with the exception of the shoreline adjoining the golf course and the fenced in "sea slide" and swimming and boat rental areas. A large enclosed pavilion is surrounded by picnic areas easily accessible from the parking lots. About 60 privately owned pedal and row boats are available to the public on an hourly rental basis and these are permitted to launch off a single ramp near the south end of the dam. Shoreline fishing is done largely along the dam and the lake enjoys a good bass and pan fish reputation. The swimming area, comprising both sand and gravel beach, is used by over 50,000 daily-fee users during the summer months of June, July, and August. The lake is used exclusively for water-based, contact and non-contact recreation activities and for providing a habitat for aquatic life--principally fish. Water is also withdrawn from the lake during summer months for irrigating the golf course, but some groundwater is pumped into the lake from a well near the bath house. Because of the proximity of Champaign-Urbana, the investment in facilities and properties surrounding the lake, and the unavailability of other suitable lakes in the nearby area, Lake of the Woods needs to be maintained in a good condition for realization of recreation benefits to their maximum potential for years to come.

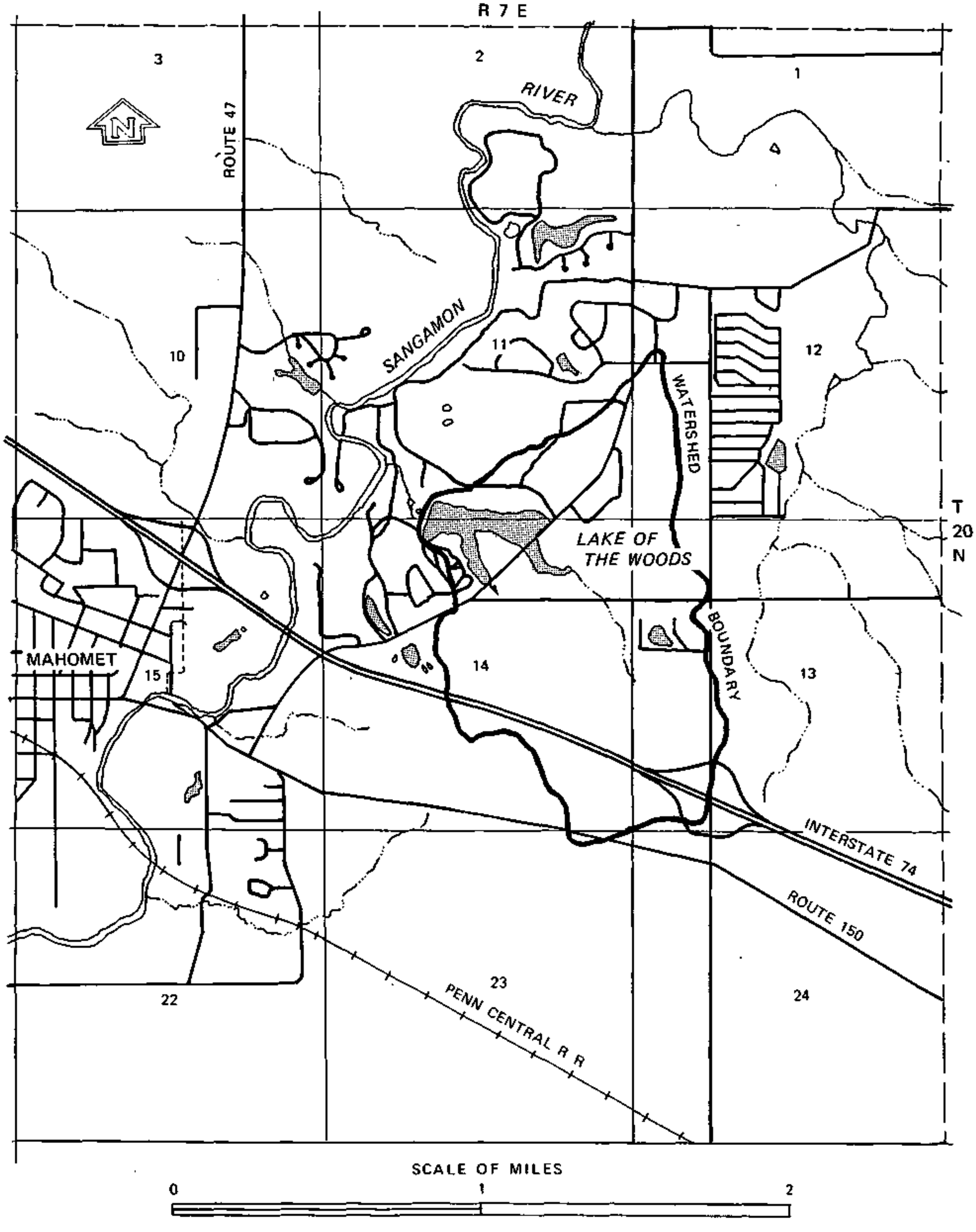

Figure 2. Location map of Lake of the Woods

IDENTIFICATION OF PROBLEMS

The Illinois Environmental Protection Agency funded a diagnostic study to identify problems which need attention and remedial measures for maintaining and managing Lake of the Woods, improving the quality and quantity of existing recreation, and safeguarding against any future degradation. The study was conducted by the Natural History Survey. The State Water Survey prepared the general watershed description, hydrologic budget, and erosion and sediment assessment. The following problems have been identified.

1. The total phosphorus concentrations in lake water and tributary inflows were monitored from April 1981 to January 1982. The mean concentrations near the lake surface and lake bottom were 0.072 and 0.100 mg/l, respectively. The phosphorus concentration was 0.080 mg/l for tributary streams. The year 1981 was a very wet year with inflow during May to September being about 2.8 times that for a corresponding period in an average flow or normal year. The sediment and allochthonous nutrient inputs to the lake were thus greatly increased. It is estimated that 80 percent of the total phosphorus concentration was due to allochthonous inputs, whereas in a normal year it is about 50 to 60 percent (the total phosphorus concentration in the lake water ranges from 0.04 to 0.05 mg/l in a normal year). Phosphorus in any lake or in any stream at the point where it enters the lake should not exceed 0.05 mg/l. The excessive phosphorus levels during very wet years and very high inflow periods need to be lowered for reduction in algal blooms and improvement in water quality, as well as for reduction in DO level depressions in the lake and supplies of nutrients to macrophytes.

2. In a lake, the dissolved oxygen concentration should not fall below 5 mg/l and should be at least 6 mg/l during 16 hours of any 24-hour period. The DO profiles developed from the information collected during the monitoring program in 1981 show that the lake began to stratify in late April and that it was stratified throughout the summer. The DO level varied from as low as near zero at the bottom to 2 to 3 mg/l at the top of the hypolimnion. Autumn overturn began in early October and the lake was homogeneous by the end of the month. The lake was stratified under the ice in late January. It is evident that some remedial measures are needed for raising the DO level in deeper waters, not only to increase the fish habitat space but also to inhibit circulation of phosphorus from the lake bottom sediments. Concentrations of ammonia exceeded 1.5 mg/l in late August in the deep water near the dam. All other measurements throughout the year were less than 1.5 mg/l. The improvement in DO in deep waters will also reduce ammonia concentrations.

3. General water quality standards include limits for heavy metals. Metals were analyzed in elutriates from the sediment cores but not in water samples collected as a part of the regular monitoring program. Concentrations of arsenic, cadmium, chromium, iron, and zinc in the elutriates were below the general water quality standards. Mercury concentrations were very low. Copper and lead exceeded the standards by not more than 0.01 mg/l. However, concentrations of 2.25 and 2.5 mg/l were obtained for manganese. If dredging is a part of the remedial measures package, the manganese in the elutriates from the dredged sediments may exceed the general water quality standards.

The results of sedimentation surveys of the lake in 1948 and 1980 indicate a reduction in lake storage volume from 259.7 to 224.6 ac-ft. An accumulation of 35.1 ac-ft of sediment has occurred in the lake over the 32-year period. The annual reduction in storage is estimated as 0.42 percent, a rate much lower than most of the other lakes in Illinois. The rate for the present conditions may be less than the 32-year average because of the reduction in cultivated agricultural area and increase in pasture and camping area. Out of 35.1 ac-ft of sediment, about 12 ac-ft lies in the upper 8-ft depth. The reduction in sediment input will not only increase the useful life of the lake but also reduce the amount of nutrients carried by sediments into the lake.

4. In 1981, the standing crop of phytoplankton throughout the lake increased 2 to 3 times in a 2-month period, July and August, achieving maximum standing crops of 23 to 27 million algal units per liter. Chlorophyll a concentrations ranged from 0 to 136 mg/m^3, with a mean concentration of 21.3 mg/m^3. This corresponds to the eutrophic condition on the basis of various trophic state criteria. The lake was both phosphorus- and nitrogen-limited in August. Some remedial measures are needed to control algal growths and chlorophyll a production.

5. Aquatic plant growth along the northern shoreline of the lake generally follows the 8-ft water depth contour. It occupies most of the northern shore and the northern one-half of the east basin. The plant growth along the south and southwest shoreline is discontinuous and much less extensive, and the aquatic plants do not appear to grow in water deeper than 6 feet. The abundant plant growth along the shoreline is unsightly, reduces recreation potential, and adds to the nutrients after decomposition. Macrophyte control is indicated for reduction in aquatic plant growth.

6. The hydrologic budget study shows that the lake will be at its normal pool level most of the time during average rainfall years, even with the present withdrawals of water from the lake for irrigation of the golf course area and with input of groundwater from the existing well near the bath house. However, during droughts, the lake water level may lower up to 2 feet because of diminished inflows and increased irrigation needs. Generally, swimming and the need for irrigation water peak together during the hot, normally dry months of July and August when the rate of evaporation also reaches the highest level. Reduced water levels impact safe use of diving boards, water slides, and the "sea slide"; cause mud flats and curtail bank fishing; and result in an increase in water temperature and algal growth, with increased chances of summer fish kill due to depletion of dissolved oxygen already in short supply. Reduced water levels also worsen the DO level in and extend the hypolimnetic zone, substantially reducing fish habitat area and increasing aquatic plant growth. Remedial measures are needed to control these problems as well as to ensure the availability of more water for the golf course and its future expansion.

FEASIBLE ALTERNATIVES FOR LAKE RESTORATION

Various restoration and protection methods have been described under "Lake Restoration Methods." The feasibility of alternative techniques for solving each of the six identified problems is considered below.

Reduction in Total Phosphorus Concentration

The feasibility of the following techniques for achieving reduction in total phosphorus concentration is investigated.

1. Drainage Basin Alterations. Sediment from the cultivated and fertilized farmland has been found to be the most important source of nitrogen and phosphorus inputs to the lake. Soil erosion from the cultivated agricultural area in the lake watershed, 141 acres or about 25 percent of the watershed contributing sediment to the lake, accounts for 62 percent of the total erosion. With contour-farmed terraced fields, the erosion from the agricultural area can be reduced to about 1/5th of its present value. Comparable results can be obtained with no-till farming. The sediment input from the entire watershed can, thus, be reduced to about 50 percent. The total phosphorus concentration of 0.08 mg/l in tributaries where they enter the lake may be reduced to about 0.04 mg/l during extremely wet years such as 1981, or less than 0.02 mg/l during average rainfall years.

2. Reduction in Sediment Input. The outside-lake methods involve some low check dams upstream of the lake, diversion of sediment-laden water, and use of sedimentation pools. The low check dams are not feasible on shallow, intermittent tributaries. The diversion of sediment-laden water by a 3- to 4-foot diameter pipe, laid along the length of the lake from the bridge downstream of the Sportsman Club to a point below the dam,

will not only be very costly but also require costly operation and control. A sediment pool can be constructed in the eastern part of the lake just downstream of the road bridge below the Sportsman Club. The sediment from such a pool can be excavated every 8 years by lowering the lake water level by 8 to 10 feet during October-November. If the lake is allowed to refill in January, it will be at its normal pool level by the middle of May in an average rainfall year, but may need pumping of groundwater into the lake to raise the level by 2 to 3 feet during a low-flow year.

3. Aeration of Water. When DO levels fall close to zero, more phosphorus is released from the sediments under the prevailing anaerobic conditions in the lower layers of the hypolimnion. One ameliorative technique is to pump hypolimnetic water to the surface and allow it to mix with warm epilimnetic water, or force the epilimnetic water to the hypolimnion. Another technique is to supply air under pressure to perforated pipes laid in the hypolimnion. Both methods have been used in various lakes with remarkable success.

4. Admission of Unpolluted Water or Dilution. A new well can be drilled and sufficient groundwater routed to the lake after aeration and removal of iron. The effectiveness of this technique depends on the difference between nutrient concentrations in the inflow and lake waters, as well as on the proportion of water used for dilution. Dilution reduces phosphorus, chlorophyll a, and biomass. It improves secchi disk visibility. Admission of groundwater will reduce lake water temperatures and help in the development of trout fishery.

5. Admission of Unpolluted Water and Hypolimnetic Drainage. Water for irrigation of the golf course area can be withdrawn from the deeper parts of the lake by installing a suitable intake pipe system, and

groundwater can be admitted to the lake to compensate for the withdrawals or even exceed them. This will result in significant lowering of nutrient levels and a washout of algal cells. Such dilution is shown to reduce phosphorus, chlorophyll a, and biomass. It improves the secchi disk visibility. Hypolimnetic water withdrawals result in an increased nutrient export and a decrease in the dispersion rate from the sediments to the water because of nutrient reduction in the top layer. Admission of groundwater will decrease surface water temperature. It will not, however, ensure 5 or 6 mg/l DO in the hypolimnion.

6. Lake Deepening or Dredging. Removal of sediments reduces internal cycling of nutrients, removes any toxic sediments, and reduces nuisance aquatic macrophyte growth. Some short-term environmental problems may stem from dredging operations. The total accumulated sediment in the lake is 35.1 ac-ft or 13.5 percent of the original storage capacity. Sediment-regenerated phosphorus contributes about 0.01 to 0.03 mg/l to the total phosphorus concentration in the lake. With dredging and disposal costs of about $3 per cubic yard, the removal of 35.1 ac-ft sediment may cost $170,000. A suitable reduction in sediment-regenerated phosphorus can be obtained by other methods at a much lesser cost. Thus, the dredging of the lake is considered economically an infeasible alternative.

7. Lake Bottom Sealing. To reduce or prevent the nutrient release from lake bottom sediments under anaerobic conditions, the sediment can be covered with perforated plastic sheets, usually 0.1-mm thick. However, the cost of installing such sheets in lake areas, with water depths more than 8 feet, will be about $20,000 per acre. The lake area with water depths exceeding 8 feet is 12.5 acres. The total cost, therefore, will be $250,000. To maintain the effectiveness of the sheets, the accumulated

sediment over the sheets may have to be removed every 10 years. The effectiveness of these sheets as an efficient means of lake bottom sealing is still questionable. This alternative is, therefore, considered infeasible because of the high cost and doubtful effectiveness. If littoral zone phosphorus sources are of the same order as hypolimnetic sediments, the cost of covering the entire lake bottom may run close to one-half million dollars.

8. Phosphorus Precipitation. This method involves successive applications of aluminum sulfate or alum to disrupt the internal phosphorus cycle. Alum controls the phosphorus in sediments through the sorptive capacity of the aluminum hydroxide floc formed in alkaline water. Phosphorus precipitation can be effective only in lakes with less allochthonous nutrient input. It is best suited for lakes which stratify and flush very slowly. Lake of the Woods has significant allochthonous inputs and flushes about twice a year. Therefore, phosphorus precipitation is not considered a feasible alternative.

Artificial Destratification and Hypolimnetic Aeration

The DO deficiency during summer occurs mainly because of the decomposition of organic material in the hypolimnion and the thermal stratification, which restricts movement of cold, dense water in the hypolimnion to the overlying waters in the metalimnion and epilimnion. When the DO levels fall close to zero, more phosphorus is released from the sediments under the prevailing anaerobic conditions. These hypolimnetic waters can be oxygenated and circulated by artificial destratification and hypolimnetic aeration. Two techniques were described under item 3 in the last section. Both of these are in use on various lakes and performing satisfactorily.

With an increased oxygen level in the hypolimnion, there is a reduction in the release of nutrients from the bottom sediments. The range of benthic populations is extended to the profundal region which was once anaerobic; there is a reduction in surface water temperature and hence a reduction in the evaporation rate, water clarity is increased, and winter fish kills may be avoided by aerating water during winter. Some disadvantages are an increase in the heat budget of the lake, and some temporary increase in water turbidity because of some resuspension of bottom sediments. Expanded habitat following destratificaion and aeration benefits the fish population because of increased food supply and less crowding into the epilimnetic zone during summer.

Dredging Sediments

The results of sedimentation surveys for Lake of the Woods show an accumulation of 35.1 ac-ft of sediment during the period 1948-1980. This is about 13.5 percent of the original lake volume. The average annual reduction in storage because of sediments entrapped is estimated as 0.42 percent. The present rate is believed to be less than the average rate for the 32-year period. Monitoring of heavy metals during the year 1981 indicated a high concentration for manganese only. Some other heavy metals come from the herbicides and algicides used in the lake. Thus, the main advantage of dredging the lake is in increasing its present storage capacity to its original capacity. The cost of sediment removal by dredging, including disposal, is estimated as $170,000 under item 6 in the last section. The dredging will result in a reduction in internal cycling of nutrients and in nuisance aquatic macrophyte growth. However, these results can be achieved at a much lesser cost by other methods. The increase in storage, though good for the fish habitat, is not necessary for most of the present uses of the lake. Thus, the dredging of sediment is not considered an economical, feasible alternative.

Chemical Control of Algae

Nuisance algal blooms reduce the recreational potential of the lake. Copper sulfate has been widely used for control of blue-green algae. The effectiveness of the copper ion in controlling algae is enhanced by using a chelating agent, such as citric acid, and a follow-up application of potassium permanganate to oxidize the decaying algae and to reduce the DO-depressing effect of these dying algae. Use of copper sulfate as an algicide does not impact the diversity of the benthal population.

Control of Aquatic Plants

Use of herbicides and mechanical harvesting of biomass are the two effective methods for controlling nuisance weed or macrophyte growth in lake areas with water depths up to 6 or 8 feet. "Aqua Screens" can be used in certain selected areas.

1. Herbicides for Weed Control. Tests conducted on effectiveness, toxicity, and residues of herbicides have led to a limited number of very effective products for weed control. These herbicides can be easily applied to areas difficult to reach with mechanical harvesters. Aquathol and Komeen are presently being used in Lake of the Woods.

2. Mechanical Harvesting of Biomass. The aquatic weeds or macrophytes can be harvested twice a year. This method accelerates the nutrient outflow from the lake because of the disposal of harvested macrophytes at a location away from the lake. Some significant advantages are: immediate removal of nuisance vegetation and certain amounts of plant

nutrients without affecting use of the lake, use of harvested weeds for compost and mulch, and inhibiting of macrophyte regrowth in subsequent years.

3. Aqua Screens. Provision of "Aqua Screens" may be desirable for better macrophyte control near the water slide and boat ramp areas. The aquatic weeds in these areas are in the upper 6 feet of water. A lake level drawdown in November will facilitate installation of the screens (polyvinyl sheets with fine perforations), or these screens can be installed by one or two scuba divers. The screens will require cleaning every 2 years for removing sediments deposited on them.

Supply Well and Irrigation Withdrawals

A well tapping the lower glacial unit (Banner Formation of Kansan Age) in the Mahomet bedrock valley was drilled in 1955 near the bath house on the southeastern shoreline. This well yields about 150 gpm (gallons per minute) and has been in operation 8 to 16 hours a day during dry periods to partially compensate for some of the water withdrawn from the lake for irrigation of the golf course area. This groundwater improved the conditions for swimming in the beach area. With the expected expansion in the golf course area, the irrigation demand will increase in the future. The expansion is desired because of the increasing demand from Champaign-Urbana and other nearby towns.

To provide for increased irrigation withdrawals, a 600 gpm well (10-12 inches diameter and with gravel pack) may be drilled near the northern shoreline. The water pumped from the 600 gpm well can be passed through an aeration screen, for increasing DO and precipitating iron, and routed to the lake. The lake level will not go below normal pool even in droughts.

The admission of unpolluted groundwater will significantly improve the water quality in the lake and lower surface water temperatures during the summer. Combined with artificial aeration and destratification, the temperatures throughout the lake can be kept below 70°F. This will allow development of trout fishery.

Water for golf course irrigation can be withdrawn with the present system, even up to 600 gpm, when the lake is artificially aerated and destratified. Or the 600 gpm can be pumped from the hypolimnion by connecting an intake pipe system to the present withdrawal system together with a new pump for the increased total dynamic head. A bypass can be provided so that hypolimnetic water is discharged to the Sangamon River via a ditch when water is not needed for irrigating the golf course area.

Miscellaneous

The diagnostic study indicates that high fecal coliform bacteria concentrations were observed in the south tributary of the lake. The sanitary facilities at the Tin Cup campground should be investigated to correct the situation.

COST OF FEASIBLE ALTERNATIVES

The cost of various feasible alternatives for lake restoration, discussed in the previous section, are estimated. Some methods serve more than one purpose. The best desirable, practical, and economical management scheme can be developed from the cost data as well as efficiency criteria.

Reduction in Sediment and Allochthonous Nutrient Input

The two alternatives together with their costs are given below.

Drainage Basin Alterations. This involves application of Best Management Practices to 141 acres of cultivated agricultural land to reduce the soil erosion and sediment and allochthonous nutrient contributions to the lake. The Soil Conservation Service personnel are in touch with farmers and are providing them with guidance for implementation of sound practices for erosion control to retain precious soil and to maintain its productivity. The cost to the farmers is estimated as $21,150 at the rate of $150 per acre. The main benefit to the lake is the reduction in sediment and allochthonous nutrient input to about one-half of the present level.

Sediment Retention Basin. A sediment retention basin, less than 2 acres in area, just downstream of the road bridge below the Sportsman Club can be constructed by lowering the lake level by 8 feet in November, and making a curtain wall of treated wood with 4 in. x 4 in. verticals sunk 2 to 3 feet below the original lake bed, at 18-inch centers, with 1-inch-thick planking nailed to these verticals. The top of the curtain wall will be 3 or 4 feet below the normal pool level. The sediment retention basin will entrap about 5 ac-ft of sediment in 8 years. The sediment can be excavated at a lower cost than dredging if the lake level is lowered by 8 feet in October-November. The excavated sediment can be used to extend the high ground above the 100-year floodplain of the Sangamon River. The construction cost of the basin is estimated as $10,000. Excavation and disposal of 5 ac-ft of sediment, once in every 8 years, will cost about $17,000 at the rate of $2 per cubic yard. The sediment input to the lake will be reduced to one-half but the reduction in nutrient input will be less. Construction of such a sedimentation basin will take away about 2 acres from the present 23.2-acre area of the lake.

Artificial Destratification and Hypolimnetic Aeration

There are 2 systems in use for achieving artificial destratification and hypolimnetic aeration.

Quintero-Garton System. The main components of this system are a 1.5-HP reversible axial flow pump, a spare motor as a standby, a 7 ft x 7 ft platform, and accessory mountings and stainless steel nuts and bolts and other fixtures. The hypolimnetic water is pumped to the lake surface and allowed to mix with epilimnetic water, or the epilimnetic water is pumped to the hypolimnion to diffuse and disperse and to replace the hypolimnetic water. The cost of the system, including installation and testing, is estimated as $15,000. With continuous operation, the energy cost per month will be $70. The system may be operated from April to September and some months during winter. The system causes very little noise but the platform may have to be fenced off to prevent accessibility to boaters.

Compressed Air System. About 1000 feet of perforated vinyl pipe will be laid in the hypolimnion and connected at both ends to tubes delivering compressed air. A 4-HP compressor will deliver 25-30 SCFM (standard cubic feet per minute) of air which will insure adequate circulation. Turnover rate for the lake will be less than one-half day. The cost of the system including installation and housing to suppress compressor noise is estimated as $18,000. The energy cost per month will be $140. The system does not need a platform, but the compressor noise, though muffled to some extent by the housing structure, may be distracting to lake users.

Admission of Groundwater (and Hypolimnetic Drainage)

This scheme is considered under two alternatives.

Admission of Groundwater or Dilution. This includes drilling of a 600 gpm well near the north shoreline and routing of the pumped groundwater to the lake after aeration and precipitation of iron. The cost is estimated as $50,000. The monthly electric charges, considering 24-hour operation, are estimated as $450. A 600 gpm water supply over a period of one month equals about 80 ac-ft of water, which is a little more than a third of the total storage volume of the lake. The system provides ample capacity for input of unpolluted waters and has a high potential for significant improvement in lake water quality. In actual practice, operation for only 10 to 18 hours a day will be sufficient and the electrical charges will be reduced accordingly. The pumpage may be needed for 4 months or part thereof during the summer. The water temperature can be kept lower than 70°F. This will allow development of trout fishery which will greatly increase the recreational use of the lake.

Admission of Groundwater and Hypolimnetic Drainage. If the lake is not artificially aerated and destratified, hypolimnetic drainage may be considered together with pumping of groundwater into the lake. The drainage system will involve provision of a multi-inlet pipe system from the hypolimnion to the present irrigation withdrawal main, a new pump for the irrigation and withdrawal system, and a bypass to a ditch flowing to the Sangamon River. The cost of this system will be $5000 in addition to $50,000 for the well and pump system. The extra cost of dewatering the hypolimnion at the rate of 600 gpm, 24 hours a day, for one month is estimated as $270. A volume of 80 ac-ft can be pumped out in one month. In actual precice, the drainage pump may run about the same time as the well pump.

Chemical Control of Algae

Chelated copper sulfate application followed by potassium permanganate is a viable technique for algae control and is being used in Lake of the Woods. Four applications are needed during June through September. The cost at the rate of $7 per acre per application comes to $650 per year.

Aquatic Weed Control

There are 3 items considered under this heading. One of the first two is necessary; the third one is a safety meaure for the water slide and boat ramp area.

Herbicides for Weed Control. Macrophytes in Lake of the Woods are controlled at the present with Aquathol and Komeen. About 4 to 5 acres of weed bed is treated. Two applications are made each year to control rooted vegetation. The annual cost is estimated as $1000.

Mechanical Harvesting of Biomass. Considering that a mechanical harvester will be available on a rental basis from a location within 100 miles of the Lake of the Woods, the harvesting of macrophytes and their disposal twice a year will cost about $5000 a year, at the rate of $500 per acre.

Aqua Screens in Selected Areas. Provision of "Aqua Screens" near the water slide and near the boat ramp area will improve the safe operation in these areas because of the removal of aquatic weeds. An Aqua Screen roll of 100 ft x 7 ft costs $182. The cost of material and installation over an area of 100 ft x 30 ft near the water slide and 40 ft x 50 ft near the boat ramp is estimated as $2670. The screens will have to be pulled out, cleaned, and reinstalled every 2 years. The cost of this operation will be about $1600 every 2 years.

BEST MANAGEMENT SYSTEM

A critical review of the efficiency and costs of various feasible alternatives for improving the water quality of the Lake of the Woods, maintaining the improved water quality, and maximizing the recreation potential, indicates the following mix of alternatives as the <u>best management system</u>.

1. Drainage basin alteration (Best Management Practices for 141 acres of cultivated agricultural land)

   Cost to be borne by the farmers

2. Artificial destratification and hypolimnetic aeration: Install a Quintero-Garton system.

Initial cost	$15,000
Electrical costs	$70 per month for about 6 months each year

3. A 600 gpm well for delivering groundwater to the lake.

Initial cost	$50,000
Electrical costs	$1800 per year (approximately)

4. Continue use of chelated copper sulfate followed by potassium permanganate, 4 times during June-September.

Annual cost	$650

5. Continue aquatic weed control with Aquathol and Komeen.

Annual cost	$1000

6. Install "Aqua Screens" in water slide and boat ramp areas.

Initial cost	$2670
Cost every two years	$1600

REFERENCES

Ahlgren, D. 1978. Response of phytoplankton and primary production to reduced nutrient loading in Lake Norrviken. Proceedings of 20th Congress Internationale Vereiningung fur Theoretische und Angewandte Limnologie, Copenhagen, p. 840-845.

Ahlgren, I. 1978. Response of Lake Norrviken to reduced nutrient loading. Proceedings of 20th Congress Internationale Vereiningung fur Theoretische und Angewandte Limnologie, Copenhagen, p. 846-850.

Allum, M.O., R.E. Glessner, and J.M. Gakstatter. 1977. An evaluation of the national eutrophication survey data. USEPA Corvallis Environmental Research Laboratory Working Paper 900, 84 pages.

Barnes, R.A., P.F. Atkins, Jr., and D.A. Scherger. 1972. Ammonia removal in a physical-chemical wastewater treatment process. USEPA-R2-72-123, 66 pages.

Born, S.M., T.L. Wirth, E.M. Brick, and J.O. Peterson. 1973. Restoring the recreational potential of small impoundments. Technical Bulletin 71, Wisconsin Department of Natural Resources.

Britten, L.J., R.C. Averett, and R.F. Ferreira. 1975. An introduction to the processes, problems and management of urban lakes. U.S. Geological Survey Circular 601-K, 22 pages.

Burns, D.E., and G.L. Shell. 1973. Physical-chemical treatment of a municipal wastewater using powdered carbon. USEPA-R2-73-264, 230 pages.

Cachter, R. 1976. Lake restoration by water siphoning. Schweizerische Hydrologie, Vol. 38, No. 1, p. 1-28.

Carlson, R.E. 1977. A trophic state index for lakes. Journal of Limnology and Oceanography, V. 22(2):361-369.

Clark, J.E. , W. Viessman, Jr. and M.J. Hammer. 1971. Water supply and pollution control. International Textbook Company, 661 pages.

Cohen, J.M., and J.J. Westrick. 1975. Overview of physical-chemical treatment. Symposium on Physical-Chemical Treatment from Municipal and Industrial Sources, USEPA, 159 pages.

Cooke, G.D. 1980a. Lake level drawdown as a macrophyte control technique. American Water Resources Association, Water Resources Bulletin, V. 16(2): 317-322.

Cooke, G.D. 1980. Covering bottom sediments as a lake restoration technique. American Water Resources Association, Water Resources Bulletin, V. 16,(5), p. 921-926.

Cooke, G.D. , R.H. Kennedy, and S.A. Peterson. 1981. Precipitation and inactivation of phosphorus as a lake restoration technique. USEPA-600/ 3-81-012, 41 pages.

Cooke, G.D., and R.H. Kennedy. 1978. Effects of a hypolimnetic application of aluminum sulphate to a eutrophic lake. Proceedings of 20th Congress Internationale Vereiningung fur Theoretische und Angewandte Limnologie, Copenhagen, p. 486-489.

Dawson, G.W., and B.W. Mercer. 1979. Method for lake restoration. Battelle Memorial Institute, Official Gazette of the United States Patent Office, V. 978(3):982.

Dobson, H.F.H., M. Gilbertson, and P.G. Sly. 1974. A summary and comparison of nutrients and related water quality in lakes Erie, Ontario, Huron and Superior. Journal of the Fisheries Research Board Canada, V. 31: 731-738.

Dougal, M.D. 1970. Physical and economic factors associated with the establishment of stream water quality standards, Vol I. Iowa State University, Ames, Iowa, 327 pages.

Drehwing, F. , A.J. Oliver, D.A. MacArthur, and P.E. Moffa. 1979. Disinfection/treatment of combined sewer overflows. USEPA-600/2-79-134, 243 pages.

Dunst, R.C. et al. 1974. Survey of lake rehabilitation techniques and experience. Technical Bulletin No. 75, Wisconsin Department of Natural Resources, 179 pages.

Echelberger, Jr., W.F. Tenney, and M.W. Tenney. 1969. Wastewater treatment for complete nutrient removal. Journal of Water and Sewage Works, V. 116(10):396-402.

Edmondson, W.T. 1977. Trophic equilibrium of Lake Washington. Washington University Report --EPA-600/3-77-087, 35 pages.

Edmondson, W.T., and P. Murtaugh. 1980. Selective predation by mysids in lake restoration by biomanipulation. Washington University, Seattle, Washington, 28 pages.

Fair, G.M., J.C. Geyer, and D.A. Okun. 1971. Elements of water supply and wastewater disposal. John Wiley and Sons, 752 pages.

Fast, A.W. 1979. Nitrogen gas supersaturation during artificial aeration of Lake Casitas, California. The Progressive Fish Culturist, V. 21(3):153-155.

Fitzgerald, G.P. 1971. Algicides. Literature Review No. 2, Eutrophication Information Program, University of Wisconsin Water Resources Center, 50 pages.

Freedman, P.L., and R.P. Canale. 1979. Impact of waste diversion on water quality in lakes. American Society of Civil Engineers, Journal of the Environmental Engineering Division, V. 105(5):867-881.

Hamm, A. 1978. Nutrient load and nutrient balance of some subalpine lakes after sewage diversion. Proceedings of 20th Congress Internationale Vereiningung fur Theoretische und Angenwandte Limnologie, Copenhagen, p. 975-984.

Illinois Department of Conservation. 1976. Aquatic weeds, their identification and methods of control. Illinois Department of Conservation, Springfield, Illinois, Fishery Bulletin 4, 56 pages.

Illinois Environmental Protection Agency. 1978. Clean lakes strategy for Illinois. Illinois Environmental Protection Agency Staff Report, 55 pages.

Janik, J.J., W.D. Taylor, and J.W. Barks. 1980. A compilation of common algal control and management techniques. U.S. Army Corps of Engineers, Washington, D.C., 53 pages.

Jorgensen, S.E. 1980. Lake management: water development, supply and management. Vol 14, Pergamon Press, Oxford, U.K., 167 pages.

Kothandaraman, V., D.P. Roseboom, and R.L. Evans. 1980. Pilot lake restoration investigations--aeration and destratification in Lake Catherine: second-year operation. Illinois State Water Survey Contract Report 228, 47 pages.

Kothandaraman, V., and R.L. Evans. 1982a. Aeration-stratification of Lake Eureka using a low energy destratifier. Illinois State Water Survey Contract Report 294, 32 pages.

Kothandaraman, V., and R.L. Evans. 1982b. Diagnostic-feasibility study of Lake Le-Aqua-Na. Illinois State Water Survey, in print.

Laing, R.L. 1974. A non-toxic lake management program. Journal of Hycinth Control, V. 12, p. 41-43.

Lang, I. 1978. Hungary's Lake Balaton: a program to solve its problems. Ambio, V. 7(4):164-168.

Lorenzen, J., and A.W. Fast. 1977. A guide to aeration/circulation techniques for lake management. Available from NTIS or EPA-600/3-77-004, 142 pages.

National Academy of Sciences and National Academy of Engineering. 1972. Water quality criteria--a report of the committee on water quality criteria. National Academy of Sciences and of Engineering, Washington, D.C. , 594 pages.

O'Farrell, T.P., D.F. Bishop, and A.F. Cassel. 1973. Nitrogen removal by ammonia stripping. USEPA-670/2-73-040, 23 pages.

Pastorok, R.A., T.C. Ginn, and M.w. Lorenzen. 1981. Evaluation of aeration/ circulation as a lake restoration technique. USEPA-600/3-81-014, 58 pages.

Pechlander, R. 1975. Eutrophication and restoration of lakes receiving nutrients from diffuse sources only. Verhandlungen Internationale Vereiningung Limnologie, p. 1272-1278.

Peterson, S.A. 1981. Sediment removal as a lake restoration technique. USEPA-600/3-81-013, 55 pages.

Rose, W.J. 1977. Hydrologic considerations associated with dredging spring ponds in Wisconsin. Water Resources Investigations 77-18, U.S. Geological Survey, Wisconsin, 35 pages.

Sakamoto, M. 1966. Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth. Archiv fur Hydrobiologie, V. 62:1-28.

Sefton, D.F., M.H. Kelly, and M. Meyer. 1980. Limnology of 63 Illinois lakes, 1979. Illinois Environmental Protection Agency, 247 pages.

Shannon, E.E., and P.L. Brezonik. 1972. Eutrophication analysis: a multivariate approach. American Society of Civil Engineers, Journal of Sanitary Engineering, V. 98(SA1):37-57.

Sikorowa, A. 1978. Changes of the distribution and number of the bottom fauna as an effect of artificial lake aeration. Proceedings of 20th Congress Internationale Verininingung fur Theoretische und Angewandte Limnologie, Copenhagen, p. 1000-1003.

Sonnichsen, T. 1978. Toxicity of phosphate-reducing agent (aluminum sulphate) on the zooplankton in the Lake Lyngo So. Proceedings of 20th Congress Internationale Vereiningung fur Theoretische und Angewandte Limnologie, Copenhagen, p. 709-713.

Starkey, J.R., Jr., M.E. Kub, A.E. Binks, and K.K. Jain. 1973. An investigation of ion removal from water and wastewater. USEPA-660/3-74-022, 116 pages.

Storch, T.A., W.M. Barnard, and W.J. Metzger. 1978. Relationship between phosphorous loading and phytoplankton standing crops in Chautauqua Lake, New York. Proceedings of 20th Congress Internationale Vereiningung fur Theoretische and Angewandte Limnologie, Copenhagen, p. 490-495.

Theis, T.L. et al. 1979. Treatment of Lake Charles East, Indiana sands with fly ash. USEPA-600/3-79-060, 120 pages.

USEPA. 1973. Methods for identifying and evaluating the nature and extent of non-point sources of pollutants. USEPA Report 430/9-73-014, 261 pages.

USEPA. 1974. The relationships of phosphorous and nitrogen to the trophic state of northeast and northcentral lakes and reservoirs. USEPA National Eutrophication Survey Working Paper No. 23.

USEPA. 1980. Restoration of Medical Lake. Capsule Report, USEPA-625/2-80-025, 12 pages.

Weber, W.J., Jr. 1975. The role of activated carbon in physico-chemical treatment. Symposium on Physical-Chemical Treatment from Municipal and Industrial Sources, USEPA, 159 pages.

Weber, W.J., Jr., and J.G. Kim. 1965. Preliminary evaluation of the treatment of raw sewage by coagulation and adsorption. Univeristy of Michigan, TM-2-65.

Welch, E.B. 1981. The dilution/flushing technique in lake restoration. USEPA-600/3-81-016, 13 pages.

Wetzel, R.G. 1975. Limnology. W. B. Saunders Company, Philidelphia, Pennsylvania, 743 pages.

Wilkin, D.C., and S.J. Hebel. 1982. Erosion, redeposition, and delivery of sediment to midwestern streams. Water Resources Research, V. 18(4):1278-1282.