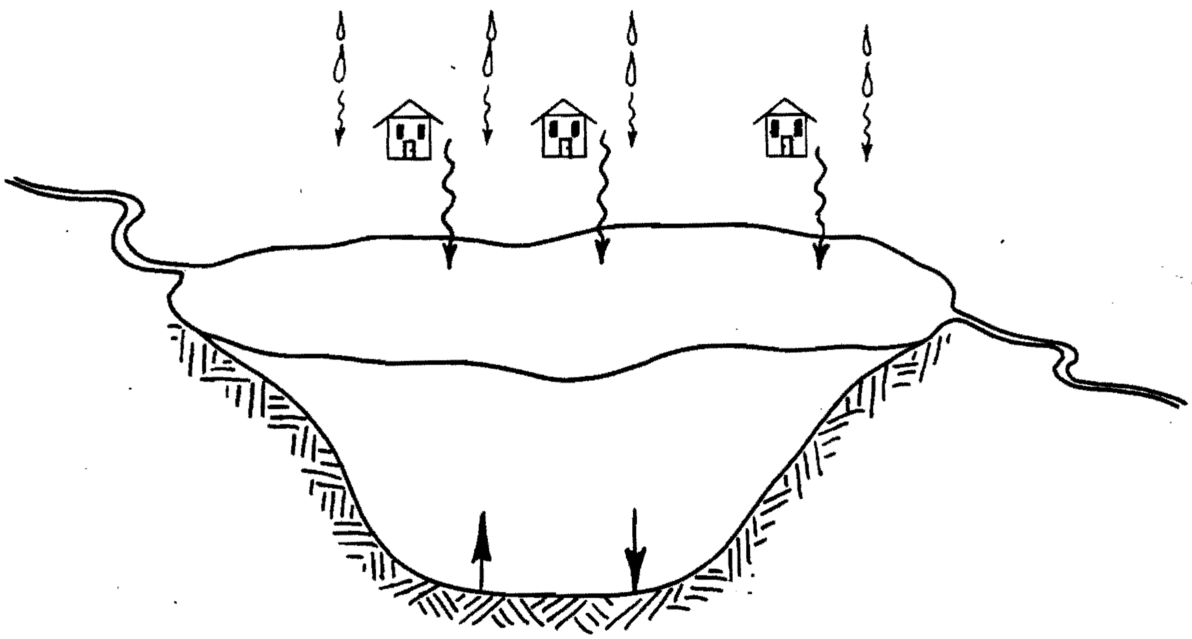
LAKE MOREY
DIAGNOSTIC – FEASIBILITY STUDY
1980 – 1984
FINAL REPORT



STATE OF VERMONT

AGENCY OF ENVIRONMENTAL CONSERVATION

DEPARTMENT OF WATER RESOURCES

AND ENVIRONMENTAL ENGINEERING

WATER QUALITY DIVISION

MONTPELIER, VERMONT

Lake Morey
Diagnostic-Feasibility Study

Final Report - April, 1984

as authorized by the Revised
Regulations for Section 314 of the
Clean Water Act of 1977, P.L. 95-217

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MS-1-484-2

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ACKNOWLEDGEMENTS

Many individuals made substantial contributions to the Lake Morey Diagnostic-Feasibility Study. Some of these contributions are acknowledged at appropriate points within the text. The authors would also like to thank the following individuals for their efforts on behalf of the study. The staff of the Vermont Department of Water Resources and Environmental Engineering Laboratory, including John Townsend and Donald Keyser in particular, performed the chemical analyses on all water samples taken during the study. Phytoplankton counts were performed by Douglas Burnham. Charles Harroun participated in the field work during the early phases of the study. John Cotton and Ken Toppin of the U.S. Geological Survey in Concord, N.H., contributed valuable advice and field assistance. The report was typed by Alison Begin and Vicki Bresset.

A special thanks is given to the Lake Morey Citizen's Advisory Committee, and to Richard Allen in particular, for their advice, assistance, patience, and encouragement throughout the course of the study.

ABSTRACT: The shallow Fairmont Lakes in southern Minnesota have been treated with copper sulfate for 58 years to reduce excessive algal growth. Copper sulfate was applied to five lakes at cumulative rates upo to 1647 kg/ha (1470 lb/acre), totaling 1.5 million kilograms. Data collected since treatment of the Fairmont Lakes began in 1921 provide alarming insights into lake responses to sustained chemical treatment with copper sulfate. Short-term and long-term effects have occurred. Short-term effects include: a) the intended temporary killing of algae, b) dissolved oxygen depletion by decomposition of dead algae, c) accelerated phosphorus recycling from the lake bed and recovery of the algal population within 7 to 21 days, and d) occasional fish kills due to oxygen depletion or copper toxicity or both. Long-term effects are shown to include: a) copper accumulation in the sediments, b) tolerance adjustments of certain species of algae to higher copper sulfate dosages, c) shift of species from green to blue-green algae and from game fish to rough fish, d) disappearance of macrophytes, and e) reductions in benthic macroinvertebrates. The conclusion is that while copper sulfate treatments enjoy great popularity because they kill and remove algae almost instantaneously, other immediate or cumulative side effects can be harmful to many other aquatic organisms.
(KEY TERMS: lakes; eutrophication; lake management; lake restoration; toxicity; lake ecosystems; copper sulfate.)

INTRODUCTION

The Lake Morey Diagnostic-Feasibility Study was undertaken by the Vermont Department of Water Resources and Environmental Engineering under grant agreements with the U.S. Environmental Protection Agency, as authorized by Sections 314 and 208 of the Federal Clean Water Act of 1977. The purpose of this study was to diagnose the cause of water quality problems in Lake Morey and to use the results of the diagnostic work to direct feasibility studies for lake restoration. The ultimate purpose was to develop specific recommendations for measures to restore appropriate water quality conditions to the lake. These recommendations will provide the basis for a funding request for a Phase II lake restoration project under Section 314.

Lake Morey has had a long-standing problem of excessive algae and aquatic plant growth that has, at times, severely interfered with the recreational use of the lake. Herbicides such as 2,4-D and Diquat were applied to the lake as early as 1963 to control nuisance conditions. The algicide copper sulfate was applied lake-wide every year from 1970 until 1975, when its use was discontinued except for localized shoreline treatments. The degree of the algae problem in Lake Morey has been quite variable from year to year, and also from week to week within a season. At times, blooms of blue-green algae and other algal types have formed extensive surface scums that have made the lake undesirable for most recreational purposes. These nuisance conditions have been interspersed with periods of relatively good water quality.

Water quality problems in the lake have long been a major concern of the Lake Morey Protective Association. This citizen's group has been actively involved in a number of study and planning efforts dating back to the early 1970's, conducted by state and local governments and by private engineering firms, all aimed at finding a solution to the lake's eutrophication problem.

An early study of the eutrophication problems at Lake Morey and their possible solutions was conducted by Dubois and King, Inc. (1974) for the Town of Fairlee, Vermont. Based on a study of Lake Morey by the Academy of Natural Sciences of Philadelphia (1972), Dubois and King, Inc. concluded that nutrient inputs to the lake from shoreline septic systems were the major cause of excessive algae growth in the lake. This conclusion was reiterated by the Vermont Department of Water Resources (1975). In both studies, the conclusion that septic system inputs were significant was based primarily on circumstantial evidence such as the presence of many homes located on steep slopes with minimal setback from the lake, and the prevalence of soil types with poor suitability for septic systems. In neither case were nutrient inputs from septic systems directly quantified and compared with inputs from other sources. Dubois and King, Inc. (1974) concluded that a sewer system and treatment plant serving the shoreline residences and commercial establishments around Lake Morey was the best way to curtail eutrophication in the lake. The cost of this system was estimated to be $1,094,400.

Based on the work of Dubois and King, Inc., a Section 201 Step I Facilities Planning grant was awarded to the Town of Fairlee under the U.S. Environmental Protection Agency's Construction Grants Program. Dufresne-Henry, Inc. began the facilities planning work in 1979. However, a preliminary modeling study of Lake Morey conducted by the Vermont Department of Water Resources (1979) resulted in the conclusion that septic systems could be a significant phosphorus contributor to Lake Morey only if the shoreline soil phosphorus attenuation characteristics were among the poorest reported in the literature. A second modeling analysis (Walker, 1980) indicated that about 20% of the phosphorus loading to the lake might be attributed to septic system inputs, but also that internal phosphorus recycling appeared to be of major significance. The uncertainty as to whether septic system contamination was, in fact, the cause of the lake's eutrophication problem, and the high cost associated with the construction of a sewer and wastewater treatment system ($3,000,000 based on 1984 costs) indicated that more detailed lake studies were necessary before proceeding with the facilities planning process. Consequently, the facilities planning work was halted, and the present Lake Morey Diagnostic-Feasibility Study was initiated in 1980.

The focus of the diagnostic portion of this study was the evaluation of the various sources of phosphorus to the lake (i.e., the construction of a phosphorus budget for the lake). Four possible sources of phosphorus to Lake Morey were quantified by means of an extensive program of sampling and field work:

1. tributary inflow
2. groundwater inflow, including septic system inputs
3. precipitation direct to the lake surface
4. internal loading from the lake sediments

In addition to the development of a phosphorus budget, there were a number of other areas of diagnostic study. The eutrophication history of Lake Morey was studied by paleolimnological techniques to determine how past human activities in the watershed have affected water quality in the lake. Biological surveys were conducted in Lake Morey in order to describe the existing populations of algae, aquatic macrophytes, and fish, and to provide a basis for the documentation of any biological changes that might result from future lake restoration efforts. Finally, the sampling frequency and methods of data analysis used in the diagnostic study were evaluated to determine how future studies on Vermont lakes could be designed more effectively.

The results of the phosphorus budget studies and other diagnostic work were used to direct feasbility studies of various lake restoration techniques for Lake Morey. A modeling analysis was also conducted to estimate the water quality gains expected from specific lake restoration methods. Together, the diagnostic, feasibility, and modeling results formed the basis for the report recommendations.

BACKGROUND AND DESCRIPTIVE INFORMATION

Location and Description of Lake Morey

Lake Morey lies centrally within the boundaries of the Town of Fairlee in Orange County, Vermont, at approximately 43°55'N latitude and 72°09'W longitude. A map of the lake and tributary streams is shown in Figure 1. The lake has a NNE-SSW orientation, and is 3.1 km (1.9 mi.) in length, at an elevation of 127 meters (416 ft.) above sea level. The lake has a surface area of 2.20×10^6 m^2 (543 acres), a volume of 1.86×10^7 m^3 (15,075 acre-ft.) and a maximum depth of 13.1 m (43 ft.). Depths greater than 8 meters (26 ft.) are found under 66% of the lake's surface. More detailed morphometric data is given in Table 1.

The 1.90×10^7 m^2 (4,698 acre) watershed of Lake Morey is drained by nine major tributary streams (shown in Figure 1). The watershed is predominantly forested with mixed deciduous and coniferous species. The outlet stream at the lake's southern end flows 2.5 km (1.6 mi) to its junction with the Connecticut River. The outflow is controlled by a dam at the lake's southern end. The dam is owned and maintained by the State of Vermont. Originally built in 1921 and reconstructed in 1953-54, this concrete-reinforced structure has removable flashboards to facilitate control over lake level. A 1-2 foot drawdown normally takes place in late fall to minimize ice damage on lakeshore property during winter.

The lake's present water quality status is Class B, as determined by the Vermont Water Resources Board in 1978. This classification indicates that the lake is to be managed for bathing, boating, fishing, agricultural usage, and private water supply with filtration and disinfection.

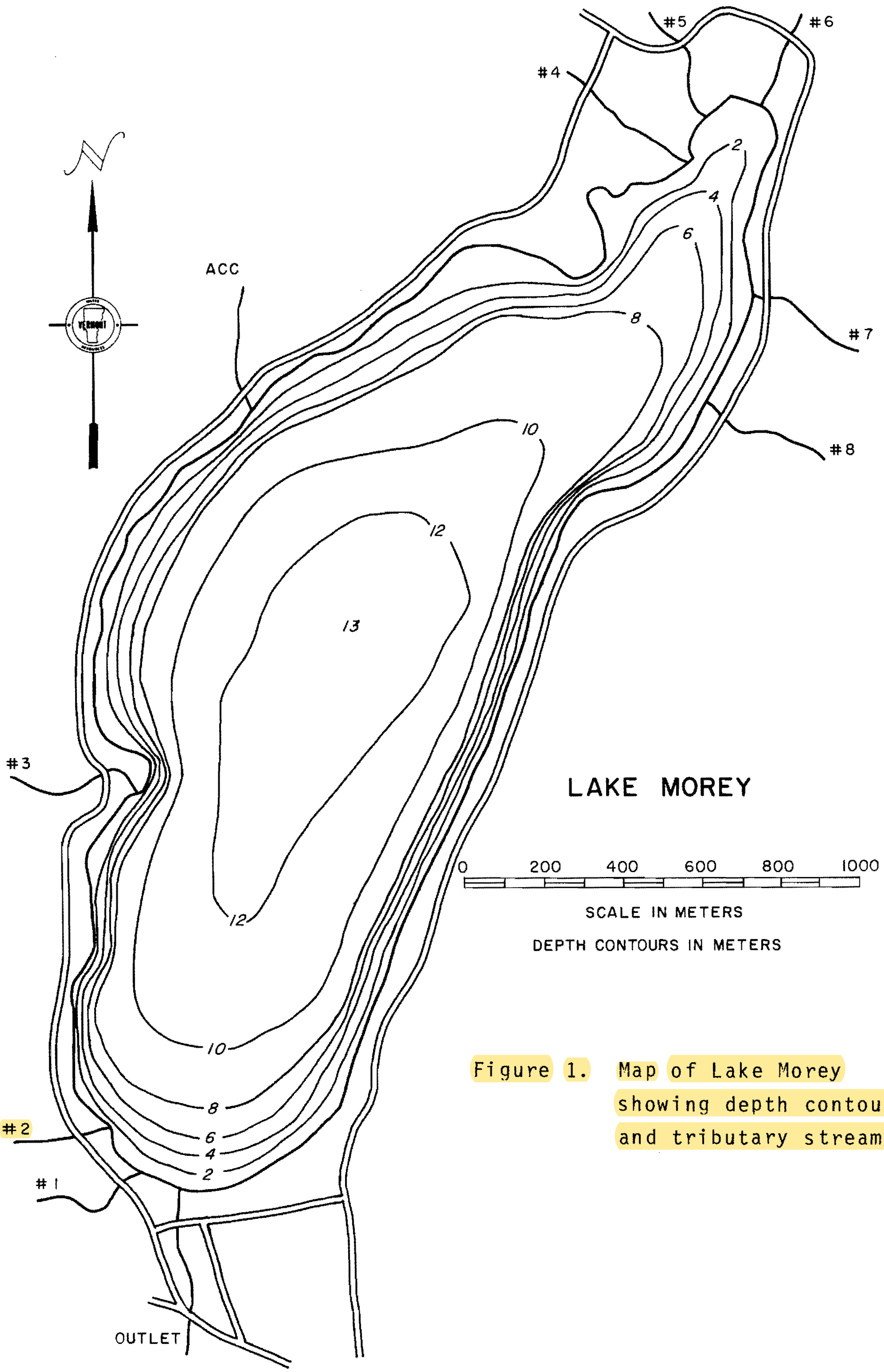

Figure 1. Map of Lake Morey showing depth contours and tributary streams.

Table 1. Morphometric data for Lake Morey.

Depth (m)	Area ($10^6 m^2$)	Stratum (m)	Volume ($10^6 m^3$)
0	2.20	0 - 0.5	1.08
1	2.05	0.5 - 1.5	2.07
2	1.97	1.5 - 2.5	1.97
3	1.88	2.5 - 3.5	1.88
4	1.80	3.5 - 4.5	1.80
5	1.71	4.5 - 5.5	1.72
6	1.64	5.5 - 6.5	1.64
7	1.56	6.5 - 7.5	1.55
8	1.45	7.5 - 8.5	1.44
9	1.28	8.5 - 9.5	1.26
10	1.03	9.5 - 10.5	1.01
11	.71	10.5 - 11.5	.70
12	.37	11.5 - 13.1	.43
13.1	0		
		Total	18.55

Geological Description of the Lake Morey Watershed

The Lake Morey drainage basin is located in the Vermont Piedmont Division of the New England Upland Physiographic Province. This area is characterized by north-south trending hills and valleys of moderate relief. Bedrock is largely made up of Ordovician and Devonian age metasediment with some interspersed metavolcanics and igneous intrusives (U. S. Soil Conservation Service, 1978). The Ordovician metasedimentary rocks are part of a thick accumulation of carbonaceous sand and mud which contains, between some layers, basic lavas and some tuffs. These are overlain in some areas by lighter colored sandstone and shale. The Devonian rocks consist of thickly layered sandstone and shale overlain by more thinly layered, dark, dominantly shaly rocks (Hadley, 1950). This bedrock has undergone periods of intensive folding and metamorphism during the Acadian and Appalachian Orogenys, and during most of the last 200 million years has been subject to erosion. The rounded hills, lakes, ponds, swamps, and stony or sandy subsoil characteristic of this area have been attributed to the advance and retreat of the continental ice sheet during the last million years (Hadley, 1950).

It has been suggested that at least one large glacial lake (Lake Hitchcock and possibly Lake Upham) once occupied the section of the Connecticut Valley in which Lake Morey is located. Varved clays, laminated silts, and lacustrine sands are commonly found along the valley (Stewart, 1961). This suggestion is further supported by evidence from seismic profiles and well installations completed by the United States Geological Survey and the Vermont Department of Water Resources and Environmental Engineering in the summer of 1981 as part of this study. Seismic profiles from west to east across the areas north and south of Lake Morey indicate a depth to bedrock of up to 140 feet and up to 300 feet, respectively. Split spoon samples taken during the drilling of test wells indicated rhythmitic clays to a depth exceeding 100 feet on the north shore of the lake. South of the lake, several distinct layers of sand, silt, and rhythmitic clay to a depth of at least 292 feet were discovered (John Cotton, personal communication).

It is believed that the origin of Lake Morey is related to the later stages of the melting of the ice sheet during the Wisconsin glacial stage, about 13,000 years ago. According to Hadley (1950), the lake occupies a large kettle hole in what may once have been a preglacial channel of the Connecticut River. The part of this channel now occupied by the lake was possibly widened and deepened during glaciation, and the presence of kame deposits along the west side of the lake suggests that a body of stagnant ice remained in this depression after most of the ice sheet had retreated.

Bedrock within Lake Morey's drainage basin consists predominantly of metamorphosed sedimentary and volcanic rocks of the Orfordville formation of Ordovician age, the Meetinghouse slate of Devonian age (Hadley, 1950). Nearly all of the bedrock on the west side of the drainage basin is Meetinghouse slate, a dark gray, lustrous, fissile slate containing many thin white quartzite beds. It consists of very fine grained quartz, sericite, and chlorite along with minutely dispersed, black, opaque material; the lighter colored layers contain quartz with small amounts of alkali feldspar and muscovite (Hadley, 1950).

Bedrock to the south, northeast, and along the southeast shore of the lake is a dark gray to black slate of the Orfordville formation. Its color is due to the presence of finely divided carbon and iron sulfide (Hadley, 1950). Bedrock in the eastern part of the drainage basin, along the northwest shore consists of metamorphosed volcanic rock of the Sunday Mountain member of the Orfordville formation. These rocks consist predominantly of greenstone, chloritic schist, felsite, and quartz-feldspar-sericite schist (Hadley, 1950).

Soils in the Lake Morey Watershed

Soils in the vicinity of Lake Morey were formed mostly in glacial material over the past 11,000 to 13,000 years. In the Lake Morey drainage basin, this material is represented by glacial till, glaciofluvial kame deposits, glaciolacustrine littoral (shallow-water, sandy) material, and lake bottom (silt and clay) deposits. The drainage basin soils have formed both in water-deposited materials in the valley and in glacial till on the uplands. A map of inlet and shoreline soil types in the Lake Morey watershed is provided in Figure 2. Detailed information on the nature of these soils is provided in Tables 2, 3, 4, and 5.

Those soils formed in valley water-deposited materials can generally be included in one of two major soil associations: the Belgrade-Hartland association and the Merrimac-Agawam-Windsor-Winooski association. The Belgrade-Hartland association consists of level to steep, moderately well drained and well drained, medium textured soils which are located on dissected terraces along major streams. It consists of about 50 percent Belgrade soils, 40 percent Hartland soils, and a 10 percent mixture of related soils (U.S. Soil Conservation Service, 1978). The soils in this association have a high erosion potential and a moderate runoff potential. Steep slopes in many places, a seasonal high water table in some places, and slow percolation combine to severely restrict the absorption of effluent from septic tank absorption fields.

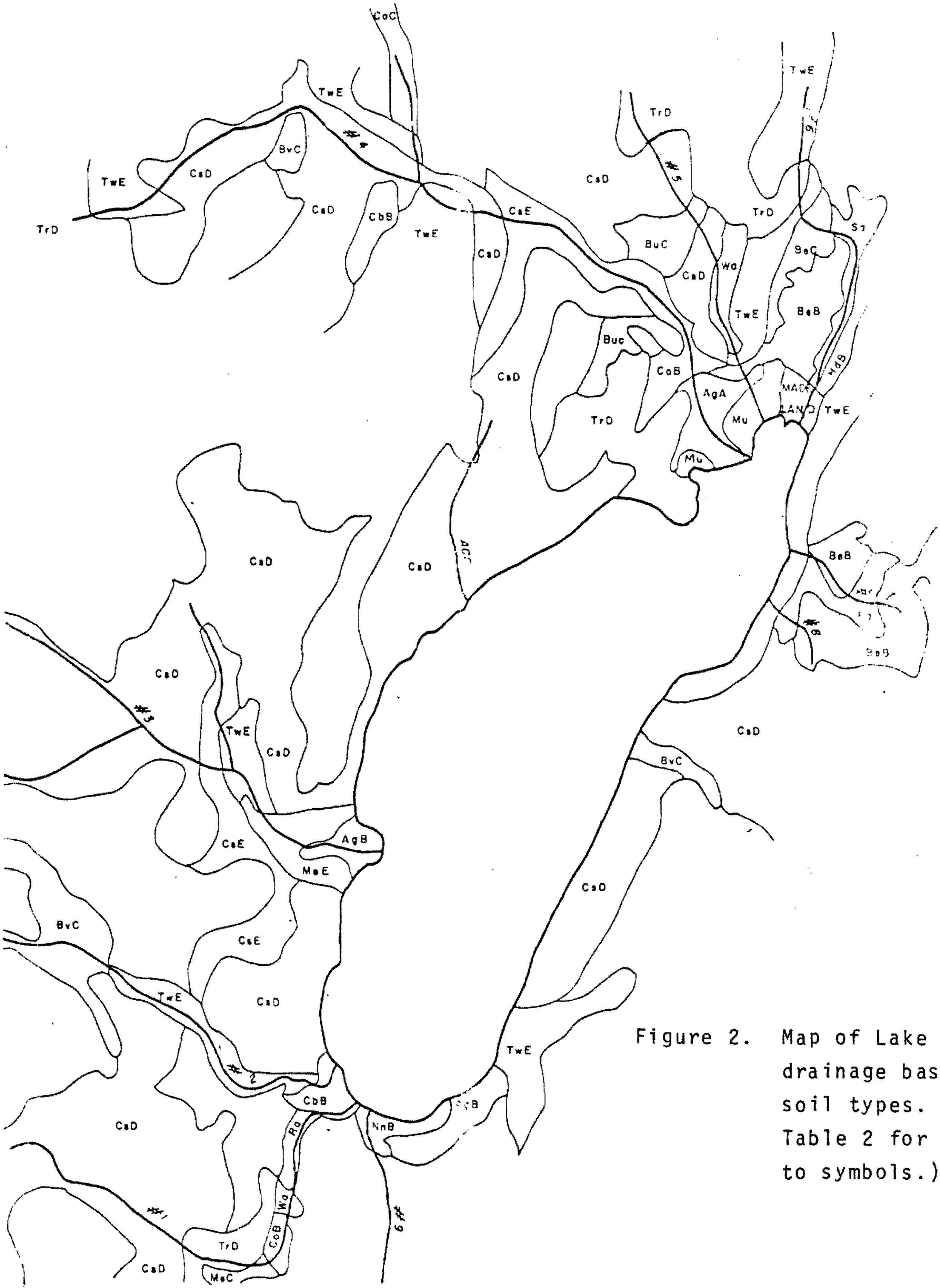

Figure 2. Map of Lake Morey drainage basin soil types. (See Table 2 for a key to symbols.)

The Barton River, located in northern Vermont, drains approximately 450 km^2 (176 mi^2) and discharges to Lake Memphremagog at Newport, Vermont. The average discharge of the Barton River is 6.7 cms (240 cfs). Discharge records are estimated using runoff coefficients established at the USGS flow monitoring station located on the Black River at Coventry, Vermont. Land use in the basin is heavily agricultural at lower elevations and primarily forested at the higher elevations. Residential development is moderate.

Prior to the Vermont detergent phosphorus restrictions, municipal point sources accounted for approximately 38-63 percent of the total phosphorus loading to Lake Memphremagog from that drainage basin.

The Clyde River, located in northern Vermont, drains approximately 368 km^2 (144 mi^2) and discharges to Lake Memphremagog at Newport, Vermont. Average discharge for the Clyde River is 6 cms (216 cfs). Discharge records were obtained from a USGS flow monitoring station located on the Clyde River at Newport, Vermont. The drainage basin is characterized by several large run-of-the-river lakes. Land use is basically un-developed (forested) with light agricultural and residential development in some areas. Flow is highly regulated by a series of hydropower impoundments. The lakes and impoundments in the basin probably exert an attenuating effect on upstream phosphorus loading. There is a major municipal point discharge (Newport wastewater treatment facility) downstream of the last impoundment on the river.

Total phosphorus concentrations observed in the study rivers before and after the implementations of detergent phosphorus restrictions will be compared under conditions of "low" river flows. The rationale behind this scheme is two-fold.

First, periods of high river flow are usually related to periods of heavy precipitation. Such conditions increase surface runoff, consequently increasing the phosphorus loading to a river from non-point sources. With high non-point loadings, the effects of reductions in point source loading on phosphorus concentrations in the river could very well be masked.

The Merrimac-Agawam-Windsor-Winooski association consists of level to steep, excessively drained to well drained, moderately coarse textured and coarse textured soils on stream terraces, and moderately well drained, medium textured soils on bottom lands. It consists of about 35 percent Merrimac soils, 20 percent Agawam soils, 15 percent Windsor soils, 10 percent Winooski soils, and a 20 percent mixture of miscellaneous soils (U.S. Soil Conservation Service, 1978). Since this soil association is found to the south of Lake Morey, where drainage is mostly away from the lake, discussion of factors such as erosion, permeability, runoff, and septic system limitations, is not considered pertinent to this aspect of the study.

Those soils which have formed on uplands, in predominantly glacial till, can generally be included in one major soil association: the Tunbridge-Woodstock-Colrain-Buckland association. This is the dominant soil association in the drainage basin, and consists of sloping to steep, excessively drained to moderately well drained, shallow to deep, moderately coarse textured to medium textured soils. It consists of about 25 percent Tunbridge soils, 20 percent Woodstock soils, 20 percent Colrain soils, 10 percent Buckland soils, and a 25 percent mixture of miscellaneous soils (U.S. Soil Conservation Service, 1978). The soils in this association have a relatively moderate erosion potential, and a moderate to high runoff potential. Steepness of slope, a shallow depth to bedrock, wetness, and slow percolation are characteristics of the soils within this association which combine to severely limit the effectiveness of septic tank absorption fields.

Table 2. Parent material of Lake Morey drainage basin soils.

Soil Series	Parent Material
Agawam	Stratified outwash derived mainly from schist, granite, gneiss, and phyllite.
Belgrade	Silt loam and very fine sandy loam glaciolacustrine material.
Buckland	Glacial till derived mainly from schist, shale, and sandy limestone.
Cabot	Glacial till derived mainly from schist, shale, and sandy limestone.
Colrain	Glacial till derived mainly from siliceous limestone and schistose rocks.
Hartland	Glaciolacustine silt and very fine sandy loam.
Merrimac	Stratified outwash sand and gravel derived from granite, schist, quartizite, gneiss, and phyllite.
Muck	Highly decomposed remains of reeds, sedges, and wood plants.
Ninigret	Stratified outwash derived from granite, quartz, gneiss, and schist.
Raynham	Silt loam and very fine sandy loam glaciolacustrine material.
Saco	Very fine sandy loam and silt loam alluvium.
Tunbridge	Glacial till derived mainly from silicious limestone and schistose rocks.
Woodstock	Glacial till derived mainly from silicious limestone and schistose rocks.
Walpole	Stratified outwash and gravel derived mainly from granite, quartz, gneiss and schist.

Table 3. Lake Morey shoreline soils in order of dominance.

Map Symbol	Soil Type	Slope	Limitations for Septic Tank Absorption Fields	*Hydrologic Group	*Erosion Factors K	T	Permeability in/hr.
CsD	Colrain very stony fine sandy loam	8 to 25%	Severe: due to slope	B	0.20	3	2.0-6.0
TwE	Tunbridge-Woodstock complex	25 to 50%	Severe: due to slope and depth to rock	C/D	0.20	2	2.0-6.0
AgB	Agawam fine sandy loam	3 to 8%	Slight	B	0.17	3	2.0-20
MeE	Merrimac fine sandy loam	25 to 50%	Severe: due to slope	A	0.17	3	2.0-20
NnB	Ninigret fine sandy loam	0 to 8%	Severe: due to wetness	B	0.17	3	2.0-20
TrD	Tunbridge-Woodstock Rock Outcrop Complex	8 to 25%	Severe: due to slope and depth to rock	C/D	0.20	2	2.0-6.0
Mu	Muck	0	Severe: due to wetness	D	0.28	3	0.6-6.0
CbB	Cabot very stony silt loam	3 to 15%	Severe: due to slow percolation and wetness	D	0.28	3	0.6-0.2
Aga	Agawam fine sandy loam	0 to 3%	Slight	B	0.17	3	2.0-20
BvC	Buckland very stony loam	8 to 25%	Severe: due to slope, slow percolation, and wetness	C	0.24	3	0.06-0.2

*See Table 4 for explanation of hydrologic groups and erosion factors.

Table 4. Lake Morey inlet stream soil types.

Map Symbol	Soil Type	Slope	*Hydrologic Group	**Erosion Factors K	T	Permeability in/hr.
Aga	Agawam fine sandy loam	0 to 3%	B	0.28	3	2.0-6.0
AgB	Agawam fine sandy loam	3 to 8%	B	0.28	3	2.0-6.0
BeB	Belgrade silt loam	0 to 8%	B	0.49	3	0.6-2.0
BeC	Belgrade silt loam	8 to 15%	B	0.49	3	0.6-2.0
BuC	Buckland stony loam	8 to 15%	C	0.24	3	0.6-2.0
BvC	Buckland very stony loam	8 to 25%	C	0.24	3	0.6-2.0
CaC	Cabot stony silt loam	8 to 15%	D	0.28	3	0.6-2.0
CbC	Cabot very stony silt loam	3 to 15%	D	0.28	3	0.6-2.0
CoB	Colrain stony fine sandy loam	3 to 8%	B	0.20	3	2.0-6.0
CsD	Colrain very stony fine sandy loam	8 to 25%	B	0.20	3	2.0-6.0
CsE	Colrain very stony fine sandy loam	25 to 50%	B	0.20	3	2.0-6.0
HdB	Hartland silt loam	0 to 8%	B	0.49	3	0.6-2.0
MeC	Merrimac fine sandy loam	8 to 15%	A	0.17	3	2.0-6.0
MeE	Merrimac fine sandy loam	25 to 50%	A	0.17	3	2.0-6.0

Table 4 (Cont.)

Map Symbol	Soil Type	Slope	*Hydrologic Group	**Erosion Factors K	T	Permeability in/hr.
Mu	Muck	0	D	0.28	3	2.0-6.0
Ra	Raynham variant silt loam	0	D	0.49	3	0.6-2.0
Sa	Saco mucky silt loam	0	D			0.6-2.0
TrD	Tunbridge-Woodstock-Rock Outcrop Complex	8 to 25%	C/D	0.20	2	2.0-6.0
Twe	Tunbridge-Woodstock Complex	25 to 50%	C/D	0.20	2	2.0-6.0
Wa	Walpole fine sandy loam	0	C	0.20	3	2.0-6.0

* Hydrologic groups are used to estimate runoff after rainfall. Different kinds of soils have different runoff potentials when other factors affecting runoff are constant. There are four hydrologic soil groups (A, B, C, D), group A being those soils having a high infiltration rate (low runoff potential) when thoroughly wet, and group D being those soils having a very low infiltration rate (high runoff potential) when thoroughly wet.

** K and T, variables within the Universal Soil Loss Formula, are used to predict the erodibility of a soil and its tolerance to erosion in relation to specific kinds of land use and treatment. For more detailed definitions of the hydrologic groups and the erosion factors, refer to the U.S. Dept. of Agriculture Soil Conservation Service's Technical Handbook and the Universal Soil Loss Formula.

Table 5. Lake Morey inlet stream soil types, by individual inlet stream, and in order of dominance.

Inlet Stream	Soil Types	Inlet Stream	Soil Types
#1	CsD	#5	CsD
	TrD		TrD
	Ra		Wa
	CbD		Mu
	CoB		BuC
	Wa		BeB
	MeC		AgA
#2	TwE	#6	TwE
(Pavillion Brook)	BvC		Sa
	CbB		BeB
			BeC
#3	CsD		TrD
(Glen Falls Brook)	TwE		HdB
	MeE		
	AgB	#7	BeB
			Ra
#4	CsD		TwE
(Big Brook)	CsE		BeC
	TwE		
	CaC	#8	BeB
	AgA		Ra
	CoB		TwE
	TrD		
	Mu	ACC	CsD

Lake Uses and Economic Importance

The major recreational uses of Lake Morey are swimming, boating, fishing, water skiing, and simple aesthetic enjoyment. There are about 120 lakeshore homes on Lake Morey, of which 46 are year-round residences. The lake also supports three large resort inns, two summer children's camps, and one outdoor recreation center.

Public access to the lake is available at a Vermont Fish and Game Department boat launch area on the west shore and at a public beach maintained by the Town of Fairlee at the lake's southern end. Lake Morey is accessible from the major population centers in New England via Interstate Highway 91, which has an exit within one half mile of the lake. Public transportation to the lake is available through Vermont Transit Company bus service to Fairlee, Vermont.

Within an 80 kilometer radius of Lake Morey (excluding New Hampshire), there are 62 lakes and ponds greater than 20 acres in surface area (29 of these lakes exceed 100 acres). Twenty of these lakes are comparable in their opportunities for swimming, fishing, boating, and public boat access (Vermont Department of Water Resources and Environmental Engineering, 1981). Of these twenty lakes, only four have comparable numbers of seasonal cottages and permanent houses. However, the extensive commercial development of the lakeshore with several resorts and camps makes Lake Morey unique in Vermont in that respect.

Lake Morey is of considerable importance to the local economy. The summer lakeshore resident population is about 1,050, in comparison with the year-round population of 770 for the entire Town of Fairlee. Seasonal vacation housing units account for 32% of the total housing in Fairlee (based on the 1980 U.S. Census). Vacation cottages contribute 23% of the total property tax revenues for the Town of Fairlee and near-lake resort inns and camps another 9% (based on the Town of Fairlee 1981 Grand List). Indirect tax revenue brought in by tourism via the village commercial property tax is difficult to estimate but is probably significant. Information on meals, lodging, and sales tax revenues for the area was not available but should be included when considering the lake's impact on the State's economy.

Employment directly related to lake use (i.e., employment by inns and camps) is of major local importance. Lake-related employment in 1981 was 101 employees, comprising 38% of the total employment in Fairlee (based on data from the Vermont Department of Employment and Training). Again, indirect contribution via those employed in Fairlee in tourist-related services is probably significant but was difficult to assess.

Land Use in the Lake Morey Watershed

Land use within the 1,902 hectare drainage basin was examined by means of a land use map (Figure 3) produced from a high-altitude color infrared photograph taken in 1978 as part of a wetland survey conducted by the U.S. Fish and Wildlife Service and the U.S. Army Corps of Engineers. The areas of land in several use categories were determined by planimetry from this map and are given in Table 6.

Table 6 shows that the Lake Morey watershed is predominantly forested. Residential and recreational land uses are the next most major use categories. Farming activities in the watershed are very minor in extent.

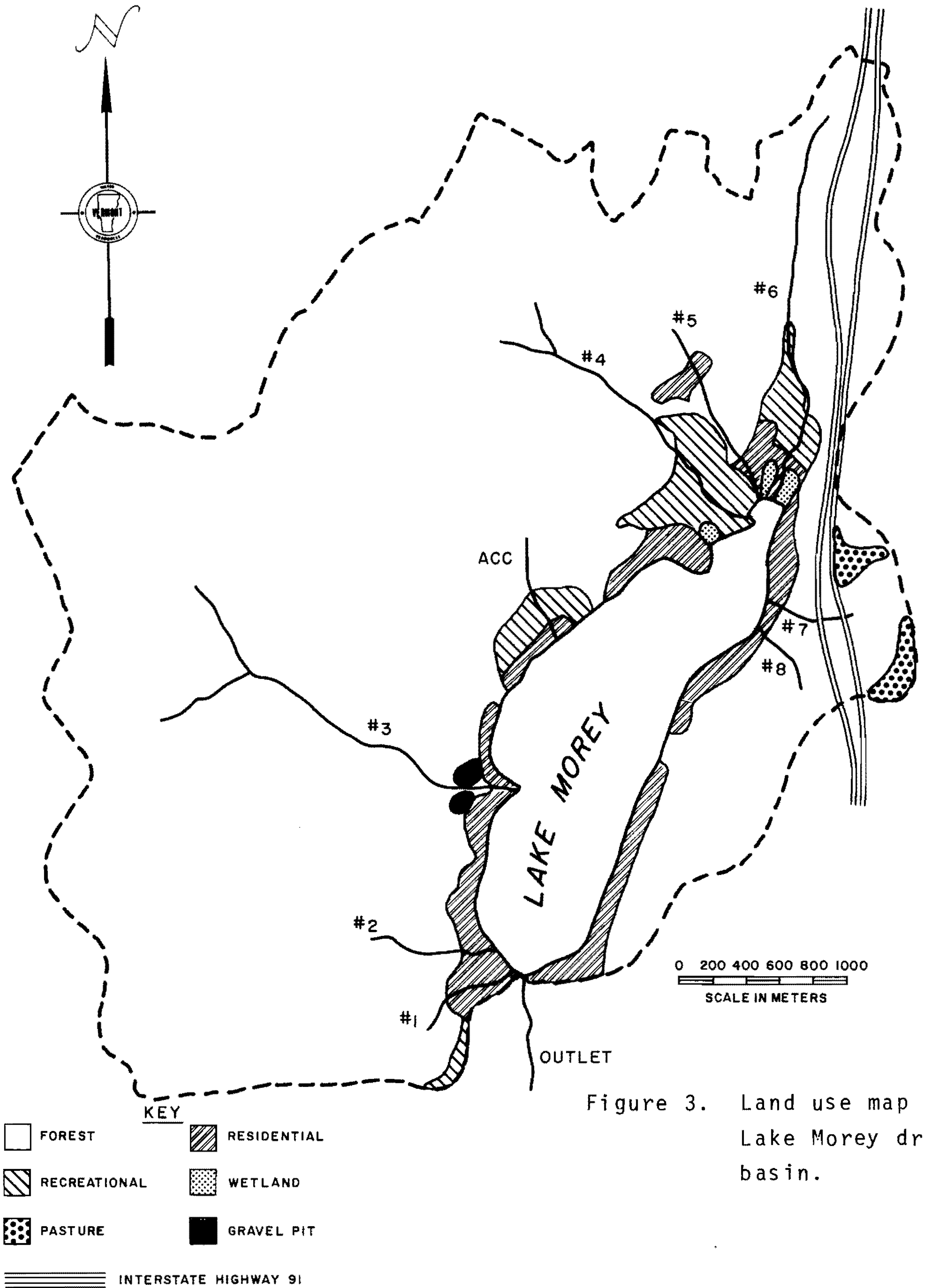

Figure 3. Land use map for the Lake Morey drainage basin.

Table 6. Areas of various land use categories within the Lake Morey watershed.

Land Use Category	Area hectares	Area %
Forest	1755	92.3
Pasture	22	1.2
Wetland	2	0.1
Residential	74	3.9
Recreational	48	2.5
Gravel pit	1	0.1
Total	1,902	100
Lake	220	---

DIAGNOSTIC STUDY METHODS

Lake Sampling Methods

Lake samples were obtained at discrete depth intervals by means of a peristaltic water pump at one station located over the deepest region of the lake. When filtration was necessary, this was done in-line with the peristaltic pump at the time of sampling, using 0.45 um membrane filters. A list of parameters sampled and the sampling schedule during 1981-1982 is given in Table 7. All water quality data collected on Lake Morey (and its tributaries) during the course of this study is stored in the U.S. Environmental Protection Agency's STORET system and is available on request.

Stream Sampling Methods

Stream flow measurements were made at Lake Morey tributary streams and at the outlet from February, 1981 to December, 1982 to assist in the construction of a water budget for the lake and to estimate phosphorus loading rates. The design, implementation, and data reduction for the stream flow sampling program was done with the direct assistance of the U.S. Geological Survey. Flows were measured continuously at the four major inlets (#3, #4, #5, and #6) and at the outlet. The four continuously gaged inlets represented 55% of the total drainage area of the lake. Continuous measurements on the four inlet streams were made by installing Parshall flumes in the streams, with stage recorders operating in adjacent stilling wells. During low flow periods, 90° V-notch weir plates were inserted into the flumes to increase sensitivity. Continuous flow measurements were made in the outlet in a rated section of the stream using a nitrogen gas manometer system to measure stream stage.

Table 7. Sampling program for Lake Morey from April, 1981 to December, 1982.

	Open-Water Season		Winter	
Parameter	Sampling Frequency	Depth Interval	Sampling Frequency	Depth Interval
Secchi disc	weekly	---	bi-monthly	---
Temperature	weekly	1m	bi-monthly	1m
Dissolved oxygen	weekly	1m	bi-monthly	1m
Total phosphorus	weekly	1m	bi-monthly	1m
Total dissolved phos.	weekly	1m	bi-monthly	1m
Chlorophyll-a	weekly	1m	bi-monthly	1m
Algal counts	bi-weekly	composite	monthly	composite
Total iron	bi-weekly	1m	monthly	1m
Total dissolved iron	bi-weekly	1m	monthly	1m
Total manganese	monthly	1m	monthly	1m
Total Kjeldahl Nitrogen, NH_3-N NO_3+NO_2-N	monthly	3m	3/winter	3m
Conductivity	monthly	3m	3/winter	3m
pH, Alkalinity	monthly	3m	3/winter	3m
Magnesium, Calcium	monthly	3m	3/winter	3m
Sodium, Potassium	monthly	3m	3/winter	3m
Total silica	monthly	3m	3/winter	3m
Sulfate	monthly	3m	3/winter	3m
Sulfide	once in August	hypolimnion	---	---

For the remaining streams that were not gaged continuously, discrete flow measurements were made at an approximate weekly frequency using a variety of methods including manual staff gage readings at rated sites, current velocity measurements, and volumetric techniques. Continuous flow records were generated for these streams by graphical methods, using the hydrographs from the streams for which continuous flow measurements were made directly. Flows from ungaged portions of the watershed (19% of the total drainage area) were estimated by applying areal unit runoff rates derived from an appropriate gaged area.

All the streams were sampled for total and dissolved phosphorus on a weekly frequency from February, 1981 to December, 1982. More frequent sampling (up to twice per day) was conducted during storms and other high flow periods. Methods used for computing the stream phosphorus loading rates are discussed in Walker (1983).

Table 8. Comparison of stream identification codes used for Lake Morey.

Stream Name	Stream Number	Code for STORET System and for Walker (1983)	Drainage Area (hectares)
Rutledge Inn Brook	#1	502791	176
Pavillion Brook	#2	502792	161
Glen Falls Brook	#3	502793	425
Aloha Camp Culvert	ACC	502794	54
Big Brook	#4	502795	368
Gardenside Brook	#5	502796	96
Aloha Manor Brook	#6	502797	150
Bonnie Oaks Brook	#7	502798	73
Pine Brook	#8	502799	44
Outlet	#9	502800	2122

Various stream identification codes have been used for the streams at Lake Morey in this and other reports. To eliminate any confusion, Table 8 shows a comparison of these identification codes. Stream locations are shown on the map provided in Figure 1.

Groundwater Methods

A variety of methods were used to quantify the contribution of groundwater to the lake's hydraulic budget and to evaluate the phosphorus loading rate to the lake from shoreline septic systems. These methods included the use of monitor wells, miniature piezometers, and seepage meters. A map showing the location of these installations is provided in Figure 4. The groundwater study was designed and implemented with the assistance of Jeffrey Noyes, of Wagner, Heindel and Noyes, Inc., and the U.S. Geological Survey.

Monitor Wells

Forty-seven monitor wells were installed at Lake Morey in two stages. The first stage involved the installation of twenty-five hand-dug monitor wells (10 centimeter inside diameter, PVC) designed primarily for sampling groundwater at the lake shoreline, down-gradient from wastewater disposal systems. The well locations were chosen, after a thorough review of lakeshore development conditions, to represent various types of disposal systems, soil types, and usage conditions. Several of these wells were located, for control purposes, in undeveloped areas presumably unaffected by disposal systems. The depth of the water table determined the depth to which the wells were completed. They ranged from 0.3 meters to 1.5 meters below the ground surface. The wells also served as indicators of the height of the water table around the lakeshore in relation to the lake surface. This information, in conjunction with other data, was used to estimate the volume of groundwater discharge to the lake.

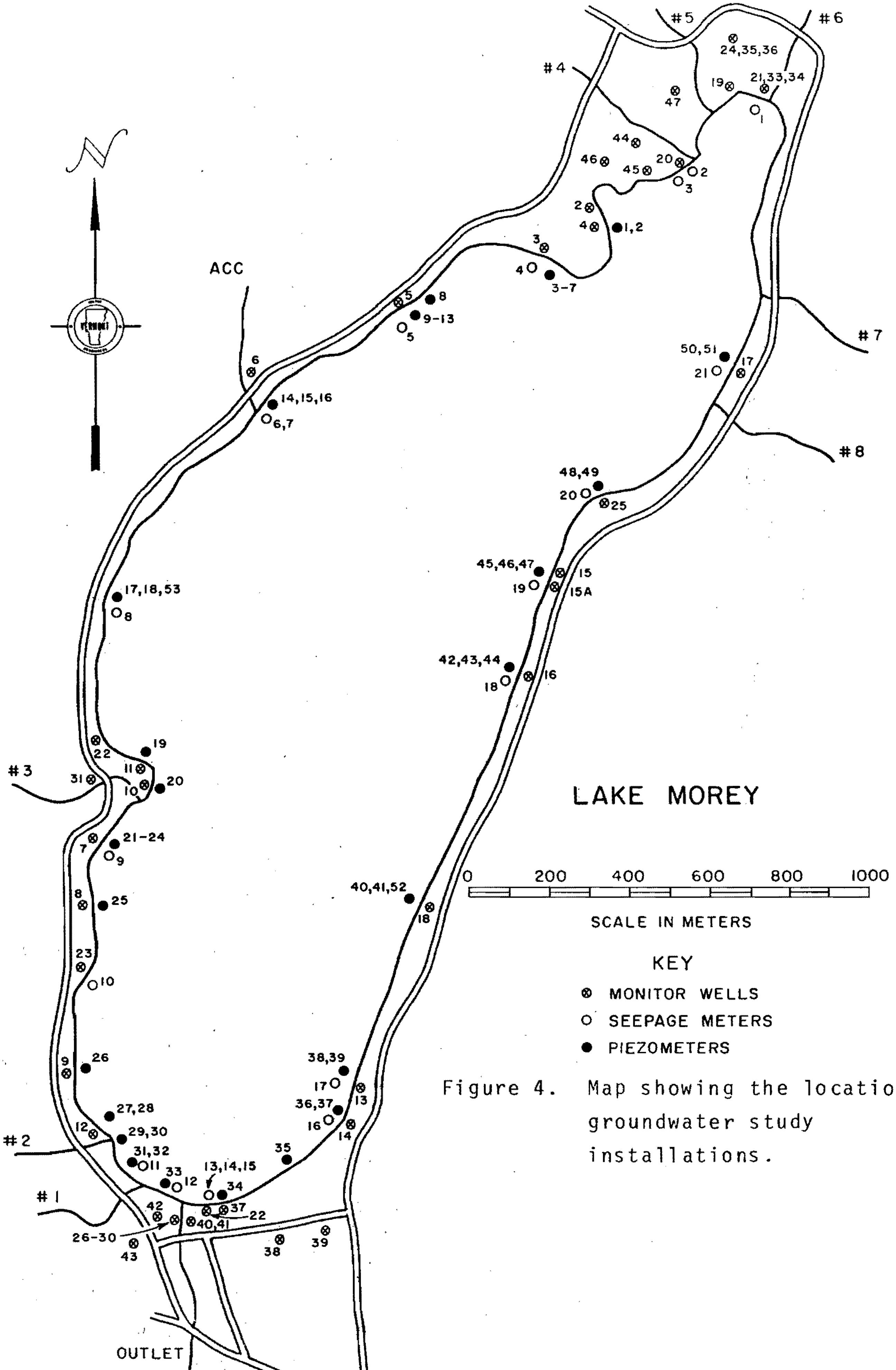

Figure 4. Map showing the location of groundwater study installations.

The second stage of monitor well installations involved drilling twenty-two wells (5 centimeter inside diameter, PVC), ranging in depth from 2.4 meters to 89 meters below ground surface, which were used primarily for determining hydraulic gradient north and south of the lake. Split-spoon samples were taken during the drilling of these wells to ascertain types and thicknesses of geologic materials. Hydraulic conductivity values were then assigned to these materials. The hydraulic conductivities and hydraulic gradients were used, in conjunction with other information, to estimate where, and at what rate, groundwater was entering or leaving the lake. The monitor wells were sampled weekly during Summer, 1982, and less frequently during other seasons. Water level measurements were made each time, and samples were obtained for dissolved phosphorus, chloride, and nitrate analysis.

Miniature Piezometers

Fifty-three miniature piezometers were installed in the near-shore lake bed of Lake Morey. Head measurements in the piezometers were made weekly during the ice-free seasons. They were installed between 1.2 meters and 21.6 meters from shore, at 23 sites around the lake, and ranged in depth from 0.3 meters to 1.2 meters into the sediment. Each mini-piezometer consisted of a 3-meter section of 0.64-centimeter inside diameter translucent polyethylene tubing which was fastened at one end to a 10.2-centimeter section of 1.3-centimeter inside diameter rigid polyethylene tubing. The section of rigid tubing was perforated and wrapped with fiber glass filter fabric and the open end was sealed. The mini-piezometer was installed in the lake bed using a 2.1-meter section of thick walled, 2.5-centimeter inside diameter steel pipe. The pipe was loosely fitted at each end with lag bolts (the top lag bolt protected the pipe from being damaged by the sledge hammer; the bottom one prevented the pipe from being filled with sediment as it was driven in), and was hammered into the lake bed sediment to the desired depth. The top lag bolt was then removed, the piezometer was inserted in the pipe and held in place while the pipe was pulled out, and the bottom lag bolt remained in the sediment (technique from Lee, 1978). The piezometer tubing which remained above the lake bottom was then attached to a vertical stake with its open end raised above the lake's surface.

Two miniature piezometers were installed at the north and south ends of the lake's central basin. These profundal mini-piezometers consisted of 6-meter sections of 2.3-centimeter inside diameter polyvinyl chloride pipe. The sections were joined with glued couplings and cut to a manageable length for installation. Winter was chosen for time of installation because the ice cover provided a stable surface for working and minimized lake water surface disturbance due to wave action that would have made precise measurements difficult. The pipe was loosely fitted at each end with lag bolts and hammered into the lake sediment. The pipe was pulled up about 10 centimeters to allow the bottom lag bolt to drop out, leaving an open-ended, unscreened pipe. The north and south end mini-piezometers were driven 3.8 meters and 4.9 meters into the sediment, respectively, in 9.3 meters and 10.7 meters depths of water.

Seepage Meters

Seepage meters were installed at 21 sites around the lake, between 1.2 meters and 14.9 meters from shore, usually in conjuction with mini-piezometer installations. A seepage meter consisted of a 15-centimeter long, end section (57-centimeter diameter) of a 55 gallon steel drum. A 3-centimeter hole was cut in the top of the section, near the edge. The cylinder was pushed slowly, open end down, into the lake bed sediment until its top was about 2 centimeters above the sediment. The cylinder's hole was elevated slightly to allow gas from the sediment to escape. The measuring device which was attached to the cylinder consisted of a 4-liter, heat-sealed plastic bag fastened to a 15-centimeter long modified plastic tube which, in turn, was connected to a one-hole rubber stopper. The bag was partially filled with a known quantity of water, air was removed from the bag and tube, and the stopper was inserted into the cylinder hole. The change in water volume in the bag was measured over time (apparatus and technique modified from Lee, 1978). Flow measurements were made in each seepage meter several times throughout the ice-free seasons.

Precipitation Methods

Total precipitation volume to the surface of Lake Morey during 1981-1982 was estimated using a combination of direct measurements and data from nearby National Oceanic and Atmospheric Administration (NOAA) observation stations. During open water periods, precipitation was directly measured at two collection stations, one mounted on a 2 x 2 meter raft moored in the center of the lake, and the other on a platform 15 meters offshore from the lake's northern end. Each station was equipped with a manually read rain gage and a bulk precipitation collector. In 1982, the northern station was also equipped with a recording rain gage. Precipitation was measured as frequently as possible (usually daily), according to standard procedure. Daily precipitation measurements were also available from the three nearest NOAA observation stations (Chelsea, VT; South Newbury, VT; and Hanover, NH). During periods of freezing temperatures, precipitation to Lake Morey was estimated as the average of the precipitation measured at these three stations.

Phosphorus loading to the lake surface via precipitation was estimated by bulk precipitation sampling. Bulk precipitation was operationally defined as that which fell into a continuously open collector filtered with sterile cotton plugs in the collector funnel to prevent contamination from insects and other large debris. The samples therefore included both wet precipitation and an unknown fraction of the particulate and gaseous material that eventually reached the lake surface. Bulk precipitation measurements probably better approximate loading to the lake surface than does wet precipitation sampling (Scheider *et al*, 1979).

Bulk precipitation samples were collected weekly at the two collection stations from June, 1981 to December, 1982 and analyzed for total phosphorus. Phosphorus loading to the lake was calculated for each collection period using the total phosphorus concentration and the precipitation volume for the period.

Evaporation Methods

Total evaporation from Lake Morey was estimated using on-site evaporation pan data with evaporation data from the NOAA observation station located at Essex Junction, Vermont. The evaporation pan used at Lake Morey was a standard U.S. Weather Bureau Class A pan, mounted at the northern end of the lake. Evaporation rates were measured at Lake Morey only during the period of July 15 to November 9, 1982. Annual evaporation rates for the lake were calculated using the Essex Junction station data, as described in a later section of this report.

Analytical Methods

Phosphorus samples were analyzed by an automated, colorimetric, ascorbic acid method (U.S. Environmental Protection Agency, 1979). Total phosphorus and total dissolved phosphorus samples were digested in an autoclave using acid persulfate. Dissolved phosphorus samples were filtered in the field through a 0.45 um membrane filter prior to digestion.

Total Kjeldahl nitrogen was analyzed by a potentiometric method (U.S. Environmental Protection Agency, 1979). Ammonia and nitrate/nitrite nitrogen were analyzed by automated colorimetric methods (U.S. Environmental Protection Agency, 1979).

Dissolved silica was analyzed by an automated colorimetric method (Technicon, 1976) after filtration through a 0.45 um membrane filter. Total silica was analyzed on unfiltered samples by the same method after digestion with sodium carbonate according to a procedure modified from Paasche (1980).

Dissolved oxygen was analyzed by the azide modification of the Winkler method (American Public Health Association, 1981).

Chlorophyll was extracted in 90% acetone, corrected for the presence of pheophytin, and analyzed fluorometrically for chlorophyll-a (American Public Health Association, 1981). All results reported as "chlorophyll" represent chlorophyll-a.

Samples for phytoplankton analysis were preserved in the field with Lugol's solution. Organisms were enumerated using the inverted microscope technique (Lund et al, 1958) and identified using a variety of standard taxonomic keys. Phytoplankton biovolume estimates were made according to American Public Health Association (1981).

Sample pH was measured using a pH electrode standardized according to American Public Health Association (1981). Alkalinity was determined by potentiometric titration with sulfuric acid, according to American Public Health Association (1981).

Iron, magnesium, manganese, calcium, sodium, and potassium were analyzed by the atomic absorption direct aspiration method (U.S. Environmental Protection Agency, 1979).

Sulfate was analyzed by an automated colorimetric methyl thymol blue method (U.S. Environmental Protection Agency, 1979).

DIAGNOSTIC STUDY RESULTS

Water and Phosphorus Budgets for Lake Morey.

The major diagnostic study efforts at Lake Morey were aimed at developing water and phosphorus budgets for the lake. The budget information was used to identify the major sources of phosphorus to the lake so that phosphorus control measures could be directed at those sources. The information was also used in developing water quality models for the lake to predict the benefits expected from the recommended phosphorus controls.

Streams

A hydrograph representing total surface water inflow to Lake Morey during 1981-1982 is shown in Figure 5 to provide a description of the seasonal pattern of runoff observed during the study period. Average values for surface water inflow and total phosphorus loading from the various streams for the period February, 1981 to December, 1982 are shown in Table 9, and discussed in detail in Walker (1983). Outflow rates for water and total phosphorus measured at the outlet are also shown in Table 9.

Groundwater

As described earlier, a variety of methods were used to evaluate groundwater influences on Lake Morey. These methods involved the use of seepage meters, monitor wells, and mini-piezometers (see Methods section for a description of these devices). The seepage meters proved useful in estimating groundwater flows into the lake through the near-shore lake bed. The seepage meter data is discussed in Wagner, Heindel, and Noyes, Inc. (1983). The mini-piezometers proved to be of limited value in directly establishing rates of groundwater flow through

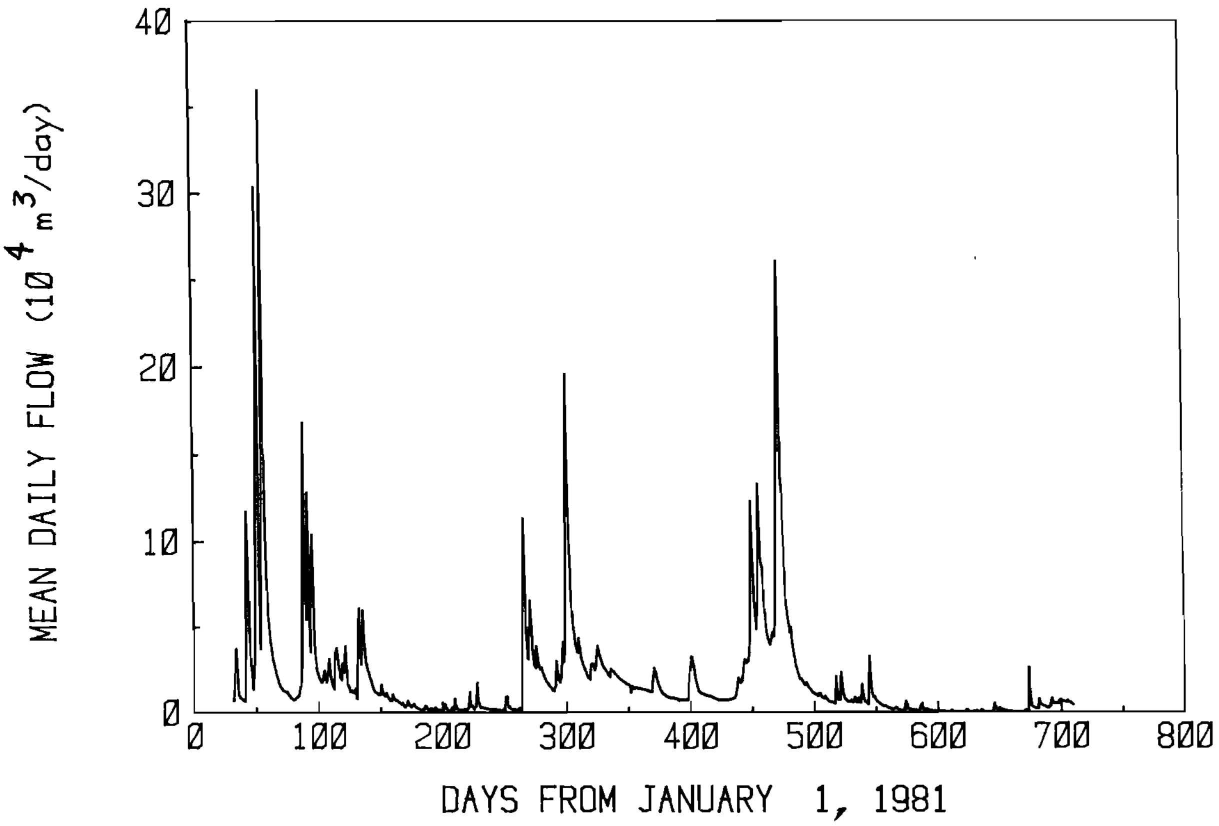

Figure 5. Hydrograph showing mean daily inflow to Lake Morey during 1981-1982.

the lake bed. The low hydraulic conductivities and low hydraulic gradients in many areas of the lakeshore prevented the use of the falling head test or the constant head test (Lee, 1978). However, the mini-piezometers did prove useful in establishing the width of the groundwater flow zone along the shoreline, as discussed by Wagner, Heindel, and Noyes, Inc. (1983).

Table 9. Average surface water flow and total phosphorus loading rates to Lake Morey during the period February 1, 1981 to December 12, 1982, as calculated by Walker (1983).

Stream	Flow ($10^6 m^3/yr$)	Total Phosphorus Loading (kg/yr)	Average Phosphorus Concentration (mg/m^3)
#1	.82	24.3	30
#2	.74	12.5	17
#3	2.14	36.3	17
ACC	.05	3.7	74
#4	1.79	46.4	26
#5	.48	34.2	71
#6	.73	19.6	27
#7	.34	25.5	76
#8	.21	35.6	173
Ungaged area	1.76	56.8	32
Total Inflow	9.06	294.9	33
Outlet (#9)	9.59	290.7	30

The monitor wells were used primarily for water quality sampling purposes. A summary of the total dissolved phosphorus concentrations observed in the wells is provided in Table 10. The data on dissolved phosphorus and other groundwater chemical constituents was used by Wagner, Heindel, and Noyes, Inc. (1983) to evaluate the extent of septic system contamination of Lake Morey. In addition, water level measurements made in the wells provided information that was used to produce a second, independent estimate of groundwater flow to the lake, as discussed below.

Table 10. Total dissolved phosphorus concentrations (mg/l) recorded in the monitor wells from December, 1981 to November, 1982. (See Figure 4 for a map of well locations.)

Well Number	Mean	Standard Deviation	Number of Sample Dates
2	.012	.006	26
3	.069	.064	24
4	.104	.067	26
5	.011	.006	18
6	.176	.168	19
7	.006	.003	26
8	.010	.008	26
9	.010	.004	14
10	.008	.004	25
11	.008	.006	25
12	.007	.003	23
13	.022	.011	26
14	.007	.004	26
15	.009	.005	26
15A	.083	.047	21
16	.009	.004	26
17	.013	.010	26
18	.007	.005	26
19	.006	.004	3
20	.020	.009	4
21	.031	.030	7
22	.009	.004	4
24	.021	.006	5
25	.065	.006	26
35	.077	.017	25
36	.143	.047	25

The Wagner, Heindel, and Noyes, Inc. (1983) report contains a discussion of the groundwater hydrogeology of Lake Morey. The study also developed estimates of phosphorus loading rates to the lake via groundwater, based on the groundwater hydrologic and water quality data. The results of the Wagner, Heindel, and Noyes, Inc. study will be briefly summarized here.

Wagner, Heindel, and Noyes, Inc. (1983) used the seepage meter data to estimate an annual average groundwater inflow rate to the lake in the range of 0.20×10^6 to 0.34×10^6 m^3/yr. The septic system component of this flow was estimated to be in the range of 0.034×10^6 to $0.059 \times 10^6 m^3$/yr, based on lake population data and typical per capita water use values. The results of total dissolved phosphorus analyses performed on samples obtained from the monitoring wells were used with the seepage meter flow data to estimate phosphorus loading rates to the lake via groundwater. It was estimated by Wagner, Heindel, and Noyes, Inc. (1983) that phosphorus inputs to the lake from shoreline septic systems were in the range of 0.9 to 1.1 kg during the five month summer use season. Using an average groundwater total dissolved phosphorus concentration of 0.010 mg/l, the total groundwater phosphorus input to the lake should be in the range of 2.0 to 3.4 kg/yr.

In order to provide a check on the Wagner, Heindel, and Noyes, Inc. estimates, the groundwater inflow rates to Lake Morey were evaluated by a second, independent method. This second estimate was based on an application of Darcy's law (equation 1).

$$Q = KiA \tag{1}$$

where Q = rate of groundwater flow
K = hydraulic conductivity
i = hydraulic gradient
A = cross-sectional area of flow

The shoreline of Lake Morey was first divided into 27 sections, as shown in Figure 6. Within each section, characteristics such as slope, soil type, and groundwater flows were relatively homogeneous. One or more monitor wells were chosen to best represent each section. Bailed well recovery tests were performed on each well, once during Spring, 1982, and once during Fall, 1982. The hydraulic conductivity term (K) in equation 1 was calculated from the bailed well recovery rate by the technique of Bouwer and Rice (1976) for partially perforated, screened wells penetrating unconfined aquifers. The spring and fall measurements were averaged to determine a K value for each shoreline section. The cross-sectional area term (A) in equation 1 was calculated for each section as the product of the length of the section (given in Table 11) and the estimated depth of the saturated zone.

Water levels in the wells were measured monthly from November, 1981 to May, 1982, and weekly from June to October, 1982. On each sampling date, the hydraulic gradient term (i) in equation 1 was determined from the elevation difference between the monitor well water level and the lake surface. Using this information with equation 1, average groundwater flow rates (Q) were calculated for each shoreline section.

Annual average groundwater inflow rates to each shoreline section are given in Table 11. The lake-wide total annual groundwater inflow rate calculated by this method was $0.25 \times 10^6 m^3/yr$, a value well within the range estimated by Wagner, Heindel, and Noyes, Inc. (1983) from the seepage meter data. Thus, this second, independent method served to confirm the hydrological aspects of the Wagner, Heindel, and Noyes, Inc. results.

It should be noted that the U.S. Geological Survey is continuing to analyze data collected as part of the Lake Morey groundwater study. When the U.S.G.S. analysis is completed, it is likely that a more detailed understanding of the groundwater hydrology of Lake Morey will be available.

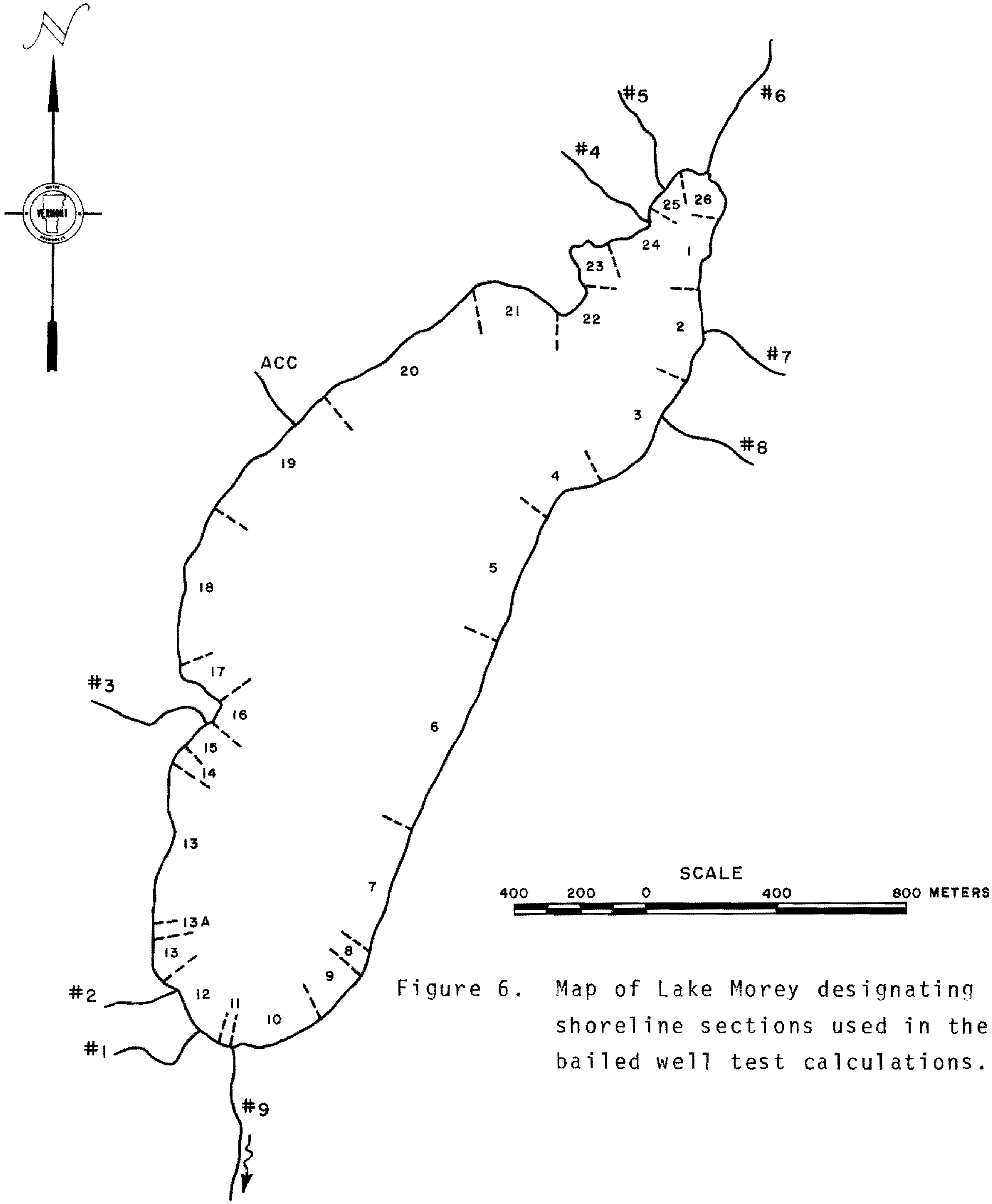

Figure 6. Map of Lake Morey designating shoreline sections used in the bailed well test calculations.

Table 11. Annual average groundwater flow rates for each shoreline section, calculated from the monitor well data, using bailed well recovery tests. (See Figure 6 for a map showing shoreline sections.)

Shoreline Section	Section Length (m)	Average Flow ($10^3 m^3/yr$)
1	220	3.3
2	341	0.8
3	372	0.8
4	287	7.6
5	311	1.9
6	823	5.0
7	408	0.3
8	79	6.1
9	226	0.8
10	305	-35.7
11	76	0.1
12	274	2.2
13	707	11.5
13A	12	4.3
14	12	10.6
15	116	13.6
16	128	12.7
17	171	30.8
18	488	7.8
19	524	25.2
20	646	117.3
21	220	5.4
22	238	3.8
23	158	1.0
24	256	14.0
25	158	0.5
26	165	2.9
Total	7721	254.6

Precipitation

Precipitation volume and phosphorus loading direct to the surface of Lake Morey were estimated by methods described previously in this report. Precipitation quantities totaled 0.69 meters during June-December 1981, and 0.76 meters during January-December 1982. These rates indicate an average annual volumetric input to the lake surface of about 2.1 x 10^6 m^3/yr.

Phosphorus loading rates to Lake Morey by direct bulk precipitation averaged 0.041 mg/m^2/day during June-December, 1981, and 0.056 mg/m^2/day during January-December, 1982. These rates indicate an average annual rate of about 18 mg/m^2/yr, a value well within the range of values reported in the literature, as reviewed by Uttormark _et al_ (1974). At this rate, the annual phosphorus load to Lake Morey by direct precipitation would be about 40 kg.

Evaporation

Evaporation rates from an evaporation pan located at Lake Morey were measured by methods described previously in this report. Evaporation rates recorded at Lake Morey during the period of July 15 to October 31, 1982 were compared with rates measured at the NOAA observation station located at Essex Junction, Vermont. Annual rates at Essex Junction were estimated from measurements made during May-October, 1982. The May-October rates were adjusted upward by adding 20% in order to calculate annual rates (Kohler _et al_, 1959). The Lake Morey rates consistently averaged only about 82.5% of the Essex Junction rates. Annual evaporation rates at Lake Morey were calculated by adjusting the annual rates estimated for the Essex Junction station downward accordingly. Using a 1982 annual evaporation rate for Essex Junction of 0.87 m/yr, the Lake Morey pan evaporation rate was calculated to be 0.71 m/yr. A pan-to-lake conversion factor of 0.75 was applied to the pan rate in order to estimate the evaporation rate from the lake surface (Kohler et al, 1959; Knox and Nordenson, undated). The resulting annual evaporation rate estimate for Lake Morey was 0.53 m/yr, corresponding to a volumetric rate of 1.2×10^6 m^3/yr.

Budget Summary

A summary of the annual water and phosphorus budget results is provided in Tables 12 and 13. It can be seen in Table 12 that the water budget annual input-output values were in nearly perfect balance, differing by only 6%. This comparison provides a check on the hydrologic methods, and the close balance indicates that a high degree of confidence can be placed in the hydrologic data. Tables 12 and 13 also show that groundwater was of very minor importance both hydrologically and as a phosphorus loading source. Total groundwater inputs of phosphorus, including septic system inputs, were only 1% of the total external supply of phosphorus to the lake.

The average phosphorus concentration in the total stream inflow was 33 mg/m^3 (see Table 9). As expected from the forested nature of the Lake Morey drainage basin, this value represents fairly good water quality, typical of undeveloped, predominantly forested watersheds in the eastern U.S. (Omernik, 1977). Certain streams, however, showed somewhat elevated phosphorus concentrations. Concentrations in streams #5, 7, 8, and ACC averaged 71, 76, 173 and 74 mg/m^3, respectively. In at least some of these cases, human activities may have been responsible for the increased phosphorus loading rates, indicating that phosphorus control measures should be sought for these sites and implemented where feasible.

Another significant aspect of the phosphorus budget was the very small degree of phosphorus retention by the lake. Data given in Table 13 indicate a phosphorus retention coefficient of only 0.14. Based on the lake's hydrologic and morphometric

Table 12. Annual water budget for Lake Morey, based on data obtained during the period of February, 1981 to December, 1982.

	Rate ($10^6 m^3/yr$)	Percent of Total
Inputs		
Streams	9.1	79
Groundwater	0.3	3
Precipitation	2.1	18
Total Inputs	11.5	100
Outputs		
Outflow	9.6	89
Evaporation	1.2	11
Total Outputs	10.8	100

Table 13. Annual phosphorus budget for Lake Morey, based on data obtained during the period of February, 1981 to December, 1982.

	Rate (kg/yr)	Percent of Total
Inputs		
Streams	295	87
Groundwater	3	1
Precipitation	40	12
Total Inputs	338	100
Outputs		
Outflow	291	100

characteristics alone, Lake Morey would be expected to have a phosphorus retention coefficient of 0.71 (Ostrofsky, 1978). The observed low retention value suggests that internal recycling of phosphorus is important in Lake Morey.

The water and phosphorus budgets shown in Tables 12 and 13 were computed on an annual basis. To better examine the mechanisms controlling phosphorus levels in the lake, particularly the internal mechanisms, it was necessary to examine phosphorus dynamics on a seasonal, time-dependent basis. A time-dependent phosphorus mass balance analysis for Lake Morey was performed and discussed by Walker (1983).

The Walker (1983) Report

A major portion of the data analysis relating to the diagnostic aspects of the Lake Morey Study was conducted by Dr. William Walker, with funds provided under Section 208 of the Federal Clean Water Act. The Walker (1983) report contains an evaluation of various techniques for computing phosphorus loading rates from stream flow and phosphorus concentration data. Walker used this data to compute both annual average and seasonal, time-dependent phosphorus mass balances for Lake Morey. The phosphorus mass balance results were followed by a discussion of the significance of internal recycling of phosphorus between the water and the sediments in Lake Morey. Walker also developed a lake model for use on Lake Morey to predict the water quality benefits expected from various management techniques aimed at controlling phosphorus levels in the lake. Finally, in the Walker report appendices, there is a comprehensive graphical presentation of all lake water quality data collected during the course of the study.

Much of the discussion and conclusions that follow in this report are dependent on the findings presented in Walker's report. Therefore, it would be appropriate for the reader to refer to the Walker report at this point in order to find documentation for the discussion that follows. Walker's conclusions, excerpted directly from his report, are given below.

(1) Monitoring data from Lake Morey and its tributaries collected under this study provide a good basis for assessment of eutrohpication-related water quality conditions and controlling factors.

(2) The modified flow-interval method is a valid and useful technique for calculating average loadings based upon tributary flow and concentration data. Compared with alternative schemes, the method is less sensitive to random variations in sampling design and scheduling because it corrects for differences in the distributions of sampled vs. unsampled flows and provides approximate estimates of error variance which can be used to improve monitoring efficiency.

(3) Transient mass balances expressed in terms of cumulative flux (including input, output, change in storage, and net sedimentation terms) are useful for assessing long-term and seasonal variations in phosphorus dynamics without resorting to a detailed kinetic model.

(4) Mass balances over a two-year period indicate that, on the average, only a relatively small portion of external total phosphorus loadings is deposited to Lake Morey bottom sediments. Thus, the lake has a relatively low assimilative capacity for external loadings.

(5) External phosphorus loadings consist of gauged lake tributaries (71%), estimated direct ungauged inputs (17%) and atmospheric inputs (12%). An independent estimate of phosphorus input from septic systems via groundwater amounts to less than 1% of the total loading. Unusually high total and/or dissolved phosphorus concentrations and loadings were detected in a few tributaries; these are possible targets for lake restoration activities.

(6) The total phosphorus mass balance is controlled largely by seasonal factors influencing the sedimentation and recycling of phosphorus. Deposition rates are positive (net sedimentation) during summer stratification. Total phosphorus appears to be relatively conservative in the water column during the winter (no net sedimentation).

(7) Approximately 75% and 25% of the dissolved phosphorus lost from the water column during dynamic fall-overturn periods is explained by algal uptake and co-precipitation with dissolved iron, respectively. Mass balances indicate that most of the phosphorus taken up by algae during this period is later regenerated for use the following spring.

(8) Both morphometric and chemical factors contribute to oxygen depletion, internal phosphorus recycling, and low assimilative capacity.

(9) While a transient period of nitrogen limitation may have developed early in the 1982 growing season, algal populations are primarily phosphorus-limited and relationships among surface phosphorus, chlorophyll-a, and transparency are typical of those found in other Vermont lakes.

(10) A calibrated version of LEAP can be used to project lake responses to changes in external phosphorus loading and internal recycling characteristics, provided that thermal stratification is unaltered.

Historical and Paleolimnological Studies

The finding (discussed elsewhere in this report) that internal loading of phosphorus from the lake sediments is the major cause of elevated lake phosphorus concentrations and excessive algal growth raised the issue of whether the lake is naturally predisposed towards extensive internal loading, or whether human activities in the watershed have aggravated the situation. Because the major period of cultural development in the lake's watershed occurred during the early 1900's, an historical water quality perspective extending back at least a century was necessary to resolve this issue. Detailed water quality monitoring of Lake Morey has been conducted only since the mid-1970's. Sporadic sampling has been conducted since the 1930's, but the data was not sufficient to establish whether there have been any significant long-term trends in water quality.

The issue of whether the internal loading is natural or culturally induced in Lake Morey is an important one to consider in making management decisions about lake restoration. If the lake had extensive internal phosphorus loading even before the period of watershed settlement and development of lakeshore homes and resorts, then "restoration" efforts directed at eliminating this phosphorus source would probably not be successful over the long-term. Restoration efforts directed at a natural internal loading situation would also contradict a stated policy of the Vermont Department of Water Resources and Environmental Engineering (Morse, 1979) not to conduct "restoration" projects on naturally eutrophic lakes. If, on the other hand, human activities in the watershed at some time in the past initiated extensive internal recycling that has since been perpetuated, then efforts to reduce the internal recycling might meet with long-term success in restoring the lake to its earlier condition.

To resolve this issue, a paleolimnological study was conducted on Lake Morey. A core of the lake sediments was obtained in November, 1982 at a site located in the deepest portion of the lake basin. With the aid of a scuba diver, a

4-inch diameter plastic coring tube was pushed into the sediment. The tube was then sealed at the top, removed from the sediment, sealed at the bottom with a rubber stopper, and returned to the surface. The core was extruded vertically and sectioned into 1 cm intervals, to a depth of 80 cm. The samples were placed in plastic bags and refrigerated in the dark until they were analyzed.

The sediment samples from 25 levels in the core were analyzed by Edward Swain of the University of Minnesota for a variety of factors including weight loss at 110°C and 500°C, authigenic iron and manganese, and algal pigments such as chlorophyll derivatives, total carotenoids, oscillaxanthin, myxoxanthophyll, and percent native chlorophyll. The analytical methods used are described in Engstrom and Wright (1983) and in Swain (1984). The core was dated by Dr. Richard Brugam of Southern Illinois University at Edwardsville (Brugam, 1983a), using the Lead-210 technique. Sediment accumulation rates at various levels in the core were calculated using the constant rate of supply method (Appleby and Oldfield, 1978).

Depth in the core and sediment accumulation rate are plotted vs. date in Figure 7. Figure 7 shows that prior to 1900, sediment accumulation rates were relatively low and stable in the lake. Beginning about 1900, sediment accumulation rates accelerated, reaching a sharp peak in the early 1920's. Since then, sediment accumulation rates have declined and stabilized somewhat, but at higher rates than existed before 1900.

A plot of percent organic content of the sediment (Figure 8) shows that the materials deposited during the early 1920's peak sedimentation period were relatively enriched in inorganic matter. This suggests that the sharp sedimentation peak was caused by activities such as logging, land clearing, or excavation near the lake that resulted in extensive erosion of mineral soils. Since then, however, the sediments have become progressively more enriched with organic matter.

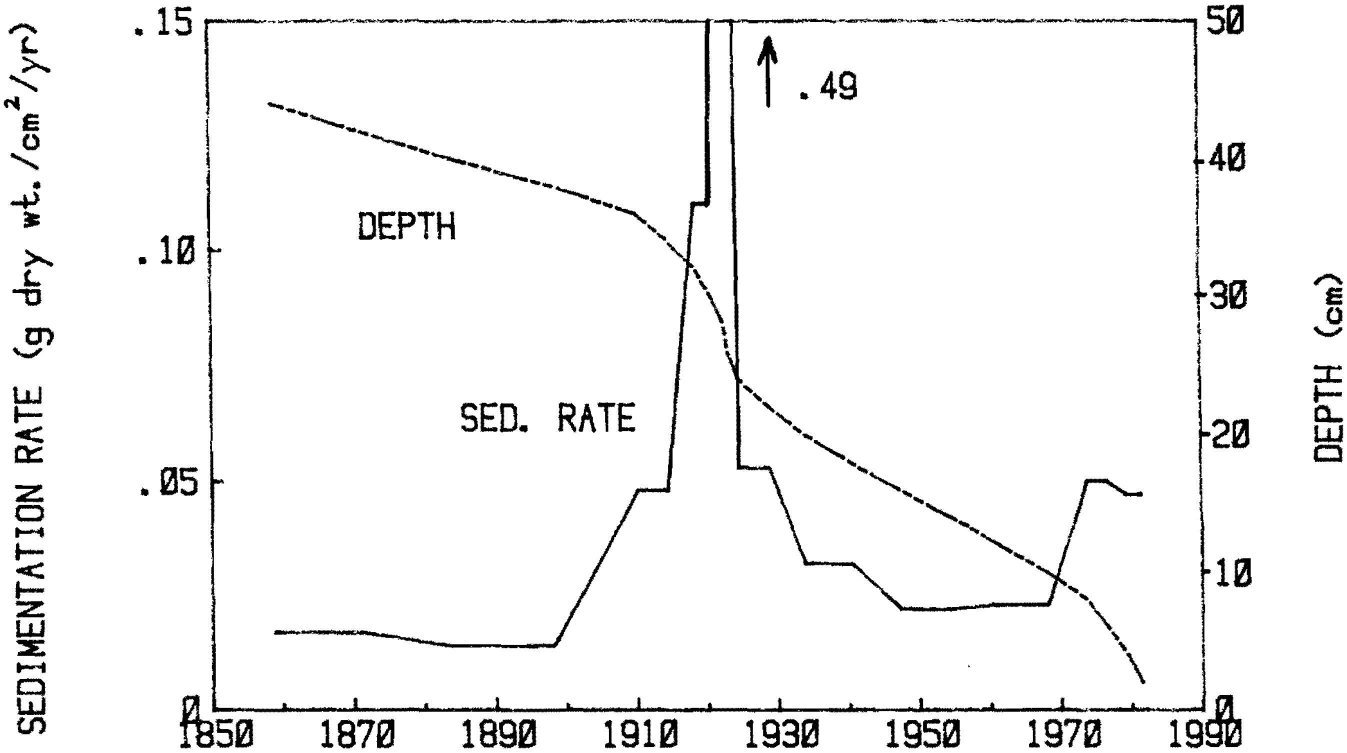

Figure 7. Plot of sediment accumulation rate and depth in the core as a function of date, based on the lead-210 dating analysis.

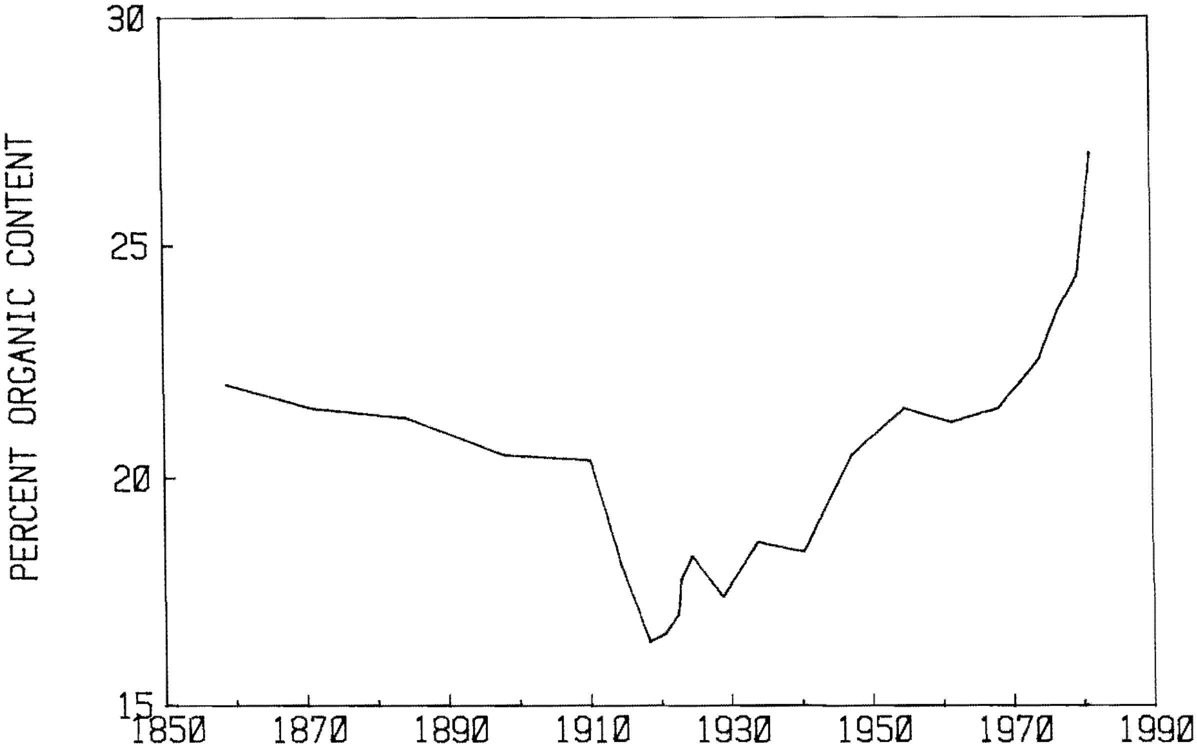

Figure 8. Plot of percent organic content in the core vs. date.

Concentrations of authigenic iron and manganese are plotted vs. date in Figure 9. Because the solubility of both iron and manganese is determined by redox conditions, concentrations of these elements in lake sediments have been used to indicate changes in past hypolimnetic oxygen conditions. Declines in the concentrations of these elements in a core have been interpreted as indicating increased mobilization from the sediments to the water column as a consequence of reducing conditions associated with greater hypolimnetic oxygen depletion (Mackareth, 1966). Alternatively, however, increases in iron and manganese concentrations, and selective enrichment of manganese relative to iron, have been interpreted as indicating the onset of partial hypolimnetic oxygen depletion causing a cycle of dissolution and enhanced redeposition in the profundal regions of a lake (Engstrom et al, 1983). In the Lake Morey core (Figure 9), both iron and manganese show concentration increases beginning about 1920. Interpretation of these changes is further complicated by the fact that the sediment accumulation rate increased dramatically at this time. Thus, the iron and manganese concentrations in the core may indirectly reflect altered shoreland erosion conditions as well as in-lake redox levels. For these reasons, it is probably best to regard the iron and manganese results as being inconclusive as to past oxygen conditions in the lake.

As reviewed by Brugam (1983b) and Swain (1984), algal photosynthetic pigments preserved in lake sediments have been used to study the history of algal production in lakes. Interpretation of pigment concentration data is complicated by the fact that concentrations within a core could be affected by changes in algal production, by changes in preservation conditions at the time of deposition, or by both of these factors. In addition, because pigment concentrations are commonly expressed per unit of organic matter, any changes in the organic sedimentation rate independent of algal production could also affect the concentration values. Fortunately, however, increased production and enhanced preservation as a result of low hypolimnetic oxygen conditions should generally both occur

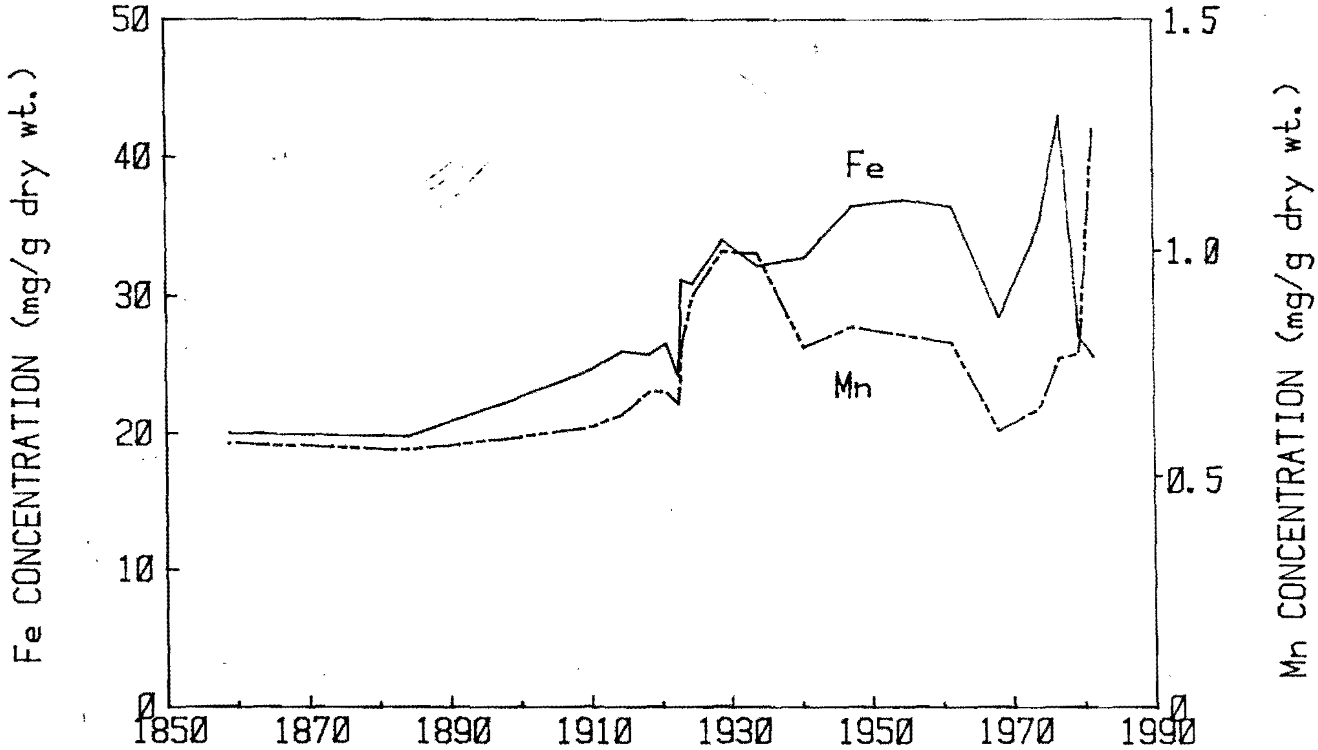

Figure 9. Plot of authigenic iron and manganese concentrations in the core vs. date.

together as eutrophication progresses. Therefore, a concentration increase in a universally present algal pigment such as chlorophyll can generally be unambiguously interpreted as indicating an increased degree of eutrophication. This is particularly true if sediment accumulation rate information is used with the concentration data to express the results in terms of pigment accumulation rates in the sediment, thereby compensating for any changes in the organic sedimentation rate.

Concentrations of chlorophyll derivatives (referred to below as simply "chlorophyll") in the Lake Morey core are plotted vs. date in Figure 10. There was an increasing trend in chlorophyll concentration over time, with a particularly sharp increase since 1970. The results are also expressed as chlorophyll accumulation rates in Figure 10. For reasons discussed above, it is the chlorophyll accumulation rate record that probably best indicates the history of algal abundance in the lake. Chlorophyll accumulation rates were relatively low and stable before 1900, but then climbed dramatically to a peak around 1920. Apparently, the factors that caused the sharp rise in sedimentation rates at this time (see Figure 7) also resulted in increased chlorophyll accumulation in the sediments. Chlorophyll accumulation rates declined after 1920, but remained about twice as high as the pre-1900 baseline rates. Another period of sharply increased chlorophyll accumulation rates has occurred since 1970.

Another sediment pigment parameter that has been useful in interpreting lake eutrophication history is percent native chlorophyll, based on absorbance measurements made before and after acidification of pigment extracts (Swain, 1984). Percent native chlorophyll appears to indicate the degree of pigment preservation, with higher native chlorophyll percentages corresponding with periods of lower hypolimnetic oxygen levels (Engstrom *et al*, 1983; Swain, 1984). Percent native chlorophyll in the Lake Morey core is plotted vs. date in Figure 11. Figure 11 shows that there was a sharp jump in percent native chlorophyll about 1920. Native chlorophyll percentages have remained elevated from 1920 to the present. The increase in native chlorophyll that occurred at 1920 may indicate a drop in

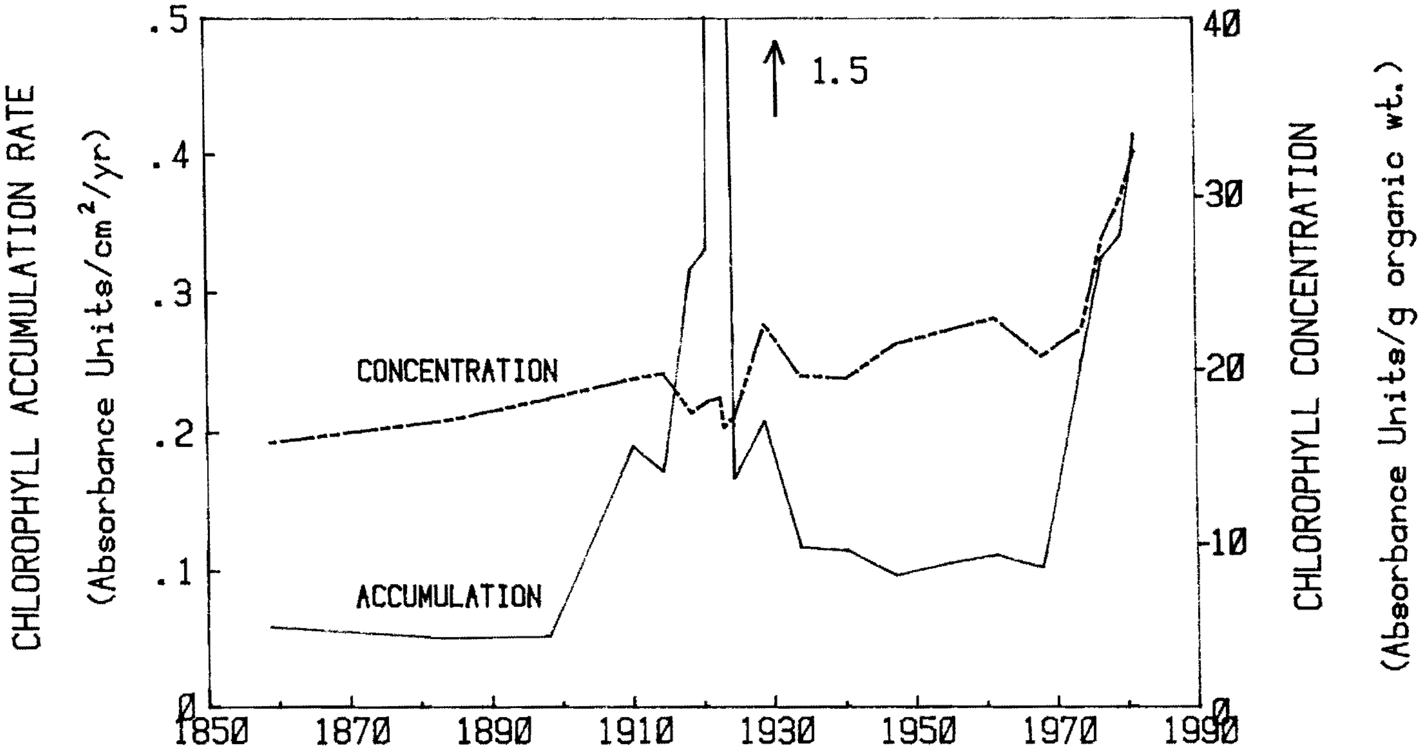

Figure 10. Plot of the accumulation rate and the concentration of chlorophyll derivatives in the core vs. date.

Figure 11. Plot of percent native chlorophyll in the core vs. date.

hypolimnetic oxygen conditions at that time, or it may indicate better preservation resulting from higher sedimentation rates and more rapid burial. The fact that percent native chlorophyll remained elevated after 1920 even though sediment accumulation rates declined suggests that enhanced preservation resulting from lower oxygen conditions was probably a significant factor in the increase.

To assist in interpreting the data from the core, a history of human activities in the Lake Morey drainage basin was obtained. A timetable of events that could potentially have affected water quality in the lake is provided in Table 14. This history was based on interviews with members of the Town of Fairlee Historical Society.

From Table 14, it can be seen that prior to 1880, human impact on water quality in Lake Morey was probably minor. Farming activities were confined to a small portion of the drainage area and were concentrated at some distance from the lake. The period from 1880 to 1920, however, was one of extremely intense commercial and residential development. Most of the existing shoreline homes were built during this period, along with several large resort hotels. It is likely that the land clearing and excavation associated with this development resulted in considerably increased rates of erosion of sediment and nutrients into the lake. In addition, it can be speculated that large amounts of untreated sewage from the resort inns and private homes were discharged directly into the lake during this period, as this was a common practice at the time. After 1920, relatively little further development occurred, although there were events such as construction of the gravel pits, filling at the north end, and construction of the interstate highway that could have caused increased erosion into the lake.

When the historical information in Table 14 is combined with the data from the core, a fairly clear picture emerges as to the history of human impact on water quality in Lake Morey. Prior to about 1880, human disturbance in the watershed was limited to relatively minor farming and logging activities. Water quality in the lake appeared to be little affected by these early

Table 14. Timetable of historical events in the Lake Morey watershed.

Date	Event
1780	The first road in the area was constructed near the northeast corner of the lake.
1800-1840	Farming began in the northwest portion of the watershed. A relatively large settlement existed by about 1820 on Big Brook, about a mile upstream from the lake. Logging occurred on about 1500-3000 acres of land on the southwest side of the lake. The first dam was built on the outlet stream, about 900 feet downstream from the lake.
1880-1890	A recreation hall (Pond View Pavillion) and a large hotel (Glen Falls House) were built on the lakeshore. A road was built along the entire west shore of the lake.
1890-1900	Many of the lakeshore cottages were built during this decade.
1900-1910	A road was built along the east shore of the lake. A children's camp (Aloha Camp) on the lake was constructed. Another large hotel was built on the lakeshore (Kaulin, now the Lake Morey Inn).
1910-1920	Most of the existing lakeshore cottages were in place by the end of this decade. Another large hotel (Bonnie Oaks) was built on the lakeshore.
1930-1940	Gravel pits on the west side of the lake were developed. An existing boarding house was converted to a resort inn (the Rutledge Inn).
1940-1960	Much of the wetland area at the north end of the lake was filled with sand, gravel, and trash.
1970-1972	The section of Interstate Highway 91 traversing the Lake Morey drainage basin was constructed.

activities, as indicated by the stability of the sediment accumulation rate, the chlorophyll accumulation rate, and chlorophyll preservation (percent native chlorophyll) during this period (see Figures 7, 10, and 11). The period of 1880-1920, however, was one of very rapid and intensive residential and commercial development along the lake's immediate shoreline. This development apparently had a major impact on lake water quality. The sediment accumulation rate in the lake accelerated sharply, probably as a result of increased erosion of disturbed shoreline soils. Algal growth in the lake, as indicated by the chlorophyll accumulation rate in the sediments, also increased dramatically. The increased algal production was probably caused by nutrient inputs both from soil erosion and from the presumed discharge of untreated sewage into the lake from the resort inns and private homes. Oxygen conditions in the hypolimnion, as indicated by the percent native chlorophyll, also deteriorated sharply during this period, probably as a consequence of increased organic production by the algae.

By 1920, the major development phase near the lake was completed. Water quality indicators in the sediments showed improvements after 1920. Re-vegetation of disturbed soils and better sewage disposal may have accounted for the improvement. However, sediment accumulation rates, chlorophyll accumulation rates, and percent native chlorophyll never returned to the baseline levels that existed prior to 1900. Apparently, the intensive development of the lake in the early 1900's has had a long-lasting adverse impact on water quality.

Since 1930, the major disturbance in the watershed has been the construction of Interstate Highway 91 during 1970-1972, involving extensive fracturing of the bedrock, excavation, and filling. The sediment accumulation rate and the chlorophyll accumulation rate both increased around 1970. The apparent increase in algal production at this time may have been caused by erosion of nutrients resulting from the excavation and filling activities. In addition, the increased loading of sulfate to the lake from the rock fill areas may have contributed to the internal recycling of phosphorus from the lake sediments (see following discussion of sulfur and internal phosphorus loading).

In summary, the historical and paleolimnological evidence indicates that the intensive development of the lakeshore during 1880-1920 had a significant adverse impact on lake water quality that has since been perpetuated. Present-day limnological evidence, discussed elsewhere in this report, indicates that internal recycling of phosphorus from the lake sediments, rather than phosphorus loading from watershed sources, is the major cause of elevated phosphorus and algae levels in the lake. It is reasonable to suppose that the earlier development enriched the lake water and sediments with phosphorus and that this historical load of phosphorus has been recycled annually ever since. Anoxic conditions in the hypolimnion of Lake Morey are a key factor in the internal recycling of phosphorus and it appears that oxygen levels (as indicated by percent native chlorophyll) also deteriorated during the early 1900's. The heavy phosphorus loading and oxygen depletion that apparently occurred during the intensive development phase probably initiated the internal recycling of phosphorus that has kept the lake in a relatively eutrophic condition to the present day, even in the absence of continued excessive phosphorus loading from the watershed.

Sulfur and Internal Phosphorus Loading in Lake Morey

Concern for the possible role of sulfur in promoting internal loading of phosphorus in Lake Morey began when it was observed that sulfate levels appeared to be elevated in the lake. Sulfate concentrations in Lake Morey averaged about 20 mg/l during 1981-1982, a level higher than what is found in most Vermont lakes. It has been suggested (Hasler and Einsele, 1948; as cited in Hutchinson, 1957) that addition of sulfate to a lake could act to fertilize the lake with phosphorus. If the sulfate were reduced to sulfide in the anoxic hypolimnion, as occurs in Lake Morey, then much of the iron present could be precipitated as ferrous sulfide. This mechanism could eliminate much of the iron that would otherwise be available to form an insoluble ferric phosphate precipitate when the hypolimnetic water is oxygenated during fall turnover. The phosphorus released from hypolimnetic sediments could therefore stay in solution and be mixed into the surface waters where it would be available for algal growth.

The source of the elevated sulfate concentrations in Lake Morey appears to be the rock fill used in the construction of U.S. Interstate Highway 91 near the eastern shore of the lake (see Figure 3). As described earlier in this report, the bedrock through which the highway passes is a dark gray or black slate containing iron sulfide. The blasting and filling operations associated with the highway construction resulted in extensive fracturing of this bedrock into small pieces with vastly increased fresh rock surface area exposed for weathering and leaching of sulfate.

As shown in Table 15, sulfate concentrations in two streams (#6 and 7) draining the highway fill areas were markedly elevated, relative to concentrations found in other parts of the lake's watershed. Furthermore, samples from stream #7 taken at a point upstream of the highway had an average sulfate concentration of only 23 mg/l, in contrast with the downstream average value of 234 mg/l.

Another piece of evidence that the highway construction has enriched the lake with sulfate came from a comparison of sulfate levels in other Vermont lakes. Baren (1967) reported sulfate concentrations in several Vermont lakes, based on surface samples obtained during mid-summer. In Table 16, these historical values are compared with sulfate concentrations found in seven of the lakes, including Lake Morey, during a follow-up study conducted in late Fall, 1982. Table 16 shows that for all lakes except Lake Morey, the reported sulfate levels declined from 1966 to 1982. This apparent decline may have been related to differences in sampling or analytical methods between the two studies, rather than to actual changes in lake chemistry. However, the apparent doubling in sulfate levels in Lake Morey is in marked contrast

Table 15. Average sulfate concentrations found in Lake Morey tributary streams, based on six sample dates during 1982. "*" indicates streams affected by interstate highway drainage.

Stream	Sulfate (mg/l)
#1	10.7
#2	8.9
#3	9.0
#4	9.7
#5	9.2
#6	163
#7	234
#8	10.3
#9	10.3
ACC	13.9

Table 16. Comparison of the 1966 and 1982 sulfate levels (mg/l) reported in seven Vermont lakes.

Lake	1966	1982
Harvey's	14	9.2
Ewell	14	8.5
Carmi	12	8.1
Brownington	12	8.3
Elmore	8	7.5
Parker	11	8.4
Morey	9.5	20

with the results from the other lakes, and indicates that sulfate levels in Lake Morey have sharply increased since 1966. The section of Interstate Highway 91 near Lake Morey was constructed during the period of 1970-1972. Thus, it appears that not only has the highway caused increased rates of sulfate loading to the lake, but that this additional loading has caused a significant increase in sulfate levels within the lake.

The significance of the elevated sulfate levels for internal phosphorus loading in Lake Morey was addressed by Walker (1983) and by Ostrofsky (see letter in Appendix). Based on the high sulfide levels in the hypolimnion of Lake Morey (exceeding 20 mg/l during the summer) and on stoichiometric calculations, Walker concluded that there was sufficient sulfide present to significantly interfere with the formation of ferric phosphate at fall turnover.

Both Walker and Ostrofsky concluded, however, that sulfate concentrations in Lake Morey were in excess of levels that would limit the rate of sulfide formation. In other words, even at times of peak sulfide accumulation, an excess of sulfate remained in the lake. Thus, at present, the extent of sulfide formation in the lake may not be influenced by changes in the rate of sulfate loading from the watershed. It is possible, however, that in the past, sulfate levels did limit sulfide formation in Lake Morey. The construction of the interstate highway could have caused excessive sulfate loading, resulting in increased sulfide production that is now limited by other factors.

The suggestion that the highway construction promoted sulfide formation in the lake and increased internal phosphorus loading is further supported by the paleolimnological evidence (discussed earlier in this report). The only obvious historical event that could have caused the increased chlorophyll accumulation rates in the sediments since 1970 (shown in Figure 10) was the construction of the interstate highway.

Phytoplankton Survey

The spatial and temporal distribution of chlorophyll concentration in Lake Morey during 1981-1982 was described and discussed by Walker (1983). Walker analyzed the chlorophyll data primarily in the context of developing a model to predict algal response to phosphorus controls in Lake Morey. Direct microscopic phytoplankton species identifications and counts were also made during the study. Vertically-integrated samples of the euphotic zone were obtained by lowering a hose to twice the Secchi disc depth at the time of sampling. Samples were obtained bi-weekly during the ice-free seasons and monthly during winter from April, 1981 to November, 1982. These phytoplankton results will be discussed here.

A plot of total algal biovolume during 1981-1982 is shown in Figure 12. Algal population dynamics in Lake Morey were characterized by a series of sharp population maxima that occurred throughout the open water season. An interesting feature of the algal dynamics in Lake Morey was that these transient bloom peaks were caused by a variety of different species. As shown in Figure 12, diatoms were largely responsible for the spring blooms. The major summer blooms were caused by the dinoflagellate Ceratium. At times, this alga was in such great abundance that it formed an obnoxious yellow paint-like mass throughout the lake. Other bloom peaks were caused by blue-green algae, particularly Aphanizomenon and Anabena.

The average taxonomic composition of the phytoplankton in Lake Morey during 1981-1982 is shown in Table 17. Blue-green algal dominance in Lake Morey (31% of the total algal biovolume) was less than what is found in most other eutrophic lakes. The "other" taxonomic category, composed primarily of Ceratium, was the most prevalent group (45% of the total). Diatoms and green algae were relatively minor in importance.

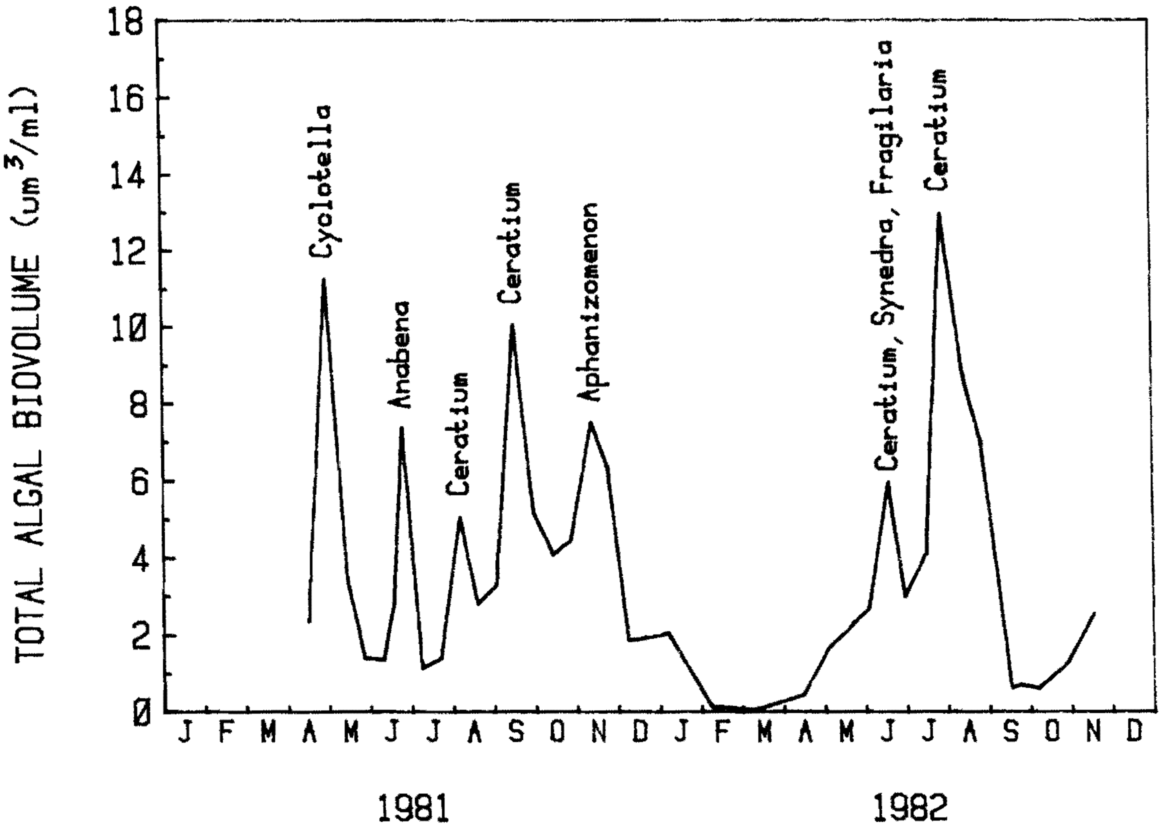

Figure 12. Plot of total algal biovolume in Lake Morey during 1981-1982. The dominant genera present at each population maximum are indicated.

Table 17. Annual average phytoplankton taxonomic composition, based on 37 sample dates during 1981-1982.

Taxonomic Group	Average Biovolume (um^3/ml)	Average Percent of Total
Diatoms	0.77	20
Greens	0.07	4
Blue-Greens	1.10	31
Other	1.84	45
Total	3.78	100

Aquatic Plant Surveys

There have been several aquatic plant surveys conducted on Lake Morey in the past thirty-four years. On August 5, 1949, the Vermont Fish and Game Service examined the aquatic vegetation in the northern portion of the lake in detail, covering the area north of Gilmore's Point. A limited survey was conducted in the northern portion of the lake again in June 1963, in areas where chemical control with 2,4-D was proposed (and subsequently used). In late August 1966, the entire lake was surveyed for aquatic plants as part of a biological study of selected Vermont lakes. The next lake-wide macrophyte survey was conducted on June 14, 1975, in conjunction with a Department of Water Resources and Environmental Engineering water quality study of Lake Morey. Limited plant surveys were conducted on three occasions during the summer of 1976 by a Water Resources sampling crew. Complete lake-wide surveys were undertaken again on July 7, 1981 and August 27, 1982, as part of the Lake Morey Diagnostic-Feasibility Study. The 1981 and 1982 surveys were conducted to identify and map the rooted aquatic vegetation currently found in the lake, locate any exotic plant species that may have been recently introduced into the lake, and assess any long-term changes that may have occurred in the species composition or extent of plant growth in Lake Morey.

Figure 13 presents a generalized overview of the extent of plant growth in Lake Morey in 1981-82. Vegetation tended to be more dense toward the northern end of the lake, north of Gilmore's Point and Breezy Bay. The eastern and western shores were characterized by rocky, steep slopes with scattered dense patches of plants. The southern portion of the lake had only sparse plant growth in most areas. Plant growth was generally more widespread and dense in 1982 than in 1981. A low-growing mat of *Heteranthera dubia* and *Najas flexilis* covered most shallow water areas of the lake. *Potamogeton amplifolius* was widespread, and dense areas of growth often reached the water surface in 1-2 meters of water, presenting a problem for recreational users of the lake. *Elodea canadensis*, *Vallisneria*

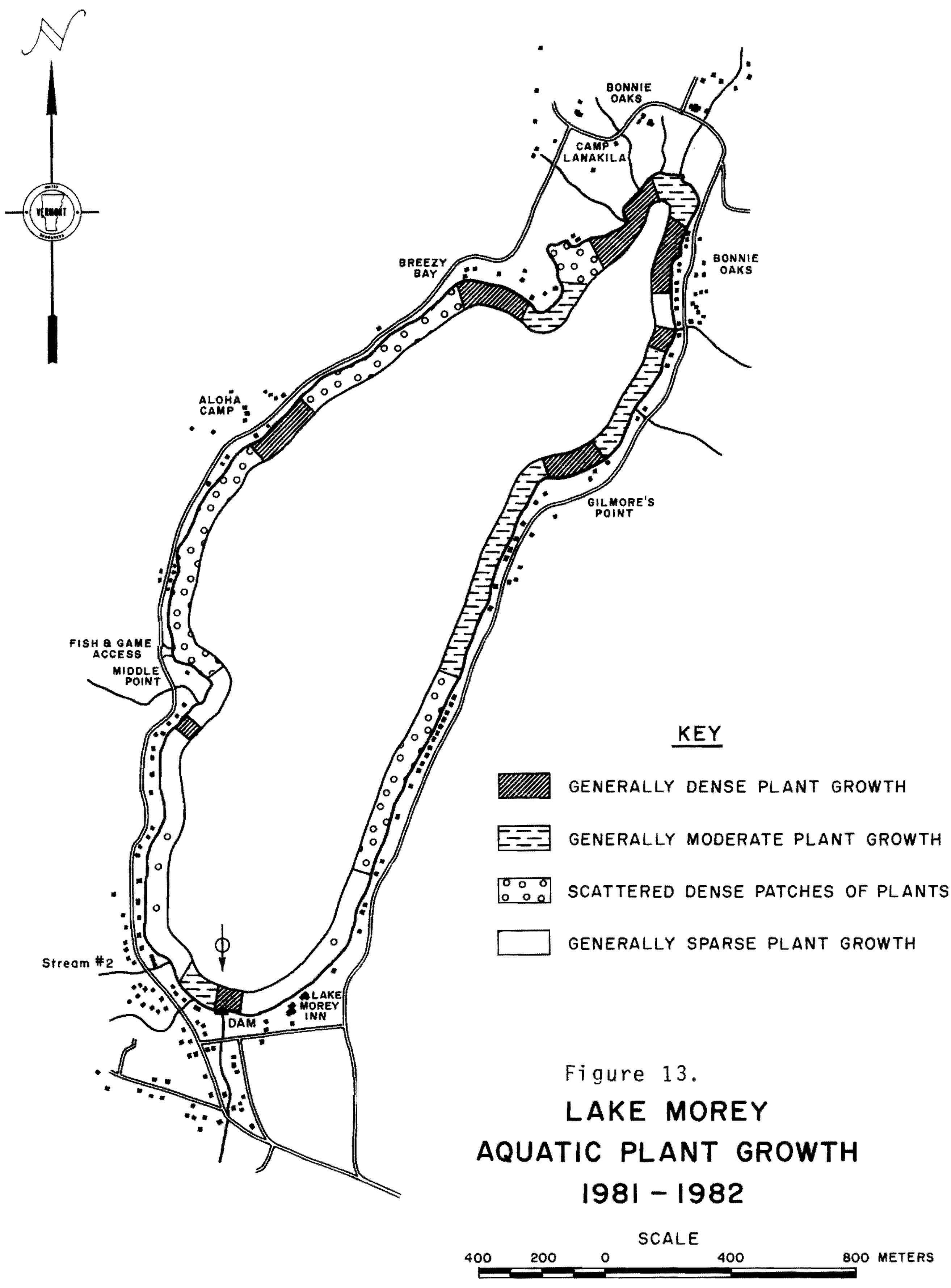

Figure 13.

LAKE MOREY AQUATIC PLANT GROWTH 1981 - 1982

americana and Ceratophyllum demersum were also widespread with some dense areas. Megalodonta Beckii occurred in localized dense patches.

When the Department of Water Resources and Environmental Engineering receives an increasing number of complaints concerning the recreational impairment of a lake due to nuisance aquatic plant growth, the cause is sometimes a new plant species in the lake. Due to increasing complaints on Lake Morey and the recent invasion of Myriophyllum spicatum in several Vermont lakes, a special effort was made in 1981 and 1982 to locate the Myriophyllum sp. that was reported in Lake Morey in 1966 and 1976, to determine whether it was a native or exotic plant. However, no Myriophyllum was found in Lake Morey in either 1981 or 1982, and it is possible that the earlier surveys misidentified Megalodonta Beckii. M. Beckii was found to be common in 1949 and again in 1981 and 1982. However, this species was not mentioned in intervening surveys.

While no Myriophyllum spicatum was identified in the lake, a new population of another exotic plant was found in Lake Morey in 1982. A small patch of Phragmites maximus, consisting of approximately 100 plants, was located at the mouth of stream #2 (Figure 13). Phragmites maximus has become a nuisance in several wetland areas of Vermont where it has replaced more beneficial Typha stands. It is recommended that this patch of plants be removed from the lake to prevent its undesirable spread.

Although it was determined that the recent increase in complaints concerning plant growth on Lake Morey was not caused by an exotic plant species, the possibility remained that the native plant species composition in the lake had changed to include more nuisance types. A total of 42 species of aquatic plants have been identified in Lake Morey since 1949 (Table 18). The dominant plant species over the years have been Potamogeton amplifolius, Ceratophyllum demersum, Heteranthera sp., Elodea canadensis and several pondweeds including P. praelongus, P. Robbinsii, P. gramineus, P. pectinatus and Najas flexilis. The identification of species of Potamogeton is notoriously difficult and it is possible that some of the different dominant species

Table 18. Aquatic plants identified in Lake Morey since 1949. The presence of a species during a survey is indicated by an "X". An asterisk "*" shows the dominant plants. Surveys in 1949 and 1963 were limited to a small area of the lake.

	SURVEY						
SPECIES	1949	1963	1966	1975	1976	1981	1982
ISOETACEAE							
Isoetes sp.							X
TYPHACEAE (cattail)							
Typha latifolia			X	X			X
T. angustifolia	X						
Typha sp.		X			X	X	
SPARGANIACEAE (bur reed)							
Sparganium americanum	X						
NAJADACEAE (pondweed)							
Potamogeton amplifolius	X	X	X	X	X	X	X
P. foliosus							X
P. gramineus				X		X	X
P. natans				X			
P. pectinatus				X			
P. praelongus			X	X		X	X
P. Richardsonii			X				
P. Robbinsii	X	X	X	X	X		
P. Vaseyi			X				
Potamogeton spp.	X	X			X		
Najas flexilis	X		X		X		X
ALISMACEAE							
Alisma Plantago-aquatica (water plantain)	X						
Sagittaria graminea (arrowhead)		X	X				
S. latifolia	X						
Sagittaria sp.					X	X	X
HYDROCHARITACEAE							
Elodea canadensis (waterweed)	X	X	X	X	X	X	X
Vallisneria americana (wild celery)	X		X	X	X	X	X
GRAMINEAE							
Phragimites maximus							X

+ Note: This species may have been *Heteranthera* sp.

Table 18 (continued)

	1949	1963	1966	1975	1976	1981	1982
CYPERACEAE (sedge)							
Carex spp.	X	X					
Eleocharis acicularis	X						
E. palustris	X		X				
Scirpus americanus			X				
Scirpus cyperinus	X						
Scirpus validus var. *creber*			X				
unidentified			X			X	
LEMNACEAE (duckweed)							
Lemna minor	X	X		X			
ERIOCAULACEAE (pipewort)							
Eriocaulon septangulare					X	X	X
PONTEDERIACEAE (pickerelweed)							
Pontederia cordata	X		X	X		X	X
Heteranthera sp.	X					X	X
JUNCACEAE (rush)							
Juncus spp.	X			X		X	X
IRIDACEAE (iris)							
Iris versicolor				X			
POLYGONACEAE							
Polygonum spp. (smartweed)	X						
CERATOPHYLLACEAE							
Ceratophyllum demersum (coontail)	X	X	X	X	X	X	X
NYMPHAEACEAE							
Nymphaea odorata (water lily)	X		X			X	X
Nymphaea sp.	X			X	X	X	
Nuphar variegatum (yellow water lily)			X	X			X
Nuphar sp.	X	X			X	X	
RANUNCULACEAE (buttercup)							
Ranunculus sp.	X						
HALORAGIDACEAE (water milfoil)							
Myriophyllum sp.			X		X		
COMPOSITAE							
Megalodonta Beckii (water marigold)	X					X	X
CHARACEAE (stonewort)							
Chara vulgaris			X				X
CHLOROPHYCEAE (green algae)							
Spirogyra sp.	X	X		X		X	X

found through the years (particularly the Potamogeton spp. and Heteranthera sp.) may actually have been the same species, misidentified. The dominant plant species have generally remained fairly constant and it appears that the species of rooted aquatic plants found in Lake Morey have not changed significantly in the past 34 years.

Having ruled out an exotic plant species or a change in native plant species as the cause of recent nuisance aquatic plant problems in Lake Morey, an attempt was made to assess long-term trends in plant growth in the lake. Unfortunately, any changes that may have occurred since 1949 in the extent or density of macrophyte growth in the lake were difficult to document. The 1949 and 1963 surveys were limited to the northern end of the lake, and the map accompanying the 1966 study was not available. The areas of plant growth mapped in 1975 and 1976 seemed to correlate with the areas where plants were found in 1981 and 1982, so no changes in the extent of plant growth in the lake could be shown. A comparison of density estimates made in different surveys by different observers is not very dependable due to the subjective nature of such estimates. In addition, the 1981 and 1982 macrophyte surveys showed that plant density in Lake Morey can vary considerably from year to year. Aquatic vegetation in 1982 was generally more widespread, more dense, and reached the water surface earlier than in 1981. Swimming and boating activities were impaired in some areas of dense growth in 1982, while plant growth in 1981 did not interfere with the recreational uses of the lake. Even in 1982, however, plant growth was not as widespread and dense as it had been in some previous years. Given the existing information on macrophyte growth in Lake Morey and the yearly variation in plant growth documented in the lake, it was not possible to substantiate claims by lakeshore residents that plant growth has increased in recent years.

Despite the lack of evidence showing a change in the rooted aquatic plant population in Lake Morey in recent years, there is little question that plant growth in the lake does, at times, present a problem to recreational users of the lake. Swimming classes at the municipal beach have occasionally been cancelled until dense plant growth could be cleared out. Swimmers, boaters, waterskiers and fishermen have become tangled in aquatic vegetation, spoiling an otherwise enjoyable recreational experience on the lake. Problems have existed in some areas of the lake at least since 1963.

Historical control of rooted aquatic plant growth in Lake Morey has been mainly through the use of herbicides, including the application of a total of 154 kg (340 lbs.) of 2,4-D to eight areas in the northern end of the lake in 1963, the application of 693 kg (1,526 lbs.) of 2,4-D to the same areas in 1964, the application of 0.25 liters (0.25 quarts) of 2,4-D to a 232 square-meter (2,500 square-foot) area at the southern end of the lake in 1974 and 1975, and the application of an unspecified amount of endothall to the northern end of the lake in 1976. Herbicide applications are expensive and in the past have given only fair results in Lake Morey. Any future use of herbicides in Lake Morey is not recommended.

Alternative methods to control rooted aquatic vegetation include bottom screening, drawdown, dredging and mechanical harvesting. Plant growth in Lake Morey is too widespread for effective large-scale control with bottom screens. Some lakeshore residents do currently use Aquascreen to limit plant growth in small areas. Drawdown is not a practical alternative for Lake Morey. The existing dam would have to be modified before the water level could be lowered sufficiently to impact the deeper beds of plants. In addition, periodically lowering the lake water level would have an unacceptable adverse impact on the fishery in the lake. Dredging is an extremely expensive alternative and its ability to control plant growth for long periods of time is not well documented. The situation on Lake Morey does not warrant such an expensive and experimental control method.

Given the patchiness of the macrophyte areas in Lake Morey and the yearly variation in the severity of the plant problem, mechanical harvesting is the most practical way to manage nuisance aquatic plants while leaving areas that are critical for fish habitat unaltered. In addition, the effort and expense of the control program can vary yearly with the extent of the problem. Harvesting is not experimental. The benefits are immediate and predictable. It is therefore recommended that aquatic plant harvesting be conducted on Lake Morey to manage the nuisance plant growth in the lake and restore the recreational uses of the lake to their full potential.

Fish Survey

A fish survey was conducted on Lake Morey from May 19 to June 30, 1981, to assess the fishery status at current water quality conditions. This assessment will serve as a basis against which future comparisons may be made, particularly after any lake restoration measures have been implemented.

Three methods were employed for this survey, using three types of gear: trap net, gill net and electro-fishing gear. Each method was selective for different fish species, and location and time of sampling also introduced sampling biases. All three methods were used to more effectively assess the presence and distribution of the lake fish species.

Specifications of the gear used are:

Trap net - 0.9 x 1.5 meter rectangular frame trapnet with 3-meter leader, 6-meter wings with bonnet, and 3.2-cm square mesh.

Gill net - 2 x 30-meter nylon gill net composed of four 7.6-meter panels of different mesh sizes (3.6, 6.3, 10.2, 14.4 cm^2)

Shocker - a 3000 W, 230 V, three-phase 60 cycle, A.C. generator powering an electode mounted on the bow of a 4.9-meter boat.

The trap net was set at a 2-meter depth approximately 30 meters off shore with the leader going into shore. The trap net was placed off the lake's northwestern prominent point for 24 hours once per week for six weeks during May 19 - June 30. This site is within the major spawning and nursery area of many of the lake fish species. The gill net was set concurrently with the trap net at a 7.5-9 meter depth, the set beginning 20 meters off the midpoint of the eastern shoreline. The net location was chosen to detect the possible presence of any salmonids or smelt. Electro-fishing was conducted on the night of May 21 along representative lengths of shoreline around the lake. Results of the 1981 survey are given in Table 19.

A similar fish survey was conducted on Lake Morey on August 1-7, 1969, by the Vermont Department of Fish and Game, employing the methods used in the 1981 survey. Species dominance did not change dramatically over the past twelve years, with yellow perch being the most common species found. Largemouth bass were the dominant game fish, with smallmouth bass, chain pickerel, and northern pike also present. Although 1981 gill net specimens of yellow perch averaged slightly greater in length compared with the 1969 fish, the average length remained unchanged among yellow perch specimens found in the trapnet or by shocking. Three species found in the earlier survey, Osmerus mordax (rainbow smelt), Etheostoma sp. (darter), and Catostomus catostomus (longnose sucker) were not found in 1981. Although Salmo gairdneri (rainbow trout) were stocked in 1972-1978, none were found in 1981 and there has been no angler report of the species from Lake Morey since 1979. Etheostoma sp., found in small numbers in 1969, may have been missed in 1981 sampling.

Table 19. Results of Lake Morey fisheries survey, May 19 - June 30, 1981

	TRAP				GILLNET				SHOCKER				TOTAL	
Species	#	Mean Len. (cm)	Std. Dev. (cm)	% of Method Total	#	Mean Len. (cm)	Std. Dev. (cm)	% of Method Total	#	Mean Len. (cm)	Std. Dev. (cm)	% of Method Total	# of Species	% of Total #
Perca flavescens (yellow perch)	50	22.9	2.3	13	438	23.9	2.5	99	82	22.9	1.8	24	565	49
Lepomis gibbosus (pumpkinseed)	81	17.3	2.0	20	1	16.8	---	1	93	17.0	4.6	29	175	15
Notemigonus crysoleucus (golden shiner)	222	20.6	1.5	55	1	14.7	---	1	5	19.3	2.8	2	228	20
Ambloplitus rupestris (rock bass)	19	20.8	3.6	5	1	---	---	1	74	19.3	4.0	23	94	8
Micropterus salmoides (largemouth bass)									42	26.2	4.6	13	42	4
Micropterus dolomieui (smallmouth bass)	1	16.8	---	1					5	32.0	11.7	2	6	1
Ictalurus nebulosus (brown bullhead)									10	29.5	3.3	3	10	1
Esox niger (chain pickerel)	5	38.6	7.9	1	2	33.0	3.0	1	6	29.2	7.4	2	13	1
Esox lucius (northern pike)	2	30.7	0.8	1	1	33.8	---	1					3	1
Lepomis auritus (redbreasted sunfish)									5	18.3	0.5	2	5	1
Catostomas commersoni (white sucker)	20	30.2	3.81	5	3	40.4	16.8	1	1	44.5	---	1	24	2
TOTALS	400				447				318				1163	

Designing Future Diagnostic Studies on Vermont Lakes

In addition to determining the cause of water quality problems in Lake Morey, a secondary purpose of the Lake Morey Diagnostic-Feasibility Study was to evaluate methods of sampling and data analysis so that future lake diagnostic studies in Vermont could be designed more effectively and efficiently. The Lake Morey Study was designed to employ a variety of field and data analysis methods so that an evaluation of alternative methods would be possible. Also, sampling of the lake and streams was conducted at the maximum frequency possible so that an evaluation could be made as to what level of sampling effort was really necessary to produce good results. The findings from these methods evaluation efforts are discussed here.

Groundwater Methods

The use of a variety of field techniques at Lake Morey involving monitor wells, seepage meters, and mini-piezometers permitted a comparison of various methods for estimating groundwater flow and phosphorus loading to the lake. For water quality sampling purposes, the near-shore, shallow monitor wells were by far the most useful device. Attempts were made to obtain samples from the mini-piezometers, but the slow recharge rates severely restricted the volumes that could be obtained. Water quality sampling using the seepage meters was not attempted because of concerns about possible alterations in physical or chemical conditions at the sediment-water interface caused by the enclosure that might influence the results.

Groundwater flow into the lake was calculated by several methods. One method was to estimate the groundwater flow as the residual term from the surface water budget. Wagner, Heindel, and Noyes, Inc. (1983) rejected this approach because of the very large statistical error involved in estimating a relatively small groundwater flow rate from the difference between large surface inflow and outflow rates. A precise estimate of groundwater flow by this method would be impossible for most Vermont lakes where errors in the estimates of the various surface hydrologic inputs would be large, relative to the magnitude of the groundwater flow. However, the water budget data (Table 12) did serve to confirm the qualitative conclusion that groundwater flow to Lake Morey is minor in significance, relative to surface inputs.

Wagner, Heindel, and Noyes, Inc. (1983) concluded that the use of seepage meters would be an acceptable way to determine near-shore groundwater inputs to lakes. There were, however, some difficulties involved with the use of seepage meters in Lake Morey. Much of the near-shore sediment area in the lake was composed of substrate types that were either rock, silt, or organic muck. The proper placement of seepage meters requires a sandy substrate to insure a good seal about the seepage meter and a sufficiently conductive material to permit measureable flow rates. Therefore, much of the shoreline of Lake Morey was less than ideal for the use of seepage meters, and this may have contributed to the considerable variability in the measured flows.

An alternative approach using the monitor wells only, based on bailed well recovery rates, was also used to estimate groundwater flow to the lake. The estimate based on this method compared very well with the Wagner, Heindel, and Noyes, Inc. estimate, suggesting that this second approach might be suitable in cases where the use of seepage meters was impractical.

Stream Phosphorus Loading Estimation

Walker (1983) compared several methods of computing phosphorus loading rates from stream flow and phosphorus concentration data obtained at Lake Morey. Given a continuous flow record with sporadic phosphorus sampling, Walker concluded that the best loading computation procedure was the "flow-interval" method in which the data was stratified with respect to flow, and separate average loading estimates were developed for each of several flow intervals. This method produced an unbiased estimate of loading with minimum error, relative to the other computation techniques compared.

To use the flow-interval technique successfully on future lake diagnostic studies, a continuous flow record should first be generated. The phosphorus stream sampling program should be aimed at providing an equal number of samples for each flow interval, or perhaps should favor the higher flow ranges. A rigid (e.g. weekly) sampling schedule would provide excessive coverage of the low flow ranges, because high flows are relatively infrequent. As pointed out by Walker, a much more efficient stream sampling program at Lake Morey would have eliminated many of the samples obtained during low flows and added more high flow samples. A more flexible sampling schedule, aimed at providing equitable coverage across all flow ranges, should be the goal of future stream sampling programs. The actual level of sampling effort should be determined by the degree of precision required, and by the variability in phosphorus concentrations expected within each flow interval.

Lake Sampling

Sampling of Lake Morey was done at the maximum frequency feasible, with respect to depth and time. During the ice-free season, samples were obtained weekly at one-meter depth intervals. The lake total phosphorus and chlorophyll data was analyzed to determine how much precision would be lost in estimating annual mean values for these two parameters if the sampling effort were reduced. To simulate the effect of reducing the sampling effort, a variety of sampling schemes (shown in Table 20) were tested by eliminating data from the original data set. The mean values over the entire sampling period for total phosphorus and chlorophyll were then re-computed for each sampling scheme. The values for individual dates were based on volume-weighted depth averages, where appropriate weighting factors were applied, depending on the proportion of the lake's volume represented by samples obtained at a given depth.

As shown in Table 20, nine different sampling schemes were tested, involving various combinations of reduced sampling effort with respect to time and depth. The mean lake concentrations of total phosphorus and chlorophyll for the entire sampling period, and 95% confidence limits, were computed for each sampling scheme and shown in Figures 14 and 15.

In the case of total phosphorus (Figure 14), sampling schemes (C, F, and I) involving only three depths within the water column produced means that were inaccurate and biased strongly upwards. The bias was probably caused by high summer phosphorus levels at the 12 meter depth that overestimated average concentrations in the deep lake stratum. Sampling at two-meter depth intervals (schemes B, E, and H) produced means that were comparable to those derived from sampling at every meter. Sampling at reduced frequency with respect to time appeared to have little effect on the accuracy of the means, but the precision of the estimates, as indicated by the 95% confidence intervals, was considerably reduced at the lower frequencies.

Similar results were obtained for the chlorophyll data (Figure 15). However, the sampling schemes (C, F, and I) involving only three depth intervals produced means that were biased downwards, rather than upwards. This may have been caused by the omission of depths where a stratified, metalimnetic algal population existed at times.

The general conclusions from this lake sampling frequency analysis appear to be that the number of depths sampled could not have been greatly reduced without having run the risk of producing a biased estimate. Sampling frequency with respect to time could probably have been reduced somewhat, although a sampling frequency less than biweekly would have resulted in much less precise estimates. These conclusions probably apply only to lakes with patterns of spatial and temporal variability similar to those found in Lake Morey, and to situations where the goal of the lake sampling program is to produce an estimate of the annual mean total phosphorus or chlorophyll value. Examples of such

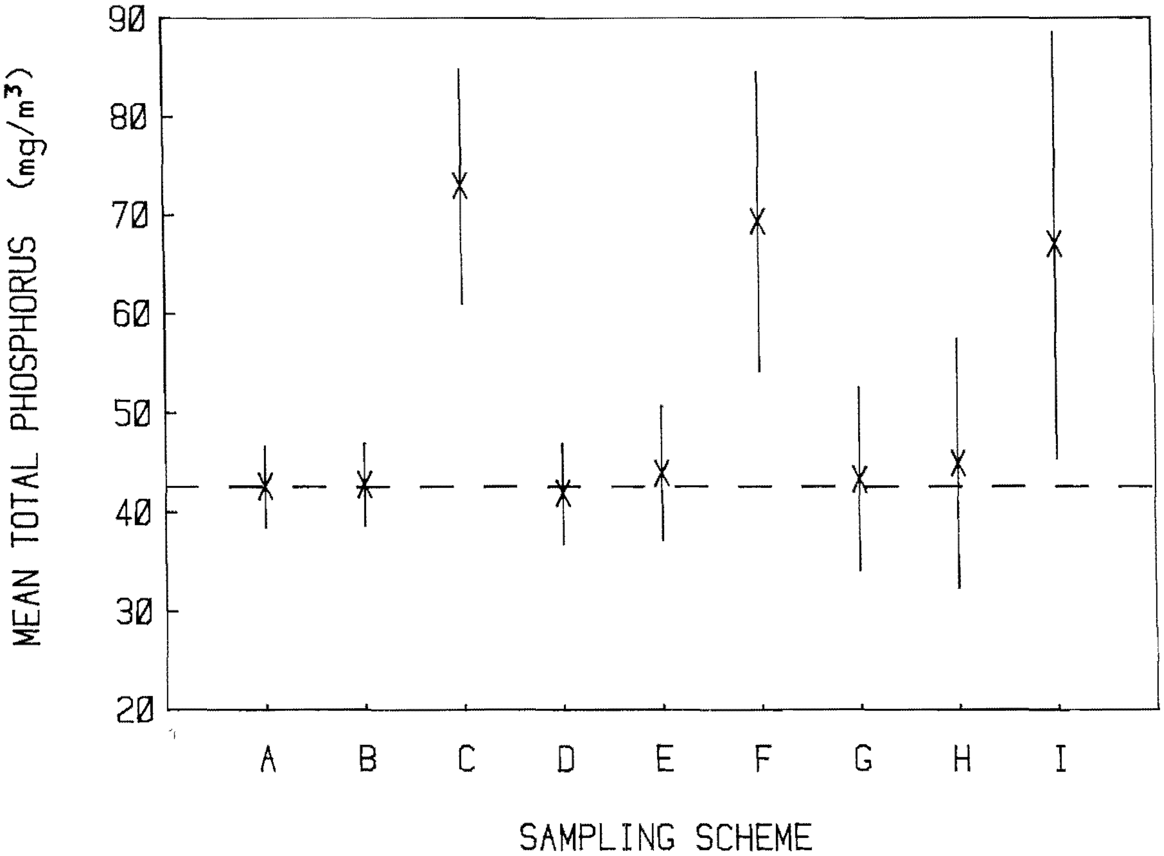

Figure 14. Mean total phosphorus concentrations for Lake Morey computed on the basis of nine different sampling schemes. Error bars represent 95% confidence limits about the means. Dotted line represents the "best" estimate of the mean, based on sampling scheme A. See Table 20 for a key to sampling schemes.

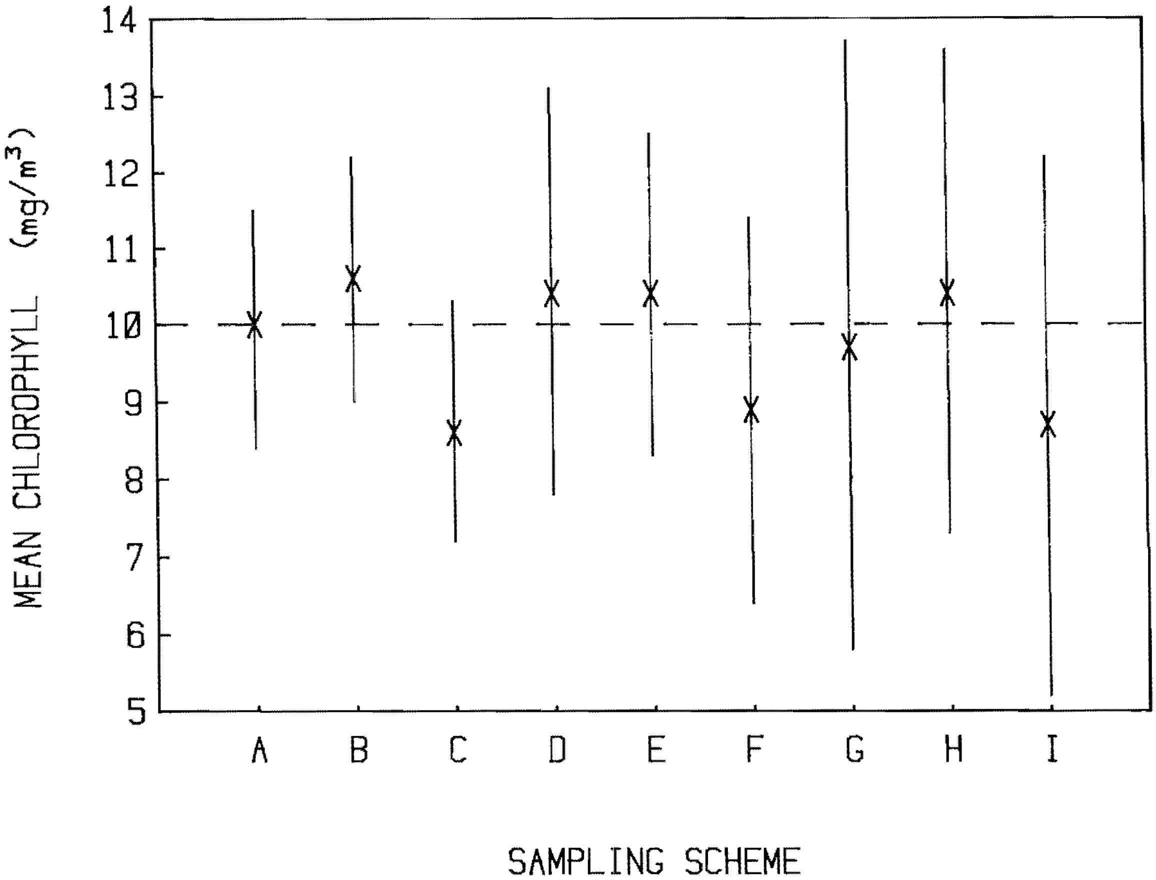

Figure 15. Mean chlorophyll concentrations for Lake Morey computed on the basis of nine different sampling schemes. Error bars represent 95% confidence limits about the means. Dotted line represents the "best" estimate of the mean, based on sampling scheme A. See Table 20 for a key to sampling schemes.

situations might include lake classification, monitoring of trends between years, and simple, steady-state phosphorus modeling. This sampling frequency analysis does not address other situations, such as mechanistic, time-dependent modeling, where more than annual mean values are required. In these more demanding situations (of which the Lake Morey Study is an example), a lake sampling program involving the maximum feasible effort would probably produce the best results.

Table 20. Sampling schemes used for lake total phosphorus and chlorophyll sampling frequency analysis.

Time Sampling	Depth Sampling Frequency		
Frequency	every meter	1, 3, 5, 7, 9, 11 m	1, 6, 12 m
every week	A	B	C
every other week	D	E	F
every fourth week	G	H	

FEASIBILITY STUDIES

Internal Phosphorus Loading Controls

When it became clear from the diagnostic study results that lake restoration efforts at Lake Morey should be directed at controlling internal phosphorus loading, a variety of techniques for reducing internal loading were considered. These techniques included alum treatment, hypolimnetic aeration with compressed air, total destratification, and hypolimnetic aeration by pumped withdrawal. The first three of these techniques were evaluated in a feasibility study conducted by Booker Associates, Inc. under a contractual agreement. The reader should refer to the Booker Associates (1983) report at this point for a description of these techniques, an evaluation of their effectiveness in Lake Morey, and an estimate of their cost. Comparative summaries of each technique are provided in Tables 21, 22 and 23, based largely on the Booker Associates report.

Hypolimnetic aeration by pumped withdrawal was also considered for Lake Morey, based on the apparent success of this technique in Lake Waramaug, Connecticut (D.D. Henry, personal communication). This technique is similar in purpose to hypolimnetic aeration with compressed air, with the difference being that hypolimnetic water is pumped to a shore-based aeration facility and then returned to the hypolimnion. The Lake Waramaug system involved aeration of the water by means of an aeration tower, followed by retention in a lagoon before return to the hypolimnion. This system may have some advantages over hypolimnetic aeration with compressed air in that some removal of phosphorus, sulfide, and other reduced, oxygen-demanding compounds occurs as the water is passed over the aeration tower and retained in the lagoon. Also, because the aeration occurs at atmospheric pressure, it eliminates any possibility of nitrogen gas supersaturation as a threat to fish. The water quality benefits of the Lake Waramaug system, which began operation in 1983, have not yet been fully evaluated, however.

Table 21. Feasibility study results for alum treatment.

Definition

Treatment of the deep sediments of the lake with aluminum compounds to prevent phosphorus release from the sediments.

Cost

chemical	$146,500.00
application	68,000.00
operation and maintenance	0.00
contingency (15%)	32,200.00
TOTAL	$246,700.00

Advantages

1. Effectiveness has been demonstrated in other lakes for at least 10 years when applied properly.
2. No operation or maintenance committment required.

Disadvantages

1. Treatment could fail to provide long-term control of lake phosphorus levels if not applied properly.
2. If not properly applied, aluminum toxicity to fish and other aquatic organisms could result.

Table 22. Feasibility study results for <u>hypolimnetic aeration with compressed air.</u>

Definition

Aeration of the hypolimnion with compressed air to oxidize the sediment surface and prevent phosphorus release while maintaining thermal stratification.

Cost

equipment (aeration device, air lines, power hook-up, housing)	$191,000.00
contingency (10%)	19,000.00
operation and maintenance (primarily electrical cost)	10,000.00/year
TOTAL initial cost	$210,000.00
operating cost	10,000.00/year

Advantages

1. Maintains natural thermal stratification (in contrast to total destratification).
2. Could improve habitat for trout.

Disadvantages

1. Effectiveness at controlling phosphorus release from sediments not as extensively demonstrated as for alum treatment.
2. Low iron concentrations in Lake Morey could partly preclude phosphorus precipitation even under aerated conditions.
3. A local committment to meet annual operation and maintenance costs indefinitely would be required.
4. Would create a long-term increase in energy consumption.
5. The capabilities of the lowest cost system studied (Atlas Copco Co.) have not been independently verified.

Table 23. Feasibility study results for total destratification.

Definition

Circulation of the entire vertical water column in the lake with compressed air to aerate the sediments and prevent phosphorus release.

Cost

equipment (compressor, air lines, power hook-up, housing)	$36,000.00
contingency (10%)	4,000.00
operation and maintenance (primarily electrical cost)	12,000.00/year
TOTAL initial cost	$40,000.00
operating cost	12,000.00/year

Advantages

1. Lowest initial cost alternative.

Disadvantages

1. Has all of the same disadvantages as hypolimnetic aeration with compressed air (except #5).
2. Total destratification can sometimes increase, rather than decrease, algae levels. The biological mechanisms involved are poorly understood and difficult to predict.
3. Would disrupt the natural thermal stratification characteristics of the lake.

Table 24. Feasibility study results for <u>hypolimnetic aeration by pumped withdrawal.</u>

<u>Definition</u>

Aeration of the hypolimnion by pumped withdrawal of hypolimnetic water to a shore-based aeration facility, and a return of aerated water to the hypolimnion.

<u>Cost</u>

equipment (pipe, pump, housing, aeration tower, power hook-up)	$220,000.00
contingency (23%)	50,000.00
operation and maintenance	20,000/year
TOTAL initial cost	$270,000.00
operating cost	20,000.00/year

<u>Advantages</u>

1. Has all the same advantages as hypolimnetic aeration with compressed air.
2. May provide some treatment of hypolimnetic water for removal of phosphorus and sulfide.

<u>Disadvantages</u>

1. Has all the same disadvantages as hypolimnetic aeration with compressed air (except #5).
2. Requires a shore-based aeration facility.

The feasibility of hypolimnetic aeration by pumped withdrawal for Lake Morey was evaluated by Robert Finucane, a Facilities Engineer with the Vermont Department of Water Resources and Environmental Engineering (see memorandum in Appendix). Finucane evaluated two types of shore-based aeration facilities, one involving a waterfall-type aerator, and the other involving downflow air injection in a buried U-tube installation. Both of these systems were designed to supply 2,130 kg/day of oxygen to the hypolimnion, based on the oxygen requirement calculated by Booker Associates (1983).

The system involving downflow air injection proved to be the more cost-effective of the two. However, in comparison with the compressed air technique, hypolimnetic aeration by pumped withdrawal would be more expensive for Lake Morey in terms of initial cost and would require more electric power, resulting in a greater annual operating cost. The costs, advantages, and disadvantages of hypolimnetic aeration by pumped withdrawal for Lake Morey are summarized in Table 24.

A comparison of all four alternative lake restoration methods for Lake Morey (Tables 21-24) as to their technical feasibility indicated that all could be implemented with a good probability of success, with the possible exception of total destratification. Total destratification has had a very mixed record of success in lakes where its effects have been evaluated (Pastorok et al, 1980). In Lake Morey, the recirculation of nutrients into the surface waters by total destratification could offset the intended benefits of sediment aeration and light limitation of photosynthesis, causing an increase, rather than a decrease, in algal levels (Forsberg and Shapiro, 1980). Because of the uncertainty of success, and the desire to preserve the natural thermal stratification characteristics of the lake as much as possible, total destratification was eliminated from consideration as a restoration technique for Lake Morey.

Booker Associates (1983) evaluated both a whole-lake and a hypolimnetic alum treatment. However, the whole-lake treatment was rejected because of its very high cost, and because the limnological data (see Walker, 1983) indicated that the internal phosphorus loading was derived primarily from the anoxic hypolimnetic sediments. Therefore, there was little justification for a whole-lake application.

A comparison of alum treatment with the two hypolimnetic aeration systems showed that these methods were fairly similar as to their technical feasibility. Both approaches have certain disadvantages. The effectiveness of hypolimnetic aeration in controlling internal phosphorus loading has not been as extensively demonstrated as has the effectiveness of alum treatment. Low iron concentrations in Lake Morey may partly preclude the precipitation of phosphorus, even under aerated conditions. However, the major period of sediment phosphorus release is during the summer anoxia, and this observation indicates that even with low iron levels, aeration should still provide substantial benefits.

The major drawback of alum treatment is probably the potential for toxic effects on fish and other aquatic organisms. Acute toxicity at the time of treatment can be avoided by proper application techniques. Cooke and Kennedy (1980, 1981) reviewed several studies in which possible toxic effects of an alum treatment were examined. They concluded that acute toxicity should not be a problem provided that residual dissolved aluminum concentrations were maintained below 50 ug/l and pH was maintained above 6.0. They cited numerous case histories of lakes worldwide that have undergone alum treatment with no apparent toxic effects. Booker Associates (1983) conducted laboratory tests on Lake Morey water to determine the correct application rate. With the use of an alum and sodium aluminate mixture, it was found that pH and residual dissolved aluminum concentrations could be maintained at safe levels. Monitoring of pH and dissolved aluminum concentration in the lake during the actual application would provide an additional safeguard against toxicity problems.

Long-term chronic toxicity resulting from an alum treatment has not been thoroughly researched. Lamb and Bailey (1983) conducted experiments to evaluate chronic toxicity of alum to rainbow trout and chironomid (midge) larvae. They found no chronic toxicity effects on trout, but did note some adverse effects on the midge larvae. Dominie (1980) also conducted long-term laboratory bioassay experiments using chironomid larvae in anticipation of an alum treatment of Annabessacook Lake, Maine. Dominie found no toxic effects over a 30-day period. In both studies, the chironomid larvae were reported to be moving and feeding normally in the alum floc layer, apparently uninhibited by the physical properties of the floc. Other research, reviewed by Cooke and Kennedy (1980), generally has shown no significant chronic toxicity problems resulting from alum treatment of lakes, but further research is needed before the risks can be completely assessed.

A comparison of the alum treatment and hypolimnetic aeration alternatives from an economic perspective favors alum treatment since there would be no operation or maintenance costs after the alum was applied. The annual operation and maintenance requirement was an important concern in evaluating the potential for successful lake restoration by hypolimnetic aeration. There was no guarantee that aeration would someday become unnecessary to maintain good water quality in the lake. Thus, if the annual operating expenses ever became too large a burden for local residents, the lake restoration benefits of the project would be in jeopardy.

After consideration of the advantages, disadvantages, and costs of each alternative, the decision was made that alum treatment would be the best choice for Lake Morey. The risks of either acute or chronic aluminum toxicity were judged to be sufficiently small as to be justifiable, given the potential benefits of the treatment. The prospects for successful, long-term water quality improvement in Lake Morey resulting from an alum treatment appear to be good. Alum treatments have provided long-term benefits in other lakes when applied in the proper situation (Garrison and Knauer, 1983). Because present-day inflowing water quality is good, and historical phosphorus loading recycled from the sediments is the lake's major phosphorus source, Lake Morey is an excellent candidate for such a treatment.

Watershed Phosphorus Controls

The diagnostic study results indicated that internal phosphorus recycling, rather than loading from the watershed, was the major cause of elevated phosphorus concentrations in Lake Morey. Consequently, the major feasibility study effort was directed towards lake restoration measures to control internal loading. However, to be most effective, measures aimed at controlling internal recycling require that external phosphorus supplies be reduced to the maximum extent feasible. Therefore, an effort was made to identify any controllable watershed phosphorus sources.

The stream sampling results (Table 9) indicated that four Lake Morey tributaries (#5,7,8 and ACC) had elevated phosphorus concentrations. Of these four, two (#5 and 8) had no obvious cultural source of phosphorus in the drainage basin. Most (over 90%) of the phosphorus load carried by these two streams was in particulate form (based on data in Walker, 1983), indicating that erosional processes were probably the cause of the elevated phosphorus concentrations. Due to the lack of cultural influences, significant reductions in phosphorus loading from these two streams would probably be very difficult to achieve.

Of the other two streams with elevated phosphorus concentrations, one (ACC) was obviously affected by a faulty septic system at a summer camp for girls. This small stream was characterized by a high proportion of dissolved phosphorus and by fecal coliform bacteria counts in excess of Vermont Water Quality Standards. The septic system was repaired by the landowner during 1983, and presumably the problem has been corrected.

Continued sampling of bacteria levels in this stream should be a part of the State's summer monitoring program on Lake Morey, however, in order to verify that no further septic system contamination exists.

The remaining stream (#7) with elevated phosphorus levels may have been affected by seepage from nearby sewage lagoons operated by a commercial resort inn. Repairs to the inn's sewage treatment system were made during 1983 to safeguard against failures that could cause a direct surface discharge to the stream or the lake. Further improvements to the existing system to eliminate any possibility of subsurface seepage do not appear to be technically feasible, however.

MODELING STUDIES

The results of the diagnostic and feasibility studies, discussed previously in this report, indicated that techniques aimed at controlling internal phosphorus recycling would be appropriate lake restoration measures for Lake Morey. Modeling analyses were conducted to evaluate the water quality benefits expected from measures such as alum treatment or hypolimnetic aeration. A major difficulty in simulating the effects of these treatments resulted from the fact that it was not possible to estimate with much precision the extent to which internal phosphorus loading would be reduced in Lake Morey. While hypolimnetic aeration and particularly alum treatment have been used extensively in other lakes to control internal phosphorus recycling, there is, as yet, no method whereby the impacts of these treatments can be predicted quantitatively for use in a lake modeling analysis. In view of this limitation, the modeling approach chosen for Lake Morey was to examine the sensitivity of lake phosphorus concentrations to a range of projected internal recycling conditions.

Walker (1983) used this approach in applying the Lake Eutrophication Analysis Procedure (LEAP) model to Lake Morey. The LEAP model was calibrated and tested using data from over 40 Vermont lakes and included an internal phosphorus recycling term that was dependent on the hypolimnetic oxygen depletion rate and lake morphometry. Walker concluded that phosphorus concentrations in Lake Morey should be quite sensitive to changes in internal recycling.

A simpler lake model (modified from Dillon and Rigler, 1974) was also applied to Lake Morey for comparison with the LEAP model results.

$$P = \frac{W\ (1-R)}{Q} \qquad (2)$$

where P = steady-state lake phosphorus concentration (mg/m^3)

W = phosphorus loading rate (mg/yr)

R = phosphorus retention coefficient

Q = water loading rate (m^3/yr)

In Figure 16, lake phosphorus concentrations predicted from equation 2 are plotted as a function of the phosphorus retention coefficient. Lake phosphorus concentrations predicted from the LEAP model are also plotted in Figure 16 as a function of the LEAP internal phosphorus loading parameter (see Walker, 1982, for the derivation of this parameter). The values for water and phosphorus loading rates measured during the 1981-1982 study period were used as inputs for both models.

Figure 16 shows that lake phosphorus concentrations predicted from both the LEAP and the Dillon-Rigler models declined sharply as the LEAP internal loading parameter was decreased or the phosphorus retention coefficient was increased. An internal loading parameter value of 8.0 was the value originally calibrated to a cross section of Vermont lakes. Using this value, the LEAP model predicted a spring phosphorus concentration of 33 mg/m^3, a level identical to the seven-year (1977-1983) average spring phosphorus concentration observed in Lake Morey (Vermont Department of Water Resources and Environmental Engineering data). The effects of lake restoration measures to control internal phosphorus recycling were simulated by forcing the internal loading parameter downward from 8.0 to 0. A value of zero for this parameter, corresponding to the complete elimination of redox-related internal recycling (Walker, 1983), would predict a spring phosphorus concentration of only 12 mg/m^3.

Similar results were obtained from the Dillon and Rigler model. The phosphorus budget results for the 1981-1982 study period (Table 13) indicated a phosphorus retention coefficient of 0.14, corresponding to a predicted spring phosphorus value of 25 mg/m^3, a value slightly lower than the observed 1977-1983 mean of 33 mg/m^3, but probably not significantly different from the observed mean, considering the errors involved in applying the model and in estimating the model terms. The phosphorus retention value of 0.14 is much lower than what would be expected from various general, empirical models predicting phosphorus retention from lake hydrologic and morphometric characteristics. Retention models such as Kirchner and Dillon (1975), Ostrofsky (1978), and Reckhow (1979) predict retention coefficients for

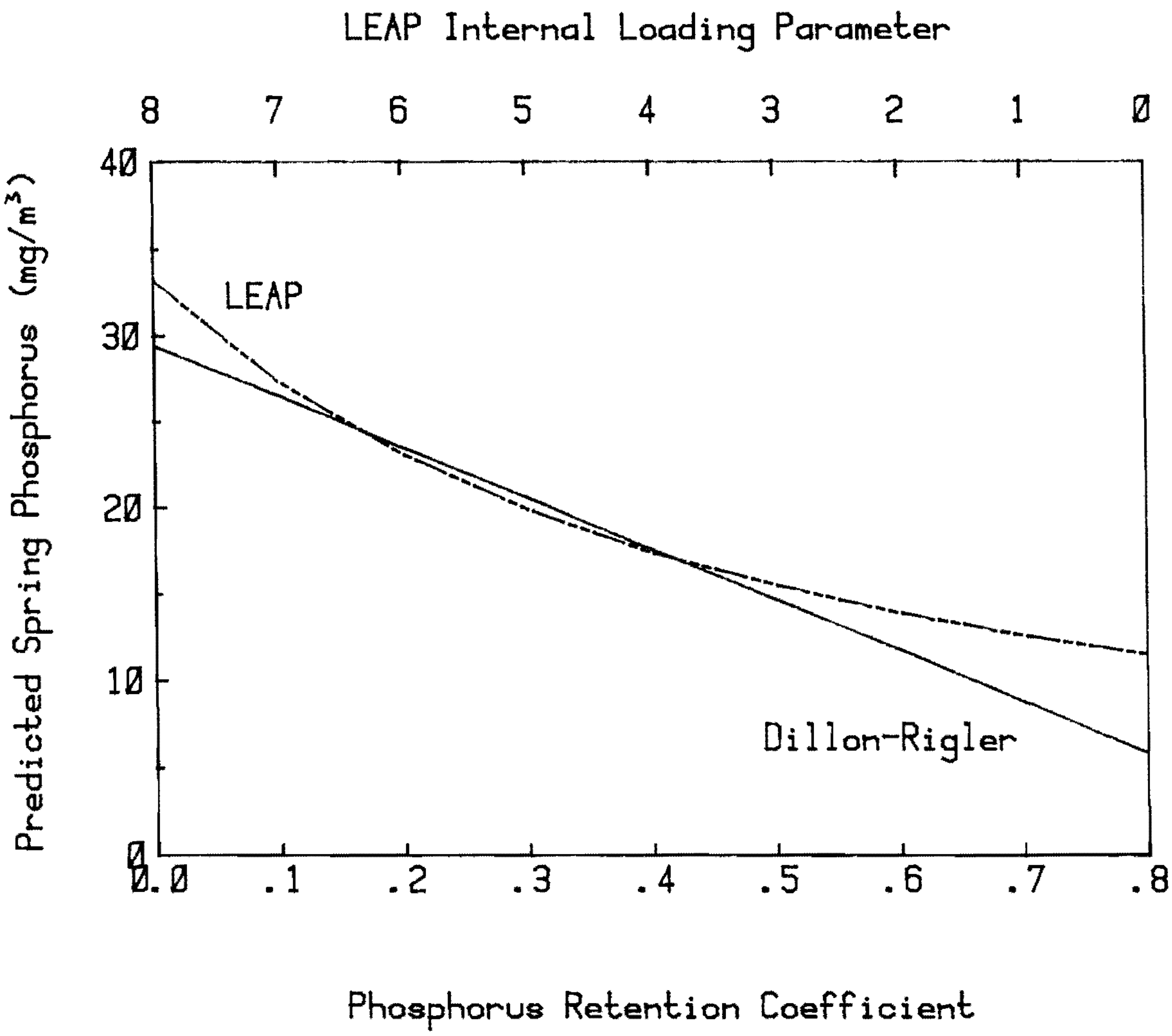

Figure 16. Predicted spring phosphorus concentrations in Lake Morey vs. the LEAP model internal loading parameter and the Dillon and Rigler (1974) model phosphorus retention coefficient.

Lake Morey in the range of 0.63-0.71, corresponding to predicted spring phosphorus concentrations (using equation 2) in the range of 9-11 mg/m^3. These retention models were generally not calibrated for lakes such as Lake Morey with extensive internal phosphorus recycling. The spring phosphorus model predictions of 9-11 mg/m^3 therefore represent conditions that would exist in Lake Morey if the lake had phosphorus sedimentation and retention characteristics typical of lakes less dominated by internal recycling.

The major conclusion to be drawn from Figure 16 and this modeling analysis is that phosphorus levels in Lake Morey should be highly sensitive to changes in internal phosphorus loading. Eliminating redox-related internal phosphorus recycling (simulated by reducing the LEAP internal loading parameter from 8.0 to 0) should reduce lake spring phosphorus concentrations from present levels down to about 12 mg/m^3. Establishing more "typical" phosphorus retention characteristics in Lake Morey (simulated by increasing the phosphorus retention term to 0.71) should also reduce lake phosphorus concentrations to the same extent. Significant reductions in lake phosphorus levels would also be expected even with only partial elimination of internal phosphorus loading.

As noted earlier, it was not possible to quantitatively predict the reduction in internal loading expected with either hypolimnetic aeration or alum treatment. Therefore, the model predictions illustrated in Figure 16 can only be used qualitatively to conclude that signficant declines in lake phosphorus levels would be expected from either treatment if internal phosphorus recycling were reduced. If the treatment reduced internal phosphorus recycling to levels typical of lakes without anoxic hypolimnia or other characteristics causing extensive phosphorus release from the sediments, then the decline in phosphorus concentrations in Lake Morey could be very dramatic.

Declines in phosphorus concentrations in Lake Morey would be accompanied by improvements in other related water quality factors. Algal levels, as indicated by chlorophyll concentrations, should decline and water transparency should improve. The calibrated LEAP model for Vermont lakes (Walker, 1982) was used to predict changes in chlorophyll concentrations and Secchi disc transparency resulting from reduced internal phosphorus loading, as illustrated in Figure 17. Figure 17 shows that the potential also exists for marked improvement in these factors if lake phosphorus levels were successfully reduced by hypolimnetic aeration or alum treatment.

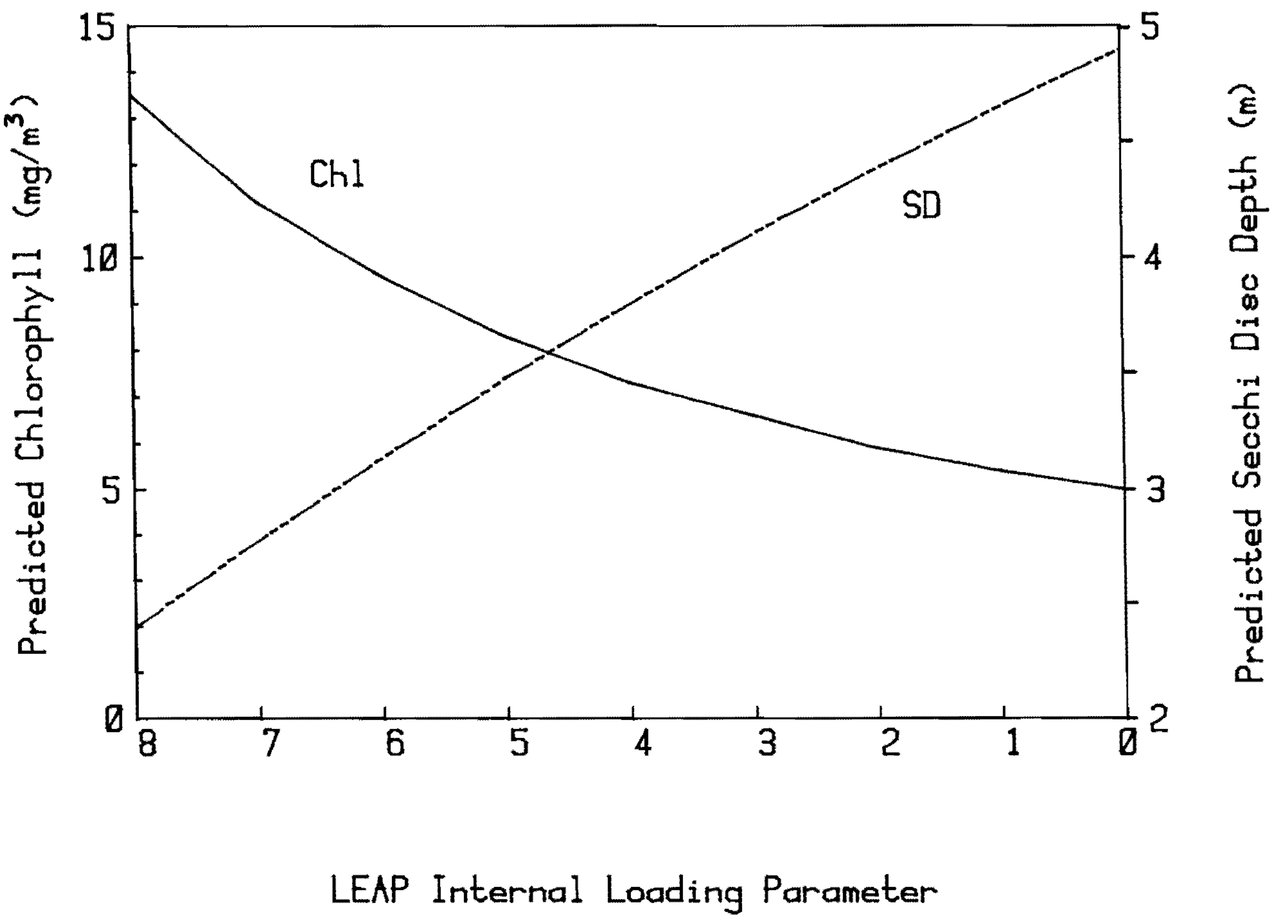

Figure 17. LEAP model predictions for chlorophyll concentration and Secchi disc transparency in Lake Morey vs. the LEAP model internal loading parameter.

SUMMARY AND CONCLUSIONS

Lake Morey is a highly valued recreational resource attracting and supporting such diverse uses as fishing, swimming, boating, residency in lakeshore homes, and commercial resort inns. These uses all depend on the maintenance of good water quality conditions in the lake. However, water quality problems related to lake eutrophication, such as excessive algae and aquatic plant growth, periodically interfere with these uses.

The diagnostic studies on Lake Morey were designed to determine the cause of the water quality problems by first evaluating the various sources of phosphorus to the lake. Phosphorus inputs from shoreline septic systems via groundwater were found to be very minor in significance. In spite of the large number of shoreline residences located on steep slopes with soils poorly suited for waste disposal, the phosphorus contribution from this source represented less than 1% of the total phosphorus input. Therefore, a proposed sewer system and wastewater treatment plant for Lake Morey would result in no significant lake-wide reduction in phosphorus loading or algal growth, and would be unjustified economically.

There remain, however, some good reasons for proper maintenance and improvement of existing shoreline septic systems. First, there are obvious public health concerns associated with failing systems. Violations of Vermont Water Quality Standards for fecal coliform bacteria have occurred in Lake Morey in the past, indicating the possible presence of disease-causing organisms that could infect swimmers and other lake users. A second reason for good septic system maintenance is that some of the aquatic plant growth in Lake Morey may be related to localized nutrient sources along the shoreline. A failing septic system could contribute excessive amounts of nutrients to the groundwater passing through the near-shore lake bed, and thereby nourish aquatic plant growth. Thus, while the shoreline septic systems at Lake Morey appear to have no significant impact on the lake-wide growth of algae, they may contribute to localized problems of aquatic plant growth in some areas.

Phosphorus concentrations in the tributary inflows to Lake Morey were generally found to be low and typical of predominantly forested, undeveloped watersheds. Overall, the water quality in the streams appeared to be little affected by human activities, although there were some possible problem areas identified for corrective measures. The modeling studies showed that if Lake Morey had phosphorus sedimentation and retention characteristics less dominated by internal phosphorus loading, then the phosphorus levels in the stream inflows would not be high enough to produce the water quality problems observed in the lake.

Transient phosphorus mass balances for Lake Morey performed by Walker (1983) indicated that phosphorus concentrations in the lake were controlled primarily by the processes of sedimentation and internal loading. The magnitude of this internal recycling was so great as to overwhelm the effects of external phosphorus loading from tributary, groundwater, and direct precipitation sources. The major period of internal phosphorus release was the summer stratification period, corresponding to conditions of hypolimnetic anoxia.

Walker (1983) discussed a number of factors that may contribute to the extensive internal phosphorus recycling in Lake Morey. First, the morphometric characteristics of lake Morey probably predispose the lake to hypolimnetic oxygen depletion and a large area of sediment subject to phosphorus release. Chemical conditions in the hypolimnion such as low oxygen and low iron concentrations appear to be very important factors in causing phosphorus release from the sediments. The low iron levels may be partially caused by excessive sulfate loading to the lake and the resulting precipitation of iron sulfide.

The historical and paleolimnological studies indicated that the algae problems in Lake Morey are related to a past period of pollution, the effects of which have since been perpetuated by internal phosphorus recycling. The major residential and commercial development of the lakeshore, which culminated around 1920, apparently caused significant water quality degradation in the lake. Water quality in the lake has improved since then, but has never recovered to pre-development levels, even with the revegetation of disturbed shoreland areas and the presumably better means of waste disposal that now exist. More recently, the construction of Interstate Highway 91 in the watershed has caused increased sulfate loading to the lake which, in turn, has apparently promoted internal phosphorus recycling and resulted in increased algal levels in recent years.

To summarize the diagnostic study results, it is clear that the algae problems in Lake Morey are caused by extensive internal phosphorus loading. The earlier period of lakeshore development apparently enriched the lake and its sediments with phosphorus and created conditions in which the phosphorus has been recycled internally ever since, thereby maintaining elevated lake phosphorus concentrations even in the absence of excessive subsequent loading from the watershed. These results indicate that lake restoration efforts for Lake Morey should be aimed primarily at controlling internal phosphorus loading.

Four alternative restoration techniques for controlling internal phosphorus loading in Lake Morey were compared as to their advantages, disadvantages, and costs. These alternatives included alum treatment, hypolimnetic aeration with compressed air, total destratification, and hypolimnetic aeration by pumped withdrawal. The alum treatment and the two hypolimnetic aeration alternatives were determined to be technically feasible. Both approaches had certain disadvantages, and neither was clearly superior from a purely technical standpoint. Alum treatment was the least expensive of the feasible alternatives since, unlike the other alternatives, it involved no annual operation and maintenance cost. After consideration of all technical and economic factors, the judgement was made that alum treatment would provide the best opportunity for long-term water quality benefits in Lake Morey.

A modeling analysis was conducted to evaluate the water quality improvements expected from control of internal phosphorus loading in Lake Morey. Although a quantitative prediction was not possible, the modeling results indicated the potential for dramatic improvements in water quality factors such as phosphorus, chlorophyll, and Secchi disc transparency in response to an alum treatment. Significant improvements in these factors would provide substantial benefits to lake users.

An ideal, comprehensive lake restoration program for Lake Morey would involve efforts in several areas. First, the control of lake-wide algae growth should be achieved by means of an alum treatment to reduce or eliminate internal phosphorus recycling. However, to insure that the inflowing water quality remains as high as possible, efforts to upgrade and maintain existing septic systems should continue. Systems serving the large resort inns and summer camps should be maintained with particular care. In addition to these efforts aimed at controlling phosphorus inputs and algal growth in the lake, a program of mechanical weed harvesting should be implemented for those areas of the lake where aquatic plant growth has reached nuisance proportions. This combination of efforts will provide the best chance for the successful restoration of Lake Morey.

TENTATIVE PROJECT BUDGET

A tentative budget for a Federal Clean Lakes Program Phase II Lake Restoration Project on Lake Morey is given in Table 25. Based on a total project cost of $400,000, the federal, state, and local requirements for cash, in-kind services, and indirect costs are shown in Table 26. This budget will be finalized prior to the submission of a completed application to the Region I office of the U.S. Environmental Protection Agency for a lake restoration project on Lake Morey.

Table 25. Tentative lake restoration project budget for Lake Morey.

Item	Cost
Alum treatment	$246,700.00
Aquatic plant harvesting	35,000.00
Supplies	5,000.00
Equipment	2,500.00
Temporary personnel	11,125.00
State full-time personnel	14,500.00
Travel	3,000.00
Lay Monitoring services	1,300.00
Citizens Advisory Committee services	1,000.00
*Indirect costs (cash)	9,000.00
*Indirect costs (non-cash)	70,406.00
TOTAL:	$399,531.00

*Indirect costs were computed at a rate of 25% of the sum of all other costs, exluding equipment.

Table 26. Federal, State, and local requirements for cash, in-kind services, and indirect costs, based on a $400,000 total project cost.

	Federal	State	Local
Cash	$200,000.00	$ 35,000.00	$ 42,700.00
In-Kind	0.00	14,500.00	37,300.00
Indirect (non-cash)	0.00	50,500.00	20,000.00
TOTAL:	$200,000.00	$100,000.00	$100,000.00

RECOMMENDATIONS

1. Internal phosphorus loading in Lake Morey should be controlled by means of an alum treatment of the deep lake sediments.

2. Planning for a sewer line and treatment plant serving the Lake Morey shoreline should be discontinued, as there would be minimal water quality benefits from such a system.

3. Efforts should be made to properly construct and maintain all shoreline septic systems.

4. The aquatic plant problem in Lake Morey should be controlled by mechanical harvesting.

5. Federal, State, and local governments should plan for funding of a lake restoration project on Lake Morey, based on the cost figures given in the tentative project budget.

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APPENDIX

Lead-210 analysis of Morey Lake sediment

by

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Supported by a contract

from the

Department of Water Resources

and

Environmental Engineering

State of Vermont

Introduction

Lead-210 analysis is one method of determining sedimentation rates in lakes (Krishnaswami et al. 1971). Lead-210 is a naturally occuring radionuclide produced from the decay of atmospheric radon-222 which in turn is produced by the radium-226 that is present in the earth's crust. Lead-210 is a useful dating tool because it accumulates in lake sediment and decays there (half life is 22 yrs.).

The decay of lead-210 in the sediment forms the basis of the dating method. If lead-210 arrives at the top of an accumulating sediment column at a constant rate and if the sediment is accumulating at a constant rate the activity of atmospherically derived lead-210 should decline exponentially with increasing depth in the sediment. The steepness of the decline should vary with the sedimentation rate. The relationship between lead-210 activity and depth is expressed by equation 1.

1) $$A_z = A_o e^{-(\lambda/s)z}$$

Where: Az = activity at depth z

A_o = activity at depth 0

λ = the decay rate of PB-210 (0330)

z = depth

s = sedimentation rate (cm/yr)

A simple method of determining the sedimentation rate of a lake using this equation is to fit experimentally determined points to the logarithmic version of equation 1(shown in equation 2).

2) $$\ln A_z = \ln A_o - (\lambda/s)z$$

This method of analysis was first employed by Krishnaswami et al. (1971) and has been termed the constant initial concentration or c.i.c. method.

Unfortunately, many lakes do not have sedimentation rates that are constant enough to fulfill the assumptions of the c.i.c. model. Appleby and Oldfield (1978) have proposed an alternative model termed the "constant rate of supply" (c.r.s.) model. This model assumes that influxes of lead-210 to the sediment are constant. Sedimentation rates may vary widely without affecting the c.r.s. model. In this model the standing stock of atmospherically derived lead-210 is assumed to have been constant throughout time. Thus the standing stock of lead-210 beneath any depth lamina in the sediment was equal to the present day standing stock when that depth lamina was at the sediment surface. This initial standing stock of lead-210 decays away with time. The decay can be modeled using equation 3.

3) $$SS_z = SS_o e^{-\lambda t}$$

Where: SS_z = the standing stock of lead-210 below depth z

SS_o = the total standing stock of lead-210

t = the age of depth z

For the c.r.s. method to work the sediment column must be sampled without gaps.

Both models of lead-210 accumulation were applied to a core from Morey's lake near Fairlee, Vermont.

Methods

A sediment core was taken from Morey's lake by a diver employed by the Vermont Department of Water Resources. The 80-cm core was sample by the Department at 1 cm intervals. For lead-210 analysis equal volume subsamples were made from each centimeter and were combined over 4 cm intervals and homogenized. These subsamples were packed in plastic bags and sent to Edwardsville, IL for analysis.

Lead-210 analysis followed the Bismuth ingrowth technique of Kharkar *et al*. (1976). Five milliliter subsamples of the material sent to me were dried at 105°C and ashed at 450°C. A known quantity of lead-210-free lead nitrate was added to the ashed sample as a carrier. The ashed sample was leached overnight in 6N HCl and lead was removed from the leachate by ion exchange. The lead was deposited as lead chromate on planchettes. Each planchette was covered with a 1 mil Mylar film to prevent spurious counts of less energetic nuclides than bismuth-210. The planchette was stored for 1 week to allow the decay of short-lived radionuclides. Beta emissions from bismuth-210 were counted using a Beckmann-Sharp Low Beta II anti-coincidence beta proportional counter. Each sample was counted twice over a period of a month for at least 500 minutes each time. The preparation and counting technique is designed to follow the appearance of bismuth-210, a daughter of lead-210, as the separated lead ages.

Results

Figure 1 shows the data graphed as the natural log of lead-210 activity versus the depth in the Morey lake core. Table 1 shows the raw data in the first column.

To calculate sedimentation rates using either the c.i.c. or the c.r.s. methods it is first necessary to separate the atmospherically derived lead-210 from that which is formed in the sediment from radium-226 present there (supported lead-210). To determine supported lead-210 activities for sediment layers below 48 cm were averaged. The 48 cm level was chosen because figure 1 shows that this is the level at which atmospherically derived lead-210 has decayed away.

Application of the c.i.c. method to the data presented in figure 1 proved difficult because of the lack of a constant sedimentation rate. When all lead-210 activities above 48 cm were used to establish a regression line, the data proved to fit the line rather poorly. Equation 4 presents the regression line.

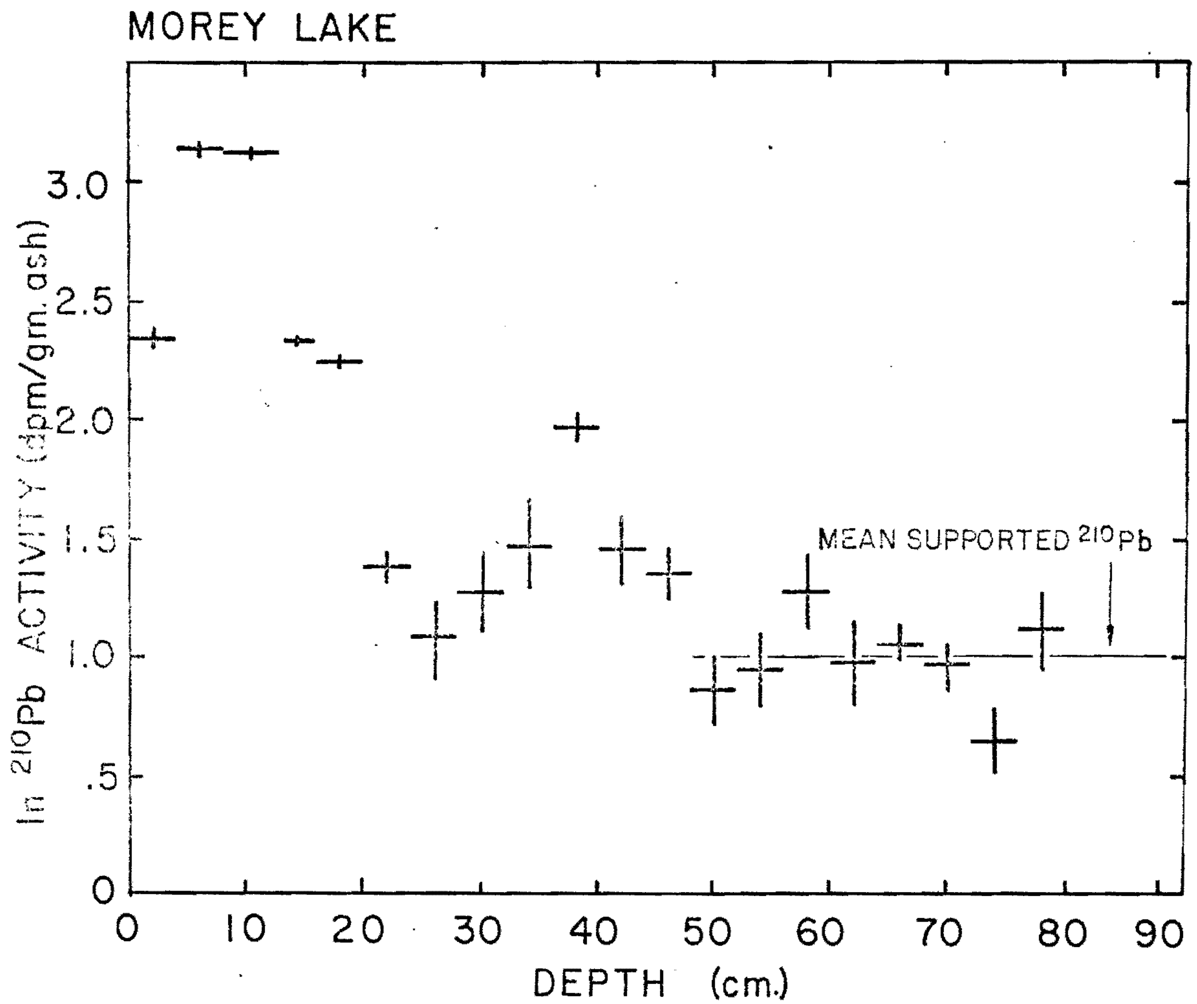


Figure 1: Variation of lead-210 activity with depth in the Morey Lake core

4) $\ln A_z = 2.62 - .061z$

$r = -.66$

This equation implies a sedimentation rate of .54 cm/yr and an age at 48 cm of 88 years. This figure is suspect because of the widé variance in lead-210 activities.

Table 1 and Figure 2 present the results of the c.r.s. method. Table 1 shows the calculations made for the c.r.s. method. The last column shows the dates of sedimentation of the bottoms of each 4 cm interval of the core. Figure 2 shows the depth versus the age curve for the core.

It is apparent that sedimentation rates have varied widely over the last 126 years of the lake's history. Between 1917 and 1922 there was a period of particularly rapid sedimentation that resulted in the deposition of the core interval from 32 to 21 cm. Also from 1971 on sediment accumulation rates have been higher than in the past.

Discussion

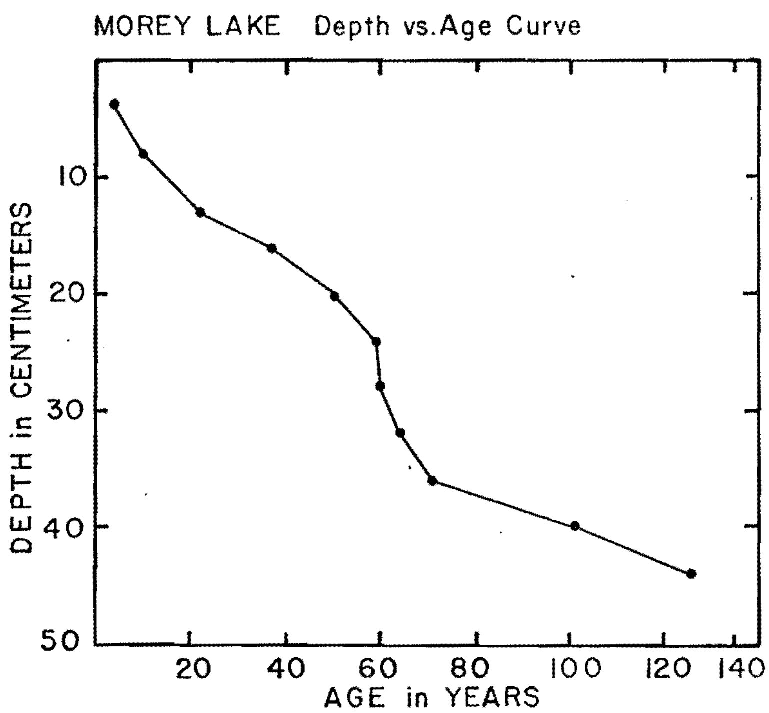
It would be valuable to relate changes in sediment accumulation rates to land-use around Morey's lake but such a comparison is not possible with the historical data presently available. For example, the greatly increased sediment accumulation rate between 1916 and 1922 does not seem to be related to any human activity in the lake watershed. It may be that the construction of the Bonnie Oaks Hotel added enough sediment to the lake to increase sedimentation at the core site, but it is doubtful that such construction would have caused enough landscape disturbance to produce a 10 cm layer of inorganic sediment. The gravel pits on the west shore of the lake might be a good source of this added sediment, but the dates of their development do not coincide with the time of increased sedimentation in the core.

Table 1: Morey Lake c.r.s. model data

MOREY LAKE PB210 DATA

DEPTH	ACTIVITY DPM/GMASH	UNSUPTED ACTIVITY DPM/GMASH	ASH WGT GM.	UNSUPTED ACTIVITY DPM/CM3	UNSUPTED ACTIVITY PER LENGT	CUMULATIV SUMS SSz 26.790
1-4	10.302	7.576	.5637	.854	3.416	23.373
5-8	22.874	20.148	.2471	.995	3.982	19.390
9-13	23.904	21.178	.3871	1.630	8.198	11.192
14-16	10.868	8.142	.7009	1.140	3.424	7.768
17-20	9.402	6.676	.5170	.690	2.761	5.007
21-24	3.979	1.253	1.2405	.310	1.243	3.763
25-28	2.95	.224	.7309	.032	.131	3.632
29-32	3.827	1.101	.5787	.127	.509	3.122
33-36	4.315	1.589	.6116	.194	.777	2.349
37-40	7.338	4.612	.3879	.357	1.431	.913
41-44	4.286	1.560	.4082	.127	.509	.404
45-48	3.938	1.212	.4167	.101	.404	0
49-52	2.390			TOTAL SSo 26.790		
53-56	2.596					
57-60	3.647					
61-64	2.684					
65-68	2.904					
69-72	2.624					
73-76	1.903					
77-80	3.058		END OF	SUPPORTED PB210		
AVERAGE	2.725					

DEPTH	FRACT. OF STAND. STOCK	LN FRACT. STAND. STOCK	AGE AT BOTTOM OF INTERV	DATE OF CORE LEVEL
1-4	.872	-.13	-4.13	1977
5-8	.723	-.32	-9.79	1972
9-13	.417	-.87	-26.45	1955
14-16	.289	-1.23	-37.51	1944
17-20	.186	-1.67	-50.82	1931
21-24	.140	-1.96	-59.48	1922
25-28	.135	-1.99	-60.55	1921
29-32	.116	-2.14	-65.13	1916
33-36	.087	-2.43	-73.81	1908
37-40	.034	-3.37	-102.38	1879
41-44	.015	-4.19	-127.09	1854
45-48	0			



MOREY LAKE Depth vs. Age Curve
DEPTH in CENTIMETERS
10
20
30
40
50
20
40
60
80
100
120
140
AGE in YEARS

Figure 2

The increase in sediment accumulation after 1971 seems to be related to the construction of the interstate highway along the northeast edge of the watershed. I suspect that this disturbed drainage patterns and resulted in the regrading of parts of the watershed.

In summary, it appears that sediment accumulation rates at Morey's lake have been chaotic in the past. It is, however, difficult to assign specific causes to changes in sediment accumulation rates.

Literature Cited

Appleby, P.G., and F. Oldfield. 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 5:1-8

Kharkar, D.P., J. Thomson, K.K. Turedian, and W.O. Forster. 1976. Uranium and thorium in decay series nuclides in plankton from the Caribbean. Limnology and Oceanography 21: 296-301

Krishnaswami, S., D. Lal, J. Martin, and M. Meybeck. 1971 Geochronology of lake sediments. Earth and PLanetary Science Letters 11: 407-414

ALLEGHENY COLLEGE
Meadville, Pennsylvania 16335

June 21, 1983

Ms. Virginia Garrison
Aquatic Biologist
Vermont Department of Water Resources
Agency of Environmental Conservation
Montpelier, Vermont
05602

Dear Ms. Garrison;

In your letter of May 23 you asked me to comment on a variety of topics from the Lake Morey study. I have examined all the data which I have been sent and my comments are outlined below. Where appropriate I have explained my thinking in developing an argument. If you see any lapses in logic, let me know.

Basic Water Quality Parameters

At the beginning of the project I recommended periodic analysis of basic water quality parameters. At the time, I had no specific reason for doing so except that these measurements might be useful at a later date and that the time and cost involved in sampling and analysis would be negligible. If for some reason you needed one of these parameters after the Lake Morey study was complete, it would be impossible to obtain. The data on basic water quality parameters has proven invaluable - often in ways which could not have been forseen. Consider the following examples:

1) The phosphorus-chlorophyll relationship of Dillon and Rigler only applies to lakes where the spring N:P ratio is greater than 12. You have the necessary nitrogen data to determine if this is the case. If the N:P ratio is less than 12, then algal biomass will not respond readily to a reduction in phosphorus loading. Since this will probably be one of your recommendations, you don't need any surprises.

2) Since the Lake Morey study began, the Dillon and Rigler phosphorus-chlorophyll model has been improved (Smith, 1982 Limnol. Oceanogr. 27:1101) to give better predictions. This revised model requires nitrogen data. You now have it.

3) The hypothesis that relatively high sulfate loading may interfere with the phosphorus cycle could not have been advanced or tested without the sulfur or iron data.

4) Based on your experience at Harvey's Lake you can make some inferences about the possibility of silicon limitation of diatoms at Lake Morey now that you have silica data.

The data base may be of further use in the future as you try to understand the cycling of nutrients in Lake Morey, and predict changes under a scenario of reduced phosphorus loading.

Sulfur/Iron Interference with the Phosphorus Cycle

Hutchinson (1957) suggests that in lakes where a "considerable" amount of H_2S is formed in the hypolimnion some FeS may precipitate. This may remove enough iron so that after autumnal circulation, there is not enough iron available to precipitate the hypolimnetic phosphorus. This would probably result in the persistence in the surface waters of dissolved phosphorus of hypolimnetic origin. While this scenario appears to be possible, I was able to find no evidence for its occurrence. Hutchinson's comment is based on Hasler and Einsele (1948. Fertilization for increasing productivity of natural inland waters. Trans. N. Amer. Wildl. Conf. 13:527-555). Our library does not get this journal, nor does any nearby library. I suspect that UVM library does not have it either. I won't have time to get this on interlibrary loan so I cannot be sure precisely what the argument is. I have pieced together a probable argument based on a couple of citations in Hutchinson. Hasler and Einsele suggest that lake fertility may be increased by interrupting the iron cycle, either by adding sulfate and relying on the above described scenario, or by adding oxidized manganese. Hutchinson implies that these are both theoretical arguments and probably no data exist to support either strategy. If you are able to get a copy of Hasler and Einsele you can easily verify this.

I am reluctant to accept this as a major factor influencing the availability of phosphorus for a number of reasons. Hutchinson suggests that a "considerable" amount of H_2S needs to be formed. Although he does not quantify what amount is necessary, I don't think there is that much in Lake Morey. Although the sulfate concentrations you report (around 20 mg/l) are relatively high for lakes in crystalline basins, lakes in sedimentary or metamorphic basins often have far higher concentrations. Considering that many lakes have as much or more sulfur than does Lake Morey, if FeS could interfere appreciably with the availability of phosphorus it certainly would have been looked at by now.

Any research dealing with how the abundance of sulfur could interfere with phosphorus would have most certainly make use of the original paper by Hasler and Einsele. I checked the Science Citation Index from 1976 to 1983 (earlier issues are unavailable here). During this interval, Hasler and Einsele had only been cited three times. Two of these citations (Bachman, 1980. J.W.P.C.F. 52:2425, and Hepher, 1978 in:Gerking (Ed.) Ecology for Freshwater Fish Production. Wiley, N.Y.) only made reference to the observed fact that artificial fertilization can potentially increase fish yield. The third, and most promising citation was not available for my examination (Banoub, M.W. 1977. Experimental investigation on release of phosphorus in relation to iron in freshwater mud system. In: H.L. Golterman (Ed.) Interactions between sediments and freshwater. Proceedings of an international symposium, Amsterdam, Netherlands. Sept. 6-10, 1976. Published by Dr. W. Junk, Hague, Netherlands). If you can get a copy it may contain some useful information for you.

It is quite likely, however, that no one has documented the phenomenon. It would appear that although there may be H_2S generated in the Lake Morey hypolimnion, your results indicate that there is also an abundance of iron (in excess of 300 ug/l) most of which is dissolved, i.e. ferrous iron, up until the date of fall turnover. This is enough iron to precipitate the hypolimnetic phosphorus present. In order to support the Hasler and Einsele hypothesis, I think you would have to document a simultaneous decrease in Fe and H_2S which would indicate precipitation of FeS. You do not have the data on H_2S (at least not in what you have sent to me) and your Fe data goes contrary to the hypothesis.

I guess the reason I'm not too excited about the sulfur angle is that I don't believe that coprecipitation with iron is a significant return mechanism to get phosphorus back to the sediments. Most phosphorus is sedimented as particulate organic material. Rigler has suggested that about 2% of all epilimnetic phosphorus is sedimented daily. This is replaced by new phosphorus added by surface discharges, precipitation, etc. Nevertheless, Rigler suggests that there should be a continuing and gradual decrease in epilimnetic phosphorus with time. This appears to be the case in Lake Morey. In May, 1982, the phosphorus concentration in the epilimnion is around 30 ug/l and throughout the summer it gradually declines to about 12 ug/l just prior to turnover in October. If you wish to calculate the sedimentation rate, you may easily do so using your stream discharge data, stream phosphorus concentrations and lake phosphorus concentration. Hypolimnetic phosphorus which is brought into the epilimnion at times of turnover is rapidly taken up biologically and supports the spring and fall proliferation af algae (see your Lake Morey chlorophyll data) rather than being immediately precipitated with iron. I don't think interrupting the iron cycle will have much of an effect on the availability of phosphorus.

One more point before leaving this issue. For the moment, assume that the Hasler and Einsele hypothesis is correct. In order for there to be appreciable amounts of H_2S there must be significant quantities of sulfur-containing organic matter available to be decomposed anaerobically. The amount of sulfate is irrelevant. In fact, due to the small biological demand for sulfur, sulfate acts very conservatively in most all lakes. That is, most sulfate delivered to Lake Morey washes out the discharge unused. Assuming that the lake is phosphorus limited, the amount of sulfur-containing organic matter is a function of the amount of phosphorus. If phosphorus input is reduced, then less H_2S can be produced as a result, lessening any effect that FeS may have on the phosphorus cycle.

Internal Phosphorus Loading

As you know, I don't think Mortimer's model for phosphorus release is as important as the literature suggests. I will admit that my doubts are based on very limited data: two lakes here in Pennsylvania on which I have worked, and a lake in ELA on which Schindler and Lean have worked. However, all other lake studies do not necessarily support Mortimer, rather there is inadequate data on which to base a counter argument.

Mortimer's model suggests that under oxygenated conditions iron, phosphorus and other elements are oxidized and form insoluble complexes. This resulting chemical precipitate sediments out of the water and is incorporated in the sediments. Here all elements are immobile. However, if the water overlying the sediments becomes anoxic then the component elements are reduced, become soluble once again and are released into the overlying water. From this proposed sequence of events one can construct a couple of hypotheses which may be tested with field data.

1) Mortimer's hypothesis predicts that there should be increasing concentrations of phosphorus in the anoxic hypolimnion of a lake. There should be no increase in phosphorus concentration prior to complete anoxia.

2) The increase in total phosphorus in the anoxic hypolimnion is due to the release of PO_4 bound to ferric iron. The increase in hypolimnetic phosphorus is therefore due to an increase in soluble phosphorus.

To test the first hypothesis I determined the volume of water in each stratum of Lake Morey from the information given on the bathymetric map (Vermont Department of Water Resources, Revised February 1973). In case you do not have this information I have included it as Table 1. Having the volume of each stratum, I multiplied by the total phosphorus concentration at each stratum. The product is the mass of phosphorus. At this point I arbitrarily defined the hpyolimnion as that volume of the lake below 8 meters in depth. This was based on the time-depth isopleths for dissolved oxygen for 1981 and 1982. I calculated the mass of hypolimnetic phosphorus by summing the masses of phosphorus from all strata greater than 8 meters in depth, and graphed the mass as a function of time.

When I did this for the summer of 1982 data (see Figure 1) the hypolimnetic phosphorus mass was more or less constant from May 3 to June 11. The dissolved oxygen data indicated that the hypolimnion was oxidizing during this interval. From June 18 to October 8 there is an abrupt increase in the hypolimnetic phosphorus mass. This interval corresponds to anoxia in the hypolimnion. This supports the first hypothesis.

I decided to look at the winter data. I did the same calculations for data collected from January 7, 1982 to April 1. I excluded the April 15 data since the phosphorus measurement at 12 meters is obviously in error; probably the kemmerer tripped on the way up or down and sampled at some intermediate depth - the dissolved oxygen value supports this probability. In this case there is a continual increase of hypolimnetic phosphorus mass even though anoxia was not observed until April 1 (see Figure 2). The winter data do not support Mortimer's hypothesis.

For the second hypothesis I compared your data for total phosphorus and for total dissolved phosphorus in the hypolimnion. For the summer data set, about half of the hypolimnetic phosphorus is dissolved - and by difference, the remaining half is particulate. For the winter data set, almost all of the hypolimnetic phosphorus is in the dissolved form.

The results of this analysis are certainly inconclusive. It would seem that in the winter, soluble phosphorus is increasing in the hypolimnion long before anoxia is reached. This contradicts both Mortimer's hypothesis and mine which is based on sediment focusing. In the summer, however, there is no apparent phosphorus buildup until anoxia is reached, and half of this increase is particulate - which implies sedimenting particles, rapid biological uptake near the sediment/water interface, or some other mechanism. The first possibility is unlikely - why would sedimenting particles wait for anoxia before allowing gravity to work? The second possibility is not supported by my Pennsylvania lake data although this does not preclude the possibility that Lake Morey behaves differently. In the end, we have learned little from the above approach except that Mortimer's model may work some of the time, but probably not.

An alternate approach, which I cannot try since I don't have all of the data, would be to construct a mass balance model for very short time intervals (i.e. the length of time between samplings). For example, you can easily calculate the mass of phosphorus in the lake for any date for which you have data. Somewhere in your files you also have stream phosphorus, stream discharge, loading from bulk precipitation, groundwater discharge and phosphorus concentration, and outflow volume and phosphorus concentration. From these observations you can construct a phosphorus budget from one sampling date to the next. Any difference between predicted and observed phosphorus mass will be due to sedimentation, of sediment return, depending on whether you must account for a phosphorus surplus or deficit. For example, several years ago Mitchell and I were looking at sediment as a source of phosphorus in a reservoir. Data for one time interval are as follows:

lake phosphorus mass (March 31, 1980)	188.3 kg
from March 31 to April 17:	
loading from stream discharge	146.8 kg
bulk precipitation	none recorded
groundwater	negligible
loss via discharge	311.6 kg
predicted mass for April 17	23.5 kg
observed phosphorus mass, April 17	158.9 kg
phosphorus return from sediments	135.4 kg

In this manner you can construct a graph of sediment contribution vs. time. I suspect you will find that the overwhelming process is sedimentation except during turnover, when some sedimented material may be resuspended, and perhaps some real sediment return during periods of anoxia. This may seem obvious after considering the buildup of phosphorus in the hypolimnion in both summer and winter, but keep in mind that this often can be balanced by losses from the epilimnion (particulate hypothesis). Another thing to keep in mind is that the weakest link in the calculation will be the groundwater/septic contribution. This was the acknowledged weak spot from the beginning of the study. Presumably, if you were able to get a reliable measure of phosphorus loading from septic systems then the remainder of the analysis was incidental.

So there you have it. If anything seems vague, let me know. Although the study is over, I would be interested in seeing the results of your calculations, and in getting a copy of the final report. If you have anything to add to the story on sulfur or internal loading, I woukd be interested in that, too.

Sincerely,

Milton L. Ostrofsky

Milton L. Ostrofsky
(Biology Department)

Table 1: Volume calculations for Lake Morey, Vermont

Contour interval in meters	Volume of 1 meter thick stratum
0	198 x 10^4 m^3
1	185 "
2	175.5 "
3	168.5 "
4	161 "
5	154 "
6	146.5 "
7	136.5 "
8	124.5 "
9	109 "
10	80.5 "
11	45 "
12	15.5 "
13	0 "
	1699.5 x 10^4 m^3

Figure 1: Mass of Hypolimnetic Phosphorus in Lake Morey

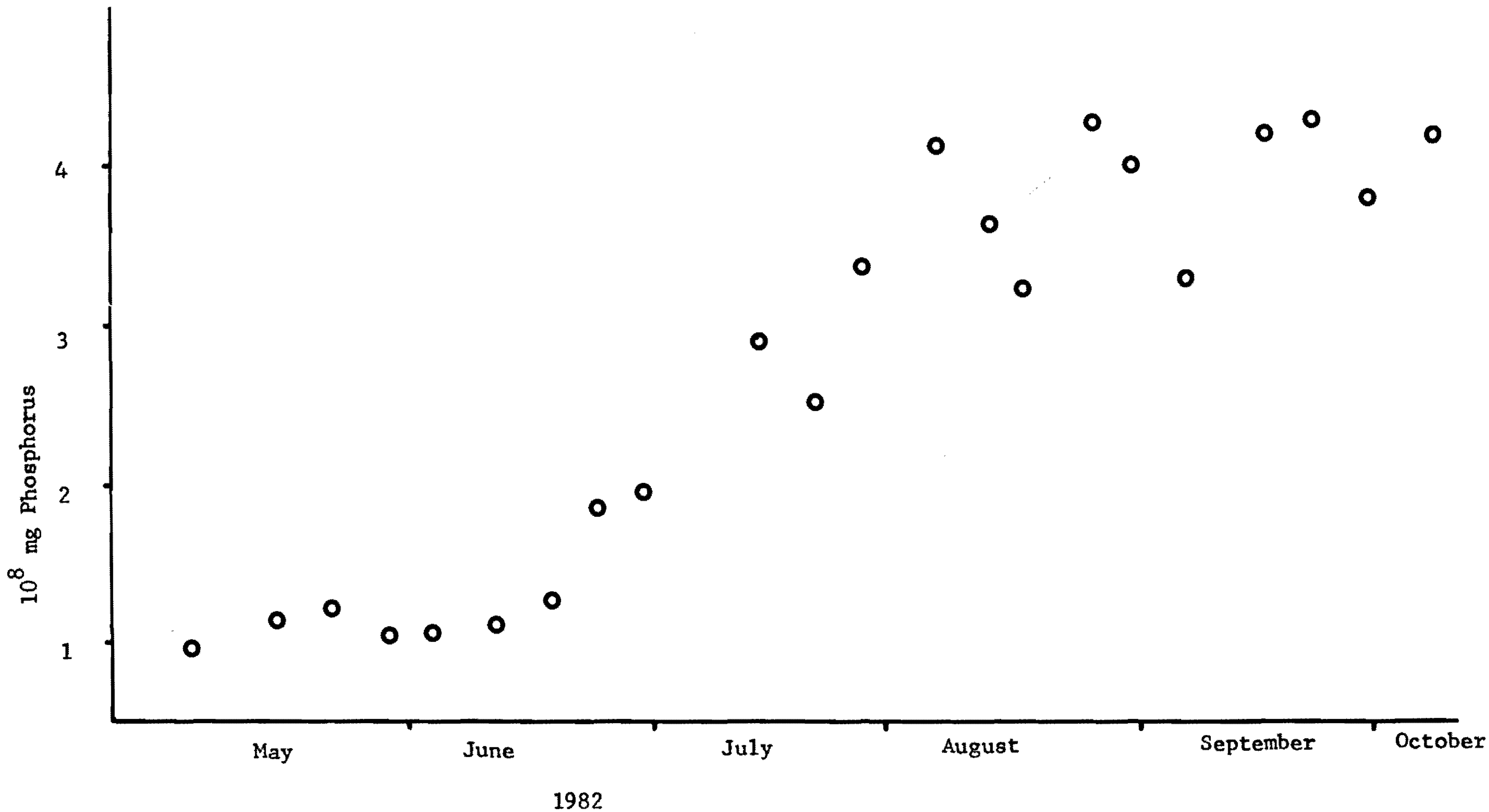
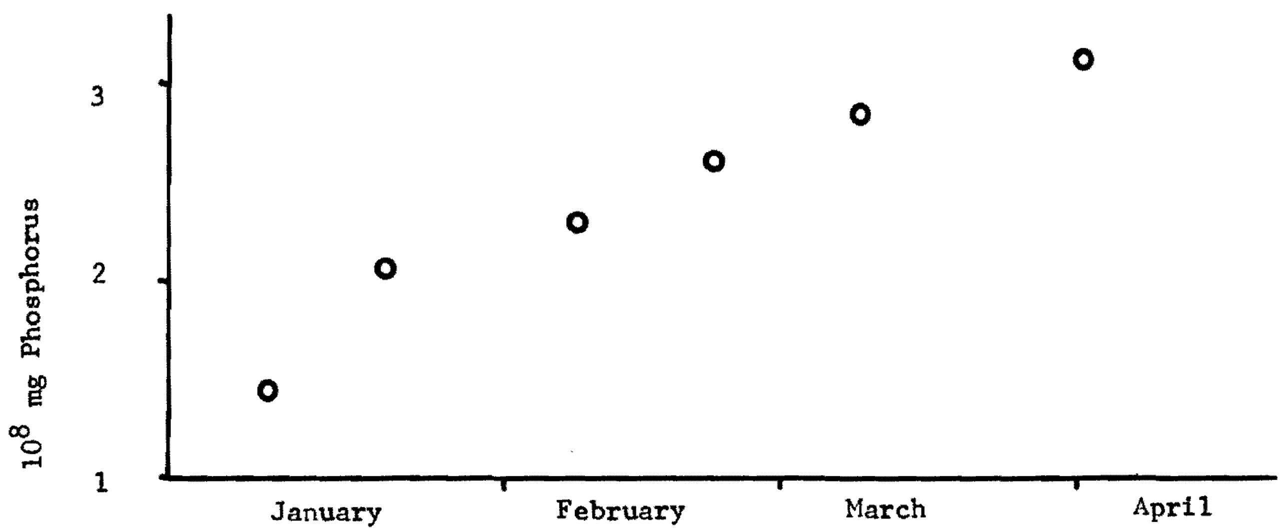


Figure 2: Mass of Hypolimnetic Phosphorus in Lake Morey



State of Vermont

AGENCY OF ENVIRONMENTAL CONSERVATION

Montpelier, Vermont 05602
Department of Water Resources
and
Environmental Engineering

Department of Fish and Game
Department of Forests, Parks, and Recreation
Department of Water Resources & Environmental Engineering
Natural Resources Conservation Council

M E M O R A N D U M

TO: Eric Smeltzer, Aquatic Biologist

FROM: Robert B. Finucane, P.E., Facilities Engineer

SUBJECT: Lake Morey Feasibility Study of Hypolimnetic Aeration Alternatives

DATE: February 28, 1984

As discussed, I have reviewed the Booker Report and considered some of the alternatives to full-lift and partial-lift hypolimnetic aeration which were mentioned in the report. Based on a study of the report and of literature available here and at UVM, I evaluated the shore-based mechanical agitation system and the downflow-air injection system. I found that the mechanical agitation system, contrary to my initial impression, is without merit for this application. I find the downflow-air injection system on shore would have costs about the same as the full-lift system.

Mechanical Agitation

The mechanical agitation scheme involves pumping water from the hypolimnion to a trickling filter or waterfall-type aerator located on shore and piping the return back to the bottom of the lake.

This approach is not a good one for several reasons. Because the oxygen transfer occurs at atmospheric pressure, rather than at the pressures available at the bottom of the lake, transfer efficiencies are low. The full-lift flow rates have to be used or exceeded. A D.O. target level above 2 mg/l could not be achieved by these methods and consequently, a cold water fishery is not possible with this approach.

Friction losses are incurred by the long intake and outfall lines. However, short-circuiting of aerated water would be reduced by separating the intake and outfall under such a scheme.

These friction losses in the 1,800' long intake and outfall lines, added to the headloss thru aerators of these types, plus the energy required to lift the water to a treatment plant location above the lake level increase the pump horsepower and operating costs for this type of treatment to an amount in excess of the full-lift aerator system proposed.

Further, this system would require at least 1,000 square feet of lakefront and would probably prove fatal to any fish that were entrained in the flow.

Costs would be as listed below (all costs discussed in this paper are for the full 2,130 Kg 02/day):

Piping off-shore	$ 220,000
Treatment plant	$ 40,000
Pumps and controls	$ 20,000
Building	$ 10,000
3-Phase power	$ 25,000
Subtotal	$ 315,000
Contingency - 20%	$ 65,000
Total	$ 380,000

180 day annual operating cost $ 35,000

<u>Downflow-Air Injection</u>

Downflow-air injection is a system which seeks to take advantage of both the better efficiency of mechanical pumping over air pumping and the better efficiency of lake-bottom gas transfer over atmospheric-pressure gas transfer.

In a shore-based U-Tube installation, the water would be pumped to the treatment area which includes a 10' x 10' hole 40' deep with a partition which forces the flow down one side and up the other. Air is added to the downflowing side in bubbles which are swept downward and underneath the partition by the flowing water (Figure 1). The air bubbles come out on the downstream side of the partition and the treated water returns by gravity flow to the lake.

The headloss from one side of the partition to the other is slight. Compressor requirements are reduced because the air is added at surface level. But gas transfer continues 40' underwater.

This treatment is quiet compared to the full-lift system. No fish kills would be expected. Only a small shoreside area would be required. Reduced flow rates would be used in view of no short circuiting and efficient gas transfer.

Costs for this system would be as listed below:

Piping off-shore	$ 110,000
U-Tube	$ 60,000
Pump and compressor	$ 15,000
Building	$ 10,000
Power	$ 25,000
Subtotal	$ 220,000
Contingencies	$ 50,000
Total	$ 270,000

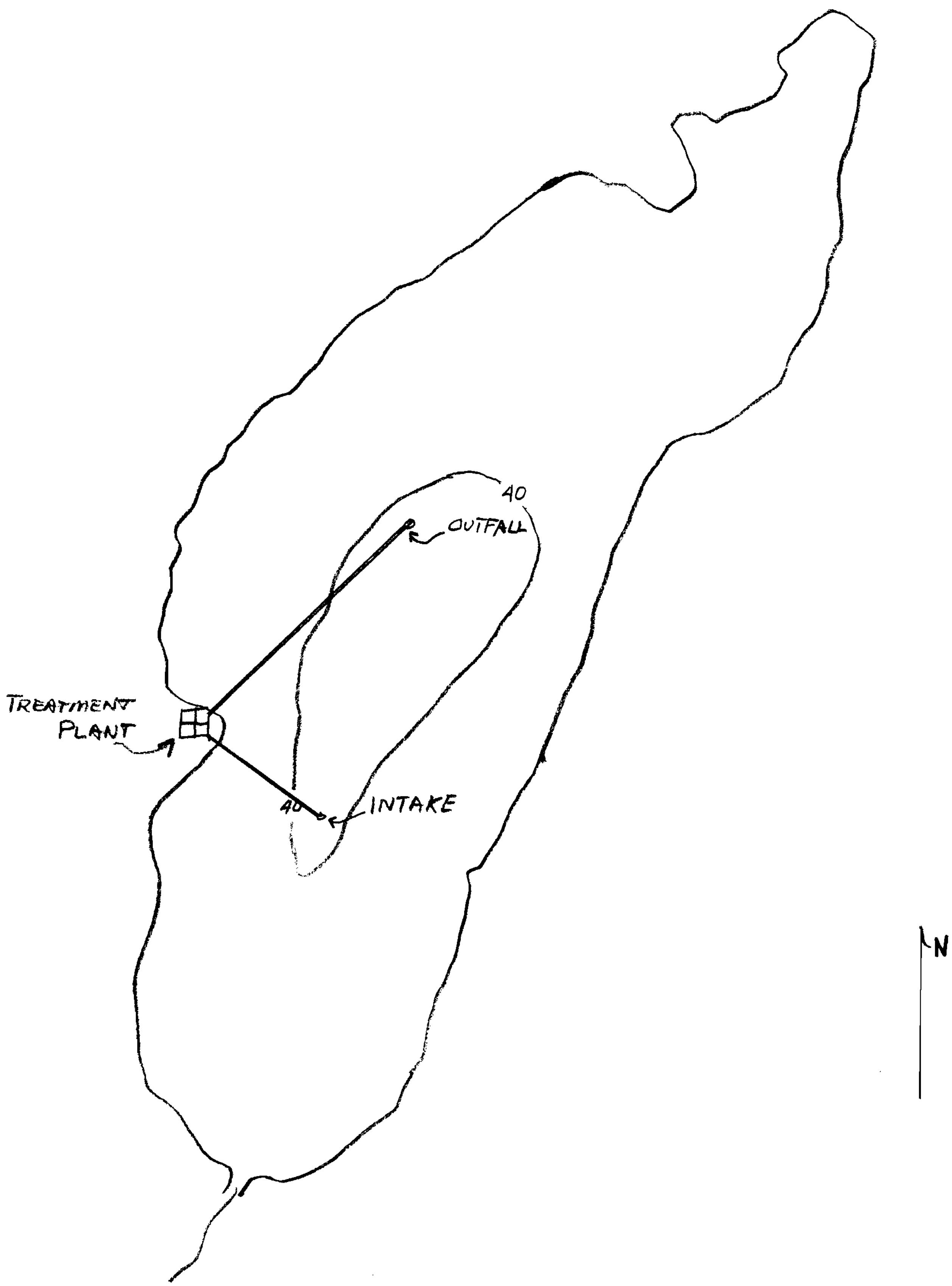
180 day annual operating cost $20,000

RBF:arm
CC: Reginald A. LaRosa, Chief of Operations

BY RLF DATE 2/27/84 SUBJECT LAKE MOREY SHEET NO. ...... OF ......

CHKD. BY ...... DATE ...... HYPOLIMNETIC AERATION JOB NO. ......

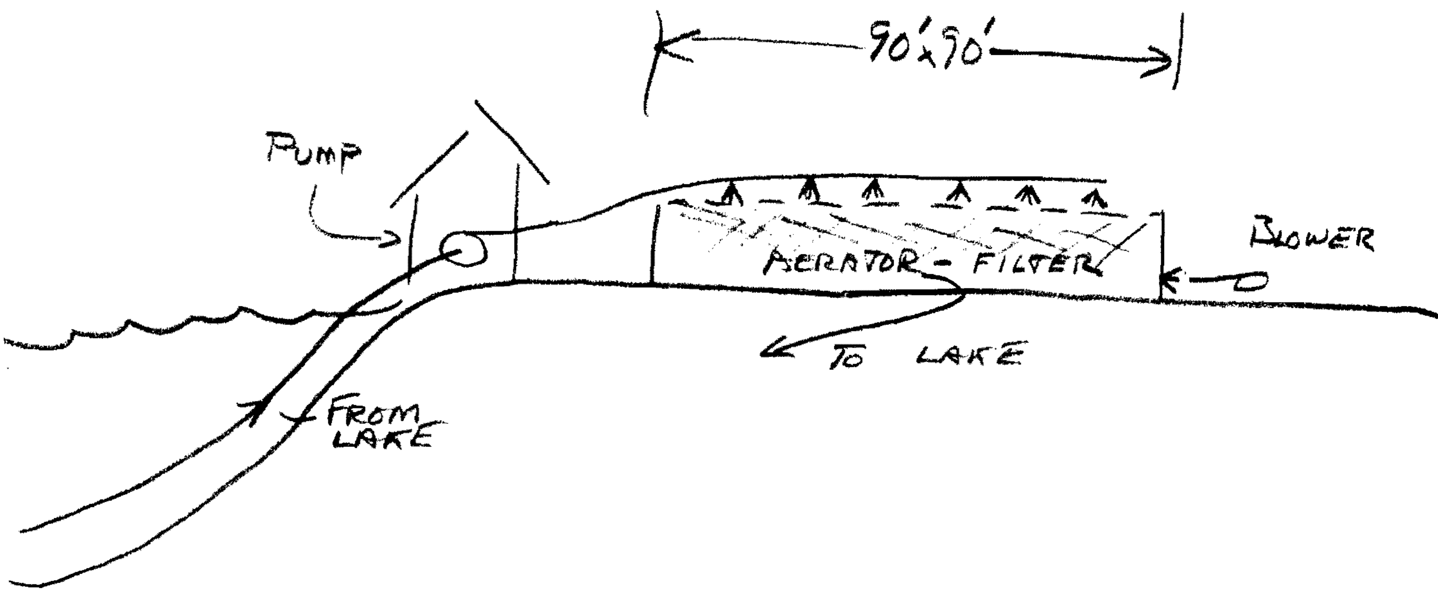
ON-SHORE TREATMENTS



BY P.L.F. DATE 2/27/84 SUBJECT LAKE MOREY SHEET NO. ...... OF ......

CHKD. BY ...... DATE ...... HYPOLIMNETIC AERATION JOB NO. ......

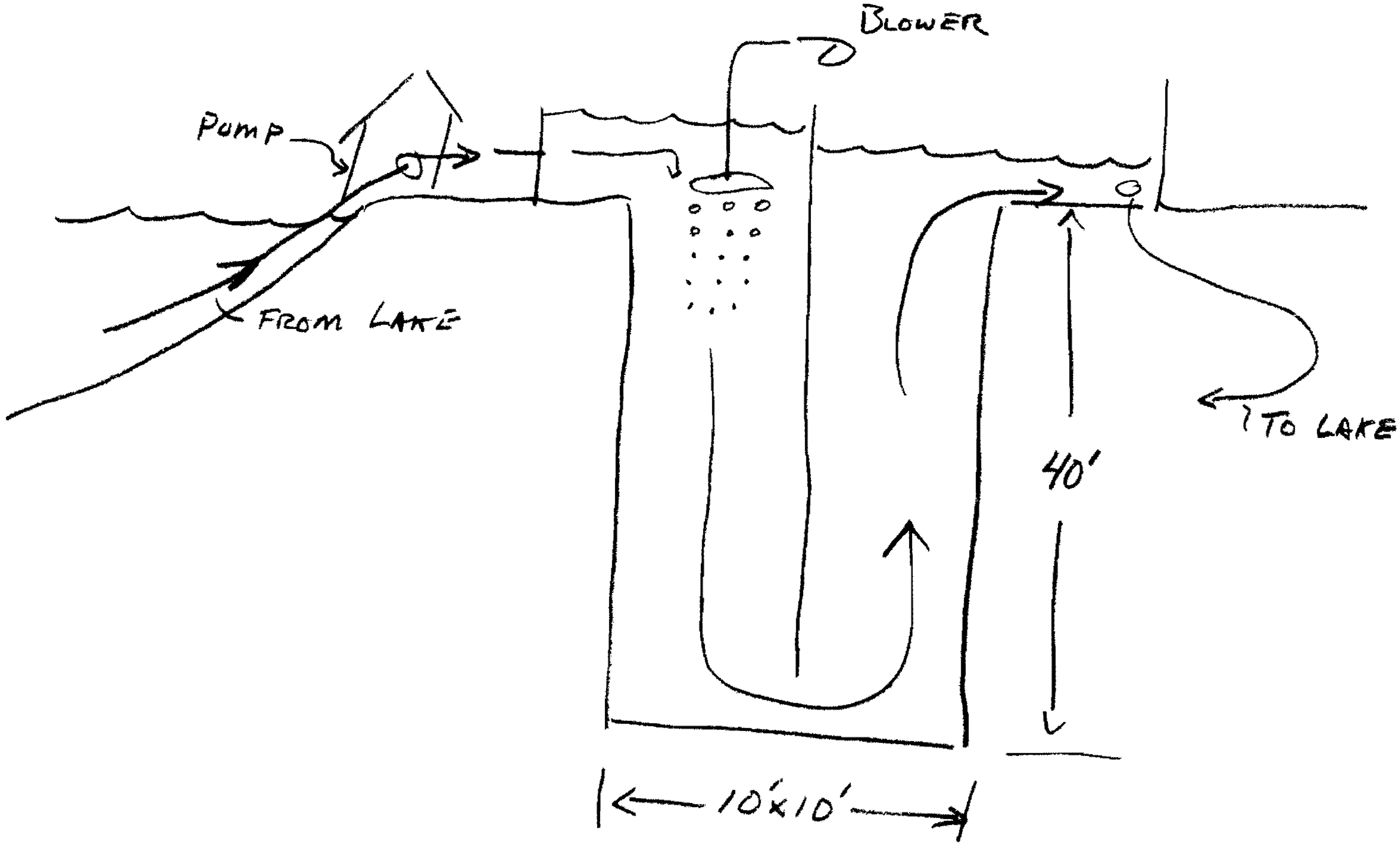
MECHANICAL AGITATION



SCHEMATIC

NO SCALE

BY R.B.L. 2/27/84 DATE .... SUBJECT LAKE MOREY SHEET NO. .... OF........
CHKD. BY ....DATE .... HYPOLIMNETIC AERATION JOB NO. ....
ONSHORE DOWNFLOW AIR



SCHEMATIC
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