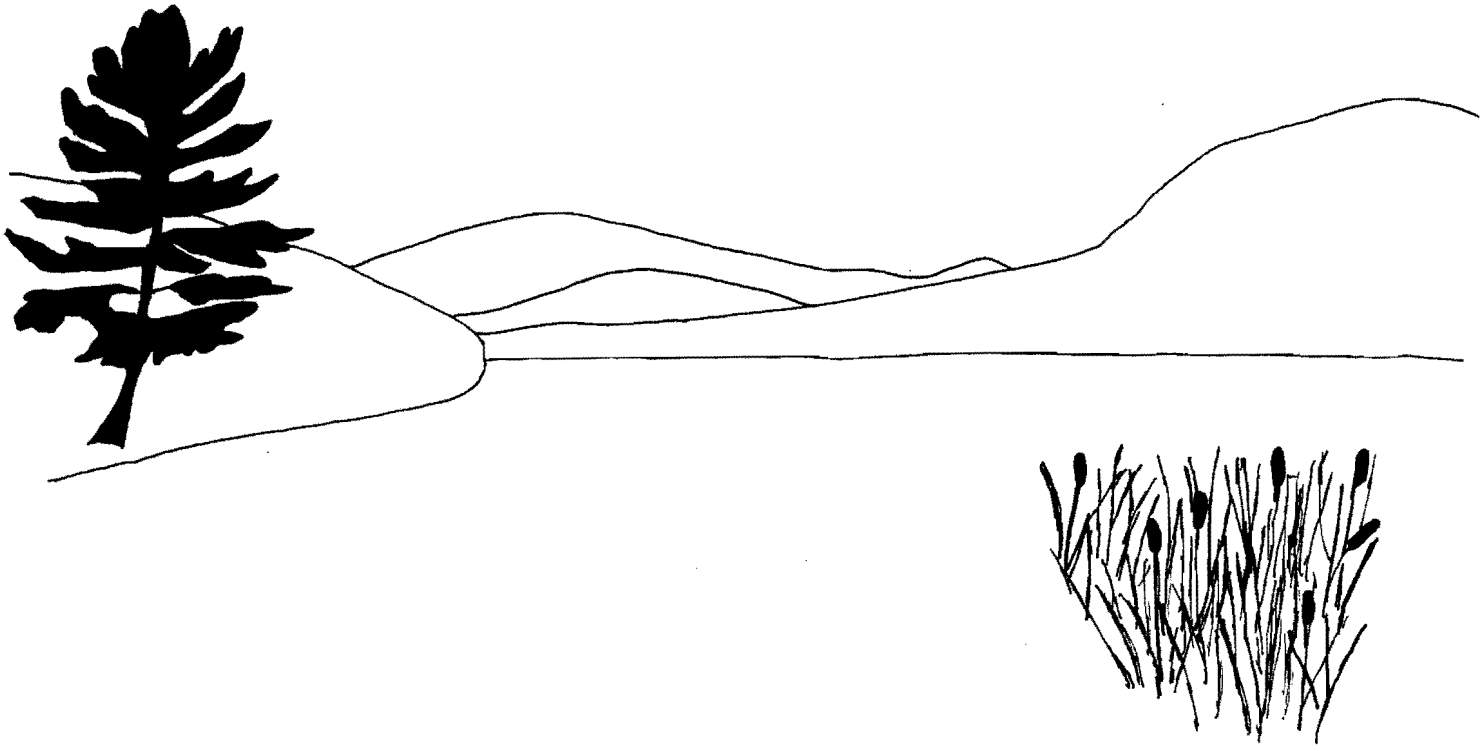
HARVEY'S LAKE
DIAGNOSTIC – FEASIBILITY STUDY
1980 – 1983
FINAL REPORT



STATE OF VERMONT

AGENCY OF ENVIRONMENTAL CONSERVATION

DEPARTMENT OF WATER RESOURCES

AND ENVIRONMENTAL ENGINEERING

WATER QUALITY DIVISION

MONTPELIER, VERMONT

Harvey's Lake
Diagnostic-Feasibility Study

Final Report - April, 1983

as authorized by the Revised
Regulations for Section 314 of the
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Co-Authors
Katherine Enright and Eric Smeltzer

Vermont Department of Water Resources
and Environmental Engineering
Montpelier, Vermont 05602

Prepared for

Region I
U.S. Environmental Protection Agency
Boston, Massachusetts

Project Officer
Ronald Manfredonia

CONTENTS

	Page
ACKNOWLEDGEMENTS	i
INTRODUCTION	1
BACKGROUND AND DESCRIPTIVE INFORMATION	8
Location and Description of Harvey's Lake	8
Geological Description of the Harvey's Lake Watershed	11
Present and Historical Lake Uses	12
Comparison of Uses of Harvey's Lake With Other Vermont Lakes Within an Eighty Kilometer Radius	15
Land Use in the Harvey's Lake Watershed	16
The Ecology of *Oscillatoria rubescens*	18
ANALYTICAL METHODS	23
GENERAL WATER QUALITY STUDIES	24
Historical Water Quality Data Source Inventory	24
Limnological Conditions in Harvey's Lake	25
Trends in Phosphorus and Chlorophyll Levels During 1977-1982	36
Paleolimnological Studies	41
The Relationship Between Algae and Transparency in Harvey's Lake	46
The Effect of Blue-Green Algae on the Efficiency of Energy Transfer Between Trophic Levels	48
Phosphorus "Stripping" by Algal Populations	62
Hypolimnetic Oxygen Depletion	63
Nitrogen and Phosphorus as Limiting Nutrients	69
SILICA ADDITION STUDIES	73
Lake Observations	73
Limnocurtain Experiment	73
Silica Enrichment Bag Experiments	81
Allelopathy Studies	86
Comparative Lake Study	92
PHOSPHORUS BUDGET AND MODELING STUDIES	99
Introduction	99
Methods	99
Budget Study Results	103
Model Development	109
Model Results	123
PHOSPHORUS CONTROL FEASIBILITY STUDIES	128
Diversion of Farm Runoff	128
Improved Manure Management	130
Correction of the Outlet Backflow	131
CONCLUSIONS	135
RECOMMENDATIONS	141
REFERENCES	142
APPENDIX	150

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INTRODUCTION

The Harvey's Lake Diagnostic-Feasibility Study was undertaken by the Vermont Department of Water Resources and Environmental Engineering under a grant agreement with the United States Environmental Protection Agency as authorized by Section 314 of the Federal Clean Water Act of 1977. The purpose of this study was to diagnose the cause of water quality problems in the lake 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.

Concern for water quality conditions in Harvey's Lake began in the mid 1970's when ice fishermen reported bright red algal scums emerging from holes bored into the ice. Subsequent investigations, documented in Vermont Department of Water Resources (1977), revealed that the algal community in Harvey's Lake was dominated year-round by blue-green algae, particularly *Oscillatoria rubescens* which caused the red color. Blue-green algae are characteristic of nutrient-rich, biologically productive lakes and their presence in a historically clear, unproductive lake such as Harvey's Lake was considered alarming. *Oscillatoria rubescens* was known to have appeared in many similar lakes worldwide that were undergoing a transition from oligotrophic to eutrophic conditions as a result of man-caused nutrient enrichment (see description of *Oscillatoria* ecology in a later section of this report). Concern for the implications of the presence of this alga in Harvey's Lake led to the initiation of the present study.

Diagnostic and feasibility studies at Harvey's Lake encompassed three major areas. The first of these areas was general water quality study aimed at assessing the magnitude of the problem and the implications of the *Oscillatoria* presence for the lake's ecology. The second area was an investigation of the

feasibility of shifting dominance of the algal community from blue-greens to diatoms by the addition of silica to the lake. The third area was an evaluation of the various sources of phosphorus to the lake and a study of the feasibility of reducing phosphorus inputs from these sources. Each of these three areas of study will be explained in greater detail below.

General water quality studies at Harvey's Lake served a variety of purposes. Extensive sampling of the lake was conducted during 1980-1982 to document existing water quality conditions. This data was used with other data obtained during previous years to determine whether any deteriorating trends in water quality existed during recent years. Water quality trends were further examined on a historical time scale through paleolimnological study of a sediment core obtained from the lake. The issue of whether deterioration in water quality has occurred over time in Harvey's Lake is significant in light of the policy of the Vermont Department of Water Resources and Environmental Engineering to conduct lake restoration activities only on those lakes known to have suffered water quality degradation as a result of human activities (Morse, 1979). Because it was not known with certainty whether the *Oscillatoria* presence in the lake was a long-standing, natural phenomenon or whether it was brought about by cultural activities, the historical perspective was considered an important aspect of the diagnostic study.

Other general water quality studies were aimed at determining the influence of the *Oscillatoria* on the ecology of the lake and at evaluating the ecological gains that might occur if the algal community were shifted in favor of diatoms. The use of silica enrichment to shift lake algal populations from blue-greens to diatoms as an alternative lake restoration technique is discussed in more detail later in this section. Assuming that such a shift could be achieved, it was initially suggested that this might have a number of effects on the lake's ecology that would be beneficial even if there was no reduction in the rate of nutrient supply to the lake.

One suggested benefit was that a shift from blue-green algae to diatoms would improve the aesthetic appearance of the water by promoting algal types that do not form floating scums. An analysis of transparency-chlorophyll relationships in Harvey's Lake addressed this question. Another suggested benefit of the species shift was that it would lead to improved efficiency of energy transfer through the aquatic food chain. This possibility was based on the idea that blue-green algae provide a relatively poor food source for zooplankton. Shifting the primary producers in the lake to diatoms might therefore improve zooplankton production efficiency and provide more food for the fish populations in the lake. The issue of the effect of blue-green algae on trophic efficiency in lakes in general, and specifically in Harvey's Lake, was explored in depth during this study. A third suggested benefit of a species shift was that diatoms would enhance nutrient "stripping" from the surface waters by virtue of their relatively high sinking rates. Finally, it was suggested that the elimination of the Oscillatoria might improve oxygen levels in the hypolimnion. Each of these possible benefits is addressed in later sections of this report.

One final area of general water quality study involved an assessment of which of the two nutrients, nitrogen or phosphorus, was most limiting for Harvey's Lake phytoplankton. In evaluating the various sources of phosphorus to the lake and in predicting water quality improvements expected from phosphorus control, as will be done in this report, the assumption is generally made that phosphorus is the key nutrient controlling algal growth. This assumption should be valid in most situations, but nitrogen levels can have an important influence in cases where this nutrient is low in concentration, relative to phosphorus (see Smith, 1982). Thus, an analysis of nitrogen and phosphorus as limiting nutrients was undertaken for this study.

The second major area for diagnostic and feasibility study involved an investigation of whether silica addition to the lake would produce an algal species shift from blue-greens to diatoms. The use of silica addition is an untried lake restoration method suggested by the work of Schelske and Stoermer (1971) on Lake

Michigan. Schelske and Stoermer offered evidence of a decline in dissolved silica in Lake Michigan and hypothesized that this decline was caused by phosphorus enrichment of the lake which resulted in increased diatom growth and silica uptake. It was then suggested that as silica declined to levels that were limiting to diatoms, the diatoms began to be replaced by other algal forms such as blue-greens.

The evidence used by Schelske and Stoermer (1971) to document a silica decline in Lake Michigan has been questioned (Shapiro and Swain, 1983). However, seasonal depletion of dissolved silica as a consequence of lake eutrophication is a well known phenomenon (Lund, 1969; Kilham, 1971; Schelske, 1975). There is also evidence from phytoplankton records in Lake Michigan that a shift from diatoms to green and blue-green algae has occurred during this century (Schelske and Stoermer, 1972). The same situation may exist in Lake Huron. Silica depletion appears to have occurred there in recent decades (Schelske, 1975), and the deletion of silica from nutrient enrichment experiments using Lake Huron phytoplankton resulted in markedly reduced proportional abundance of diatoms in the algal community (Lin and Schelske, 1979). Thus, the hypothesis of phosphorus enrichment causing silica depletion and a shift from diatoms to other algal types remains a potentially valid one.

The logical extension of this hypothesis is that addition of silica to a phosphorus enriched lake could reverse the process and promote diatom growth. This is the reasoning on which the concept of silica addition as a lake restoration method is based. Another related piece of research is that of Keating (1976) who found that blue-green algae, once established in a lake, could inhibit the growth of other algal types through the production of allelopathic metabolites. Laboratory experiments by Keating also suggested that blue-green algal inhibition of diatoms could be overcome by silica addition. Again, this research supports the concept that silica addition to Harvey's Lake might be successful in reversing the dominance of the algal community from *Oscillatoria* to diatoms.

The feasibility of shifting algal dominance to diatoms by silica addition in Harvey's Lake was studied by a variety of methods. The first method was to examine changes in diatom and Oscillatoria numbers in the lake from season to season in relation to variations in levels of dissolved silica. The lake data was analyzed for evidence of silica depletion and for negative interactions between diatoms and Oscillatoria. A second method was to experimentally enrich enclosed Harvey's Lake water with silica and determine whether the diatoms responded to silica addition. Silica enrichment experiments were performed inside a single large (67 m^3) limnocurtain enclosure and inside numerous smaller (32 liter) plastic bags. A bag experiment was also used to test for possible allelopathic interactions between diatoms and Oscillatoria. Finally, the Schelske and Stoermer hypothesis was tested for Harvey's Lake and for Vermont lakes in general by a comparative study of 22 Vermont lakes. These lakes were sampled for phosphorus, silica, and phytoplankton species composition to determine whether silica and phosphorus levels influenced the competitive balance between diatoms and other algal types across a broad selection of lakes.

The third major area for diagnostic and feasibility study involved an evaluation of the various sources of phosphorus to the lake and a study of the feasibility of reducing the major Man-caused inputs. The focus on phosphorus was based on the fact that phosphorus is generally the key limiting nutrient controlling algal growth in lakes. Control of phosphorus inputs to lakes leads to reduced algal abundance and a slowing or reversal of the eutrophication process.

Flows and phosphorus concentrations in eight streams tributary to Harvey's Lake were sampled intensively during this study. This data was used to construct a phosphorus budget which quantified the phosphorus loading rates from each sub-watershed. The phosphorus budget information was then used to develop a phosphorus model for the lake for use in predicting changes in lake phosphorus levels expected with reduced phosphorus loading rates from the watershed. Based on the results of the phosphorus budget, feasibility studies were initiated to reduce or eliminate

phosphorus inputs from the major Man-caused sources. The results of the feasibility studies were then used with the modeling analysis to estimate the water quality gains to be expected from specific phosphorus control measures.

In summary, the diagnostic and feasibility studies were organized around the following series of questions.

(1) What is the severity of the water quality problem in Harvey's Lake?
   a. What are the existing conditions?
   b. What water quality trends exist over time?

(2) How feasible is silica addition as a restoration technique for Harvey's Lake?
   a. Would silica addition shift the algal populations from blue-greens to diatoms?
   b. If the shift could be achieved, would it be desirable? What impact would it have on:
      1. water transparency?
      2. food chain efficiency?
      3. nutrient stripping?
      4. hypolimnetic oxygen depletion?

(3) How feasible is phosphorus control as a restoration technique for Harvey's Lake?
   a. What are the major sources of phosphorus to the lake?
   b. How much of the Man-caused phosphorus input is it technically feasible to eliminate?
   c. What water quality gains would be achieved through the elimination of this input?

These questions will be addressed at the conclusion of this report, and the answers to these questions will provide the basis for the report recommendations.

The scope of this report is limited to <u>technical</u> aspects of the diagnostic and feasibility studies for lake restoration at Harvey's Lake. There are some non-technical aspects of a complete Phase I feasibility study which are not addressed in this report. These include the following:

(1) A Phase II monitoring program.

(2) A description of non-federal funds to be obtained for the proposed Phase II project.

(3) A description of the relationship of the proposed Phase II project to other Federal programs.

(4) A summary of public participation.

(5) A description of the State operation and maintenance plan for the proposed project.

(6) Copies of relevent Federal and State permits.

(7) An environmental evaluation (partially completed in this report).

(8) Submission of a Phase II project budget.

These factors will be addressed with the submission of a funding proposal for a Phase II lake restoration project.

BACKGROUND AND DESCRIPTIVE INFORMATION

Location and Description of Harvey's Lake

Harvey's Lake is located in the Village of West Barnet, Caledonia County, Vermont. A map of the lake showing sampling locations, major tributaries, and bathymetric contours is given in Figure 1. Morphometric data for the lake is given in Table 1.

Harvey's Lake has been designated as Class B waters, according to the Vermont Water Quality Standards. As such, it is to be managed in a manner compatible with uses including bathing and recreation, irrigation and agriculture, good fish habitat, good aesthetic value, and public water supply with filtration and disinfection.

Jewett Brook, entering the lake on the southeastern shore, is the major tributary to Harvey's Lake. Several smaller streams are located on the eastern and western shores. The outlet stream from Harvey's Lake joins with South Peacham Brook to form the Stevens River which, in turn joins the Connecticut River at Barnet, Vermont. There are no other lakes in the Harvey's Lake watershed, although a series of beaver ponds exists on Jewett Brook. Harvey's Lake is a deep, cold-water lake that supports an excellent salmonid fishery including lake trout, landlocked salmon, and rainbow trout. The majority of the shoreline exhibits a rapid drop-off in depth and is generally devoid of aquatic vegetation.

A dam controlling the water level of Harvey's Lake is located on the outlet stream 457 meters downstream from the lake. It is situated below the confluence of the outlet stream and South Peacham Brook. The dam has been reconstructed several times during its history and is presently being used for recreational purposes. The lake level is maintained by the dam to provide spawning areas for lake trout. A fish ladder was added to the structure in 1971 to encourage natural propagation of landlocked salmon and rainbow trout. A further function of the dam is to facilitate small boat traffic between the lake and the village of West Barnet.

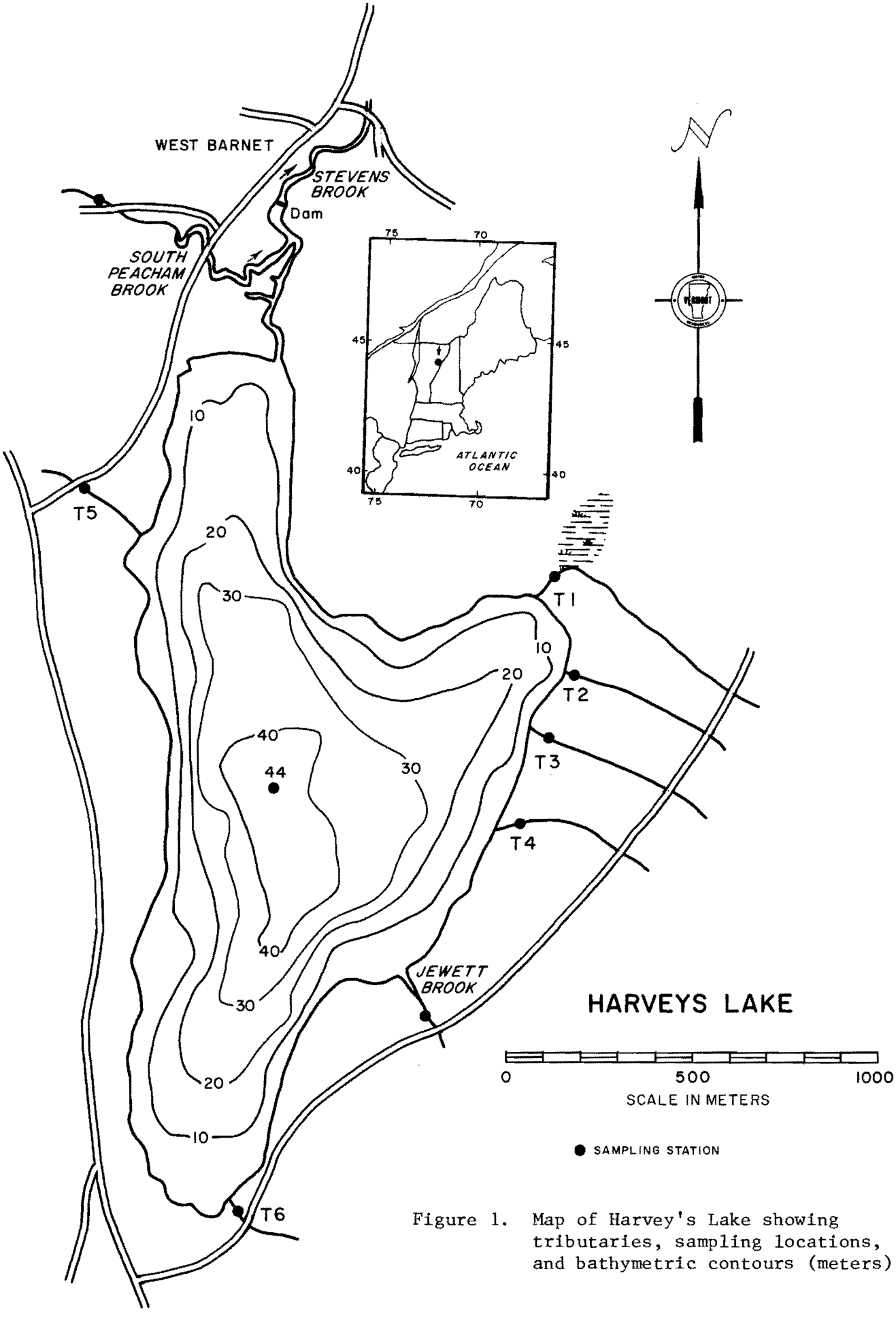


Figure 1. Map of Harvey's Lake showing tributaries, sampling locations, and bathymetric contours (meters).

During periods of high runoff, the dam restricts the flow of water such that part of the flow from South Peacham Brook is directed southward into the lake. This occasional backflow of water into the lake through the outlet contributes a considerable quantity of sediment and nutrient load to the lake.

Table 1.
Harvey's Lake morphometric data.

Depth (m)	Area ($10^6 m^2$)	Stratum (m)	Volume ($10^6 m^3$)
0	1.56	0 - 2.5	3.30
5	1.26	2.5 - 7.5	5.79
10	1.14	7.5 - 12.5	4.99
15	.96	12.5 - 17.5	4.58
20	.78	17.5 - 22.5	3.09
25	.60	22.5 - 27.5	2.70
30	.45	27.5 - 32.5	1.99
35	.29	32.5 - 44	1.70
		Total	28.14

Geological Description of the Harvey's Lake Watershed

The primary drainage basin of Harvey's Lake is that which contains Jewett Brook and the area immediately surrounding the lake. According to Hall (1959), the predominant geological feature of this region is the Gile Mountain formation. This was formed during the Devonian Age with depositions of argillaceous sandstones and shales and quartzose sandstones. The dominant rock types of this formation are micaceous schists and "sandy" schists. Quartz, muscovite, and biotite make up the predominant mineral forms of the rocks. Other rock types found in the watershed basin are granite, calcareous granulites and calcareous schists.

South Peacham Brook is a second drainage basin contributing inflowing water to Harvey's Lake. The parent material is quite different from that of the Harvey's Lake basin. The geological structure dominating this region is the Waits River formation which was formed during the Silurian and/or Devonian periods. Calcareous shales and calcareous sandstones which predominate the structure were formed by sedimentation. Calcite and quartz are the essential minerals, along with phlogopitic biotite, dolomite, feldspar, actinolite, diopside, and other calc-silicate minerals. Also found in this drainage basin are areas of granite and micaceous and "sandy" schists.

Present and Historical Lake Uses

Present Uses

The major recreational uses of Harvey's Lake and the immediate surrounding area are fishing, swimming, boating, water-skiing, and camping. A Fish and Game boat launch owned and maintained by the State of Vermont is located at the southern end of the lake. The cold-water fishery in the lake is excellent and draws people year-round from Canada and other New England states. A description of the fish stocking program can be found in annual Fish Distribution Reports published by the Vermont Department of Fish and Game. The projected stocking program of the Vermont Fish and Game Department is to stock lake trout and rainbow trout on a yearly basis to supplement the naturally propagating population.

A municipally-owned swimming beach located at the northern end of the lake has recently been expanded and improved. Approximately 10,000-11,000 people use the beach area during the summer. There are an estimated 101 cottages situated on the shore of Harvey's Lake. Approximately 17 of these are or could be used as year-round homes. In addition, there are about 25 houses located near, but not on the lakeshore. A privately owned campground of 52 sites and a privately owned seasonal trailer park/campground of approximately 70 sites are also situated near the lakefront.

Historical Uses

The following historical information was assembled from published sources including Wells (1975), Walter (1953), Vermont Historical Society (1943), Vermont Public Service Commission (1952), and from personal communications with long-term local residents including Mr. Francis Roy, Mr. Karl Jurentkuff, and Mr. Elmer Faris.

Early Settlement

Prior to white settlement of the Harvey's Lake region there was no known habitation by Indians. It is believed that Indians used the area only for hunting and fishing. The Town of Barnet, in which the village of West Barnet is located, was established as a settlement for a Scottish emigration company of the name "United Company of Farmers for the Shires of Perth and Barnet". In 1775, Alexander Harvey and John Clark came from Scotland as agents of the company to begin settlement of the town. When Harvey first saw the lake, he described in his personal journal the surrounding land as forested with pine, oak, maple, and birch. That first year he cleared land, built his house, and planted crops on the side of Harvey's Mountain on the western side of the lake. Besides the account of Alexander Harvey, there is little information on early settlement. There are no other known records kept by settlers, and old town and emigration company records were destroyed in a fire.

In May or June of 1776, construction of the Bayley-Hazen Military Road took place in the Harvey's Lake watershed. It ran up and along the western slope of Harvey's Mountain. In the spring of 1785, a road was surveyed which was to run from the outlet of Harvey's Lake to the town of Barnet located six miles down the Stevens River on the Connecticut River.

A sawmill was built on Jewett Brook in 1780. Sawdust from the mill entered the lake until about 1920. The mill ran year-round and produced about 400,000 board feet/year. Much of the lumber came from Roy Mountain, which is situated on the eastern side of the lake. The mill burned in 1934 or 1935.

Dams on the Stevens River

Many dams have been built on the Stevens River in West Barnet throughout the history of the town. Until 1908, all of these dams were located downstream from the site of the present dam, and probably would not have affected water levels in Harvey's Lake. A dam was built at the present site in 1908 for

the purpose of storing and releasing water from the lake and from South Peacham Brook to operate a hydroelectric generating plant in Barnet about six miles downstream. Between the years of 1908 and 1927, the lake was drawn down during the summer months, and the lake level was often about three and a half feet below normal by the end of the summer. The dam was last used for hydroelectric purposes in 1927, at which time it was damaged by a flood.

The present day phenomenon of the backflow of South Peacham Brook into the lake through the lake's outlet was described earlier. There is a difference of opinion by local residents as to when the occurrence of a backflow began. Francis Roy, a local dairy farmer, first observed the phenomenon at the outlet about 1950. Karl Jurentkuff Sr., who operates a campground on the outlet brook, maintains that he never observed the backflow until South Peacham Brook was channelized in 1972-1973. This brook, he says, used to meander through a field and was bordered by an alder thicket. Stormwaters would spread out and be absorbed into this area instead of rushing down to the Stevens River unobstructed, as they do now. Jurentkuff remembers that the outlet was wider and deeper before, and that silt did not begin to accumulate in this area until the backflow began occurring following the channelization.

Farming in the Harvey's Lake Watershed

The acreage of cleared land in the Harvey's Lake watershed has declined in recent years. This follows the trend of land use which has taken place over most of Vermont. Due to the lack of historic documentation, it is difficult to estimate the magnitude of the change around Harvey's Lake.

Shoreline Development

There were approximately ten houses on Harvey's Lake prior to 1945. Most shoreline development has taken place in the past 25-30 years. There are approximately 101 cottages along the shore of the lake today. There have been two summer camps on the lake which were small and short-lived.

Comparison of Uses of Harvey's Lake with Other Vermont Lakes Within an Eighty Kilometer Radius

In comparing Harvey's Lake with other lakes within an eighty kilometer radius, three criteria of recreational importance were considered. These resources, which are all found at Harvey's Lake, are the combined fishery resource of landlocked salmon, lake trout, and rainbow trout; a public swimming beach; and a public boating access. Within the eighty kilometer radius there are 164 Vermont lakes of twenty or more acres. Of these, only three lakes have the same combination of features and therefore provide a similar recreational experience to Harvey's Lake. These lakes are Lake Willoughby in the town of Westmore, Caspian Lake in Greensboro, and Echo Lake in Charleston. Of the three factors considered, the salmon fishery particularly limits the number of lakes which are comparable to Harvey's Lake. Only ten lakes within the area considered can provide this resource. Information for this comparison was obtained from the Vermont Fish and Game "Fish Distribution Reports" of 1977, 1978, and 1979 and from Vermont Department of Water Resources (1971).

Land Use in the Harvey's Lake Watershed

The Harvey's Lake watershed encompasses 2,024 hectares of predominantly forested land. Jewett Brook, the major tributary to the lake, drains 78% of this area. As described earlier, the backflow of South Peacham Brook into the lake through the lake's outlet occasionally provides inflow from an entirely separate watershed. The South Peacham Brook watershed is larger (3,014 hectares) with more extensive agricultural development.

The land use of these two watersheds was examined by means of a land use map produced from a high-altitude color infrared photo taken in October, 1978 as part of a wetland survey conducted by the U.S. Fish and Wildlife Service and the U.S. Army Corps of Engineers. This map is shown in Figure 2. The areas of several categories of land use were then determined by planimetry from this map. These areas are given in Table 2.

Table 2. Areas of various land use categories within the Harvey's Lake and the South Peacham Brook watersheds.

	Harvey's Lake		S. Peacham Brook	
Land Use Category	Area (ha)	%	Area (ha)	%
Forest	1437	71	1959	65
Cropland & Grassland	405	20	965	32
Residential	142	7	30	1
Water	40	2	60	2
Total	2024	100	3014	100

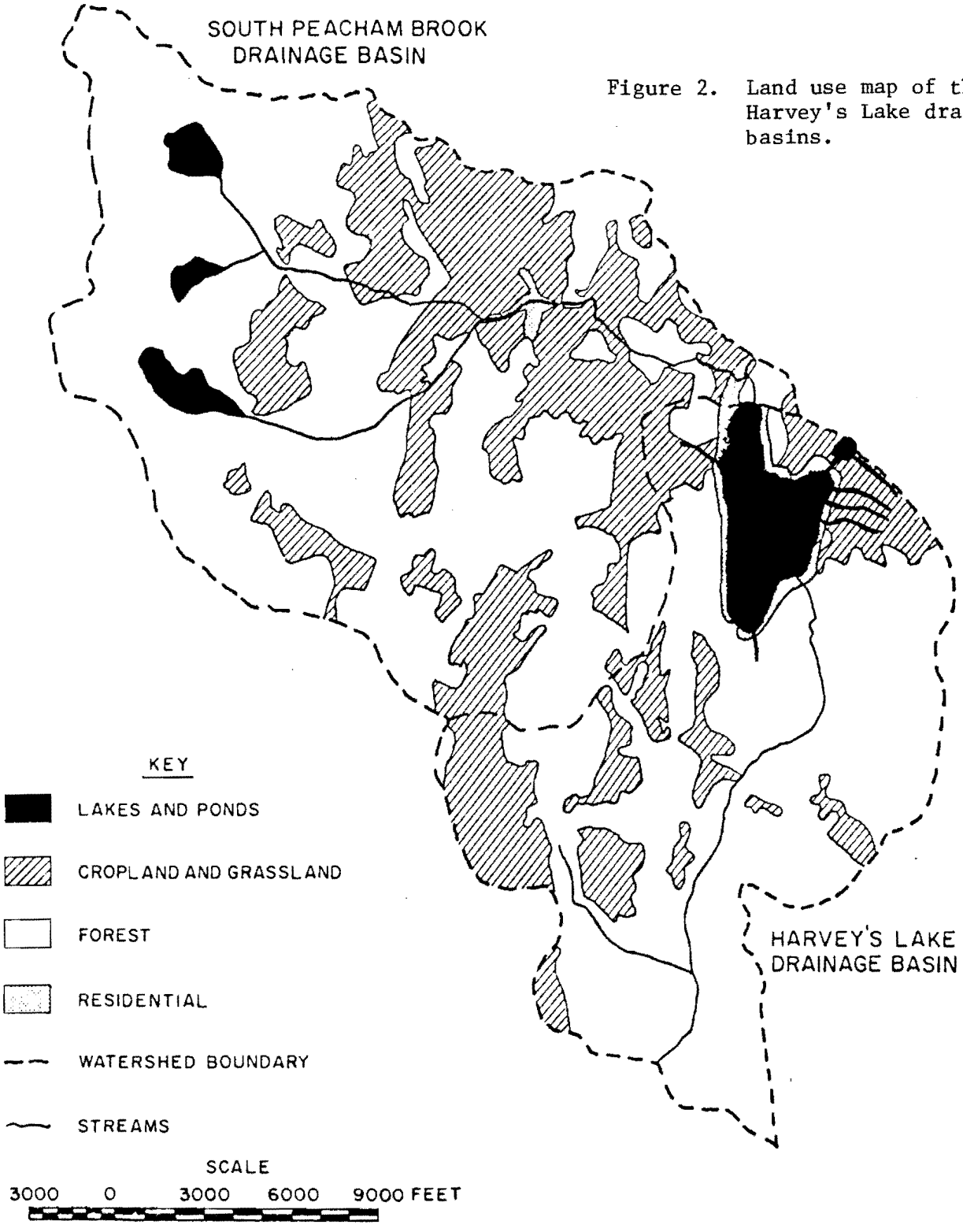


Figure 2. Land use map of the Harvey's Lake drainage basins.

The Ecology of *Oscillatoria rubescens*

Since the first documented occurrence of a bloom of *Oscillatoria rubescens* in Switzerland's Lake Murten in 1825, the alga has recurrently been noted as being a biological indicator of a lake in transition from an oligotrophic to a eutrophic state (Skulberg, 1978; Jaag, 1972; Ravera, 1968). Most of the alpine lakes of Europe (Jaag, 1972) as well as numerous other temperate lakes in the United States (Konopka, 1982), Japan (Ravera, 1968), and Norway (Skulberg, 1980) have experienced blooms of the alga. The presence of *Oscillatoria rubescens* in the European alpine lakes has usually been accompanied by a transition from game fish to other species of fish. There has also been an associated decline in hypolimnetic dissolved oxygen to the point of complete exhaustion in many lakes (Jaag, 1972; Fricker, 1980). The appearance of *Oscillatoria rubescens* has therefore become a significant indicator of declining water quality.

There are several factors which seem to create a favorable environment in which *Oscillatoria rubescens* is able to attain dominance. The alga typically migrates down to the metalimnion or upper hypolimnion for the period of summer stratification. It can inhabit this region only if the euphotic zone depth exceeds that of the epilimnion, according to Findenegg, as cited in Reynolds and Walsby (1975). In a lake with low nutrients and sparse epilimnetic algal populations, light may penetrate beyond the metalimnion. If under these conditions, the rate of enrichment is accelerated, *Oscillatoria rubescens* is able to establish itself in the metalimnion and increase in numbers (Reynolds and Walsby, 1975). This occurrence has been observed many times in the European alpine lakes, with the increased enrichment attributed to human development in lake watersheds (Fricker, 1980).

Oscillatoria rubescens typically remains in the metalimnion or upper hypolimnion throughout the entire summer stratification period. In order for the alga to remain in this region undisturbed, the thermal stratification must be stable. Therefore *Oscillatoria rubescens* is found in lakes that are

somewhat sheltered from wind action by surrounding mountains (Reynolds and Walsby, 1975).

Once Oscillatoria rubescens becomes established as the dominant phytoplankter, it has the unusual characteristic of persisting as a year-round population. Unlike most other types of algae which die off as environmental conditions change and become unfavorable, Oscillatoria is able to sustain its existence by creating an environment favorable for itself, but one in which other algae find it difficult to compete. During spring circulation, Oscillatoria rubescens, which is already present in the water from the previous winter season, takes up most of the available nutrients, more than it actually needs, and then sinks down to the bottom of the euphotic zone. The alga can sometimes live for a whole year on these stored reserves, according to Findenegg.

Its position in the metalimnion or upper hypolimnion is also advantageous as this is a region rich in available nutrients (Wetzel, 1975). Once the alga has migrated from the epilimnetic region, it leaves behind waters which are low in nutrients and which will subsequently have low algal populations and high light transmission according to Findenegg, as cited in Reynolds and Walsby (1975).

The ability of Oscillatoria rubescens to move vertically in the water column is due to its possession of internal gas vacuole structures. The relative size of these structures in relation to the volume of the algal cell determines the buoyancy of the alga in the surrounding water (Wetzel, 1975). Experiments have indicated that the size of the gas vacuoles, and hence the buoyancy of Oscillatoria is regulated by an interaction of light and nutrients, specifically ammonia-nitrogen (Klemer et al, 1982). High light intensity and low levels of ammonia can both independently induce gas vacuoles to collapse, and thereby cause the algae to lose buoyancy and sink. These two conditions both develop in the epilimnion with the onset of thermal stratification in the spring. Oscillatoria rubescens therefore responds by migrating from the region of high light intensity and low nutrients (epilimnion) to one of low light and high nutrients (metalimnion-upper hypolimnion) (Klemer et al, 1982).

The ability of Oscillatoria to exist under varied light conditions appears to be due to its regulation of pigment synthesis, according to experiments performed by Van Liere (1978). This enables it to have an optimal pigment content under several environmental circumstances. The minimum intensity of light which enables photosynthesis to occur is approximately one percent of that reaching the lake surface (Cole, 1975). The light intensity reaching the Oscillatoria rubescens layer during thermal stratification has been found to be between only one and three percent of the intensity at the lake surface (Konopka, 1981; Konopka, 1982; Fricker, 1980). A secondary pigment, phycobilin, may be particularly advantageous under these low light conditions. This pigment can be used photosynthetically, and is found in greater concentrations in red algae (Prescott, 1968). Phycobilins use yellow light for photosynthesis (Prescott, 1968), and it is a mixture of green-yellow light which reaches to the greatest depths in many clear lakes (Cole, 1975).

Once Oscillatoria rubescens becomes established as the dominant phytoplankter, there are several mechanisms by which it may maintain this position. One may be the previously mentioned removal of most of the available nutrients from the upper euphotic zone during the summer months. It was also hypothesized by Keating (1978) that blue-greens maintain their dominance by excreting allelopathic metabolites. The natural competitors of Oscillatoria rubescens for available nutrients during the early spring would be diatoms. Keating (1978) found that spring diatom population levels varied inversely with the size of the previous winter's blue-green algal population. She hypothesized that it was the blue-green metabolites which inhibited the growth of diatoms. The inhibitory mechanism might be due either to direct allelopathic effects or to a process in which available silica bonds chemically with the metabolic excretion and becomes unavailable for uptake by diatoms (Keating, 1976). Silica therefore would become the limiting nutrient for diatoms.

The ability of Oscillatoria rubescens to establish and maintain dominance over diatoms is evidenced by the examples of the European alpine lakes Zurich and Maggiore. In these lakes,

large populations of the diatom Tabellaria fenestrata were replaced by Oscillatoria rubescens. In a third alpine lake, Lake Mergozzo, Oscillatoria rubescens had developed very dense populations due to nutrient loading from sewage. With the construction of sewer systems around the lake, and the subsequent reduction in levels of incoming nutrients, the population of Oscillatoria rubescens declined, and was replaced by diatoms (Fricker, 1980).

Populations of Oscillatoria rubescens fluctuate considerably in size both seasonally (Konopka, 1981) and annually (Jaag, 1972; Fricker, 1980). In the European alpine lake region Oscillatoria rubescens has repeatedly been documented as having appeared suddenly in large dense blooms. The reason for its occurrence has been consistently linked with accelerated rates of enrichment from human development. Sources of pollution that are most often cited are sewage, industry, or agricultural runoff (Fricker, 1980). The size of an Oscillatoria rubescens population seems to be unpredictable from one year to the next. The alga can produce large blooms for several years, followed by its disappearance, only to reappear years later (Jaag, 1972). This situation occurred in Switzerland's Lake Geneva where massive blooms of other types of blue-greens developed in the intervening years between the Oscillatoria rubescens blooms. In Lake Mergozzo and Lac de Nantua however, Oscillatoria rubescens maintained dense populations for years. It has also been observed that with continually increasing levels of nutrients, Oscillatoria rubescens can eventually be replaced by other types of algae. This occurred in Lake Zurich and Lake Baldegg where Oscillatoria rubescens was replaced by Aphanizomenan flos-aquae (Fricker, 1980).

The concern for the appearance of Oscillatoria rubescens is that it is often accompanied by a deterioration in water quality. Severe oxygen depletion has occurred in many Oscillatoria rubescens lakes, including Lake of Logano, Lake of Baldegg, Lake of Hallwill, Lake Zurich, Lake Maggiore, Rotsee, Lake Geneva, and others (Jaag, 1972; Fricker, 1980). Some lakes have also experienced a decline in fisheries. For example, Lake Logano has

recently been experiencing massive fish kills. Lake Baldegg historically had an abundance of white fish. *Oscillatoria rubescens* appeared in 1870, and dominated until 1965. Between the years of 1884 and 1940, a healthy population of white fish was able to be maintained only by stocking. In 1940, the white fish population died out completely. Today the lake is dominated by carp, perch and pike.

Concern for deteriorating conditions has led to many lake restoration projects in the European alpine lakes region, including the construction of secondary and tertiary sewage treatment facilities, the diversion of sewage from the lake watershed, and the removal of nutrients from the hypolimnion by means of a siphon. In each case, where there were no other uncontrolled sources continuing to enrich the lake, the populations of *Oscillatoria rubescens* have declined dramatically and hypolimnetic oxygen levels have begun to increase. The best known North American example of nutrient enrichment causing *Oscillatoria rubescens* to flourish is that of Lake Washington (Edmondson, 1966). The eutrophication process in Lake Washington has been successfully reversed by means of sewage diversion (Edmondson and Lehman, 1981).

ANALYTICAL METHODS

Unless otherwise indicated, lake samples were obtained at five-meter depth intervals over the deepest region of the lake, using a Kemmerrer water sampler. All water quality data collected on Harvey's Lake 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.

Phosphorus samples were analyzed by an automated, colorimetric, ascorbic acid method (U.S. Environmental Protection Agency, 1979). Total phosphorus and dissolved phosphorus samples were digested in an autoclave using acid persulfate. Dissolved phosphorus samples were filtered through a .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, 1977).

Dissolved silica was analyzed by an automated colorimetric method (Technicon, 1976) after filtration through a .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).

GENERAL WATER QUALITY STUDIES

Historical Water Quality Data Source Inventory

A considerable amount of sampling on Harvey's Lake, for a variety of purposes, was conducted by the Vermont Department of Water Resources and Environmental Engineering prior to the present study. This historical water quality information has been compiled from the following sources, and relevant aspects of the data will be described and discussed elsewhere in this report.

Vermont Department of Water Resources. 1977. Harvey's Lake Water Quality Report. Lake Eutrophication Series Report No. 13. 73 pp.

Vermont Department of Water Resources Phosphorus/Chlorophyll Program (1977-1979)

Vermont Department of Water Resources Hypolimnetic Dissolved Oxygen Program (1978-1979)

Vermont Department of Water Resources Lay Monitoring Program (1979-1982)

Vermont Department of Water Resources Harvey's Lake File (Miscellaneous sampling results, pre 1980)

Baren, C.J. 1967. A preliminary biological survey of selected lakes and ponds in Vermont. Vermont Department of Water Resources. Biological Survey Bulletin No. I. 96 pp.

Limnological Conditions in Harvey's Lake

The most striking limnological feature of Harvey's Lake is the development of a layer of algae in the mid-depths of the lake between 10 and 15 meters. Microscopic examination of phytoplankton samples indicates that the layer was dominated by a single species, identified according to Skulberg (1978) as the filamentous blue-green alga *Oscillatoria rubescens*. Concentrations of *Oscillatoria* filaments are sometimes high enough to impart a pink color to water samples obtained from the algal layer. Many of the biotic and abiotic components of the Harvey's Lake ecosystem are strongly influenced by the presence of *Oscillatoria*.

The distribution of *Oscillatoria* in Harvey's Lake follows a distinct cycle which is repeated annually with slight variations. During spring overturn, the *Oscillatoria* is found evenly distributed vertically. With the onset of thermal stratification, the alga migrates downward in the water column. During early summer, a dense horizontal band of *Oscillatoria* forms in the metalimnion or upper hypolimnion and remains there throughout the summer (see Figure 3). With the erosion of thermal stratification during the fall overturn, the alga again becomes homogeneously distributed throughout the water column. As ice forms on the surface of the lake, *Oscillatoria* develops a weak stratification of its population with the maximum numbers located between the depths of zero and ten meters.

One important consequence of the *Oscillatoria* seasonal distribution pattern is the resultant distribution of algal nutrients. During spring overturn, the *Oscillatoria*, which has a high luxury uptake ability, incorporates a large amount of the lake's nutrients into its cells. When the alga then migrates down out of the epilimnetic waters, it takes these nutrients with it, making them unavailable for uptake by other types of algae. The removal of these nutrients, and the subsequent effect on algal distribution, as represented by chlorophyll, can be seen in Figure 3. On this day of July 30, 1980 approximately 75% of the lake's chlorophyll, 42% of the total phosphorus, and 41% of the

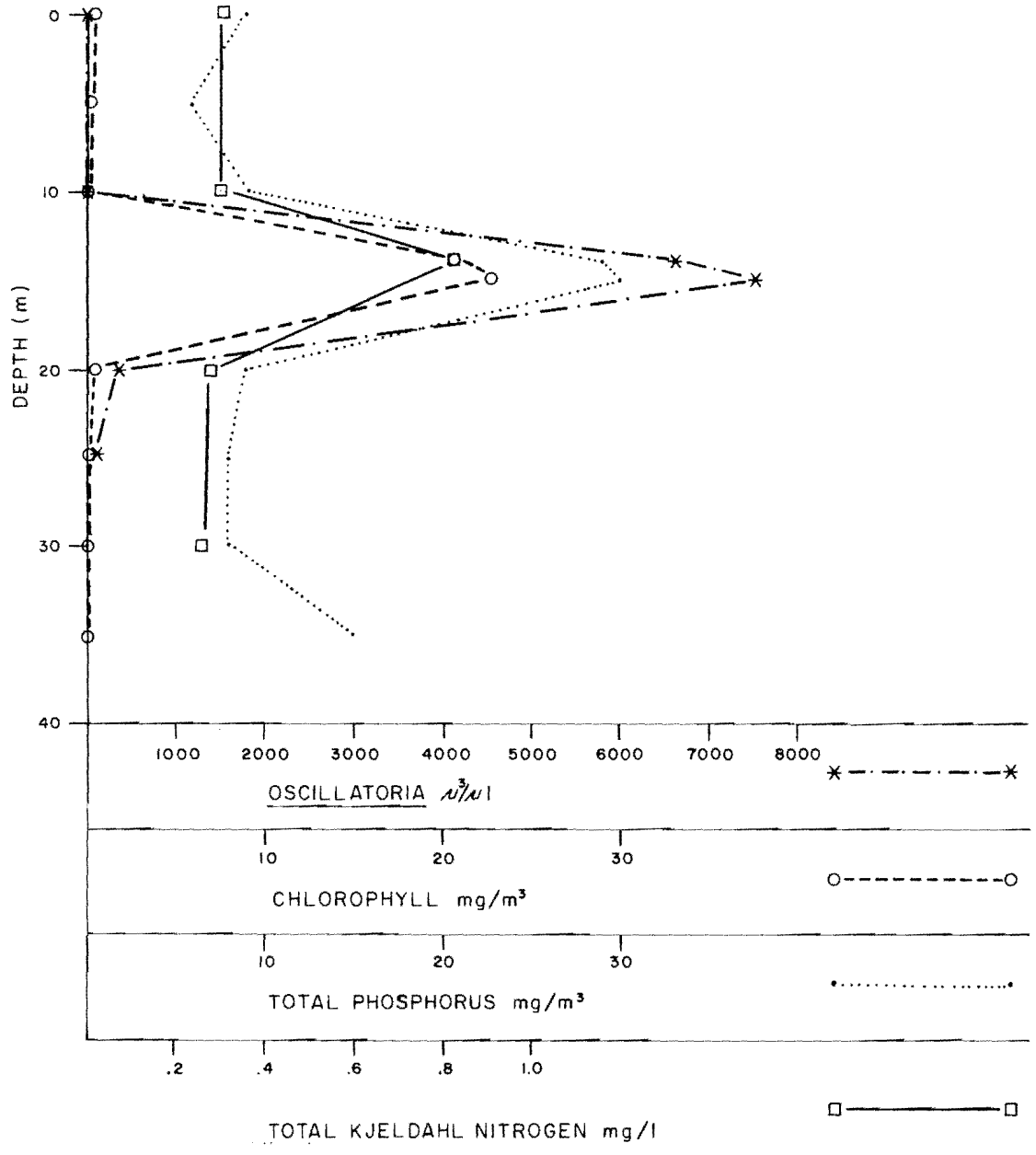


Figure 3. Depth profiles of Oscillatoria, chlorophyll, total phosphorus, and total Kjeldahl nitrogen on July 30, 1980.

total Kjeldahl nitrogen was incorporated into the Oscillatoria layer. The effect of this concentration of nutrients by Oscillatoria is also illustrated in Figures 4, 5, and 6, which are depth-time isopleth diagrams of chlorophyll, total phosphorus, and total nitrogen during 1980.

The reduction of algal nutrients therefore results in less algal biomass being produced in the epilimnetic region. The effect of this is a greater transparency, as illustrated in Figure 7. After the disappearance of Oscillatoria from the epilimnion in late spring, the algal biomass remains relatively low for the remainder of the year. This pattern of reduced biomass in the surface water is reflected in the Secchi disc transparency measurements. As the Oscillatoria population sinks from this region, the transparency becomes correspondingly deeper (see Figure 7). The transparency levels remain fairly high during the summer months except during periods of moderate surface algal population increases.

Once the Oscillatoria population settles to its location in the mid-depths, it moves only a few meters verticallyfrom that position for the rest of the summer stratification period. During the summer of 1980, the depth of the population maximum ranged from depths of thirteen to sixteen meters; in 1981, it varied from ten to twelve meters; and during 1982, the greatest concentration fluctuated from twelve to fifteen meters. The Oscillatoria population is typically concentrated in a horizontal band from two to four meters thick.

Temperature does not seem to be a critical factor in the environment of the Oscillatoria. During 1980, the temperature at which the population was located ranged from 5.0°C to 7.0°C. In 1981, the temperature span was 7.7°C to 11.7°C. In 1982, the temperature was again in the lower range of 4.8°C to 5.0°C.

Photosynthetic oxygen production by the large Oscillatoria population in the stable waters of the metalimnion or hypolimnion results in a very pronounced positive heterograde oxygen curve (Figures 8 and 9). The oxygen maximum continues to increase in concentration throughout the summer until the fall overturn disrupts the thermal stratification. The maximum measured oxygen

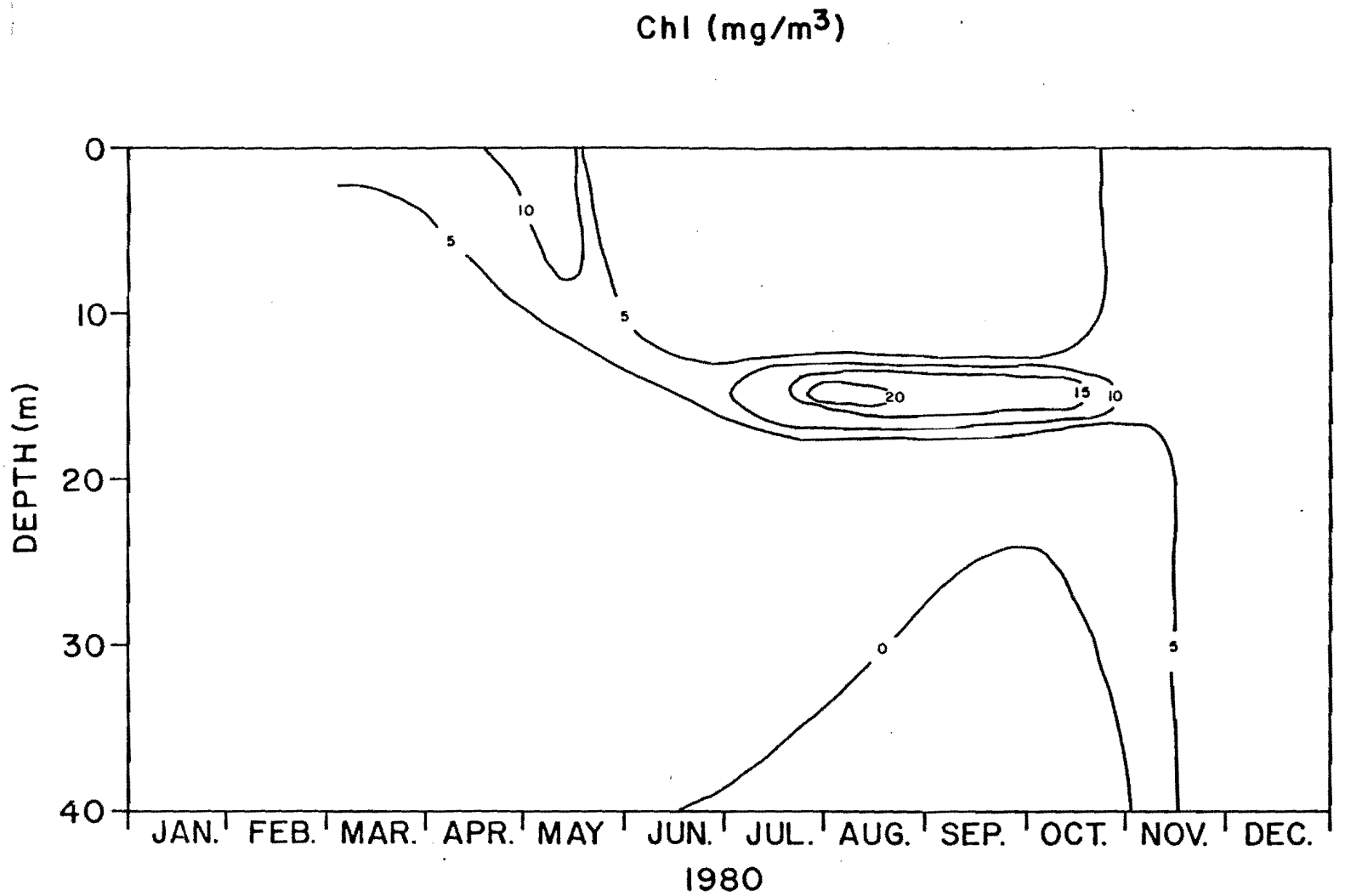


Figure 4. Depth-time isopleths for chlorophyll during 1980.

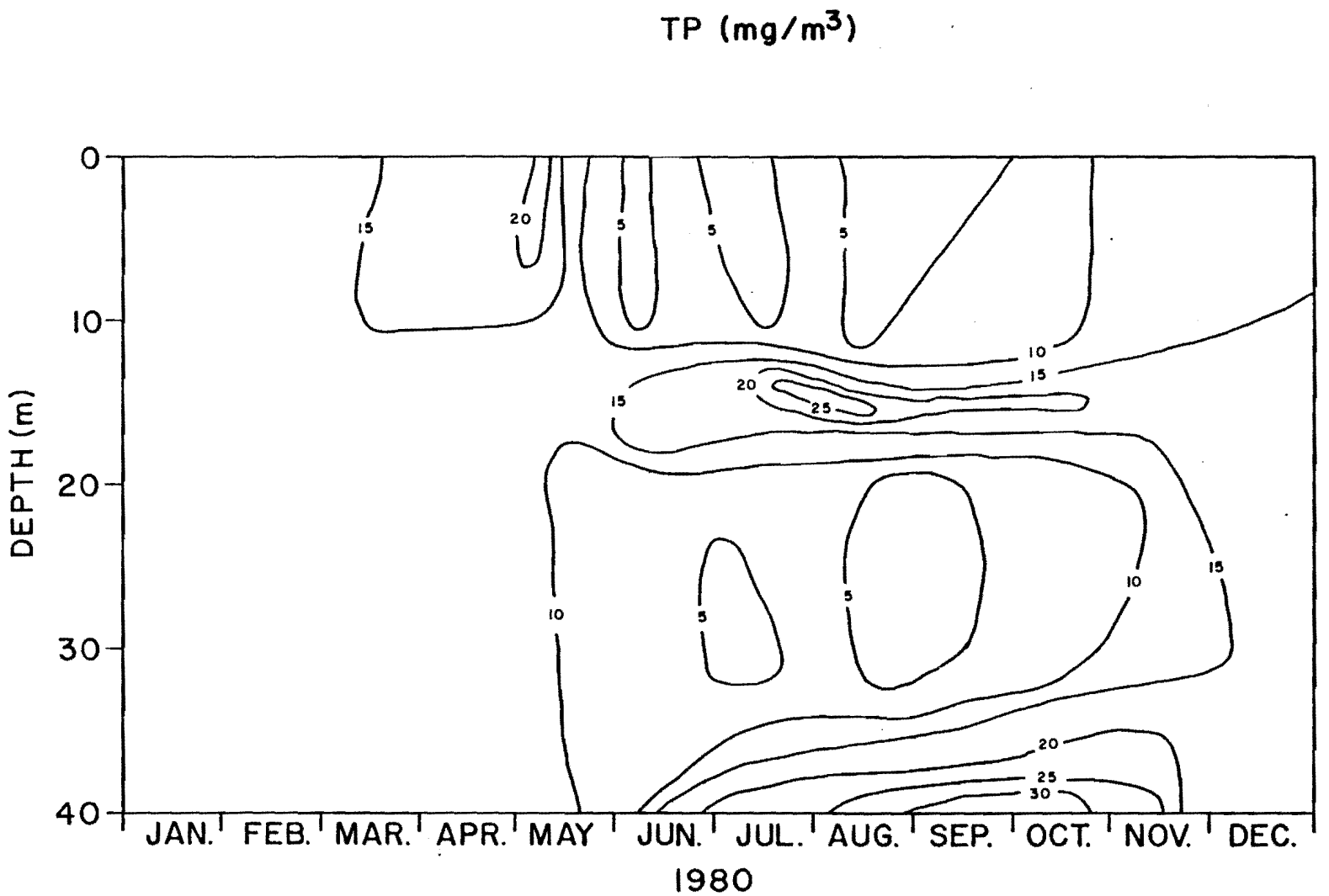


Figure 5. Depth-time isopleths for total phosphorus during 1980.

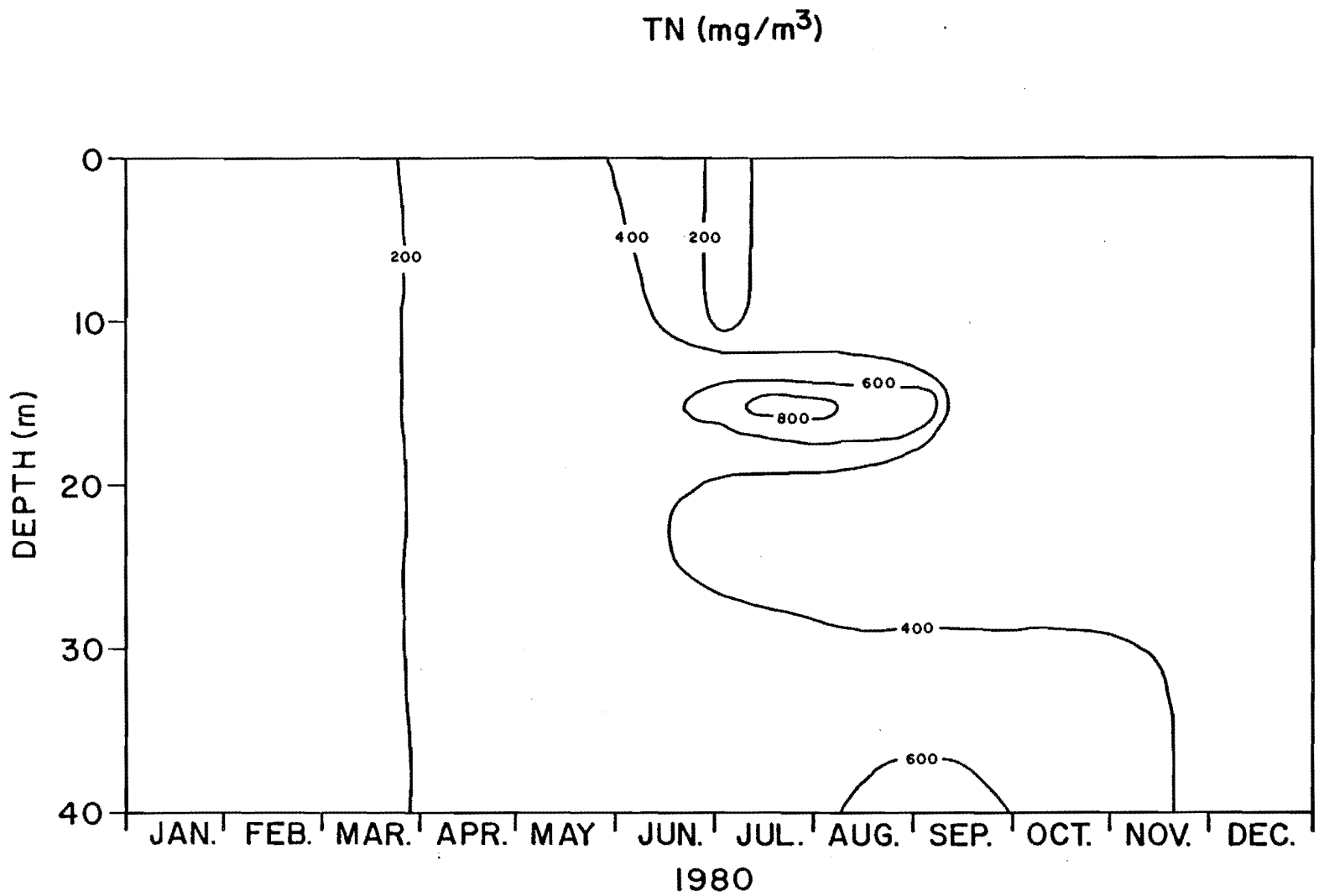


Figure 6. Depth-time isopleths for total nitrogen during 1980.

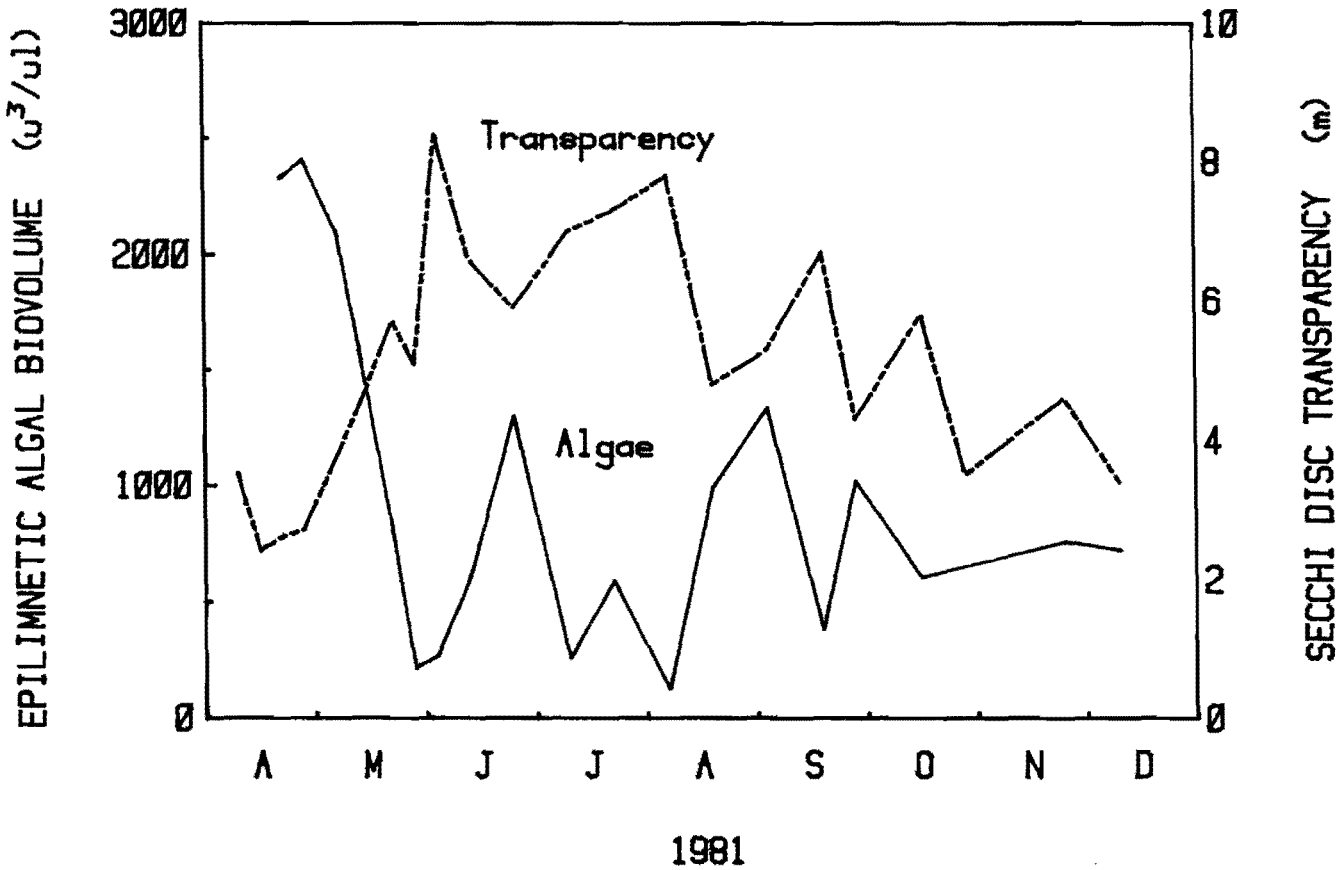


Figure 7. Plot of epilimnetic (0-5m) total algal biovolume and Secchi disc transparency during 1981.

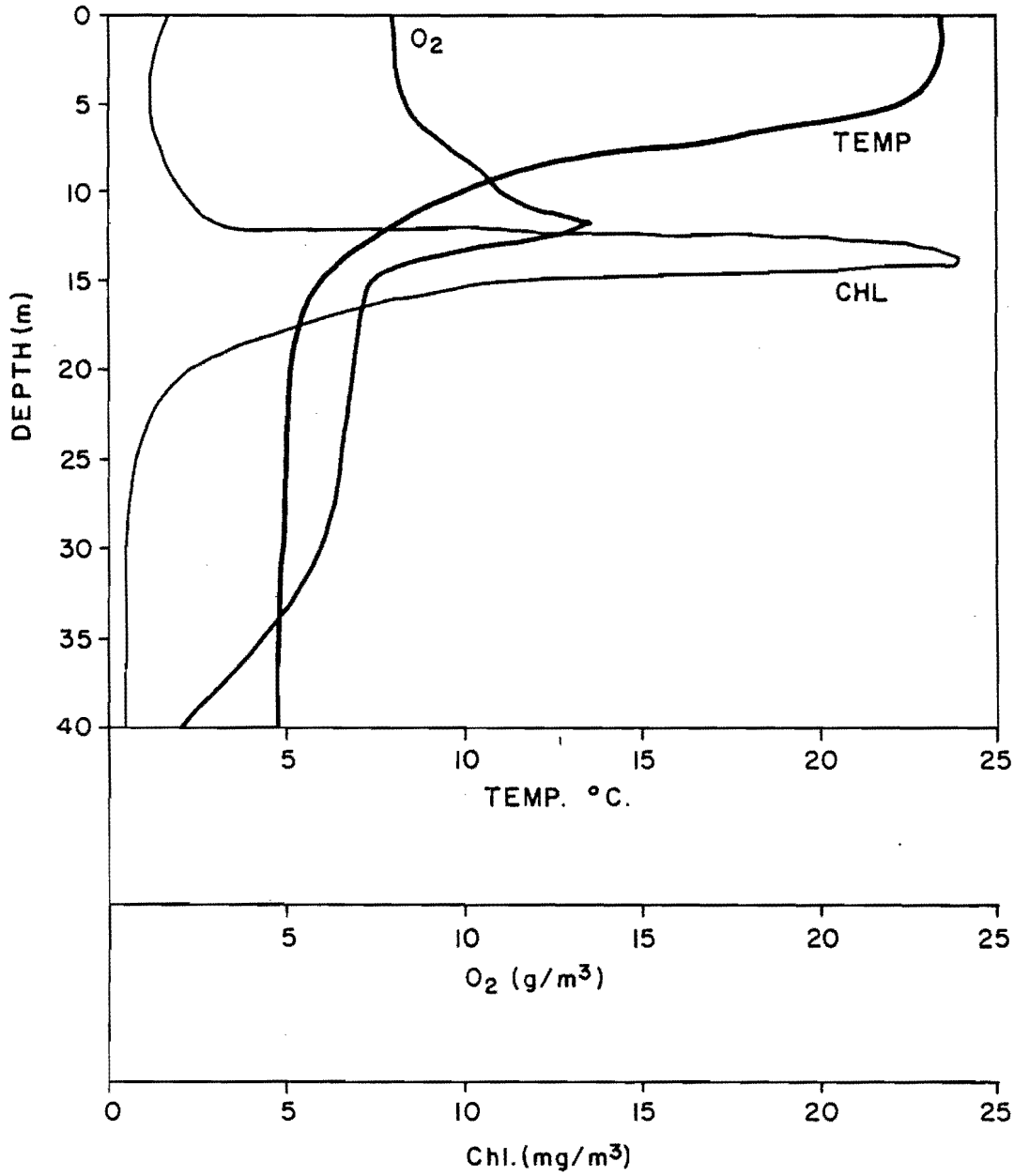


Figure 8. Depth profiles of temperature, oxygen, and chlorophyll on August 4, 1980.

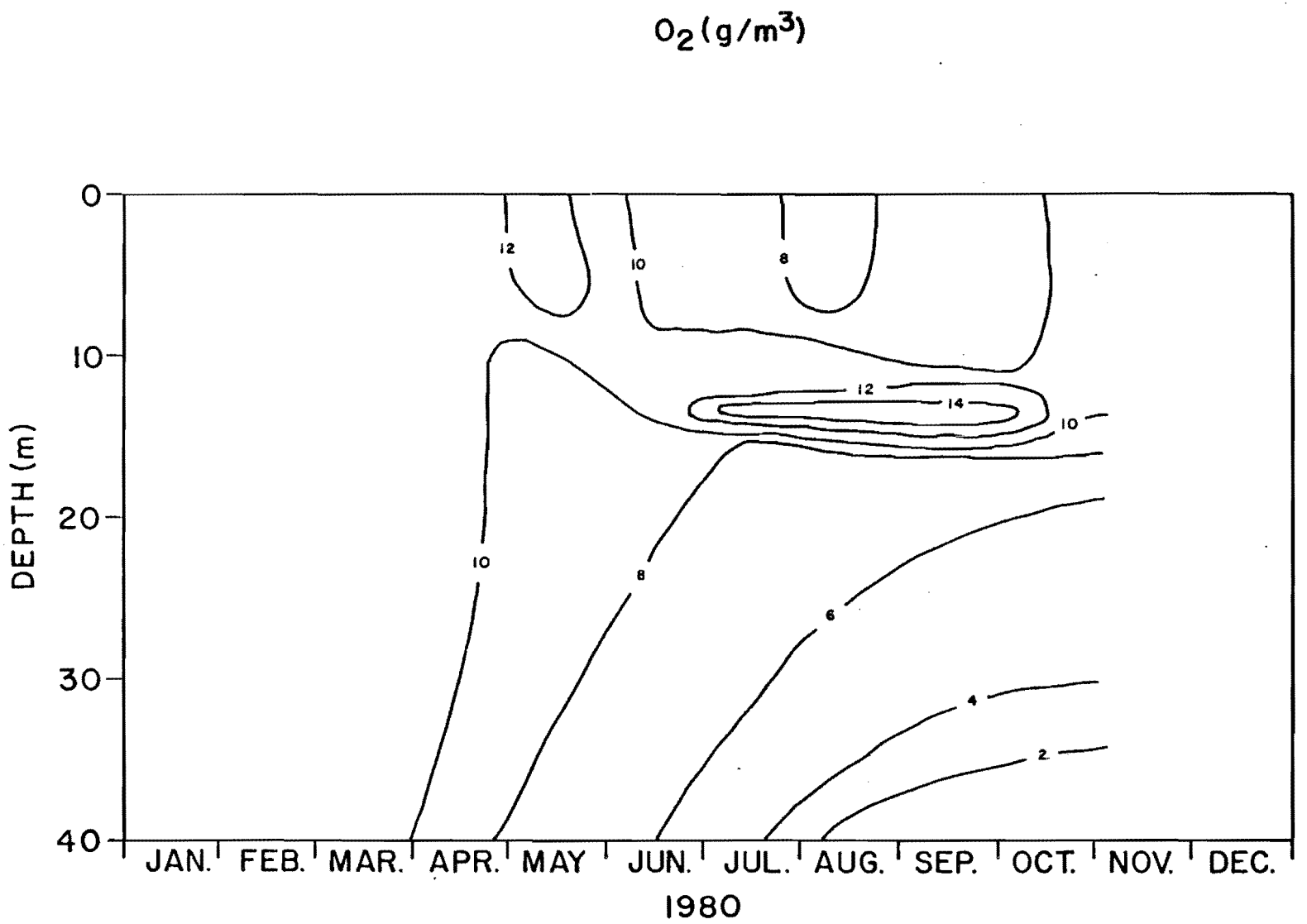


Figure 9. Depth-time isopleths for oxygen during 1980.

concentration in 1980 was 14.70 mg/l (120% saturation) at the fourteen meter depth on August 26th. In 1981, the maximum occurred on August 5th and was measured at 19.45 mg/l (170% saturation) at ten meters. The maximum observed oxygen concentration in 1982 of 16.30 mg/l (133% saturation) occurred again at ten meters.

The oxygen maximum generally occurred approximately one meter above the maximum concentration of the Oscillatoria population. Dissolved oxygen levels declined sharply below the depth of maximum concentration. Konopka (1981) attributes this occurrence to a rapid decrease in light intensity due to the density of Oscillatoria filaments and a resulting shift from net oxygen production to net respiration. Below the sharp oxygen maximum there was sometimes a slight oxygen minimum.

Although the maximum concentration of dissolved oxygen continues to increase in the metalimnion or hypolimnion throughout the summer stratification period as a result of the presence of Oscillatoria, the population of the alga gradually declines. Figure 10 shows the maximum measured biomass of the Oscillatoria in 1981 to have been 3113 u^3/ul, integrated over the 0-15 meter layer, on May 28. The population declined from that date with occasional fluctuations in size.

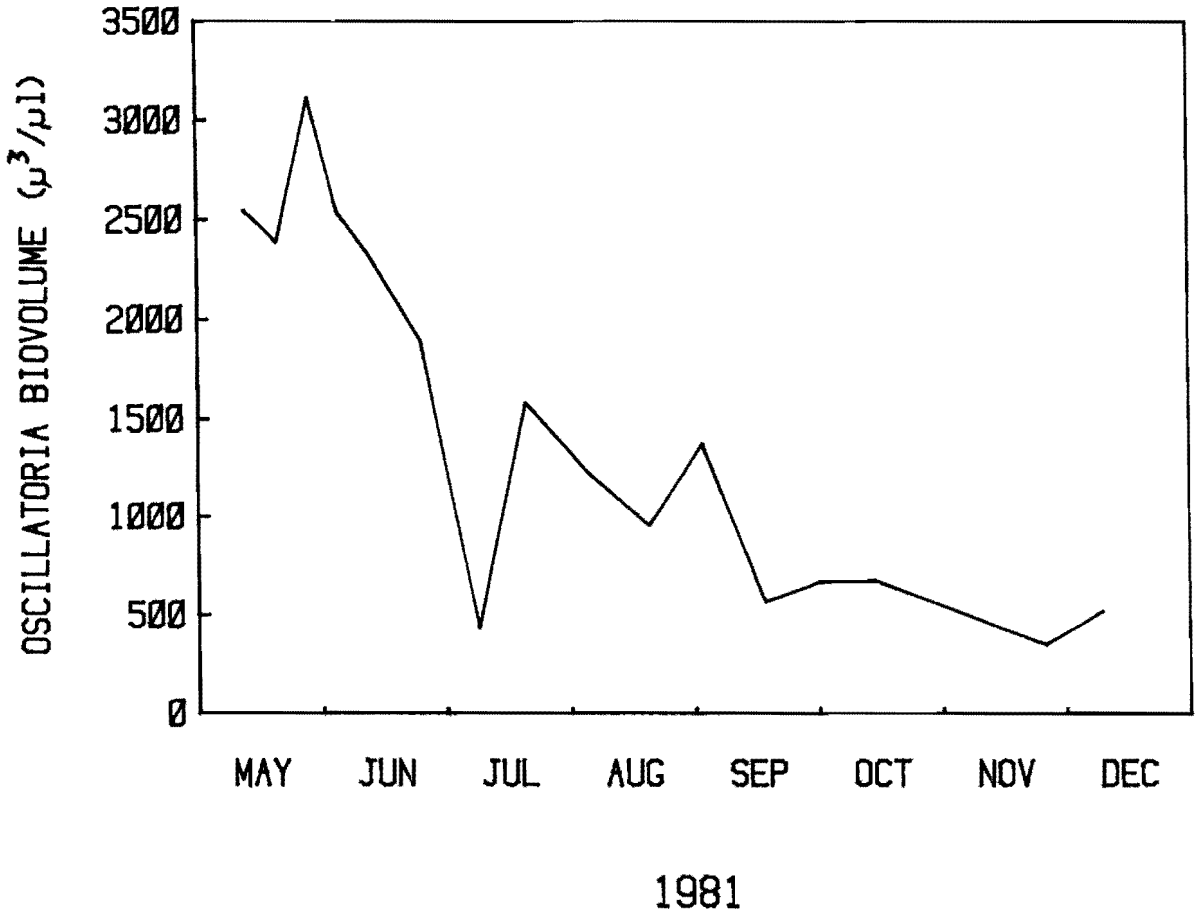


Figure 10. Plot of Oscillatoria concentration, integrated over the 0-15 meter depth layer, during 1981.

Trends in Phosphorus and Chlorophyll Levels During 1977-1982

Harvey's Lake has been sampled for spring total phosphorus and summer chlorophyll-a concentrations for six consecutive years during the period 1977-1982. A plot of this data is shown in Figure 11. Chlorophyll levels showed no significant trends during this period. However, spring phosphorus increased every year from 1977 to 1981, with a partial decline observed in 1982. This increasing trend is alarming in that it might indicate an increase in nutrient loading to the lake in recent years.

An analysis of the six-year phosphorus data was undertaken to determine the statistical significance of the trend. The phosphorus values were based on samples obtained on a single sample date each year immediately after spring turnover. Samples were obtained with replication at each of three lake stations by means of a vertically-integrating hose sampler. Thus, each total phosphorus value is the mean of six to nine individual samples.

The phosphorus trend was analyzed by means of a one-way analysis of variance, as shown in Table 3. Phosphorus differences between years were tested with an F test and found to be significant at $p < .01$. Variability in phosphorus levels between years was further partitioned into a linear component and a lack of linear fit component using the method of orthoganal polynomials (Steel and Torrie, 1960). The linear component was also found to be significant at $p < .01$. The downturn observed during 1982 resulted in a significant lack of fit component. This analysis shows that spring total phosphorus levels in Harvey's Lake differed significantly from year to year during the period of 1977-1982. Furthermore, the analysis shows that a significant increasing linear trend in phosphorus levels existed during this period.

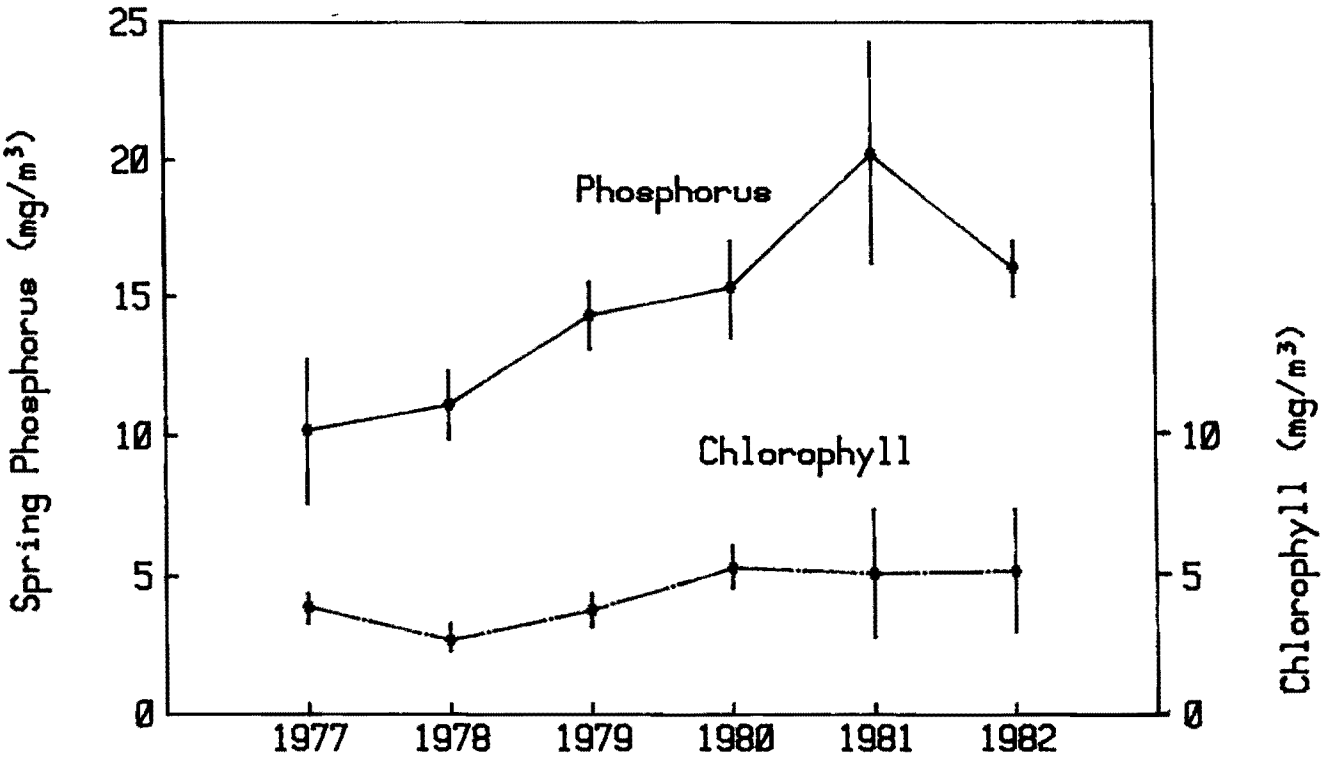


Figure 11. Trends in spring total phosphorus and summer chlorophyll in Harvey's Lake during 1977-1982. Chlorophyll samples were depth-integrated by means of a hose lowered to a depth of twice the Secchi disc depth. Spring phosphorus values were obtained from depth-integrated samples on a single sample date immediately after ice-out each year. Error bars about the chlorophyll values are 95% confidence intervals about the summer means, based on a weekly sampling program. Error bars about the phosphorus values are 95% confidence limits, based on six to nine replicate samples.

Table 3. Analysis of variance table for spring total phosphorus data, 1977-1982. Asterisks (*) indicate a significant F ratio at $p < .01$, using the residual error term.

Source	d.f.	SS	MS	F
Years	5	517	104	13.7*
linear	1	351	351	46.2*
lack of fit	4	166	41.5	5.5*
Residual	43	329	7.6	

The question remains as to whether this trend is the result of local changes in the watershed that have caused increased phosphorus loading to the lake, or whether the trend is merely the chance result of year to year variations in weather and runoff patterns. It is possible to differentiate between local effects and climatic effects by comparing the Harvey's Lake trend with data obtained on other Vermont lakes during the same time period. As part of the Vermont Department of Water Resources and Environmental Engineering Spring Phosphorus Program, 19 other lakes were sampled for spring total phosphorus each year during 1977-1982. This data can be used to establish a statewide spring phosphorus trend for this period against which the Harvey's Lake results can be compared.

Since the 19 lakes covered a wide range of trophic states, the year-to-year variability in phosphorus values differed greatly between lakes. Consequently, in order to compare trends among these 19 lakes, the phosphorus data was transformed as follows.

$$P_s = (P-M)/S \qquad (1)$$

where P_s = standardized phosphorus value
P = original phosphorus value
M = five year mean phosphorus value for a lake
S = standard deviation of phosphorus data for a lake

The effect of this transformation is to provide each lake with a six-year mean P_s value of 0 and a variance of 1.

The mean P_s values for all 19 lakes are plotted for each year in Figure 12. Based on a linear regression analysis, the slope of the statewide spring phosphorus trend shown in Figure 12, while positive, does not differ significantly from 0 at $p < .05$. The transformed data for Harvey's Lake is also plotted in Figure 12. The Harvey's Lake slope was significantly positive at $p<.05$. However, the Harvey's Lake slope was not significantly greater than the slope of the statewide trend over the entire 1977-1982 period. Thus, the possibility cannot be ruled out that the phosphorus trend in Harvey's Lake was the result of regional (e.g. climatic) factors that had a statewide effect, rather than local factors such as increased nutrient export from the lake's watershed.

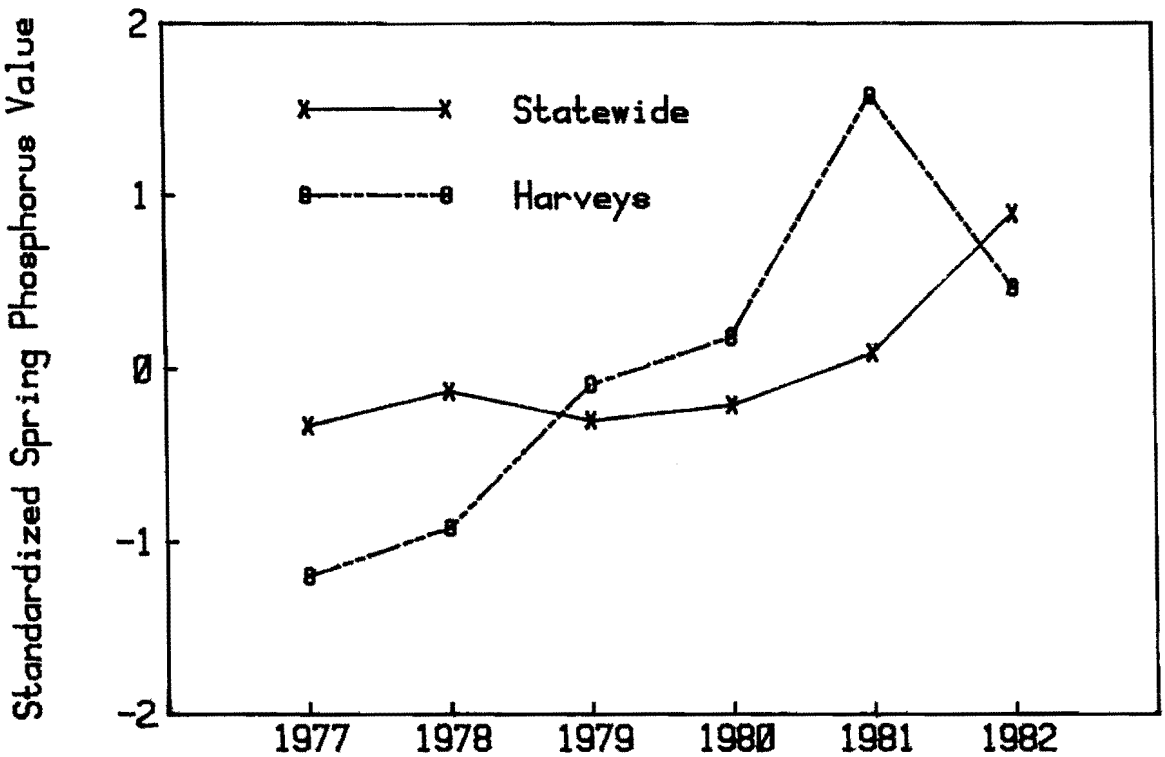


Figure 12. Standardized spring total phosphorus values for Harvey's Lake and for 19 other statewide Vermont lakes during 1977-1982. See text for an explanation of the standardization procedure.

Paleolimnological Studies

To examine the history of eutrophication in Harvey's Lake, a core of the lake sediments was obtained in September, 1981 and analyzed by paleolimnological techniques. This work was done under a contractual agreement with Edward Swain of the University of Minnesota. The paleolimnological study of Harvey's Lake is fully documented in Engstrom, Swain, and Kingston (1983). The summary of the results given below is based on direct excerpts from their report.

The millenium of sediment accumulation represented in the Harvey's Lake core can be divided into three periods of contrasting limnological development. A summary of the history is provided by a composite diagram of key stratigraphic variables in Figure 13. The oldest period from the base of the core to 34 cm (estimated dates of 850-1780 A.D.) is characterized by highly stable conditions -- relative to subsequent events -- during which time only minor fluctuations occur in sediment chemistry, pigments, or fossil diatoms. Oscillaxanthin accumulation is very low and diatom assemblages are dominated by benthic forms (65-75% of total valves). By all indications pre-settlement Harvey's Lake can be characterized as a clear-water oligotrophic system in which blue-green algae figured in only a minor way. Gradual shifts in the surrounding vegetation, particularly a regional increase in spruce are not reflected in other aspects of sediment stratigraphy.

Beginning at the settlement horizon (1780), however, a major departure from stability occurs. This event is marked by the first appearance of woodchips from the Jewett Brook sawmill and the sudden shift of pollen composition that resulted from the inception of logging activity and colonial agriculture. During the immediate post-settlement era total sediment accumulation increased four-fold over pre-settlement rates, primarily because of increased soil erosion from land clearance. At the same time, net accumulation of both benthic and planktonic diatoms increase, though the plankton at a higher rate, so that the diatom assemblage shifts markedly to one dominated by plankton forms, particularly *Cyclotella* spp. We interpret this shift to represent increased diatom production caused by an accelerated flux of nutrients from agricultural activity in the catchment.

The direct dumping of sawmill wastes into Harvey's Lake, a practice that continued until 1920, is manifest in the stratigraphic profiles of authigenic manganese and native chlorophyll as well as the presence of laminated sediments during this interval. The striking correlation between woodchip concentration and these three variables provides strong evidence for an early episode of increased sedimentary anoxia in the post settlement period of lake development that resulted from

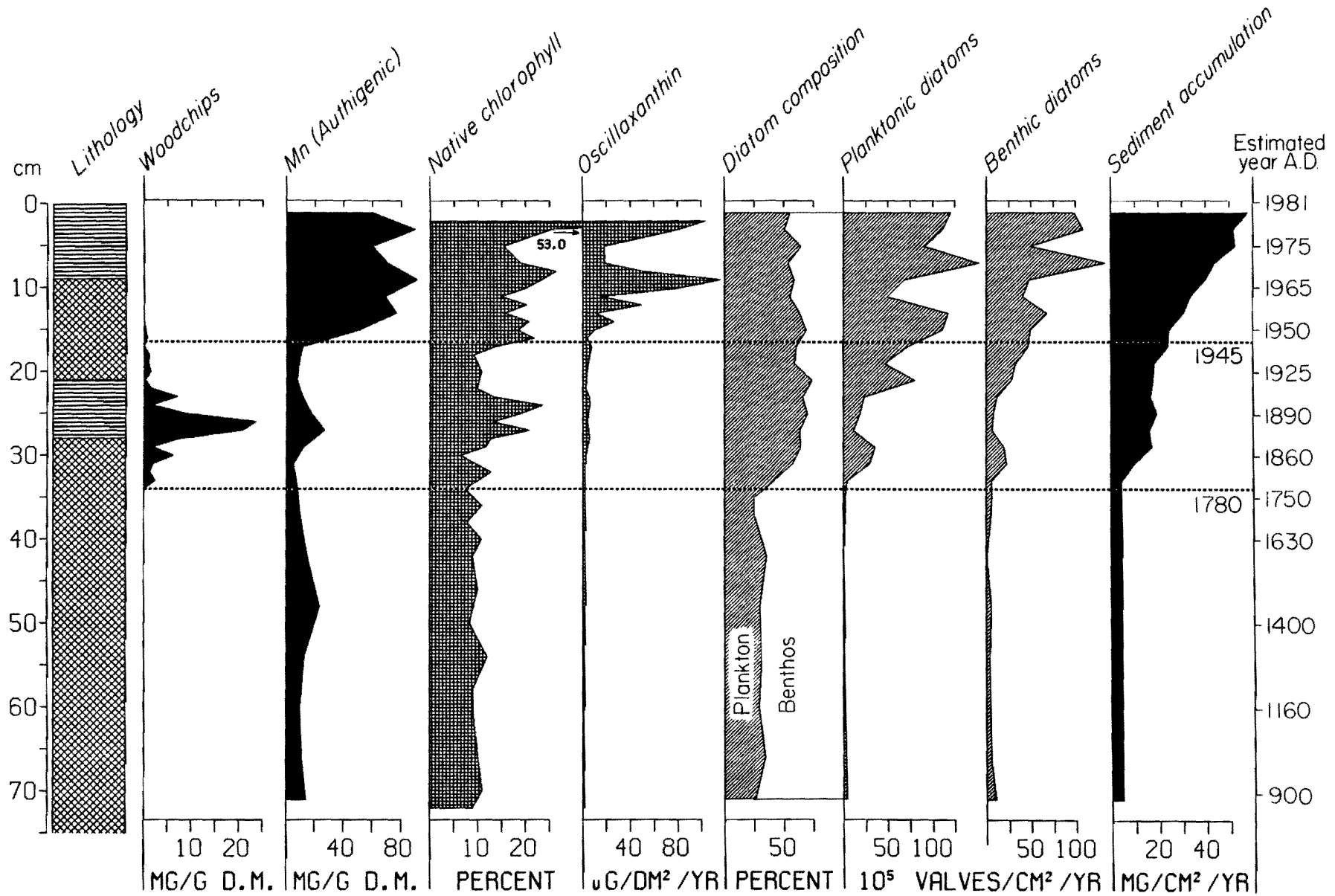


Figure 13. Summary of Harvey's Lake paleolimnological results. (From Engstrom et al, 1983)

bacterial degradation of sawdust. The anoxia increased Mn deposition at the core site through redox mobilization and focusing, enhanced chlorophyll preservation, and preserved laminations through the elimination of sediment mixing by benthic invertebrates. A decline in Mn and % native chlorophyll and the disappearance of laminations corresponds to the cessation of sawdust discharge in 1920 and indicates a return to lowered rates of hypolimnetic oxygen depletion at that time. Sawdust discharge itself does not appear to have increased overall diatom productivity as valve accumulation rates decline slightly during peak woodchip deposition (although poor preservation may figure in here) and pigment accumulation rates also show no change.

Despite these various perturbations, the accumulation of blue-green algal pigments does not increase significantly during this second period of the lake's history (1780-1945) and throughout most of the interval until about 1940 sediment accumulation remains nearly constant, although elevated above pre-settlement rates. The lake appears to have remained oligotrophic throughout and productivity changes during the first 165 years after settlement were small relative to more recent events. During the episode of increased sedimentary anoxia the hypolimnion probably remained largely oxygenated during stratification as it does today.

The most recent phase in the history of Harvey's Lake, which began about 1945, is marked by three independent events in the sedimentary record: (1) A second and perhaps more severe episode of sedimentary anoxia as indicated by the massive increase in Mn deposition and rise in chlorophyll preservation; (2) the first appearance of substantial blue-green algal pigments and *Stephanodiscus hantzschii*, which signals the transition to a eutrophic phytoplankton community; (3) the rapid acceleration of sediment accumulation that has continued unabated to the present.

The return to more reduced sediments suggests that oxygen depletion from organic loading to the hypolimnion increased markedly at this time. This condition has persisted to the present and is also marked by the reappearance of laminations above 9 cm. Historical trends in the hypolimnetic oxygen depletion rate calculated from direct measurement of oxygen profiles substantiate our conclusions from the sedimentary record. From 1978 to 1981 depletion rates ranged from 280 to 381 kg/day whereas for 1939 -- the only year for which historical data are available -- an oxygen depletion rate of 90 kg/day was calculated.

The 1945 increase in hypolimnetic oxygen depletion appears to be linked to increased autochthonous production unlike the earlier episode where allochthonous organic matter in the form of wood fiber was the cause. The earlier episode provides a controlled experiment whereby the stratigraphic changes in pigments and geochemistry associated with increased primary production can be separated from changes resulting from anoxia alone. This allows us to conclude that the sharp rise in

oscillaxanthin after 1945 is not an artifact of enhanced preservation, but actually marks the first appearance of the large populations of Oscillatoria rubescens that dominate the phytoplankton today. Actually Oscillatoria production may not have initiated sedimentary anoxia -- as the latter predates the oscillaxanthin increase by several years -- but instead increased productivity by other phytoplankton, particularly diatoms, which rise concurrently with Mn and native chlorophyll, probably was responsible for the initial shift in oxygen depletion.

Elevated primary production after 1945 almost certainly stems from increased nutrient flux to the lake, and two historically contemporaneous events in the watershed are the likely source of these inputs. First, the expansion of dairy farming in the watershed and the channelization of farm-waste runoff into Harvey's Lake about 1950 are the most probable causes for nutrient enhancement of algal production. The proliferation of summer homes along the shoreline -- each with individual septic systems -- represents a second potential source of nutrient enrichment. Moreover, the continuous acceleration in overall sediment accumulation since 1945 can largely be attributed to increasing erosion caused by excavation and land clearance from home-building activity near the lake shore.

Certain changes in diatom populations precede the 1945 horizon -- in particular the increase in nutrient-enrichment indicators such as Asterionella formosa and Fragilaria crotonensis begin about 1920 and contributes to the rise in planktonic diatom accumulation rates at that time. Land-use history for the Harvey's watershed is incomplete for this period so that anthropogenic influence is difficult to assess. Nonetheless, sedimentary evidence for productivity changes after 1945 is most striking, and the development of large populations of eutrophic indicators such as Stephanodiscus hantzschii and Oscillatoria attest to the major impact of events after 1945.

While planktonic and benthic diatoms, as well as oscillaxanthin, all exhibit trends of increasing accumulation since 1945, there exists rather marked fluctuations in each of these profiles up to the present. Oscillaxanthin shows distinct peaks in the periods 1965-1970 and 1978-1980 while the diatoms are low at these strata but higher in between. Chlorophyll derivatives, on the other hand show a steady increase in accumulation throughout and since both blue-green algae and diatoms produce chlorophyll, the fluctuations in their respective profiles apparently result from changes in algal composition rather than shifts in overall primary production. The inverse relationship between oscillaxanthin and planktonic diatoms is particularly striking in this regard and provides historical evidence for the kind of long-term negative interaction between blue-green algae and diatoms documented by Keating (1978). In addition, the percentage of planktonic diatoms in the total sedimentary assemblage declines slightly at strata where peak

blue-green algal pigment accumulation occurs. Any negative influence of large Oscillatoria populations should most affect planktonic diatoms, which these data indicate.

Thus, the recent limnological trend in Harvey's Lake, as revealed in the sedimentary record, is one of increasing eutrophy, hypolimnetic oxygen depletion and Oscillatoria dominance of the phytoplankton. Production by diatom populations including benthic forms has also increased which indicates that water clarity has not seriously diminished. Present-day transparency in Harvey's Lake is anomolously high relative to other lakes with similar P-loading because much of the mid-summer biomass resides in the metalimnion. However, this present condition has developed only in recent years and may represent a transitional stage in water quality that could be succeeded by epilimnetic blue-green algal populations if nutrient loading continues to accelerate. From the sedimentary record we see no evidence that nutrient enrichment has abated and indeed, water quality monitoring has revealed increasing phosphorus levels in the lake over the last five years.

Our stratigraphic analysis of Harvey's Lake sediments clearly shows that limnological conditions today are radically different from the oligotrophic state that existed prior to settlement and that much of the change occurred in very recent times. While the anthropogenic eutrophication of Harvey's Lake is not, in itself, an unique story our reconstruction of this history is unusually detailed and unambiguous because of the synthesis of several sedimentary parameters and precise sediment dating. Like any type of historical research, paleolimnology is most reliable when several independent lines of evidence are brought to bear.

The Relationship Between Algae and Transparency in Harvey's Lake

Secchi disc transparency in Harvey's Lake averaged 6.3 meters during the summers of 1979-1982. This value was based on a weekly sampling program conducted during June-August each year under the Lay Monitoring Program of the Vermont Department of Water Resources and Environmental Engineering. This high degree of water clarity is a consequence of the deep-living habits of the *Oscillatoria* population. Relatively few algae exist in the surface waters during the summer months (see Figure 8). A shift in algal species composition away from *Oscillatoria* dominance could result in increased epilimnetic populations and, hence, in a reduction in transparency. Secchi disc data obtained from Harvey's Lake can be used to predict the extent of the transparency reduction to be expected with increased algal abundance in the surface waters.

Chlorophyll sampling conducted at 5 meter depth intervals during 1980 was used with concurrent Secchi disc measurements to develop a relationship between epilimnetic chlorophyll levels and transparency in Harvey's Lake. Secchi disc transparency in lakes is influenced by the concentration of light-attenuating materials, including algal cells and their pigments, dissolved organic coloring matter, and suspended inorganic particles. Theoretical considerations (Brezonik, 1978; Megard *et al*, 1980) indicate that the reciprocal of the Secchi depth (1/SD) should be a linear function of the concentration of light-attenuating materials. A linear regression of 1/SD on epilimnetic chlorophyll concentration (Chl) can therefore be used to analyze the dependence of transparency on algal abundance. This regression produced the following equation for Harvey's Lake during the 1980 ice-free season.

$$1/SD = 0.019\ Chl + 0.12 \qquad (2)$$
$$(R^2 = .80)$$

Equation 2 can be used to predict the impact of increased epilimnetic chlorophyll levels on Secchi disc transparency.

It is difficult to accurately foresee the changes in epilimnetic chlorophyll levels that would occur if the Harvey's Lake phytoplankton community shifted in favor of surface dwelling populations. If it is assumed that the quantity of chlorophyll in the entire water column would not change with such a species shift, but would be compressed into the top 5 meters, then a tentative estimate can be made of the epilimnetic chlorophyll increase to be expected. Numerical integration of chlorophyll concentrations over the 0-15 meter layer indicated that areal chlorophyll concentrations averaged 61 mg/m^{-2} during June-September, 1980. If this quantity of chlorophyll was compressed into the 0-5m layer, then the resulting epilimnetic chlorophyll level would be 12 mg m^{-3} (compared with the observed June-September mean of 1.9 mg m^{-3}). From equation 2, it can be predicted that this increase in chlorophyll concentration would result in a reduction in the summer Secchi disc transparency from 6.7 to 2.9 meters.

This prediction probably represents the "worst case" that could be expected if algal species composition shifted to epilimnetic populations. It is unlikely that chlorophyll levels as high as 12 mg m^{-3} would be sustained throughout the summer. Chlorophyll levels of 12 mg m^{-3} lie at the upper limit of the range of values that are expected from the phosphorus-chlorophyll relationship of Dillon and Rigler (1974), given the observed spring total phosphorus levels of 15 mg m^{-3} in Harvey's Lake during 1980. Therefore, the actual transparency reduction would probably be less severe than the prediction given above.

The Effect of Blue-Green Algae on the Efficiency of Energy Transfer Between Trophic Levels

One of the possible benefits of an algal species shift in Harvey's Lake away from *Oscillatoria* dominance in favor of diatoms is an increased efficiency of zooplankton production. Increased zooplankton production would, in turn, be passed on to planktivorous fish and, ultimately, to the adult salmonid populations in the lake that are valued by fishermen. The suggestion that this benefit would occur is based on the supposition that blue-green algae such as *Oscillatoria* suppress zooplankton production, either by providing a nutritionally poor food source, or by secreting toxic compounds.

To examine the question of whether the blue-green algal dominance in Harvey's Lake is causing reduced energy flow to higher trophic levels, this report will do the following:

(1) Review the evidence from published zooplankton feeding studies that blue-green algae reduce zooplankton production.

(2) Review the evidence from published whole lake production studies that trophic efficiencies decline with increasing degree of eutrophication and with increasing dominance of the phytoplankton community by blue-green algae.

(3) Present the results of production studies carried out on Harvey's Lake and compare the trophic efficiency in Harvey's Lake with efficiencies determined for other lakes.

(4) Describe the spatial and temporal distribution of zooplankton in Harvey's Lake with respect to the *Oscillatoria* layer to determine whether avoidance of the *Oscillatoria* by zooplankton is occurring.

Zooplankton Feeding Studies.

The suggestion that blue-green algae "short-circuit" aquatic food chains by providing a poor food source for zooplankton

herbivores receives support from various zooplankton feeding studies. It appears that blue-green algae are ingested less readily than are other algal types. The colonial or filamentous growth form of many blue-greens can interfere with the filter-feeding apparatus of zooplankton (Burns, 1968). The physical unmanageability of certain blue-greens may result in reduced exploitation by zooplankton (Porter, 1973; Vijverberg, 1976). Even when they are ingested, blue-green algae may be assimilated into zooplankton tissue less efficiently than other algal types (Arnold, 1971). Finally, there is evidence that blue-green algae, or extracts from blue-green algal cultures, can produce toxic effects on zooplankton (Stangenberg, 1968; Arnold, 1971; Lampert, 1981).

Whole Lake Production Studies.

Field studies on the influence of blue-green algae on food chain efficiency are rare. Pederson et al (1976) provided a test of the hypothesis, which they attribute to Hillbricht-Ilkowska (1972), that zooplankton food supply in lakes is used less efficiently with increasing eutrophy. By quantifying primary and secondary production rates in three Washington lakes, Pederson et al found that the energy transfer efficiency, defined as the ratio of herbivore production/primary production, was greatest for the most oligotrophic of the three lakes, and declined with increasing eutrophy. In further support of the hypothesis, Pederson et al analyzed data from Hall et al (1970) in which three experimental ponds were artificially enriched with algal nutrients. The efficiency of energy transfer from algae to zooplankton in these ponds declined with increasing degree of nutrient enrichment.

While the two studies cited above tend to support the hypothesis of reduced energy transfer efficiency between algae and zooplankton with increasing eutrophy, they suffer the limitation of being based on a limited number of lakes. There is a considerable quantity of lake primary and secondary production data that was obtained through studies conducted under the

International Biological Program (IBP) and published in Kajak and Hillbricht-Ilkowska (1972). This data source has been used to construct plots of zooplankton productivity vs. phytoplankton productivity (Brylinsky and Mann, 1972; Makarewicz and Likens, 1979). These plots show positive relationships between zooplankton productivity and primary productivity. In analyzing data from eleven lakes, Makarewicz and Likens found, surprisingly, that the ratio of zooplankton productivity/primary productivity increased with increasing primary production rates, suggesting that trophic efficiency is greater, rather than lower, in more eutrophic lakes. However, McCauley and Kalff (1981) analyzed an independent data set and found that the ratio of zooplankton biomass to phytoplankton biomass decreased with increasing phytoplankton biomass. Furthermore, McCauley and Kalff reanalyzed the Makarewicz and Likens data using formal statistical methods and found that the ratio of zooplankton productivity to phytoplankton productivity, in fact, decreased with increasing phytoplankton production rates. Thus, the bulk of the data reviewed by these studies supports the hypothesis of reduced energy transfer between algae and zooplankton with increasing eutrophy.

This report will extend the analysis of Makarewicz and Likens (1979) by expanding the data base to include thirty lakes, and by obtaining data on phytoplankton community composition for each lake to determine specifically whether dominance by blue-green algae leads to lowered trophic efficiency. Published data from the IBP and from other sources was obtained for thirty lakes on which both phytoplankton and zooplankton productivity measurements were available. Phytoplankton primary production rates reported in the original sources were measured either as oxygen production, or as C-14 assimilation. All primary production rates were converted to net primary production (NPP) in units of $Kcal/m^2/day$, according to the conversion factors given in Table 4. The productivity measurements apply to time periods which ranged from as little as a few weeks during a single season up to periods encompassing one or more years.

However, phytoplankton and zooplankton production rates reported for each lake, were, in all cases, measured concurrently and apply to the same time period.

Descriptions of phytoplankton community composition were also obtained for each lake. This data varied in detail from brief qualitative descriptions to complete and quantitative taxonomic information. The best available phytoplankton data was used to place each lake into one of three categories, based on the degree of dominance by blue-green algae during the period in which the production measurements were made. These three categories are defined in Table 5.

The results of the survey of thirty lakes are given in Table 6. In Figure 14, zooplankton production is plotted against net phytoplankton production. The data was transformed logarithmically in order to equalize the residual error about the regression line.

The plot shows a positive relationship between zooplankton production and phytoplankton production, as found by Brylinsky and Mann (1973) and Makarewicz and Likens (1979). The slope of the regression line in Figure 14 was found to be significantly less than 1.0 ($p < .05$), indicating that the ratio of ZP/NPP (i.e., the trophic efficiency) declines with increasing net primary production. This is in agreement with the results of the earlier analyses cited above.

The slope of the line in Figure 14 suggests that more productive lakes tend to have somewhat reduced trophic efficiencies. However, when the ratio of ZP/NPP is plotted against the degree of blue-green algal dominance, as in Figure 15, no significant relationship is apparent. Thus, this analysis of thirty diverse lakes provides no firm evidence for the hypothesis that increasing blue-green algal dominance is the causal factor leading to reduced efficiency of energy transfer from phytoplankton to zooplankton.

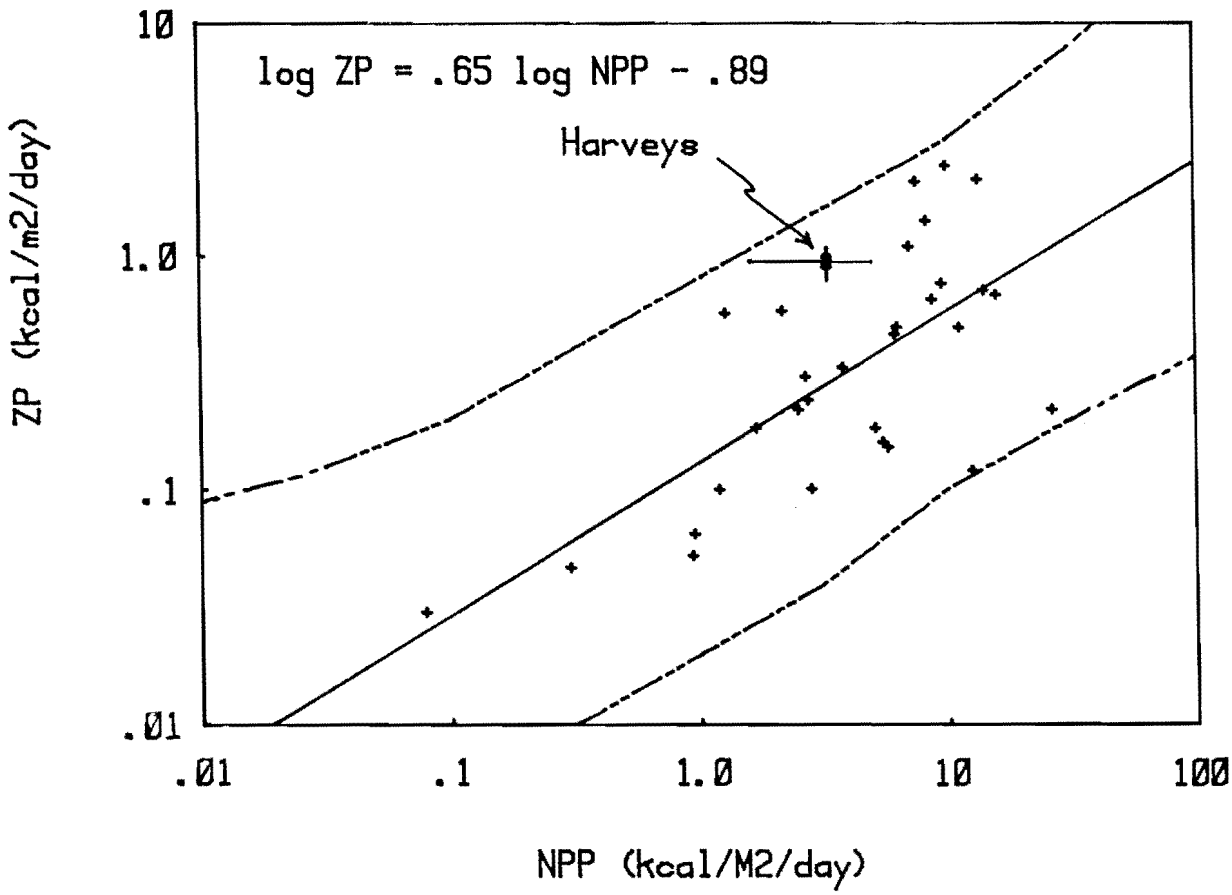


Figure 14. The regression of zooplankton production (ZP) on net primary production (NPP) for 30 globally distributed lakes. Dotted lines represent the 95% confidence intervals about the regression line. The Harvey's Lake point, with error bars (see text for explanation), is also shown.

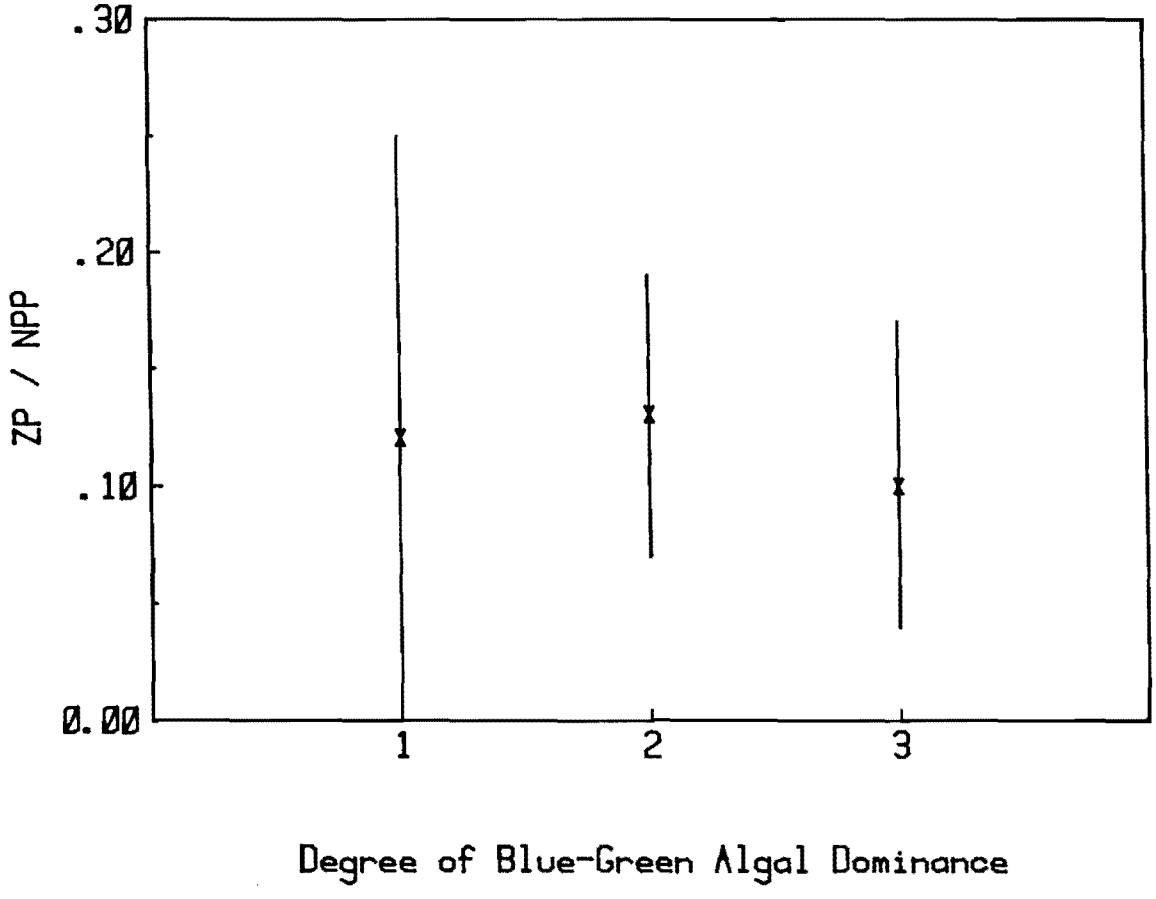


Figure 15. Plot of trophic efficiency (ZP/NPP) against degree of blue-green algal dominance. See Table 5 for definitions of blue-green algal dominance categories. Error bars represent 95% confidence intervals about the mean efficiency for each blue-green algal dominance category.

Table 4. Conversion factors used in productivity calculations, with supporting references.

NPP = 0.8 x gross O_2 production rate, where 1 g O_2 = 3.5 Kcal (Winberg *et al*, 1972; Hillbricht-Ilkowska *et al*, 1972).

NPP = C-14 assimilation rate, where 1 g C = 9.4 Kcal (Brylinsky and Mann, 1973).

1 g Zooplankton dry weight = 5.5 Kcal (Pederson *et al*, 1976).

Table 5. Definitions of three categories of blue-green algal dominance used in the production literature survey.

Category	Definition
1	Few or no blue-green algae present.
2	Blue-green algae present, but not dominant in the phytoplankton.
3	Blue-green algae dominant in the phytoplankton. This category includes lakes that experience a spring diatom bloom but have blue-green algal dominance through most of the summer.

Zooplankton Production Efficiency in Harvey's Lake.

Rates of phytoplankton and zooplankton production were measured in Harvey's Lake during 1981. These measurements can be compared with data shown in Table 6 to examine the question of whether the prevalence of *Oscillatoria* in the Harvey's Lake phytoplankton community is resulting in lowered efficiency of zooplankton production.

Phytoplankton production rates were measured by the light and dark bottle method. Glass 300ml B.O.D. bottles were filled with lake water and incubated *in situ* at the depths from which

they were filled. Paired light and dark bottles were incubated from dawn to dusk at depths of 0, 2.5, 5, 10, and 15 meters once every two weeks during the period of June-September. Differences in oxygen concentration between light and dark bottles were used to calculate rates of gross primary production. The average summer depth profile of gross primary production is shown in Figure 16. A productivity maximum existed in 10 meters corresponding to the *Oscillatoria* layer, but most of the production occurred in the surface waters, in spite of low algal densities there.

Gross production rates were converted to units of $Kcal/m^3/day$ according to the conversion factors given in Table 4. These volumetric rates were integrated with depth to obtain areal production rates, averaged over all sample dates. The June-September mean net primary production rate in Harvey's Lake determined in this manner was 3.3 $Kcal/m^2/day$, with a standard error of 0.76 $Kcal/m^2/day$, based on eleven sample dates.

Zooplankton production rates in Harvey's Lake were measured during the same period, as follows. Zooplankton samples were obtained once every two weeks during June-September using a 27.5 liter Schindler-Patalas type quantitative zooplankton trap (Schindler, 1969). Samples were obtained at five-meter depth intervals through the entire 40 meter water column. Equal volume aliquots from all samples were then pooled into a single composite sample, representing the average zooplankton concentrations for all dates and all depths in the 40 meter water column. The various zooplankton taxa present in the composite were identified according to Ward and Whipple (1959) and counted microscopically using a Sedgewick-Rafter counting cell. Zooplankton biomass was determined by measuring the body length of each individual counted and by applying appropriate length vs. dry weight regression relationships from Dumont *et al* (1975).

The results of the zooplankton counts are given in Table 7. The June-September, 1981 mean zooplankton biomass in Harvey's Lake was 89.5 mg dry $weight/m^3$, or 3.6 g/m^2 in the entire 40 meter water column. Zooplankton biomass was dominated by cladocerans (71% of the total biomass), particularly by *Daphnia*

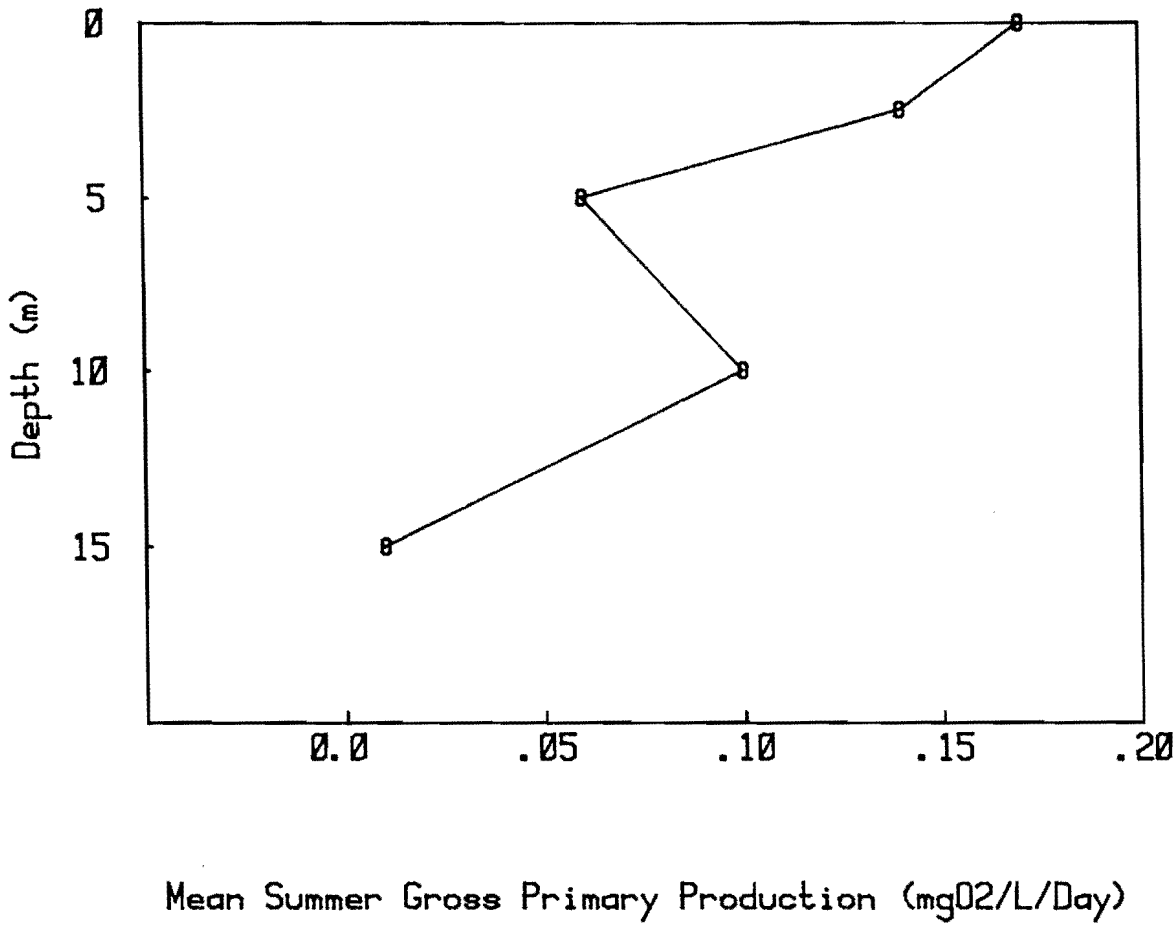


Figure 16. Average summer depth profile of gross primary production in Harvey's Lake, 1981.

Table 6. Summary of production data on thirty globially-distributed lakes.
NPP = net primary production (Kcal/m^2/day),
ZP = zooplankton production (Kcal/m^2/day),
BG = degree of blue-green algal dominance (see Table 5)

Lake	NPP	ZP	BG	Reference
Canyon Ferry Res.	8.4	1.4	2	Wright (1965)
Mirror	.95	.065	2	Makarewicz & Likens (1979)
Severson	12.7	.12	3	Comita (1972)
Bysjon	6.1	.46	1	Coveny *et al* (1977)
Vechten	3.8	.33	2	Gulati (1975)
Tjeukemeer	14.1	.70	3	"
LN	1.7	.18	1	Hall *et al* (1970)
MN	5.5	.16	1	"
HN	26.3	.22	3	"
Smyslov	2.2	.58	3	Korinek (1972)
Rybinsk Res.	2.7	.24	3	Sorokin (1972)
Kurakhov	5.7	.15	3	Pidgaiko *et al* (1972)
Clear	1.3	.56	1	Schindler (1972)
239	2.8	.10	1	"
Baikal	2.5	.22	1	Moskalento & Votinsev (1972)
Lock Leven	15.8	.68	2	Morgan (1972)
Mikolajskie	13.5	2.2	3	Hillbricht-Ilkowska *et al* (1972)
Sniardwy	11.2	.49	1	"
Taltowisko	10.3	2.4	2	"
Flosek	7.7	2.1	3	"
Findley	.93	.052	2	Pederson *et al* (1976)
Chester Morse	1.2	.096	2	"
Sammamish	5.1	.18	3	"
Red	6.4	.48	2	Andronikova (1972)
Krivoe	.30	.047	2	Alimov *et al* (1972)
Krugloe	.079	.030	2	"
Naroch	2.7	.30	2	Winberg *et al* (1972)
Batorin	8.6	.64	3	"
Myastro	9.6	.76	2	"
Kiev Res.	7.1	1.1	3	Gak *et al* (1972)

Table 7. Mean June-September, 1981 zooplankton concentrations in Harvey's Lake.

	Numbers/liter	Dry Weight Biomass (mg/m^3)
Cladocera		
Daphnia pulex	1.9	29.7
Daphnia parvula	0.9	7.6
Daphnia galeota mendotae	1.8	24.7
Bosmina sp.	1.5	1.9
Total Cladocera	6.1	63.9
Copepoda		
Calanoida	0.6	4.6
Cyclopoida	2.3	7.2
nauplii	18.2	3.6
Total Copepoda	21.1	15.4
Rotifera		
Keratella quadrata	26.8	8.5
Keratella cochlearis	7.6	0.8
Kellicottia sp.	8.7	0.9
Polyartha sp.	0.8	0.1
Total Rotifera	43.9	10.2
Total Zooplankton	71.1	89.5

pulex and *Daphnia galeata mendotae*. Zooplankton biomass was converted to units of $Kcal/m^2/day$ according to the conversion factors given in Table 4.

Zooplankton production was calculated by applying an assumed production/biomass (P/B) ratio to the June-September mean biomass. Waters (1977) reviewed an extensive literature on secondary production measurements and concluded that most P/B ratios for whole zooplankton communities fell in the range of 15-20 $yr.^{-1}$, corresponding to a daily P/B ratio of .041-.055 day^{-1}.

Application of these P/B values to the June-September mean biomass could lead to a slight underestimate of production rates because annual-based P/B ratios are generally lower than those obtained during summer (see Pederson *et al*, 1976). However, the effect of this problem is probably minor because many of the P/B ratios given in Waters (1977) were actually based on summer or growing season periods, rather than on full year measurements. Use of the P/B values given above results in a zooplankton production rate estimate for Harvey's Lake during June-September, 1981, of 0.8-1.1 $Kcal/m^2/day$.

The Harvey's Lake phytoplankton and zooplankton production data can now be compared with data from thirty globally-distributed lakes shown in Figure 14. Precision estimates for the Harvey's Lake data were derived from the variability among sampling dates in the case of phytoplankton production, and from the likely range of P/B values in the case of zooplankton production. Error bars about the Harvey's Lake point in Figure 14 represent the 95% confidence interval about the phytoplankton production rates, based on an assumed P/B range of .041-.055 day^{-1}. Error in the zooplankton production rate is somewhat underestimated because error resulting from the sample compositing and counting procedure was not taken into account.

It can be seen from Figure 14 that the Harvey's Lake point is above the zooplankton vs. phytoplankton production regression line, but falls within the 95% confidence interval about the regression line. Zooplankton production in Harvey's Lake is at or above levels expected for a lake with its primary production

characteristics, based on this comparison with a diverse set of thirty lakes. Thus, this analysis does not support the conclusion that dominance of the Harvey's Lake phytoplankton community by Oscillatoria is interfering with zooplankton production.

Vertical Distribution of Zooplankton in Harvey's Lake

To examine the question of whether the zooplankton in Harvey's Lake avoided the Oscillatoria layer at 10-15m depth, the zooplankton were sampled at five meter depth intervals during June-September, 1981. Samples were obtained using the 27.5 liter zooplankton trap described above. Direct visual microscopic counts were made of animals filtered onto membrane filters. Average "total" zooplankton numbers (cladocerans plus copepods) at each depth, based on 10 sample dates during June-September, 1981, are shown in Figure 17. Maximum zooplankton concentrations were found in a broad depth layer from 5 to 15 meters, overlapping with the Oscillatoria. This pattern was consistent throughout the summer. The slight minimum value observed at the 10 meter depth was not statistically different from mean zooplankton concentrations at the 5 and 15 meter depths. Thus, it appears that the zooplankton showed no avoidance of the Oscillatoria layer.

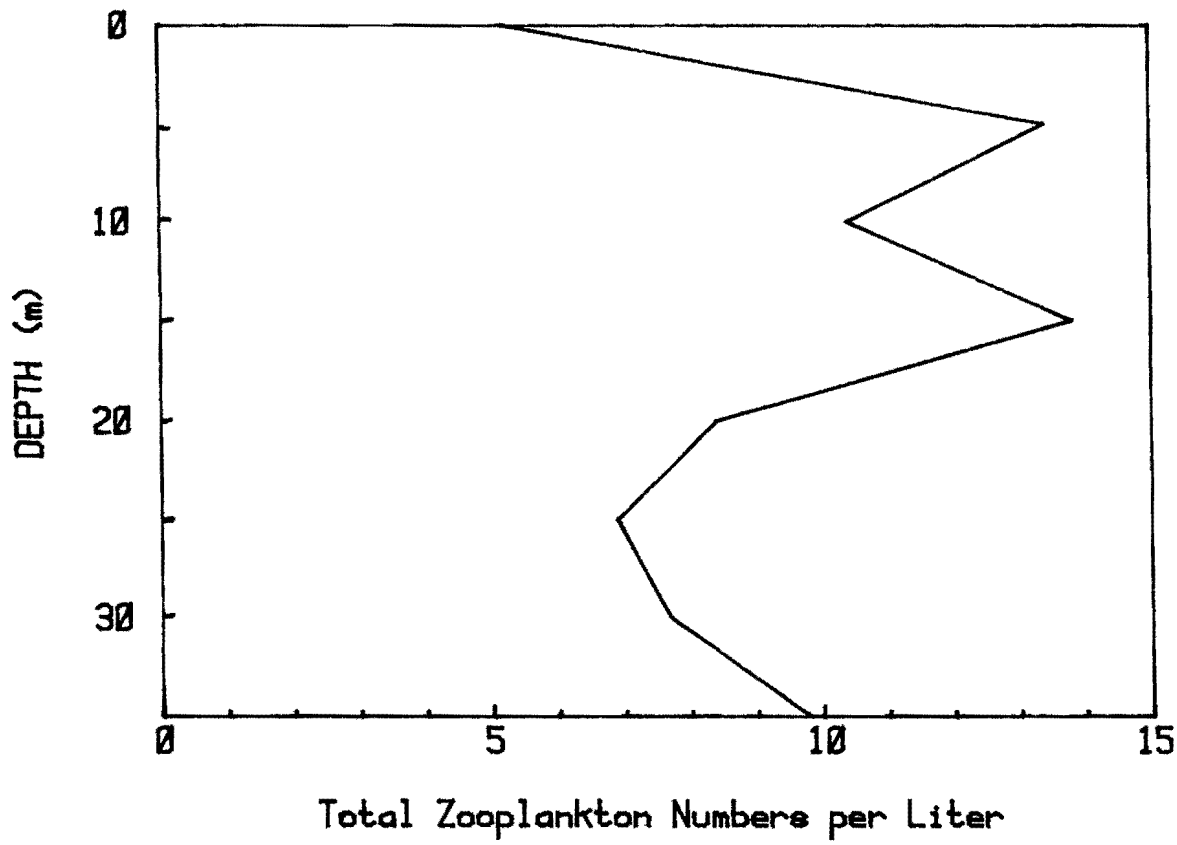


Figure 17. Depth profile of average summer zooplankton numbers, 1981.

Phosphorus "Stripping" by Algal Populations

One possible benefit of a species shift to diatoms by silica addition is the enhanced sedimentation of phosphorus that might occur via diatom sinking. For example, Vignon (1976) determined that substantial removal of epilimnetic phosphorus occurred during spring diatom blooms in two Wisconsin lakes. Phosphorus sedimented below the thermocline in this manner was unavailable to support summer growth of algae.

The 1980 sampling results indicate that an effective phosphorus stripping mechanism may already exist in Harvey's Lake. Figure 5 shows that, with the onset of thermal stratification, there was a downward movement of phosphorus and an accumulation of phosphorus in the *Oscillatoria* layer near 15 meters. These observations indicate that when the *Oscillatoria* migrated downward to the depths at which they existed throughout the summer, they took a substantial portion of the lake's phosphorus with them. The result was that epilimnetic total phosphorus concentrations during summer declined to 28% of spring levels. The low levels of phosphorus that remained in the epilimnion (mean summer TP = 4.8 mg/m^3) supported very little algal growth, with epilimnetic chlorophyll concentrations averaging less than 2.0 mg/m^3 during the summer months.

Hypolimnetic Oxygen Depletion

Sampling for dissolved oxygen at five meter depth intervals was carried out in Harvey's Lake throughout the entire stratification period during the summers of 1980-1982. This section will do the following:

(1) Describe the hypolimnetic dissolved oxygen conditions observed in Harvey's Lake and evaluate the magnitude of any threat to fish.

(2) Calculate hypolimnetic oxygen depletion rates and compare them with values predicted for Harvey's Lake by various empirical models based on physical, hydrological, and trophic state characteristics.

(3) Compare the hypolimnetic oxygen depletion rates observed during this study with data from past years to determine whether a trend toward deteriorating oxygen conditions exists.

(4) Evaluate the role of the deep-living *Oscillatoria* population in the hypolimnetic oxygen regime of Harvey's Lake.

Hypolimnetic Oxygen Conditions

A typical summer depth profile of dissolved oxygen and temperature obtained during the course of this study is shown in Figure 8. A sharp oxygen maximum existed in the upper portions of the hypolimnion, resulting from photosynthetic oxygen production by the *Oscillatoria* population. A significant oxygen deficit was observed in the deeper portions of the hypolimnion. However, oxygen concentrations in the hypolimnion during the course of the study never declined to levels that would threaten fish or promote anaerobic metabolism in the water column. The volume-weighted mean oxygen concentration in the hypolimnion reached 5.0 mg/l only at the very end of the stratification period. Maximum oxygen concentrations in the hypolimnion never

fell below 5.0 mg/l, and levels below 1.0 mg/l were observed only in the water adjacent to the sediments in the deepest portions of the basin. A threat to fish could develop, however, if substantial further deterioration in oxygen conditions were to occur.

Oxygen Depletion Model Predictions

Hypolimnetic oxygen depletion rates for Harvey's Lake during 1980-1982 were calculated according to the method of Lasenby (1975) from oxygen samples obtained at five meter depth intervals. A depth of 12.5 meters was chosen as the upper boundary of the hypolimnion, with a corresponding hypolimnetic area of 9.3×10^5 m^2 and a volume of 14.1×10^6 m^3. Regression analyses of hypolimnetic oxygen content vs. time indicated that the hypolimnetic oxygen depletion rates were 290 kg/day in 1980, 540 kg/day in 1981, and 370 kg/day in 1982.

A number of empirical models have been developed to predict areal hypolimnetic oxygen depletion (AHOD) rates for lakes. These models are based on lake physical, hydrological, and trophic state characteristics. The AHOD rates observed in Harvey's Lake during this study can be compared with values expected from these models to determine whether Harvey's Lake is unusual with respect to its hypolimnetic oxygen depletion rate. Limnological data from Harvey's Lake obtained from Vermont Department of Water Resources (1977) and from 1980 sampling results were used to generate the model predictions. Observed and predicted AHOD rates for Harvey's Lake are shown in Table 8. AHOD rates for Harvey's Lake averaged 430 $mg/m^2/day$ during 1980-1982, while the model predictions ranged from 188 to 452 $mg/m^2/day$. Therefore, it cannot be said that hypolimnetic oxygen depletion rates in Harvey's Lake are unusual for a lake of its physical, hydrological, and trophic state characteristics.

Table 8. Comparison of the areal hypolimnetic oxygen depletion rates (AHOD, $mg/m^2/day$) for 1939 with rates observed during 1978-1982, and with rates predicted from six lake oxygen depletion models.

AHOD	Source
90	1939 observed
280	1978 observed
323	1979 observed
312	1980 observed
581	1981 observed
398	1982 observed
268	Model Prediction (Cornet & Rigler, 1979)
379	Model Prediction (Welch, 1979)
251	Model Prediction (Rast and Lee, 1978)
452	Model Prediction (Walker, 1979)
188	Model Prediction (Lasenby, 1975)
338	Model Prediction (Charlton, 1980)

Historical Trends in Hypolimnetic Oxygen Depletion Rates

There is some limited dissolved oxygen data available for Harvey's Lake from past years. Data collected during 1978 and 1979 was used to calculate AHOD rates for those years. The results, shown in Table 8, indicate that there has been no discernable trend in AHOD rates during the five year period of 1978-1982.

A single oxygen profile from Harvey's Lake was obtained on August 23, 1939. The 1939 profile is compared with a profile obtained on a similar date in 1980 in Figure 18. It is apparent from this comparison that the hypolimnetic oxygen deficit is much more severe now than it was in 1939. This change may indicate a substantial increase in lake productivity during the past 40 years.

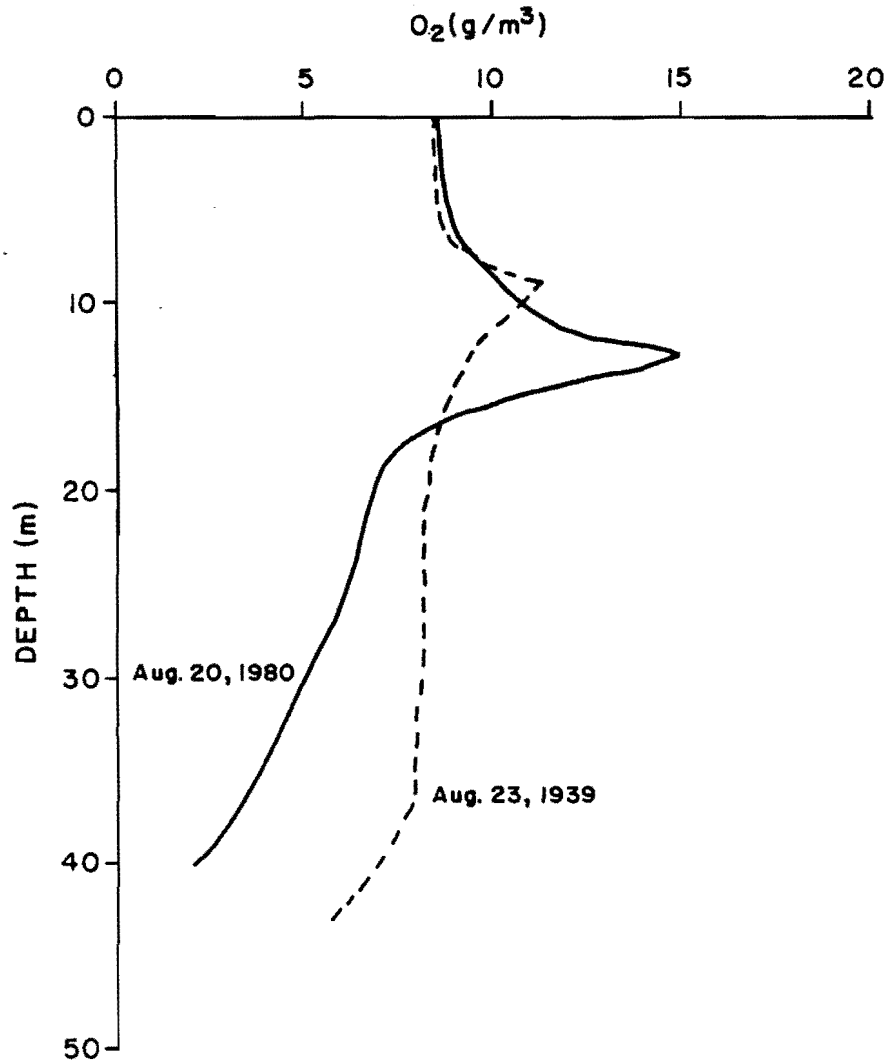


Figure 18. A comparison of August oxygen profiles in 1939 and 1980.

Since the 1939 data was based on only a single sample date, it should be interpreted with some caution. However, it is unlikely that day to day fluctuations in oxygen conditions within a season resulting from factors such as vertical mixing processes would be sufficient to cause such high levels in 1939 without a substantially lower oxygen depletion rate than exists at present. The mass of oxygen recorded in the hypolimnion on August 23, 1939 was 118×10^3 Kg, a value well in excess of any August oxygen levels measured during 1980-1982.

A hypolimnetic oxygen depletion rate for 1939 was calculated by assuming an oxygen level of 126×10^3 Kg for May 20. This value is the mean oxygen level observed on May 20 during the period 1978-1982. With this assumption, an AHOD rate of 90 $mg/m^2/day$ can be calculated for 1939. In Table 8, the 1939 rate is compared with areal hypolimnetic oxygen depletion rates calculated for the years 1978-1982, and with rates predicted for Harvey's Lake from six lake oxygen depletion models. It is apparent from Table 8 that the 1939 AHOD rate is markedly lower than the range of rates observed during the period 1978-1982. It is therefore unlikely that the low rate observed in 1939 could be attributed to normal year to year fluctuation in these rates. A more likely explanation for the apparent increase in AHOD rates since 1939 is an increase in lake productivity. The AHOD rate predictions from the six lake models shown in Table 8 also are considerably higher than the 1939 value, but are similar to the rates observed in 1978-1982. Each of these models incorporate one or more variables related to lake trophic state to generate a predicted AHOD. The fact that the 1939 AHOD value falls well below the predicted range suggests that there has been a change in the trophic state of Harvey's Lake in the direction of greater eutrophy during the past 40 years. A continuation of this trend could have serious adverse consequences for the salmonid fishery existing in the lake.

The Role of *Oscillatoria* in the Hypolimnetic Oxygen Regime

The type of algae present in a lake can have a significant influence on oxygen depletion rates. For example, during the

eutrophication of Lake Washington, the shift to blue-green algal dominance may have actually ameliorated the effect of increased algal biomass and productivity on the oxygen deficit by shifting the site of algal decomposition from the hypolimnion to the surface waters (Edmondson, 1966). In Harvey's Lake, the Oscillatoria population is at times photosynthetically active within the hypolimnion (see Figure 8). If some of the organic matter produced by these algae is sedimented and permanently incorporated into the mud, then photosynthetic oxygen production in the hypolimnion would exceed the oxygen demand exerted by decomposing cell materials. The hypolimnetic algae may therefore be a net asset in the oxygen balance of the hypolimnion, relative to the impact of an equally productive surface-dwelling population.

Some support is given to this suggestion when the depth location of the Oscillatoria layer is compared with the hypolimnetic oxygen depletion rates measured during each summer of this study. The depth location of the maximum Oscillatoria abundance was determined on each summer sampling date by means of in vivo fluorescence measurements (using a Turner Model III fluorometer) at close depth intervals. During the summers of 1980 and 1982, maximum Oscillatoria levels occurred in the depth range of 12-15 meters, within the uppermost portion of the hypolimnion. During 1981, however, the Oscillatoria remained at depths of only 10-12 meters, above the upper boundary of the hypolimnion. From Table 8, it can be seen that the hypolimnetic oxygen depletion rate was much higher in 1981 than in either 1980 or 1982. The difference was statistically significant at p .05, based on the regression analysis used to calculate oxygen depletion rates. The higher hypolimnetic oxygen depletion rate observed in 1981 may have resulted from the absence of photosynthetic oxygen production by the Oscillatoria within the hypolimnion during that year.

Another possible explanation for the greater oxygen depletion rate observed in 1981 is that algal productivity was higher in 1981 than in 1980 or 1982. However, this is unlikely because summer chlorophyll levels showed no significant change between 1980 and 1982 (see Figure 11), indicating that levels of algal photosynthetic activity probably remained the same.

Nitrogen and Phosphorus as Limiting Nutrients

Because phosphorus control is being evaluated as a lake restoration measure for Harvey's Lake, it is important to determine the degree to which algal abundance in the lake depends on phosphorus levels. Any nutrient control measures implemented at Harvey's Lake would most likely reduce nitrogen as well as phosphorus. However, quantitative prediction of algal response to nutrient controls generally depends on the assumption that phosphorus is the limiting nutrient. The question of whether nitrogen or phosphorus limits the growth of Harvey's Lake phytoplankton was explored in two ways: by examination of nitrogen/phosphorus ratios, and by nutrient enrichment bag experiments.

Nitrogen/Phosphorus Ratios

Sampling of Harvey's Lake at discrete depth intervals for total phosphorus (TP), total Kjeldahl nitrogen (TKN), and nitrate plus nitrite (NO_3 + NO_2) was conducted throughout 1980 and 1981. Total nitrogen (TN) was calculated as $TN=TKN+NO_3+NO_2$. The TN/TP mass ratio can be used to determine which of the two nutrients is most likely to be limiting. In Harvey's Lake, the mean TN/TP ratio, averaged over all sample dates and depths, was 43 in 1980 and 34 in 1981. These ratios indicate strong phosphorus limitation of algal abundance as indicated by chlorophyll (Sakamoto, 1966), and of primary productivity (Smith, 1979). The mean TN/TP ratios found in the *Oscillatoria* layer were lower, at 25 in 1980 and 14 in 1981, but still high enough to suggest phosphorus limitation at most times.

Nutrient Enrichment Experiments

Three nutrient enrichment bag experiments were conducted in Harvey's Lake; one in August, 1980, and two in August, 1981. Plastic bags were filled with 32 liters of water obtained from the depths at which the bags were suspended. For the 1980

experiment, the bags were filled from the depth of the *Oscillatoria* layer at 13 meters. In 1981, two separate experiments were conducted simultaneously at two depths. One set of bags was filled with epilimnetic water from 3 meters depth. The second set of bags was filled with water from the *Oscillatoria* layer at 10 meters. For all experiments, the bags were treated with nutrients, returned to the depth from which they were filled, and incubated for a period of sixteen days. The following four nutrient treatments were distributed in triplicate among twelve bags at each depth.

Phosphorus (P): 50 mg/m^3 as $KH_2 PO_4$
Nitrogen (N): 1000 mg/m^3 as $NH_4 NO_3$
Nitrogen plus Phosphorus (N+P): 1000 mg/m^3N + 50 mg/m^3P
Control (C): No nutrients added

The algal growth response was determined at intervals during the incubation period by measuring the concentration of algal pigments as indicated by *in vivo* fluorescence (using a Turner Model III fluorometer). For each bag, the average change in fluorescence units during the incubation period, relative to the initial value, was taken as a measure of the algal growth response. The results are shown in Table 9.

The experiments were analyzed statistically as 2 x 2 factorial designs, with two factors (nitrogen, phosphorus), two levels of each factor (added, not added), and three replicates within each treatment. The results of a two-way analysis of variance for each experiment are shown in Table 10.

The results of the 1980 experiment conducted in the *Oscillatoria* layer at 13 meters show that phosphorus addition resulted in no significant growth response by the algae. Nitrogen addition had a significant positive effect on growth, however, as indicated by an F test. There was no significant interaction between nitrogen and phosphorus. In contrast, the results of the 1981 experiment conducted in the *Oscillatoria* layer at 10 meters showed no significant response to either

Table 9. Results of nutrient enrichment experiments. Values are average change in fluorescence units during the incubation period.

Treatment	Mean Algal Growth Response 1980 13m	1981 3m	1981 10m
C	-9.3	-3.1	-7.2
N	6.0	0.0	-6.6
P	0.3	-2.8	-8.6
N+P	6.1	39.5	-7.9

Table 10. Analysis of variance results for nutrient enrichment experiments. Asterisk (*) indicates a significant F ratio at $p < .01$.

August, 1980 — 13 meters

Source	d.f.	Mean Square	F
N	1	121.0	52.1*
P	1	1.3	.55
NXP	1	.9	.39
Error	8	2.3	

August, 1981 — 3 meters

Source	d.f.	Mean Square	F
N	1	1541	95.8*
P	1	1188	73.9*
NXP	1	1156	71.9*
Error	8	16.1	

August, 1981 — 10 meters

Source	d.f.	Mean Square	F
N	1	1.1	0.4
P	1	5.2	1.6
NXP	1	0.0	0.0
Error	8	3.2	

nitrogen or phosphorus. The experiment conducted in the epilimnion at 3 meters during 1981 gave entirely different results. There was a highly significant interaction between nitrogen and phosphorus. The addition of these two nutrients together produced a large positive algal growth response that overwhelmed any response that occurred when the two nutrients were added singly.

These contrasting results are difficult to interpret. The positive response of the *Oscillatoria* to nitrogen addition in 1980 was consistent with the results found by Klemer (1976) in which a similar mid-water *Oscillatoria* population in Deming Lake, Minnesota, was found to be limited more by nitrogen than by phosphorus. However, the response to nitrogen was not reproduced the following year in Harvey's Lake. Furthermore, the TN/TP ratios observed in Harvey's Lake indicate strong phosphorus limitation. It is probably safe to conclude that phosphorus is the most limiting nutrient in Harvey's Lake, but the occasional nitrogen limitation and the synergistic effects of nitrogen and phosphorus documented in the bag experiments could complicate the quantitative prediction of algal response to phosphorus controls.

SILICA ADDITION STUDIES

Lake Observations

The feasibility of shifting algal dominance in Harvey's Lake from *Oscillatoria* to diatoms by silica addition was investigated by a variety of approaches. One approach was to make observations on seasonal changes in levels of algae and silica in the lake. Figure 19 shows a plot of *Oscillatoria*, diatom, and dissolved silica concentrations in the epilimnion of Harvey's Lake during 1980-1981. Figure 19 shows that dissolved silica levels declined during periods of diatom abundance. However, dissolved silica levels were never depleted below 3.0 mg/l and remained well above the limiting value of 0.5 mg/l suggested by Lund (1964). Thus, it is unlikely that dissolved silica depletion occurs in Harvey's Lake to a degree that would seriously restrict diatom abundance.

Limnocurtain Experiment

The feasibility of shifting algal dominance in Harvey's Lake in favor of diatoms by silica addition was investigated on a large scale by means of a long term *in situ* experiment using a limnocurtain. One limnocurtain enclosure, an octagonal tube measuring 8 meters in diameter and 18 meters in length, was constructed by Anchor Industries Inc., Evansville, Indiana, based on a design supplied by John Penny of the Freshwater Institute, Environment Canada, and was placed in the lake in November, 1980. Flotation was provided by a styrofoam collar at the surface. The bottom edge, open to the sediments, was anchored by cement blocks, completely enclosing a water column of approximately 15 meters in depth. The limnocurtain remained in place for one year. Fifteen hundred grams of silica in the form of sodium metasilicate (Na_2SiO_3 $9H_2O$) were added to the limnocurtain to raise the level of SiO_2 by 5.4 mg/l. The addition took place on May 5, 1981. This time was chosen to correspond with the time at which spring diatom blooms typically occur in Vermont

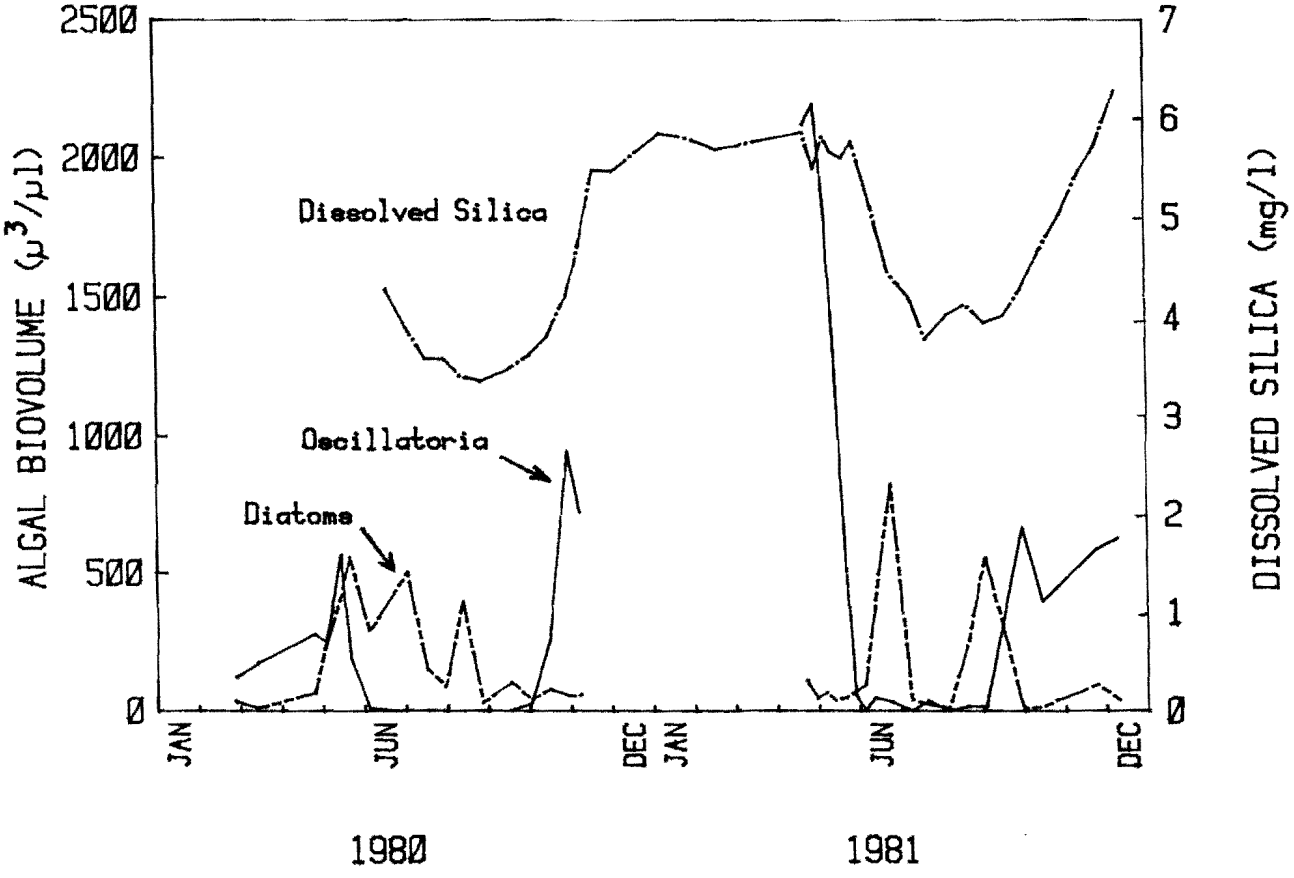


Figure 19. Plot of Oscillatoria, diatom, and dissolved silica concentrations in the epilimnion (0-5m) of Harvey's Lake during 1980-1981.

lakes. Levels of total and dissolved silica, total and dissolved phosphorus and populations of diatoms and Oscillatoria were monitored inside the limnocurtain and at a nearby lake station. Samples were taken from both sites prior to the silica addition for baseline levels of nutrients and algae.

Unfortunately, difficulty was encountered in anchoring the limnocurtain to prevent movement. Winds or water currents caused the limnocurtain to become dislodged and drift out into deeper waters. The large size prevented relocation of the structure to the proper depth. Rather than being sealed in the bottom sediments as intended, the enclosure was open to the lake waters at the bottom when the experiment began.

Results of the experiment (Figure 20) show that the added silica remained inside the limnocurtain for only one week. The mean level of total silica inside the enclosure was increased by 5.43 mg/l on the day following the addition. This was what had been intended with the 5.4 mg/l addition. On May 12, the mean total silica level inside the limnocurtain was only 0.34 mg/l greater than it had been prior to the beginning of the experiment. The loss of silica in the limnocurtain could have resulted either from exchange with lake water through the bottom or from lake water being introduced over the top by wave action, or both.

Concentrations of diatoms and Oscillatoria inside the limnocurtain were not significantly different from those found in the lake in the week following the beginning of the experiment (Figures 20 and 21). These results should be considered inconclusive, however, due to the rapid loss of silica.

The decision to use a limnocurtain in Harvey's Lake was made because it offered certain advantages over smaller enclosures used for experimental purposes. The large volume of the limnocurtain and the ability to enclose a vertical water column provided a much better simulation of the lake environment than could have been achieved with bag enclosures. These considerations were particularly important for work with Oscillatoria-diatom competition because of the tendency of the Oscillatoria populations to stratify with depth.

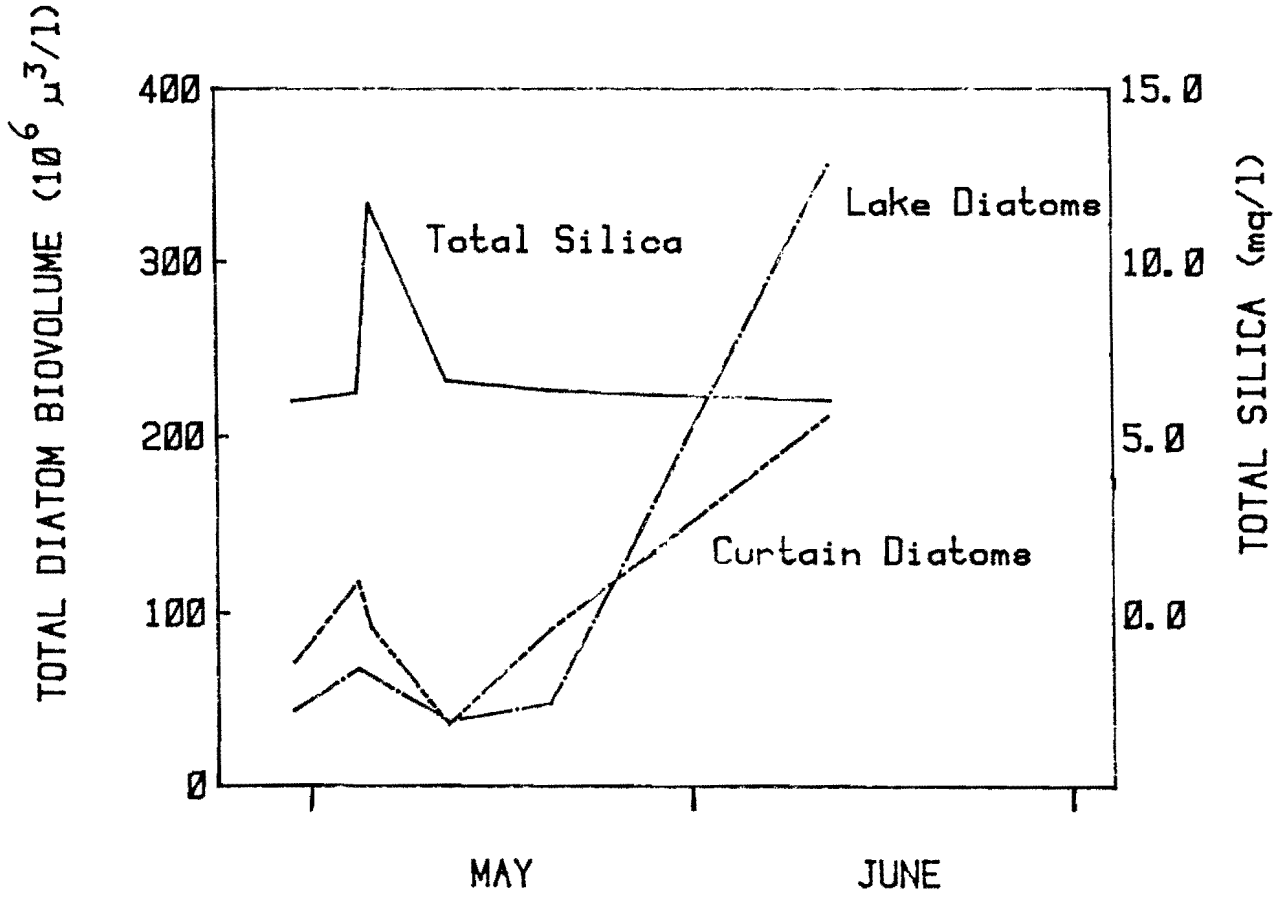


Figure 20. Changes in total silica concentrations and diatom biovolume in the lake and in the limnocurtain during May-June, 1981. Values are averaged over the 0-5 meter depth layer.

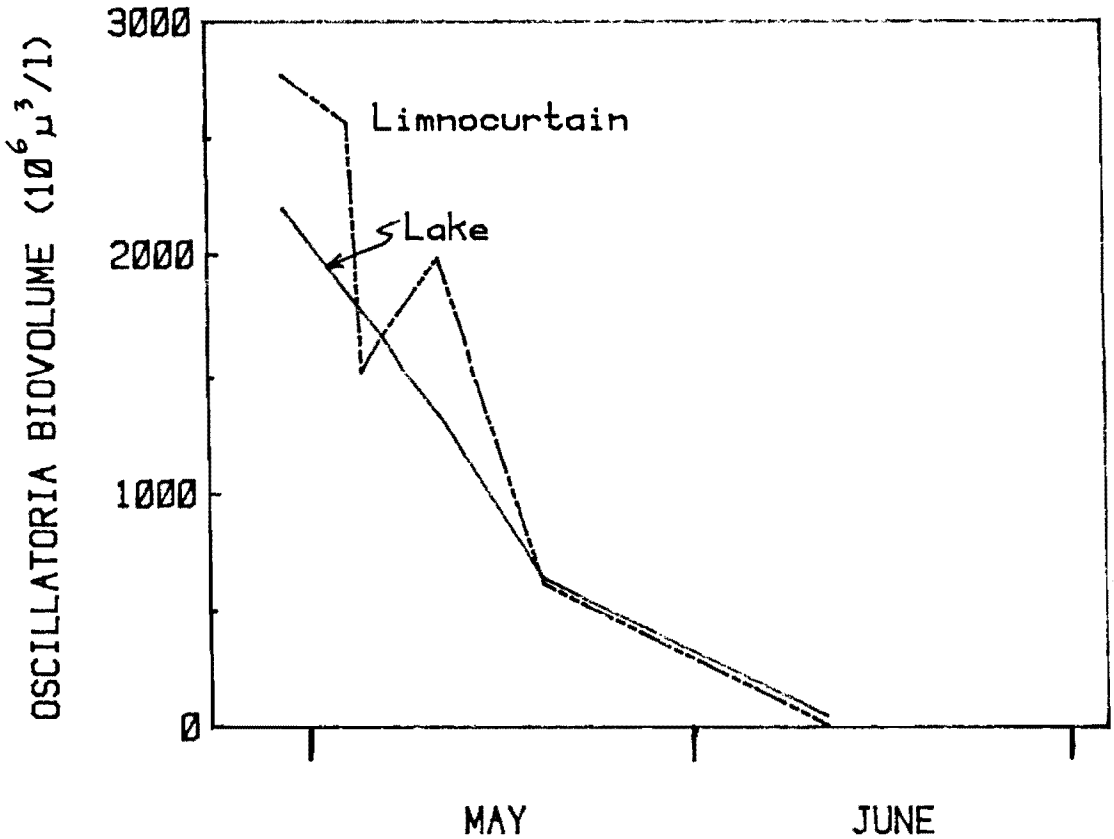


Figure 21. Changes in Oscillatoria biovolume in the lake and in the limnocurtain during May-June, 1981. Values are averaged over the 0-5 meter depth layer.

Samples collected from the limnocurtain and from the lake during the period of November 1980 to June 1981 provided an opportunity to examine how similar the limnocurtain environment was to the lake. Total phosphorus levels in the limnocurtain and in the lake during this period are shown in Figure 22. Phosphorus levels in the limnocurtain tended to be higher than those found in the lake. This observation is surprising in view of the expectation of greater phosphorus sedimentation rates in the enclosed water and the elimination of any source of phosphorus resupply from watershed loading. *Oscillatoria* vertical stratification patterns were similar in the limnocurtain and in the lake, as shown in Figure 23. The *Oscillatoria* maximum occurred at a slightly shallower depth in the limnocurtain, but the profiles were generally very similar, indicating that the limnocurtain provided a good analog to the lake environment as far as *Oscillatoria* growth is concerned.

Aside from the loss of added silica from the limnocurtain which resulted in the failure of the experiment, there were other major disadvantages encountered in using the limnocurtain. The major problem was the extreme difficulty in placing an enclosure of this size in the lake and in retrieving it at the end of the experiment. These operations required the use of several large horsepower motorized boats, about fourteen people, and a team of trained SCUBA divers. Another disadvantage was the inability to provide a sufficient degree of experimental replication for statistical purposes, due to the high cost ($3,200) of each limnocurtain. Considering these disadvantages, it is our recommendation that limnocurtains of the size used for this study not be employed in the future for lake diagnostic studies, particularly when alternatives such as small bag enclosures could achieve some of the same purposes.

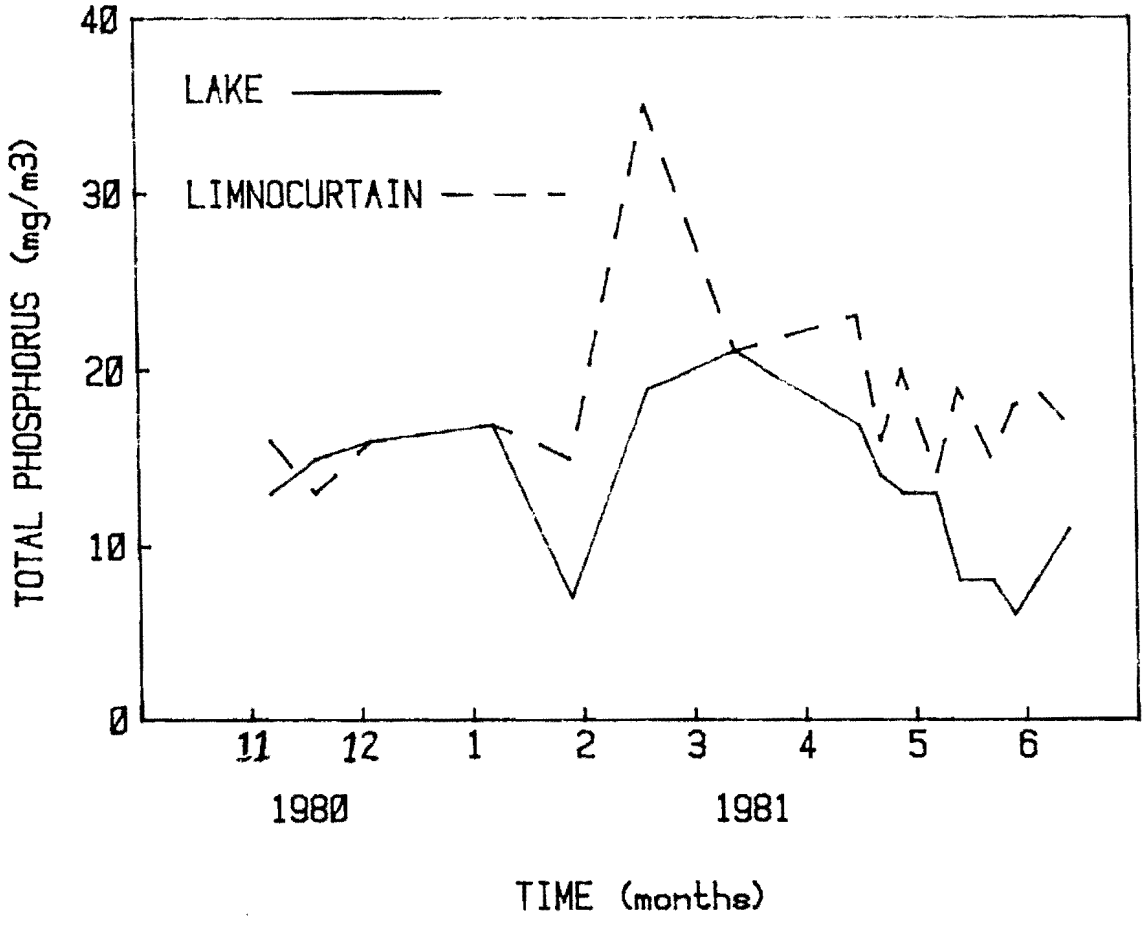


Figure 22. A comparison of 0-10 meter mean total phosphorus levels in the lake and in the limnocurtain during the period of November, 1980 to June, 1981.

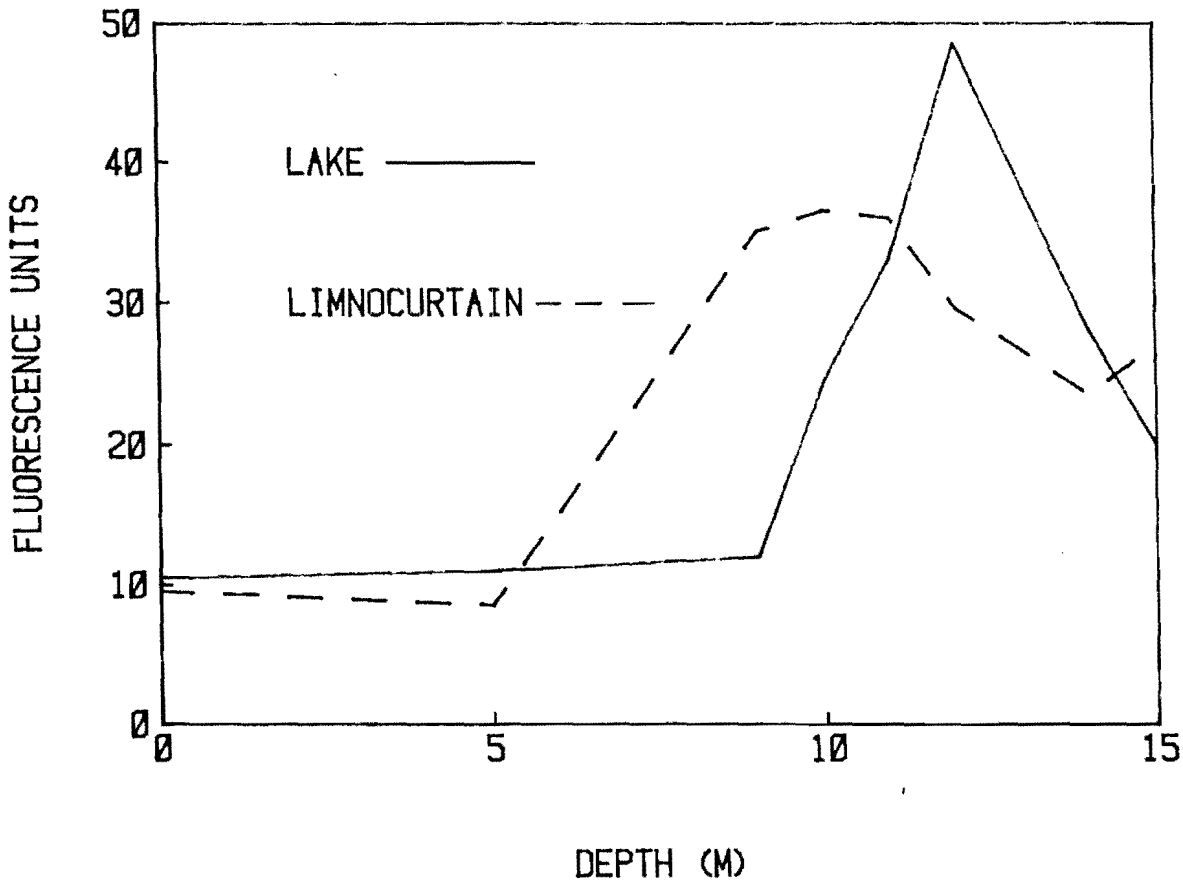


Figure 23. Depth profiles of relative chlorophyll concentrations (as indicated by the technique of *in vivo* fluorescence) obtained in the lake and in the limnocurtain on June 11, 1981.

Silica Enrichment Bag Experiments

A series of four consecutive small enclosure experiments was conducted *in situ* in Harvey's Lake in 1981. Each experiment was composed of untreated control bags and bags with varying levels of silica addition. Response to silica addition was determined by analyzing for changes in total diatom numbers by visual microscopic counts. The experiments began April 21, 1981 and ended on June 16, 1981.

The enclosures were 32-liter clear plastic bags. They were filled with lake water taken from a depth of three meters. They were then either left untreated, or were innoculated with a concentrated silica solution which would raise the SiO_2 level in each bag by 5, 10, or 20 mg/l. Each experiment was composed of nine to twelve bags, with triplicates of each treatment level. The bags were then arranged randomly along a horizontal bar and suspended at a depth of three meters. The experiments lasted for two weeks each and samples were withdrawn from the bags for diatom analysis on the initial and final days of each experiment.

Diatom response to silica enrichment was calculated for each bag as a specific growth rate (r, day^{-1}) for the total diatom population.

$$r = \frac{\ln N_t \ / \ \ln N_o}{t} \qquad (3)$$

where N_t = total diatom concentration (cells / ml) on the final day of the experiment.

N_o = total diatom concentration on the initial day of the experiment.

t = duration of the experiment (days).

The results of the four bag experiments are shown in Table 11. Treatment designations are as follows.

Control (C): no silica addition
Low (L): 5 mg/l SiO_2 addition
Medium (M): 10 mg/l SiO_2 addition
High (H): 20 mg/l SiO_2 addition

Ambient lake surface dissolved silica concentrations during the period of the experiments remained quite constant at about 5.8 mg/l. *Oscillatoria* cell counts were obtained from the lake water used to fill the bags on the initial dates of each experiment. The *Oscillatoria* concentrations are also shown in Table 11.

Statistical analysis of these results was conducted as follows. Each of the four experiments was analyzed by a one-way analysis of variance, with three to four treatments, and three replicates (unbalanced in some cases) within each treatment. The F ratios resulting from the four analysis of variance procedures are given in Table 12. None of the F tests proved significant at the $p < .05$ level, indicating that there was no significant overall treatment effect on diatom growth. The results were explored further, however, by means of a t test comparing the mean growth rate for the control bags with the combined mean growth rate for the silica treated bags. The t statistics for each experiment are also shown in Table 12. A significant t value ($p < .05$) was obtained for experiment A, indicating that diatoms in the silica treated bags showed a significantly positive growth response, relative to the controls. However, none of the other experiments produced a significant t value at $p < .05$.

The statistical analysis of these results was carried one step further with the combination of all four experiments into a single factorial design. This design featured two factors: treatment (four levels) and date (four dates), with three replicates (unbalanced in some cases) for each treatment and date. The combined experiments were analyzed by means of a two-way analysis of variance. The results are shown in Table 13.

Table 11. Results of silica enrichment bag experiments, expressed as total diatom population specific growth rate (r, day^{-1}).

Experiment:		A	B	C	D
Starting date:		4-21	5-5	5-18	6-3
Initial Oscillatoria (cells/ml):		23,057	7,243	12,329	234
Treatment	Replicate				
C	1	.015	.060	.014	.094
"	2	.013	.00	.055	.14
"	3	--	.075	.074	.11
"	mean	.012	.045	.048	.12
L	1	.060	.013	.041	.084
"	2	.034	.14	.049	.18
"	3	.065	.079	.030	--
"	mean	.053	.077	.040	.13
M	1	.072	.074	.039	.21
"	2	.021	.071	-.0079	.17
"	3	.031	.071	.043	.21
"	mean	.041	.072	.025	.20
H	1	--	.033	.034	.15
"	2	--	.093	.044	.13
"	3	--	.014	.018	.12
"	mean	--	.047	.032	.13

Table 12. Statistical summary of individual enrichment bag experiment results. See text for an explanation of the experimental designs.

d.f. = degrees of freedom
p = probability of a greater value
NS = not significant at $p < .05$

	Analysis of Variance			t Test		
Experiment	d.f	F	p	d.f.	t	p
A	2,5	2.3	NS	6	2.11	.04
B	3,8	.46	NS	10	.76	NS
C	3,8	.59	NS	10	1.11	NS
D	3,7	3.7	NS	9	1.53	NS

Table 13. Analysis of variance table for combined silica enrichment bag experiment results.

p = probability of a greater F value
NS = not significant at $p < .05$

Source	d.f.	Mean Square	F	p
Treatments	3	.00615	2.06	NS
Date	3	.0812	27.18	.0001
Treatments X Date	8	.0108	1.36	NS
Error	28	.0279		

From Table 13 it can be seen that there was no significant main effect of silica treatment. There was, however, a highly significant main effect of date. Diatom growth rates tended to increase later in the season. These increased growth rates corresponded with reduced Oscillatoria abundance in the surface waters (see Table 11), and may have been related to reduced inhibitory effects of Oscillatoria on diatoms. The possibility of allelopathic effects of Oscillatoria on diatoms is discussed elsewhere in this report.

The two-way analysis of variance summarized in Table 13 also provides a test for the interaction between treatment and date. If the factor "date" is interpreted as representing "Oscillatoria level", then the interaction test becomes a test for the hypothesis (Keating, 1976) that silica addition can overcome allelopathic effects of blue-green algae on diatoms. The interaction was not significant, however.

Finally, the combined results for all four experiments were analyzed by a t test, comparing mean growth rates for all control bags vs. the mean growth rates for all silica treated bags. This comparison produced a t value that was not significant at $p < .05$, confirming the results of the individual experiment analyses that silica addition generally failed to produce a significant positive diatom growth response.

In summary of the results of the silica enrichment bag experiments, it was shown that a significant positive diatom growth response was observed for one experiment, begun in April, 1981. However, in three subsequent experiments conducted throughout the Spring of 1981 no other significant responses were detected. A combined analysis of all four experiments produced the general conclusion that silica addition to Harvey's Lake surface waters during spring failed to stimulate diatom growth. Diatom growth rates increased significantly in the later experiments, corresponding with reduced Oscillatoria concentrations in the surface waters. However, this apparent negative relationship between diatom growth and Oscillatoria abundance was not influenced by the level of silica addition. It

is possible that the Oscillatoria were exerting an allelopathic influence on the diatoms early in the spring, but this influence could not be overcome by silica addition, up to 20 mg/l.

Allelopathy Studies

An in situ bag experiment was conducted during July, 1982 to explore the question of whether Oscillatoria exerts allelopathic influences over diatoms in Harvey's Lake. The experiment was begun after the Oscillatoria and diatoms had become physically separated into metalimnetic and epilimnetic populations. The experiment involved the enclosure of epilimnetic water subjected to six different treatments, as follows.

(1) Control, no addition.
(2) Addition of 10 mg/l SiO_2.
(3) Addition of filtered metalimnetic water from the Oscillatoria layer (filter mesh size = 20 um).
(4) Addition of 10 mg/l SiO_2 plus filtered metalimnetic water.
(5) Addition of unfiltered metalimnetic water containing Oscillatoria cells.
(6) Addition of 10 mg/l SiO_2 plus unfiltered metalimnetic water.

Each treatment included four replicates for a total of 24 bags. The bags were incubated in the epilimnion for a period of ten days. Samples were drawn from the bags at the beginning and the end of the incubation period for analysis of diatom cell numbers. The bags were also sampled on the initial date of the experiment for total phosphorus, total Kjeldahl nitrogen, and total silica. Treatments 3, 4, 5, and 6 involved mixtures of equal volumes of epilimnetic and metalimnetic water taken from depths of 3 and 10 meters, respectively. The 10 meter water contained a dense population of Oscillatoria.

The experiment was designed to answer a number of related questions. Comparison of diatom response in treatment 1 vs. treatment 2 should indicate whether the diatoms were nutritionally limited by silica at the time of the experiment.

Comparison of treatments 1 and 2 vs. treatments 3, 4, 5, and 6 should indicate whether the Oscillatoria presence exerts a negative influence on diatom growth. Comparison of treatments 3 and 4 vs. treatments 5 and 6 should indicate whether the degree of inhibition depends on the direct presence of Oscillatoria cells. Finally, comparison of treatments 3 vs. 4 and 5 vs. 6 should indicate whether this inhibition can be overcome by silica addition, as suggested by Keating (1976). The results of the experiment are shown in Table 14.

It should be noted that addition of metalimnetic water to the bags would be expected to raise nutrient concentrations in the bags, relative to epilimnetic nutrient levels. This effect cannot be completely controlled, and comparisons between treatment effects could be complicated by differences in nutrient levels between treatments. To evaluate the extent of nutrient differences between treatments, samples were taken from the bags on the initial date of the experiment. The results of the nutrient analyses on these samples are given in Table 15. It can be seen that the control samples, to which no metalimnetic water had been added, were actually richer in nutrients, particularly phosphorus, than the Oscillatoria treated bags. Unfortunately, the start of the experiment coincided with a major storm and runoff event which caused markedly elevated phosphorus levels in the surface waters. This explains the unexpectedly high nutrient levels in the control bags. Phosphorus levels were lowest in the Oscillatoria filtrate treated bags as a consequence of the filtration. These nutrient differences between bags introduce an element of ambiguity in the interpretation of diatom growth response to the various treatments. Increased growth in the control bags, relative to the Oscillatoria treated bags, could be attributable to nutrient enrichment as well as to possible allelopathic effects.

The experiment was analyzed by means of a one-way analysis of variance, using five orthogonal, single degree of freedom contrasts. A list of the comparisons made, and the analysis of variance results, are shown in Table 16. There was an overall significant treatment effect that was further explored by means

Table 14. Results of allelopathy bag experiment values are total diatom population specific growth rates (r, day^{-1}).

Oscillatoria Treatment	Replicate	Silica Treatment: No Addition	Silica Treatment: 10 mg/l Addition
Control	1	(Trt. #1) .24	(Trt. #2) .16
	2	.20	.13
	3	.27	.18
	4	.22	.24
	mean	.23	.18
Unfiltered metalimnetic water added	1	(Trt. #3) .07	(Trt. #4) .09
	2	.09	.16
	3	.06	.12
	4	.14	.12
	mean	.09	.12
Filtered metalimnetic water added	1	(Trt. #5) .14	(Trt. #6) .11
	2	.11	.11
	3	.17	.16
	4	--	.12
	mean	.14	.13

of the five individual comparisons. Comparison of the control bags vs. all the Oscillatoria treated bags showed greater diatom growth in the controls, with a highly significant F ratio. This result suggests that allelopathy could be occurring but, as noted above, nutrient differences between treatments make the interpretation of this result difficult. No significant differences were noted between bags treated with filtered or unfiltered Oscillatoria water. If allelopathy was occurring, it apparently did not depend on the presence of whole Oscillatoria cells. Surprisingly, significantly less diatom growth was observed in the control bags treated with silica than in the controls without silica. The reason for this unexpected result is unknown. Other comparisons involving Oscillatoria treatments with and without silica showed no differences in diatom growth. This result indicates that any allelopathic effects that might have been occurring were not altered by the presence of added silica.

The results of this experiment can be compared with the combined results of the silica enrichment bag experiments presented in Table 11. Diatom growth rates increased later in the spring season as Oscillatoria cells became scarce in the surface waters. This result is suggestive of a release from allelopathic effects, but it is not possible to definitely assign allelopathy as the cause of depressed diatom growth rates earlier in the season. Numerous other environmental changes could also have occurred during the time period of the silica enrichment experiments, and factors other than the levels of Oscillatoria could have accounted for differences in diatom growth rates.

Another set of observations relevant to the allelopathy question is illustrated in Figure 19. Figure 19 shows that there was a negative correlation between epilimnetic populations of diatoms and Oscillatoria during 1980-1981. Diatoms were most abundant in the epilimnion during periods in which the Oscillatoria were located in the metalimnion. Other environmental factors could account for these population changes, but the negative correlation is at least suggestive of allelopathic effects of Oscillatoria on diatoms. It is also

Table 15. Results of nutrient analysis on allelopathy bag experiment initial date samples. Values are means for each treatment (mg/l).

Treatment	Total Phosphorus	Total Kjeldahl Nitrogen	Total Silica
(1) Control, no silica	.019	.60	5.6
(2) Control, with silica	.020	.38	14.6
(3) *Oscillatoria* cells, no silica	.012	.32	6.2
(4) *Oscillatoria* cells, with silica	.015	.33	15.6
(5) *Oscillatoria* filtrate, no silica	.007	.31	6.2
(6) *Oscillatoria* filtrate, with silica	.008	.30	16.5

interesting to note that this negative correlation between *Oscillatoria* and planktonic diatoms may extend over a longer time scale. Paleolimnological studies of Harvey's Lake (see Engstrom *et al*, 1983 and Figure 13) show that during the past 40 years, periods of peak *Oscillatoria* abundance correspond with years of minimum planktonic diatom levels.

In summary, it can be stated that the evidence from various bag experiments and in-lake observations do not rule out the possibility of allelopathic effects of *Oscillatoria* on diatoms. Some of the results suggested that allelopathic effects do exist, but the inability to provide more closely controlled experimental situations has made it impossible to demonstrate allelopathy with certainty.

Table 16. Analysis of variance results for allelopathy bag experiment.

List of Comparisons

C1: Control vs. *Oscillatoria* Cells (Treatments 1, 2 vs. 3, 4, 5, 6)

C2: *Oscillatoria* Cells vs. *Oscillatoria* Filtrate (Treatments 3, 4 vs. 5, 6)

C3: Control No Silica vs. Control with Silica (Treatments 1 vs. 2)

C4: *Oscillatoria* Cells No Silica vs. *Oscillatoria* Cells with Silica (Treatments 3 vs. 4)

C5: *Oscillatoria* Filtrate No Silica vs. *Oscillatoria* Filtrate with Silica (Treatments 5 vs. 6)

Analysis of Variance Table

Source	d.f.	Mean Square	F
Treatments	5	.0100	9.06*
C1	1	.0395	35.47*
C2	1	.0024	2.13
C3	1	.0061	5.43*
C4	1	.0021	1.90
C5	1	.0004	.35
Residual	17	.0011	

*indicates a significant F ratio at $p < .05$.

Comparative Lake Study

As discussed earlier, the use of lake silica enrichment as a restoration technique is based on the hypothesis (Schelske and Stoermer, 1971) that increasing phosphorus inputs to lakes results in depletion of dissolved silica and a shift in algal species from diatoms to other forms, such as blue-greens. One way to examine the feasibility of shifting algal species in Harvey's Lake through silica addition is to test this hypothesis and determine its applicability to Harvey's Lake. This was done by means of a comparative study of diatom, silica, and phosphorus relationships in 22 Vermont lakes during 1981.

A diverse set of lakes (including Harvey's Lake), representing the full range of trophic state conditions found in Vermont, was chosen for study. Each lake was sampled four times during 1981: once during spring turnover, once during late spring, and twice during summer. Depth-integrated samples of the euphotic zone were obtained by lowering a hose to a depth of 2½ times the Secchi disc depth, determined for each lake at the time of sampling. Samples were analyzed for total phosphorus (TP), dissolved phosphorus (DP), total silica (TSi) and dissolved silica (DSi). In addition, complete phytoplankton counts were obtained on each sample. The results of this sampling program are shown in Tables 17 and 18.

These results were analyzed in a variety of ways. First, the data was examined to determine whether depletion of dissolved silica does, in fact, occur in lakes rich in phosphorus. The minimum levels of dissolved silica recorded for each lake are plotted against mean total phosphorus values in Figure 24. From Figure 24 it can be seen that minimum dissolved silica levels do decline with increasing phosphorus concentrations. Depletion of dissolved silica to levels of 0.5 mg/l or less generally occurs in lakes with mean phosphorus concentrations of 15 mg/m^3 or greater. Harvey's Lake was a striking exception to this trend, however. Dissolved silica concentrations in Harvey's Lake remained above 4.0 mg/l in spite of relatively high phosphorus levels.

Table 17. Comparative lake study phosphorus and silica data.

Sample times (1981): 1. early spring 2. late spring 3. mid-summer 4. late summer

Lake	TP (mg/m^3)				DP (mg/m^3)				TSi (mg/l)				DSi (mg/l)			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Willoughby	3	4	1	5	2	2	1	3	2.5	2.2	1.8	1.7	2.3	1.8	1.2	1.1
Maidstone	3	3	4	6	3	2	2	3	2.6	2.4	2.3	2.2	2.7	2.4	2.0	2.0
Caspian	4	5	5	3	3	2	5	3	2.8	2.7	2.1	2.1	3.0	2.4	2.2	1.9
Shadow	5	5	5	6	4	2	1	3	6.7	5.8	6.1	6.3	6.1	5.4	5.7	5.5
Joe's	5	3	5	7	3	2	1	3	4.9	4.1	4.0	3.4	5.0	4.0	4.1	3.9
Eden	5	8	5	8	3	2	1	3	6.1	5.9	5.0	6.3	6.1	5.1	5.5	5.7
Seymour	6	7	12	6	3	2	2	3	3.3	2.3	1.4	.90	3.0	1.9	.77	.81
Dunmore	6	6	5	17	2	2	2	3	2.7	2.1	1.9	1.6	2.4	1.9	1.6	1.8
Echo	7	3	6	6	3	3	3	3	3.1	2.1	1.9	1.4	2.9	2.0	1.7	1.5
Groton	7	6	7	12	3	2	4	3	6.3	5.7	5.9	5.0	5.8	5.4	5.7	5.3
Glen	12	5	7	5	4	4	4	3	3.4	2.7	1.5	.96	3.1	2.4	1.1	1.2
St. Catherine	13	10	9	11	5	4	4	3	2.1	1.5	1.1	.86	1.9	.94	1.0	.96
Elmore	15	10	10	12	3	2	4	3	4.3	2.4	.54	1.3	3.9	1.6	.43	.72
Hortonia	16	10	15	37	4	3	2	4	1.9	1.7	2.2	1.2	1.8	1.6	2.1	1.1
Great Hosmer	16	21	17	23	4	2	5	3	1.8	.52	.88	.91	1.3	.52	.45	.79
Beebe	14	9	9	18	3	5	2	3	2.0	1.9	1.4	1.4	1.9	1.3	1.5	1.7
Fairfield	19	16	8	12	7	4	1	5	1.5	.10	.14	.92	1.2	.10	.46	.71
Carmi	20	20	11	23	8	4	3	8	5.3	1.3	1.8	3.8	4.4	.39	1.7	3.3
Iroquois	20	21	12	23	6	5	3	7	1.2	.18	.49	1.4	1.0	.10	.62	1.6
Harvey's	27	14	12	16	7	3	1	3	6.2	5.7	5.3	4.3	6.0	5.6	5.1	4.8
Ticklenaked	43	35	24	23	5	2	4	3	2.5	1.4	2.6	3.8	.10	1.3	2.3	3.9
Morey	46	12	20	24	13	4	8	5	1.3	.28	.44	.48	1.2	.20	.50	.52

Table 18. Comparative lake study phytoplankton biovolume data (um^3/ul)

Sample times (1981): 1. early spring 3. mid-summer
2. late spring 4. late summer

Lake	Diatoms				Greens				Blue-Greens				Other			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Willoughby	263	1047	916	82	12	50	20	8	0	10	0	10	61	183	164	75
Maidstone	473	115	53	42	60	2	24	26	0	1	12	54	142	47	63	75
Caspian	65	188	131	74	19	19	48	23	5	1	14	7	151	107	125	48
Shadow	1	50	81	29	24	11	24	30	3	1	41	40	171	387	448	448
Joe's	11	12	132	43	25	39	41	32	2	61	813	45	196	163	231	444
Eden	1	110	95	26	91	76	247	48	0	0	4	79	150	482	109	239
Seymour	304	281	128	28	25	41	45	16	18	1	17	38	92	99	65	60
Dunmore	470	256	378	41	61	149	40	32	10	97	167	146	278	307	1203	184
Echo	327	587	214	42	50	18	27	30	4	0	52	6	328	45	69	94
Groton	45	40	119	129	73	498	45	122	1	22	6	52	424	127	331	873
Glen	28	86	409	17	158	102	21	121	4	9	23	8	352	111	33	137
St. Catherine	600	1722	108	85	74	6	26	237	6	143	157	538	857	332	1016	286
Elmore	165	729	291	102	216	32	37	159	14	7	95	98	404	388	158	125
Hortonia	91	277	334	665	74	35	47	87	916	92	122	460	657	1134	421	222
Great Hosmer	1525	139	170	62	449	24	249	159	1	19	129	480	591	107	275	958
Beebe	57	594	83	26	14	28	21	60	9	22	60	232	192	854	391	96
Fairfield	273	438	152	87	344	1660	285	116	161	3400	2914	1888	498	158	1060	488
Carmi	2741	1549	152	125	367	51	130	275	21	904	11049	3782	1518	74	1474	1825
Iroquois	463	251	324	52	1036	110	595	163	55	1672	5449	230	566	567	343	200
Harvey's	58	105	303	369	10	18	39	31	1890	2662	973	752	180	159	166	115
Ticklenaked	9122	893	70	53	766	905	691	278	69	210	647	3964	808	1017	300	429
Morey	91	469	93	19	365	23	70	27	43	868	386	1465	1912	43	744	10310

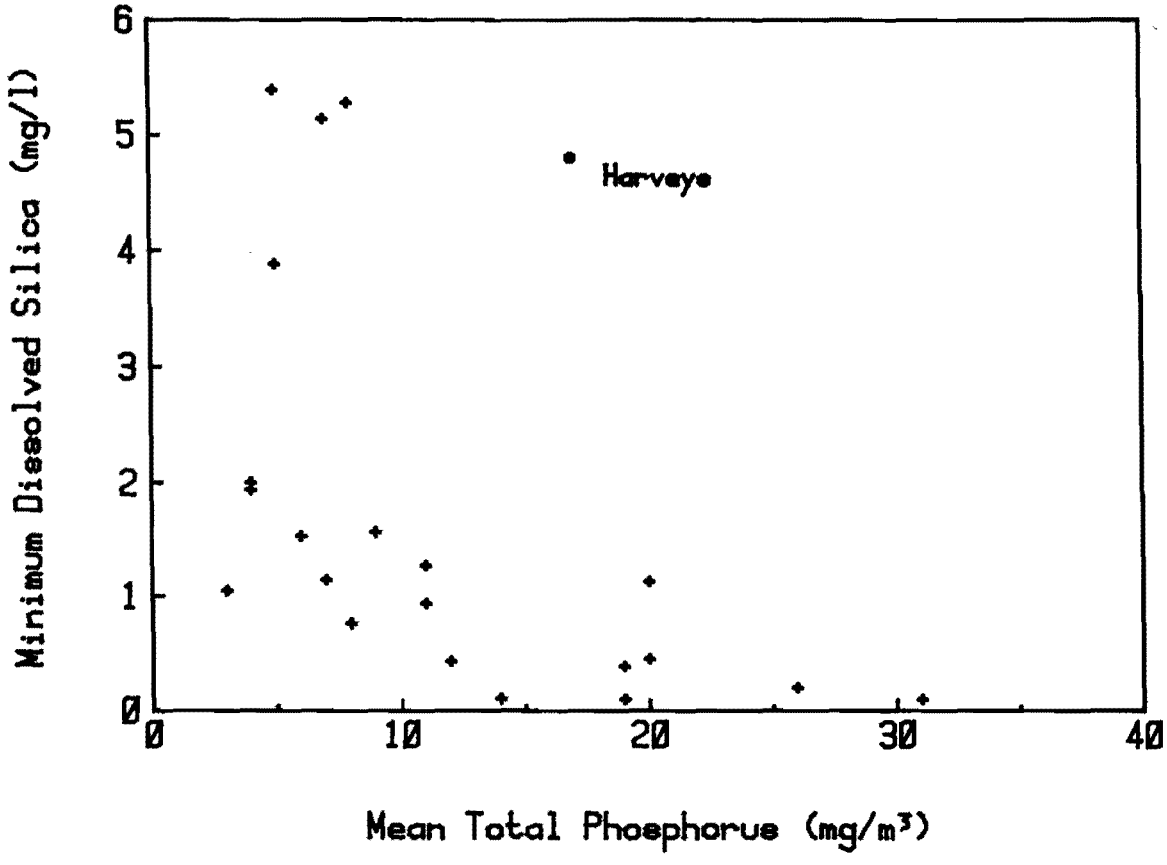


Figure 24. Plot of minimum dissolved silica levels recorded during 1981 vs. 1981 mean total phosphorus levels for 22 Vermont lakes.

The phytoplankton data was also examined to determine whether the proportion of diatoms in the summer algal community was reduced in lakes where silica was in short supply, relative to phosphorus, as indicated by the ratio of total silica to total phosphorus present in early spring. The ratio of summer diatom to total algal biovolume is plotted against early spring TSi/TP ratios for each lake in Figure 25. This plot shows a positive relationship between diatom proportional abundance during summer and the spring TSi/TP ratio. The statistical significance of this relationship was tested by transforming both variables logarithmically and by performing a linear regression analysis. The slope of the regression was greater than zero ($p < .05$), indicating a significant positive trend. From Figure 25 it can be seen that diatoms make up less than 10% of the summer algal community in lakes with spring TSi/TP ratios less than 100.

The analysis of this comparative lake data leads to some interesting conclusions concerning the feasibility of shifting algal species to favor diatoms through silica enrichment, both for Harvey's Lake and for lakes in general. The observation that depletion of dissolved silica occurs with increasing degree of eutrophication is consistent with conclusions drawn from other studies (Lund, 1969; Kilham, 1971; Schelske, 1975). The fact that a considerable amount of dissolved silica remains in Harvey's Lake waters despite the relatively high phosphorus levels is in marked contrast with the behavior of the other Vermont lakes studied and suggests that some factor other than limited phosphorus fertility may be preventing the diatoms from using this available silica. The possibility of allelopathic effects of *Oscillatoria* on diatoms was discussed earlier in this report. The comparison of silica and phosphorus relations in 22 Vermont Lakes (Figure 24) lends further support to the suggestion that diatoms in Harvey's Lake may be suffering from allelopathic effects.

The observation (Figure 25) that diatoms are of only minor importance in the summer algal communities in lakes with spring TSi/TP ratios less than 100 suggests that TSi/TP ratios during spring turnover of less than 100 lead to depletion of silica

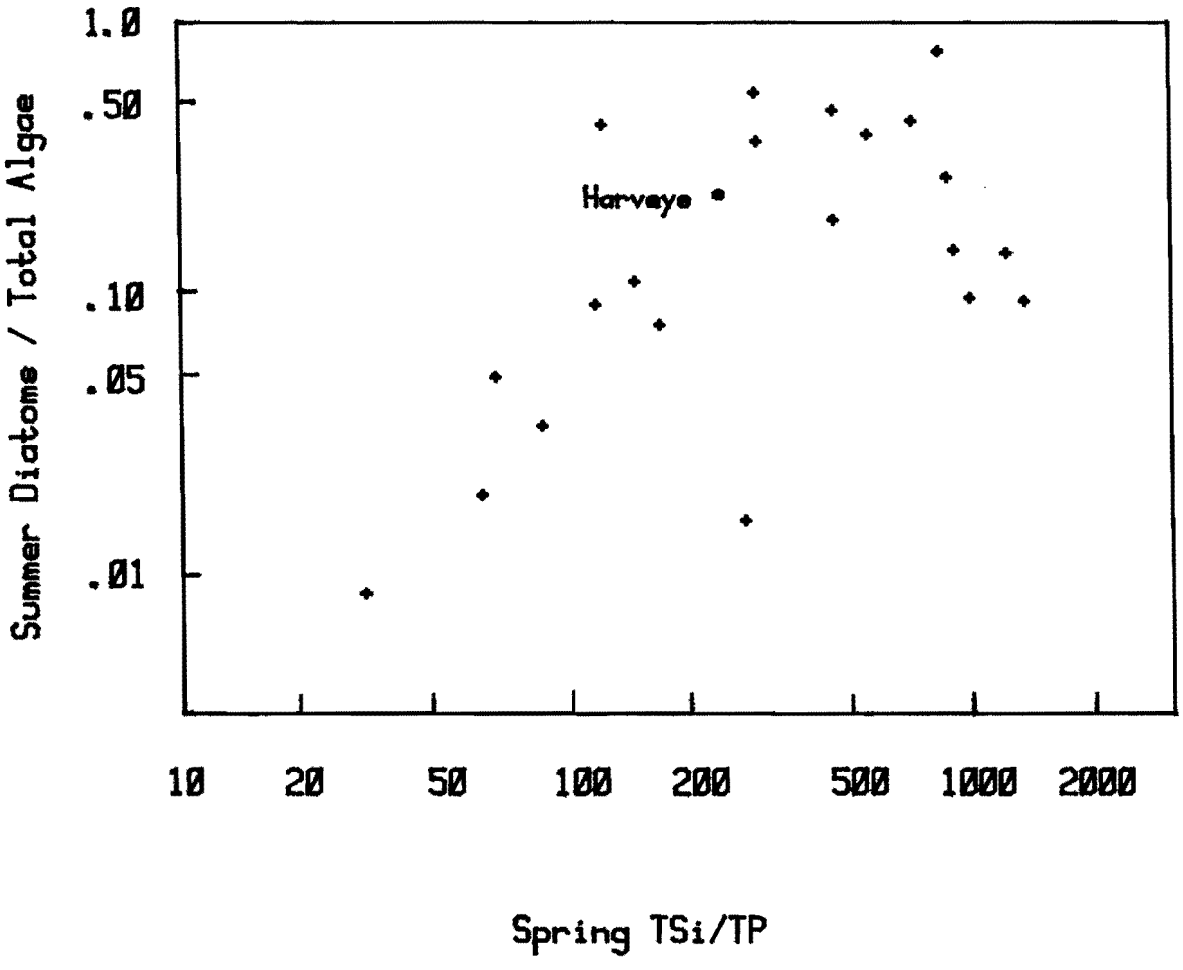


Figure 25. Plot of the ratio of summer diatom/total algal biovolume vs. the spring total silica/total phosphorus ratio for 22 Vermont lakes during 1981.

during the spring diatom growth period and a succession to other algal forms later in the season. This ratio is similar to silica/phosphorus uptake ratios of 51 and 84 measured for Lake Michigan diatoms during nutrient enrichment experiments (Schelske and Stoermer, 1972) and is within the range for mean cellular silica/phosphorus ratios of 28-140, calculated for 10 species of diatoms by Schelske (1975).

These results suggest that it might be feasible to promote diatom growth by silica addition in lakes with spring TSi/TP ratios less than 100. From Figure 25 it can be seen that relative diatom abundance during summer has no significant relationship to the TSi/TP ratio for lakes where this ratio exceeds about 200. Apparently, in situations where the TSi/TP ratio exceeds 200, silica is not limiting and other environmental factors control the relative abundance of diatoms in the algal community. In Harvey's Lake, the spring TSi/TP ratio was 229 in 1981, a value intermediate among the Vermont lakes studied. It appears, therefore, that phosphorus enrichment of Harvey's Lake has not yet proceeded to the point where silica is limiting for the diatoms. Based on this analysis, silica addition to Harvey's Lake would probably not significantly increase the relative abundance of diatoms in the algal community.

PHOSPHORUS BUDGET AND MODELING STUDIES

Introduction

An extensive phosphorus sampling program was conducted on Harvey's Lake and its tributaries during the course of this study. The purpose of this sampling program was to quantify the various sources of phosphorus to Harvey's Lake and to develop a phosphorus budget for the lake. The phosphorus budget will serve two purposes. First, it will be used to determine which of the tributaries to the lake are most important in supplying the lake with phosphorus. Phosphorus control measures can then be directed effectively towards these sub-watersheds. Second, the budget will yield information used in a modeling analysis to evaluate the gains in water quality expected with various phosphorus control measures. The methods used in the development of the phosphorus budget and the results of the budget and modeling studies are discussed below.

Methods

Eight tributary streams in the vicinity of Harvey's Lake were monitored for flow and phosphorus concentration during the period of October, 1980 to October, 1982. A map showing stream locations and sampling sites is given in Figure 1. Drainage areas for each sub-watershed are provided in Table 19. Sampling was conducted on an approximate weekly frequency during the period of October, 1980 to October, 1981. Data obtained during this period was used to determine qualitatively which streams were the major contributors of phosphorus and to develop stage-discharge relationships at selected sites. Sampling for both total (TP) and dissolved (DP) phosphorus was conducted during this period. Instantaneous flow rates were determined from measurements of stream cross-sectional depth and current velocity, using a top-setting wading rod with a Marsh-McBirney Model 201 current meter.

Table 19. Drainage areas for Harvey's Lake sub-watersheds.

Sub-watershed	Drainage area (ha)
Jewett Brook	1583
T1 + T2 + T3 + T4	161
T5	53
T6	40
Ungaged area	185
Total Direct to Harvey's Lake	2024
South Peacham Brook	3212

During the period of November, 1981 to October, 1982, an attempt was made to monitor flow and phosphorus concentrations in these streams on as nearly a continuous basis as possible, for one complete year. It is this data which was used to develop an annual phosphorus budget for the lake. Sampling for flow and total phosphorus was conducted on a daily frequency during this one year period. The daily sampling was accomplished through the employment of local lake residents who took water samples and read staff gages at rated sites each day. The exception to this schedule was the period of December to March when ice cover on the streams made measurements impossible. During the ice-free months, samples for total phosphorus analysis were collected daily at all eight sites. Staff gages placed in five streams (Jewett, South Peacham, T1, T3, and T4) were also read daily for flow determinations. Daily flows at streams T2 and T5 were estimated from statistical relationships linking instantaneous flow rates at these sites to flow rates at Jewett Brook. Data used to generate these relationships was obtained from numerous flow determinations made in the field during the course of this study. Daily flow rates in stream T6 were estimated by multiplying flows determined for Jewett Brook by .025, a factor equal to the ratio of the two drainage areas.

It was not possible, using once per day measurements, to accurately determine flow and phosphorus fluxes at the lake outlet. The occasional occurrence of the backflow of South Peacham Brook into the lake through the outlet prevented the establishment of a reliable stage-discharge relationship. An additional difficulty was the variable nature of the backflow, with the flow changing direction and magnitude within hours. To overcome these problems, two recording flow meters (ISCO Model No. 1870) were installed, one in South Peacham Brook and one in the Stevens River below the dam. These meters operated nearly continuously from April to October, 1982. The direction and magnitude of flow at the outlet was determined from the flow difference between South Peacham Brook and the Stevens River. These continuous flow records for the outlet were numerically integrated over time for each day. During periods of backflow, phosphorus loading to the lake was calculated from these flow measurements and from South Peacham Brook phosphorus concentrations, measured daily.

Other sources of flow and phosphorus to Harvey's Lake that were not directly measured include surface runoff from ungaged areas of the watershed, groundwater inflow, and direct precipitation. Inflow and phosphorus loading from the ungaged areas were estimated by multiplying Jewett Brook daily flows and phosphorus loading rates by a factor of .117, equal to the ratio of ungaged drainage area to the Jewett Brook drainage area.

Groundwater inflow, which would include any phosphorus inputs from shoreline septic systems, was not included in the phosphorus budget. However, groundwater phosphorus inputs were assumed to be insignificant for two reasons. First, Harvey's Lake is located in a region determined to have low groundwater potential for well drilling purposes, according to a groundwater favorability map made by the Vermont Department of Water Resources in 1967. This determination was based on the presence of glacial till deposits and numerous bedrock outcrops in the area. Second, bacteriological sampling conducted around the shoreline of the lake nearly every summer since 1965 by the Vermont Department of Water Resources and Environmental

Engineering has shown consistently low levels of fecal coliform bacteria. No evidence has been found of significant septic system contamination of the lake.

Net hydrologic inputs from precipitation direct to the lake surface were also assumed to be insignificant (i.e., that precipitation equals evaporation from the lake surface). Phosphorus loading to the lake from direct precipitation was calculated to be 31 Kg/yr, by applying precipitation measurements made at a nearby gage (National Oceanographic and Atmospheric Administration - Sleepers River Research Watershed near Danville, Vermont) to Harvey's Lake and by assuming a mean total phosphorus concentration in bulk precipitation of 20 mg/m^3 as measured by the Vermont Department of Water Resources and Environmental Engineering as part of the Lake Morey Diagnostic-Feasibility Study.

Using the methods described above, it was possible to generate daily water and phosphorus loading rates to the lake from each sub-watershed and from the outlet backflow for most dates during the one year period of November, 1981 to October, 1982. However, it was necessary to estimate loading rates for those dates when no samples were obtained before completing the annual budget calculations. As noted earlier, daily measurements were not possible during the winter months. During months other than the winter months, missing values exist for only a minor fraction of all dates.

Missing loading values were estimated by means of statistical relationships linking flows and phosphorus loadings to flows determined on a continuous basis at the nearby Sleepers River Research Watershed. Average daily flows measured at a weir (designated "W3", drainage area = 845 ha) maintained by the National Oceanographic and Atmospheric Administration in the Sleepers River Watershed were used to develop regression relationships predicting daily flows and phosphorus loading rates for each Harvey's Lake tributary, with the exception of the outlet backflow. The regression relationships were based on numerous flow and phosphorus loading rate measurements obtained on the same dates in both watersheds. The regression equations

are given in Table 20. These equations were used to estimate flows and loading rates for Harvey's Lake tributaries on those dates when direct measurements were not obtained. The hydrologic complexity of the backflow process prevented the establishment of a predictive relationship for this phenomenon. However, it is believed that no major backflow events were missed by the recording flow meters and phosphorus sampling of South Peacham Brook.

The phosphorus content of the lake was also measured throughout the course of this study. Samples for total phosphorus analysis were obtained at five meter depth intervals over the depth range of 0-35 meters by means of a Kemmerer type water sampler. Each sample was assumed to represent the phosphorus concentration of each five meter lake stratum, of which the sample depth was the mid-point. The phosphorus concentration in each sample was multiplied by the volume of the corresponding stratum (from Table 1) to calculate the mass of phosphorus in the stratum. The total mass of phosphorus in the lake was then obtained by summing over all depth strata. Sampling for lake phosphorus content was conducted on a frequency of approximately once every two weeks during the period of April, 1980 to October, 1982.

Budget Study Results

Daily streamflow and loading rates of total phosphorus for each sub-watershed of Harvey's Lake were calculated for the period of November, 1981 to October, 1982 by methods described above. The daily rates were summed for each month and the monthly totals are given in Tables 21 and 22. Annual total flow and loading rates are summarized in Table 23. These loading rates are probably close to rates that could be expected during a "normal" runoff year. Data obtained from the nearby Sleepers River Research Watershed indicated that the runoff rate recorded at weir W3 during the one year period of November, 1981 to October, 1982 was .64 meters (calculated from provisional flow data), compared with a fifteen year (1960-1974) average of .63

Table 20. Regression relationships between flows and phosphorus loading rates for Harvey's Lake tributaries and average daily flows at the Sleepers River Research Watershed weir W3. All regressions were of the following form.

$$\log Y = a \log X + b \quad (N, R^2)$$

where Y = Harvey's Lake tributary flow (cfs) or phosphorus loading rate (Kg/day)
X = Average daily flow at the Sleepers River Watershed weir W3 (cfs)
a = Slope of regression equation
b = Intercept of regression equation
log = Indicates base 10 logarithum
N = Number of sample dates
R^2 = Proportion of the variance of Y accounted for by the regression.

Stream	Variable	a	b	N	R^2
Jewett Brook	Flow	1.06	- .096	192	.63
	Loading	1.12	-1.67	192	.47
T1	Flow	1.04	-1.62	142	.63
	Loading	1.36	-2.53	142	.57
T2	Loading	1.14	-2.82	138	.44
T3	Flow	1.02	-2.19	140	.44
	Loading	1.22	-2.73	140	.42
T4	Flow	1.04	-1.58	158	.56
	Loading	1.51	-3.04	158	.48
T5	Flow	1.18	-1.96	152	.71
	Loading	1.77	-3.76	152	.56
T6	Flow	1.32	-1.76	57	.70
	Loading	2.18	-3.67	57	.68
S. Peacham Brook	Flow	1.10	.21	154	.83
	Loading	1.76	-1.82	154	.67
Stevens River	Flow	1.15	.32	180	.54

meters/year (Anderson et al, 1977). Thus, the one-year budget data presented in Table 23 probably has long-term generality under conditions of unchanging land use.

From Table 23 it can be seen that Jewett Brook was the major tributary, contributing 73% of the total surface inflow during the study period. Although Jewett Brook was the largest single source of phosphorus, it contributed only 40% of the phosphorus loading from the lake's watershed. The outlet backflow was a significant hydrologic input (10% of the total inflow), and was the second largest single contributor of phosphorus to the lake (19% of the total loading). The streams T1, T2, T3, and T4 drain a common agricultural region (see Figure 2) composed of portions of two dairy farms. Together, these four small streams contributed only 4% of the total inflow while supplying 27% of the phosphorus received from the watershed. Other tributaries and ungaged areas contributed the remaining 13% of the inflow and 14% of the phosphorus loading.

Table 23 also reveals which of the Harvey's Lake tributaries are most strongly affected by human activities. It is these subwatersheds to which phosphorus control measures should be directed. Phosphorus loads carried by Jewett Brook appear to be only slightly affected by cultural activities. Jewett Brook has some agricultural activity within its watershed (see Figure 2) but these areas are a minor fraction of the drainage area and tend to be in the upper portions of the watershed, distant from the lake. The flow-weighted mean phosphorus concentration in Jewett Brook of 15 mg/m^3 was the lowest of all Harvey's Lake tributaries. The phosphorus export rate from the Jewett Brook watershed, expressed per unit of drainage area, was 5.3 $mg/m^2/yr$, a value typical of undeveloped, predominantly forested watersheds in the Eastern United States (Omernik, 1976). It is unlikely, therefore, that phosphorus loadings to the lake by Jewett Brook could be significantly reduced through phosphorus control measures in this watershed.

The predominantly agricultural sub-watershed of Harvey's Lake drained by streams T1, T2, T3, and T4 produced the highest phosphorus levels of all lake tributaries, with a combined mean

Table 21. Monthly total flows ($10^4 m^3$) for Harvey's Lake sub-watersheds, November, 1981 to October, 1982.

	Sub-watershed								
	Jewett	T1	T3	T4	T5	T6	Ungaged	Backflow	Total
Nov	58	1.3	.52	1.7	.91	1.1	6.7	0	70
Dec	34	1.0	.27	1.1	.46	.67	3.9	2.0	43
Jan	25	.62	.16	.69	.34	.51	2.9	0	30
Feb	25	.60	.16	.66	.33	.52	2.9	0	30
Mar	38	1.2	.50	1.1	.55	.86	4.4	4.1	51
Apr	225	5.0	1.7	6.2	3.6	8.2	26	6.3	282
May	48	1.4	.27	1.6	.74	1.1	5.6	12	71
June	48	1.4	.28	.87	.74	1.1	5.5	29	87
July	21	.58	.14	.62	.31	.44	2.4	1.2	27
Aug	11	.24	.018	.15	.13	.24	1.3	12	25
Sept	5.9	.30	.012	.034	.056	.12	.69	4.9	12
Oct	16	1.1	.049	.27	.22	.37	1.9	8.0	28

Table 22. Monthly total loadings of total phosphorus (Kg) for Harvey's Lake sub-watersheds, November, 1981 to October, 1982.

	Jewett	T1	T2	T3	T4	T5	T6	Ungaged	Backflow	Total
Nov	5.3	1.3	.42	.65	.51	.25	.32	.61	0	9.4
Dec	3.1	1.0	.25	.36	.28	.088	.15	.36	.39	6.0
Jan	3.0	.62	.19	.25	.19	.046	.092	.35	0	4.7
Feb	2.8	.60	.18	.25	.19	.049	.12	.32	0	4.5
Mar	5.5	1.2	.53	4.2	1.7	.54	.66	.64	13	31
Apr	35	5.0	2.3	6.1	8.7	1.8	14	4.0	6.2	91
May	8.0	1.4	.39	.46	.40	.27	.45	.93	2.4	15
June	12	1.4	.45	.54	.45	.25	.48	1.4	15	32
July	3.3	.58	.15	.24	.18	.043	.024	.38	.13	5.0
Aug	2.7	.24	.049	.020	.097	.028	.044	.31	.81	4.3
Sept	1.1	.30	.0013	.018	.009	.004	.011	.13	.33	1.9
Oct	3.0	1.1	.021	.080	.11	.025	.039	.34	2.2	6.9

Table 23. Summary of annual flows and phosphorus loading rates for Harvey's Lake sub-watersheds, November, 1981 to October, 1982.

Sub-watershed	Flow ($10^4 m^3$)	Phosphorus Loading (Kg)	Mean Phosphorus Concentration (mg/m^3)	Phosphorus export per unit drainage area (mg/m^2)
Jewett Brook	555	84	15	5.3
T1	15	25	167	-
T2	*	4.9	*	-
T3	4.1	13	317	-
T4	15	13	87	-
entire agr. area	34	56	165	34.8
T5	8.4	3.4	40	6.4
T6	15	17	113	42.0
Ungaged Area	64	9.8	15	5.3
Outlet Backflow	79	41	52	-
All Sub-watersheds	756	211	28	8.4 **

* flows not significant, relative to the total

** excludes outlet backflow

stream phosphorus concentration of 165 mg/m^3 and with maximum concentrations at times as high as 4-6 mg/l. The phosphorus export rate from this combined drainage area was 35 $mg/m^2/yr$, a value characteristic of heavily agricultural watersheds in the Eastern United States (Omernik, 1976). It appears that agricultural activities in this small portion of the lake's watershed have resulted in greatly increased rates of phosphorus export and that efforts should be made to control this relatively localized source.

The outlet backflow produced a mean phosphorus concentration of 52 mg/m^3, reflecting the greater agricultural development of the South Peacham Brook watershed, relative to the Harvey's Lake watershed. The phosphorus contribution of the backflow process should be considered entirely culturally caused, as it results from the placement of the dam below the confluence of South Peacham Brook and the outlet channel.

Of the other drainages, only T6 contributed significant phosphorus loads to the lake. This stream drains a forested watershed, and the surprisingly high mean phosphorus concentration of 113 mg/m^3 may have been caused by logging operations conducted in this sub-watershed during the course of the study. Because the logging disturbance should be transient, it is unlikely that this stream will constitute a continually significant source of phosphorus to the lake.

The phosphorus budget results discussed above involve concentrations and loading rates of total phosphorus. It might be expected that some of the total phosphorus in the streams was in a particulate form that would settle quickly without becoming available to the algae. It is therefore of some interest to compare the various streams as to their proportion of dissolved to total phosphorus (DP/TP). Those streams with higher DP/TP ratios would be expected to have a disproportionately greater impact on lake productivity.

The mean DP/TP ratios for each Harvey's Lake tributary are given in Table 24. Very high DP/TP ratios were observed for streams T2 and T3, draining portions of the agricultural sub-watershed. These high ratios suggest a strong influence of

manure or fertilizer runoff. Lower DP/TP ratios were found in streams T1 and T4 which also drain this farmland. These streams are apparently more influenced by erosional processes which contributed greater particulate phosphorus loads. Intermediate DP/TP ratios were found for tributaries such as Jewett Brook, T5, and T6 with predominantly forested watersheds. South Peacham Brook carried relatively heavy particulate phosphorus loads, perhaps reflecting the influences of cultivation and stream channelization in this drainage.

Table 24. Mean ratios of dissolved phosphorus to total phosphorus (DP/TP) for Harvey's Lake tributaries. N indicates number of sample dates on which the means are based.

Stream	DP/TP	N
Jewett	.88	63
T1	.69	27
T2	.97	39
T3	.96	51
T4	.67	52
T5	.89	41
T6	.82	15
South Peacham	.67	62

Model Development

The results of the phosphorus budget study showed that phosphorus control measures could be most effectively directed at two sources: the outlet backflow and the agricultural area in the northeast portion of the watershed. However, in order to quantitatively assess the water quality gains in the lake that would result from phosphorus control measures in these areas, it was necessary to develop a model for the lake that linked phosphorus loadings from the watershed to phosphorus levels in the lake.

Data on stream flow, phosphorus loading rates, and lake phosphorus content obtained during the course of this study was used to develop such a phosphorus model for Harvey's Lake. Monthly mean lake phosphorus levels for the period of April, 1980 to October, 1982 are shown in Figure 26. Figure 26 shows considerable short-term fluctuation in the phosphorus content of the lake. Phosphorus levels ranged from a low of 169 Kg, recorded in August, 1980, to a high of 619 Kg in August, 1981. Average phosphorus levels during the entire period of study were 390 Kg, corresponding to a volume-weighted mean concentration of 13.9 mg/m^3. There was a statistically significant ($p < .05$) increasing trend in phosphorus levels during this time period, as determined by a linear regression analysis of phosphorus content vs. time. However, during the latter two years of study, phosphorus levels appear to have stabilized around an average level of about 420 Kg (15 mg/m^3).

In developing the model, an effort was made initially to predict the short term, month by month, fluctuations in the observed phosphorus content of the lake using a time-variable model. To do this, it was first necessary to estimate stream flows and phosphorus loading rates for the entire period of study. Using the monthly total flows and loading rates previously determined for the lake (Tables 21 and 22) with monthly total flow data obtained on a provisional basis from the Sleepers River Research Watershed for the period of November, 1981 to October, 1982, it was possible to develop regression relationships to predict flow and loading rates for Harvey's Lake for months when this data was not obtained directly. These regression relationships are shown in Figures 27 and 28.

Using the regression equations given in Figures 27 and 28 with monthly total flow data obtained from the Sleepers River Research Watershed, monthly total flow and phosphorus loading rates to Harvey's Lake were calculated for the period of April, 1980 to October, 1981. Values for total inflow rates, total phosphorus loading rates, and lake phosphorus levels determined for each month during the entire period of study are summarized

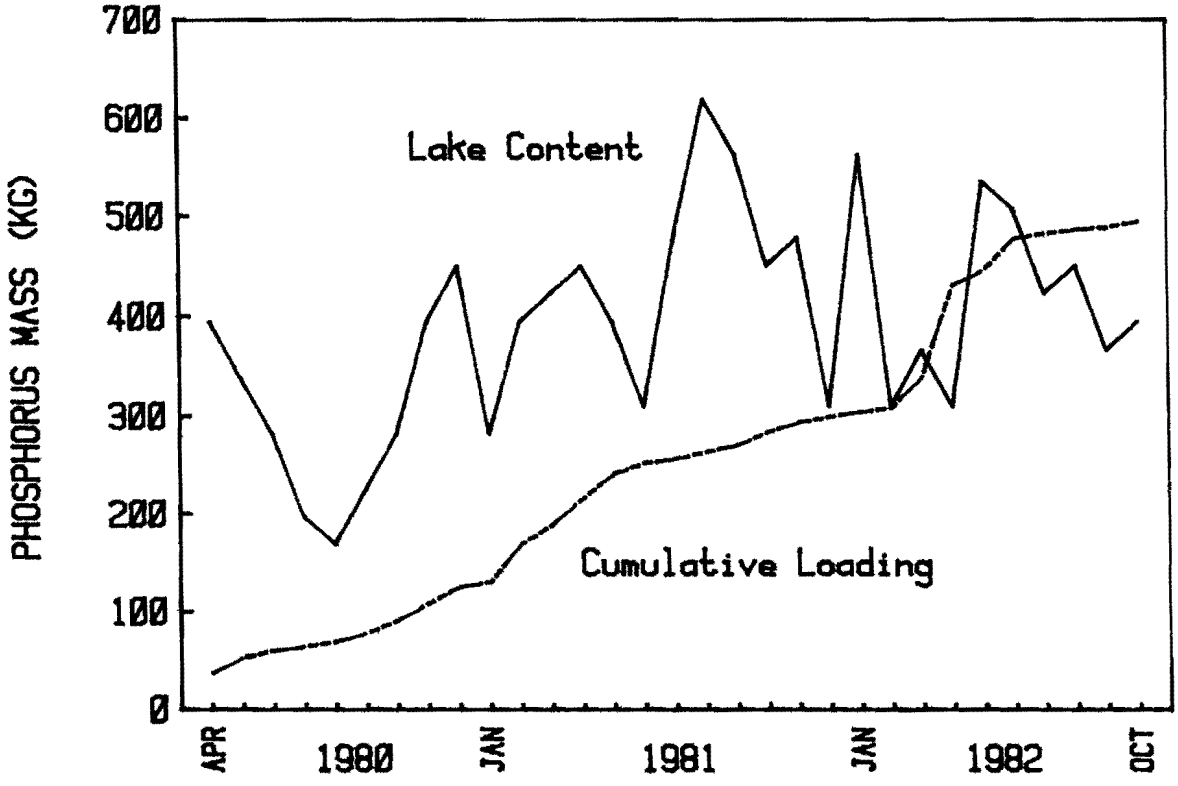


Figure 26. Plot of lake phosphorus content and cumulative phosphorus loading for the period of April, 1980 to October 1982.

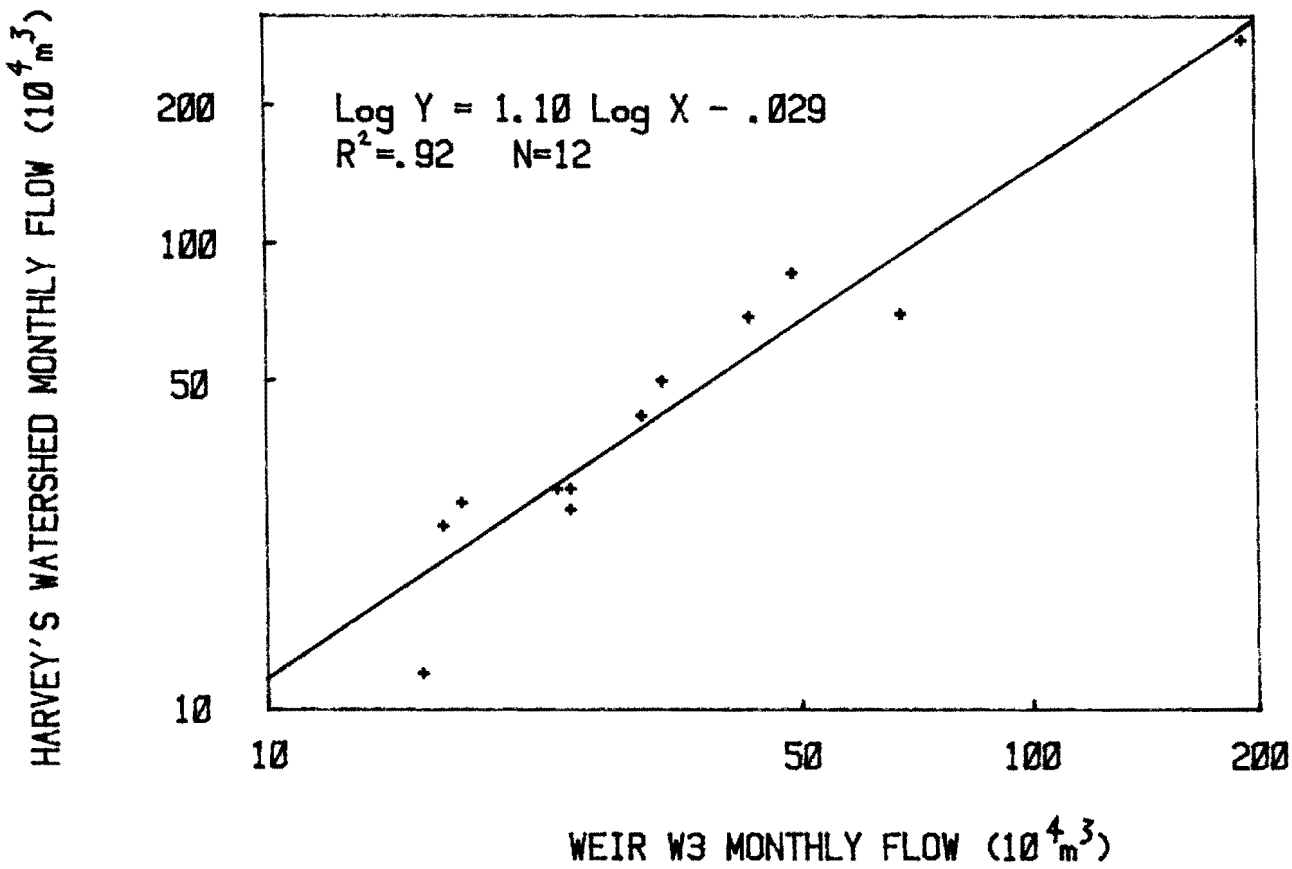


Figure 27. Regression of total monthly inflow to Harvey's Lake vs. total monthly flow at the Sleepers River Research Watershed weir W3 during the 12 month period of November, 1981 to October, 1982.

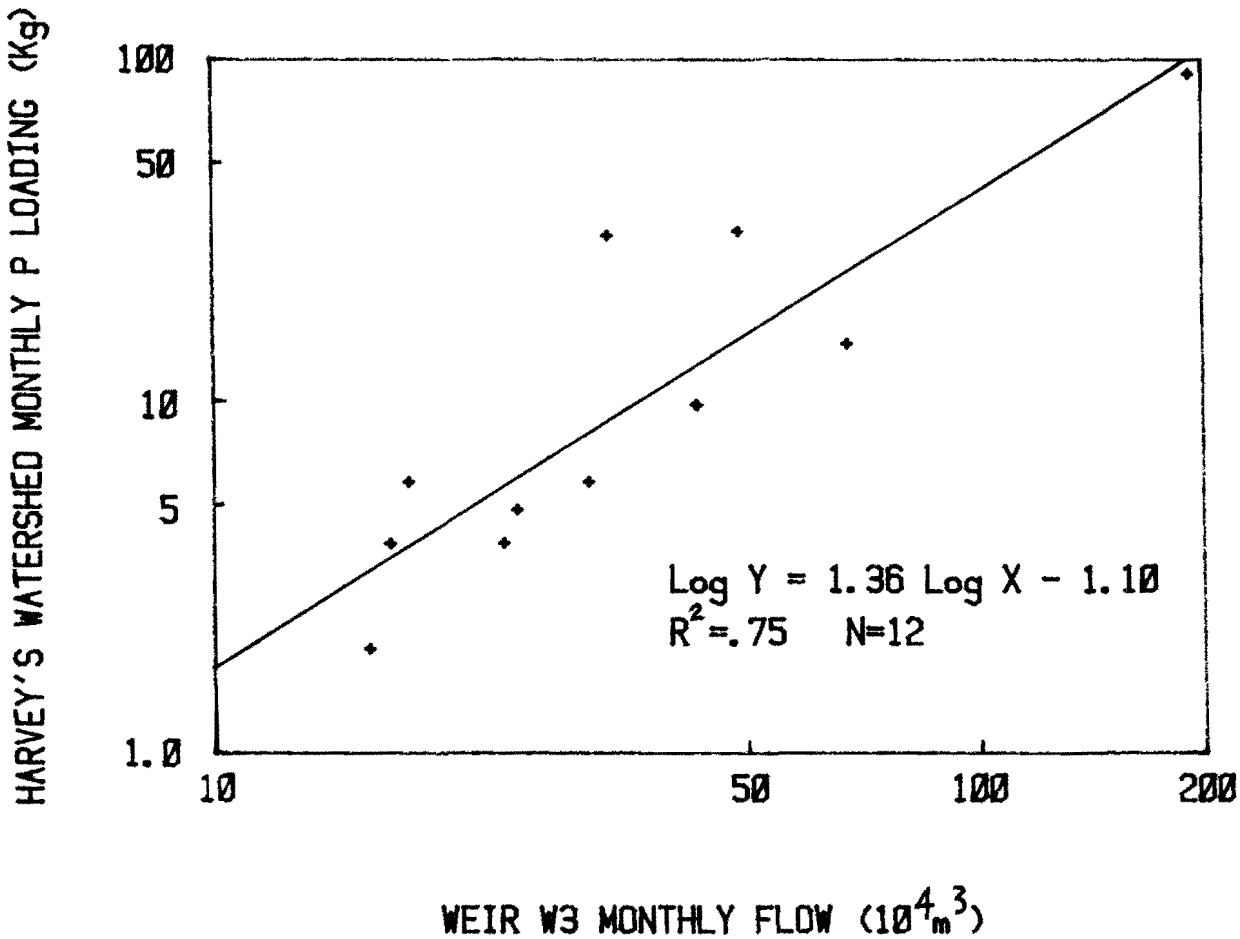


Figure 28. Regression of total monthly phosphorus loading to Harvey's Lake vs. total monthly flow at the Sleepers River Research Watershed weir W3 during the 12 month period of November, 1981 to October, 1982.

in Table 25. Cumulative phosphorus loadings from April, 1980 to October, 1982 are compared with lake phosphorus levels in Figure 26.

The model initially chosen for testing is given in equation 4. This model is the time-variable solution for lake phosphorus concentration, based on the differential equation for phosphorus mass balance developed by Vollenweider (1969).

$$P_t = P_o e^{-at} + \frac{W\,(1-e^{-at})}{Q + SV} \qquad (4)$$

where P_t = lake phosphorus concentration at time t (mg/m^3)

P_o = lake phosphorus concentration at time o

a = (Q + SV)/V

W = total loading of phosphorus from all external sources (mg/mo) during month t

Q = water inflow rate (m^3/mo) during month t

S = net sedimentation coefficient (mo^{-1}) during month t

V = lake volume (m^3)

t = time, in months

The model given in equation 4 was run using the data from Table 25 for one month time intervals over the period of April, 1980 to October, 1982. A sedimentation coefficient (S) of .02 mo^{-1} was calibrated to the observed lake phosphorus levels using only data obtained during the period of direct flow and loading measurements (November, 1981 to October, 1982). This calibration factor was held constant as the lake phosphorus levels were predicted for the entire study period. A comparison of predicted and observed lake phosphorus concentrations is shown in Figure 29.

Figure 29 shows that the model failed to adequately predict the apparent short-term fluctuations in lake phosphorus levels. There are a number of possible reasons for this failure. These possibilities are discussed below.

Table 25. Summary of monthly inflow, phosphorus loading and average lake phosphorus concentration estimated for the entire period of study.

Year	Month	Flow ($10^4 m^3$)	Loading (Kg)	Average Lake Phosphorus Concentration (mg/m^3)
1980	Apr	134	37	14
	May	68	16	12
	June	34	7	10
	July	24	4	7
	Aug	27	5	6
	Sept	42	9	8
	Oct	59	13	10
	Nov	71	17	14
	Dec	71	17	16
1981	Jan	27	5	10
	Feb	140	39	14
	Mar	77	19	15
	Apr	107	28	16
	May	97	25	14
	June	50	11	11
	July	23	4	17
	Aug	34	7	22
	Sept	37	7	20
	Oct	57	13	16
	Nov	70	9	17
	Dec	43	6	11
1982	Jan	30	5	20
	Feb	30	4	11
	Mar	51	31	13
	Apr	282	91	11
	May	71	15	19
	June	87	32	18
	July	27	5	15
	Aug	25	4	16
	Sept	12	2	13
	Oct	28	7	14

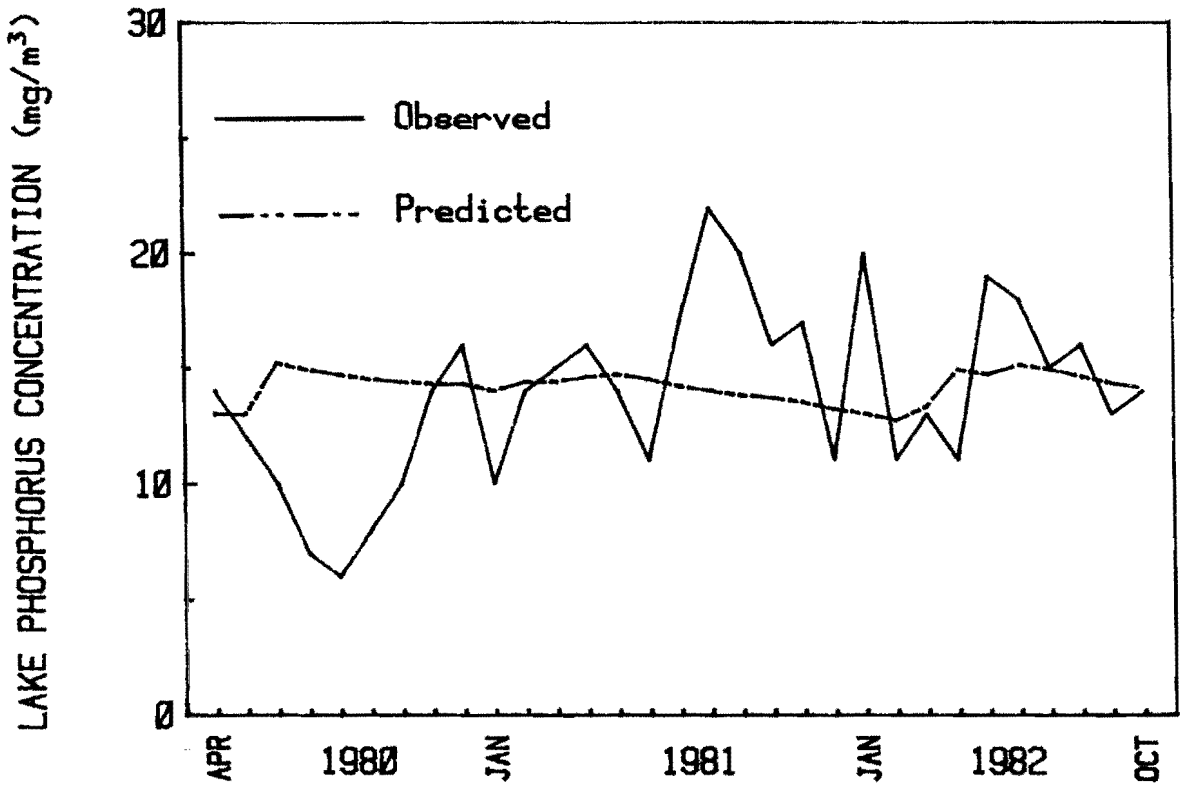


Figure 29. A comparison of observed lake phosphorus concentrations with values predicted from the time-variable model for the period of April, 1980 to October, 1982.

From the comparison of lake phosphorus content vs. cumulative phosphorus loading in Figure 26, it can be seen that there were periods in which apparent large increases in lake phosphorus levels were not accompanied by corresponding phosphorus inputs from the watershed. This observation raises the possibility that phosphorus loading rates were vastly underestimated by the methods used in this study.

One way to check this possibility is to compare runoff rates (flows normalized for drainage area) estimated for the Harvey's Lake watershed with rates measured at other nearby watersheds during the period of November, 1981 to October, 1982. Monthly runoff during this period at Harvey's Lake (excluding the outlet backflow) is compared in Figure 30 with rates measured at the Sleepers River Watershed weir W3 (drainage area = 845 ha) and at the gage station maintained by the U.S. Geological Survey on the Wells River, at Wells River, Vermont (drainage area = 25,500 ha). The Wells River data is based on provisional flow data supplied by the U.S. Geological Survey for water year 1982. Figure 30 shows that monthly runoff rates from the three watersheds were highly correlated but that the Harvey's Lake watershed consistently yielded the lowest rates of runoff. Flows, and consequently phosphorus loading rates, at Harvey's Lake may have been underestimated by the failure of the daily sampling program to adequately evaluate these rates during the few periods of extremely high storm related flows. However, if this were the case, it would be expected that the Harvey's Lake runoff rates should fall below the rates for the other watersheds primarily during those months of peak flows. During the months of July-October 1982, there were few storms and stream flows fluctuated only slowly. Under these conditions, daily sampling should be quite accurate. Figure 30 shows that Harvey's Lake runoff estimates were about equally lower than those for the other two watersheds throughout the year. This comparison suggests that the daily sampling frequency was not the problem and that the Harvey's Lake watershed may actually yield less runoff than the other two watersheds, for reasons which are not known.

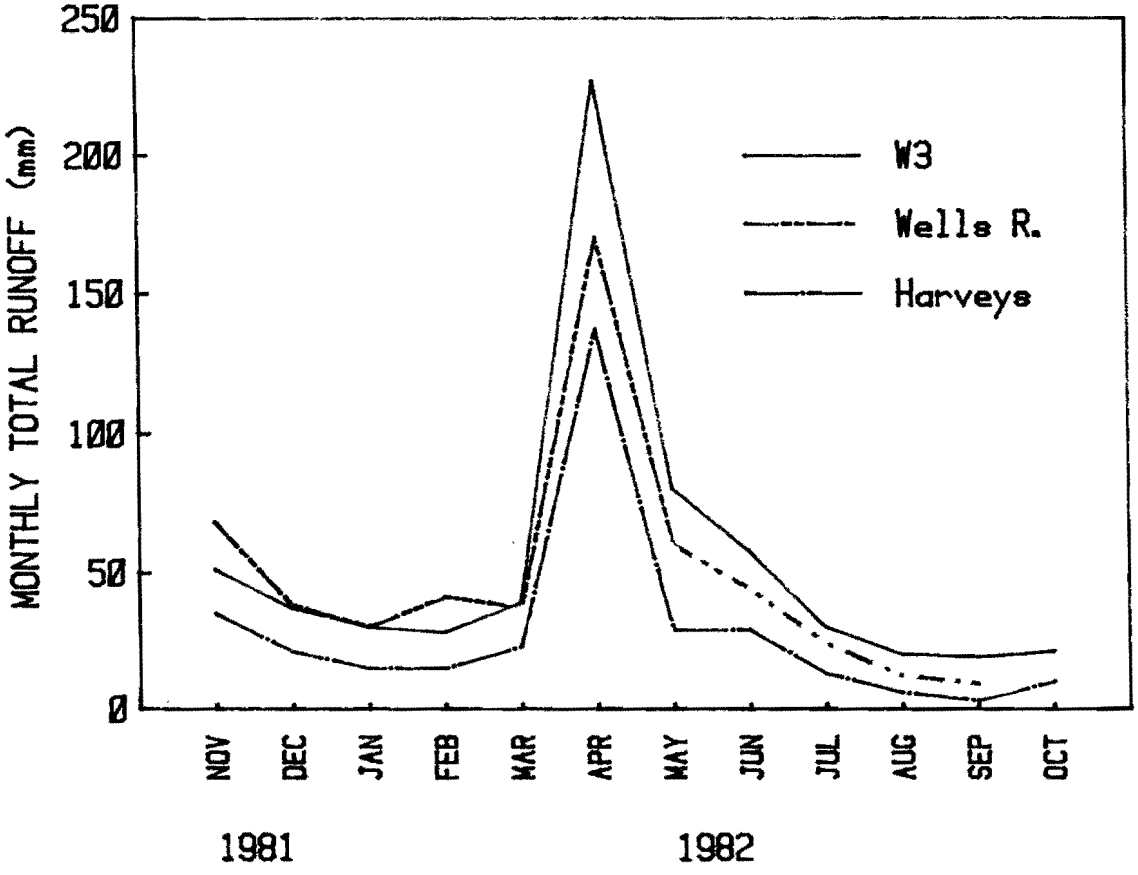


Figure 30. A comparison of monthly runoff rates estimated for Harvey's Lake during November, 1981 to October, 1982 with rates observed at two other nearby gaged watersheds.

Another possible explanation for the failure of the model to accurately predict the variations in lake phosphorus content is that the model did not include all significant phosphorus loading sources. Internal loading of phosphorus from the sediments of the hypolimnion may have been the cause of the large increase in total lake phosphorus content during June-September, 1981, a period of very little phosphorus contribution from the watershed (see Figure 26). Examination of phosphorus depth profiles obtained during this period reveals that most of this increase did in fact occur in the hypolimnetic strata. As discussed earlier in this report, the highest rate of hypolimnetic oxygen depletion during the three years of study occurred during Summer, 1981. The relatively low oxygen levels in the hypolimnion during this time may have resulted in increased rates of phosphorus release from the bottom sediments. It appears, however, from Figure 26, that with the onset of fall turnover and restored oxygen concentrations, this phosphorus disappeared from the water column. Thus, this temporary period of internal loading did not have a long term effect on lake phosphorus levels.

A third possible explanation for the failure of the time-variable model is that lake phosphorus levels were not measured accurately by the sampling methods employed. For example, the pronounced minimum in lake phosphorus content during Summer, 1980 (see Figure 26) may have resulted from too infrequent sampling with depth. The *Oscillatoria* layer during Summer, 1980 was particularly compact in a narrow depth band located between 10 and 15 meters depth. Much of the lake's phosphorus existed in the *Oscillatoria* cells during this period, and the depth sampling at 5 meter intervals may have missed this layer during most of the summer.

Another possible error in lake phosphorus measurements may have resulted from the fact that the low phosphorus concentrations of less than 10 mg/m^3 that often existed in the lake, particularly in the surface layers, were so low as to approach the limits of analytical sensitivity. Because much of the lake's volume is contained in the surface water strata,

considerable errors in estimating total lake phosphorus content could have resulted from unavoidable analytical imprecision associated with dilute samples.

Finally, another source of error in the lake phosphorus measurements may have been too infrequent sampling with time. Most of the monthly phosphorus values shown in Figure 26 were based on means for two or more sample dates. However, in some cases the values were based on only a single sample date during the month. One such case is that of January, 1982 during which time there was an apparently huge but temporary jump in lake phosphorus content during a period of insignificant loading from the watershed. Thus, this value should be regarded with suspicion.

Whatever the reasons for the failure of the time-variable model to predict month by month variations in lake phosphorus content, it is clear that a different modeling approach must be used. The most reasonable approach appears to be the use of a simpler steady-state model that predicts long-term average phosphorus levels in the lake. The various possible sources of error in estimating lake phosphorus content may cast suspicion on individual monthly values, but it is likely that long-term average lake phosphorus levels were estimated accurately enough for use in developing such a steady-state model. The possibility of inaccuracy in estimating phosphorus loading rates remains a serious one for a steady-state model. However, the steady-state model presented below has the advantage that predictions of phosphorus changes in the lake expected from reduced phosphorus loading rates would be valid, provided that the <u>relative</u> contributions of the various tributaries were estimated accurately. This is true because of the direct proportionality between lake phosphorus concentration and loading (see equation 5). Because each tributary was sampled on the same schedule of daily visits during the period of phosphorus budget measurements, it is likely that this assumption of correct relative loading rates would hold true even if there was some systematic error associated with the stream sampling methods.

The steady-state model chosen for use with the Harvey's Lake data is given in equation 5.

$$P = W/(Q + vA) \qquad (5)$$

where P = steady-state, volume-weighted mean phosphorus concentration (mg/m^3)
W = phosphorus loading rate (mg/yr)
Q = water inflow rate (m^3/yr)
v = apparent phosphorus settling velocity (m/yr)
A = lake surface area (m^2)

The model given in equation 5 was calibrated to the Harvey's Lake data for the period of November, 1981 to October, 1982. Values for the model terms estimated during this one year period of intensive stream sampling are given in Table 26. A value for the apparent phosphorus settling velocity (v) of 5.6 m/yr was calibrated to the observed lake phosphorus levels.

The model was tested using data from the previous 19 month period of April, 1980 to October, 1981. Values for model terms estimated for this period are also given in Table 26. Holding the calibration factor (v) constant at 5.6 m/yr, the model predicts a lake phosphorus concentration of 13.1 mg/m^3 for this earlier period, which compares very well with the observed mean of 13.3 mg/m^3. This comparison suggests that the model can be used with some confidence to predict long-term average lake phosphorus levels under various conditions of phosphorus loading.

It is interesting to compare the calibrated settling velocity value for Harvey's Lake with settling velocities predicted by empirically-derived models based on a broad selection of lakes. Chapra (1975) and Dillon and Kirchner (1975) have suggested that apparent phosphorus settling velocities might be fairly constant from lake to lake. Ostrofsky (1978) presented a relationship for predicting the phosphorus retention coefficient (R) for lakes such as Harvey's Lake with low areal

water loading rates (Q/A less than 10 m/yr). Phosphorus settling velocity is related to R according to equation 6, as derived by Chapra (1975).

$$R = v(Q/A + v) \qquad (6)$$

Ostrofsky's model and equation 6 predict an apparent phosphorus settling velocity of 11.7 m/yr for Harvey's Lake. This value is considerably larger than the calibrated value of 5.6 m/yr.

The calibrated settling velocity for Harvey's Lake may be lower than expected for a number of reasons. One possibility is that phosphorus loading rates were underestimated and that the calibration term had to be adjusted downward accordingly. This possibility presents a serious problem for using the model to predict changes in lake phosphorus levels from changes in

Table 26. Values of the terms used in calibration and testing of the annual steady-state model.

Calibration Period - November, 1981 to October, 1982

Term	Value
Observed lake phosphorus concentration (P)	14.8 mg/m^3
*Phosphorus loading rate (W)	242×10^6 mg/yr
Water inflow rate (Q)	756×10^4 m^3/yr
Lake surface area (A)	1.56×10^6 m^2

Testing Period - April, 1980 to October, 1981

Term	Value
Observed lake phosphorus concentration (P)	13.3 mg/m^3
*Phosphorus loading rate (W)	210×10^6 mg/yr
Water inflow rate (Q)	745×10^4 m^3/yr
Lake surface area (A)	1.56×10^6 m^2

*includes loading from direct precipitation of 31 Kg/yr.

phosphorus loading rates. However, as discussed earlier, it is only necessary that the loading rates from the various streams be evaluated correctly on a relative basis for the model to make accurate predictions.

Another possibility is that the lake does, in fact, have a lower than average phosphorus settling velocity. One reason for this might be the strong influence of the *Oscillatoria* population on the internal phosphorus dynamics of the lake. As described earlier in this report, these algae have the ability to regulate their buoyancy. By taking up a large proportion of the lake's phosphorus and by maintaining their population at the mid-depths of the lake during much of the year, the *Oscillatoria* may reduce the net loss of phosphorus from the water column to the sediments. Finally, it should be noted that, while low, the calibrated phosphorus settling velocity of 5.6 m/yr for Harvey's Lake is still within the range of values of 1.4 - 60 m/yr indicated by the data of Kirchner and Dillon (1975) and Dillon and Kirchner (1975) for a broad selection of lakes.

Model Results

The results of the phosphorus budget were used to identify the major Man-caused phosphorus sources to Harvey's Lake and to direct feasibility studies for the control of these sources. The feasibility studies for phosphorus control are described elsewhere in this report. The results of the feasibility studies showed that it is possible to substantially reduce phosphorus loading to the lake from these sources. The steady-state phosphorus model for the lake can be used with the results of the feasibility studies to quantify the gains in lake water quality expected under various combinations of phosphorus control measures.

Three specific phosphorus control measures were determined to be technically feasible (see later report section on phosphorus control feasibility studies). These three measures are briefly described in Table 27. The reduction in lake phosphorus concentrations expected from the implementation of these phosphorus control measures was evaluated using data for

Table 27. Summary of three phosphorus control measures evaluated for Harvey's Lake.

Measure	Description	Loading Reduction Expected
A	Reduce outlet backflow by building a stoplog structure in the outlet channel and lowering the effective elevation of the existing dam	81% of backflow volume in an average runoff year (assume 81% of backflow phosphorus loading).
B	Divert flow from streams T1 and T2 out of the lake's watershed	100% of loading from T1 and 80% (estimated) of loading from T2.
C	Improve manure management practices in the T3 and T4 drainage basins	50% (estimated) of loading from T3 and T4.

the period of November, 1981 to October, 1982 (Table 23) with the model given in equation 5. The model results are shown in Table 28.

The model results show that it would be possible to reduce lake phosphorus levels by about 27% if all three phosphorus control measures were implemented. Control of the outlet backflow alone would reduce lake phosphorus levels by about 10%, as would the partial diversion of the farm runoff, alone. The complete implementation of all three measures should reduce lake phosphorus levels below 11 mg/m^3. These levels would be similar to those observed in Harvey's Lake several years ago before the recent, alarming rise in lake phosphorus concentrations (see Figure 11).

It is often desirable to express water quality improvements resulting from phosphorus controls in terms of changes in chlorophyll, transparency, and hypolimnetic oxygen depletion rates. These factors are of more direct significance to lake users than are phosphorus values alone. In the case of Harvey's Lake, such predictions are difficult to make in a quantitative manner. Chlorophyll, transparency, and oxygen depletion rates in Harvey's Lake are strongly influenced by the Oscillatoria population, and predictions of the response of these factors to phosphorus changes would have to take into account the effect of such changes on the Oscillatoria. At present, surface chlorophyll and transparency levels are considerably better than what would be predicted from the lake's phosphorus concentration, based on relationships developed from a broad selection of Vermont lakes (Vermont Department of Water Resources and Environmental Engineering, 1980). As discussed earlier, this circumstance is a consequence of the deep-living habits of the Oscillatoria. It is unlikely, therefore, that substantial improvements in surface algal abundance or transparency could be achieved with the phosphorus control methods modeled above.

The chief value of phosphorus controls in terms of chlorophyll, transparency, and oxygen levels in Harvey's Lake lies with the lake protective role that such controls would play. If continuing phosphorus enrichment of the lake results in a

Table 28. Model results - expected reductions in lake phosphorus concentrations with various combinations of phosphorus control measures.

Control Measures	*Total Annual Phosphorus Loading (Kg)	Total Annual Flow ($10^4 m^3$)	Predicted Lake Phosphorus Concentration (mg/m^3)	**Percent Lake Phosphorus Reduction
Existing Conditions	242	756	14.8	0%
A only	209	692	13.3	10
B only	213	741	13.2	11
C only	229	756	14.1	5
A and B	180	677	11.6	22
A and C	196	692	12.5	16
B and C	200	741	12.4	16
A, B and C	167	677	10.8	27

* includes 31 Kg from direct precipitation

** reduction relative to existing conditions

shift to surface dwelling algal populations, as has been documented for other Oscillatoria lakes (see report section on Oscillatoria ecology), then dramatic water quality degradation could result. As shown earlier in this report, existing algal levels in the water column of Harvey's Lake are sufficient, if compressed into the epilimnion, to cause a marked (up to 57%) reduction in transparency. The transparency reduction could be even more extreme than this prediction because continued phosphorus enrichment could cause not only a shift to surface dwelling populations, but increased algal standing crops, as well. Furthermore, it is likely that if continued nutrient enrichment resulted in a shift to surface dwelling populations, along with increased rates of organic production in the lake, then greater hypolimnetic oxygen depletion rates will result (see report section on hypolimnetic oxygen depletion). Thus, phosphorus controls can protect Harvey's Lake in two ways. First, by restoring phosphorus concentrations in the lake to lower levels, they can arrest, and to some extent reverse, the adverse effects of the lake eutrophication process on levels of algae, transparency, and hypolimnetic oxygen. Second, phosphorus controls should decrease the probability that the Oscillatoria population will be replaced by surface-dwelling algae with the associated floating scums, reduced transparency, and increased hypolimnetic oxygen depletion that would accompany a shift to surface populations.

PHOSPHORUS CONTROL FEASIBILITY STUDIES

Diversion of Farm Runoff

The results of the phosphorus budget study showed that runoff from agricultural land in the northeast portion of the lake watershed was a major source of phosphorus to Harvey's Lake. Consequently, feasibility studies to control phosphorus loading from the two farms in this area were conducted with technical assistance from the U.S. Soil Conservation Service.

The first two alternatives considered were the construction of facilities for better manure management at both farms and the control of barnyard runoff at the Joe Roy farm by means of fencing, diversion of water above the barn, and the installation of eaves troughs and downspouts. Barnyard controls were not considered for the Francis Roy farm because the barnyard is out of the lake's watershed. From an analysis conducted by Mr. Larry Knight of the U.S. Soil Conservation Service (see letter in Appendix), it was concluded that construction of manure storage facilities at one or both of the farms would be expensive and would control relatively little of the phosphorus loading. Barnyard runoff controls, on the other hand, were determined to be a relatively inexpensive means of significantly reducing the portion of the farm runoff that originates in the barnyard.

The barnyard runoff control scheme has two major limitations, however. First, barnyard runoff from the Joe Roy farm affects only stream T1. Streams T2, T3, and T4 also carry significant agriculturally-derived phosphorus loads, and phosphorus inputs to the lake from these streams would not be reduced by barnyard measures alone. Second, the proposed barnyard phosphorus control measures would improve the water quality of the barnyard runoff, but would not prevent this water from entering the lake. Any failure in the system of controls would cause continued excessive nutrient loading to the lake. All of the specific barnyard control measures suggested would require continual maintenance by the landowner with little or no

economic benefit to the farm. Therefore, it might be difficult to insure the permanent successful operation of the barnyard runoff control system.

In view of the limitations of barnyard runoff control measures alone in reducing agricultural phosphorus loading to the lake, other alternatives were sought. Preliminary feasibility studies by Dr. Richard Downer (see report in Appendix) resulted in the recommendation that a series of diversions be built to divert the majority of the farm runoff northward, out of the lake's watershed. This alternative has the advantage of providing a complete and permanent removal of the phosphorus inputs from those streams which can be diverted. More detailed studies of the feasibility of nutrient diversion were conducted by Mr. Richard Fisher of the U.S. Soil Conservation Service (see letters in Appendix).

Based on several field visits and survey work, it was determined that diversion of streams T2, T3, and T4 would not be feasible because of the deep entrenchment of the stream beds. However, it would be possible to entirely divert stream T1, which carries the barnyard runoff and is the largest single contributor of agriculturally-derived phosphorus to the lake. In addition, it would also be feasible to divert the upper portion of the T2 watershed which includes a cornfield with serious erosion and runoff potential.

Preliminary design and cost estimates for the T1 and T2 diversion were conducted by Mr. Fisher and summarized in two letters contained in the Appendix. The design calls for the improvement of an existing waterway for stream T1 on the Francis Roy property and the construction of a new waterway diverting the upper part of stream T2 into the existing T1 waterway. The combined drainage would flow into a marshy area near the northeast shore of the lake (see Figure 1) through which stream T1 presently flows. To divert this flow away from the lake, it was proposed that dikes be constructed at both ends of the marsh with a slow release structure at the north end. The dikes were designed to store water for a 10 year frequency storm and release the flow northward at a rate of about 0.5 cfs.

From the marshy area, the water would flow northward through a wooded area where some minor channelization may be required. From here, it was proposed that the diverted stream pass across farmland owned by Mr. Charles Choate and then enter the Steven's River downstream of the village of West Barnet. Construction of a stable outlet ditch is planned for the Choate property. This ditch could also be used as an outlet for any field drains needed on the Choate farm.

The proposed diversion system should prevent all of the phosphorus load carried by stream T1 from entering the lake and it should control roughly 80% of the phosphorus load contributed by stream T2. Itemized cost estimates for individual components of the diversion plan are provided in the April 28, 1983 letter from Mr. Fisher. The total plan cost was estimated to be $24,000.

Improved Manure Management

Feasibility studies for stream diversion showed that it would not be possible to divert streams T3 and T4 out of the lake's watershed. However, because these two streams contribute a substantial proportion of the agriculturally-derived phosphorus to the lake, an alternative means of controlling phosphorus runoff from these sub-watersheds was sought. Streams T3 and T4 drain farmland that is primarily pasture and hayfields on which manure is spread for fertilizing purposes.

As discussed earlier, however, the construction of manure storage facilities for the Joe Roy farm would not be a cost-effective means of preventing excessive phosphorus runoff. The best alternative appears to be to obtain the voluntary cooperation of the landowner in avoiding those manure spreading practices that lead to excessive nutrient runoff. If practices such as spreading on frozen ground and piling manure directly in the watercourses were avoided, it is likely that a substantial reduction (perhaps 50%) in phosphorus runoff from streams T3 and T4 would result. To accomplish these changes, Mr. Laurence

Hamel, District Conservationist with the U.S. Soil Conservation Service, has indicated his willingness to work with the landowner to develop mutually advantageous means for improved manure management on this farm (see letter in Appendix).

Correction of the Outlet Backflow

Based on the results of the phosphorus budget study, it was concluded that the outlet backflow represents a substantial Man-caused contribution of phosphorus to Harvey's Lake. Feasibility studies were therefore initiated to find ways to reduce or eliminate the backflow. A number of alternatives were evaluated for their technical feasibility by Dufresne-Henry Inc. (1983) under a contractual agreement.

The Dufresne-Henry study found that the most hydraulically and economically feasible solution was to construct a small stop-log structure at the lake's immediate outlet while lowering the effective elevation of the existing dam by removing stop-logs and opening the gate. The effect of these measures would be to create a greater water surface elevation gradient between the lake and the existing dam, thereby countering the tendency of water from South Peacham Brook to flow towards the lake. Hydrologic studies indicated that these measures would eliminate about 81% of the backflow volume in an average runoff year.

Some of the environmental impacts of this solution were addressed in the Dufresne-Henry study. It was found that flood levels in Harvey's Lake would be beneficially reduced by any measure that reduced the backflow. The potential for increased downstream flood levels was evaluated because, at present, Harvey's Lake provides storage for flood waters from South Peacham Brook. Reduction in the backflow could therefore result in higher flood peaks downstream. The Dufresne-Henry study concluded that construction of the stop-log structure at the lake outlet should have only minimal detrimental impact on downstream flooding. Furthermore, it was pointed out that the U.S. Army Corps of Engineers Flood Plain Information Study that exists for the area did not consider the effect of storage in Harvey's Lake

of South Peacham Brook flood waters. Thus, flood levels predicted in the Flood Plain Information Study should not be exceeded even if the backflow were completely eliminated. Finally, the Dufresne-Henry study addressed the issue of whether the construction of the stop-log structure would cause increased erosion either in the outlet channel or in South Peacham Brook. It was found that current velocities would increase only slightly under this alternative, resulting in a minimal increase in erosion potential.

There were a number of other concerns associated with the stop-log alternative that needed to be addressed. One concern was the impact it would have on the wetland associated with the outlet channel. Water levels in the outlet channel would be lowered under this alternative and the wetland would probably change in character. However, the wetland to a large extent owes its existence to the downstream location of the existing dam and is thus of unnatural origin. Further comments by Stephan Syz, Water Resources Planner for the Vermont Agency of Environmental Conservation, based on an initial site visit to the wetland, are provided in the Appendix.

Another major area of concern was the impact the stop-log structure would have on fish movement and reproduction. Discussions with representatives of the Vermont Fish and Game Department indicated that there are two aspects of the stop-log proposal that could have adverse impacts on the Harvey's Lake fishery. One such adverse impact is the obstruction of fish passage at the outlet. Species such as rainbow trout and landlocked salmon present in Harvey's Lake may use portions of South Peacham Brook and the Stevens River for spawning and nursery purposes. Provisions for fish passage through the proposed stop-log structure to insure that the fish have continuing access to these areas would eliminate this adverse impact.

A second adverse impact of the proposal is that reducing the effective elevation of the existing dam would result in the creation of a flowing river-like rather than a lake-like environment in the outlet channel. At present, the outlet

channel is an extension of the lake with very low flow velocities. The Vermont Fish and Game Department has plans to take advantage of this situation by encouraging fish spawning in South Peacham Brook, which is effectively a tributary to the lake under present conditions. Reducing the effective elevation of the existing dam would force the fish to travel first downstream before turning upstream to spawn in South Peacham Brook. Efforts to manage South Peacham Brook as a spawning area might be less successful under these conditions. Reducing the elevation of the dam could also interfere with the operation of the existing fish ladder.

One other area of concern associated with the stop-log alternative was that it would restrict small boat navigation in the outlet channel. It is not known how many people actually use the channel for this purpose but there are a number of sites in a private campground for which the outlet channel provides the only direct access to the lake. The owner of this campground, Mr. Karl Jurentkuff, has indicated that he would suffer lost property value if lake access from these sites were eliminated (see letter in Appendix). The Dufresne-Henry study indicated that there was no hydraulic reason why the stop-log structure could not be located immediately above the confluence of South Peacham Brook and the outlet channel in order to provide lake access from these campsites. Further study needed to be done, however, to determine whether it would be feasible to construct a small dam at this location.

To address these possible negative impacts and resolve some of the remaining questions about the feasibility of constructing a stop-log structure to control the outlet backflow, a second, supplemental study was conducted by Dufresne-Henry, Inc. The first purpose of the supplemental study was to determine whether lake-like conditions could be maintained in the outlet channel to aid fish movement while still controlling the backflow effectively. The results of this study showed that, with the new stop-log structure in place as proposed, removal of stop-logs at the existing dam would provide only minimal additional benefit in controlling the backflow. With a new stop-log structure placed

just above the confluence of South Peacham Brook and the outlet channel, reduction in the effective elevation of the existing dam by as little as one foot would reduce the annual backflow volume by 81% under conditions of an average runoff year and average lake level. Further analysis of channel conditions expected between the proposed stop-log structure and the existing dam showed that velocities would be increased and depths reduced only slightly, under most conditions, if the existing dam were lowered by as little as one foot. Thus, it appears that it would be possible to control the backflow effectively while maintaining a nearly lake-like environment below the proposed stop-log structure. It should also be possible to preserve the operation of the fish ladder.

Some provision for fish passage through the new stop-log structure will be required. Discussions with representatives of Dufresne-Henry Inc. indicated that modifications such as a submerged culvert opening or a V-notch overflow would not significantly impair the hydraulic effectiveness of the stop-log structure. The final selection of a design for fish passage will be made with advice from the Vermont Department of Fish and Game.

A second purpose of the additional study was to determine the structural feasibility of locating the new stop-log structure just above the confluence of South Peacham Brook and the outlet channel to provide for small boat navigation between this site and the lake. Hand auger probes showed that an apparently suitable foundation material existed at a depth of about 8 feet below the surface. Because of the additional length of structure required, the estimated cost of $28,000 for building the stop-log structure at the confluence of South Peacham Brook is 65% greater than the $17,000 cost of placing it at the lake's immediate outlet. A final decision on the location of the proposed stop-log structure will be made after additional discussion with affected landowners.

CONCLUSIONS

Harvey's Lake is a highly valued resource attracting and supporting a diverse set of recreational uses including fishing, swimming, boating, camping, and lakeshore home development. Each of these uses depends on the maintenance of good water quality conditions in the lake.

Present limnological conditions in the lake are dominated by the presence of dense populations of the alga *Oscillatoria rubescens* growing at the mid-depths during summer stratification. Vertical distribution patterns of dissolved oxygen, phosphorus, and nitrogen are strongly influenced by the *Oscillatoria*, with each of these factors showing a pronounced maximum at the depth of the *Oscillatoria* population. Water quality conditions are, at present, good enough to support the wide variety of recreational uses. Water transparency is very high, primarily as a consequence of the deep-living habits of the *Oscillatoria* population. Hypolimnetic oxygen depletion does occur to a considerable extent, but oxygen conditions have thus far remained suitable for fish and other aquatic life. Surface blooms of algae are rare and have never severely interfered with recreational use, although occasional complaints about floating clumps of algae are received. The major significance of the *Oscillatoria* presence is that it is characteristic of lakes undergoing a transition from oligotrophic to eutrophic conditions as a result of nutrient enrichment. There are numerous examples of both European and North American lakes in which the development of *Oscillatoria* populations has presaged much more serious water quality problems later.

There are a number of independent lines of evidence pointing to the conclusion that water quality in Harvey's Lake has been deteriorating over time. First, there has been a significant increasing trend in spring phosphorus levels in the lake over the past six years, although this trend may have been caused in part by regional climatic or other factors operating throughout Vermont. Second, there has been a substantial decline in hypolimnetic oxygen levels during recent decades, as indicated by

the comparison of a 1939 oxygen profile with present day profiles. Finally, a major paleolimnological study of Harvey's Lake sediments revealed that pronounced human-caused shifts in trophic status have occurred during the lake's history. The initial settlement of the watershed around 1780 caused small but discernable increases in indicators of past lake productivity. A dramatic increase in lake eutrophication has occurred since 1945. Oscillatoria first became abundant in the lake only 30-40 years ago. The period since 1945 has also been marked by an accelerating sedimentation rate, by increased rates of influx of algal remains to the sediments, and by geochemical evidence of declining oxygen conditions and increased phosphorus loading. Viewed as a whole, the limnological and the paleolimnological data present a clear picture. Water quality in the lake is presently good, but is undergoing a process of deterioration that, if allowed to continue, could seriously impair the future recreational use of the lake.

The feasibility of improving water quality by adding silica to the lake to shift algal dominance from Oscillatoria to diatoms was investigated in a variety of ways. The results showed that it would not be possible to induce such a species shift by silica addition in Harvey's Lake. Although diatoms were poorly represented in the algal community, particularly when Oscillatoria is abundant, dissolved silica in the lake was never depleted to levels that could be considered limiting for diatoms. Silica enrichment bag experiments demonstrated that diatom growth rates were generally not stimulated by silica addition. There was some evidence from bag experiments that allelopathic effects of Oscillatoria on diatoms might have existed, but these effects were not overcome by silica addition. A comparative study of 22 Vermont lakes indicated that silica addition might promote diatom relative abundance in lakes with total silica/total phosphorus ratios less than 100. However, the comparative study showed that Harvey's Lake, with its high silica/phosphorus ratio and its lack of dissolved silica depletion, would not be a good candidate for silica addition as a lake restoration measure.

Even if a species shift to diatoms had been possible, there are a number of reasons why such a shift would not be desirable in Harvey's Lake. First, the deep-living habit of the Oscillatoria population results in much better water transparency than would exist with a comparable algal standing crop growing in the surface waters. Second, food chain efficiency does not appear to be impaired in Harvey's Lake by the Oscillatoria dominance. Zooplankton production in Harvey's Lake is at or above levels expected based on primary production rates in the lake, and there is little evidence from a globally-distributed set of 30 lakes that blue-green algal dominance causes reduced trophic efficiency. Third, the migration of the Oscillatoria population to the mid-depths of the lake with the onset of summer stratification provides an effective nutrient stripping mechanism. It is not likely that a diatom-dominated algal community could provide, via sinking, a more efficient removal of nutrients from the epilimnion. Fourth, it appears that photosynthetic oxygen production by the Oscillatoria population within the hypolimnion reduces the rate of hypolimnetic oxygen depletion, relative to what this rate would be with a surface-dwelling population of comparable productivity. Thus, the Oscillatoria might be considered to be a relative asset to the water quality of Harvey's Lake. By a variety of mechanisms related to its deep-living habits, it delays and ameliorates the obvious symptoms of increasing eutrophication in the lake. If it were to be replaced by a surface-dwelling algal population, the apparent condition of the lake would probably be much worse.

The feasibility of improving water quality in Harvey's Lake by phosphorus control measures in the watershed was investigated first by determining the major sources of phosphorus to the lake. A phosphorus budget for the lake was developed for the one year period of November, 1981 to October, 1982. This period appears to be fairly representative of long-term average runoff conditions for the region.

Phosphorus loads contributed by nine sub-watersheds were estimated and compared to identify the major human-caused sources. Jewett Brook, the major hydrologic input, was also the

largest single contributor of phosphorus (40% of the total). However, the very low phosphorus export rate per unit of drainage area indicated that Jewett Brook phosphorus levels were little impacted by human activities and that significant further improvement would be difficult to achieve.

A single agricultural area in the northeast portion of the lake's watershed was the next major contributor of phosphorus to the lake (27% of the total). The phosphorus export rate per unit of drainage area from this farmland was high enough to indicate heavy agricultural impact.

Another major phosphorus contribution (19% of the total) reached the lake by the backflow of South Peacham Brook through the lake's outlet. This source is entirely caused by cultural activities, as it results from the placement of the Harvey's Lake dam below the confluence of South Peacham Brook and the outlet channel. The remaining 14% of the phosphorus budget was contributed by various small streams having relatively minor human impact within their drainages.

The phosphorus budget results indicated that feasibility studies to control phosphorus loading to the lake should be directed at two areas: reduction of phosphorus runoff from the farmland, and correction of the outlet backflow. Feasibility studies to control the farm runoff led to the conclusion that the best approach would be to divert stream T1 and part of stream T2 northward out of the lake's watershed. The cost of this diversion project was estimated to be $24,000. In addition, it was concluded that the best way to control phosphorus runoff from streams T3 and T4 would be to secure the cooperation of the landowner in modifying manure spreading practices in these sub-watersheds, with the assistance of the St. Johnsbury District Office of the U.S. Soil Conservation Service.

Feasibility studies to control the outlet backflow concluded that the best alternative would be to build a new stop-log structure in the outlet channel. The stop-log structure would control the lake level at 892.5 feet MSL. Provisions for fish passage through this structure should be provided. The existing dam should be operated in such a way as to provide optimum

control of the backflow while maintaining sufficient depth and low flow velocities downstream of the new structure so as to encourage fish passage to South Peacham Brook. The studies indicated that these purposes could be achieved with minimal reductions in the operating elevation of the existing dam. However, it is likely that some experimentation and monitoring will be required to establish the optimum operating policy to balance the needs of backflow reduction and fish movement.

The backflow studies also showed that two alternative sites for the new stop-log structure were feasible: at the lake's immediate outlet (for a cost of $17,000) and at the confluence of the outlet channel and South Peacham Brook (for a cost of $28,000). The lower, and more expensive, site has the advantage of permitting small boat navigation between this site and the lake. Additional discussion with affected landowners will be required before a final decision can be made on the location of the proposed stop-log structure.

A lake modeling analysis was conducted to evaluate the water quality gains expected from the various lake restoration measures proposed. The modeling analysis concluded that lake phosphorus levels would be reduced by about 27% if all proposed lake restoration measures were implemented. Correction of the outlet backflow alone would reduce lake phosphorus levels by 10%. Control of farm runoff by means of stream diversion and improved manure management would reduce lake phosphorus concentrations by about 16%.

A major value of phosphorus control lake restoration measures for Harvey's Lake is in the role such measures would play in protecting the lake from the development of surface-dwelling algal populations. It is likely that the deep-living *Oscillatoria* population will eventually be replaced by surface-living algae if existing elevated rates of phosphorus loading continue. Surface algal blooms could dramatically degrade the aesthetic quality of the water and impair the recreational use of the lake. Another value of phosphorus controls is that they should reverse the trend of deteriorating

hypolimnetic oxygen levels observed during the past few decades. A continuation of this trend could have serious adverse consequences for the important trout fishery in the lake.

Thus, the opportunity exists by relatively simple and inexpensive means to restore water quality in Harvey's Lake to the more suitable conditions that existed in the lake's past. Failure to arrest the eutrophication process in Harvey's Lake at its present stage could eventually lead to more serious water quality problems requiring more expensive and complex lake restoration measures in the future.

RECOMMENDATIONS

1. Silica addition should not be used as a lake restoration measure in Harvey's Lake. This treatment might be suitable in lakes with low diatom abundance and with total silica to total phosphorus ratios less than 100.

2. Phosphorus inputs to Harvey's Lake from agricultural runoff should be controlled by diverting streams T1 and T2 northward, out of the lake's watershed, as described in this report.

3. Agricultural phosphorus runoff in streams T3 and T4 should be controlled by improving manure management practices in these sub-watersheds. Efforts should be made to secure the cooperation of the landowner to achieve this purpose.

4. Phosphorus inputs to the lake from the outlet backflow should be reduced by constructing a stop-log structure in the outlet channel and by operating the existing dam in a manner that would balance the needs of backflow reduction and fish movement, as described in this report.

REFERENCES

Alimov, A.F., V.V. Boullion, N.P. Finogenova, M.B. Ivanova, N.K. Kuzmitskaya, V.N. Nikulina, N.G. Ozeretskuvskaya, and T.V. Zharowa. 1972. Biological Productivity of Lakes Krivoe and Kruglue. pp. 39-56. In. Kajak, Z. and A. Hillbricht-Ilkowska (eds.) op. cit.

American Public Health Association. 1981. Standard Methods for the Examination of Water and Wastewater. 15th edition. Washington, D.C.

Anderson, E.A., R.Z. Whipkey, H.J. Greenin, and C.T. Machell. 1977. NOAA-ARS Cooperative Snow Research Project - Watershed Hydro-Climatology and Data for Water Years 1960-1974. National Oceanic and Atmospheric Administration.

Andronikova, I.N., V.G. Drabkova, K.N. Kozmenko, N.F. Michailova, and E.A. Stravinskaya. 1972. Biological productivity of the main communities of the Red Lake. pp. 57-72. In. Kajak, Z. and A. Hillbricht-Ilkowska (eds.) op. cit.

Arnold, D.E. 1971. Ingestion, assimilation, survival, and reproduction by Daphnia pulex fed seven species of blue-green algae. Limnol. Oceanogr. 16:906-920.

Brenzonik, P.L. 1978. Effect of organic color and turbidity on Secchi disk transparency. J. Fish Res. Bd. Can. 35:1410-1416.

Brylinsky, M. and K.H. Mann. 1973. An analysis of factors governing productivity in lakes and reservoirs. Limnol. and Oceanogr. 18:1-14.

Burns, C.W. 1968. Direct observations of mechanisms regulating the feeding behavior of Daphnia in lakewater. Int. Rev. Ges. Hydrobiol. 53:83-100.

Chapra, S.C. 1975. Comment on "An empirical method of estimating the retention of phosphorus in lakes" by W.B. Kirchner and P.J. Dillon. Water Resources Res. 11:1033-1034.

Charlton, M.N. 1980. Hypolimnion oxygen consumption in lakes: Discussion of productivity and morphometry effects. Can. J. Fish. Aquatic. Sci. 37:1531-1539.

Cole, G.A. 1975. Textbook of limnology. C.V. Mosby Co. St. Louis 426 pp.

Comita, G.W. 1972. The seasonal zooplankton cycles, production and transformations of energy in Severson Lake, Minnesota. Arch. Hydrobiol. 70:14-66.

Cornett, R.J. and F.H. Rigler. 1979. Hypolimnetic oxygen deficits: Their prediction and interpretation. Science. 205:580-581.

Coveny, M.F., G. Cronberg, M. Enell, K. Larsson, and L. Olofsson. 1977. Phytoplankton, zooplankton and bacteria - standing crop and production relationships in a eutrophic lake. Oikos. 29:5-21.

Dillon, P.J. and W.B. Kirchner. 1975. Reply to S.C. Chapra. Water Resources Res. 11:1033-1034.

Dillon, P.J. and F.H. Rigler. 1974. The phosphorus - chlorophyll relationship in lakes. Limnol. Oceanogr. 19:767-773.

Dufresne-Henry Inc. 1983. A feasibility study for the correction of the backflow problem at the Harvey's Lake outlet. N. Springfield, Vermont. 34 pp.

Dumont, H.J., Van de Velde, I., and Dumont, S. 1975. The dry weight estimate of biomass in a selection of Cladocera, Copepoda, and Rotifera from the plankton, periphyton and benthos of continental waters. Oecologia. 19:75-97.

Edmondson, W.T. 1966. Changes in the oxygen deficit of Lake Washington. Verh. Int. Ver. Limnol. 16:153-158.

Edmondson, W.T. and J.T. Lehman. 1981. The effect of changes in the nutrient income on the condition of Lake Washington. Limnol. Oceanogr. 26:1-29.

Engstrom, D.R., E.B. Swain, and J.C. Kingston. 1983. A paleolimnological record of human disturbance from Harvey's Lake, Vermont: Geochemistry, oscillaxanthin, and diatoms. University of Minnesota Limnological Research Center Contribution No. 287.

Fricker, H. 1980. OECD Eutrophication Program, Regional Project, Alpine Lakes. Cooperative program for monitoring of inland lakes. 234 pp.

Gak, D.Z., V.V. Gurvich, I.L. Korelyakova, L.E. Kostikova, N.A. Konstantinova, G.A. Olivari, A.D. Primachenko, Y.Y. Tseeb, K.S. Vladimirova, and L.N. Zimbalevskaya. 1972. Productivity of aquatic organism communities of different trophic levels in Kiev Reservoir. pp. 447-456. In Kajak, Z. and A. Hillbricht-Ilkowska (eds.) op. cit.

Gulati, R.D. 1975. A study on the role of herbivorous zooplankton community as primary consumers of phytoplankton in Dutch lakes. Verh. Int. Ver. Limnol. 19:1202-1210.

Hall, D.J., W.E. Cooper, E.E. Werner. 1970. An experimental approach to the production dynamics and structure of freshwater animal communities. Limnol. Oceanogr. 15:839-928.

Hall, L.M. 1959. The Geology of the St. Johnsbury Quandrangle, Vermont and New Hampshire. Vermont Development Commission, Montpelier, Vermont. Bull #13. 105 pp.

Hillbricht-Ilkowska, A. 1972. Interlevel energy transfer efficiency in planktonic food chains. International Biological Programme. December 13, 1972. Reading, England.

Hillbricht-Ilkowska, A., I. Spodniewska, T. Weglenska, and A. Karabin. 1972. The seasonal variation of some ecological efficiencies and production rates in the plankton community of several Polish lakes of different trophy. pp. 111-128. In Kajak, Z. and A. Hillbricht-Ilkowska (eds.) op. cit.

Jaag, Otto 1972. Oscillatoria rubescens D.C. In Desikachory (ed.) Taxonomy and Biology of the Blue-Green Algae. pp. 296-299.

Kajak, Z. and A. Hillbricht-Ilkowska (eds.) 1972. Productivity problems of freshwaters. Proceedings of the IBP-UNESCO Symposium on Productivity Problems of Freshwaters. Kazimierz Dolny, Poland. May 6-12, 1970. Polish Scientific Publishers. Warsaw.

Keating, K. 1976. Algal metabolite influence on bloom sequence in eutrophied freshwater ponds. EPA Research Grant #RA801387. U.S. E.P.A. Office of Research and Development. Corvallis Environmental Research Laboratory. Washington, D.C. 147 pp.

Keating, K.I. 1978. Blue-green algal inhibition of diatom growth: Transition from mesotrophic to eutrophic community structure. Science. 199:971-973.

Kilham, P. 1971. A hypothesis concerning silica and the freshwater planktonic diatoms. Limnol. Oceanogr. 16:10-17.

Kirchner, W.B. and P.J. Dillon. 1975. An empirical method of estimating the retention of phosphorus in lakes. Water Resources Res. 11:182-183.

Klemer, A.R. 1976. The vertical distribution of Oscillatoria agardhii var. isothrix. Archiv. f. Hydrobiologie Bd. 78:343-362.

Klemer, A.R., J. Fevillade, and M. Fevillade. 1982. Cynobacteria blooms: carbon and nitrogen limitation have opposite effects on the bouancy of Oscillatoria. Science. 215:1629-1631.

Konopka, A. 1981. Influence of temperature, oxygen, and pH on a metalimnetic population of Oscillatoria rubescens. Appl. and Environ. Microbiol. 42:102-108.

Konopka, A. 1982. Physiological ecology of a metalimnetic Oscillatoria rubescens population. Limnol. Oceanogr. 27:1154-1161.

Korinek, V. 1972. Results of the study of some links of the Polivannaya, O.A. Sergeeva, and T.A. Vinogradskaya. 1972. Biological productivity of Kurakhov's Power Station cooling reservoir. pp. 477-492. In Kajak, Z. and A. Hillbricht-Ilkowska. (eds.) op. cit.

Lampert, W. 1981. Inhibitory and toxic effects of blue-green algae on Daphnia. Int. Rev. Ses. Hydrobiol. 66:285-298.

Lasenby, D.C. 1975. Development of oxygen deficits in 14 southern Ontario lakes. Limnol. Oceanogr. 20:993-999.

Lin, C.K. and C.L. Schelske. 1979. Effects of nutrient enrichment, light intensity, and temperature on growth of phytoplankton from Lake Huron. U.S. Environmental Protection Agency. EPA-600/3-79-049. 64 pp.

Lund, J.W. 1964. Primary production and periodicity of phytoplankton. Verh. Internat. Verein. Limnol. 15:37-56.

Lund, J.W.G. 1969. Phytoplankton. pp. 306-330 In Eutrophication: Causes, Consequences, Correctives. National Academy of Sciences.

Lund, J.W.G., C. Kipling, and E.D. LeCren. 1958. The inverted microscope method of establishing algal numbers and the statistical basis of estimates by counting. Hydrobiol. 11:143-170.

McCauley, E. and J. Kalff. 1981. Empirical relations between phytoplankton and zooplankton biomass in lakes. Can. J. Fish. Aquat. Sci. 38:458-463.

Makarewicz, J.C. and G.E. Likens. 1979. Structure and function of the zooplankton community of Mirror Lake, New Hampshire. Ecol. Monogr. 49:109-127.

Megard, R.O., J.C. Settles, H.A. Boyer, and W.S. Combs. 1980. Light, secchi discs, and trophic states. Limnol. Oceanogr. 25:373-377.

Morgan, N.C. Productivity studies at Loch Leven (a shallow nutrient rich lowland lake). pp. 183-206. In Kajak, Z. and A. Hillbricht-Ilkowska (eds.) op. cit.

Morse, J.W. 1979. Vermont Lakes and Ponds Program. pp. 47-50 In Lake Restoration. Proceedings of a National Conference. Minneapolis, Minnesota. U.S. Environmental Protection Agency.

Moskalenko, B.K. and K.K. Votinsev. 1972. Biological productivity and balance of organic substance and energy in Lake Baikal. pp. 207-226. In Kajak, Z. and A. Hillbricht-Ilkowska. (eds.) op. cit.

Omernik, J.M. 1976. The influence of land use on stream nutrient levels. U.S.E.P.A. 600/3-76-014. 106 pp.

Ostrofsky, M.L. 1978. Modification of phosphorus retention models for use with lakes with low areal water loading. J. Fish. Res. Bd. Can. 35:1532-1536.

Paashe, E. 1980. Silicon content of five marine plankton diatom species measured with a rapid filter method. Limnol. Oceanogr. 25:474-480.

Pederson, G.L., E.B. Welch, and A.H. Litt. 1976. Plankton secondary productivity and biomass: Their relation to lake trophic state. Hydrobiologia. 50:129-144.

Pidgaiko, M.L., V.G. Grin, L.A. Kititsina, L.G. Lenchina, M.F. Polivannaya, O.A. Sergeeva, and T.A. Vinogradskaya. 1972. Biological productivity of Kurakhov's Power Station cooling reservoir. pp. 477-492. In Kajak, Z. and A. Hillbricht-Ilkowska. (eds.) op. cit.

Porter, K.G. 1973. Selective grazing and differential digestion of algae by zooplankton. Nature. 244:178-180.

Prescott, G.W. 1968. The algae: a review. Houghton Mifflin Company. Boston. 436 pp.

Rast, W. and G.F. Lee. 1978. Summary analysis of the North American (U.S. portion) O.E.C.D. eutrophication project: Nutrient loading - lake response relationships and trophic state indices. U.S. E.P.A. 600/3-78-008.

Ravera, O. and R.A. Vollenweider. 1968. Oscillatoria rubescens as an indicator of Lago Maggiore eutrophication. Schweiz. Z. Hydrol. 30:374-380.

Reynolds, C.S. and A.E. Walsby. 1975. Water blooms, Biol. Rev. 50:437-481.

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

Schelske, C.L. 1975. Silica and nitrate depletion as related to rate of eutrophication in Lakes Michigan, Huron and Superior. in: Coupling of Land and Water Systems. A.D. Hasler, Springer-Verlag. New York. 22 pp.

Schelske, C.L. and E.F. Stoermer. 1971. Eutrophication, silica depletion, and predicted changes in algal quantity in Lake Michigan. Science. 173:423-424.

Schelske, C.L. and E.F. Stoermer. 1972. Phosphorus, silica, and eutrophication of Lake Michigan. In: G.E. Likens (ed.) Nutrients and Eutrophication. Amer. Soc. Limnol. Oceanogr. Spec. Symp. 1:157-171.

Schindler, D.W. 1969. Two useful devices for vertical plankton and water sampling. J. Fish. Res. Bd. Can. 26:1948-1955.

Schindler, D.W. 1972. Production of phytoplankton and zooplankton in Canadian Shield Lakes. pp. 311-332. In Kajak, Z. and A. Hillbricht-Ilkowska (eds.) op. cit.

Shapiro, J. and E. Swain. 1983. Lessons from the silica "decline" in Lake Michigan. Science. in press.

Skulberg, Olav M. 1978. Some observations on red-colored species of Oscillatoria (Cyanophyceae) in nutrient-enriched lakes of southern Norway. Verh. Internat. Verein. Limnol. 20:776-787.

Skulberg, O. 1980. Blue-green algae in Lake Mjosa and other Norwegian Lakes. Progress in Water Technology. 12:121-140.

Smith, V.H. 1979. Nutrient dependence of primary productivity in lakes. Limnol. Oceanogr. 24:1051-1064.

Smith, V.H. 1982. The nitrogen and phosphorus dependence of algal biomass in lakes: An empirical and theoretical analysis. Limnol. Oceanogr. 27:1101-1112.

Sorokin, J.I. 1972. Biological productivity of the Rybinsk Reservoir. pp. 493-504. In Kajak, Z. and A. Hillbricht-Ilkowska. (eds.) op. cit.

Stangenburg, M. 1968. Toxic effects of Microcystis aeruginosa Kg. extracts on Daphnia longispina O.F. Muller and Eurcyprin virenc Jurine. Hydrobiologia. 32:81-87.

Steel, R.G.D. and J.H. Torrie. 1960. Principles and Procedures of Statistics. McGraw-Hill. New York. 481 pp.

Technicon. 1976. Silicates in water and waste water. Technicon Industrial Method No. 105-71 W/B.

U.S. Environmental Protection Agency. 1979. Methods for chemical analysis of water and wastes. EPA-600/4-79-020.

Vermont Department of Water Resources. 1971. Vermont lakes and ponds: 20 acres or larger - An inventory by counties. Planning and Development division. Department of Water Resources, Montpelier, Vermont 22 pp.

Vermont Department of Water Resources. 1977. Harvey's Lake Water Quality Report. Lake Eutrophication Series Report No. 13. 73 pp.

Vermont Department of Water Resources and Environmental Engineering. 1980. Vermont Lake Classification Survey. Montpelier, Vermont. 101 pp.

Vermont Historical Society. 1943. Collection III. Vol. I. The Upper Connecticut. 300 pp.

Vermont Public Service Commission. 1952. Summary of Vermont dams: Biennial report of the Public Service Commission: July 1, 1950-July 30, 1952. Montpelier, Vermont. pp. 28-44.

Vignon, B.W. 1976. The role of silica and the vernal diatom bloom in controlling the growth of nuisance algal populations in lakes. M.S. Thesis. University of Wisconsin. Madison, Wisconsin 244 pp.

Vijverberg, J. 1976. The effect of food quantity and quality on the growth, birth-rate and longevity of Daphnia Hyalina Leydig. Hydrobiologia. 51:99-108.

Vollenweider, R.A. 1969. Moglichkeit en und grenzen elementarer modelle der stoffbilanz von seen. Arch. Hydrobiol. 66:1-36.

Walker, W.W. 1979. Use of hypolimnetic oxygen depletion rate as a trophic state index for lakes. Water Resources Research. 15:1463-1470.

Walter, D.C. 1953. Vermont town names and their derivations. Vermont Quarterly. Vermont Historical Society Montpelier, Vermont. 21:193-194.

Ward, H.B. and G.C. Whipple (eds.) 1959. Fresh Water Biology, 2nd ed. John Wiley and Sons. New York, 1203 pp.

Waters, T.F. 1977. Secondary production in inland waters. Adv. Ecol. Res. 10:91-164.

Welch, E.B. 1979. Oxygen deficit - phosphorus loading relation in lakes. J. Water Poll. Contr. Red. 51:2823-2828.

Wells, F.P. 1975. History of Barnet, Vermont. Troll Press Inc. St. Johnsbury, Vermont. 691 pp.

Wetzel, R.G. 1975. Limnology. W.B. Saunders Company. Philadelphia. 743 pp.

Winberg, G.G., V.A. Babitsky, S.I. Gavrilov, G.V. Gladky, I.S. Zakharenkov, R.Z. Kovalevskaya, T.M. Mikheeva, P.S. Nevyadomskaya, A.P. Ostapenya, P.G. Petrovich, J.S. Potaenko, and O.F. Yakushko. 1972. Biological productivity of different types of lakes. pp. 383-404. In Kajak, Z. and A. Hillbricht-Ilkowska (eds.) op. cit.

Wright, J.C. 1965. The population dynamics and production of Daphnia in Canyon Ferry Reservoir, Montana. Limnol. Oceanogr. 10:583-590.

APPENDIX

United States
Department of
Agriculture

Soil
Conservation
Service

One Burlington Square
Suite 205
Burlington, Vermont 05401

July 27, 1982

Mr. Eric Smeltzer
Aquatic Biologist
VT Dept. of Water Resources
& Environmental Engineering
Heritage II Bldg.
Montpelier, VT 05602

Re: Production of Nonpoint Phosphorus Loadings to Harvey's Lake from the Roy Farms.

Dear Eric:

Since visiting the watershed and the Joe Roy Farm with Kitty, Tim, and you, I have adjusted our survey data to more accurately portray existing conditions and have rerun our phosphorus yield models for the two Roy farms.

The results of these new runs are enclosed for your information. Also, enclosed is a summary of my calculations to cost out corrective measures both for total cost and for cost per pound reduction per year.

Most of my calculations were done in an attempt to discern what alternatives might be possible. I do not pretend to believe that the figures I derived are exact because there are so many factors that could affect both the loading of P and the costs. However, I did check with Cornell University and the figures that I came up with do seem reasonable in light of the data they are generating in a test watershed in New York dealing with the same sort of problems.

It would appear that the most practical way to deal with the problem would be to treat Joe Roy's barnyard and ignore the manure management problem, (note alternatives 1, 4, and 5). Approximately 90 percent of the phosphorus is eliminated with barnyard treatment at an amortized annual cost of $590. Alternative 4 only reduces an additional 20 lbs. of phosphorus (9.5 percent of total) at an additional cost of $1,980 a year. And to gain that last 8 lbs. or 0.5 percent it would require another $5,150. On a cost per pound basis: $2.95, $11.70, and $33.90 per year.

Please feel free to call if you have any questions.

Sincerely,

Larry Knight
Engineer

Enclosure

STATE		PROJECT		
VERMONT		HARVEY'S LAKE		
BY	DATE	CHECKED BY	DATE	JOB NO.
CSK	7-22-82			
SUBJECT				SHEET 2 OF 2
COST ESTIMATE BARNYARD & MANURE MGT.				

JOE ROY FARM

1. FENCING TO EXCLUDE COWS FROM STREAM:
   1000 FT @ $0.50 = $500

2. DIVERSION ABOVE BARN:
   500 FT @ $2.00 = $1,000

3. EAVES TROUGHS & DOWNSPOUTS:
   1000 FT @ $2.50 = $2,500

SUBTOTAL FOR BARNYARD: $4,000

4. MANURE STORAGE FACILITY:
   112' X 112' X 8' STRUCTURE 180 DAY STORAGE

PREFAB WALLS	$26900
SLAB	$12700
PUMP	$8500

SUBTOTAL FOR MANURE MGT. $47,900

TOTAL FOR FARM $51,900

FRANCIS ROY FARM

MANURE [redacted] STORAGE FACILITY:
EXCELLENT LOCATION FOR GRAVITY
OPERATED EARTH PIT.
TOTAL COST ≈ $20,000

SOIL CONSERVATION SERVICE

STATE		PROJECT		
VERMONT		HARVEY'S LAKE		
BY	DATE	CHECKED BY	DATE	JOB NO.
CSK	7-22-82			
SUBJECT				SHEET 2 OF 2
COST ESTIMATE BARNYARD & MANURE MGT.				

COST PER POUND PHOSPHORUS REDUCTION

BASIC ASSUMPTIONS:

1. LIFE EXPECTANCY MANURE FACILITY = 20 YRS
2. " " BARNYARD " = 10 YRS
3. INTEREST RATE 7 5/8 %
4. 80% EFFICIENCY FOR BARNYARD FACILITIES
5. CALCULATED FOR AVAILABLE P REDUCTION

ALTERNATIVES CONSIDERED:

1. BARNYARD ONLY - JOE ROY
2. BARNYARD + MANURE - JOE ROY
3. MANURE ONLY - FRANCIS ROY
4. BARNYARD - JOE + MANURE - FRANCIS
5. BARNYARD - JOE + MANURE - BOTH

ALT 1:

REDUCTION AVAILABLE P = 200 LBS/YEAR
COST OF SYSTEM: $590/YEAR
COST PER LB P. REDUCTION = $2.95 PER YEAR

ALT 2:

REDUCTION AVAILABLE P = 208 LBS/YEAR
COST OF SYSTEM: $5,740/YEAR
COST PER LB. P. REDUCTION = $27.60 PER YEAR
(200 lb @ $2.95/lb & 8 lb @ $643.75/lb)

ALT 3:

REDUCTION AVAILABLE P = 20 LBS/YEAR
COST OF SYSTEM: $1,980/YEAR
COST PER LB P REDUCTION = $99.00 PER YEAR

ALT 4:

REDUCTION AVAILABLE P = 220 LBS/YEAR
COST OF SYSTEM: $2,570/YEAR
COST PER LB P. REDUCTION = $11.70 PER YEAR
(200 lb @ $2.95/lb & 20 lb @ $99.00/lb.)

ALT 5:

REDUCTION AVAILABLE P. = 228 LB/YEAR
COST OF SYSTEM: $7,720/YEAR
COST PER LB P. REDUCTION = $33.90 PER YEAR
(200 lb @ $2.95/lb & 28 lb @ $254.65/lb.)

ALTERNATIVES FOR REDUCING PHOSPHOROUS LOADINGS

TO HARVEYS LAKE WEST BARNET, VERMONT

Richard N. Downer, P.E.
Consulting Engineer
Shelburne, Vermont 05482

July 1982

Submitted to

Mr. Eric Smeltzer
Project Manager
Harveys Lake Diagnostic/Feasibility Study
Water Quality Division
Vermont Department of Water Resources
Heritage II
Montpelier, Vermont

1 Outlet Controls

1.1 Background

A peculiar feature of the location of the Harveys Lake dam is that it is approximately 1500 feet from the mouth of the lake. A dam at the mouth or outlet would only have had to be a very minor structure. The present location on South Peacham Brook nearly doubles the contributing area of the lake (See Figure 1). Most of the time water flows north out of the lake, joining South Peacham Brook before dropping over the dam. However, at times of high runoff on South Peacham Brook, the flow from the brook backs up the channel and flows into the Lake.

The advantages of this configuation is to store excess water lessening the potential damage downstream during high runoff. The channel also serves as a navigation route from the Lake to West Barnet Village, which has a store and service station for gas and oil.

The principal disadvantage is the reversal of flow causes debris and silt to be carried into the channel and deposited in the Lake. A rather large silt delta of recent origin has formed in the Lake at the mouth of the channel.

Prior to 1971 a 41.0 foot wide rectangular spillway dam existed at the present site. This dam was replaced with 98.4 foot wide spillway with a slightly sloping sill, effectively doubling the width of the spillway. As a part of the reconstruction contract South Peacham Brook was also dredged for a distance of about 200 feet immediately upstream of the dam. Over the last decade the brook has silted in, restricting the flow in the brook encouraging backflow into the lake.

At least three factors have probably contributed to this silting of the Brook:

1. The new, wider spillway reduced the average velocities in the Brook and thus encouraged deposition of material on the inside of the curve immediately upstream of the dam

2. The dam site has had little or no maintenance, ie, cutting of brush, clearing of snags and drift wood

3. Beavers have been allowed to build a dam across the Brook approximately 500 feet upstream of the dam and downstream of the confluence of the Brook with the outlet channel (see location A on Figure 1).

1.2 Alternative Solutions for Outlet

1.2.1 Solution Requiring Immediate Attention

Immediately remove the beaver dam and beavers. Restore the Brook to its average depth of 3 to 4 feet.

The beaver dam removal could best be accomplished by a combination of hand and limited machine work preceded by a lowering of the water in the Brook by removing 3 to 4 stoplogs for a short period of time. The beaver dam can be approached over firm ground on the east side. A small backhoe with an extended boom could be used. A small dozer with a winch and a hand-operated drag-scoop would probably be the most effective and have the least environmental impact. The spoil can be spread in some local low spots back from the bank.

The estimated time to remove this beaver dam is one day. The estimated cost is less than $500.00.

Removal of the beaver dam should be undertaken as soon as possible regardless of the status of other alternatives.

1.2.2 Stoplog Structure on Channel at Lake Outlet

Construct a stoplog structure approximately 70 feet downstream from the entrance to the outlet channel (see location B on Figure 1). The structure could consist of two H-piles driven into the sediments at the edges of the channel (see Figure 2). This structure need not be impervious or watertight as its only function is to create a pronounced gradient or slope in the water surface between the lake and the dam. Once this structure is in place some of the stoplogs in the existing dam should be removed.

The creation of a gradient would encourage all the normal flow from South Peacham Brook to be directed over the dam. It would also increase the velocities in the Brook by promoting scouring or, at the least, by decreasing deposition of material in the Brook. The higher velocities would also tend to discourage additional beaver activity.

At moderately high flows the increased gradient would lessen the tendency for flow reversals. If a flow reversal occurred such a stoplog structure would prevent bedload silt from migrating into the lake. The suspended load and some debris might still enter the lake. Because the top of the stoplog structure would be set at or just below the present average lake level the lake could still act as a reservoir for high flows in South Peacham Brook since reversed flow could easily overtop the stoplog structure.

The loss of a navigation route from the lake to West Barnet Village is a disadvantage which must be weighed. Presently no more than 10 boats per day use the channel. An actual trip survey would probably show an even smaller number of necessary trips compared to curiosity or recreational trips.

The Channel would not be dewatered. The water depth would vary from four feet at the outlet end to three feet at the Brook end. It could still be navigated by canoes that portaged across the stoplog structure.

A small culvert placed under the stoplogs would allow for the passage of fish both to and from the lake. The higher velocities in the culvert, caused by the differential head on either side of the stoplog structure, should act as an attractant for fish and the same time promote localized scouring of the Channel bottom.

The cost of this alternative is also rather inexpensive. The estimated cost is less than $2500.00 for materials and labor. The unit costs are as follows: steel, $0.45/lb - $800; wood $0.50 board foot - $500; culvert $50.

1.2.3 Training Dike

Construct a riprapped training dike along the east side of South Peacham Brook from the confluence with the Channel 700 feet upstream to a point beyond the low bank where high flows short-cut across to the Channel (see location D on Figure 1 and Figure 3).

The primary advantage of this alternative is maintenance of the status quo with respect to the location and alignment of South Peacham Brook. All disturbance and construction would take place in the swampy area between the Brook and the Channel.

The curvature of the downstream end of the dike would force the flow to turn around the corner and vector toward the dam. It might, however, increase the rate of erosion of the west bank immediately behind the West Barnet Garage. The momentum of the flow should

discourage backflow and the deposition of debris in the channel. The Channel would remain navigable to the Dam. Some backflow would occur during extreme high flows.

The estimated cost of this alternative is less than $10,000. The breakdown of estimated costs is as follows: dozer work to raise embarkment - $2500; gravel 150 yards at $4.50/yard - $675; dumped riprap 200 yards at $17.50 - $3500; seeding and mulching 0.5 acre at $150/acre - $75. The unit costs for this work may be higher because access to the work area is limited and extremely wet. A haul road and temporary bridge will be necessary.

1.2.4 Relocate South Peacham Brook

Relocate South Peacham Brook into a long sweeping curved channel from the bridge to the dam (see location C on Figure 1). Relocation of the Brook would lessen the likelihood of flow reversals since the flow vectors would be pointed directly toward the dam without any sudden changes in direction.

If properly designed most of the debris would be forced over or toward the dam. Most silt, both suspended and bedload would also be carried toward the dam (see Figure 4). An acute angle between the Brook and the Channel at their confluence would cause the Brook to be essentially self-cleaning, yet at low flows would allow water from the lake to flow over the dam.

At high flows some water could still backup into the Lake providing temporary storage and relief for the downstream riprians.

Much of the swampy area adjacent to the west side of the Brook could be raised and reclaimed for agricultural use. The west bank would

be bordered by a riprapped dike. The land behind the dike would remain essentially undisturbed. The outlet channel would also be undisturbed except at its confluence with the Brook.

The Channel would remain navigable all the way from the Lake to the Village.

This alternative would require the greatest amount of planning, number of permits, and involve the most number of landowners. Once in place, however, it should result in a nearly maintenance free solution which should minimize backflow while still allowing free passage to the Village.

The estimated cost of this alternative is approximately $22,000. The breakdown of estimated costs is as follows: dragline excavation, 900 feet at $2.50/yard - $7500; dumped riprap 500 yards at $15.00/yard - $7500; gravel 500 yards at $3.50/yard - $1750; seeding and mulching 22000 square feet at $150/acre - $75. Planning, attorney and engineering design fees may force the cost of this alternative closer to $30,000.

2 Control of Runoff from Roy Farms

2.1 Background

A. Francis Roy actively farms (spreads manure and fertilizer) on approximately 130 acres on the west side of the Roy Neighborhood Road. Joe Roy also intensively farms approximately 200 acres east of the road of which 130 drain across A. Francis Roy's land and hence to the Lake.

A. Francis Roy's barnyard is not within the watershed. However, the majority of his manure is spread on his 130 acres draining toward the Lake. His present operations requires that he spread daily, thus most of his winter manure is transported to these fields.

Joe Roy employs an open stall arrangement. His barnyard and fields are within the watershed and essentially all drain to the Lake by way of a small waterway which runs parallel to his driveway, through a culvert and across the lands of A. Francis Roy (see location E on Figure 1).

This unnamed waterway (location E) thus becomes the major contributor of organic loading to the Lake. Changes in A. Francis Roy's mode of operations, ie, a manure pit with intermittent spreading, would still not materially lessen the impact of organic loading on this waterway.

Although diverting some of the surface and roof water away from Joe Roy's barnyard might lessen the loading, the diverted water would still enter the waterway and Joe Roy would still continue to spread manure on the fields which eventually drain to the Lake.

2.2 Alternative Solutions for the Farms

2.2.1 Beaver Pond Dike

Presently nearly all the flow from the 260 acres of A. Francis and Joe Roy enter the Lake. More than two thirds of the flow goes down waterway E into the Beaver Pond. Hence through a culvert into the Lake.

Construct an earth embankment approximately 3 feet high 12 feet wide and 200 feet long across the southerly end of the Beaver Pond, thus forcing the discharge from the Pond to flow out the northerly end and hence to the Stevens River. In times of high water the Pond presently flows in both directions. The northern outlet is clearly visible on the 1974 areal photograph, Figure 5.

Do not improve the northern outlet, ie, dredge. The effect will be three-fold: the Pond will act as a temporary storage for flood waters decreasing their impact downstream. Secondly, the longer residence time in the Pond will allow particulate phosphate to settle out. Thirdly, algae blooms, weeds and grasses will help consume the nutrient load. The warm water fishery should improve, namely bull frogs and turtles.

A. Francis Roy seems agreeable to this scheme if funds for constructing the dike could be found. The Pond area does not now, nor will it ever have any agricultural value. The area south of the proposed dike might later be reclaimed for pasture or recreational land. The only apparent disadvantages of this proposal include the increased discharges and possible increased nutrient loadings going directly to the Stevens River.

The estimated cost for construction of the dike is less than $2500. The breakdown of estimated costs is as follows: clearing and grubbing

of dike site - $200; buy, load, haul, place, spread and dozer compact 600 yards of local borrow at $3.75/yd - $2250; seed and mulch - $75.

2.2.2 Improvement of Waterway E

Waterway E (see Figure 5) shows signs of erosion problems. The upper end adjacent to A. Francis Roy's corn field has vertically incised nearly two feet in recent years. There is absolutely no native armor to prevent future rapid lateral and headwall erosion.

The central portion of the waterway is located in an old hedgerow and is reasonably well armored.

The lower end is in need of immediate attention. Headwall erosion is apparent in the field between the Beaver Pond and the end of the hedgerow.

The upper and lower ends of the waterway should be shaped and riprapped. The entire length should be fenced to keep out the cattle.

Cost of these improvements is estimated to be $3500. The breakdown of costs is as follows: 600 feet riprapped waterway at $5.00/foot - $3000; 2000 feet of fence at $30/1000 feet plus labor - $300.

2.2.3 Lateral Diversions into Waterway E

Construction of four lateral diversions into waterway E (see Figure 1 and 5) would result in the collection of 99% of the organic load presently reaching the Lake from both the A. Francis and the Joe Roy farms. Three (E1, E2, E3) ditches are on A. Francis Roy's land, while the fourth (E4) is on the lands of Joe Roy.

These diversions total approximately 1000 feet. Cost of these diversions would be about $2500.00.

3 Conclusions

3.1 Outlet

The beaver dam and beavers should be removed immediately. Certainly before the fall hurricane season, August- October. Cost - $500.00.

The least costly, most cost effective alternative is to close off the Channel with a stoplog structure. the environmental impact is minimal. The annual maintenance should be minimial. It will, however, prevent navigation from the Lake to the Village. It could be manipulated to allow passage during the camping season, with the logs in place from September 15th to May 15th. Cost - $2500.00.

The most effective solution is probably a combination of relocating South Peacham Brook and building the stoplog structure. This should virtually eliminate the backflow and the associated debris problems. The degree of planning is much greater for this alternative. The cost is also high - $30,000.

I recommend the stoplog structure.

3.2 Farm Runoff

All three improvements should be made at a total cost of $8500.00.

To build manure pits for either Roy farm would cost nearly $50,000, and the problem would still not be solved since spreading would continue.

Money spent on diverting the organic loading from the Lake will be the most cost effective.

I recommend that all three improvements be made.

4 Suggestions for Future Study

A literature review and limited study should be implemented on the impact and/or assimilative capacity of swamps and logs to high organic loadings. I have seen recent literature on the estimated benefit/cost of sewage treatment by swamps but I can not locate it. I'll keep looking.

In cooperation with the U.S. Soil Conservation Service a cost effectiveness study should be made of the diversion of flow versus farm practice changes for reducing the loading.

Public meetings should be held at Harveys Lake during the summer to ascertain the sentiments of the campers and landowners effected.

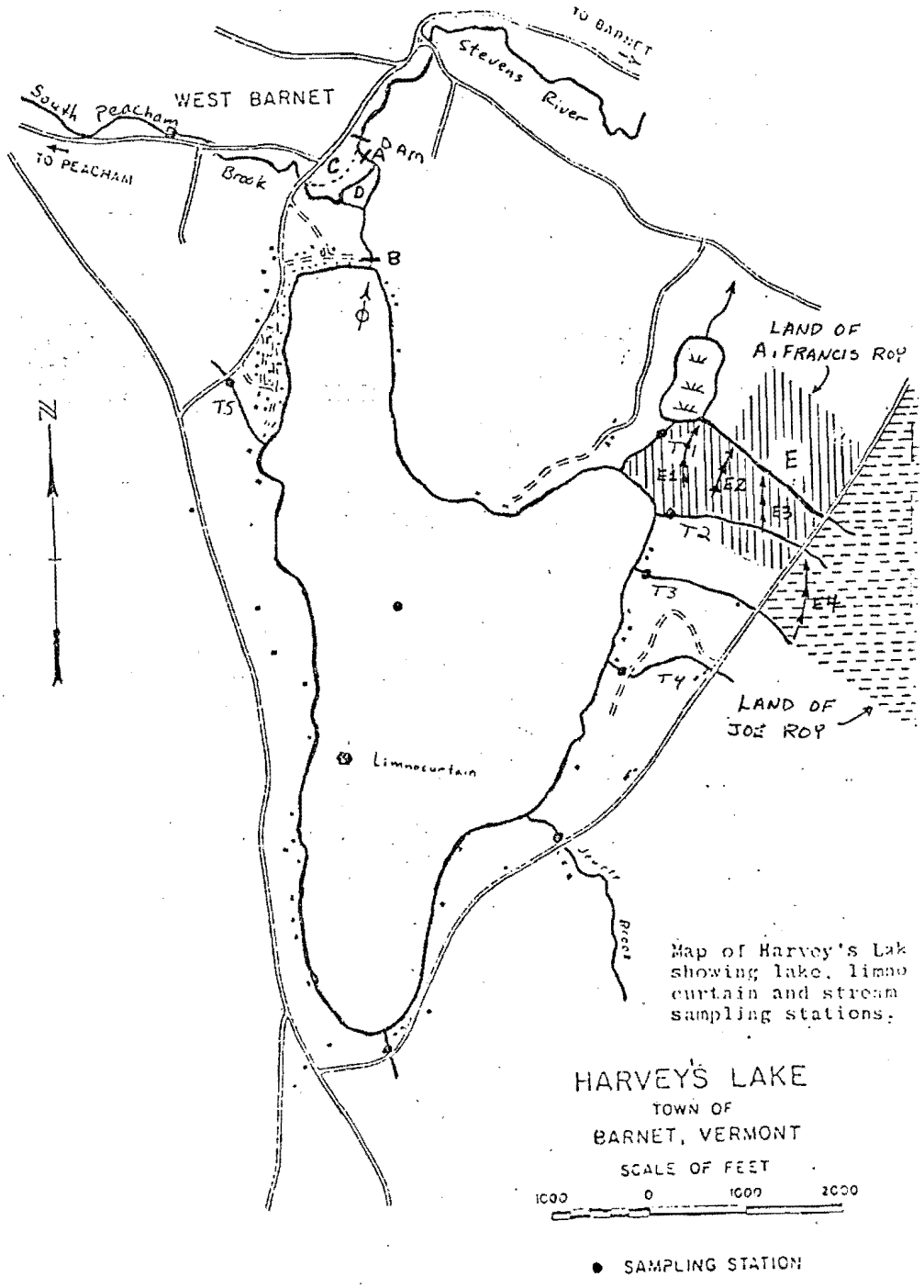


Figure 1

Location Map

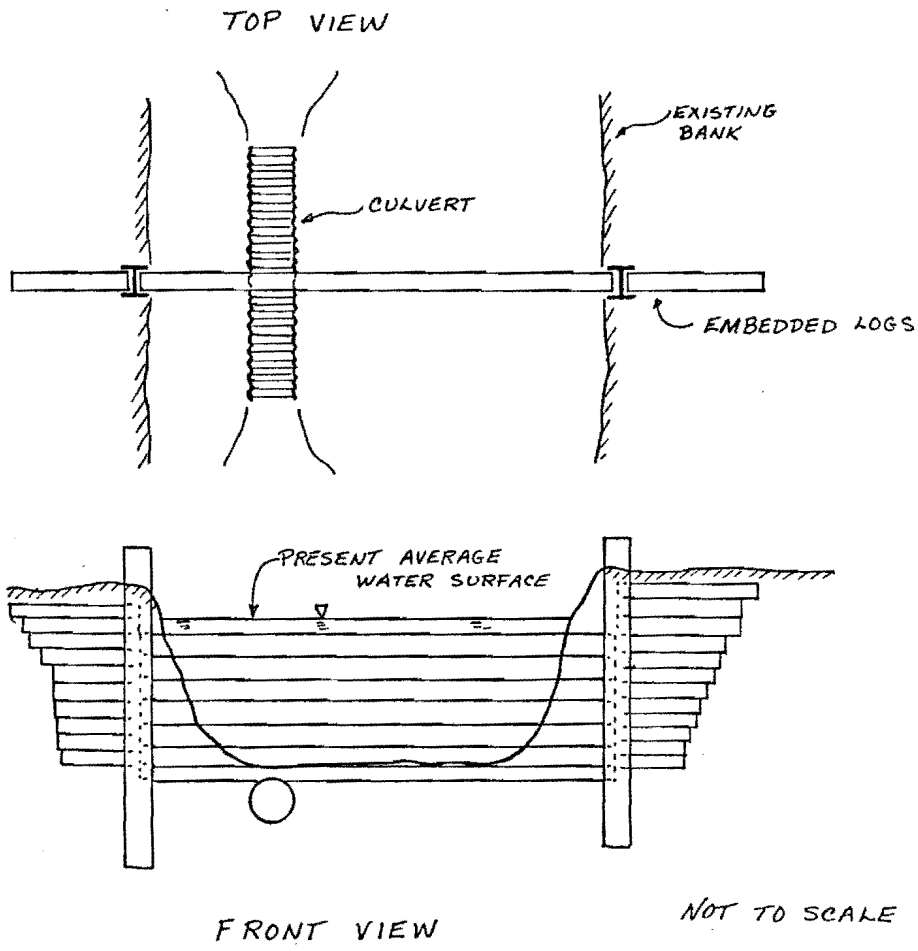


Figure 2

Stoplog Structure

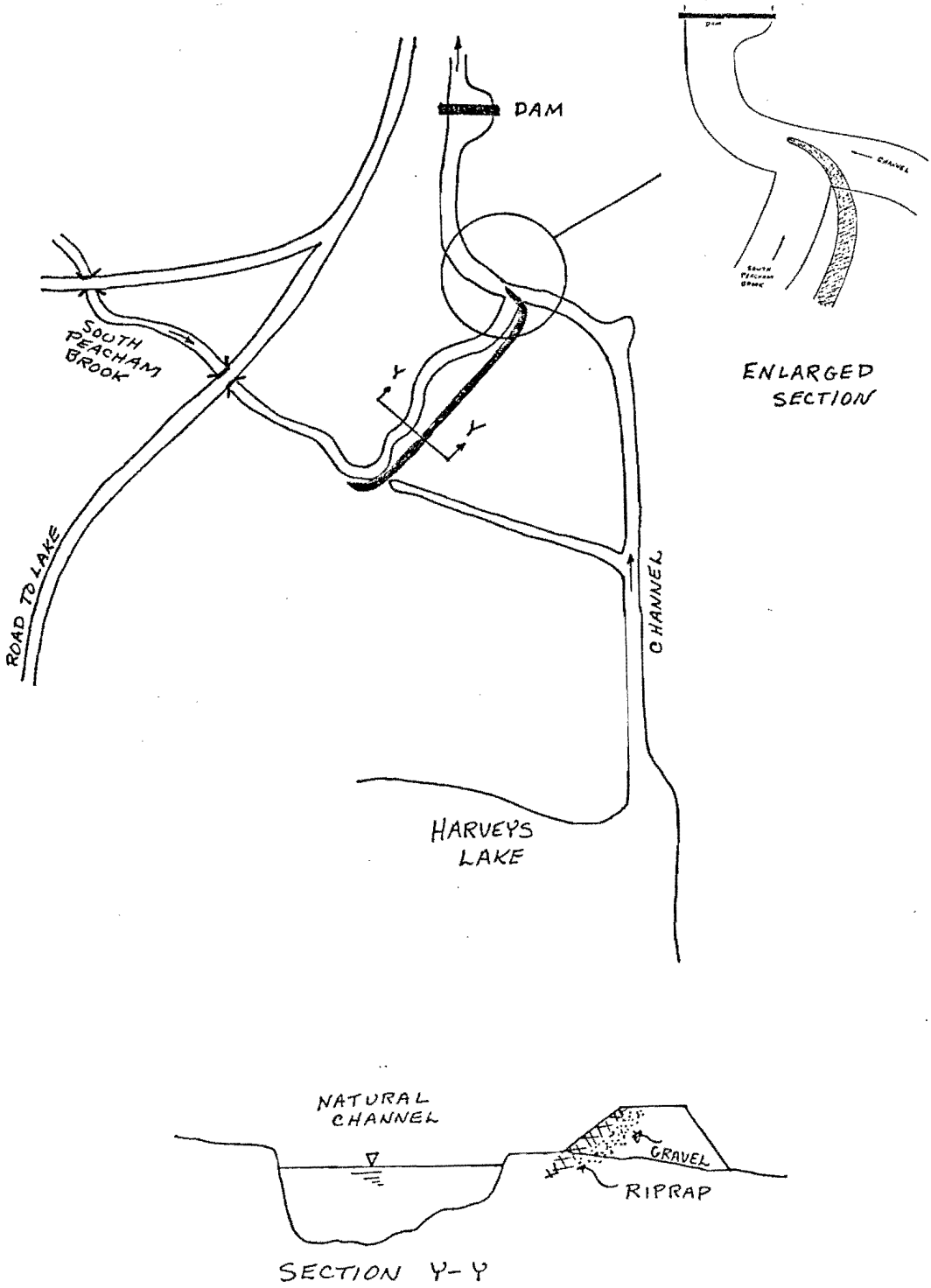


Figure 3

Training Dike

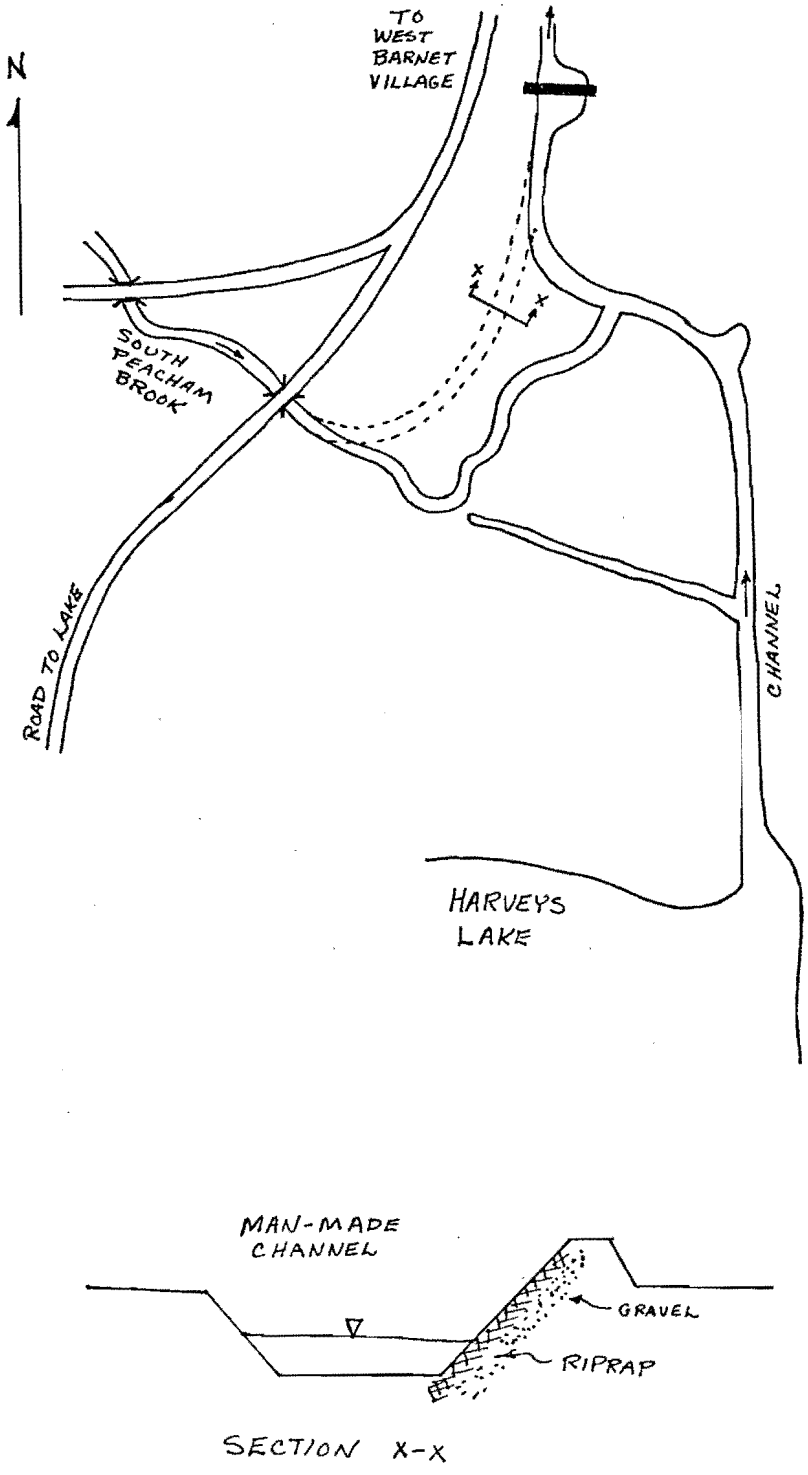


Figure 4

Channel Relocation

Figure 5
Beaver Pond, Roy Farms, Waterway E and Diversions

United States
Department of
Agriculture

Soil
Conservation
Service

One Burlington Square
Suite 205
Burlington, Vermont 05401

April 28, 1983

Mr. Eric Smeltzer
Dept. of Water Resources
Environmental Engineering
State Office Building
Montpelier, VT 05602

Subject: Harvey's Lake Agricultural Runoff Control

Dear Eric:

The attached schematic location map shows the four basic components of the Harvey's Lake Agricultural Runoff Control Project. The following is a brief description of each component including quantities and costs.

Item one is a diversion that will collect the runoff from a large field that is presently in corn and discharges it into an existing watercourse. The watercourse is stable and the additional water should not cause any problems. The diversion will be 350 feet long and cost approximately $900 to construct including the cost of a water control structure to lower the water from the diversion into the existing stream without causing erosion.

Item two is a waterway that will convey the water from the stream and the diverted runoff into a large marshy area to the northwest. The waterway will be 455 feet long and must be lined with stone to prevent erosion. The total cost of this portion of the project will be about $5,300 including excavation, gravel bedding and graded crushed rock.

Item three is the detention pond which will be formed by diking both ends of the marshy area and installing a water control structure at the north end to limit the outflow. The fill will have to be hauled in which will make it expensive. The estimated cost of this portion of the project is $10,000 which includes clearing the sites, the water control structure, and placing the earth fill.

The fourth and final item is the outlet ditch into S. Peacham Brook. This ditch will be 1,300 feet long and will cost approximately $5,000. This cost includes the cost of riprap for the upper 235 feet of the channel which has a steeper grade and needs protection from erosion.

These estimates are very preliminary and should be increased to cover items that cannot be anticipated at this time. I feel a contingency of 15% would not be unreasonable. Therefore, the estimated total project cost is as follows:

1.	Diversion	-	$ 900
2.	Waterway	-	5,300
3.	Detention Pond	-	10,000
4.	Outlet Ditch	-	5,000
	Sub Total	-	$21,200
	+ 15%		3,180
	Total	-	$24,380

Please contact me if you need further help or have any questions about these estimates.

Sincerely,

Richard A. Fisher

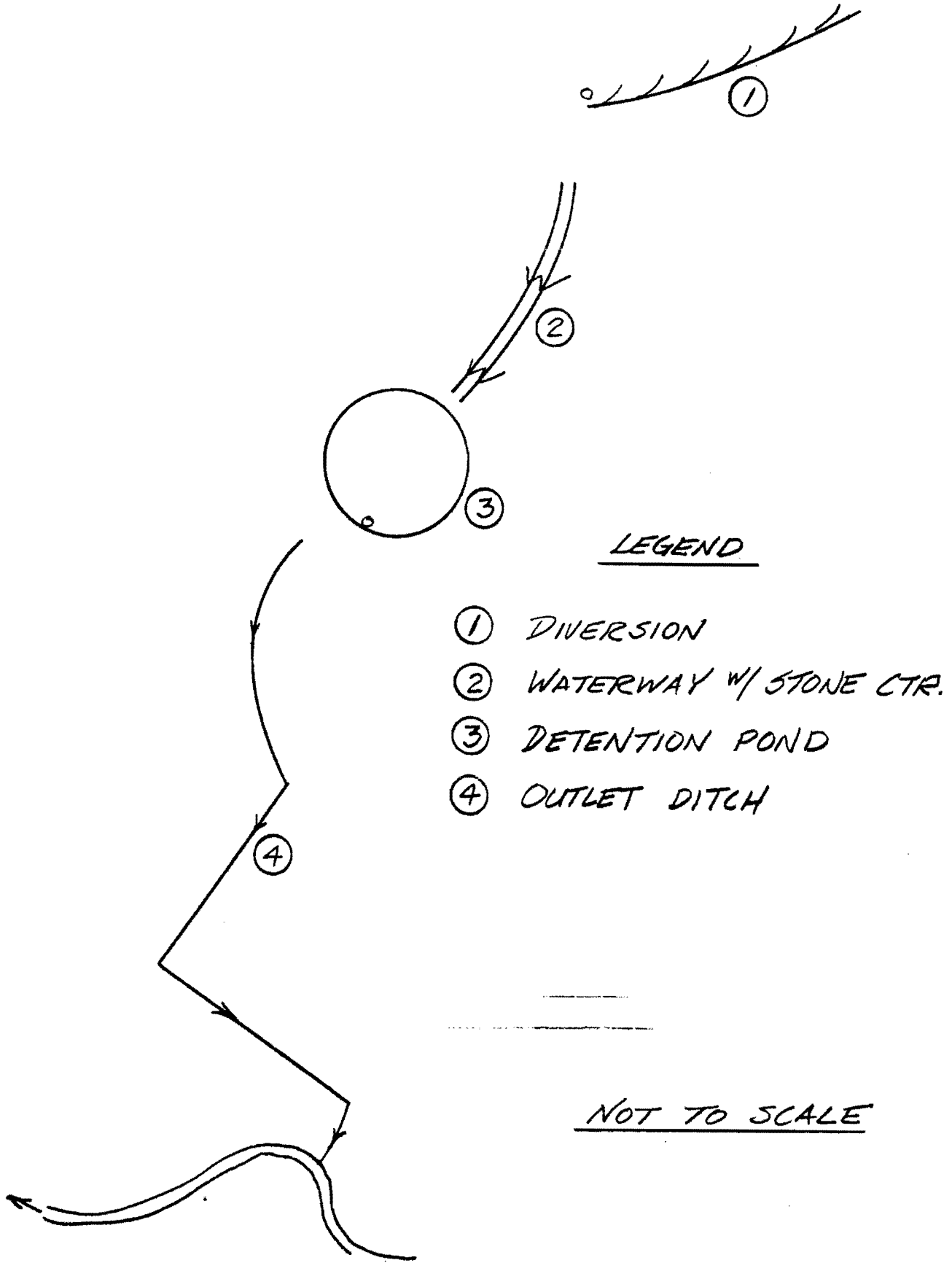
Richard A. Fisher
Civil Engineer

Attachment

COMPUTATION SHEET
SCS-ENG-523 Rev. 8-69

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

STATE Vermont		PROJECT Harvey's Lake		
BY Fisher	DATE 9/15/83	CHECKED BY	DATE	JOB NO.
SUBJECT Location Map				SHEET ____ OF ____



United States
Department of
Agriculture

Soil
Conservation
Service

One Burlington Square
Suite 205
Burlington, VT 05401

June 3, 1983

Mr. Eric Smeltzer
Department of Water Resources
Environmental Engineering
State Office Building
Montpelier, VT 05602

SUBJECT: Harveys Lake Agricultural Runoff Control

There are four intermittent streams contributing agricultural runoff to Harveys Lake from the properties of Joe and Francis Roy. These are labeled T1, T2, T3 and T4 on the attached location map. It was originally throught that T2, T3, and T4 could be diverted into T1 and handled as a single unit. However, subsequent field studies have shown that the streams are deeply entrenched and that the system of check dams and structures needed to make the diversion would be very costly. Consequently, this portion of the agricultural runoff problem will not be considered.

A portion of the drainage area for T2 can be diverted and the plans call for a diversion below Francis Roy's cornfield which will divert nearly 6 acres into stream T1. This cornfield is one of the most serious problem areas in the project area.

Stream T1 will be diverted into an existing marshy area by means of a stone centered waterway. Dikes will be constructed at both ends of the marsh to contain the runoff from a 10 year frequency storm. A slow release structure will be installed at the north dike to discharge approximately 0.5 cfs. This will draw the water level down to its original level within 10 days. Preliminary surveys show that the use of this marshy area as a detention pond is feasible.

The water from the pond will flow north through a wooded area to a culvert under a dirt road on the Choate property. This area was not surveyed so it is impossible to tell how much, if any, channel work will have to be done. A "walk through" of the area, however, indicates that if any channeling is needed, it will be minor.

A stable outlet ditch will be constructed from the culvert to the Stevens River. Survey and soils information show that this can be done with a minimum of riprap protection in a steep section near the upstream end. The ditch is designed to handle the 0.5 cfs from the detention pond and the normal annual runoff from the uncontrolled area below the pond. This totals 9 cfs. Flows in excess of the 10 year frequency will discharge through an earth channel around the south dike of the detention pond directly into Harvey's Lake in order to protect the outlet channel from erosion.

An operation and maintenance plan should be developed for the project. The plan should include annual inspections and inspections following each major runoff event. Areas of possible concern include the following:

1. Diversion - the diversion is designed on a flat grade to prevent erosion and provide temporary storage of the runoff from the cornfield. Sediment is apt to accumulate which must be removed periodically.

2. Stone Centered Waterway - the velocities in the waterway are quite high and may occasionally dislodge some of the stone lining. These will have to be replaced.

3. Detention Pond - the slow release structure will have to be checked regularly to insure that it does not become clogged with debris. Leaves, sticks, and other organic matter will be a constant source of possible problems.

4. Outlet Ditch - immediately after construction, the water draining from the sides of the ditch may cause the side slopes to slough in. High runoff events may also cause erosion of the channel sides and bottom. The ditch may have to be reshaped occasionally to keep it functioning properly.

Please feel free to contact me if you have any questions or need further assistance.

Richard A. Fisher (mlb)

Richard A. Fisher
Civil Engineer

attachments

United States Department of Agriculture
Soil Conservation Service
Box 374 St. Johnsbury, Vt. 05819 748-3885

June 15, 1983

To: Eric Smeltzer
Aquatic Biologist
Department of Water Resources
and Environmental Engineering
Montpelier, Vt. 05602

Subject: Agricultural Waste Management Plan - Harvey's Lake Watershed.

This is to review the Soil Conservation Service suggestions to help control the runoff of agricultural wastes into Harvey's Lake.

Several proposed conservation structures have been suggested to help control the polluted runoff (fertilizers, manure, soil) from the steep farmland above Harvey's Lake. It is evident that these structures will not control runoff from the majority of the fields to the south and east of Joe Roy's buildings.

The runoff of polluted water from this area of the farm could possibly be controlled with the implementation of an agricultural waste management plan. The Soil Conservation Service (SCS) works with landowners through a cooperative agreement with local county conservation districts. With the SCS providing some of the technical help landowners may volunteer to carry out best management practices on their farms to control erosion and runoff. In this case we would estimate that over a period of time Mr. Roy could adopt and carry out an acceptable agricultural waste management plan.

We would be glad to work with Mr. Roy on development of an agricultural waste management system over the next few years.

In order to work with Mr. Roy we would periodically visit with him to determine his problems and needs. Again, the farmer would have to decide and agree to follow best management practices for his animal wastes.

As we work with Mr. Roy we can then begin to determine how well the runoff problems can be solved.

Laurence Hamel

Laurence Hamel
District Conservationist
St. Johnsbury Field Office
St. Johnsbury, Vt. 05819

State of Vermont

AGENCY OF ENVIRONMENTAL CONSERVATION

Montpelier, Vermont 05602
Department of Water Resources
and
Environmental Engineering

WATER QUALITY DIVISION

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

MEMORANDUM

TO: Eric Smeltzer, Aquatic Biologist

FROM: Stephan B. Syz, Water Resources Planner

SUBJECT: Wetlands in Harvey's Lake Restoration Program

DATE: March 10, 1983

On March 9, 1983 we inspected two wetlands that will probably be influenced by the Harvey's Lake Restoration project. One wetland north-northeast of the lake contains distinct communities dominated by alder, cattails and white cedar mixed with other softwood species. The other is a deltaic marsh dominated by a mosaic of upland grasses, red-osier dogwood and cattails at the intersection of South Peacham Brook and Stevens River north of the outlet of Harvey's Lake.

The first wetland area drains toward Harvey's Lake. It appears that a farm road in conjunction with a beaver dam had blocked flow toward the lake and redirected it into the Steven's River watershed. The beavers then apparently built a long second dam midway across the wetland. More recently the dam on the Harvey's Lake side has been breached allowing the water to flow again toward the lake.

These changes in water level have persisted long enough to influence the character of the vegetation, at least in the southern end of the wetland. The recent trend has been towards increased wetness. An open cattail marshland has replaced a white cedar swamp on the southern end of this wetland. This cattail marsh grades northward through an area with scattered white cedar stumps into a transitional area dominated by cattails where white cedar is reproducing by layering and by seed germination on stumps and windthrows. This gives way to a complex of tall white cedars mixing with black spruce, yellow birch, balsam, fir and hemlock. The wetland is probably used by waterfowl in the open water within the cattail marsh. Two muskrat lodges were observed in the cattails. Beaver may or may not be present at this time. Due to the season and to the snow cover, no observation was made of small herbaceous plants, however, it is possible that some important plant species could be found within the area of undisturbed white cedars.

The plan for this area described to me would include raising the elevation of the beaver dam/road along the southern end of the wetland sufficiently to reverse the flow of water from the Harvey's Lake watershed into the Stevens River watershed. The proposal as I understand it also includes constructing a diversion which will intercept runoff from a barnyard, corn land and pasture. This will increase the sediment and nutrient load to the wetland. The question of the level of impact of these changes on the wetland cannot be answered definitively. We do not know what rare or endangered plant species may be present nor do we fully know the importance of the site to wildlife. This information should be collected in the spring. It can be conjectured that sediment accumulation in the new pool will be greatly accelerated since the water will pool and not flow down a gradient as it does at the present time. The rate of filling depends on the rate of soil loss and the degree to which added nutrients will stimulate plant growth. In view of past beaver activity it can be conjectured that the new outlet stream from the wetland to the Stevens River will be dammed as the wetland is silted. Such dams may be built at more than one site along the stream. Sediment would then continue to be deposited behind the beaver dam until some future time when the dam is breached through the absence of maintenance by beavers. An upland beaver meadow will be formed. According to this scenario the consequence of changing the site from one where water flows at a velocity sufficient to self-clean as at present into a pool will lead to a temporary trend toward greatly increased wetness and increased habitat improvement for waterfowl. This will be followed by an essentially permanent conversion to upland transected by a stream.

The second wetland at the mouth of the South Peacham Brook appears to be a deltaic/floodplain supporting wetland vegetation presently at least partly due to the existence of a dam on Stevens River just below the confluence of South Peacham Brook with the Stevens River. The dam, it appears, raised the water level of the river and the water table of various parts of this floodplain. The lower levels of the floodplain appear to contain water in which cattails have developed. Higher portions support grasses, red-osier dogwood and other species of drier sites (these observations were made without the benefit of walking through the wetland and are subject to further revision).

The plan for lake restoration will apparently call for some action to prevent South Peacham Brook from flowing back into Harvey's Lake. This will probably involve lowering the river water in the vicinity of this wetland. Even a small change in water level in this area will probably substantially alter the character of the wetland as indicated by the substantial differences in vegetation as a result of small variations in elevation within the deltaic floodplain. This hypothesis, however, should be viewed in perspective. Much of the present wetland may not have existed before the dam was constructed. Even if this area is left without modifying the elevation of the water it is likely that sediment will continue to be deposited in the wetland and that the floodplain will reach a level in relation to the river surface similar to its height above the Stevens River prior to the dam's construction. This wetland would in the long term be transitional and tending toward a drier condition naturally. In either case some wetland pockets will probably persist.

It is not possible at this time to reach a conclusion on the impact of the restoration project in relation to Federal Executive Order No. 11990 until the final restoration plans are available and until each site is examined in more detail during the spring.

SBS/rh
Encl.

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