Madbury Water District
Morong

A STUDY OF BARBADOES POND

Strafford Regional Planning Commission

January 20, 1977

Bill Morong, Chairman
Madbury Water Board
RFD # 1
Durham, New Hampshire 03824

Dear Mr. Morong:

Please find enclosed a copy of the Barbadoes Pond Report conducted by a research team from the University of New Hampshire under the sponsorship of the commission. Although much of the report is a technical discussion of the research, the major findings are described in a brief summary at the beginning of the report.

This report is the culmination of several years of research that began with a relatively simple question. Selectman Joseph Cole of Madbury asked how the pond might be utilized for recreation as it had once done in the past. Some of the answers are in this report. Other answers can only be found by further studies of the land capability adjacent to the pond. What this report has provided is important background data and general recommendations for land use near the pond. The study has secondary benefits as well. The research techniques could well be applied to other small ponds in the seacoast area. The data also provides insight about other water resources (wetlands, aquifers) in the watershed of the pond.

If you have any pertinent comments or criticism about the pond report, please contact our office.

Sincerely,

Jack Mettee

Jack Mettee
Director

JM/vs

Enclosure

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A STUDY OF BARBADOES POND, MADBURY, STRAFFORD COUNTY, NEW HAMPSHIRE

This report was prepared under the auspices of
The Strafford Rockingham Regional Council by
The Strafford Regional Planning Commission

Editor: Francis R. Hall, INER

Contributions by:
Alan L. Baker, Botany
Francis S. Birch, Earth Sciences
James F. Haney, Zoology
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March 1976

As prepared by:
Institute of Natural and Environmental
Resources, University of New Hampshire
For
The Strafford Regional Planning Commission
90 Washington Street, Dover, New Hampshire 03820

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BARBADOES POND: ITS FUTURE DEPENDS UPON LAND USE CONTROL

Barbadoes Pond is in fair if not good condition. The pond surface is at its upper long-term level of elevation, and the pond is moderately productive in a biologic sense. Two natural constraints on the system are the organic tea-brown or tepid water color, which is not particularly appealing for swimming, and the general restriction of most fish life to the uppermost four meters of water. Man-imposed problems consist mainly of increasing sediment and dissolved solids inflow which originate from urbanization along Littleworth Road and the borrow pit and other activities along the northwestern side. So far the pond seems to have weathered these problems reasonably well but it will not necessarily weather them in the future.

If present activities, such as development of land around the pond in the present wooded or borrow pit areas, continue to accelerate, obvious problems will arise. If groundwater withdrawal from Dover's municipal wells is resumed, then the pond level could be lowered to undesirable levels. The general impact of these actions would be continued filling in of the pond by sediments and increased biologic productivity by nutrient inflow. Very likely, shallow areas would develop at the northwestern end and become covered with macrophytes such as cat-tails and water lilies. Also pronounced algal blooms may occur in response to the nutrient inflow.

The research team involved in this study emphasize the following points as a result of their research:

1. Anything that changes the hydrology, particularly with respect to the water table in the vicinity of the pond, will have a definite effect. For example, significant groundwater withdrawals from Dover's wells have lowered before and will lower again the level of the pond. However, it may be possible to design a pumping schedule to minimize this lowering.

2. Increasing the areas that contribute runoff to the pond will have an adverse ecological effect with regards to dissolved and suspended matter.

3. Increased building, particularly close to the pond, could have adverse effects with respect to septic tank effluent and storm drainage. Erosion could become an important factor by adding to the sediment load of the pond.

If the pond is to be maintained for conservation purposes or recreational activities, then decisions will have to be made about land use and development around its shores. Efforts should be made to divert storm drainage away from the pond and to control sedimentation. Neither of these will be easy to do under current practices.

SECTION I. INTRODUCTION

by

Francis R. Hall

Many communities in New Hampshire have small water bodies that offer potential for recreation and/or conservation. In many cases, however, these communities and larger regional groups do not have the expertise to assess the potential in a scientific manner. Even if planning assistance is available, scientific data are scarce and evaluation becomes difficult. At the same time, the University of New Hampshire does have considerable staff talent in fresh-water resources. Major scientific disciplines represented include hydrology, geology, geophysics, water chemistry, and limnology.

The Madbury Water Board and other groups in Madbury and Dover have long had an interest in using Barbadoes Pond, which lies along the Madbury-Dover border, for recreation and/or conservation. In early 1973, the Madbury Water Board initiated contacts with UNH which resulted in the preparation of a research proposal for a scientific study of Barbadoes Pond. The proposal was never fully implemented because certain faculty members were available only for short periods of time and because funding was difficult to obtain for a multidisciplinary study. Fortunately, the Strafford Regional Planning Commission supported several key substudies which allowed completion of a large part of the original proposal.

The major purpose of the study is to provide data for planning what might be done with the pond. A longer term goal, however, is to develop a suitable methodology for investigating small water bodies in order to provide the kinds of information needed by town or regional planners. The results may also be of interest with respect to water supply in some areas.

OBJECTIVES

The objectives of the study are:

1. Develop a hydrologic or water budget for the pond by use of hydrological, geophysical, and geological methods.

2. Determine the physical and chemical properties of the water. This includes assessment of the nutrients and nutrient cycling.

3. Evaluate the flora and fauna of the pond with particular reference to phytoplankton and zooplankton and to overall productivity and biomass.

4. Prepare a report presenting and interpreting the data with emphasis on the following points:

   a. Is the pond likely to dry up or are water levels likely to change greatly in the foreseeable future?

   b. Is the pond likely to become eutrophic within the next few years?

PROJECT RESPONSIBILITY AND GENERAL APPROACH

1. Project Coordinator: Francis R. Hall, Professor of Hydrology, INER. Maintained liaison during the study, supervised part of the hydrologic work, and prepared the final report.

2. Hydrological Studies: Gary L. Kerr, a M.S. candidate in INER (with supervision from Gordon L. Byers, Professor of Soil and Water Science, INER and Professor Hall).

Mr. Kerr did most of the hydrologic field work, collected data, and cooperated with the other researchers during the period July 1973 through May 1974. He completed the requirements for his M.S. degree by submission of a report entitled, "Hydrology and Water Budget at Barbadoes Pond", (June 1974).

3. Geophysical Studies: Francis S. Birch, Assistant Professor of Geophysics, Department of Earth Sciences.

Dr. Birch prepared depth to bed rock and water-level maps by refraction seismograph techniques. He obtained the data by using the pond area as a field laboratory for a geophysics class and by additional work during the summer of 1974. Dr. Birch also provided some geologic observations and cooperated in preparation of the pond bottom contour map. He submitted a report entitled, "Geophysical Studies at Barbadoes Pond, Strafford County, New Hampshire" (1974) to the Strafford Regional Planning Commission, and it is included herein as Section IV.

4. Limnological Studies: Alan L. Baker, Assistant Professor of Botany, and James F. Haney, Assistant Professor of Zoology.

Drs. Baker and Haney, although unable to participate as fully desirable because of prior time commitments, were able to collect considerable information concerning microflora and microfauna and productivity by using the pond as a field laboratory for several courses in their respective departments. They cooperated in collection and interpretation of chemical data and in preparation of the pond-bottom contour map.

5. Computer simulation of pond-ground water system: Denis LeBlanc, a hydrology senior in INER (with supervision by Professor Hall).

Mr. LeBlanc undertook the computer project as part of his undergraduate requirements. The data used were provided by Dr. Birch and Mr. Kerr.

ACKNOWLEDGEMENTS

Mrs. Joan Schreiber and her fellow members of the Madbury Water Board initiated the project, and their cooperation throughout is deeply appreciated. Particular thanks are due to Mr. Michael J. Kulka, Director of the Strafford Regional Planning Commission, for his interest and help and to the Planning Commission as a whole for providing financial support for parts of the hydrological and geophysical studies. The Water Resource Research Center, the New Hampshire Agricultural Experiment Station, and the various academic departments at UNH provided facilities for the study.

Many people and groups cooperated in various ways and those listed below are to be especially thanked for their help:

Mr. Bruce Graves, manager of the sand and gravel pit which is operated by the Iafolla Construction Company near the pond, provided pond elevations for February through June 1973, and other information.

Mr. John Cotton, U.S. Geological Survey, Concord, New Hampshire visited the site and provided background data.

Mr. David Rundle, formerly City Engineer of Dover, and Mr. Bill Leahy, Dover Water Department, provided information regarding the water-supply well near the pond.

Mr. Joseph Rehler, formerly head of the Portsmouth Water Department provided information about the Bellamy Reservoir.

SECTION II. GENERAL BACKGROUND

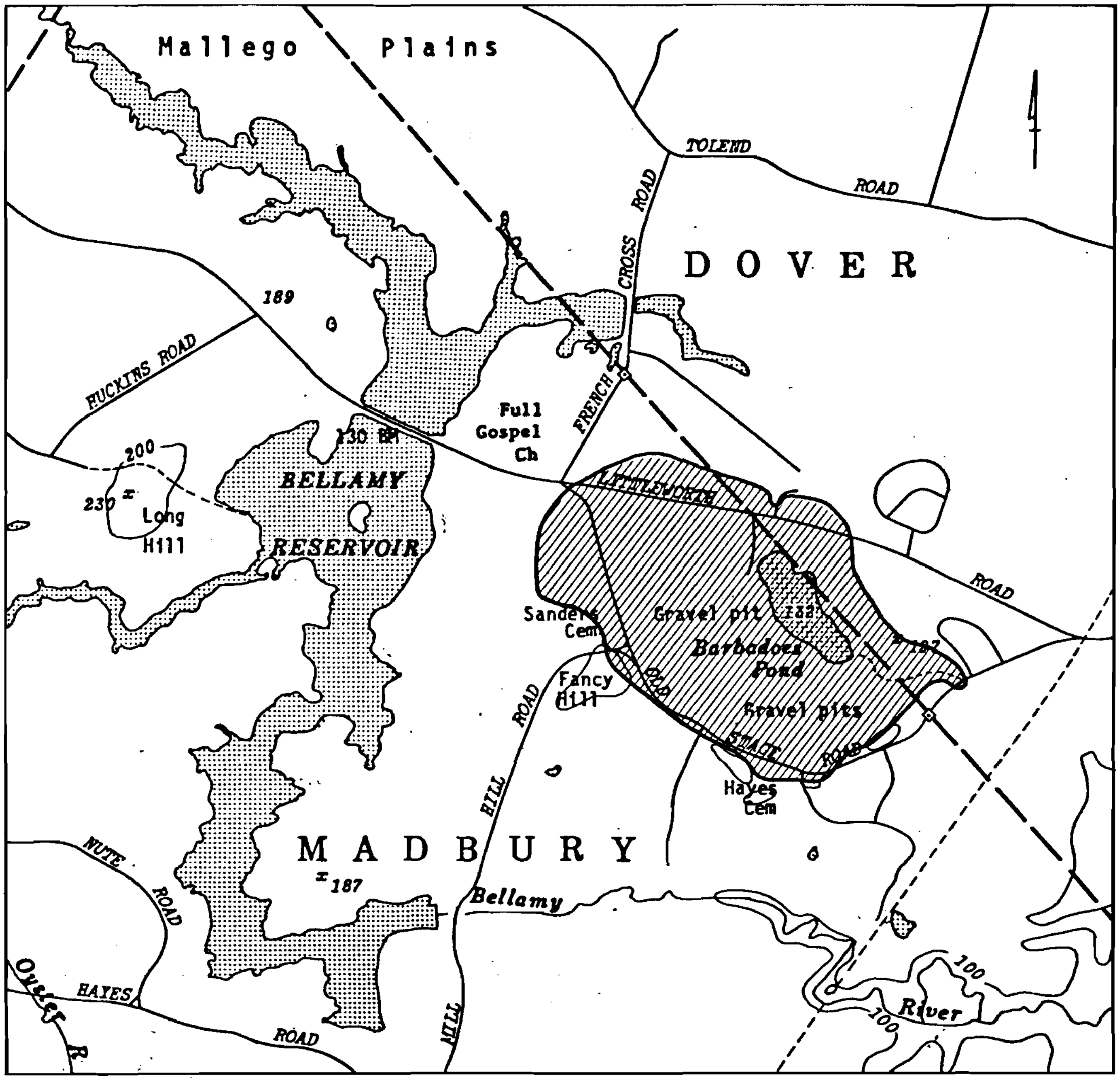
by

Francis R. Hall

LOCATION, CLIMATE AND VEGETATION

Barbadoes Pond is located along the Madbury-Dover boundary in southern Strafford County which is in southeastern New Hampshire (Figure 1). The pond is 2 and 1/2 miles from tide water (Piscataqua estuarine system) and 11 miles from the Atlantic Ocean. It has a surface area of 15.6 acres and a maximum depth of 50 feet at a surface elevation of 131 feet above sea level. The topography is gently to moderately rolling with elevations ranging from 130 to 200 feet or more above sea level. Details are given on the U.S. Geological Survey topographic quandrangle maps for Dover West (1:24,000) and Dover (1:62,500).

The climate is continental with a moderating influence from the nearby estuary and ocean. Annual precipitation is about 42 inches, with a range of 24 to 60 inches, which is rather evenly distributed throughout the year (Lautzenheiser, 1959). Evaporation from open water surfaces and evapotranspiration (primarily by vegetation) account for about 20 inches and runoff for the remaining 22 inches of the average annual value. Because evaporation and evapotranspiration do not vary greatly from year to year, actual annual runoff can be somewhere in the range of 2 inches in a very dry year to 38 inches in a very wet year. About 40 percent of the runoff occurs during the spring thaw in March and April. Annual snow fall is 60 inches with accumulations of this magnitude in some years. Open water surfaces are frozen from two to four months. The average annual temperature is about 46°F. with a monthly minimum of 24°F. in January and a monthly maximum of 69° F. in July (Lautzenheiser, 1959). The frost-free period or growing season is about 130 days, generally extending from



Surveyed 1942   U.S.G.S. Dover West   Culture revised, 1973

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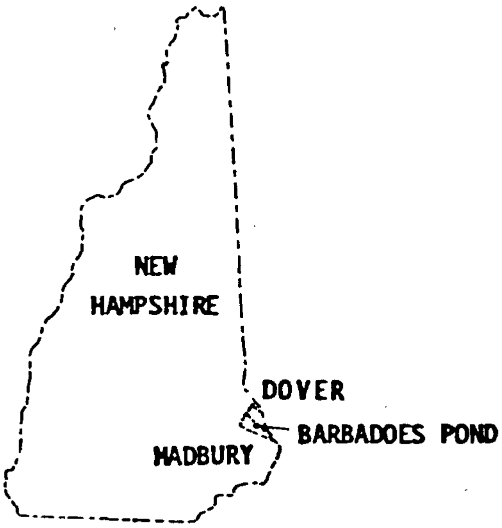
FIGURE 1. LOCATION MAP



The preparation of this map was financed in part through Comprehensive Planning Grants from the State of New Hampshire and the U.S. Department of Housing and Urban Development.

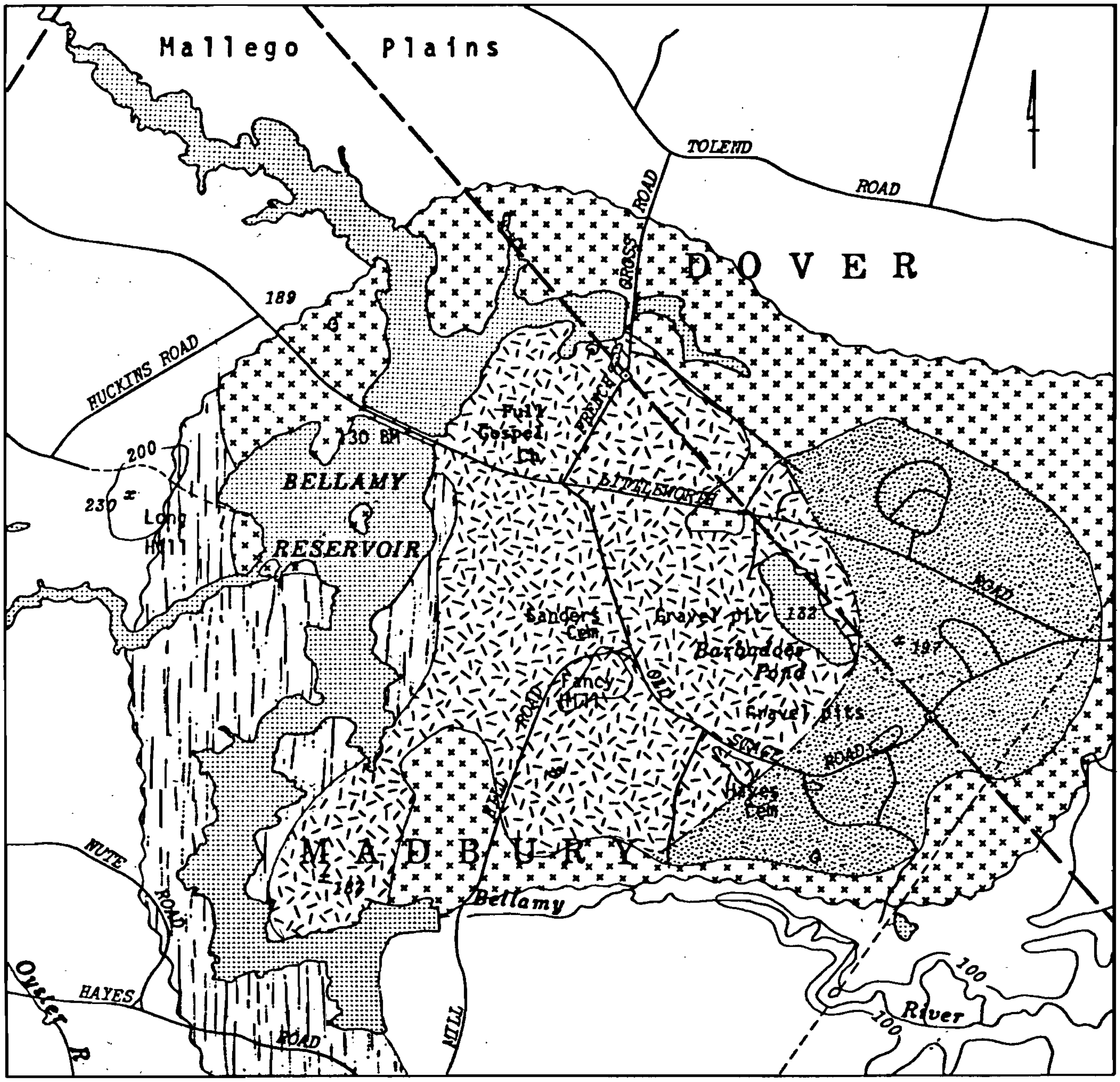
mid May to late September.

White pine is the dominant tree in the vicinity of the pond with lesser amounts of other conifers and hardwoods. The pond shoreline is characterized by swampy alder and the low areas to the north and northeast by alders, grasses, sedges, rushes and so on (Vieira and Bond, 1973). Further details on the pond vegetation are given in Section V.

GEOLOGY AND SOILS

Barbadoes Pond is what glacial geologists call a kettle hole (Bradley, 1964). That is, it represents a depression formed by the melting of a large block of ice left in the sediments during the retreat of a glacier. The kettle hole formed in and is surrounded by glacial outwash and ice contact deposits of up to 200 feet in thickness (Figure 2). These deposits are bounded to the north and northeast by marine deposits lying between the pond and the Bellamy river. The glacial deposits interfinger with marine deposits to the south and are more or less bounded by a bedrock high capped with thin glacial till or outwash to the west and by glacial outwash and till to the east. The igneous and metamorphic bedrock surface consists mainly of a deep trough extending in a northerly to northwesterly direction. The pond is situated in a bedrock depression toward the east side of the trough. The regional bedrock configuration is not known in detail, but there is evidence the trough may extend northward and southward into other drainage basins. Further details are given in Section IV.

The soils reflect the underlying parent materials with the outwash and ice contact deposits being covered with well drained Hinckley gravelly loamy sand and Hinckley fine loamy sand (Vieira and Bond, 1973). Toward the north and northeast the soils are moderately to poorly drained Elmwood fine sandy loam,



Surveyed 1942 U.S.G.S. Dover West Culture revised, 1973

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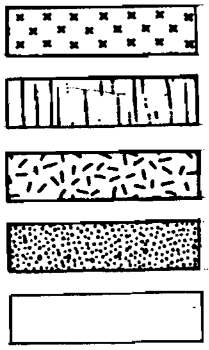
FIGURE 2. SURFICIAL GEOLOGY



MARINE DEPOSITS

GLACIAL TILL

SAND & GRAVEL

SANDS

UNDIFFERENTIATED

The preparation of this map was financed in part through Comprehensive Planning Grants from the State of New Hampshire and the U.S. Department of Housing and Urban Development.

Scantic silt loam, and Swanton fine sandy loam that are characteristic of marine or lacustrine terraces (Vieira and Bond, 1973).

REFERENCES CITED

Bradley, Edward, 1964, Geology and ground-water resources of southeastern New Hampshire: U.S. Geological Survey Water-Supply Paper No. 1695.

Lautzenheiser, R.E., 1959, Climates of the States - New Hampshire: U.S. Department of Commerce, Weather Bureau (now National Weather Service), Climatography of the United States, No. 60-27.

Vieira, F.J. and R.W. Bond, 1973, Soil survey of Strafford County, New Hampshire: USDA Soil Conservation Service.

SECTION III. HYDROLOGY

by

Francis R. Hall and Gary L. Kerr

Barbadoes Pond is in a topographically closed area of 284 acres which lies entirely within the Bellamy River basin, and it is separated by only a low divide - wetland area from the headwaters of the river, now mainly the upper end of the reservoir. There is no natural surface outlet at present levels although there is evidence for an old outlet at a much higher elevation. There does not appear to have been any natural surface inlet although human activities make this hard to demonstrate. An ephemeral inlet has developed at the eastern edge closest to Littleworth Road. If this inlet is natural then it has been much enlarged by storm drainage from the Littleworth Road area.

Under prevailing climatic conditions, however, the pond can not be a closed hydrologic system that is isolated from the Bellamy River drainage system. This is indicated by the fact that on the average, there are at least 22 inches of water per unit area to be disposed of as some form of runoff (Section II, Location, Climate, and Vegetation). Because the pond does not overflow then it seems clear that this water leaves the pond as ground water. In fact, the water-level map for 1974 (Section IV), indicates that ground water moves from the pond toward the Bellamy River in the Knox Marsh Road area below the dam.

HISTORICAL POND LEVELS

An attempt has been made to assemble all available data on pond-surface elevations (Kerr, 1974), and the results are summarized on Figure 3. Data prior to 1973 come from the U.S. Geological Survey (topographic maps, records in Concord, and Bradley, 1964) and the New Hampshire Department of Fish and Game (records in Concord). Annual rainfall is included on Figure 3 in the form of a five-year moving average for data from Durham which is about three miles to the south. Such an average tends to eliminate scatter from annual value and to show trends with time.

The limited amount of information and the complex set of events beginning in 1947 make interpretation difficult, but Figure 3, along with the pronounced shorelines that are readily visible in the field, suggests that there have been two preferred "natural" pond elevations at about 132 and 135 feet above sea level. The latter seems more prevalent since the 1940's or 1950's and the former prior to that time. There is also a shoreline with a pronounced growth of vegetation at about 120-122 feet reflecting low water levels during the 1960's and early 1970's and perhaps further in the past. This lower level is due mainly to a combination of a series of dry years and pumping of the municipal supply well.

An examination of the rainfall curve on Figure 3 indicates rather pronounced periods of wet years and dry years which fluctuate around the mean. It seems logical to infer that if the pond is directly sensitive to climatic factors (mainly precipitation, as evaporation and evapotranspiration vary little), then, it too should fluctuate around a mean level in a similar fashion from year to year. If calculations are made using reasonable assumptions about drainage area, however, it becomes apparent that the pond is not very sensitive to year to year changes in precipitation because it would overflow during wet periods and drop very low during dry ones. Although the record is meager, there is no evidence for wide variations in levels under natural conditions. As will be set forth in subsequent subsections, the main factor influencing pond elevations is the regional water table. Furthermore, the pond level must be above the water table

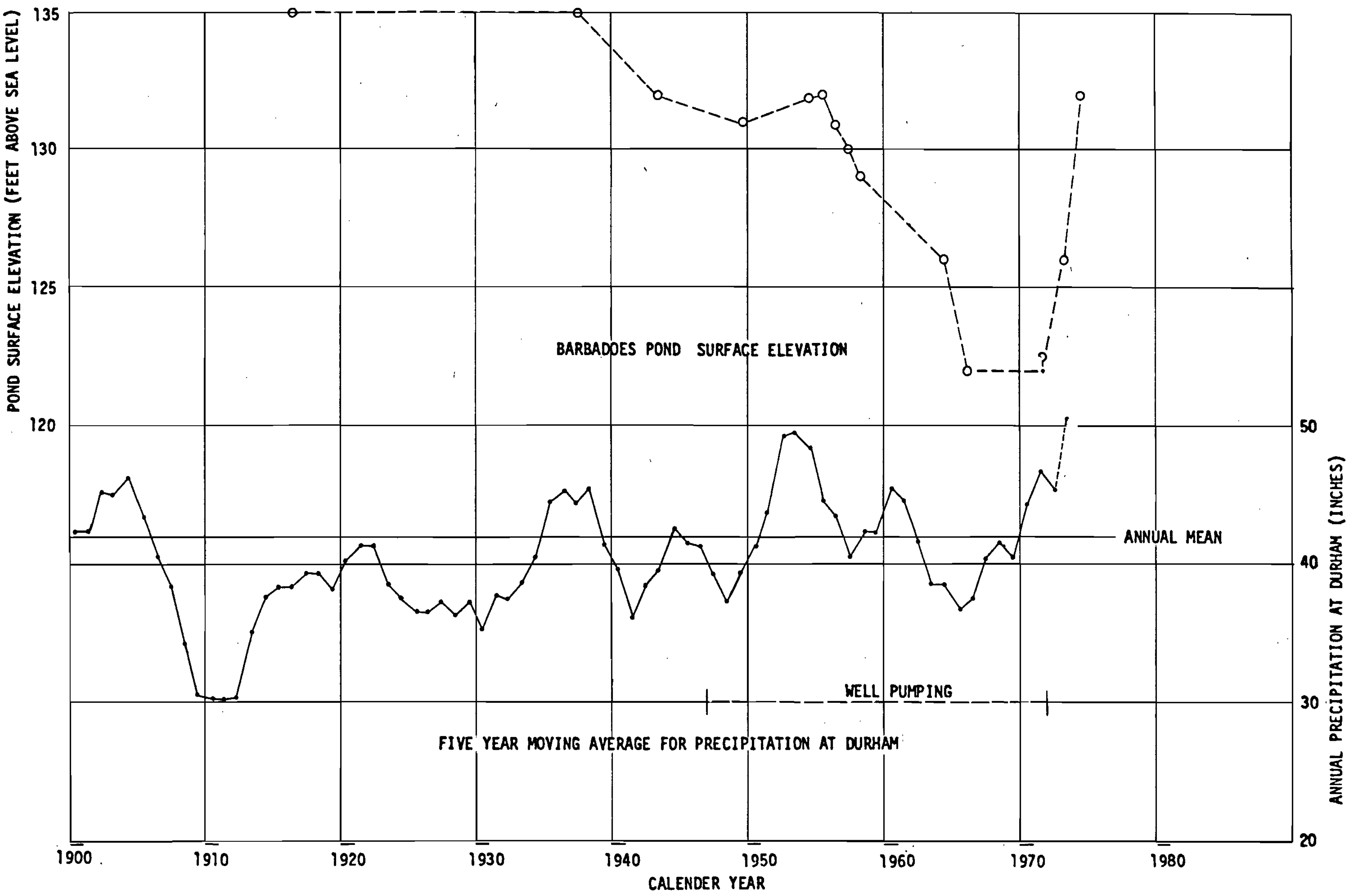


FIGURE 3. BARBADOES POND SURFACE ELEVATIONS, 1916 - 1974 AND FIVE YEAR MEAN FOR PRECIPITATION AT DURHAM

all or most of the time. Therefore, pond response to climatic variations is a subtle and complex one.

AVERAGE ANNUAL WATER BUDGET

An average annual water budget for Barbadoes Pond (Table 1) has been developed from long term precipitation and temperature records at Durham, stream gaging records for the nearby Oyster River, and a series of assumptions about pond inflow and relationships to ground water. Some salient points are:

1. The direct tributary area of 95 acres consists of 65 acres along Littleworth Road and 30 acres in the vicinity of the sand and gravel operation. Measurements by Kerr (1974) of discharge of the ephemeral inlet suggests that this is not unreasonable;

2. The lack of monthly agreement between precipitation minus evapotranspiration (Column (4)) and runoff (Column (5)) reflects a time lag due to ground water, soil moisture, and snow storage;

3. The ground-water runoff component (Column (6)) is of a speculative nature, but it is supported by unpublished analysis of records of the Oyster and Lamprey Rivers near Durham;

4. The "ground-water out" of (Column (10)) is based on an assumption of annual equilibrium conditions;

5. The pond-level fluctuations of Column (11) are obtained by an iterative procedure of solving Darcy's law in the form:

$$q = K \left(\frac{\bar{H}-\bar{h}+H+\Delta h}{L}\right) \qquad (1)$$

where q, ground-water discharge, inches/month

$\bar{H}$, average head difference between pond surface and water table, inches

K, hydraulic conductivity of pond bottom, inches/month

$\bar{h}$, average monthly inflow to pond, inches

H, actual monthly inflow to pond, inches

Δh, last month's pond level above or below mean of zero, inches

L, thickness of pond bottom, inches

and for assumed values the equation becomes:

$$q = \frac{8.1\ (104.4 - 7.05 + H + \Delta h)}{120} \qquad (1a)$$

The values for K and L are based on an analysis of a well pumping test, and have been shown to be reasonable by computer simulation (Denis LeBlanc, personal communication). It should be noted that an implicit assumption is made that the underlying water table changes very little. The historical hydrograph (Figure 3) suggests that this is reasonable for natural conditions;

6. The results of Column (11) show that the pond level fluctuates about 20 inches above a mean and 13 inches below for an annual range of 33 inches where the mean could be thought of as being in the range of 131 feet MSL.

Table 1. Barbadoes Pond Average Annual Water Budget (All values in area inches except where noted)

Month	(1) Ppt	(2) Temp, °F	(3) PE	(4) Ppt-PE	(5) Runoff	(6) GW	(7) DRO	(8) SW In	(9) Total In	(10) GW out	(11) Pond level	(12) Change in Storage
J	3.73	23.5	.30	3.43	2.07	1.00	1.07	6.53	9.96	6.61	-6.02	3.42
F	2.93	24.6	.37	2.56	1.87	1.00	.87	5.31	7.87	6.70	-4.85	1.17
M	3.96	33.0	.74	3.22	4.62	1.50	3.12	19.03	22.25	7.75	9.65	14.50
A	3.80	43.8	1.37	2.43	4.63	2.00	2.63	16.04	18.47	8.47	19.65	10.00
M	3.32	54.6	2.38	.94	2.45	1.50	.95	5.80	6.74	8.36	18.03	-1.62
J	3.22	63.4	3.58	-.36	1.09	1.00	.09	.55	.19	7.80	10.42	-7.61
J	3.50	68.6	4.13	-.63	0.51	.51	0.	0.	-.63	7.23	2.56	-7.86
A	3.22	66.7	3.12	.10	0.32	.32	0.	0.	.10	6.75	-4.09	-6.65
S	3.56	59.3	2.02	1.54	0.49	.49	0.	0.	1.54	6.40	-8.95	-4.86
O	3.17	49.2	1.17	2.00	0.51	.51	0.	0.	2.00	6.10	-13.05	-4.10
N	4.17	38.6	.60	3.57	1.49	1.00	.49	2.99	6.56	6.14	-12.62	.43
D	3.59	26.7	.37	3.27	2.03	1.00	1.03	6.28	9.55	6.37	-9.44	3.18
Total/Average	42.17	46.0	20.10	22.07	22.08	11.83	10.25	62.53	84.60	84.68	-----	0.00

EXPLANATION OF COLUMNS

1. Mean monthly precipitation at Durham, 1931-1960 (data from National Weather Service).
2. Mean monthly temperature at Durham, 1931-1960 (data from National Weather Service).
3. Monthly potential evapotranspiration calculated from (2) by Hamon method (Hall et al., 1972) and linearly adjusted so that the sum of column (1) minus the sum of (3) is equal to average annual runoff (sum of column (5)).
4. Precipitation minus potential evapotranspiration or (1) - (3).
5. Mean monthly runoff of the Oyster River near Durham, 1935-1961 (data from U.S. Geological Survey).
6. Estimated runoff from storage, mainly ground water, but including ponds and wetlands, for Oyster River.
7. Estimated direct runoff or (5) - (6).
8. Estimated surface water inflow to pond from 95 acres assuming pond surface area of 15.6 acres (equivalent to elevation of 132 feet MSL).
9. Total inflow to pond or (4) + (8).
10. Estimated ground-water discharge assuming equilibrium conditions of no net annual change.
11. Estimated pond-level fluctuation around a mean level. That is, no net change in storage.
12. Monthly change in storage from Column (11).

POND LEVELS AND BUDGET FOR 1972-1974

The measured pond elevations for March 1973, through April 1974, are displayed on Figure 4, and the elevation has not changed greatly since April 1974 when the pond reached what appears to be an equilibrium level of about 132 feet. Unfortunately, there were no measurements before the Dover well was put on standby status on November 28 or 29, 1972. An inspection of rainfall records shows, however, that although early 1972 was fairly wet, the summer and fall were fairly dry. Therefore, it is assumed that the pond was at a level of about 122 feet although November was a wet month (Table 2). This indicates a total rise in surface level of about 10 feet in 18 months. A water budget for the same period of interest is given in Table 2. The most obvious feature of Table 2 and Figure 4 is that the Dover pumping well was closed down at a time that coincided with the beginning of an extremely wet period.

Column (8) of Table 2 represents an attempt to evaluate the monthly water budget calculations. It is based on the simple assumption that:

Inflow (Col. (6)) = Outflow (Col. (7)) $\pm$ change in storage (Col. (4))

where balance = I - 0 $\mp$ change in storage

The general departure from zero for each month is a reflection both of errors in the budget and the fact that some water in storage is released over a time period of more than one month. The encouraging aspect, however, is that the budget is fairly well balanced for the entire 18 month period where:

Inflow =	249.80	inches
Outflow =	128.85	inches
In-Out =	+119.95	inches
Change in Storage =	+117.60	inches
Balance =	+ 2.35	inches

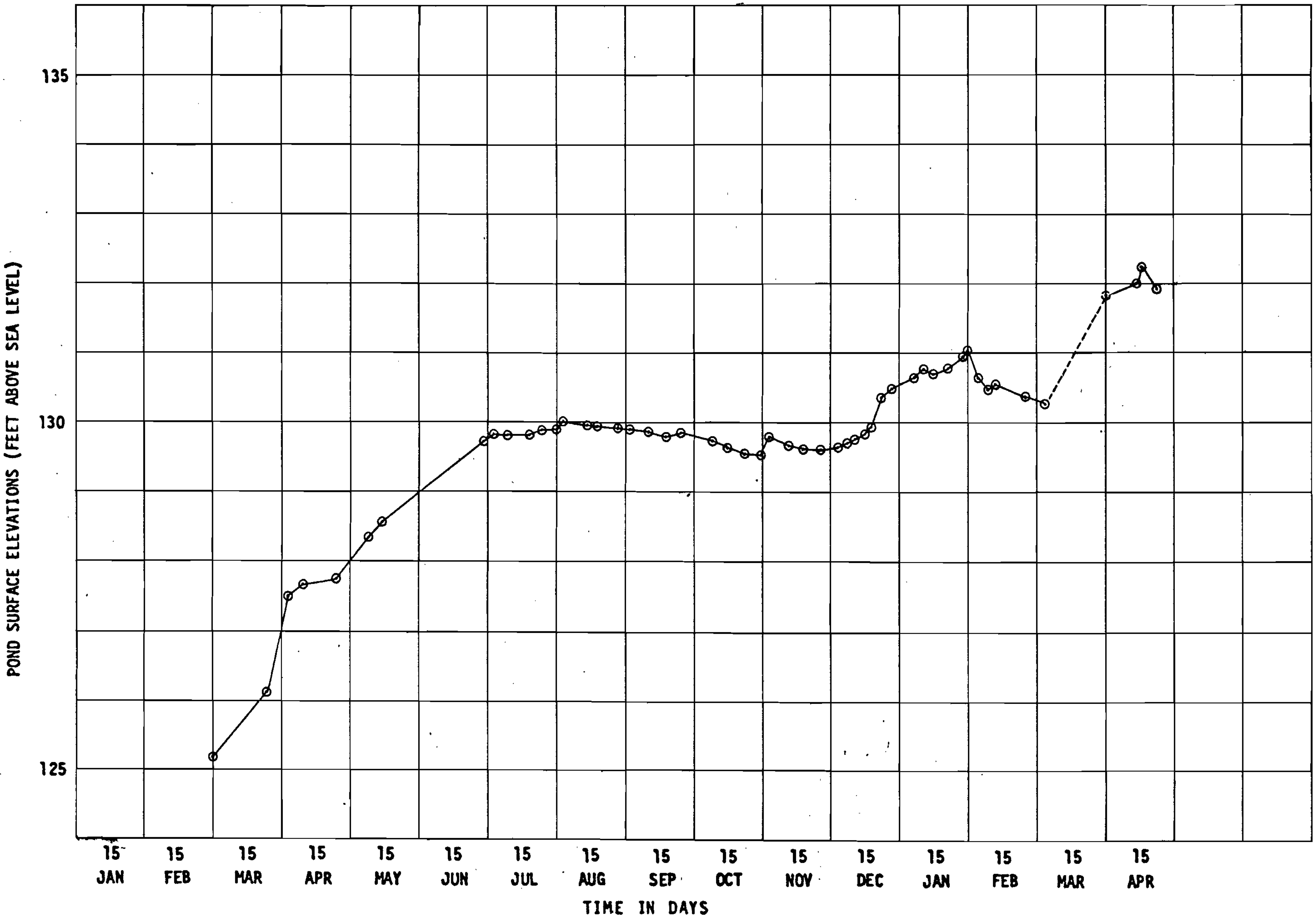


FIGURE 4. BARBADOES POND - SURFACE ELEVATIONS, MARCH 1973 - APRIL 1974

Table 2. Barbadoes Pond Water Budget - November 1972 - April 1974
(All values in area inches)

Year	Month	(1) Ppt	(2) Evap	(3) Ppt-Evap	(4) Change in Pond Level	(5) SW In	(6) Total In	(7) GW out	(8) Balance
	N	9.46	.58	8.88	----	18.30	27.18	10.00	17.18
1972	D	9.72	.35	9.37	12.00	13.91	23.28	7.05	4.23
1973	J	4.70	.50	4.20	12.00	10.31	14.51	7.05	-4.54
	F	2.68	.51	2.17	12.00	10.19	12.36	7.05	-6.69
	M	4.91	1.20	3.71	22.80	26.90	30.61	7.05	.76
	A	13.35	1.90	11.45	14.40	33.31	44.76	7.05	23.31
	M	6.32	2.58*	3.74	14.40	20.13	23.87	7.05	2.42
	J	2.38	3.47*	-1.09	3.60	.06	-1.03	7.05	-11.68
	J	2.10	3.73*	-1.63	1.20	0.	-1.63	7.05	-9.88
	A	3.11	3.70*	-.59	0.00	0.	-.59	7.05	-7.64
	S	2.15	2.20*	-.05	-2.40	0.	-.05	7.05	-4.70
	O	3.53	1.58*	1.95	-2.40	0.	1.95	7.05	-2.70
	N	2.51	.68	1.83	2.40	0.	1.83	7.05	-7.62
1973	D	7.21	.46	6.75	12.00	19.09	25.84	7.05	6.79
1974	J	3.23	.40	2.83	3.60	9.58	12.41	7.05	1.76
	F	1.95	.44	1.51	-8.40	7.14	8.65	7.05	10.00
	M	3.64	1.01	2.63	19.20	12.38	15.01	7.05	-11.24
	A	3.82	2.07	1.75	1.20	9.09	10.84	7.05	2.59
TOTAL		86.77	27.36	59.41	117.60	190.39	249.80	129.85	2.35

EXPLANATION OF COLUMNS

1. Monthly precipitation as recorded at Durham; however, an informally recorded precipitation in Madbury in April 1973 was 7.63 inches.

2. Pan evaporation at Lake Massabesic (National Weather Service) times a pan coefficient of 0.79 where marked by an asterisk; otherwise potential evapotranspiration as calculated by Hamon method (Hall et al., 1972) at Durham.

3. Precipitation minus evaporation or net direct contribution to pond surface.

4. Change in pond level based on N.H. Fish and Game measurement in March 1973; hand leveling by Bruce Graves until June 1973; and measurements by Kerr (1974) from June 1973 to April 1974. Rise of 12 inch per month for December 1972 and January and February 1973 are estimated by Hall. Also, Dover municipal well located 800 feet south of pond was put on standby basis on November 28 or 29, 1972.

5. Surface water inflow to pond from 95 acres as estimated by technique used for annual budget (Table 1).

6. Direct contribution to pond plus surface inflow or (3) + (5).

7. Ground water outflow as estimated by Hall. Figure for November 1972 is a guess, and simple average monthly values from Table 1 are assumed for the rest of the months.

8. The balance is equal to inflow minus outflow plus or minus a change in storage or (6)-(7)-(4). A plus sign means more water available that month than the monthly budget allows, and conversely for a minus sign. That is, for each month, (6)-(7)-(4) = 0, if budget were correct and time lags were less than one month

Clearly than a combination of ground-water pumpage and dry years could cause the sort of major decline observed in the early to mid-1960's.

RELATIONSHIP OF POND AND GROUND WATER

The geologic and hydrologic features of the pond vicinity have already been discussed and pond levels and water budgets have been considered. At this point, however, some additional comments about the relationships of Barbadoes Pond to ground water may be useful in understanding how the pond responds to external events. It is well to remember that the topographic divide around the pond is not a hydrologic divide except in a general way on the side closest to the Bellamy Reservoir. Furthermore, the pond can discharge water only to ground water and the atmosphere, and given the prevailing hydrologic regime, it's level must be above the water table all or most of the time. Also, the pond is not very sensitive to normal annual variations in precipitation. However, the pond elevation is sensitive to changes in the regional water table, and any factors that cause pronounced rises or falls of the water table will similarly affect the pond. The general vicinity of the pond is a ground-water recharge area, and the Knox Marsh Road area to the south is a discharge area.

An extensive pumping test was conducted on the Barbadoes well for the City of Dover in late 1950 and early 1951. An analysis of data indicates the following:

1. The aquifer (water-bearing material) from which the well pumped has good transmission and storage properties, but the saturated thickness is 60 feet or less. Transmissivity is on the order of 150,000 gallons per day per foot or perhaps greater and hydraulic conductivity is about 2,500 gallons per day per square foot. The specific yield or volumetric storage ratio is 0.14. The aquifer has a relatively limited areal extent, and it does not have a great

deal of water in storage. This is substantiated by the fact that although as much as 1,080 and 1,400 gpm were pumped for periods of three or four days, Dover can only obtain some 700 gpm or less on a sustained basis

2. After pumping about 335 gpm for nearly three years from 1947 to 1950, the pond elevation at 131 feet was 12 feet higher than the water table in an observation well a few feet from the southern edge of the pond. This indicates that the pond bottom is relatively impermeable; however, it is leaky. In fact, as shown in Table 1, some 80 inches per year can pass through the pond bottom. The hydraulic conductivity of the pond bottom is on the order of 0.2 gallons per day per square foot for a bottom thickness of 10 feet.

3. The results of the test make clear that pumpage from the well will have a pronounced effect on the pond by taking water directly from it along with lowering the water table. As long as the well is pumping, even fairly wet years are likely to cause only a relative small rise in level.

4. If there is not a great deal of water in storage then the area of influence of a pumping well can stabilize or reach steady state only if sufficient ground-water recharge is available, and Table 1, Column (6) indicates that one foot per year is a reasonable estimate for the area. Under these conditions, the Dover well would have to pump from an area of 564 acres to obtain 350 gpm or 1128 acres to obtain 700 gpm on a sustained basis. Put another way, these are equivalent to circles with radii of 2800 feet and 4000 feet respectively. Therefore, the radius of influence of the well could reach nearly to the Bellamy Reservoir. Because of geologic conditions the actual area influenced by the well is more likely to be elliptical or somewhat irregular in shape.

WATER CHEMISTRY

Water quality of Barbadoes Pond is discussed in detail in Section V; however, for completeness chemical analyses done by Kerr (1974) are discussed briefly in this section and listed in Table 3. The samples were taken from the pond and nearby dug and drilled wells. In general, values for parameters such as pH and hardness are typical for this part of New Hampshire (Bradley, 1964); however, chloride for many of the wells and sometimes the pond is somewhat high for the area where 5 mg/ℓ might be expected under natural conditions and perhaps 10 mg/ℓ under present conditions (Hall, 1975). Also, total dissolved solids in terms of electrical conductivity are high in many cases. High values in wells are presumably due to road deicing salt and septic tanks, and high values in the pond are due to these sources plus storm drainage from the Littleworth Road area. It should be noted that the pond is also receiving sediment as part of the storm drainage.

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Table 3 Chemical Analyses for Barbadoes Pond and Vicinity

(All results in mg/ℓ excepted as noted)

SOURCE	Pond Surface	Pond 1.5m	Pond 3.0m	Pond 5.0m	Pond 7.0m	Pond 10.0m	Pond 13.2m	Pond Surface	Olson Well	Olson Well	Garrison Well	Garrison Well	Hanscom Well	Rogers Drilled	Rogers Drilled	Rogers Dug 1	Rogers Dug 1	Rogers Dug 2
DATE	7/73	7/73	10/73	10/73	10/73	10/73	10/73	2/74	7/73	2/74	7/73	2/74	2/74	7/73	2/74	7/73	2/74	2/74
TOTAL IRON	0.18	0.17	--	--	--	--	--	0.60	0.01	0.20	0.04	0.10	0.10	0.01	0.10	0.02	0.10	0.10
CALCIUM	3	4	5	5	5	4	4	5	14	6	58	19	6	22	20	3	4	6
MAGNESIUM	2	2	1	1	1	1	1	0	5	3	16	3	0	3	3	0	1	2
SODIUM PLUS POTASSIUM	7	6	--	--	--	--	--	7	22	20	18	43	81	18	25	7	20	6
BICARBONATE	5	5	--	--	--	--	--	1*	54	21	104	90	16	89	99	12	24	15
SULFATE	12	12	--	--	--	--	--	11	23	15	40	40	18	24	25	8	35	10
CHLORIDE	13	13	9.9	9.0	9.0	9.0	9.0	14	24	26	84	26	112	4	6	2	1	8
NITRATE	2	2	--	--	--	--	--	1	3	1	6	1	2	3	1	2	1	1
TOTAL HARDNESS (as $CaCO_3$)	16	18	13	12	12	11	10	12	56	28	208	60	15	66	60	8	16	24
ELECTRICAL CONDUCTIVITY in micromhos @25°C	98	100	129	108	83	230*	95.5	78.7	251	161	920*	292	402	205	174	70.0	63.0	76.0
pH @25°C	6.6	6.0	6.7	4.5*	6.0	6.2	6.5	6.4	6.3	6.8	6.2	7.1	6.9	7.5	8.1	5.9	6.7	6.6

* Possibly in error

SECTION IV GEOPHYSICS

(Copy of the original report submitted by Francis S. Birch to the Strafford Regional Planning Commission)

Geophysical Studies at Barbadoes Pond, Strafford County, New Hampshire

1974

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PREFACE

It is important that readers understand the interpretive nature of much geophysical work. One interpretive step is identifying geologic materials on the basis of measured velocities of seismic waves. Around Barbadoes Pond, where stream valleys, excavations and wells provide numerous checks, this problem is probably not severe. Another interpretive step is contouring the final results; only experience, guided by local geological knowledge, can reduce probable errors.

These cautions should be noted by anyone planning large scale excavation or construction. Additional information on subsurface conditions would be appreciated.

ABSTRACT

Subsurface geologic conditions beneath the drainage basin of Barbadoes Pond, a kettle pond in southeast New Hampshire, were investigated by 45 seismic refraction lines and by a magnetometer survey. The main purpose was to map bedrock topography as part of a hydrologic study of the pond. Mapping water table elevation was a secondary goal.

Refraction measurements yield subsurface layers with seismic wave velocities grouped around four distinct values: 1000, 2000, 5000 and 10000 feet per second. These are interpreted as corresponding to layers of loose sand and gravel, compact sand and gravel, water-saturated sand and gravel, and bedrock.

A buried valley about 1000 feet wide and over 100 feet deep runs through the area from northwest to southeast; it passes near the west side of the pond. West of this bedrock valley are hills composed mainly of bedrock; east of the valley are hills of sand and gravel. An east-west band including high seismic velocities in the bedrock, high evelations of the bedrock, and a constriction in the buried valley, follows the strike of the vertically dipping metamorphic bedrock. Barbadoes Pond lies in a small bedrock depression apparently connected at the north end to the buried valley.

The water table slopes downward toward the south. This implies that Barbadoes Pond is fed by ground water from the north and loses water to the south. Over the southern part of the buried valley the water table is greatly steepened implying either a low permeability layer in the valley or confinement of flow by the valley. West of the valley the water table

closely conforms to the ground topography. East of the valley the water table is much flatter.

Magnetic anomalies over the pond trend parallel to the strike of the bedrock and probably are caused by variations in susceptibility of the various bedrock layers. Detailed analysis of one distinct anomaly yields a source depth in general agreement with nearby seismic results and susceptibility contrast in agreement with outcrop samples.

INTRODUCTION

Barbadoes Pond is a small kettle pond on the border between Dover and Madbury in Strafford County, southeast New Hampshire. The drainage and bedrock geology of the surrounding region are summarized in Figure 1. The pond itself has a surface area of about 16 acres and maximum depth of about 50 feet. In recent decades the water level has fluctuated from about 10 feet below to 5 feet above the present level (elevation 132 feet). Evidence includes abandoned higher shorelines, shown by small wave-cut cliffs, coarse gravel and cobble deposits and patterns of tree growth as well as recollections of local residents. The water budget of the pond has recently been studied (Kerr, 1974). Since pond levels reflect a balance between water added to and removed from the pond the flow of water underground must be understood. This study describes subsurface conditions underneath the surface drainage basin of the pond.

The principal goal of this project was to determine the elevation of bedrock, or "ledge", under the surface drainage basin of the pond. Because bedrock is often relatively impermeable, ground water flow is confined to the region between the water table and bedrock (these surfaces may be thought of as the walls of a pipe in which the water flows). Saturated material above bedrock also stores water. The greater the amount of stored water, the less pond level will fluctuate in response to addition or subtraction of water, other things being equal. Of particular interest is whether the pond is isolated in its own bedrock basin or in connected to other drainage basins. In the latter case pumping from one basin would lower water levels in the other. A secondary goal was to map the elevation of the water table itself. The configuration of this surface determines the direction of ground water flow.

Field work was conducted during the academic year 1973-1974 by the author aided by Earth Science students from the University of New Hampshire and by Gary Kerr from the Institute of Natural and Environmental Resources, U.N.H. During the summer of 1974 the author was aided by a field assistant paid by the Strafford Regional Planning Commission. The field methods used were seismic refraction and magnetic surveying (Dobrin, 1960). In the former method the velocities of underground sound waves are measured; these velocities can be interpreted in terms of various geological materials. The method also yields the thickness of each "layer" of subsurface material. The magnetic survey reveals patterns corresponding to different magnetizations of underground materials; such differences usually correspond to different iron mineral contents.

FIELD METHODS

A topographic base map was prepared by enlargement of the Dover West United States Geological Survey map (Figure 2). A large scale aerial photograph was used to supplement the base map.

Seismic lines were laid out, using tape and magnetic compass, with reference to points (road intersections, buildings, etc) identifiable on the base map or air photo. It is estimated that all lines shown on Figure 2 are plotted within 100 feet of their true location. Lines along roads are along the shoulder; they are plotted a little farther away for clarity. Ground elevation was estimated from the topographic map except for lines in the gravel pits. Here transit and level rod were used to establish elevations.

Seismic refraction measurements were done using a Bison model 1570B engineering seismograph (Bison Instruments, Inc., Minneapolis, Minnesota). A twelve pound sledge hammer was the energy source except on some long lines in noisy locations or where attenuation was extreme. In these cases a 100 pound weight dropped from heights up to 4 feet was employed. In most cases two or three hammer blows were sufficient to produce a clear signal; in unfavourable locations as many as two dozen blows were required. Usually shots were made at 10 foot intervals to a range of 100 feet and at 20 foot intervals at greater ranges. The weight dropper was generally set up at 50 foot intervals. All but two lines, 12 and 25, were reversed to determine true seismic velocities and apparent dips of the layers.

The magnetometer survey of the pond was made when the pond was frozen. A Geometrics model G-816 proton precession magnetometer was used with the sensor mounted on an 8 foot staff (Geometrics, Palo Alto, California). Readings were made on a 30 meter grid except for one line of stations at a 20 foot spacing. Base station readings were repeated frequently to account for diurnal changes of the magnetic field of the earth.

Well data was collected by KERR in connection with his hydrologic study (1974).

DATA ANALYSIS

The seismic data were analysed by standard methods using "eyeball" best straight line fits to the travel-time graphs. A computer program, slightly modified from one provided with the instrument, uses the zerodistance time intercepts of these lines to calculate parameters for a "dipping multi-layer" model (Dobrin, 1960). In this model the subsuface is assumed to consist of a set of layers each with a distinct seismic wave velocity. The surfaces of the layers may dip or slope. The program calculates the seismic velocity, the thickness, and the dip of each layer. Errors in depths and velocities are estimated at less than 20%.

The magnetic anomalies were analyzed by comparison with theoretical anomalies expected over various "two-dimensional" bodies (Talwani et al., 1959). The parameters of the models (magnetization, dimensions, etc.) are varied until the calculated anomalies match the measured anomalies.

RESULTS AND DISCUSSION

The seismic results are presented in Figures 2, 3, 4 and 5 and in Table I. (These maps show values for center point of each line; values at each end are in general agreement with the contours).

Examination of Table I shows that the seismic velocities cluster around four common values. The first, about 1000 feet per second (fps), is found only in the uppermost layer. It is typical for sand, gravel or almost any loosely packed granular medium (Clark, 1966). The reason is that, for a loosely packed material, the velocity is controlled by the velocity of sound in the pore fluid; in this case the pore fluid is air. The geology of the area, as displayed in several gravel pits, strongly suggests that this layer is mainly sand and gravel. At two places, well 8 and line 33, a dark-colored clay occurs at depths corresponding to this velocity. At both sites ground elevation is below 140 feet. There is no evidence for clay elsewhere except for a small perched water body in one of the gravel pits (near line 21).

The second group clusters around a velocity of 2000 fps. Although commonly found below the previous layer, these velocities are found at the surface of some excavations, especially where there has been heavy trucking. These observations as well as theory suggest that this velocity corresponds to a compacted sand and gravel.

The third group, with velocities around 5000 fps, is probably sand and gravel saturated with water (the top of this layer is the water table). This value is about the same as the velocity of water as theory for a granular medium implies. Also in accord with theory is the observation that the velocity of this layer is higher, the higher the velocity of the overlying dry layer is. This phenomenon logically results from greater compaction of the medium. A possible alternative explanation for this layer is that it is a dense glacial till. This explanation is opposed by several observations. One is the apparent absence of till in this area despite many deep exposures. Another is good agreement with well data (for example lines 13 and 14 and wells 7 and 8; note, however, disagreement between line 4 and well 10). The deep Dover well (well 14) at the south end of the pond encountered only sand and gravel.

The fourth group, with velocities ranging from about 7000 to over 20000 fps, almost certainly represents bedrock. Good agreement with well data (lines 7, 9, 11 and 24 with wells 5, 6, 14 and 13) and the simple smooth contours of this surface support this interpretation. Examination of the distribution of these velocities shows that there are two distinct subgroups within this group. Low values, 7000 to 10000 fps, are found on the north and south parts of the map (Figure 3). Higher values, 11000 to 21000 fps, occur in a roughly east-west band across the center of the area. These variations and distributions may be caused by several factors.

An important technical factor is that small errors in travel-time measurement lead to large errors in velocities when the velocities are high. This effect is most serious when the lines are short relative to bedrock depth. Another possible factor is velocity anisotropy; in layered rocks the velocity often varies according to whether it is measured parallel to or across the layers. In this case the apparent absence of variation with direction of seismic lines indicates that this effect is not dominant here. Another explanation is that different layers of the bedrock have different seismic velocities. The bedrock here is a metamorphosed marine sediment, the Berwick Formation (Novotny, 1969). In this area the bedrock layers have been folded, and then eroded, so that they stand on edge and run roughly east-west. Thus the east-west band of high velocities corresponds to a layer of intrinsically higher velocity. Another explanation is that the low velocities correspond to badly weathered and fractured bedrock whereas the high velocities correspond to massive solid bedrock (rock with velocities below about 7000 fps are often "rippable" by earth-moving machinery).

Another question not answered by these measurements is whether or not layers of peat occur in the area. This material is said to have been encountered during construction in the largest gravel pit (Bruce Graves, personal communication). In this area seismic signals were commonly weaker than elsewhere; this would tend to suggest such a material.

The most prominent feature on the bedrock elevation map (Figure 3) is a deep straight valley running across the area from northwest to southwest. A similar valley was found by drilling at an area called The Hoppers, 2 miles northwest of here (Anonymous, 1971). The valley is about 1000 feet wide, at the 75 foot contour, except for a constriction near line 35. The valley appears to slope gently northward and steeply southward from this point. Seismic lines are too far apart to tell if the deepest part of the valley has been found or if this reversal of slope is real. The present form and direction of the valley suggest that it is a result of the southeastward flow of glacial ice over this part of New Hampshire (Goldthwait et al., 1951). A glacial valley can have reversed gradients (as in Figure 3); more intense erosion where basal ice flows uphill might account for the extreme depths at the north part of the area. One may speculate that the valley was originally cut by an ancestral, preglacial, Bellamy River. The present channel is cut into bedrock, elevation 110 feet, in a narrow gorge at the site of the dam on Mill Hill Road.

A second prominent feature of the bedrock topography is a line of high elevations running roughly from northeast near lines 32 and 30, to southwest, near line 36. Along this trend the buried valley narrows, near lines 17 and 20, and seismic velocities are higher than on either side. To the west, outside the study area but shown in Figure 1, one can trace, along the strike of the rock, a line of hills and the narrow gorge of the Bellamy River. East of the study area this trend is not shown by the topography but might be continued underground; this could have important consequences for ground water flow. A possible explanation for the higher bedrock, narrow valleys and gorges, and high seismic velocities is that this layer of bedrock is denser, less weathered and fractured, and less susceptible to erosion by running water and ice than the layers on either side.

The hills on either side of the buried valley have very different subsurface structure. West of the valley the hills owe their height mainly to high bedrock elevation with only a thin overburden, East of the valley, on both sides of the pond, the bedrock is deep and the hills are composed of very thick deposits of sand and gravel.

Barbadoes Pond itself lies over a small bedrock depression (there are no seismic data over the pond but water depth is great enough to reveal the existence of a depression). This depression is apparently open to the northwest (near line 15) and closed to the southeast (near lines 40 and 41). Thus the pond is not maintained solely by precipitation and evaporation from its surface and from its watershed. Since kettle ponds are formed by burial and subsequent melting of stagnant glacial ice, it is interesting to speculate that in this instance stagnation was favored by the configuration of the bedrock. It seems plausible that ice would preferentially stop and become isolated in a dead-end depression open toward the direction from which the ice was flowing.

A final important feature of the bedrock topography is a second buried valley lying east of, and parallel to, the major valley.

The map of water table elevation shows several important features (Figure 4). The most prominent is a general north to south decrease in elevation. In the extreme north, along the dike that forms the surface divide between the Bellamy Reservoir and the Barbadoes Pond drainage (near lines 43, 27, 45 and 44) the water table elevation ranges from

135 to 139 feet. The nominal elevation of the Bellamy Reservoir is 135 feet, the height of the dam on Mill Hill Road. In the extreme south, at line 25, water table elevation decreases to 102 feet. From here to the Bellamy River, less than half a mile farther south, the water table must slope very gently since the elevation of the river exceeds 95 feet. This southward water table slope implies a generally southward flow of ground water; the high water table at the north end, higher than either the pond or the reservoir, suggests that at present a ground water divide occurs in the northern part of the area.

The water table gradient greatly increases over the southern part of the large buried valley (southwards from line 19). At least two explanations are possible. One is that the southern part of the channel is partially filled with a low permeability clay so that a greater pressure gradient is required to maintain a given flow of ground water. Slight evidence for such a material is the presence of clay in well 8 and a small perched water body near line 21. Objections to this evidence is the flatness of the water table near well 8 and the fact that the small perched pond, and thus the clay that supports it, are well above the regional water table. Also, the valley at the Hoppers has clay at depth. An alternative explanation is that a high gradient is required to maintain flow through an aquifer which gets smaller to the south. This decrease is partly a consequence of general decrease in water level, which means that more of the flow is confined to the buried valley, and partly to the previously noted decrease in valley width. It would be interesting to pursue these ideas with detailed calculations.

Under the hills west of the buried valley the water table rather closely follows the surface topography. This no doubt is because these hills, as discussed above, are mainly bedrock. Taken together, these two observations suggest that bedrock in this region has low permeability. In marked contrast is water table under the hills on either side of Barbadoes Pond. Here, where data are scarce, water table appears to be very deep and almost independent of surface topography. This indicates the hills are composed of a high permeability material such as sand; this is what the seismic measurements show.

Barbadoes Pond appears to be slightly higher than the surrounding water table, at least along the southwest side (near lines 15 and 19). The implied steep gradients in the water table near the pond imply a low permeability bottom under the pond; this might be partly bedrock and partly a lake clay. Pumping tests on the Dover well (well 14) at the southeast end of the pond indicate this also (Francis Hall, personal communication). East of the pond water table is slightly above pond elevation although here data are very sparse. This suggests that ground water enters the pond along the northeast side and leaves along the southwest side.

Thickness of overburden, or unconsolidated sediment above bedrock, is shown in Figure 5. (This map was drawn from the seismic and well data as well as by graphical subtraction of Figure 3 from Figure 2). The major features previously discussed are well displayed. Both the main buried valley and the smaller valley to the east contain over 100 feet of sediment. The hills west of the main valley have less than 25 feet of overburden. East of Barbadoes Pond the hills are underlain by over 75 feet of sediment. Greatest sediment thickness, 190 feet, occurs at the extreme south end of the area where the buried valley lies under a topographic high (well 12).

Magnetic anomalies over Barbadoes Pond are shown in Figure 6. The most important feature is the northeast-southwest trend of the magnetic highs and lows. This is the direction of the strike of the vertically dipping bedrock layers. In the absence of strong evidence for much relief on the bedrock beneath the pond, these anomalies are attributed to variations in the magnetization of the various bedrock layers. The minerals most likely to cause such variation are magnetite (an iron oxide) or pyrrhotite (an iron sulphide). Detailed model calculations (Birch, unpublished), guided by measurements of magnetic susceptibility of samples of the Berwick formation, were made for the 15 gamma positive anomaly running across the center of the pond. Results indicate a bedrock source layer about 40 to 80 feet below pond level and about 160 feet wide. This depth corresponds to a bedrock elevation of 52 to 92 feet; this agrees roughly with seismic results near the shores of the pond.

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TABLE I SUMMARY OF SEISMIC RESULTS

V1, V2, V3 and V4 are seismic velocities in the subsurface layers.

E1, E2, E3 and E4 are the elevations above sea level of these layers.

NUMBER	V1	V2	V3	V4	E1	E2	E3	E4
#1 J	1210.	5126.			145.	135.		
#2 J	1042.	2174.	7547.		162.	158.	122.	
#3 J	1250.	1917.	4864.	9585.	190.	173.	135.	72.
#4 J	1339.	1840.	4286.	9676.	167.	156.	131.	68.
#6 J	1250.	1648.	5040.	10513.	173.	161.	126.	84.
#7 J	1250.	11746.			181.	162.		
#8 J	1250.	5263.	11719.		162.	152.	140.	
#9 J	1300.	4190.	14342.		163.	156.	134.	
#10	1230.	3030.	8219.		154.	126.	75.	
#10A	1442.	3030.	8218.		154.	120.	72.	
#11	1205.	4997.	8156.		150.	120.	62.	
#12	1316.	4615.	33333.		140.	135.	73.	
#13	1190.	7842.	13792.		149.	142.	66.	
#14	1316.	4938.	15510.		144.	135.	37.	
#15	1290.	3809.	5961.	17004.	138.	124.	61.	13.
#16	1923.	4054.	13295.		141.	113.	74.	
#17	1695.	13331.			148.	112.		
#18	1339.	2246.	4401.	7927.	195.	173.	129.	80.
#19	1271.	4997.	12238.		140.	129.	72.	
#19A	1271.	4997.	20353.		140.	129.	49.	
#20	1563.	6665.	28420.		143.	128.	102.	
#21	1389.	4839.	18740.		153.	127.	75.	
#22	1324.	2077.	5239.	8781.	156.	141.	102.	54.
#23	1220.	3633.	11346.		137.	116.	91.	
#24	1212.	2395.	13331.		182.	171.	115.	
#25	1116.	2053.	4800.	13714.	145.	138.	102.	33.
#26	1226.	5471.	14833.		127.	112.	72.	
#27	1563.	4615.	5473.	10910.	145.	139.	108.	-13.
#28	1625.	2500.	4769.	20768.	167.	161.	149.	102.
#29	1351.	2126.	13315.		157.	152.	135.	
#30	1250.	1931.	7388.		180.	164.	102.	
#31	949.	2020.	8861.		180.	177.	106.	
#32	1220.	2160.	18161.		148.	135.	106.	
#33	1630.	4054.	10697.		127.	115.	65.	
#34	1136.	3355.	29401.		137.	131.	103.	
#35	1184.	1561.	6544.	14288.	156.	146.	112.	50.
#36	962.	2019.	15975.		196.	190.	148.	
#37	1351.	9077.			174.	158.		
#38	943.	1770.			155.	149.		
#39	1047.	1762.	6903.		147.	139.	109.	
#40	1136.	2597.	8645.		140.	132.	109.	
#41	1333.	3224.	10502.		138.	123.	87.	
#42	1207.	2373.	9332.		135.	127.	99.	
#43	1282.	2284.	4996.	8426.	145.	140.	127.	98.
#44	1136.	5263.	8500.		145.	137.	109.	
#45	1402.	4687.	7893.		145.	138.	80.	

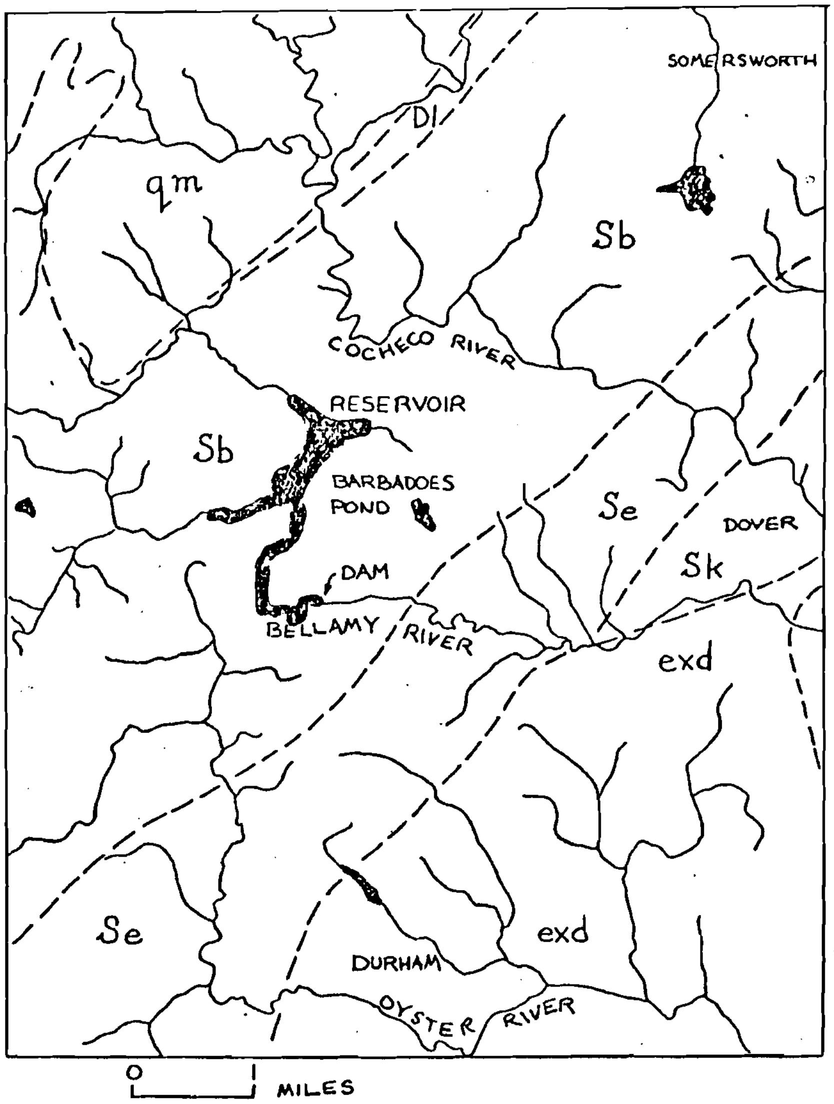
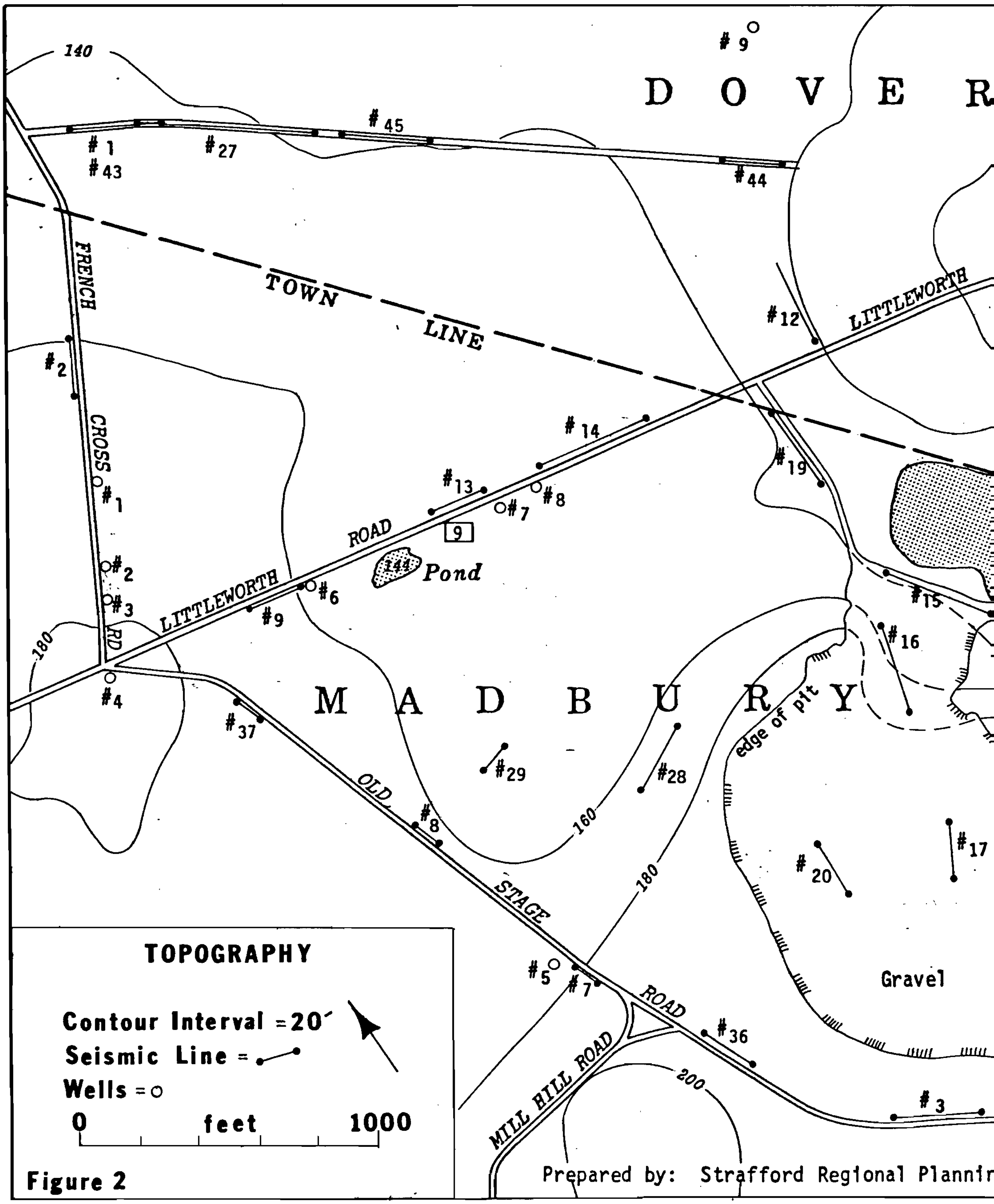


Figure 1. Surface drainage and bedrock geology (adapted from NOVOTNY, 1969). Dashed lines show contacts between formations.

qm: Devonian (?) quartz monzonite
exd: Devonian (?) Exeter diorite
Dl: Devonian (?) Littleton formation
Sb: Silurian (?) Berwick formation
Se: Silurian (?) Eliot formation
Sk: Silurian (?) Kittery formation



DOVER
MADBURY
TOWN LINE
FRENCH CROSS RD
LITTLEWORTH ROAD
LITTLEWORTH
OLD STAGE ROAD
MILL HILL ROAD
Pond
144
9
edge of pit
Gravel
140
160
180
200
9
45
1
43
27
44
12
2
14
13
8
7
19
1
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3
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16
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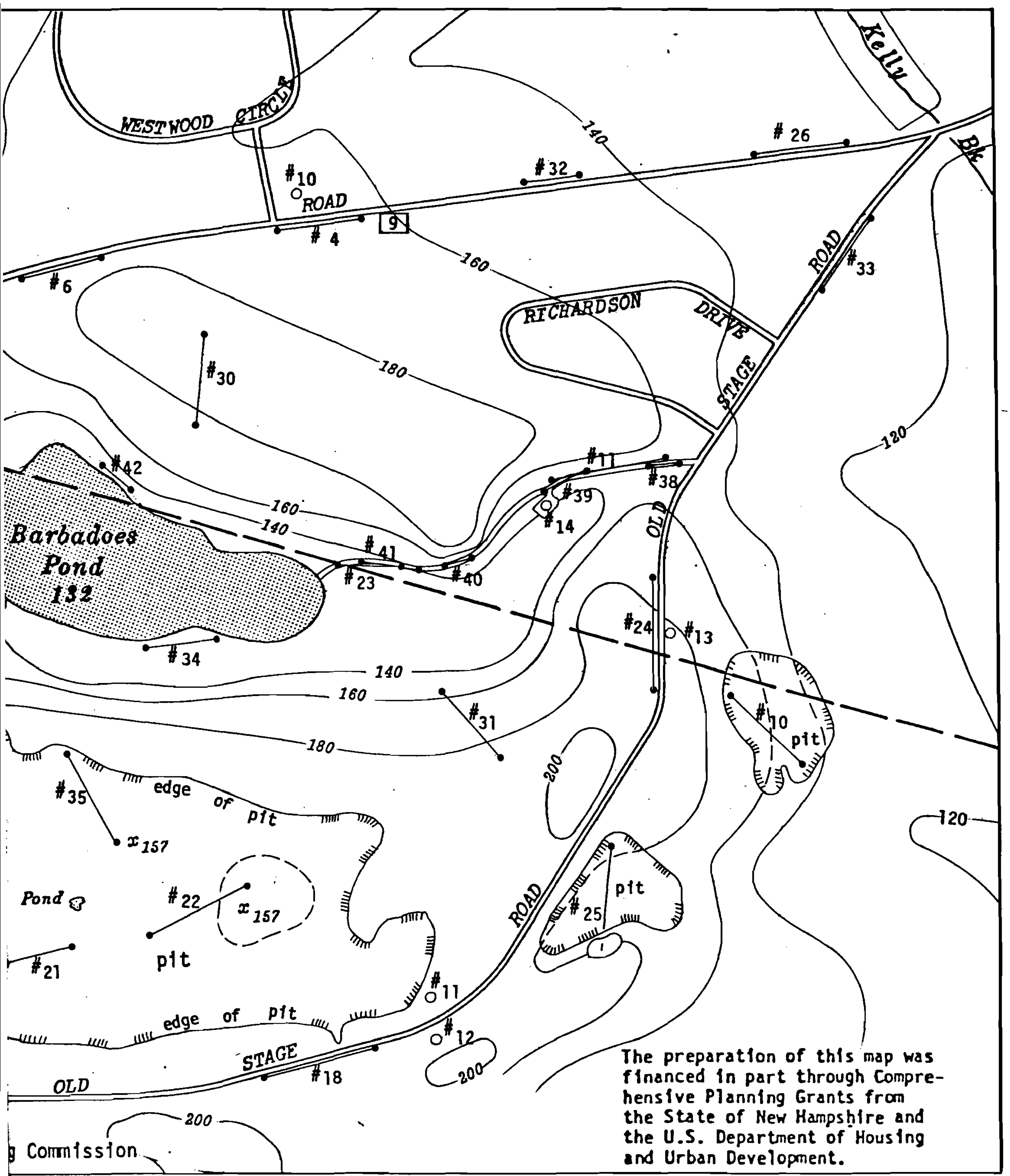
TOPOGRAPHY
Contour Interval = 20'
Seismic Line =
Wells =
0 feet 1000
Prepared by: Strafford Regional Plannir

Figure 2



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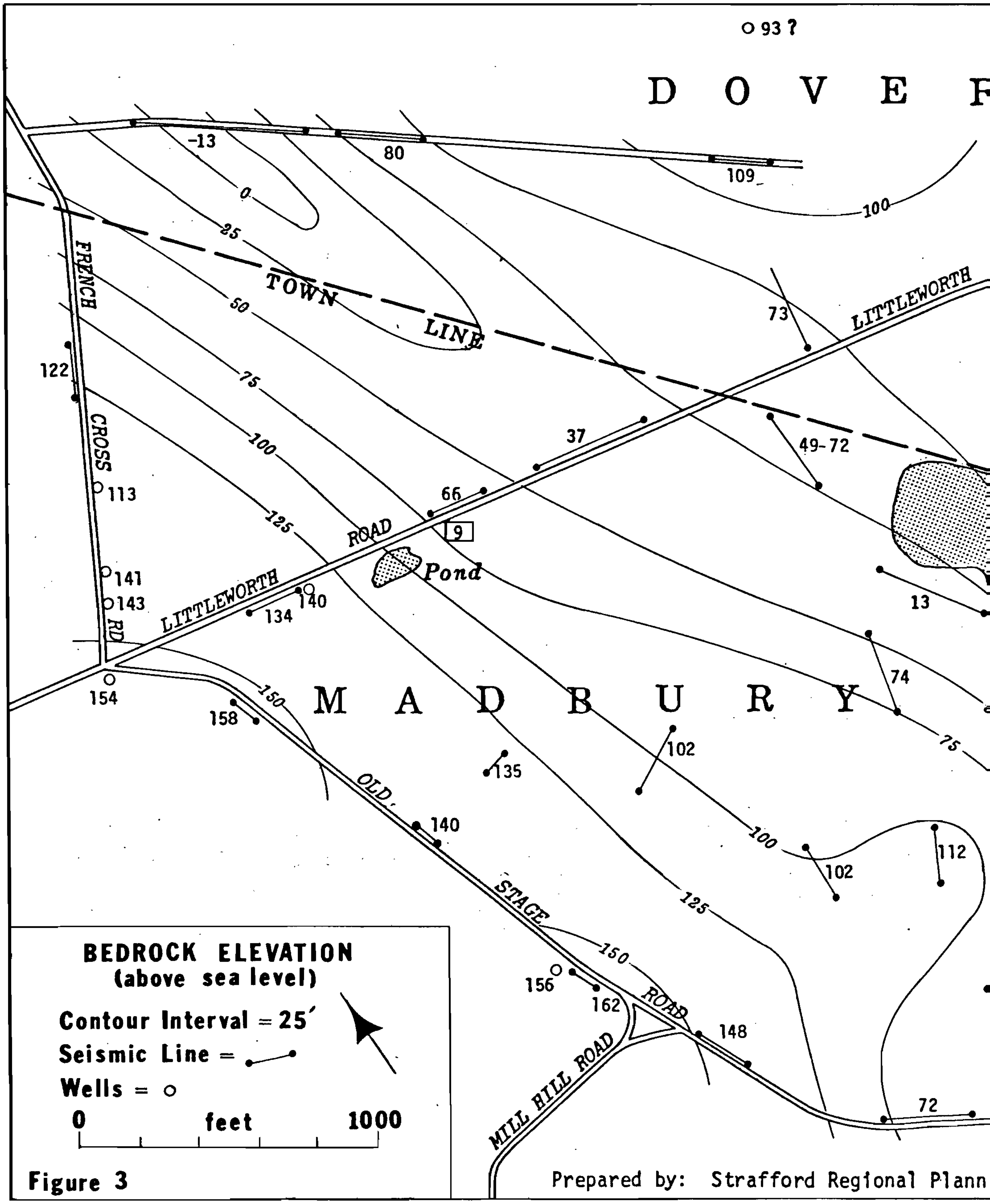
DOVER
MADBURY
TOWN LINE
FRENCH CROSS RD
LITTLEWORTH ROAD
OLD STAGE ROAD
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Pond
9
BEDROCK ELEVATION
(above sea level)
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0 feet 1000
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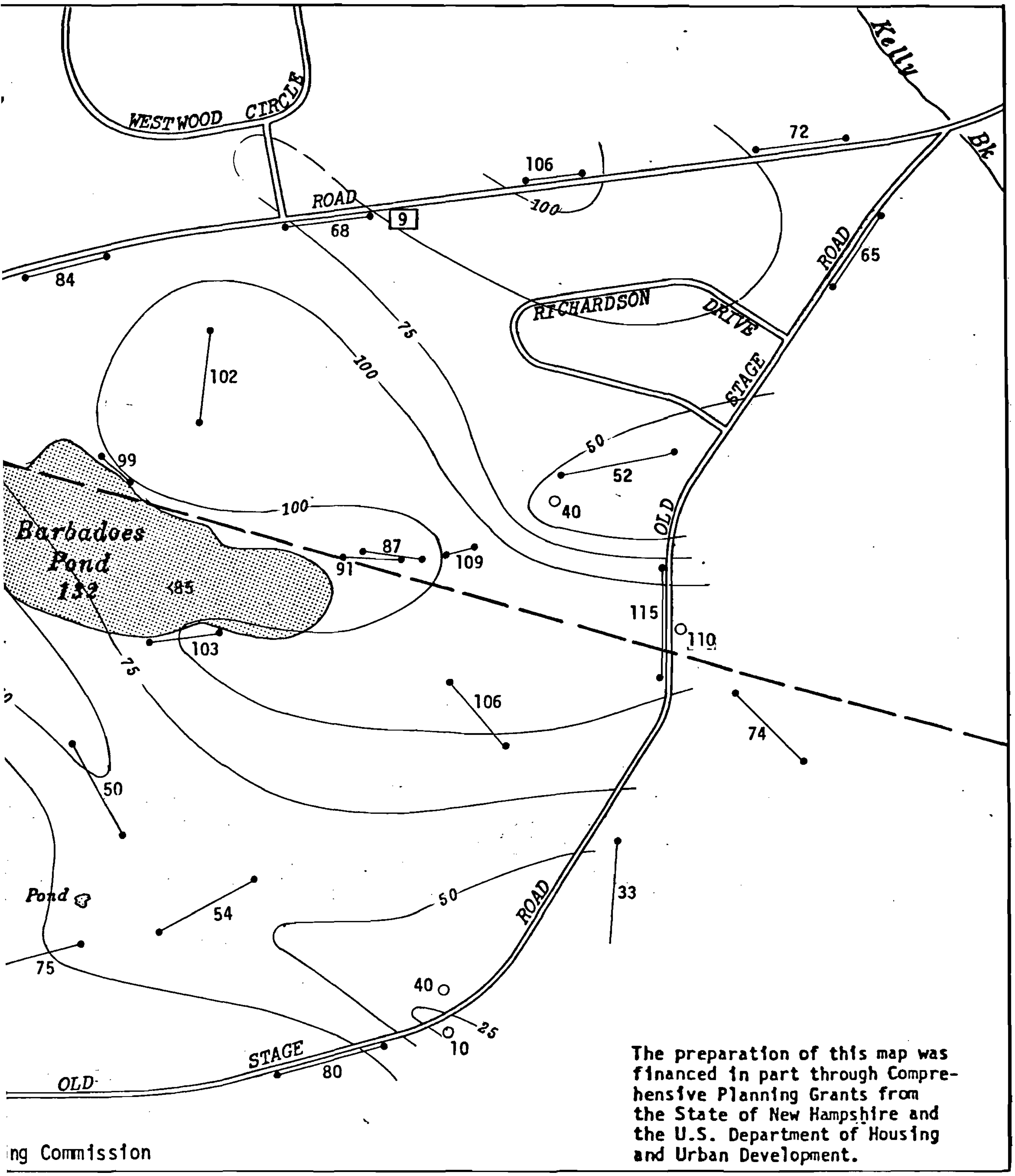
Figure 3



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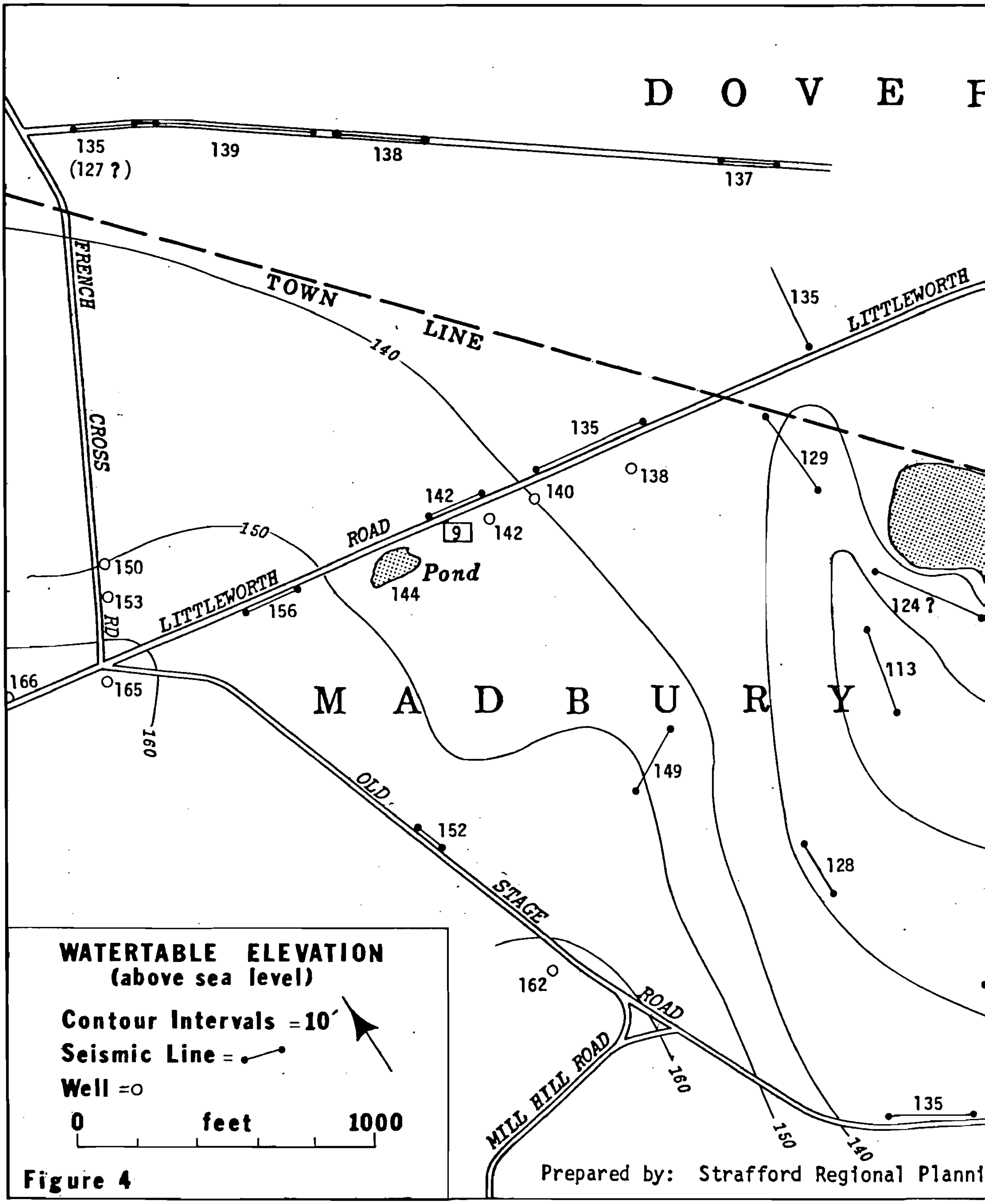
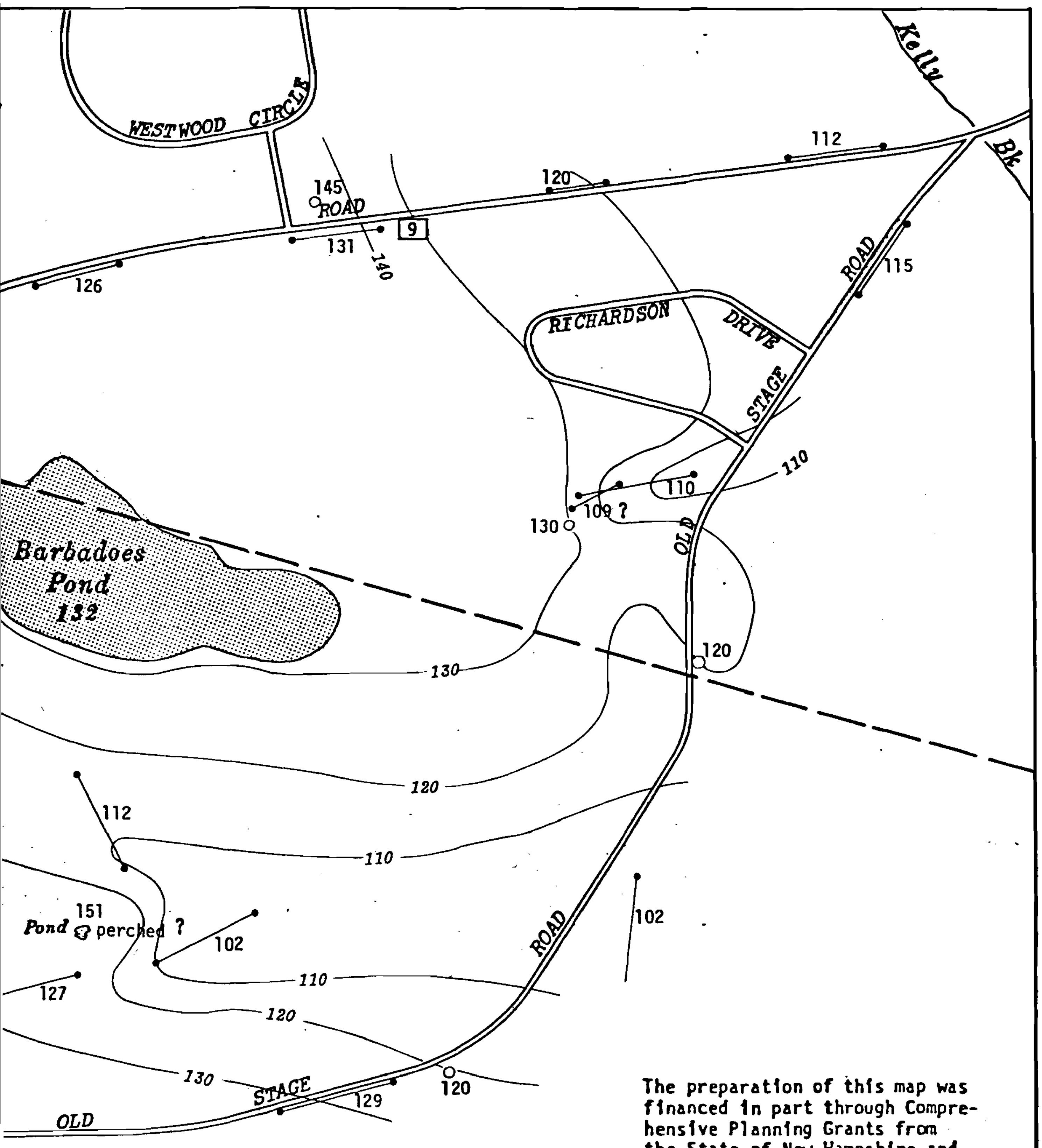


Figure 4

Prepared by: Strafford Regional Planni



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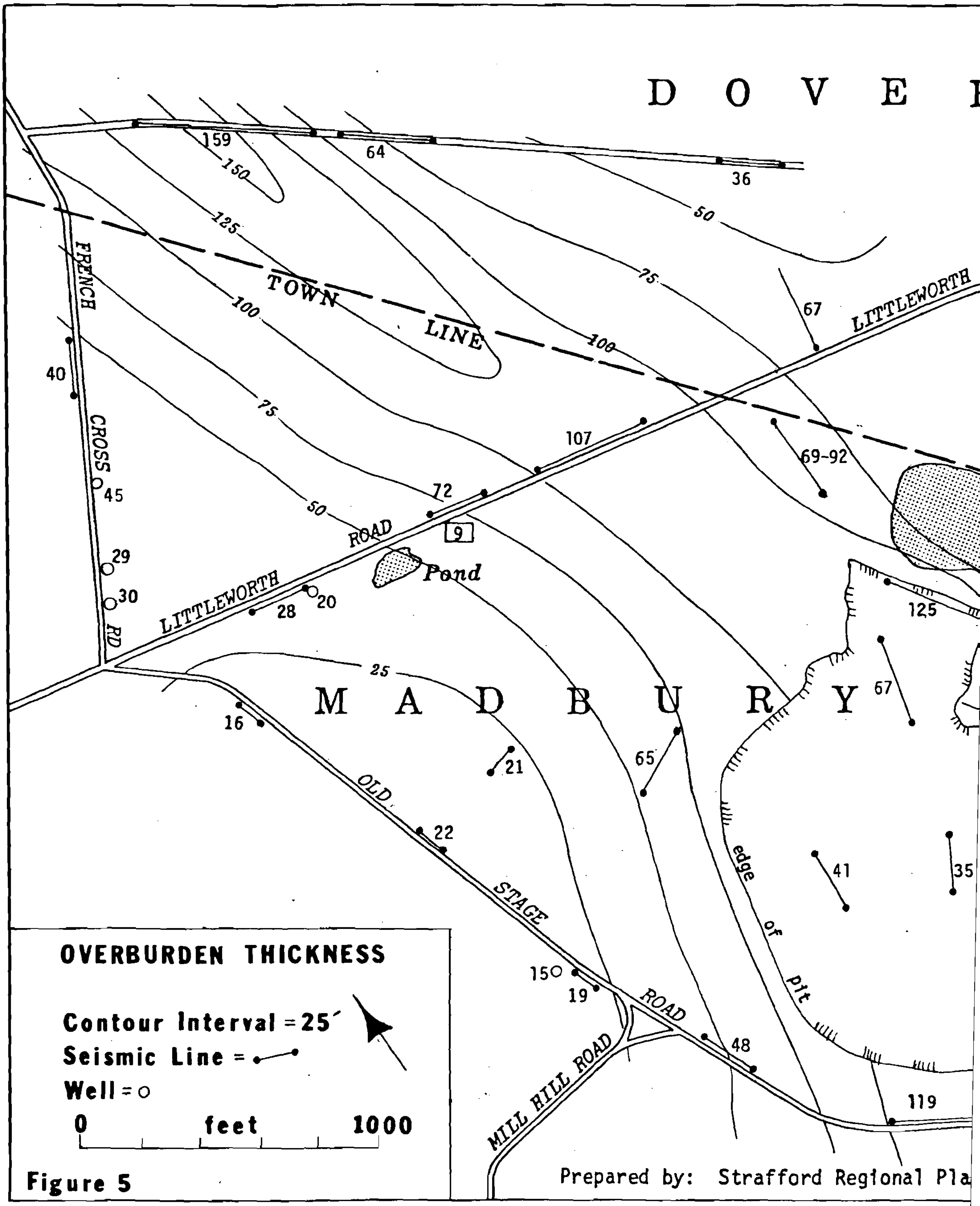
D O V E
M A D B U R Y
TOWN LINE
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LITTLEWORTH ROAD
LITTLEWORTH
OLD STAGE ROAD
MILL HILL ROAD
Pond
edge of pit
159
150
125
100
75
50
25
64
36
67
107
69-92
72
9
40
45
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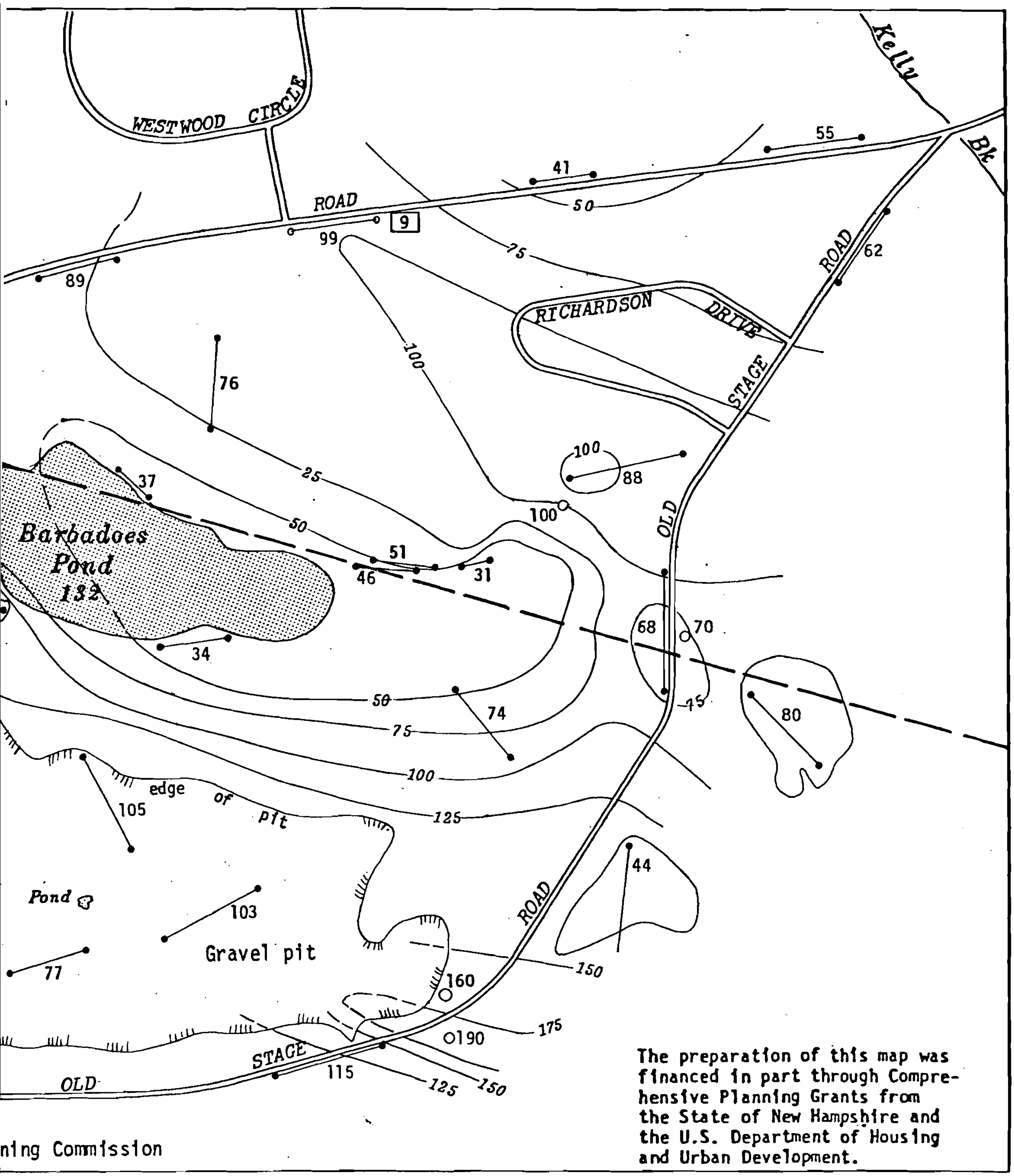
OVERBURDEN THICKNESS
Contour Interval = 25´
Seismic Line =
Well = o
0 feet 1000
Prepared by: Strafford Regional Pla

Figure 5



The preparation of this map was financed in part through Comprehensive Planning Grants from the State of New Hampshire and the U.S. Department of Housing and Urban Development.

SECTION V LIMNOLOGY

by

Alan L. Baker and James F. Haney

In this section of the Barbadoes Pond Report, the characteristics of the basin will be reviewed from the point of view of biological limnologists.

Geology and Morphometry

The shape and size of Barbadoes Pond are typical of what are called "kettle holes" or "ice-block depressions". Such basins were formed by the melting of residual blocks of glacial ice buried beneath outwash from the last receding glaciers. The process of melting of the buried block may have taken from 1000 to 2000 years after glacial retreat. Thus, the age of the basin is approximately 8000-9000 years.

A shape and bottom contour map for Barbadoes Pond is given in Figure 1, and the variation of area with depth is shown on Figure 1A. Also, the change of the mud/water ratio with depth is displayed on Figure 1B. The metric system is used herein, and the appropriate conversion factors are 1 meter (m) = 3.281 feet and 1 hectare (ha) = 2.471 acres.

The pond shoreline is relatively simple, lacking extensive bays or peninsulas, and there are no islands (Figure 1) as indicated by the low shoreline development index of 1.33. This index gives a numerical value associated with shoreline development. A circular lake has a shoreline development of 1.00, whereas complex lakes with extensive embayments (e.g. Lake Winnipesaukee) have values in excess of 4.00 or 5.00

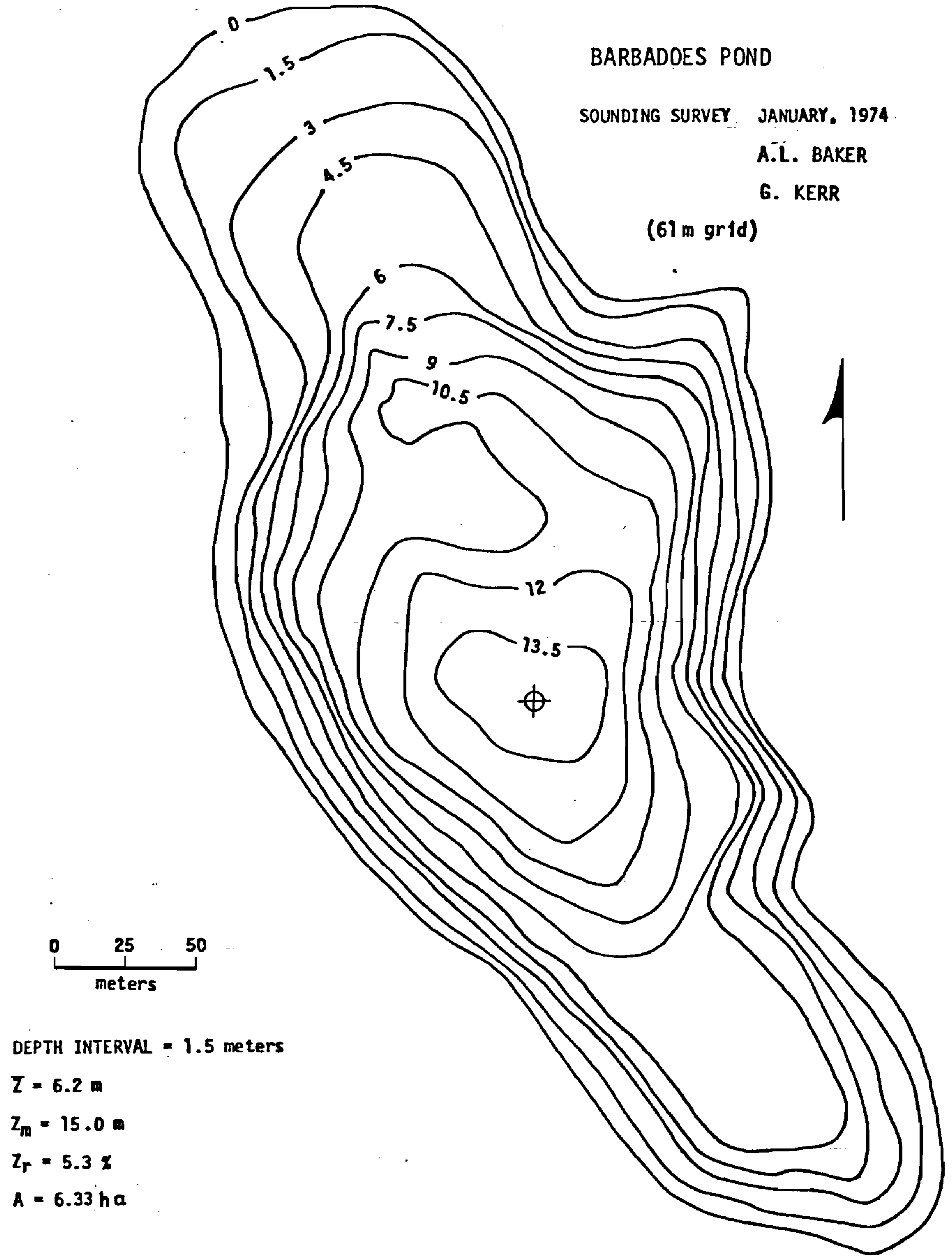


FIGURE 1. BARBADOES POND, TOWN OF MADBURY, STRAFFORD COUNTY, NEW HAMPSHIRE

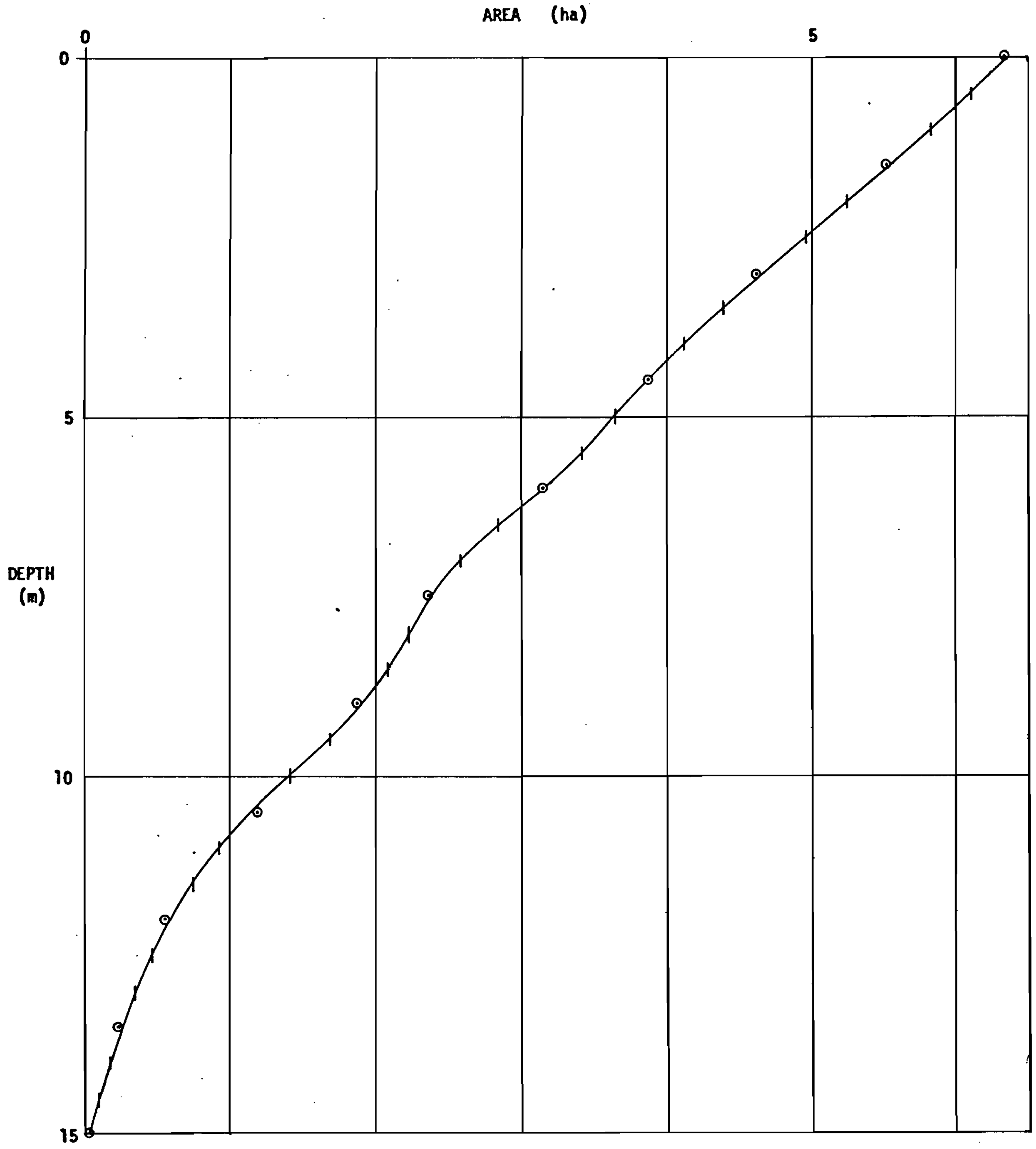


FIGURE 1a. VARIATION OF AREA WITH DEPTH FOR BARBADOES POND

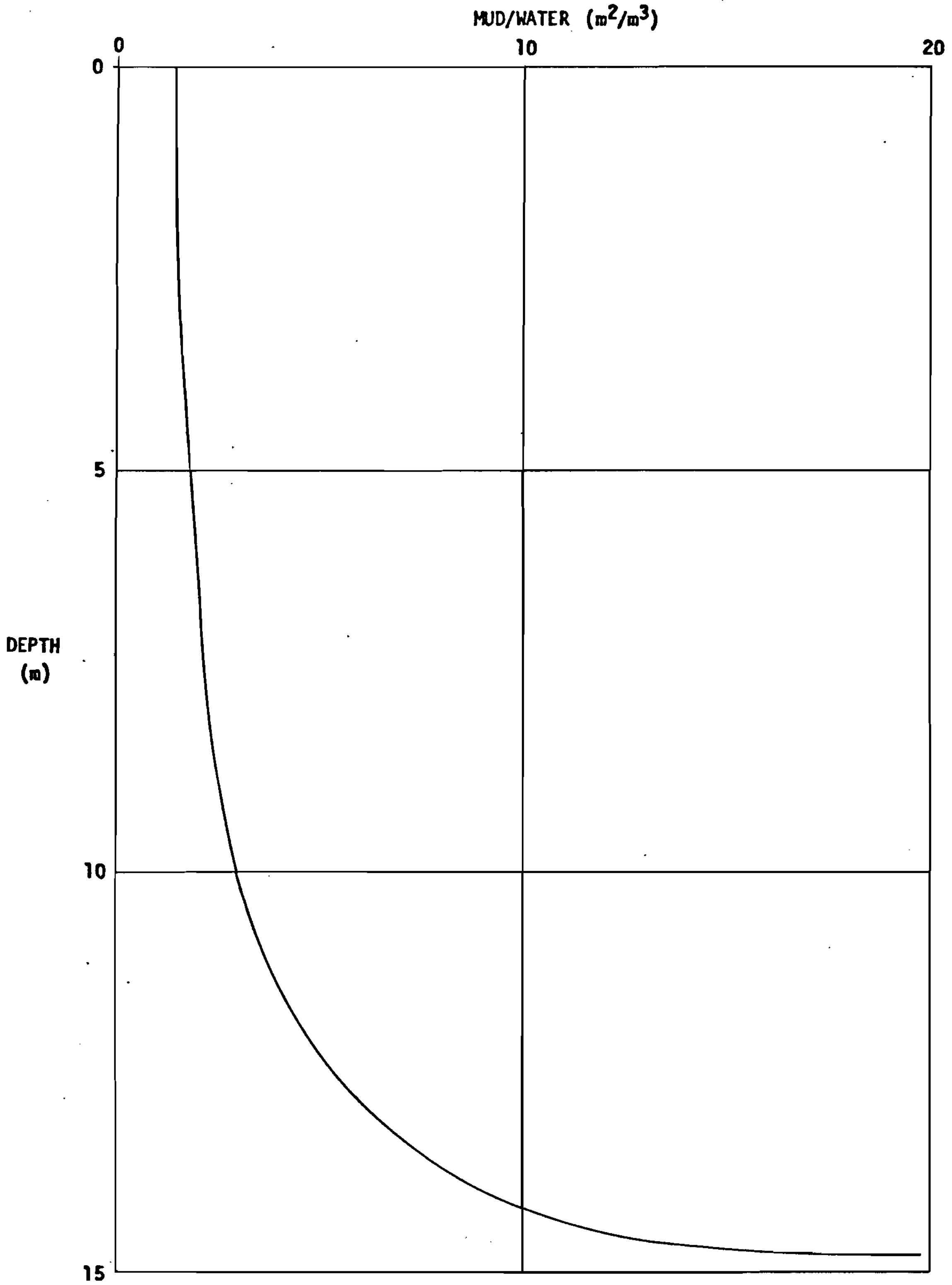


FIGURE 1b. VARIATION OF MUD/WATER RATIO WITH DEPTH FOR BARBADOES POND

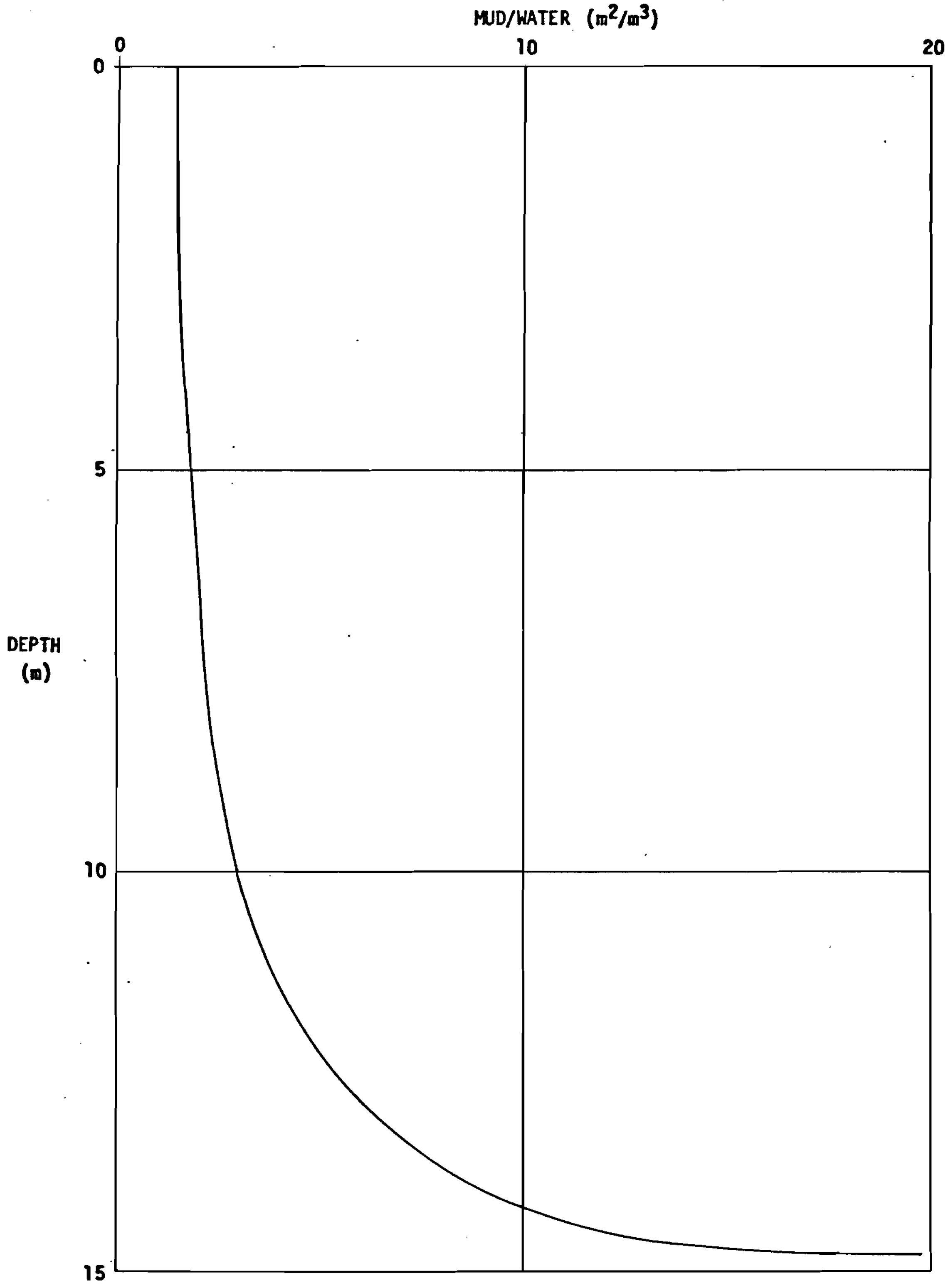


FIGURE 1b. VARIATION OF MUD/WATER RATIO WITH DEPTH FOR BARBADOES POND

The length of the lake is less than 500m and the width is only 200m. Similar to other ice-block depressions, Barbadoes is deep relative to its small area. It has a maximum depth of 15m, and an average depth of 6.3m, with both values being much greater than those found in lakes of a similar size that formed in other ways, such as ox-bow lakes, beaver meadows, and impoundments. These depth characteristics influence the water quality as is discussed below. Several morphometric characteristics of the basin are summarized in Table 1.

Sediments

The nature of the sediments, or bottom deposits, is known only from surficial observations to date. Near-shore sediments are derived from the upland surrounding the basin, and consist of coarse, clean outwash sand originally deposited in the region at the end of the last glacial retreat. The bottom contours of the basin suggest that the rate of erosion close to and deposition in the pond have been accelerated along the northwest shore, although verification of this would require an investigation of sediment cores.

Sediments at pond depths of 1 to 4m are overlain with coarse debris derived from the uplands, such as pine needles, pine cones, alder "cones" and branches, and leaves from several kinds of angiosperm trees. The sediments in these regions are a mix of sand, silt, and organic detritus.

The sediments at pond depths greater than 4m are typical lake deposits, highly organic, and comprised of silt-sized particles derived mainly from microorganisms produced within the lake (algae, invertebrates, bacteria) and from wind-blown pollen and dust. Such sediments are called "gyttja". Because of the apparent age of the basin, such deep-water sediments may be extensive in the region of the deep hole (Figure 1). Average sedimentation rates in basins

Table 1

COMPARATIVE MORPHOMETRY[1]

	Barbadoes	Winnisquam (Lower Sub-basin)	Newfound
Area (acres)	15.42	740.13	4105.1
(hectares)	6.24	299.53	1661.29
Max. Depth (ft)	49.2	58.0	182.0
(m)	15.0	17.7	55.47
Mean Depth (ft)	20.5	18.4	65.0
(m)	6.25	5.6	19.81
Volume (ft^3)	13,775,325.0	592,084,060.24	11,620,575,695.1
(m^3)	390,125.34	16,766,839.30	329,101,549.0
Shoreline Length (ft)	3866.9	32,000.0	104,544.0
(m)	1178.6	9753.6	31,865.01
Development of Shoreline	1.33	1.59	-
Length (ft)	1599.49	7750.0	30,096.0
(m)	487.5	2362.2	9173.26
Width (ft)	685.49	6000.0	12,144.0
(m)	208.94	1828.8	3701.49
Mean Width (ft)	419.97	4160.34	5941.92
(m)	128.0	1268.01	1811.01
Watershed Area (acres)	-	291,655.0*	72,433.0
Elevation (MSL)	132	482*	586
Orientation	NW-SE	N-S*	NNW-SSE
Inlets	0	9*	9
Bottom Material	100% sand	30% sand * 40% gravel 30% rock	50% sand 50% rock
Shoreline	35% meadow or cultivated 65% wooded	5% swamp * 15% meadow or cultivated 85% wooded	5% swamp 15% meadow or Cultivated 85% wooded

[1] Data by planimetry and from WRRC & NHWSPCC,1974
* From Lake Winnisquam total basin

of this type are approximately 1 m/1000 years, thus we can anticipate a deposit as thick as 8m, and perhaps an additional thickness as a result of "slumping" and re-deposition of sediments from shallower depths. Both the thickness and quality of the deposits can be evaluated by core studies.

Physical-Chemical Water Characteristics

Barbadoes Pond sharply stratifies during the summer, with warm water near the surface and colder water beneath (Figure 2), as is typical for deep lakes. Generally, the shape of the temperature profile of a lake varies with lake surface area, because wind influences the degree of mixing of warm surficial water with cold underlying water. Late-summer profiles are contrasted in Figure 2 with Lake Winnisquam and Newfound Lake, both much larger than Barbadoes Pond. Especially noticeable is the thin layer of warm water or epilimnion in Barbadoes (from surface to 4 meters) while the warm-water layer in the larger lakes is approximately 10m deep. While surface temperatures of Barbadoes Pond may exceed 25^{o}C in mid-summer, the bottom water temperature never exceeds 6^{o}C.

During two periods of the year (spring and fall), the water in Barbadoes Pond mixes entirely from surface to bottom. Thus, the lake is called "dimictic" (two periods of mixing each year) and "holomictic" (complete mixing to the bottom of the water column).

As a consequence of the pattern of mixing and stratification during the year, the profiles of several chemical parameters change with the season. During the summer, dissolved gases and salts become concentrated at some depths and depleted at others. In turn, the micro-organisms within the lake respond by developing large populations where they can tolerate the water quality, and by avoiding depths where the water quality does not permit growth or survival.

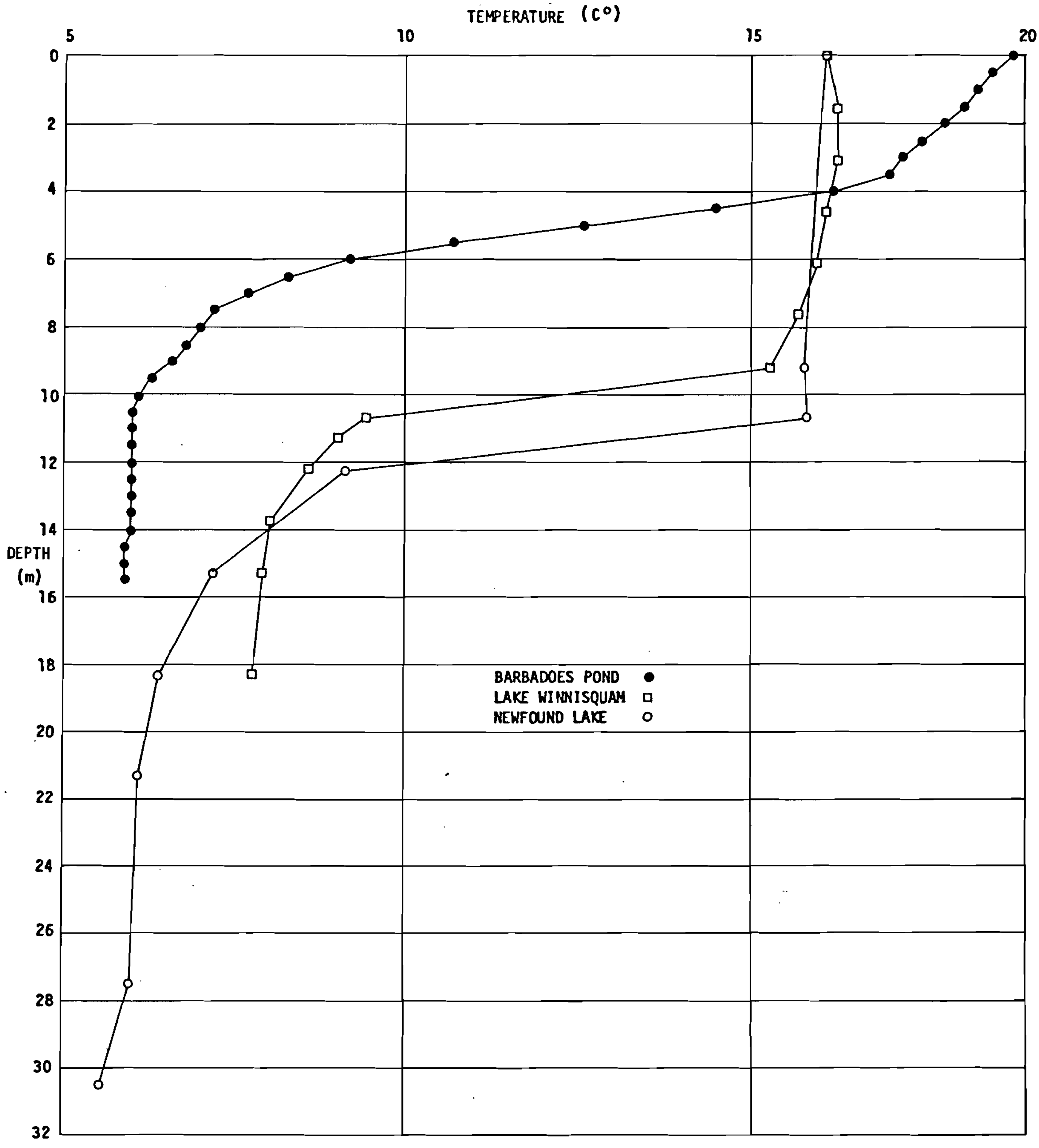


FIGURE 2. LATE SUMMER PROFILE OF TEMPERATURE WITH DEPTH FOR BARBADOES POND, LAKE WINNISQUAM, AND NEWFOUND LAKE

Only during periods of mixing can organisms and dissolved substances be found uniformly distributed throughout the lake. Late-summer profiles of selected dissolved substances reflect the thermal stratification at that time (Figure 3 and 4).

Dissolved oxygen, (O_2), is one of the most important dissolved substances for aquatic life, and profiles of its concentration reveal much about the quality and metabolism of a lake. The concentration of oxygen in Barbadoes Pond ranges from 0 to 11 ppm during the summer stratification. Maximal concentrations develop in the warm water layer at a depth of 2-3m where algae photosynthesis occurs at the highest rate. Below a depth of approximately 4 meters, the oxygen is depleted to less than 1 ppm, too low to sustain life for oxygen-requiring organisms such as fish (which generally require 3-4 ppm O_2) and microscopic algae and invertebrates. Thus, during the summer these organisms are restricted to the upper 4m or less in the oxygenated water of the lake. Only for short periods of mixing (spring and fall) does oxygen penetrate to the bottom and allow the oxygen-requiring organisms to survive at depth. The presence of anoxic (lacking oxygen) water in the hypolimnion (cold-water layer) is typical of relatively productive lakes, and is the result of respiration in the absence of photosynthesis.

Carbon dioxide, (CO_2), is another dissolved gas; the concentration of which varies inversely with that of oxygen. O_2 is produced by photosynthesis and reduced by respiration; the reverse is true of CO_2. The profile of CO_2 (Figure 3) illustrates that the gas is present in low concentration in the epilimnion and increases downward through the hypolimnion reflecting the greater decomposition in this region.

Hydrogen sulfide, (H_2S) is a third dissolved gas which indicates qualitatively

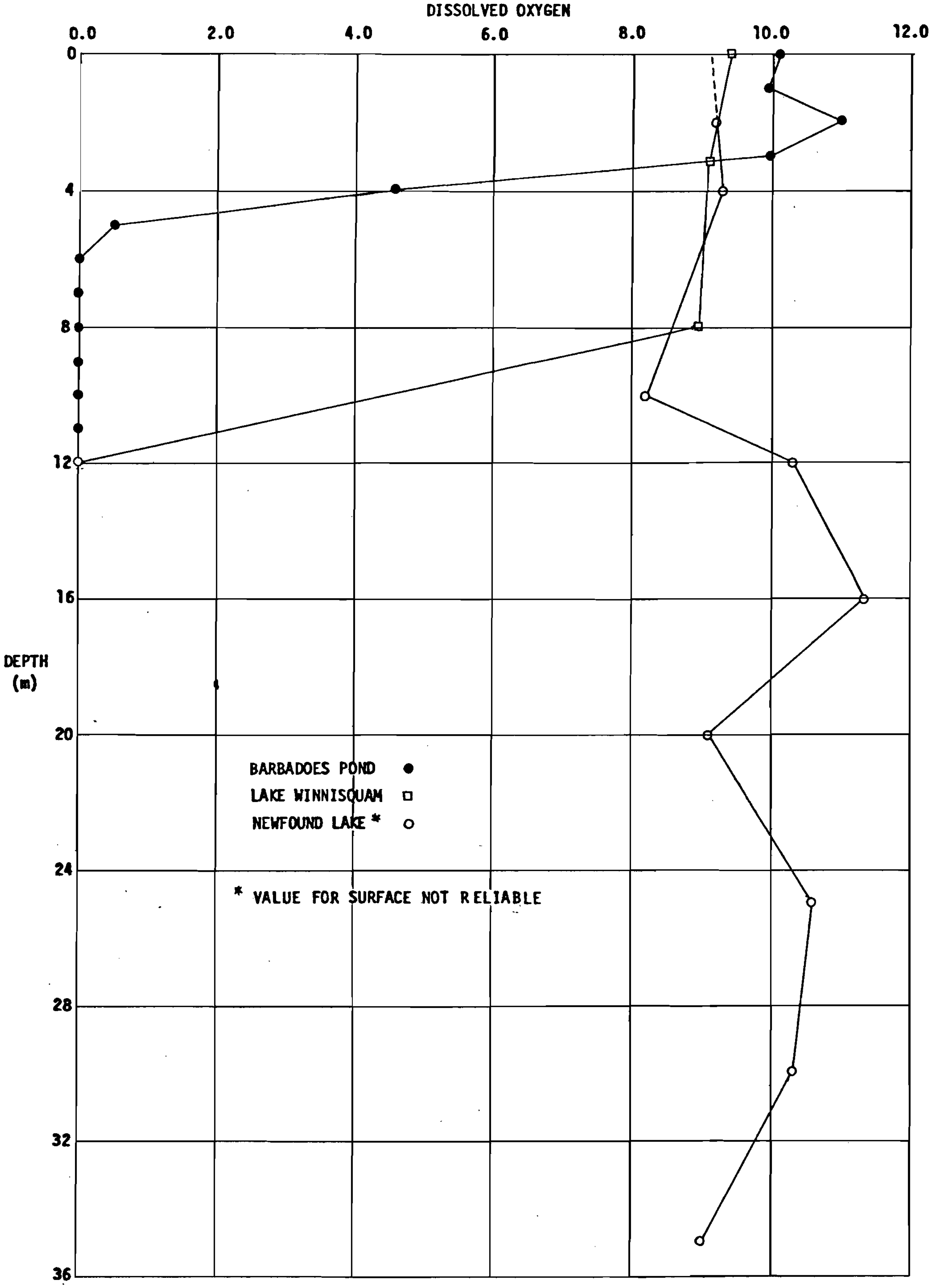


FIGURE 3a. LATE SUMMER PROFILE OF DISSOLVED OXYGEN WITH DEPTH FOR BARBADOES POND, LAKE WINNISQUAM AND NEWFOUND LAKE

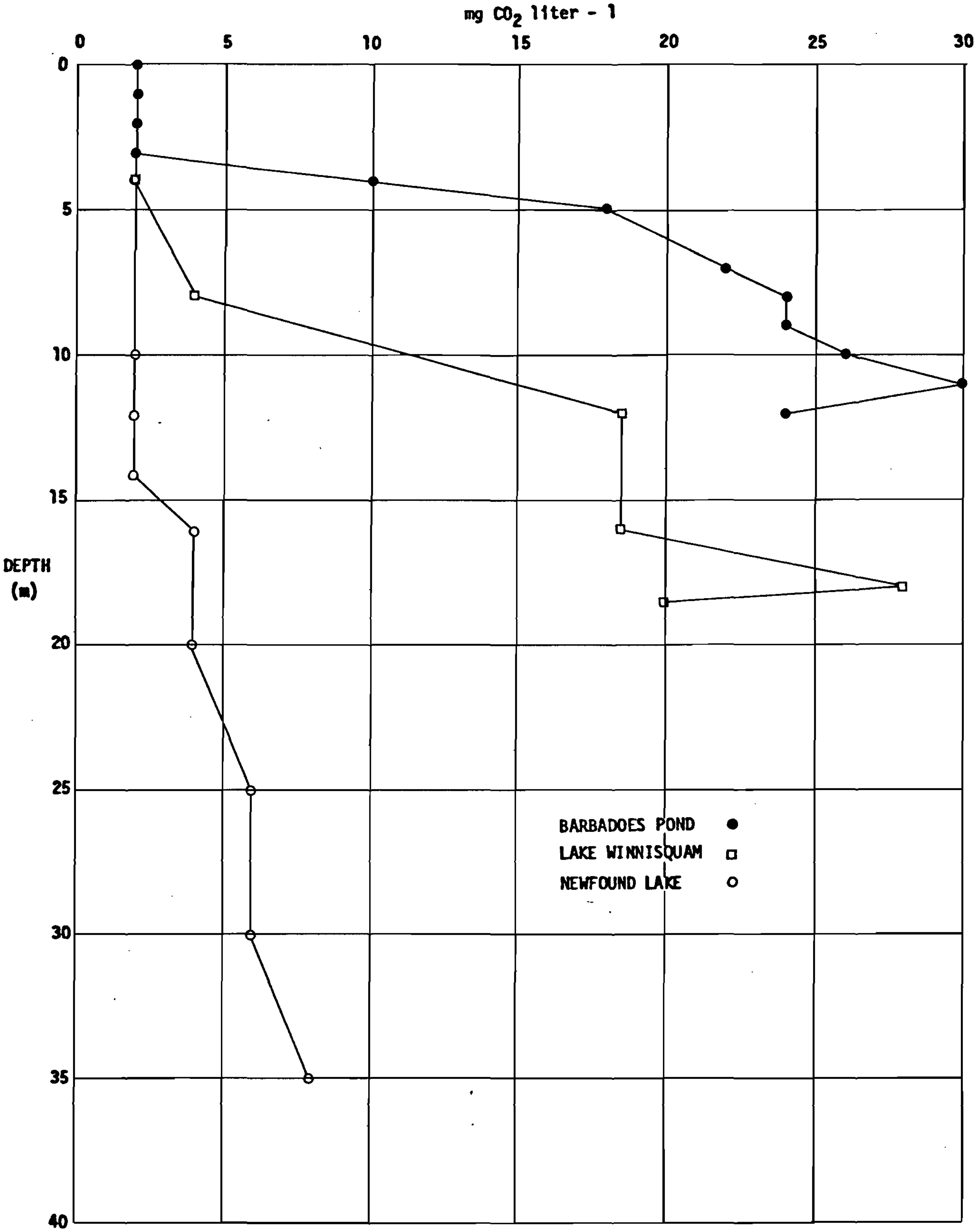


FIGURE 3B. LATE SUMMER PROFILE OF DISSOLVED CARBON DIOXIDE WITH DEPTH FOR BARBADOES POND, LAKE WINNISQUAM AND NEWFOUND LAKE the nature of lake metabolism. When the gas is present, oxygen is depleted or absent. Also, dissolved heavy metals such as iron and calcium are depleted (or protected by being attached to an organic molecule) as they form insoluble sulfide precipitates. Specialized groups of lake bacteria which can both produce and consume H_2S are found in the hypolimnion of lakes such as Barbadoes Pond.

The pH (an index of the concentration of hydrogen ion) of lake water is acidic (less than 7) in soft-water lakes of low to moderate productivity. Such is the case for Barbadoes and most New Hampshire lakes where little lime is available in the bedrock or glacial till of the watersheds. In Barbadoes, the range in pH is from 5.9 near the bottom to 6.2 at the surface(Figure 4). The higher pH value at the surface probably indicates greater algae photosynthesis in this layer. Within a lake, changes in pH are usually related to rates of photosynthesis and respiration by the microscopic algae and invertebrates. Thus, when O_2 is concentrated and CO_2 is depleted, the pH rises, and photosynthesis can be the single cause of all three changes. Respiration along reverses all three changes.

Alkalinity, which is an index of dissolved inorganic carbon as well as the hydroxide ion, is typical of soft-water lakes, being low in Barbadoes Pond (7 to 30 ppm as $CaCo_3$) (Figure 4). This reflects the absence of limestone in the watershed.

Light penetration

The quantity and quality of sunlight within a lake is dependent upon the light-absorbing qualities of the lake water. In turn, lake metabolism is dependent upon the quantity and quality of light at depth. Barbadoes Pond has brown-stained water due to the presence of dissolved organic acids (humic and fulvic

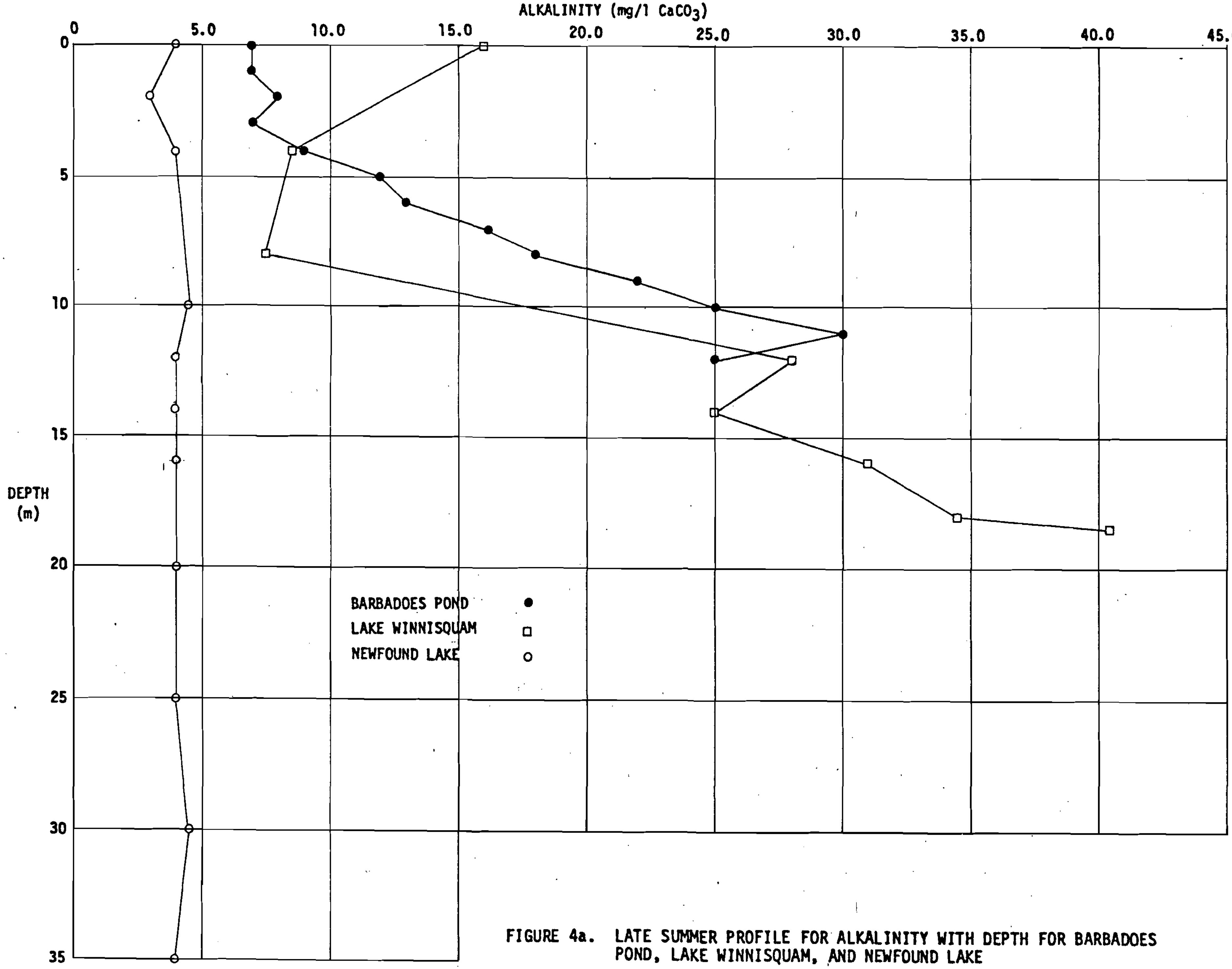


FIGURE 4a. LATE SUMMER PROFILE FOR ALKALINITY WITH DEPTH FOR BARBADOES POND, LAKE WINNISQUAM, AND NEWFOUND LAKE

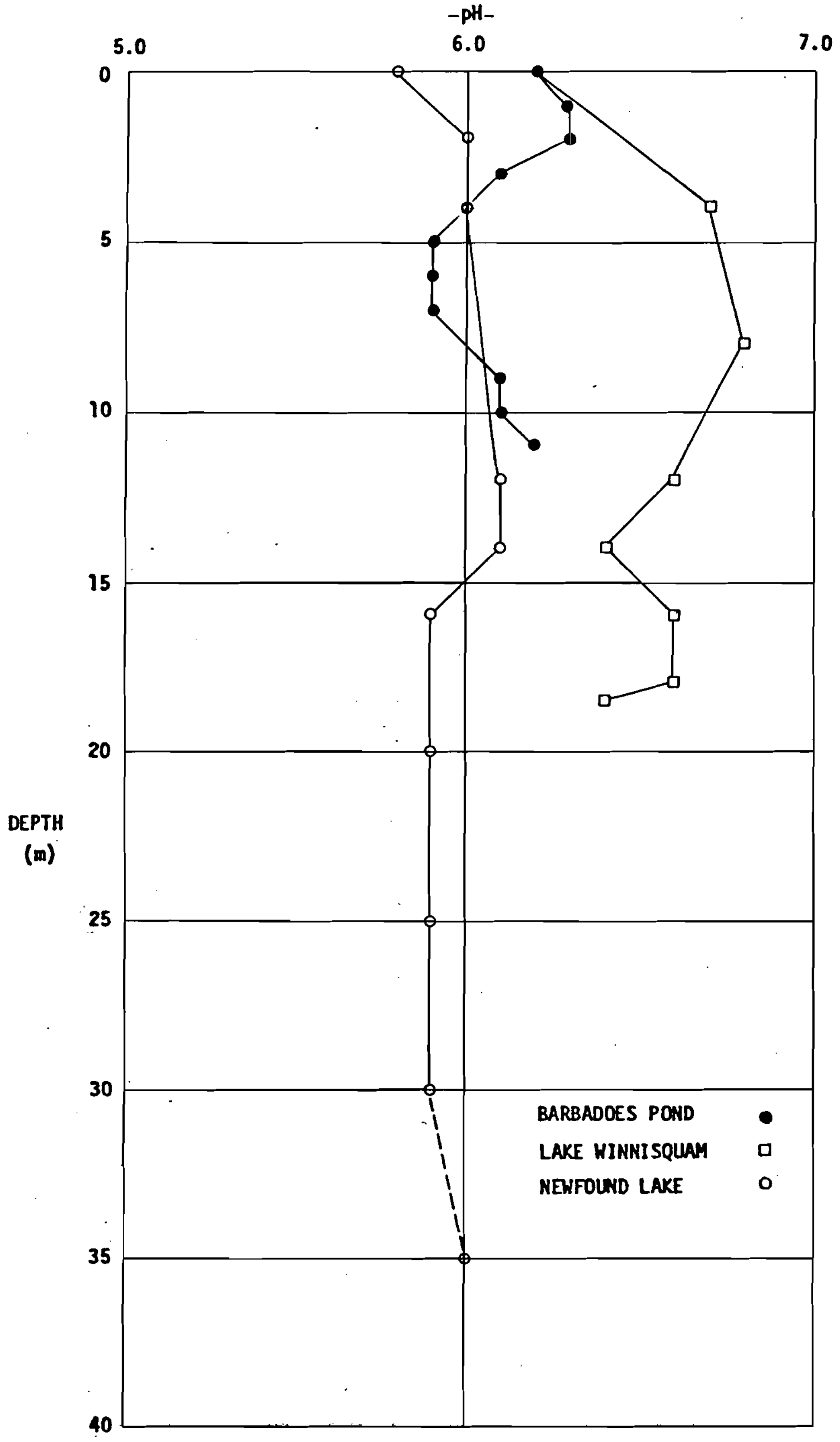


FIGURE 4b. LATE SUMMER PROFILES FOR pH WITH DEPTH FOR BARBADOES POND, LAKE WINNISQUAM, AND NEWFOUND LAKE

acids). Thus, it would be called "dystrophic". The brown-stained water absorbs sunlight rapidly so that penetration of sunlight is restricted (Figure 5) in contrast to the sunlight penetration in clear-water lakes such as Winnisquam and Newfound (which is the clearest lake in New Hampshire). While the dissolved organic acids are responsible for most of the high rate of sunlight absorption, suspended particles (living and dead) also contribute to the absorption in Barbadoes Pond.

The depth at which the quantity of sunlight present is only 1 percent of the surface intensity is generally regarded to be a good index of the lower boundary of the photosynthetic zone in a lake. Thus, in Barbadoes Pond, the production of food by the microscopic algae cannot occur much below 5m, in contrast to Winnisquam (6m) and Newfound (14m).

BIOLOGICAL WATER CHARACTERISTICS

From the point of view of the lake user, the type and amount of organisms present in lakes are much more important than the quality of sunlight and quantity of dissolved substances, although the former are closely related to the latter. Thus, one thinks of a "polluted" lake as having massive blooms of algae which form surface mats and smell badly, or of having massive fish kills, rather than having the large concentration of phosphorus and nitrogen, which in fact may be responsible for the observable biological calamities. The major groups of organisms in a lake are macrophytes (in near-shore, shallow water), algae and bacteria attached to the macrophytes, phytoplankton and zooplankton, (the microscopic plants and animals throughout the lake), the bacterioplankton, and the benthos (algae, bacteria, and invertebrates living in the surficial layers of the bottom deposits). The lakes with the least productivity and the

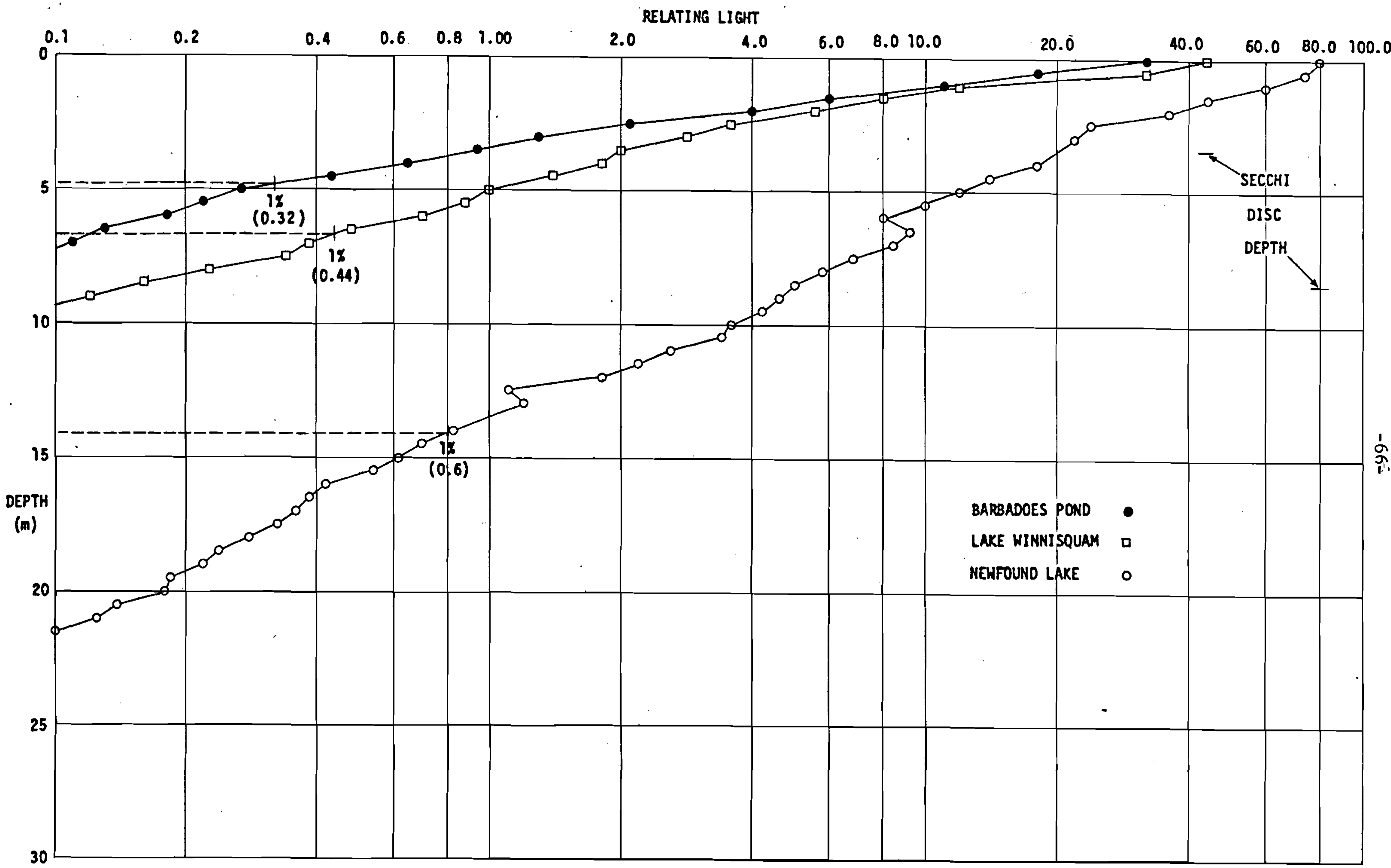


FIGURE 5. RELATING LIGHT DISTRIBUTION WITH DEPTH FOR BARBADOES POND, LAKE WINNISQUAM, AND NEWFOUND LAKE

clearest water (e.g. Newfound) have low concentrations of these organisms. Lakes such as Barbadoes, with brown-stained water, have their productivity reduced by low light penetration, but may have an abundance of planktonic organisms near the surface. Lakes of the highest productivity, which produce the most organisms and are often called "most polluted", usually have unstained water along with an abundant supply of phosphorus and nitrogen (e.g. Winnisquam).

In Barbadoes Pond, the major "macrophyte" is alder, a bushy tree whose roots survive well underwater, and many of which are host to nitrogen-fixing bacteria (cf. legumes such as beans). Thus, the alders surrounding much of the lake may be an important source of nitrogen. There are few other macrophytes in Barbadoes because of both the brown-stained water and the steeply sloping bottom. As the lake ages, the bottom will gradually fill with more sediments, until at some time (perhaps several centuries from now) much more extensive development of aquatic macrophytes and their associated algae and bacteria will occur.

The phytoplankton of Barbadoes Pond are typical of ice-block depression basins which have a moderate loading of nutrients: production is moderate (mesotrophic), and the dominant phytoplankton groups are microflagellates (greens and cryptomonads) and blue-green algae. In late summer, "mini-blooms" of these algae develop at the surface and are concentrated down-wind; the blue-green algae present in the mini-blooms include Microcystis aeruginosa and Anabaena planctonica, both of which are common in enriched lakes. The brown-stained water restricts the algae to the upper 4m of the water column where they are able to photosynthesize. The majority of phytoplankton cells are either grazed by zooplankton or sink directly into the hypolimnion. In the first case, they are converted in part to "fish-food", and in part to fecal material that sinks to the bottom. In the other case, they are decomposed by bacteria in the hypolimnion, which themselves may enter the food chain via the zooplankton, or become part of the bottom sediments. A qualitative list of genera of phytoplankton is presented (Table 2).

The primary photosynthetic pigment of the microscopic algae is chlorophyll a. Concentrations of this pigment indicate the level of productivity in a lake. In Barbadoes Pond, the chlorophyll a concentration ranged from 5 to 10 micrograms/liter, a level which is typical of mesotrophic and dystrophic lakes. In contrast, chlorophyll a in a clear lake such as Newfound is less than 2 micrograms/liter.

The zooplankton, which feed on phytoplankton and bacterioplankton, and in turn are fed upon by fish, are an important link in the food web between the algae and man. In Barbadoes Pond, densities of herbivorous or algae-eating zooplankton (Figure 6) are relatively high, especially when compared with the values found in Newfound Lake. Concentrations of the largest zooplankton genera (e.g. Daphnia) were as high as 5 individuals/liter, which is typical of moderately-enriched (mesotrophic) lakes. These moderately high concentrations suggest that an abundance of food is available for fish populations in Barbadoes Pond.

Since all of the zooplankton collected, with the exception of the predaceous phantom midge larva (Chaoborus), require oxygen, these forms are restricted to the upper 4m of the lake. In contrast, the highly-oxygenated hypolimnion water of Newfound Lake support zooplankton entirely to the bottom of the water column. Chaoborus may tolerate the absence of oxygen for extended periods of time, and therefore are found in the hypolimnion of Barbadoes Pond.

The fish of Barbadoes Pond were not investigated, nor were the organisms of the benthos. Fishermen were observed frequenting the lake with occasional

Table 2

RELATIVE PHYTOPLANKTON COUNTS

Barbadoes Pond

Genus	Number Counted	% of total counted
Staurastrum	66	41.2
Coelosphaerium	39	24.4
Peridinium	33	20.6
Cosmarium	8	5.0
Dinobryon	6	3.8
Anabaena	5	3.1
Asterionella	2	1.2
Tabellaria	1	0.6
	160	

Newfound Lake

Total numbers of species present much too low for reasonable counts.

Winnisquam Lake

Epilimnion (10m haul)			Metalimnion (12m haul)			Hypolimnion (14m haul)		
Genus	#	%	Genus	#	%	Genus	#	%
Fragelaria	26	21.8	Ulothrix	29	23.8	Eudorina	67	28.4
Eudorina	19	16.0	Asterionella	25	20.5	Fragelaria	35	14.8
Sphaerozosma	15	12.6	Eudorina	18	14.8	Asterionella	33	14.0
Asterionella	14	11.8	Fragelaria	17	13.9	Dinobryon	27	11.4
Anabaena	10	8.4	Dinobryon	10	8.2	Sphaerozosma	23	9.7
Ulothrix	8	6.7	Sphaerozosma	5	4.1	Anabaena	16	6.8
Microcystis	6	5.0	Anabaena	4	3.3	Staurastrum	12	5.1
Mallomonas	6	5.0	Coelosphaerium	3	2.4	Mallomonas	8	3.4
Staurastrum	5	4.2	Tabellaria	2	1.6	Synura	6	2.5
Tabellaria	5	4.2	Dictyosphaerium	2	1.6	Coelosphaerium	4	1.7
Sphaerocystis	1	< 1.0	Staurastrum	2	1.6	Tabellaria	2	< 1.0
Coelosphaerium	1	< 1.0	Gomphosphaerium	2	1.6	Gomphosphaerium	1	< 0.5
Synura	1	< 1.0	Synura	2	1.6	Ulothrix	1	< 0.5
Ceratium	1	< 1.0	Mallomonas	1	< 1.0	Pediastrum	1	< 0.5
Gomphosphaerium	1	< 1.0						

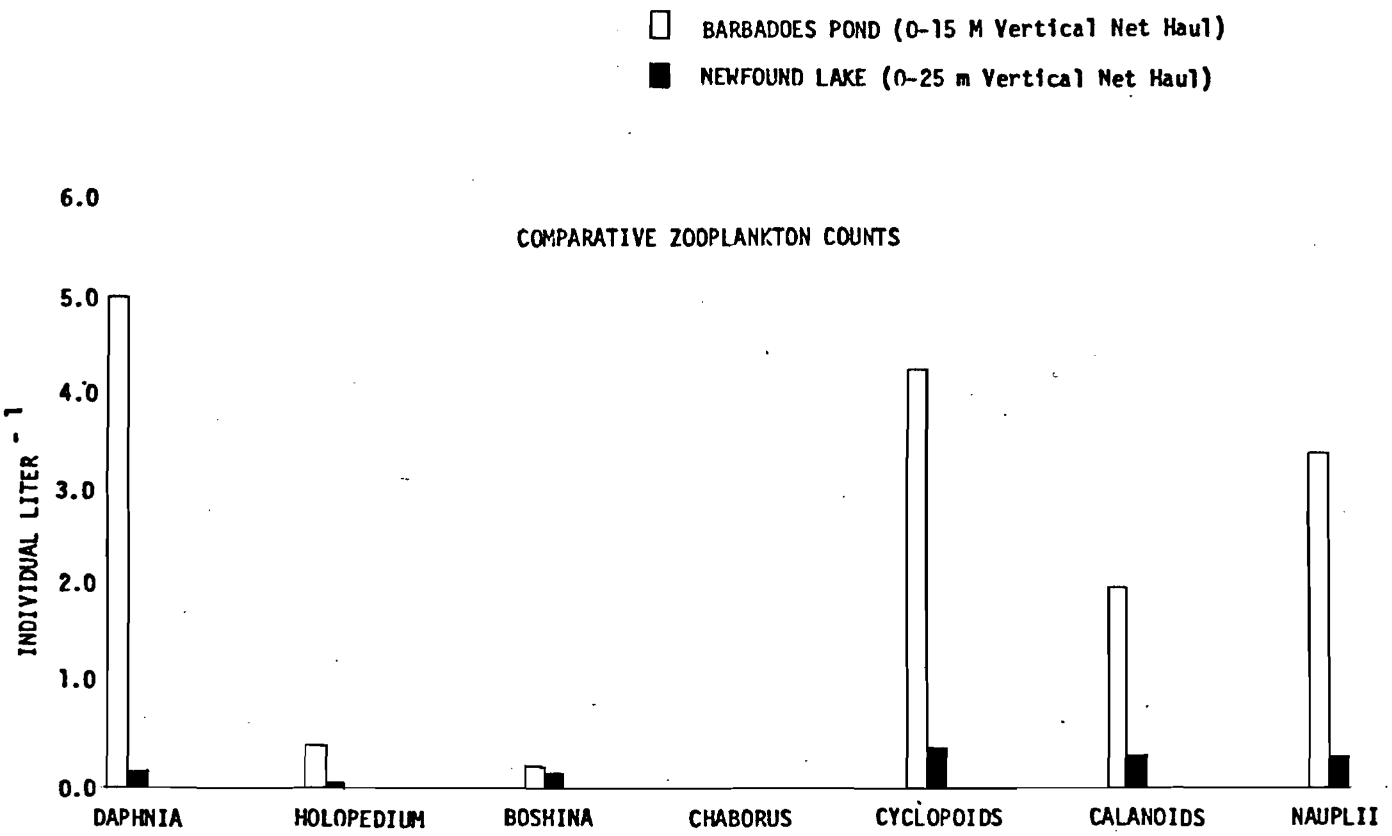


FIGURE 6. COMPARATIVE ZOOPLANKTON COUNT FOR BARBADOES POND AND NEWFOUND LAKE

success. The best information on the recent fish population and stocking of the lake can be obtained from the New Hampshire Division of Fish and Game.

SUMMARY

The physical, chemical, biological, and morphometric characteristics of Barbadoes Pond all indicate that the small lake is moderately productive (*mesotrophic*), and because of its great depth will remain so for several centuries, unless present rates of erosion or nutrient loading are accelerated. Somewhat higher rates of erosion will reduce the time needed to extend the shallow-water macrophyte community to the time when cat-tails and water-lilies may become important. Higher rates of nutrient loading (phosphorus and nitrogen from sewage and storm runoff) will probably extend the duration and intensity of the blue-green bloom which is now transient, and only visible when concentrated by the wind.

The brown-stained water will restrict production by plankton in this *dystrophic* pond. Efforts to increase fish production by fertilization with nutrients will probably be futile since only inedible blue-green algae are apt to respond with greater growth rates, and since the depletion of oxygen in the hypolimnion will become more extensive, further restricting the portion of the lake inhabitable by fish.

On the other hand, efforts to reduce algae production by the addition of algicides, for the purpose of increasing water clarity, would be only partially successful. Use of the lake for swimming will be limited to a great extent by the persistent brown-stain of dissolved organic acids, unless the flushing rate of water through the basin is increased, and the source water has a lower concentration of organic acids.