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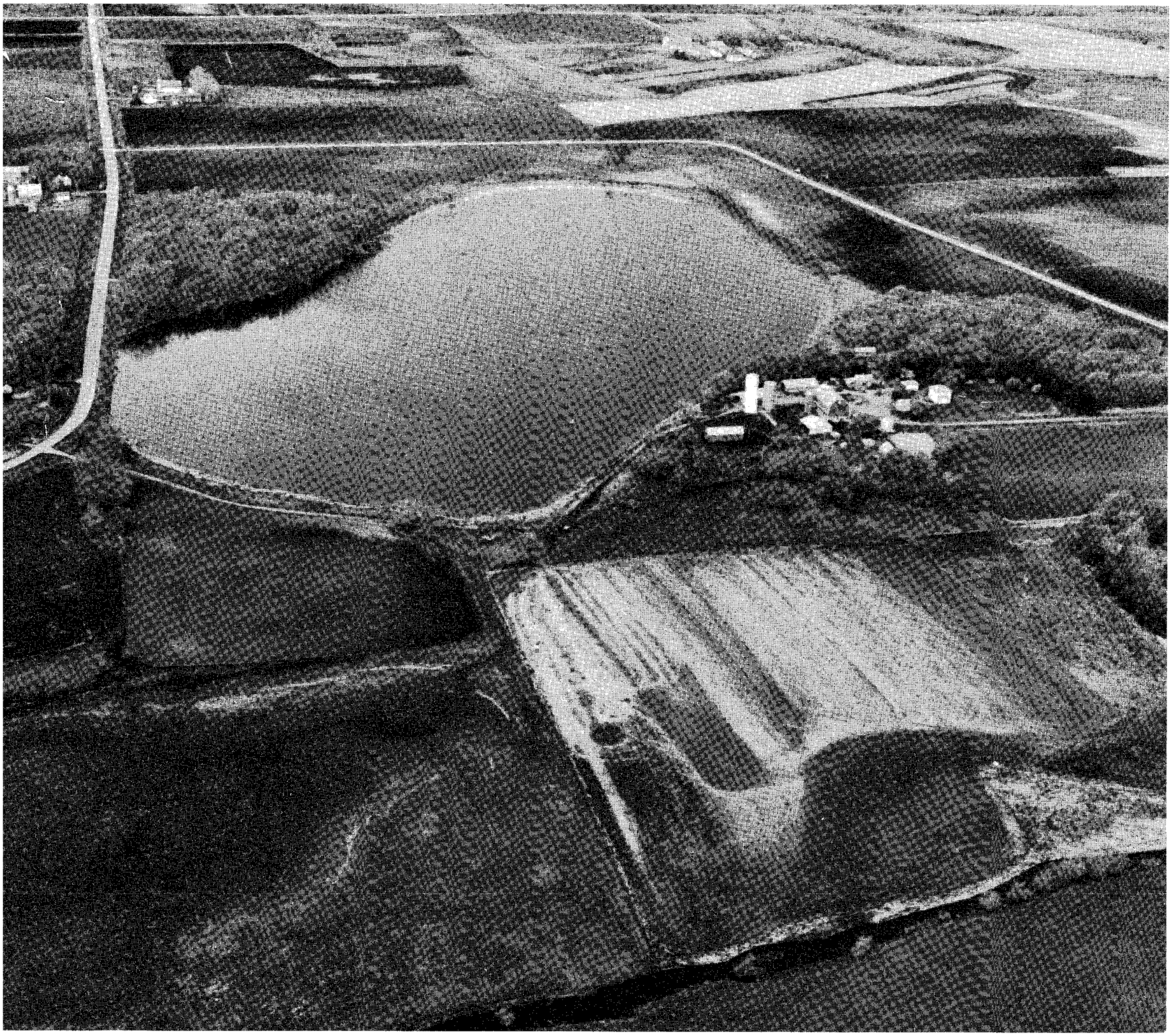

Some Aspects of the
HYDROLOGY of PONDS and SMALL LAKES

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SUMMARY

When the project was started in 1962 there was very little definite information on the history and annual regimen of small lakes and ponds (potholes) in Minnesota. These are scattered by the thousands over a wide area in Minnesota in varied topographic and geologic conditions. For these reasons about forty small bodies of water were selected in an area extending from Mankato on the south to Detroit Lakes on the northwest. For comparison, limited observations were made on several larger lakes in some of the areas.

For areas convenient to headquarters in St. Paul, observations of surface water levels were made at frequent intervals to permit plotting graphs of the changing levels from March 1963 to December 31 and for the full year 1964. Particular efforts were made to observe water and ice levels for the winters 1962-63, 1963-64, and 1964-65. This essentially eliminated evaporation as a factor affecting the levels, and precipitation was also largely eliminated as far as ice and water levels were concerned.

The usual regimen of a small body of water differs from place to place and from time to time but, nevertheless, shows a general pattern. From December 1 to about April 1 there normally is an ice cover and the water and ice level in the majority of bodies is notably stable. Data from forty-seven small water bodies indicate the average seepage loss per day is 0.0032 foot or for a year is 1.17 feet.

With the spring thaws, breakup of ice, and the usual frequent rains the water level rises; this rise may be slight or very pronounced, depending on the season. The crest of the rise may occur from mid-May to mid-June. With the advent of warmer weather and higher evaporation, the levels tend to decline rather sharply from mid-June through July and August, particularly because precipitation also tends to decline in late summer. From September until freeze-up the decline in level becomes more gentle and after the freeze-up is small or even nonexistent.

It is evident from available data that the main controlling factor of the level of water in small, shallow lakes and ponds is the relation between precipitation and evaporation. Other factors are important in individual cases. For example, a series of years of subnormal precipitation inevitably results in drastic lowering or drying up of shallow bodies. It is also true that excess precipitation, particularly if the ground is frozen, results in drastic rises, as was shown in 1965. This, however, is usually a temporary problem, as the data presented shows that the permeability of the soil and drift adjacent to the pond or lake is usually much greater than is that of the bottom. Thus, when the water level rises to flood over the normal basin, infiltration is rapid and the level tends to decline rather promptly to the usual level. From the above, we can reason that the way to conserve water for the groundwater supply is to induce infiltration over the surface by good soil practices rather than to store water in open ponds where evaporation causes it to be lost to the atmosphere.

INTRODUCTION

General Statement

The subject of the effect of drainage on the water table and the groundwater supply has been discussed and argued for many years. There is, however, a great deal of opinion and a serious lack of facts regarding the problem. Opinion depends mainly on the type of interest one has in the problem. There has been much objection to drainage because it results in the disappearance of ponds, locally called potholes, and thus destroys nesting places for ducks. The argument is also often advanced that the drainage of potholes robs the groundwater of one of its main sources of replenishment.

Because of the wide interest in various aspects of farm drainage and its effects, if any, on groundwater supplies, the Minnesota State Soil Conservation Committee assigned a modest sum to start an investigation of the problem in 1962. The Committee accordingly made funds available to the Department of Agricultural Engineering for a basic research study of the hydrology of potholes in Minnesota. An equivalent amount in funds and staff salaries was made available by the University. After the first year the project was continued by various grants to the University. When the project was under way, we learned that the U. S. Geological Survey (Shjeflo and others, 1962) had also started a project with a similar aim but limited to two areas in North Dakota. The methods and scope of the two projects are different but are valuable supplements to each other.

In view of the limited funds and personnel, we decided that the study would have to be restricted to what could be accomplished within a reasonable time and with modest expenditures.

Therefore, we planned to emphasize methods to determine the extent of water seepage out of ponds and small lakes. We also realized that highly quantitative results could not be expected with available funds, especially if potholes under widely different environments were to be studied. Federal funds, recently available through the Water Resources Institute of the University of Minnesota, have made possible the start of a highly quantitative investigation of four of the bodies of water described in this report.

Purpose of the Project

The primary purpose of the project was to determine the possible extent to which small ponds and lakes contribute to groundwater, and also to investigate, so far as practicable, other aspects of the regimen of such bodies. It is not known, for example, why many of these bodies dry up in periods of low precipitation while others are able to exist under unfavorable conditions. What, for example, can be done to maintain a desirable small pond or lake?

Information concerning all aspects of pond hydrology is sorely needed. In this study, therefore, an attempt was made to obtain as much information as possible regarding the small bodies of water and to present the information, so that anyone can draw his own conclusions as to its meaning. It was hoped that the data assembled would permit an intelligent estimate of the probable future of any small body of water present in a large part of the state.

CONDITIONS CONTROLLING THE OCCURRENCE OF PONDS

Surficial (Glacial) Deposits

As indicated earlier, the surface deposits or unconsolidated material in Minnesota is largely of glacial or fluvio-glacial origin. A significant aspect is that the glaciers which invaded Minnesota came from the north, northeast, and northwest, in part, at different times. The rocks over which the glaciers came were of different character and therefore the glacial deposits differ in composition, depending on the source. In a general way the material that came from the northwest is gray in color and has a relatively high content of limestone and clay or shale. It follows that these deposits are impervious except where sand and gravel have been sorted from the clay by running water.

The material from the north and northeast is generally brown in color and has a higher content of sand and gravel and correspondingly less limestone, clay, and shale. In general it is more permeable, except in those instances where excess fine material is present.

In addition to the variation in composition, the character and topography of the glacial deposits range widely depending on the manner of deposition. In some types of glacial deposits meltwater plays an important part.

In their simplest form, glacial and fluvio-glacial deposits are classified as terminal or end moraines, ground moraines, outwash deposits, including alluvial or floodplain deposits along the principal streams, and glacial lake deposits. In southeastern Minnesota a windblown deposit called loess is important, but this is mainly outside the area of this investigation. Each of these classes will be described briefly with particular reference to the occurrence of lakes, ponds, and marshes.

Terminal (End) Moraines

The great continental ice sheets advanced until they encountered a climate sufficiently warm and dry to prevent further advance of the ice front by melting as fast as the ice moved forward. When melting and forward movement about balanced, great masses of rock debris were piled up in a belt along the ice front. When the climate warmed enough to more than balance forward movement, the front would retreat until a colder cycle developed, at which time it would halt again. Thus successive terminal or end moraines were formed.

These belts are hilly, the relief depending on the length of time the ice halted and other modifying factors. The terminal moraines are, therefore, characterized by extremely irregular topography which resulted from unequal deposition of rock debris, and also by large ice blocks buried in the deposits to later melt and form depressions. The terminal belts are occupied by innumerable lakes, ponds, and marshes. Potholes are unquestionably more numerous in the terminal area than elsewhere. Moreover, the depressions occur at different elevations and the level of the water surfaces within the ponds or potholes is likely to be divergent.

Ground Moraine

When a glacier simultaneously became stagnant and tended to melt over a large area, it dropped whatever debris it contained but did not feed large amounts forward as in the formation of a terminal moraine. The result was thinner deposits consisting of essentially unsorted rock debris and a comparatively level area with shallow depressions where ice blocks were buried or where lesser amounts of material were present in the ice. Thus, areas of ground moraine contain a few shallow lakes and numerous marshes. Potholes are not numerous and those that do exist are shallow and tend to be intermittent. The level areas of ground moraine which cover much of western Minnesota require extensive drainage to make dependable farm land. It happens that the ground moraine or prairie areas of Minnesota are largely underlain by glacial drift deposited by ice from the northwest; this glacial drift has a high clay content and is decidedly impervious.

Outwash Deposits

Large amounts of water poured out from the front of the melting glaciers. It follows, therefore, that in front of a terminal moraine streams joined to form a veritable sheet of water moving toward the major drainageways. The velocity of the water decreased rapidly away from the ice front and so large amounts of silt, sand, and gravel were deposited to form a gently sloping surface called an outwash plain or apron. As the water joined the main streams a great flood developed and water spread over the valley. There, too, silt, sand, and gravel were deposited to form a so-called valley train of outwash extending downstream.

Glacial Lake Deposits

These have been described under the heading of level areas. They are characterized by swampy and poorly drained areas but, in general, do not have many ponds (potholes). None of this investigation took place in areas of glacial lake beds.

Composition of Surficial Deposits

The composition of the surficial deposits of an area determines its permeability and is a natural result of the manner in which the deposit originated. The source of the material incorporated in glaciers together with mode of deposition determines the character of the material deposited when the ice melts.

Deposits of sand and gravel are common in glacial deposits because of the sorting action of meltwater. Thus outwash deposits have large areas of sand and gravel. If the sorting action has been efficient, little silt and clay may remain and the deposit is highly permeable.

Silt is defined as particles of soil or earthy material between .05 mm and .005 mm in diameter. In glacial soils, silt is abundant as a result of the grinding action of ice and the rock material incorporated in it. Another important factor is that glacial climates are not conducive to chemical weathering. Therefore the rock material, especially feldspar, remains fresh instead of decomposing to clay. In general the fresh rock does not grind to below silt size.

Silt has a relatively low permeability although it is not as completely impermeable as clay. Silt is particularly important because it fills in spaces between the larger particles of sand and gravel and greatly decreases permeability. In the bottom sediments of ponds and lakes in Minnesota silt is usually more abundant than clay.

Clay is the most impermeable of rock materials. It consists of a number of complex hydrous aluminum silicates that form by decomposition of primary silicates. Because of their chemical origin, these clay minerals are prone to develop extremely minute particle size (below .005 mm), and moreover, have a layered crystal structure. When clay is wetted, water can enter between the layers and the clay becomes plastic. Water enters but will leave only by evaporation. Thus the clay is impermeable, although when dry it may be highly porous and when wet contain large amounts of water. It is evident that clay is important in the problem of seepage and movement of water in the soil and other surficial deposits.

As has been noted above, clay and shale (consolidated clay) are abundant in the glacial drift, particularly the ground moraine, which originated from the northwest. This material from the northwest has been referred to as the "young gray drift" that covers much of western and southern Minnesota which, therefore, has a soil of low permeability.

In view of the complicated glacial and fluvio-glacial origin of most of the surficial deposits of Minnesota, it is not surprising to find that mixtures of clay, silt, sand, cobbles, and boulders are common. This is particularly true of the large areas of ground moraine. There was little transportation of material by water—at least for any appreciable distance—and, therefore, very little sorting of the rock debris enclosed in the ice. As a result, huge boulders may occur with clay or other fine-grained materials. Such heterogeneous material is usually low in porosity and particularly low in permeability.

Post-Glacial Lacustrine Deposits

One of the important problems regarding seepage from ponds and lakes is the effect of bottom deposits on permeability beneath the area covered by water, now or in the past. It is well-known that bottom sediments in the permanent or semi-permanent ponds consist of both mechanical and chemical (principally biochemical) deposits. The nature of many aspects of these sediments has been the subject of exhaustive investigation, but as far as we know, their permeability has never been completely defined.

It has often been suggested that organic deposits accumulating on the bottom of lakes and ponds seal off the bottom and prevent percolation. It may be questioned whether this is true or whether the original glacial material was sufficiently impervious in the first place to permit water to accumulate in the depressions and exist long enough to allow organic deposits to accumulate. This investigation shows that combinations of sand, silt, and clay are the common initial deposits in bodies of water in glaciated areas.

Ponds and lakes must, of course, occupy depressions in the general level of an area. The depression may be very slight and the pond or lake shallow where ground moraine, outwash, and alluvial deposits exist. In that case, erosion of the adjacent land may be slight and the transportation of soil into the depression may be at a minimum. In hilly areas, mainly terminal moraine belts, some of the depressions are pronounced and sheet and gully wash are important. We can safely infer that in such areas as soon as the depression developed, and before vegetation became established, wash of clay, silt, and sand into the depression was pronounced. The pond or lake acted as a settling basin and deposits of fine-grained, relatively impervious material covered the bottom.

When a vegetation cover was established, erosion of the adjacent land was probably minimized. The situation presumably continued until settlers entered the area. As soon as an area was settled and the forest or prairie grass was removed by cultivation, sheet wash and gully erosion started again. In some potholes a deposit of mechanical sediment was found over organic sediments, which in many situations had been deposited during the long period of forest or prairie grass cover.

The fine-grained material (silt and clay) which accumulated in small lakes and ponds is of low permeability. Sampling of the bottom sediments of potholes to determine the amount and character of the mechanical sediments has been an important part of this investigation.

Marl—mainly calcium carbonate—is a common and abundant chemical and biochemical sediment on the bottom of lakes and ponds in Minnesota. Calcium carbonate is abundant in the glacial deposits, and as rainwater dissolves carbon dioxide from the air, it develops the ability to dissolve the calcium carbonate as calcium bicarbonate. Water organisms, both plant and animal, extract calcium carbonate in their life process and it accumulates as they die. Agitation of water by waves and temperature changes also cause precipitation by breaking down the bicarbonate. The widespread occurrence of marl in Minnesota is described by Thiel (1933) and Schwartz (1959).

Information on the permeability of marl deposits is largely lacking. It is known that the water content of marl as it exists in ponds and lakes is high, ranging up to 70 percent. After excavation much of the water does not drain out even after stockpiling for weeks or months. Marl is usually extremely fine-grained and may be expected to transmit water with difficulty. Preliminary tests in test holes in marl, however, indicate that water does move through it rather rapidly. More information is needed regarding the permeability of undisturbed marl.

In Minnesota, accumulation of vegetation in shallow water has gone on since the last glacial ice disappeared over 10,000 years ago. Many ponds and marshes, therefore, have extensive deposits of peat. In many situations deposits of peat overlie marl. Peat is composed of the fibrous parts of many varieties of aquatic plants along with seeds, pollen, and some inorganic matter washed or blown in from the adjacent land. Fibrous peat is doubtless permeable and probably does not act as a seal, but the conditions under which it forms indicate that water was either held in by a seal below or was a part of the water table. Fine-grained, black peat is probably impervious.

It is known from many investigations that the bottom sediments of many ponds and marshes consist of a mixture of clay, silt, and black, brown, or gray organic matter. This is commonly called muck or black mud but some investigators have used the Scandinavian word "gyttja." Muck, or gyttja, is interbedded with other bottom sediments such as marl, peat, sand, silt, clay, and various mixtures. The present investigation shows that muck is highly impermeable, as would be expected.

One fact of importance in the study was the identification of material in the bottom of the ponds which was deposited in water, that is, a part of the history of the body of water as distinguished from the glacial deposits of the area. In fresh waters in the lakes and ponds of Minnesota, diatoms are a common form of life. These are microscopic algae which have a silicified cell wall that persists as a skeleton after death. In lake sediments these appear under the microscope as long, slender rods or round cross-sections. They are easily recognized at proper magnifications. In instances where there was doubt about a fine clay or silty sediment having been deposited as part of the pond or lake sediment, a sample was examined under magnification of 300 diameters and classified as water laid if diatom skeletons were present.

We naturally wondered if many of the ponds—particulary the smaller ones— have existed most of the time since the retreat of the glacier from the area, about 10,000 years ago.

In recent years detailed studies by botanists have shown it is possible to trace the floral history of a region by a detailed study of the pollen and seeds trapped in peat and other organic sediments. Then by use of the C^{12} C^{14} ratio an age in years of wood or other organic matter can be determined for various intervals in a succession of sediments in a lake or peat bog. Once this is done, it is possible by comparison to obtain estimates of the age of the pollen assemblage from suitable samples. As detailed in Appendix II, this was done for a few selected ponds.

Topographic Relations

One of the most important factors to be considered in an investigation of lakes and ponds is the topography, that is, the configuration of the land surface. For the area of Minnesota where the so-called "pothole" problem is important, the topography ranges from hilly to rolling to level and the Mississippi, St. Croix, and Minnesota rivers are deeply incised in the general level.

The topography of the areas of immediate interest are essentially all of glacial or fluvio-glacial origin. In general the hilly areas of that part of Minnesota under discussion coincide with the belts of terminal or end moraine. This is the locus of a large percentage of the lakes and ponds of the state. The hills may vary widely but are usually round or oval, with gentle to moderately steep slopes. A wide variety of depressions are characteristic of the hill areas and most, or at least many, are undrained. Some of the areas are characterized as having knob and sag topography because of their more or less round hills and depressions. Most of the undrained depressions are ice block pits, that is, depressions left when blocks of ice within the glacial drift melted.

The hilly country passes insensibly into a more gentle or rolling topography, which may have developed as a very mild terminal moraine or ground moraine, where deposition of glacial debris was of uneven thickness. Such topography has fewer lakes and ponds than the hilly areas and the water is normally rather shallow.

The level areas are of three specific types:

Alluvial deposits along major streams (particularly the Mississippi) are of limited extent because they are normally long and narrow. In these areas, which are usually characterized by a sandy or silty soil, ponds and lakes are not numerous and are likely to be shallow. The soil is usually permeable and the lakes, ponds, and marshes often represent the groundwater level. The Anoka Sand Plain is an unusual alluvial deposit that is nearly level and has an extremely sandy soil. The Anoka Sand Plain was formed during the development of the Mississippi River, when its glacial water spilled over a wide area and formed lakes. At a later time there was modification of the sand plain by wind action.

The second type of level area is widespread in southern and western Minnesota. The level areas correspond to broad belts of ground moraine formed where the ice melted over large areas at about the same time. Lakes are usually shallow. Ponds, including temporary or intermittent bodies of water are common, and much of the soil is poorly drained, partly due to lack of sufficient gradient for good drainage and partly because the soil has a high clay and silt content.

The third type of level area is formed by sediment deposited in the temporary glacial lakes that existed during the retreat of the glaciers when the natural drainage was still blocked by ice. The bed of glacial Lake Agassiz in the Red River area is the largest, but glacial Lake Aitkin, glacial Lake St. Louis, and glacial Lake Duluth also covered large areas. These areas are characterized by large swamps or marshes rather than lakes.

Other Significant Factors

The very existence of ponds and small lakes at widely divergent levels, within short distances of each other, indicates some difference in conditions beneath the water and the adjacent land. This led to the conclusion that comparative studies must be made between the material comprising the land around the water (soil only in the broadest sense) and the sediments beneath the water. For this purpose representative samples from test holes were made on land and through the ice and subjected to laboratory study. The hydrometer method was used to obtain the fractions or percentages of gravel, sand, silt, and clay in each sample.

The permeability or transmissibility of the material is related to the amount and distribution of the various fractions of clay and to a lesser degree of silt. Materials with an abundance of clay or silt usually have low permeability, and those with sand and gravel a high permeability; in mixtures the situation is complex. In any event the size classification gives an easily recognized difference between the glacial drift or other material around the body of water and the sediments deposited in the bottom.

The clay-size fraction is made up of two or more minerals, and these differ greatly in their properties, particularly their ability to absorb water between microscopic layers of the crystals. This, in turn, bears on the capillary properties and their permeability, or lack of it. This is described later in more detail.

Relation Between Potholes and the Water Table

It is generally assumed that in moist regions below the ground surface there is a saturated zone, whose surface is called the water table. Actually, if the soil is very low in permeability, or if rocks such as granite exist at or near the surface, the water table may be discontinuous or nonexistent.

Some lake levels coincide with the water table. Others, particularly small lakes and ponds, may be perched above the main water table and perhaps coincide with a perched water table—a local saturated zone held above the regional water table by an impervious layer. With these concepts as a starting point, various situations may be inferred in which potholes occur in the complicated glacial deposits of Minnesota.

From experience it seemed that the situations were more complicated than indicated by just a twofold classification. If a pond or lake exists in highly permeable surficial deposits, such as well-graded coarse sand, the open water surface must necessarily coincide rather closely with the water table. But if the soil or bottom sediments in the pond are relatively impermeable, different possibilities arise.

A study of the many topographic maps available for Minnesota revealed a striking lack of water level adjustment of many potholes and lakes to the topography of a possible regional water table. Moreover, it is well-known that glacial sediments have a wide range of materials and size distribution.

Taking into account the many variables involved, four general types of situations seem to occur:

1. Most potholes in glacial deposits were formed by melting blocks of ice buried in debris deposited by the glacier. At places the glacial debris may be made up of sand, gravel, and boulders and is highly permeable. It seems probable, however, that the glacial drift, at first unprotected by vegetation, was often subjected to rapid sheet erosion which resulted in deposition of fine-grained sediments in the low spots. This deposition deterred seepage and started the pond formation, and later organic sediments deposited in the water helped to seal the bottom.

2. Glacial sediments are often stratified. Large areas in Minnesota have glacial sediments from the last glacial invasion overlying earlier deposits. These earlier deposits are derived from sources to the northeast, are sandy and gravelly, and transmit water readily, whereas later deposits have a high clay and silt content and low transmissibility as shown by extensive tile drainage in the later drift. In this situation a perched water table may be extensive and be expressed at the surface by small lakes and ponds.

3. Where the drift consists largely of clay and has very low permeability, water accumulated in low spots without any relation to a perched water table and with time the addition of organic matter developed a fairly effective seal. This situation exists widely over the prairie areas of western Minnesota where the drift deposited by the Des Moines Lobe has a high clay content and percolation of water downward is slow or perhaps almost absent in areas of great thicknesses of clay and silt. Wells have been drilled several hundred feet in such areas without encountering water.

4. Many lakes and potholes in the area of the Anoka Sand Plain are closely adjusted to a shallow regional water table. Somewhat similar long and narrow areas occur along the Mississippi River north of Minneapolis. The soil consists mainly of sand and is generally highly permeable. The areas are usually nearly level and not far above the drainageways.

PROCEDURE

Planning the Project

We realized that there is a great range of conditions under which potholes and lakes exist in Minnesota, as indicated by Zumberge (1951). The topographic situation of the potholes ranges from level ground moraine and outwash to extremely irregular end moraines. Moreover, the relation to the comparatively deep trenches of the Mississippi, Minnesota, and St. Croix Rivers is significant. Minnesota was invaded at different times by ice sheets from the northeast, north, and northwest. Therefore, the character of the soil and drift is variable. Soil from the northeast and north is sandy, gravelly, and low in clay and carbonate sediments, whereas soil from the northwest has high clay and carbonate content. Both drifts tend to be silty.

Because Minnesota is a large state (84,068 square miles, including 4,059 square miles of water), attention was paid to the physical and economic problem of working on widely separated bodies of water. It was necessary to travel 600 miles to obtain a reading of all water levels involved in the project. Fortunately, a wide range of conditions exists within 50 miles of headquarters (Department of Agricultural Engineering, St. Paul Campus, University of Minnesota), which simplified the problem.

There are probably tens of thousands of small ponds in Minnesota. The Minnesota Department of Conservation distinguishes between a pond (or pothole) and a lake on the basis that a lake has an area of 10 acres or more. U.S. Geological Survey topographic maps show 20 small ponds, either entirely or partly within 1 square mile a short distance south of St. Paul. But it was difficult to select a limited number of good sites for study. Furthermore, a study of smaller bodies of water could not logically be separated from reference to lakes nearby. In fact we felt that information on lakes in the area of selected ponds was essential to an understanding of the hydrology of the more than 40 smaller bodies studied. As a result, a restricted study of 11 lakes was included. The 10-acre limit between pothole and lake was not always adhered to since a small lake of 10 to 40 acres was often ideal for the purposes of the project.

Selection of the Sites

As soon as we started actual selection of sites, we found that topographic maps were essential for proper selection of areas and progress of the work thereafter. In 1962 topographic maps of about 40 percent of the state were available. All these maps were briefly reviewed and a list selected for more intensive examination. The glacial geology was checked by examination of available maps and reports aided by personal knowledge.* Finally, we selected 17 topographic map quadrangles containing from one to seven ponds or lakes suitable for study. In addition to furnishing necessary information for intelligent performance of the work and interpretation of the results, the maps will enable anyone in the future to locate the bodies of water accurately and with a minimum of effort. The general locations of the sites are shown in figure 1. Potential bodies were then selected and a brief summary of facts prepared regarding topography, geology, and other items including ready accessibility by road. A field inspection of each site followed, permission to enter the land was secured, and a supplementary report prepared for use of the fieldmen.

The following were the principal factors involved in selecting the sites:

1. Wide distribution in the state
2. As many different geological and topographical situations as possible
3. Evidence of existence of water levels over a long period, particularly for the smaller bodies
4. Lack of much man-made disturbance, other than usual cultivation and roads
5. Preferably more than one body in a given area to avoid conclusions from an exceptional situation
6. Locations to keep travel within reasonable limits
7. Accessibility by road or without undue disturbance of private lands
8. Permission for access from landowners

One unrecognized factor influencing the selection was that in 1962 water levels were normal or slightly above. This above-normal water level was followed by rather low precipitation during parts of 1963 and 1964 with the result that a few bodies of water dried up and others were severely diminished. This drying-up was, in some respects, disappointing. But the winter of 1964-65 was one of heavy snowfall followed by far above-normal rainfall with a consequent large rise in water levels. Thus the low precipitation in 1963-64 followed by above-average snow and rainfall in 1964-65 provided a valuable contrast during this continuing project.

In retrospect, it would have been a good idea to have carried a small boat and determined the depth of water before final inclusion of a pothole in the project. A list of the ponds and lakes investigated is shown in table 1. For convenience the first one to three letters of the name of the U.S. Geological Survey Quadrangle plus numbers were used to designate each pond or lake. Thus Ma 5 is the fifth body of water investigated in the Marine Quadrangle.

Field Methods

After selection of the bodies of water to be studied, we had to establish vertical control for gaging water levels. Because the topography was likely to be significant—particularly the relative level of water in nearby ponds, lakes, and streams—it was desirable to refer to sea level datum as is done on the U.S. Geological Survey topographic maps used for locations. Precise benchmarks are few; many have been destroyed by road work or other disturbances. However, the topographic maps, particularly those recently

Table 1. List of small lakes and ponds investigated

No.	Land survey location	Quadrangle	County
A 1	SW¼ SW¼, sec. 7, T. 139 N., R. 41 W., includes 4 larger lakes	Audubon	Becker
Be 1	N½, sec. 7, T. 41 N., R. 31 W.	Belle Prairie	Morrison
Bl 1	SW¼, sec. 5, NW¼, sec. 8, T. 27 N., R. 24 W.	Bloomington	Hennepin
Bl 2	SW¼, SW¼, sec. 17, T. 27 N., R. 24 W.	Bloomington	Hennepin
F 1	NE¼, sec. 20, T. 128 N., R. 31 W.	Flensburg	Morrison
F 2	NE¼, sec. 35, T. 128 N., R. 31 W.	Flensburg	Morrison
Ga 1	SW¼, sec. 33, T. 113 N., R. 28 W.	Gaylord	Sibley
Ga 2	N½, sec. 17, T. 114 N., R. 27 W.	Gaylord	Sibley
Gr 1	SE sec. 21 & NE sec. 28, T. 118 N., R. 39 W.	Gracelock	Chippewa
Gr 2	Sec. 5, 118 N. & Sec. 32, T. 119 N., R. 40 W.	Gracelock	Chippewa
In 1	SW¼, sec. 6, T. 27 N., R. 22 W.	Inver Grove	Dakota
In 2	SW¼, sec. 6, T. 27 N., R. 22 W.	Inver Grove	Dakota
In 3	SW¼, SE¼, sec. 8, T. 27 N., R. 22 W.	Inver Grove	Dakota
In 4	SW¼, SE¼, sec. 8, T. 27 N., R. 22 W.	Inver Grove	Dakota
In 5	NE¼, sec. 22 & NW¼, sec. 23, T. 27 N., R. 22 W.	Inver Grove	Dakota
In 6	NW¼, sec. 27, T. 27 N., R. 22 W.	Inver Grove	Dakota
In 7	SE¼, sec. 27 & NE¼, sec. 34, T. 27 N., R. 22 W.	Inver Grove	Dakota
Is 1	SW¼, SE¼, sec. 4, 33 N., R. 23 W.	Isanti	Anoka
Is 2	SE¼, sec. 7 & NE¼, sec. 18, T. 33 N., R. 23 W.	Isanti	Anoka
Is 3	Secs. 8, 9, 16 & 17. T. 33 N., R. 23 W.	Isanti	Anoka
Is 4	SE¼, SE¼, sec. 27, T. 33 N., R. 23 W.	Isanti	Anoka
Is 5	W½, sec. 28, T. 33 N., R. 23 W.	Isanti	Anoka
Is 6	N½, sec. 28, T. 33 N., 12.23 W.	Isanti	Anoka
L.E. 1	Secs. 23, 24 & 26, T. 29 N., 12.21 W.	Lake Elmo	Washington

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* The reader is referred to *Minnesota's Rocks and Waters, a Geological Story*, University of Minnesota Press, 1954, for a nontechnical summary of the diverse geology of Minnesota.

Table 1. List of small lakes and ponds investigated—(Continued)

No.	Land survey location	Quadrangle	County
L.E. 2	NE¼, sec. 23, T. 29 N., R. 21 W.	Lake Elmo	Washington
L.E. 3	NE¼, NE¼, sec. 22, T. 29 N., R. 21 W.	Lake Elmo	Washington
L.E. 4	NW¼, sec. 30, T. 29 N., R. 21 W.	Lake Elmo	Washington
M 1	NE¼, T. 111 N., R. 23 W.	Mankato East	Blue Earth
Ma 1	NE¼, NW¼, sec. 25, T. 32 N., R. 20 W.	Marine	Washington
Ma 2	NW¼, SW¼, sec. 24, T. 32 N., R. 20 W.	Marine	Washington
Ma 3	Sec. 26, T. 32 N., R. 20 W.	Marine	Washington
Ma 4	NE¼, sec. 16, T. 32 N., R. 20 W.	Marine	Washington
Ma 5	SW part of T. 32 N., R. 20 W.	Marine	Washington
Ma 6	Secs. 2b & 35 T. 31 N., R. 20 W.	Marine	Washington
Mo 1	NE¼, sec. 9, T. 111 N., R. 33 W.	Morgan	Redwood
Mor 1	NW¼, sec. 20 T. 125 N., R. 41 W.	Morris	Stevens
N 1	N½, sec. 19, T. 30 N., R. 23 W.	New Brighton	Ramsey
N 2	NW¼, sec. 19, T. 30 N., R. 23 W.	New Brighton	Ramsey
N 3	NW¼, SW¼, sec. 23, T. 30 N., R. 23 W.	New Brighton	Ramsey
N 4	SE¼, NE¼, sec. 22, T. 30 N., R. 23 W.	New Brighton	Ramsey
N 5	NE¼, sec. 22, T. 30 N., R. 23 W.	New Brighton	Ramsey
S.P. 1	SE¼, SE¼, sec. 17, T. 27 N., R. 20 W.	St. Paul S.W.	Dakota
S.P. 2	E½, sec. 22, T. 27 N., R. 19 W.	St. Paul S.W.	Dakota
S.P. 3	NW¼, sec. 27, T. 27 N., R. 19 W.	St. Paul S.W.	Dakota
S.P. 4	NE¼, SW¼, sec. 17, T. 29 N., R. 23 W.	St. Paul W.	Ramsey
So 1	Secs. 15 & 16, T. 120 N., R. 35 W., includes 3 larger lakes	Solomon Lk.	Kandiyohi

published, have the elevation above sea level recorded at many road intersections or other easily located spots. These elevations are given in round numbers that were considered suitable for the purpose of the project.

The most convenient elevation on the topographic map was used as a starting point for leveling to a point close to water where a temporary benchmark was established, usually by a nail in a tree or post. This temporary benchmark was then used in determining the level of water directly or by setting and reading a staff gage. As a rule, a staff gage which could be read frequently was set in all ponds and lakes but the levels of those bodies of water at a distance from headquarters were determined by using a level. For determining changes in water levels, elevations were read to hundredths of a foot.

Water level readings were tabulated as soon as read and then graphed so that fluctuations could be seen at a glance and comparisons made among all bodies of water being investigated (figures 9, 10, 25, 26, 31, 32, 42, and 43). Fluctuations in relation to rainfall, temperature, etc., were also studied. A typical tabulation of pond data is shown on page 12.

Following arrangements for determination of water levels, we began a program of test holes adjacent to the potholes to investigate the character of the soil and drift and, as far as possible, the water level in the ground near the body of water. For this purpose, an auger drill was purchased and mounted on a pickup truck and several types of hand augers were obtained. For work on the bottom sediments we used a Davis peat sampler and auger. Later, we determined that a sampler designed by Prof. H. E. Wright, Jr. and assistant was much better. As the work developed, most of the testholes were dug by hand because of inaccessibility by the truck to the exact sites desired.

Most of the sample collection from the bottom of the potholes was necessarily done during the winter when ice furnished a stable base. In general, we found that temperatures below 10° F. were undesirable because freezing made the work difficult and time consuming.

With scores of test holes available on the borders of the potholes and lakes, the question arose as to what further information beyond the water levels and samples might be obtained. We considered many schemes which would allow quantitative determination of permeability of the soil. But so many variables were involved that with available funds, this determination was considered impracticable on the scale desired. We finally decided that useful relative results could be obtained by filling 4-inch diameter holes with water and measuring the rate of decline. The decline in feet was plotted against time in minutes. When it was convenient to test two or more adjacent holes, observations extended to 2 hours or more, but at longer intervals between readings. It was found that these data furnished valuable comparisons of general transmissibility of the soil and glacial drift from different areas. Naturally the degree of soil saturation was an important variable, but a long period of dry weather during testing eliminated some of this difficulty in dealing with this variable. We believe results give an idea of the comparative receptivity of the material to water but are in no sense mathematical.

Laboratory Tests

We concluded before the work began that it would be essential to have more than a general field classification of the soil and drift. The relative amounts of clay, silt, sand, gravel, and organic matter determine the permeability of the material and together with the field infiltration tests would give an idea of the general permeability of the ground adjacent to the potholes. This in turn would enable a comparison with the nature of the bottom sediments which, to a great degree, kept the water from seeping rapidly away from the pond or small lake.

The soil class was determined by the U.S. Department of Agriculture Texture Classification Chart (gravel-size particles are larger than 2.0 mm, sand-size particles 2.0

Table 2. Typical data sheet
LE 4
Area: Lake Elmo Quadrangle (Sec. 30, T. 29 N., R. 21 W.)
P.H.: Lake Ria
B.M. 950.52. Nail in power pole

Date	Stage	Remarks	Date	Stage	Remarks
10-25-62	945.6		1-23-64	943.87	Ice
1-8-63	945.2	Water . Ice 945.29	3-12-64	943.79	Water—Ice cover
4-15-63	945.83	Gage 5.2	5-12-64	944.81	Gage 3.91
5-1-63	945.95	Gage 5.32	5-28-64	944.82	Gage 3.92
5-13-63	946.23	Gage 5.60	6-11-64	944.56	Gage 3.65
5-15-63	946.23	Gage 5.60	6-22-64	944.47	Gage 3.57
5-17-63	946.27	Gage 5.64	6-25-64	944.44	Gage 3.54 (New gage 4.06)
5-23-63	946.16	Gage 5.53	7-23-64	944.13	Gage 3.75 (Gage corrected to 3.85)
5-31-63	946.07	Gage 5.44	8-7-64	943.78	Gage 3.50
6-11-63	946.15	Gage 5.52	8-21-64	943.70	Gage 3.42 (Gage corrected to 3.81)
6-24-63	945.82	Gage 5.19	8-31-64	943.84	Gage 3.95
6-27-63	945.81	Gage 5.18	9-10-64	944.17	Gage 4.28
8-9-63	945.53	Gage 4.90	9-17-64	944.04	Gage 4.15
7-17-63	945.41	Gage 4.78	9-24-64	944.14	Gage 4.25
7-31-63	945.27	Gage 4.64	10-17-64	944.04	Gage 4.15
8-12-63	945.10	Gage 4.47	11-9-64	943.85	Gage 3.96
8-26-63	944.86	Gage 4.23	11-21-64	943.77	Gage 3.88 — Ice
8-28-63	944.82	Gage 4.19	1-9-65	943.60	Direct reading
9-5-63	944.81	Gage 4.18	4-22-65	949.44	Direct reading
9-13-63	944.68	Gage 4.05	5-1-65	949.23	Direct reading
9-26-63	944.69	Gage 4.06	5-6-65	949.10	Direct reading
10-24-63	944.45	Gage 3.82	5-15-65	948.90	Direct reading
12-20-63	944.11	Ice			

to 0.05 mm, silt-size particles 0.05 to 0.002 mm, and clay-size particles are less than 0.002 mm).

The percentage of sand, silt, and clay particles in the soil material was determined by the improved hydrometer method using the procedure described by G. J. Bouyoucos (1962).

The sand was taken as one size fraction and no further sieve analyses were done to differentiate between coarse, medium, and fine sand sizes.

When the soil material contained more than 10 percent gravel, it was designated as gravelly, and the texture class was determined on the basis of the amount of sand, silt, and clay-size particles expressed as percentage of the total weight of these three sizes only. (In the following tabulation the percentage is shown as part of the total weight of the soil material including gravel.)

The bottom samples were of special significance in the project. A large percentage of bottom samples were very fine-grained and organic matter was often abundant. In order to get a clearer idea of just what these fine sediments were like, we retained small portions for microscopic study using a petrographic microscope. All bottom samples were examined at magnifications of 128 and 320 diameters and, where coarse material was abundant, at 50 diameters.

In addition to the above routine tests, X-ray examinations were made of selected samples to identify the clay minerals. Pollen studies of other samples provided estimates of age of the bottom sediments at a given depth.

GENERAL SUMMARY OF DATA

Nature of the Glacial Deposits Adjacent to the Ponds and Lakes Investigated

The general nature of the glacial deposits has been described in the introductory part of this report and specific data have been included later to describe individual bodies of water. It is desirable to discuss and summarize the results of the investigation of the unconsolidated material adjacent to the pond and lakes and to compare them with the bottom sediments.

To investigate the nature of the drift materials adjacent to the water bodies, a total of over 200 shallow test holes were made. These ranged in depth from a few feet to a maximum of over 20 feet. Likewise, the distance of these test holes from the water's edge ranged up to 400 feet but most holes were within 100 feet of water's edge. From these holes, we collected over 100 samples, and most were classified by the laboratory methods described above.

As would be expected in glacial material, the samples showed a wide range of compositions and size of particles; nevertheless some deposits are notably consistent. This is particularly true of the sandy outwash deposits of the Belle Prairie and Isanti Quadrangles, the latter being a part of the so-called Anoka Sand Plain. For example, 100 samples from the test holes in the deposits of the Anoka Sand Plain had the following average composition: clay 3.5 percent, silt 4.7 percent, sand 91.8 percent. This is probably typical for conditions within the immediate vicinity of the ponds and lakes investigated but not necessarily of the areas as a whole. The area covered by such deposits is limited and offers a special case of permeable material from which the samples were selected. A detailed explanation of the origin of the Anoka Sand Plain is given by Cooper (1935).

Most of the other areas were believed to be more or less typical of the deposits of moraines and till plains. Seventy-five samples had an average composition of gravel, 8.8 percent; sand, 45.9 percent; silt, 26.5 percent, and clay, 18.8 percent. In addition boulders and cobbles are common in much of the drift. The material is so variable and ranges so widely that the percentages are indicative only and are by no means statistically accurate.

In the Detroit Lakes area (Audubon Quadrangle) infiltration of water in eight holes—each near the shore of separate lakes—showed a range from slight to very rapid movement of water out of the test holes. The clay-silt content of samples from the holes ranged from 9 to 76 percent, sand from 24 to 91 percent, and gravel from 2 to 41 percent. The wide range in composition is characteristic of terminal moraine deposits and thus of the range in permeability of the soils. Although the test holes at pond A 1 showed a similar wide range of composition, the water level was remarkably stable, even during winter months. (Elevation 1,389.16 on October 10, 1964 to 1,388.93 on March 25, 1965.)

Bottom Sediments

The fact that ponds and lakes exist at different elevations even within limited areas (figures 2, 17, 36, 41, and 49), in spite of the glacial deposits' ability to transmit water freely, emphasizes the importance of the sediments holding water in the bottom of the depressions. For this reason, special attention was paid to sampling, and laboratory investigation of test holes in the bottom sediments. Scores of test holes were made through the ice and a total of 61 samples were subject to detailed studies. Of the 61 samples, we judged six to be in glacial sediments below the water laid deposits, since the samples contained gravel and other material similar to that recorded for the glacial sediments taken on land.

The results of the laboratory classification of the 55 samples were then averaged for comparison with the glacial sediments. Samples from the Anoka Sand Plain were not included as the adjacent soil is about 95 percent sand.

Percent	Gravel	Clay	Silt	Sand
Bottom Sediments	0	23.5	45.6	31.9
Glacial Drift	8.8	18.8	26.5	45.9

Most of the bottom sediments contained organic matter with the sediment immediately below the water in the ponds sampled generally peat or soft water muck. Various field observations to date show that the dense peat, muck, and clay-silt sediments are highly impervious. A small portion of each bottom sample was reserved for microscopic study using a petrographic microscope to permit identification of the minerals. The results are given in the descriptions of the individual potholes, but a general summary is desirable.

As shown by the size classification, sand-size grains are abundant. Microscopic study shows that quartz is the most abundant mineral, but feldspar and lesser amounts of other silicate minerals are present. The sand-size grains range in shape from angular to round. Smaller grains of sand size were decidedly angular. As also shown by the size classification, silt-size grains are the most abundant. Quartz is by far the most abundant mineral found in bottom sediments. Pyroxene, amphibole, mica, zircon, sphene, and ilmenite were present as scattered grains in most samples.

Perhaps the most significant grains present in a majority of samples consisted of amorphous silica (chert) in the diatom skeletons. These microscopic algae are abundant in fresh as well as marine water and were useful in proving that the sediment under study was deposited in water.

The clay-size material in the samples presented a difficult problem of identification, not only because of the extremely small size of the grains, but because of the presence of abundant organic matter which tended to mask the clay particles. The laboratory classification showed that clay-size particles comprise about a fourth of the average sediment. Microscopic studies showed that the average sediment also contained two or three clay minerals, but positive identification was impractical. Determinations of the clay fraction in four samples by the X-ray method are shown in table 3. The samples came from widely separated areas and probably are representative of the clay minerals in the drift and bottom sediments.

Table 3. X-ray determinations of clay minerals*

Sample No.	Pothole	CaMontmorillonite	Muscovite (Mica)	Chlorite and Kaolinite
33B	In 3	5-6	2-3	2
162	N 4	3.5	4	2.5
166	M 1	2.7	4.5	2.7
192	Gr 1	3.0-4.0	3.0-4.0	0.1-2.0 0.5-1.0

* Analyses made by Prof. W. E. Parham, Minnesota Geological Survey.

The different clay minerals significantly affect the permeability of the clay as emphasized by Grim (p. 240, 1962). Clay tends to fill the voids between grains of silt, sand, and gravel, and there is definite correlation between clay mineral compositon and the order of magnitude of permeability.

Grim (p. 241, 1962) cites a table by Endell *et al* giving permeability K in cm/min at 65 kg/sq. cm for various mixtures of sand and clay minerals, including pure clay. Comparisons from the cited table are pertinent to the analysis shown in table 3. It is noted that quartz sand, mica, kaolinite, and ca-montmorillonite have a permeability (K) value of 1 x 10^{-3}, 4.9 x 10^{-4}, 3.0 x 10^{-6} and 2.0 x 10^{-7}, respectively.

Na-montmorillonite is impermeable. It should be explained that the X-ray method used in obtaining the analyses given in table 3 gives the dominant montmorillonite, but some Na-montmorillonite is doubtless present, as is common where ion-exchange is involved. The presence of much montmorillonite in the clays of the bottom sediments of ponds and lakes in Minnesota is important in reducing permeability.

Organic matter in the bottom sediments has been briefly noted above, but further description is desirable. The muck (and clay-silt sediment below) ranges in color from black to light gray both in bulk and under the microscope. When organic matter is abundant, its appearance under the microscope in plain polarized light ranged from black to brown to tan, depending primarily on its abundance and particle size. The prevailing characteristic of this material is that the organic matter, clay minerals, and silt particles from aggregates in which the grains of silt, mainly quartz, are clearly enclosed in aggregates. Just what effect, if any, the aggregates have on the grain size determinations in the laboratory process remains to be determined. It seems possible that aggregation or flocculation of the organic matter and fine particles makes the sediment more impervious.

Table 4. Comparison of evaporation and precipitation

	70% of Pan Evaporation (in inches) Farmington	Precipitation (in inches) Minneapolis	Excess or Deficiency of Evaporation (in inches)
1962......	25.47 (May-October only)	28.83	—3.46
1963......	27.40 (May-September only)	19.57	+7.83
1964......	29.90 (May-September only)	25.97	+3.93

Precipitation and Evaporation

That precipitation and evaporation are by far the most important factors in determining water levels in isolated bodies of water is verified by the results of the present studies. Since Minnesota has a continental climate, the weather is subject to wide fluctuations, not only throughout the year but from year to year and the effects of this are shown in the levels of the ponds and lakes included in this investigation.

It was not practical to establish rain gages at the 47 locations investigated. Instead it was necessary to use the climatological data of the Weather Bureau, U. S. Department of Commerce. Fortunately several of the sites for regular observations of precipitation were reasonably

Table 5. Precipitation in 1962 at selected locations. U.S. Weather Bureau records. (Precipitation in inches.)

	Minneapolis		Forest Lake	St. Peter		Redwood Falls		Willmar		Morris		Little Falls
Jan.	.55	—.15	34	.25	—.60	.41	—.13	.65	.07	.51	—.06	.55
Feb.	2.07	1.29	1.18	1.82	.94	1.26	.94	1.75	1.09	1.55	.87	1.22
March	1.87	.34	1.73	1.45	—.17	1.02	—.36	1.06	—.10	.79	—.35	.86
April	1.32	—.54	.98	1.22	—.94	1.79	—.18	1.60	—.44	1.60	—.69	1.00
May	8.03	4.84	5.73	6.79	3.16	4:05	.78	5.61	2.39	6.43	3.47	7.18
June	1.48	—2.52	3.00	2.15	—3.19	3.64	—.64	2.84	1.64	3.89	—.05	2.37
July	5.12	1.85	4.63	7.24	4.05	8.27	5.43	5.82	3.01	9.09	5.91	7.93
August	3.47	.29	5.90	4.19	.41	3.62	.41	1.77	—1.83	1.76	1.27	3.08
Sept.	2.46	.03	2.85	.164	—1.12	2.06	—.09	3.58	.91	3.93	2.04	2.69
October	1.69	.10	1.49	1.40	—.15	2.80	1.44	1.44	.09	.51	—.94	.65
Nov.	.52	—.98	.63	.23	—1.31	.31	—.87	.66	—.49	.46	—.55	.47
Dec.	.26	—.60	.25	.12	.81	.17	—.47	.09	—.48	.07	—.54	.10
TOTAL	28.83	4.05	28.71	38.50	.34	28.40	5.81	26.87	2.400	30.42	7.84	28.08

EVAPORATION

	Farmington	Stewart
May	7.85	6.89
June	7.76	7.05
July	5.59	6.02
Aug.	7.38	7.26
Sept.	4.55	4.29
Oct.	3.25	3.57
Total	36.38	35.08

Minus sign indicates below normal.

Table 6. Precipitation and class A pan evaporation for 1963 at selected locations

	Minneapolis		Forest Lake	St. Peter		Redwood Falls		Willmar		Morris		Little Falls
Jan.	.46	—.24	.18	.34	—.52	.62	+.08	.59	+.01	.34	—.23	.23
Feb.	.41	—.37	.20	.39	—.49	.60	—.17	.34	—.32	.68	+.02	.48
March	1.18	—.35	1.04	1.07	—.55	.88	—.50	2.03	+87.00	1.73	+.59	1.11
April	2.07	+.22	1.91	2.29	+.07	2.62	+.44	4.84	+2.80	2.70	+.56	3.44
May	5.06	+1.87	4.10	2.88	—.75	5.68	+2.41	5.38	+2.16	3.16	+.20	5.04
June	1.91	—2.09	2.94	4.92	+.36	3.39	—.89	5.46	+.98	4.33	+.39	3.08
July	1.53	— 1.74	3.35	6.36	+3.17	8.52	+5.68	3.05	+.24	4.41	+1.23	4.02
Aug.	1.55	—1.63	1.91	2.67	—1.12	3.48	+.27	2.78	—.82	3.00	+.03	4.35
Sept.	3.46	+1.04	3.15	2.56	—.19	3.72	1.57	5.36	+2.59	2.56	+.67	2.25
Oct.	.81	—.78	.38	1.85	+.30	1.44	.08	2.49	+.96	2.22	+.77	1.51
Nov.	.52	—.88	.49	.29	—1.31	.29	—.89	.45	—.70	.53	—.48	.99
Dec.	.60	—.26	.77	.36	—.57	.24	—.40	1.09	+.52	.63	+.02	1.26
TOTAL	19.21	—5.21	20.42	25.86	—2.30	31.27	+4.38	33.86	+9.39	26.29	+3.71	27.76

Class A Pan Evaporation

	Farmington	Stewart
May	7.29	7.30
June	10.11	9.74
July	8.68	7.91
Aug.	7.60	6.49
Sept.	5.46	4.81
Total	39.14	36.25

Table 7. Precipitation and class A pan evaporation for 1964 at selected locations, U.S. Weather Bureau records (Precipitation in inches)

	Minneapolis		Forest Lake	St. Peter		Redwood Falls		Willmar		Morris		Little Falls
Jan.	.67	—.23	.65	.14	—.71	.25	—.29	.24	—.34	1.21	—.34	.19
Feb.	.06	—.72	.02	Tr	—.88	.08	—.69	.20	—.46	.17	—.49	Tr
March	1.35	—.18	.98	.95	—.67	.88	—.50	1.64	+.41	1.39	+.25	1.27
April	2.98	+1.13	3.63	3.34	+1.15	2.84	—.87	4.02	+1.98	3.64	+1.50	2.52
May	3.44	+.25	4.13	4.46	+.83	2.89	—.38	2.28	—.94	.28	—2.68	1.88
June	2.18	—1.82	1.61	2.05	—3.23	1.30	—2.98	2.49	—1.99	2.75	—1.19	2.35
July	2.02	—1.25	1.44	3.63	+.44	1.71	—1.13	2.35	—.46	2.21	—.97	3.91
Aug.	5.42	2.24	4.70	6.90	+3.12	3.61	.40	6.68	+3.08	6.01	+2.98	7.83
Sept.	5.21	2.78	3.40	5.80	+3.05	2.81	—.66	1.98	—.69	1.53	—.36	2.69
Oct.	.57	—1.02	.49	.37	— 1.18	.49	—.87	.02	—1.51	.06	—1.39	.23
Nov.	1.19	—.21	1.14	1.36	—.18	.30	—.88	.74	—.41	.35	—.66	1.05
Dec.	1.08	+.22	1.53	.86	—.07	.37	—.27	.57	.00	.29	—.32	.44
TOTAL	25.97	+1.19	23.16	29.86	+1.70	17.53	—6.06	23.14	—1.33	18.89	—3.67	24.36

Class A Pan Evaporation

	Farmington	Waseca
May	9.29	8.24
June	10.11	8.46
July	10.18	9.10
Aug.	8.36	6.92
Sept.	4.78	3.71
Total	42.72	37.61

Table 8. Examples of the rise in water level in spring 1965

Pothole No.	From	To	Rise Feet
B 1	12-31-1964	4-22-1965	4.24
In 1	12-31-1964	4-22-1965	7.06
In 2	12-31-1964	4-22-1965	3.87
In 3	12-31-1964	4-22-1965	5.69
In 4	12-31-1964	4-22-1965	8.31
In 5	12-31-1964	4-22-1965	8.23
In 7	12-31-1964	4-22-1965	7.92
LE 3	12-31-1964	4-29-1965	7.18
LE 4	1- 9-1965	4-22-1965	5.84
M 1	1- 9-1965	5- 4-1965	8.69
M 2	1- 5-1965	4-29-1965	5.66
M 3	1- 9-1965	4-29-1965	5.54
N 1	1-22-1965	5- 4-1965	11.46
S.P. 1	12-31-1964	5-27-1965	4.84
S.P. 2	12-31-1964	5-27-1965	5.76
S.P. 3	12-31-1964	5-27-1965	7.57

+ for above normal.
— for below normal.

close to most of the ponds and lakes included in this investigation and probably no serious errors are involved in using the data for comparison with the fluctuations in water levels. Climatological data for this investigation were taken from the Weather Bureau's "Annual Summaries for Minnesota," and are shown in tables 5 through 7.

Evaporation, as reported by the Weather Bureau for Minnesota, normally exceeds precipitation by several inches. The best available comparison is for precipitation at the Minneapolis-St. Paul Airport and pan evaporation at Farmington, 16 miles to the south.

Precipitation during 1963 and 1964 was nominal so run-in was small and the accumulated excess evaporation over precipitation was 11.86 inches, plus additional evaporation not measured, particularly during October. This may account for the fact that many shallow ponds and marshes become dry and all water levels under this investigation were lower during this period. The above facts, plus the distribution of precipitation as shown by months, should be kept in mind later in reviewing the graphs of levels (figures 9, 10, 25, 26, 31, 32, 42, and 43).

Pond and Lake Level Changes

The detailed data presented later for the individual bodies of water show by means of graphs and water level summaries, where lesser data are available, that there is much variation in how levels react. Data accumulated since the first phase of the work was completed have emphasized these differences to a much greater degree. This is not surprising in view of the wide variety of topographic and soil conditions involved. Although weather conditions were not uniform over the study area, it is not felt that such nonuniformity was entirely responsible for the striking differences found in water level fluctuations of the ponds and lakes during a given year.

While it is recognized that topographic conditions are important, steep slopes alone may not provide abundant run-in. Pavements, road ditches, cultivated fields, etc. may result in a greater rise in levels, especially during the spring thaw when frost inhibits free infiltration into the soil. A heavy cover of grass, brush, etc. is usually effective in reducing direct run-in.

The years 1963 and 1964 were characterized in Minnesota, with some exceptions, by generally normal or below normal precipitation and high evaporation with the result that lake and pond levels in many parts of the state declined, some rather drastically. Thus ponds and lakes which appeared to be at about average levels when first examined in the summer and autumn of 1962 declined during 1963 and 1964 and a few became almost dry. One small pond (LE 3) dried up completely. A careful review of the data accumulated in the period 1962 to spring 1965 indicates that the decline in water levels was more largely due to low precipitation and excessive evaporation than to seepage, although where appreciable seepage was added to the former the effect was naturally great.

The usual regimen for a lake or pond without inlet or outlet is for fairly stable levels during the winter months when precipitation is commonly at a minimum in Minnesota (see tables 5-7). With increased spring precipitation through June, pond and lake levels usually rise. By that time, however, evaporation is high and as precipitation commonly decreases during the remainder of the year a pronounced decline in levels usually occurs until a more nearly stable situation is reached in autumn.

DISCUSSION OF RESULTS

General Statement

The amount of data resulting from this investigation is very large and some readers will doubtless be interested in the general results rather than in the detailed data. It is felt, however, that part of the detail data on the individual bodies of water should be presented so that anyone desiring to do so can review the data and form his own conclusions as to their significance. For these reasons, the general discussion is presented ahead of the detailed descriptions of the individual lakes and ponds. The figures referred to in the general section are placed with the detailed descriptions.

Significance of the Drainage Area

An important factor in the overall hydrology of potholes is the drainage area—not only its size but the typography, cover of vegetation, cultivation, pasturing, works of man and so on. Most of the potholes and small lakes investigated thus far have a relatively small drainage area. Moreover, there is normally meager evidence of run-in except during the spring thaw. Where slopes are moderate to steep there are, at places, small drainageways or gullies, but at most places there is no movement of water along them unless rainfall is abnormally heavy. The area adjacent to the potholes is mostly meadow or brush and woods and, less commonly, cultivated fields. But the presence of paved roads and accompanying ditches was an important factor in leading water into the depressions occupied by ponds or small lakes.

Available time and funds were not sufficient to map the drainage area tributary to the large number of ponds and lakes involved in the project, but it is certain from the observations made that the drainage area is not usually the main controlling factor in the water level.

Seepage

As stated earlier, one of the prime objectives of the investigation was to determine how important seepage out of ponds or potholes was in recharging groundwater. As the work progressed, it became evident that the ability of the water to seep into the soil at most places is very different between the normal basin and the area covered when high water spills out over the adjacent ground.

Numerous test holes located in the general proximity of the potholes show that the soil and glacial drift above the shoreline is usually permeable as was verified by filling the holes with water and observing the time for it to decline in the holes. The fact that the soil around the ponds does accept water is shown by a more rapid decline in the surface level of the pond or small lake when it has overflowed its normal shoreline. Thus, a relatively rapid decline occurs if there is a strong spring rise. As the high temperatures of July and August occur, the decline adjusts because of the excess of evaporation over precipitation. Heavy rainfall can, of course, interrupt the decline, but ordinary rains have only minor effect.

The second aspect of the seepage out of the ponds and small lakes under study is seepage that occurs when the surface water level is at about a normal level, that is, what is judged to be the most permanent shoreline. Experience, even in the short period of the work started in 1962, showed that much subjective estimation was involved.

Obviously there are various approaches to the problem of seepage. Shortly after work was started, we learned that the U.S. Geological Survey was starting a very detailed, localized study of the problem in North Dakota. Since the seepage problem in Minnesota dealt with a great diversity of physical situations, funds at that time did not permit intensive instrumentation. It was decided, therefore, that a preliminary estimate of the amount of seepage could be obtained by measuring water and ice levels, undisturbed when evaporation was prevented by ice cover and precipitation was largely in the form of snow. For comparison, water levels were measured throughout the year. Water levels for 1963 and 1964 are shown in a general way by the graphs of figures 9, 10, 25, 26, 31, 32, 42, and 43.

During the three winters of the period 1962 to 1965 a weighted average of 52 observations of apparent loss by seepage during ice cover was .00245 foot per day, or .894 foot per year. Several ponds and small lakes showed small gains in ice and water levels and were eliminated in obtaining the average. Reasons for the gains were not always evident but a winter rain in January 1965 was partly responsible. Detailed observations on 46 ponds and small lakes and 7 larger lakes are given in the final section of this report.

The large loss by seepage of the Ma 1 pothole on the Johnson farm in northern Washington County contrasts sharply with the small seepage losses given above. From a high level on April 4, 1963 to a low on December 19, 1963, the decline was practically 5 feet. The excess of evaporation over precipitation was somewhat less than 1 foot, so the indicated seepage during the 9-month period was 4 feet. This is an indication of the loss that might be expected if the other bodies under observation were not largely sealed in by bottom sediments.

Effects of Storm Run-Off

It was expected when the investigation began that heavy rainfall would normally result in a rise of level beyond the actual precipitation on the water surface. The gage readings soon indicated that this was not usually true even where steep slopes existed around the pond or lake. In this connection it must be remembered that Minnesota is not an area of heavy precipitation, only about 25 inches annually in the Minneapolis-St. Paul area. Nevertheless, there are occasional storms of considerable intensity. In September 1964, 6 inches of rain fell in the area in 3 weeks. Inspection of a number of the ponds and lakes under investigation showed a complete lack of evidence of surface run-in, even though steep slopes were common. This was explained, in part, by the fact that a dry period preceded the rain and the generally sandy soil had a high absorptive capacity but equally important, perhaps, was the relatively heavy cover of grass, weeds, etc.

When natural conditions are disturbed, storm water may result in a drastic rise as was shown in 1964 at pond N4, located near the corner of Lexington Avenue and Victoria Street in northern Ramsey County. During the summer there had been a great deal of disturbance at the top of a long northerly slope which ended at the pond. Streets were paved on the high ground and the slope was largely denuded of sod, brush, and trees. As a result when fairly heavy rainfall came in late August and early September runoff was increased from the pavement and bare slopes. The pond accordingly rose abruptly from 932.31 on August 7 to 934.04. Meanwhile, the lower lake (N 5), a short distance to the north, rose only a normal amount, that is, 0.37 foot.

Effects of Frost and Snow Melt

The relatively slight effects of heavy rainfall where natural conditions are not disturbed has been emphasized above. It should be noted that a different situation exists when the ground has relatively deep frost and there is snow melt and rain at the same time.

Precipitation during the winters of 1962, 1963, and 1964 was below normal. Consequently there was a small runoff in the spring and a relatively minor rise in the ponds and lakes. The late winter and spring of 1965 was, however, in sharp contrast. For example, at the Minneapolis-St. Paul International Airport the excess of precipitation over normal during February through May 1965 was 10.37 inches. A very cold winter combined with good fall moisture in the soil resulted in thoroughly frozen ground. Subnormal temperatures delayed thawing of the snow cover so thawing was rapid when the temperature finally moderated. The result was record floods in the Minnesota and Upper Mississippi Rivers and unusually heavy runoff adjacent to the potholes under study. In 16 potholes considered typical of conditions favorable to run-in during the spring thaw, the range in water level rise was from 3.87 to 11.46, with an average of 6.15 feet. Table 8 serves to emphasize the point.

In sharp contrast was the situation in the Anoka Sand Plain where the sandy soil was not saturated near the surface and the topography is of low relief. In this area the rise of five potholes and small lakes averaged only 1.36 feet from January 5 to May 25, 1965. This doubtless is accounted for by the porous sandy soil which did not retain enough water near the surface to form a frost seal. Consequently, during the thawing of the heavy snow cover, there was little, if any, direct run-in to the ponds and lakes but instead the thaw-water soaked into the ground and thence contributed to the open bodies by seepage. This situation was recognized by Storey (1955) who stated that frost in light-textured (sandy) soils is relatively ineffective in preventing percolation of precipitation. The reverse for heavy soils was emphasized by Schneider (1961) in a report of his studies on frost in Minnesota soils.

The considerable range of the rises in water levels listed in table 8 is, in part, a result of topography. Steep slopes in general caused heavy run-in, but other factors such as drainage area, paved roads and road ditches, cultivated fields versus meadows or woodlands all had their effect.

Data were obtained for five small, isolated ponds and small lakes in the prairie country of west-central Minnesota where relief is low and the soil has a relatively high content of clay and silt. The average rise of the five bodies of water was 2.44 feet for the spring of 1965, or considerably less than half of the average of table 8. The 16 bodies of water involved in table 8 are in morainic areas of considerable relief and have a variable soil.

Groundwater Movement into Ponds and Small Lakes

One of the most difficult factors to evaluate in a study of the levels of ponds and small lakes, which have neither surface inlet nor outlet, is the possibility of movement of water underground into the body. One commonly hears the statement that a water body is spring fed. In deep lakes it seems that in many cases infiltration from groundwater must be important. But in the mostly shallow bodies involved in the present investigation this is probably of little importance and, with the exception of examples where the open water and water table coincide, this movement seems to be relatively unimportant.

Several of the ponds or small lakes investigated were specifically selected because they were in relatively deep depressions, and it was assumed there would be inflow underground from the high land. When test holes were made at all of the sites, evidence of movement into the open water was uncommon and at many places nonexistent. A preliminary conclusion is that for shallow bodies, rarely 10 feet deep, inflow underground is largely limited to a wet spring period and is by no means prevalent even then at all sites.

During wet periods it was possible at a few places to find seepage out of the ground near the shore, and evidence in test holes indicated the possibility of movement toward the open water. As soon as general surface moisture dried up, these evidences largely disappeared. There are 40 small cross sections included in the detailed descriptions later in this report showing the relation of the water level in test holes near the ponds and lakes. Of these, 26 show a slope of the water surface away from the pond and three others show a slope away on one side and in toward the pond on the other. Only six showed water in the holes above pond level. The water level in seven of the holes was essentially the same as pond level. Six of these are in the Anoka Sand Plain area and one in a sandy alluvial deposit along the Mississippi River. It is particularly noteworthy that in figures 11, 12, 16, 20, 22, 34, 35, 37, 39, and 47, the water level in the holes is far below pond level, and it is doubtful if a continuous water level extends from pond level to the water level in the holes. In short, perched potholes appear to be a common situation but the relationship is certainly not simple and, as shown by the description of Pine Bend (In. 7) Pothole, the situation there was reversed within a relatively short time.

There appears to be no doubt that most open bodies of water in the Anoka Sand Plain receive water by inflow from the ground during periods of heavy evaporation and low precipitation. Because of the porous, sandy soil there is essentially no surface run-in for the isolated ponds and small lakes, so it would appear that they do not contribute to the groundwater at any time mainly because direct run-in does not occur on account of the permeable soil.

DETAILED DESCRIPTION OF LAKES AND PONDS INVESTIGATED AND RESULTS

In the course of this investigation a large mass of data was accumulated. It is not practical to incorporate all of the primary data in this report, but it is desirable to present as much as possible within limitations of space and cost. A great deal of primary data on water levels is presented by graphs. Complete files of the original tabulations are available in the Department of Agricultural Engineering and will be opened to inspection by anyone interested in more detail than is presented here. A list of the sites investigated is found in table 1.

Audubon Quadrangle (Detroit Lakes Area)

Lakes: The topographic maps of the Audubon Quadrangle and the adjacent Detroit Lakes sheet are excellent examples of the concentration of lakes and ponds on the terminal moraine of Becker County. Since elevations of the water surfaces as shown on published maps were quite variable (figure 2), an effort was made to determine the relation between characteristics of the soil and the water

Table 9. Textural classifications of samples from test holes at the Audubon Quadrangle

Sample No.	Hole	Depth	Lake	Gravel	Soil Separates		Sand	Soil Class
					Clay	Silt		
91	2	0-4′	Fox	40	1.8	3.6	54.6	Gravelly and sand
117	3	1.5-5.3′	Long	41	3.8	4.8	50.4	Gravelly loamy sand
89	1	0-3′	Long	40	1.2	4.2	54.6	Gravelly sand
90	3	1-4′	Monson	34	2.0	4.0	60.0	Gravelly sand
119	1	1.25′	Minnetonka	2	38.4	37.6	22.0	Clay loam
118	2	1.5-5.2′	Berseth	4	37.0	38.2	20.8	Clay loam
92	3	3-4.5′	A 1	Trace	21.4	46.8	31.8	Loam
171*	1B	4.0′	A 1	Trace	9.3	16.5	74.2	Sandy loam
172	1W	4.5′	A 1	Trace	8.8	24.0	67.2	Sandy loam
218*	1W	12-13′	A 1	27	6.2	1.2	65.6	Gravelly
219*	1W	18.3-19.3′	A 1	41	15.3	18.6	25.1	Loam

surfaces in lakes and ponds. In addition to the pond in section 30, described separately, preliminary investigations were made at Lakes Berseth, Fox, Long, Monson, and Sallie.

Test holes were made adjacent to each pond or lake to determine the soil types, and where possible to locate the position of the water table (see figures 3-5). The presence of rocks in the soil made it impracticable to reach the saturated zone in three holes. Table 9 shows the results of tests on the soil samples from several holes.

The presence of much sand and gravel in the moraine area is to be expected. There are several large gravel pits located in sections 31 and 36, less than a mile south of the pothole described below. These pits are also less than a mile west of Long and Monson Lakes where the soil is sandy. At Minnetonka and Berseth Lakes, however, the soil consists mainly of clay loam as is characteristic of the glacial drift derived from sources to the northwest. As would be expected, the rate at which water passes through the different soils varies widely. As shown by a number of infiltration tests, the clay loam soils transmitted water slowly and those in sand and gravel very rapidly. In accordance with the highly permeable nature of the soil in the vicinity of the larger lakes located in the outwash deposits along the east side of the quadrangle, the water levels are in close accordance and undoubtedly express the regional water table. On the contrary, the ponds and lakes to the west (on higher ground) stand at different levels and not in accordance with any reasonable water table. Moreover, it is noteworthy that the soil in that area is a clay loam (samples 118 and 119) that resists seepage.

A simple infiltration test in a 4-inch auger hole showed that the decline in water level in a hole 4.5 feet in depth at A 1 pothole, declined .67 foot in the initial 15 minutes of the test then became nearly stable. A test in a similar hole, 3 feet in depth and located on the south side of Long Lake, showed a decline of .73 foot in 15 minutes. At Fox Lake the decline was 2.8 feet in the same time interval.

At Minnetonka Lake, a test hole only 2 feet from the shoreline first encountered water in clay soil 3 feet below lake level. At Berseth Lake a hole 20 feet from the shoreline remained dry at a distance of 1.5 feet below lake level. In section 30, hole number 4 located near Pothole A 1 was sunk as a check on hole 3 and showed the water level to be 4 feet below pond level. The water table was 2 feet below pond level in hole 3, excavated September 19, 1963.

The accumulated data strongly indicate that the ponds and small lakes of the western part of the quadrangle are sealed in and do not contribute enough seepage to maintain a groundwater level at the level of the lakes. Water levels showing the relative stability of the lake levels with regard to seasonal variations in precipitation and evaporation are shown in table 10.

The January-March 1964 levels are particularly significant as the lakes were frozen over and evaporation, therefore, was negligible. Lakes Long, Monson, Sallie, and Fox rose 0.45, 0.30, 0.17, and 0.11 foot, respectively, during that period. According to the topographic map these lakes do not have streams flowing in or out. Therefore, assuming that these small rises are valid, there must have been contribution by groundwater from the higher land to the west which ranges up to elevation 1,440.

From October 10, 1964, to March 25, 1965, the levels again rose during a period when the lakes were frozen over most of the time. A rise of approximately a foot at Fox Lake indicates some surface run-in during a winter rain and thaw.

A-1 Pothole

West of the chain of lakes previously described in the area of terminal moraine are numerous lakes and potholes. Pothole A-1 in Section 30 was selected as typical of the small ponds of the area and also because it lies only about 1 mile west of the chain of lakes.

A-1 is a small pothole (about 4.5 acres) located on the Elmer Peterson farm in the SW¼, SW¼, sec. 30, T. 139 N., R. 41 W. It lies in a pronounced depression with a rather high hill on the southeast side and has a margin of cattails and also a floating bog with cattails and other

Table 10. Water levels for the Audubon Quadrangle

	Pothole	Long	Monson	Fox	Sallie
July 23, 1963	1388.8	1349.9	1328.8	1330.0	1325.5
August 21, 1963	1388.6	1350.1	1328.96	1329.1	1324.76
September 19, 1963	......	1350.03	......	......	......
January 1, 1964	1388.7	1350.25	1328.75	1330.54	1324.57
March 25, 1964	1388.63	1350.70	1329.05	1330.65	1324.74
June 19, 1964	1389.95	1350.21	1329.27	1330.57	1324.92
July 16, 1964	1389.54	1349.91	1328.99	1328.90	1324.60
August 13, 1964	1389.24	1349.77	1328.71	1328.94	1324.35
September 8, 1964	1389.2	1349.87	1328.82	1329.14	1324.54
October 10, 1964	1389.16	1349.98	1328.82	1329.26	1324.78
December 23, 1964	1389.03	1350.10	1328.90	1329.53	1324.67
March 25, 1965	1388.93	1350.10	1329.18	1330.25	1324.83
May 27, 1965	1391.73	1350.26	......	......	......
August 11, 1965	1390.80	1349.93	1328.94	1329.14	1824.57
September 21, 1965	1390.46	1350.05	1328.90	1329.36	1325.01
October 16, 1965	1390.48	1350.10	1328.98	1329.60	1324.95

marsh vegetation. Because the surrounding land has been cultivated, some soil probably has been carried in since the area was settled. The road, bordering the pond on the west, has also been graded. The pond is nearly 40 feet higher in elevation than Long Lake, located a distance of 1 mile to the east.

Test holes were installed on the south side of Pothole A-1, and on a low area which was only a foot or two above pond level (figure 5). The soil is mainly silt, but peat and sand were encountered in hole 3, about 22 feet from the water's edge. The water level in the holes when drilled was below pond level, but at a later time the level in holes 1 and 2 adjusted to pond level. The level in hole 3, although higher than when first observed, remained below pond level (figure 5). Three samples from the bottom of the pond (171, 218, and 219 of table 9) showed a high sand content.

Belle Prairie Quadrangle

Be-1. Mud Lake is located in Morrison County on a broad sandy terrace on the east side of the Mississippi River about 4 miles northeast of Little Falls. The lake, shown on the Belle Plaine topographic map, is located in the north half of Sec. 7, T. 41 N., R. 31 W., on the Dennis Douette farm. The river terrace in this area is several miles wide and ranges from 45 to 70 or more feet above the river, at average stage. A narrower flood plain or terrace exists at a lower level along the river, and Mud Lake, a shallow lake covering about 5 acres, is located on this terrace.

During wet periods a creek flows out of Mud Lake, but flow was negligible, or lacking, during the period 1962-64. The lake is surrounded by a fringe of willows at the original high-water line and by an extensive growth of marsh grass and cattails in the shallow water near the shore. The soil in the fields around the lake consists mainly of sand, and test holes on the north side indicate this to be generally the case to some depth (figure 6). Soil samples from the test holes were classified as shown in table 11.

As would be expected in view of the sandy soil, the water table in test holes near the lake is approximately the same as the level of the lake surface. Table 12 shows a summary of water level data from the test holes.

There is evidently a slight inclination of the water table toward the lake (figure 6). Hole 5 was dug 2 months after the other five holes as a check on this situation and seemed to verify the fact that Mud Lake is a water table lake. The lake level is undoubtedly maintained by movement of groundwater into it during the summer period of high evaporation. The period July 25 to September 20, 1963 was one of very low precipitation; yet the lake level declined only 0.14 foot, which is below the amount of evaporation during that period.

The decline of 0.42 foot during the period January to March 1964 when the lake and ground were frozen, following a very dry summer and fall in 1963, indicates a slight movement into the ground. The decline for a similar period in 1965 was 0.62 foot. In general, however, there is a very close adjustment between the groundwater level and lake level and there is little doubt that the water moves rather freely between lake and groundwater, depending on the weather.

To check the water's rate of movement through the soil an infiltration test was made on hole 6 which had the following log:

Log

Elevation of hole—1,139.05
Water level—1,133.45

150 feet north of Mud Lake

0-2.5 feet—Black sand
2.5-5.5 feet—Brown sand with clay-silt layers (sample 120)

The hole was filled with water to a point within .30 foot of the top and the rate of lowering observed. It was found that the water level dropped 3 feet in 20 minutes, indicating the high permeability of the outwash sand.

Table 11. Textural classification of samples from test holes at Mud Lake, Bell Prairie Quadrangle

No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
93	4	0-2.5′	none	5.3	6.6	88.1	sand
94	5	6-8′	11	5.4	14.3	80.3	loamy sand
120	6	2.5-55′	3	12.1	11.6	76.3	loamy sand
*220	1B	6.8-77.8′	3	1.9	3.6	94.5	sand
*221	1B	13-14′	none	1.8	2.0	96.2	sand

* Denotes bottom samples.

Table 12. The relation of lake level to water level in test holes at Mud Lake

Hole No.	Lake Level	Hole Elev.	Dist. to Shore	Depth to Water	Water Level	Date
1	1,133.1	1,133.5	10′	0.2′	1,133.3	7/25/63
2	1,133.1	1,134.4	25′	1.0′	1,133.4	7/25/63
3	1,133.1	1,134.9	55′	1.4′	1,133.5	7/25/63
4	1,133.1	1,135.3	70′	1.7′	1,133.6	7/25/63
5	1,132.63	1,139.05	150′	5.6′	1,133.45	9/20/63
6	1,133.1	1,142.8	400′	8′+	1,134.8	7/25/63

Table 13. Water levels of Mud Lake

Date	Elevation
July 25, 1963	1133.1
August 22, 1963	1133.2
September 20, 1963	1132.96
January 4, 1964	1132.27
March 25, 1964	1131.85
June 19, 1964	1132.83
July 15, 1964	1132.49
August 13, 1964	1132.14
September 9, 1964	1131.84
October 9, 1964	1132.83
December 29, 1964	1132.52
March 25, 1965	1131.90

Bloomington Quadrangle

Bl-1 Pothole. This small lake lies in the extreme northeast corner of Sec. 18, T. 27 N., R. 24 W. in the village of Bloomington, Hennepin County. This pothole occupies about 18 acres and is roughly equidimensional. Its topographic situation is somewhat unusual in that it lies on the west border of the alluvial plain of Ninemile Creek but is surrounded on the south and west sides by partly cultivated hills of the prominent St. Croix Moraine, thinly overlain by gray drift of the Des Moines Lobe. When first observed in 1962, the water surface was at elevation 802.04 as compared with 799.0 for Ninemile Creek, about one-fourth mile to the north. Bl-1 Pothole is cut off from the swamp along the creek by a low ridge on the north and the grade of France Avenue on the east. The pond was selected particularly to determine its relation to Ninemile Creek and to the much higher land on the south and west sides.

Several test holes were dug on the southwest side and on the north sides of the pond (figures 7 and 8). On the southwest side peat was encountered about 75 feet from the 1962 water's edge showing that earlier stages of the pond were higher. Clay and sand prevailed farther out as shown by figure 7, but an offset hole on the slope of the hill to the south revealed mainly sand and gravel. Water tables in holes near the pond were at pond level, but water was first encountered below pond level in a hole 200 feet west of Bl-1 pothole. This was contrary to our expectations, as we thought the water probably moved from the hills on the west into the pond. Laboratory classification of samples from test holes are shown in table 14.

On the north side a group of three test holes produced clay, sand, and gravel (figure 8). The water level in the holes coincided with that of the pond but was somewhat above Ninemile Creek, 802.8 as compared with 799.4 on the date of the test. The holes are approximately 1,200 feet apart.

A soil sample from hole 4 on the southwest side contained 26 percent gravel and the remainder consisted mainly of sand. Infiltration tests showed that water moved rather freely in the ordinary soil of the area and, as would be expected, very rapidly into the sand and gravel. In hole 3 (a mixture of clay and sand) the movement of water out of the hole was slow which served to emphasize the range in the soil's character. In view of the facts cited above, it is surprising that the level of the pond is 3 feet above the creek nearby.

As previously noted, the water level of the pond, when first observed on August 28, 1962, was 802.84. This level remained relatively constant during the autumn of 1962 and had an ice level of 802.79 on December 18 (figures 9 and 10).* On March 14, 1963, the water level was at elevation 802.60. Thus in a period of over 6 months the water level had declined only 0.24 foot, and during the period of ice cover from December to March the ice and water levels declined 0.04 and .10 foot, respectively. It seems that seepage losses during that period were extremely small. Beginning March 14, 1963, the water level was determined at intervals throughout the remainder of the year, as shown by figure 9. There was a rise of .8 foot between March 13 and May 13, then a relatively stable level until June 7, and the usual rather consistent decline during the warm summer months (which in 1963 happened to be almost devoid of rainfall). After mid-September the decline slackened and was very gradual to the end of the year. The total decline from May 13 to December 23 was 2.51 feet — somewhat greater than that of the average pothole included in the project. It should be noted that precipitation during June, July, and August was less than half of normal and that corrected evaporation for the 3 months was 18.5 inches.

During the winter of 1963-64 Bl-1 froze to the bottom. The following spring was very dry and only a small recovery took place. By August 1964 the pond was almost dry. Heavy rains in late August and early September resulted in some recovery, but the water remained very shallow and gage readings had little significance.

The winter of 1964-65 was one of heavy snowfall and heavy rains in the later winter and spring with the result that by April 22 the water level had risen to elevation 805.18, a rise of 4.24 feet.

Bottom Samples

In winter 1963 samples were collected from a hole through the ice in the middle of Bl-1 where the water and watery muck was 8.6 feet deep. Samples at 3, 5.3, and 8.4 feet below the bottom contained organic matter of 72, 65.4, and 62.3 percent, respectively.

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* The graphs shown on figures 9, 10, 25, 26, 31, 32, 42, and 43 show changes in levels for ponds and lakes where sufficient data is available. These graphs were plotted with days and months shown horizontally and with the vertical divided into tenths for each .4 of an inch. For the present purpose .8 of an inch was deemed suitable for one foot and reduced one-half on reproduction so the effective vertical scale is .4 inch to 1 foot.

Table 14. Textural classification of samples from test holes in the Bloomington Quadrangle

Sample No.	Hole	Depth	Gravel	Clay	Silt	Sand	Soil Class
22	4	2-8.3	26	0	2.8	71.2	Sand
101	1	4.5-5	trace	30.8	43.9	25.3	Clay loam
145*	1W	2.9	72.0%		organic matter		Muck
46*	1W	5.3	65.4%		organic matter		Muck
47*	1W	8.4	62.3%		organic matter		Muck

* Denotes bottom samples. Sample 101 is from shore of a pond at France and 102nd Street.

Bl-2 Pothole. For comparison with pothole Bl-1, limited observations were made on a small pond (Bl-2) about one mile to the south (SW¼, SW¼, sec. 17, T. 116 N. R. 24 W.). Bl-2 is located near the northeast corner of the intersection of France Avenue and 102nd Street in Bloomington and near the southern border of the morainic area noted in the preceding description. One-fourth mile to the southeast the moraine borders a high level terrace of the Minnesota River. The pond is in the corner of a pasture that extends westward from a barnyard and receives drainage from the sloping pasture land and from the pavements of France Avenue and 102nd Street. Beginning in 1964 the area was greatly disturbed by home building.

The pothole was at a normal level (851.29) when first observed August 13, 1963. The water level remained relatively stable during the fall but had dropped to 850.88 on December 23, 1963. Unfortunately a thaw resulted in water over ice on March 12, 1964 and reliable data on the change of the water level during the winter could not be obtained. The decline from August, 1963 to April 9, 1964 was 1.1 feet and from December 24 to April 9, 0.69 foot. Since this was partly a period of ice cover on the pond there was evidently a small amount of seepage and evaporation. A slight rise was observed in May, 1964 to 851.16 and then a steady decline occurred until July, owing to a period of very low precipitation and high evaporation. Heavy rains from mid-August to mid-September 1964 resulted in a rise of 2.24 feet between August 1 and September 10. In contrast, Bl-1 rose but 0.28 foot. This difference is undoubtedly due to the fact that at Bl-2 there is a heavy turf, brush, etc., to control runoff. This shows that the level in Bl-2 is primarily controlled by the amount and intensity of precipitation, and ease of runoff into the pond. Our experience with this pond also showed that worthwhile results are difficult to obtain.

A sample from a hole on the east side (101) contained a high content of silt and clay, as shown by the laboratory results given in table 14.

Flensburg Quadrangle

The glacial sediments in the area west of the Mississippi River and the city of Little Falls in Morrison County were deposited by ice which came from the north (Patrician ice sheet) and differ somewhat from those glacial sediments to the east and west. In a detailed study of the Cushing Quadrangle immediately to the north of the Flensburg Quadrangle, Schneider (1961) describes the Culdrum-Parker till plain (ground moraine), which also includes the area around Flensburg. The plain is underlain by noncalcareous brown sandy till.

F-1 Lake Beauty

This lake covers about 40 acres in a level area, in the NE ¼, sec. 20, T. 129 N., R. 31 W. on the Trampe farm. The lake is fringed by a zone of pine and hardwood trees on shore and aquatic vegetation in the shallow water along the shore. A small intermittent stream enters from the west, but there is no outlet and normally little or no inflow. Numerous swamps and ponds occur in the surrounding area.

Test holes at the south side revealed a sandy soil (figure 11) with the water level sloping away from the lake, or perhaps extending beneath it. A check of the water level in the test holes 24 hours after they were dug showed only a slight rise, and a year later during a wet period the water level had risen somewhat but was still below lake level.

Table 15. The relation of lake levels to water level in test holes at Lake Beauty

Date	Lake	Hole 1	Hole 2	Hole 3
7-25-63	1219.2	1215.9	1215.2	1215.6
7-26-63	1219.2	1216.1	1215.9	1215.9
7-17-64	1220.37	1217.65	1219.4	1219.6

Table 16. Textural classifications of samples from test holes at the Flensburg Quadrangle

No.	Hole No.	Depth	Gravel	Clay	Silt	Sand	Class
95	2	0-8′	trace	15.6	44.8	39.6	loam
222*			10.9	6.8	12.7	68.7	gravelly sandy loam
96	3	5-9′	8.5	10.3	15.5	67.7	sandy loam
97	3A	4-4′	3	11.7	25.2	60.1	sandy loam
223*	1B	10-10.3′	0	29.8	46.2	24.0	clay loam

* Denotes bottom sediment.

An infiltration test in hole 3 showed a slow movement of water into the soil at a nearly constant rate for 15 minutes, as would be expected with over 60 percent clay and silt in the typical soil sample.

Table 17. Water Levels of Lake Beauty

July 25, 1963	1219.2	October 12, 1964	1220.98
August 22, 1963	1219.8	December 29, 1964	1220.45
January 4, 1964	1218.96	March 25, 1965	1220.27
March 25, 1964	1218.85	May 27, 1965	1222.97
June 19, 1964	12200.32	August 11, 1965	1222.71
July 17, 1964	1220.37	September 21, 1965	1221.53
August 13, 1964	1219.81	October 16, 1965	1222.00
September 9, 1964	1221.64	December 5, 1965	1222.16
		December 31, 1965	1222.15

The rise in water levels during the period July-August 1964 was the result of heavy rains during that period, otherwise evaporation would have controlled water levels. The very slight loss (0.11 foot) in the nearly 2 months from January 4 to March 25, 1964 indicates very little, if any seepage losses. Again in 1964-65 the decline from December 29 to March 25 (while the lake was covered with ice) was only 0.18 foot. A large snowfall and heavy rains after the breakup in the spring of 1965 resulted in a rise in lake level of 2.5 feet.

On December 30, 1964, bottom sediment samples were obtained, and the following conditions observed: 0-4 feet, ice and water; 4-35.6 feet, peat; 35.6-36.3 feet, gray sand; and 36.3-37.3 feet, glacial drift (sample 222). A microscopic examination of sample 222 showed round to subround sand grains, many consisting of translucent chert rather than crystalline quartz. The presence of gravel indicates glacial drift rather than a water deposit in the pond.

F-2 Pothole. This pond is about 1 mile southwest of Flensburg in the NE¼, sec. 35, T. 129 N., R. 31 W. on the Edward Super farm. Pothole F-2 has an area of about 8 acres and occupies a pronounced elongated depression in a pasture. There is a small grove along its southeast side and a well-developed marsh zone around the border. At high water levels F-2 flows northward but was below that level during the present observations. Evidence indicates that it becomes dry during drought periods, at least in late summer.

Test holes south of the pond on low ground revealed a black sandy silt. Laboratory classification of a typical sample (96) is shown in table 16. Sample 97 is from a hole adjacent to a pothole in Sec. 2, T. 128 N., R. 31 W. An infiltration test in hole 96 showed moderate seepage into the ground for 2 minutes, then a gradual decrease in rate to the end of the test at 41 minutes. The total decline was 1.75 feet.

The groundwater level slopes gently away from the pond level shown by figure 12. A check a year later showed the water level in hole 1 unchanged. Although the water level had risen in holes 2 and 3, it was still below pond level. The rise in Flensburg Pothole from July to August 1963 corresponds to that in Lake Beauty about 4 miles to the northwest and indicates heavy precipitation sometime during the period.

Table 18. Observed water levels of the Flensburg Pothole

July 25. 1963	1193.5	September 12, 1964	1194.06
August 22, 1963	1194.1	October 12, 1964	1193.59
January 4, 1964	1192.3	December 29, 1964	1193.04
March 25, 1964	1193.3	March 25, 1965	1192.70
June 19, 1964	1193.42	May 27, 1965	1197.85
July 17, 1964	1193.39	August 11, 1965	1196.06
August 13, 1964	1193.00	September 21, 1965	1195.62

The loss from August 1963 to January 1964 indicates evaporation during the dry late summer and autumn. The gain of .30 foot from January to March must be due to infiltration from groundwater. Snowfall was very light during the period and should not have affected the water level. Since the amount of gain is relatively insignificant, seepage into the ground from the pond must have been lacking during that period. In the winter of 1964-65, following a very dry year, a loss of .34 foot indicates a reversal of conditions resulting in a small loss of water.

That the pond is sealed off from the groundwater seems proven by the relation of the water level in test holes to that in the pond. The level in the holes when drilled on June 7, 1963 and a year later on July 17, 1964 was consistently below pond level.

Preliminary observations made in test holes at a small pond 1.4 miles southwest of F-2 pothole (Sec. 2, T. 128 N., R. W.) also showed the water level near the pond to be below pond level. Pertinent data are as follows: Pond level 1,178.5; hole 1 — 6 feet from pond — 1,178.5; hole 2 — 21 feet from pond — 1,176.9; hole 3 — 31 feet from pond — 1,176.1. A groundwater level of 2.4 feet below the level in a pond at a distance of only 31 feet indicates a complete isolation of the pond water from the groundwater. The soil in the three test holes was reported as black, sandy clay.

On December 30, 1964 bottom sediments were taken on pond F-2. The log is as follows:

Feet	
0-4	Ice and water
4-10	Peat
10-11	Silt — difficult to penetrate, sample 223.

Sample 223 had a high silt content and similar amounts of clay and sand. Such impervious material, with the peat, undoubtedly accounts for the permanence of the pond.

Sample 223 was examined with a petrographic microscope and the presence of numerous skeletons of diatoms showed that the sample was water laid, doubtless at an early stage of the pond. A portion of the sample was therefore submitted for detailed study of its pollen content to determine, if possible, when the deposit was laid. Details of the pollen work are given in a separate section of this bulletin but the following quote of the report is pertinent: "It seems reasonable to suggest from the preceding that sample 223 is between 8,000 and 11,000 years old."

Gaylord Quadrangle

Ga-1 (Mud Lake). Mud Lake is a shallow body of water located on the Clarence Harbarth farm in the SW¼, sec. 33, T. 113 N., R. 28 W., Sibley County. It has an area of about 33 acres and lies in the typical prairie area of south central Minnesota. Geologically Mud Lake is in the midst of a large area of ground moraine or till plain deposited by the Des Moines Lobe of the late Wisconsin ice sheet. A chain of shallow lakes exists along the west side of the Gaylord Quadrangle and Mud Lake is in about the middle of the group. The U.S. Geological Survey topographic map of the Gaylord Quadrangle, field checked in 1958, records lake elevations as follows: from north to south; Schilling, 993; High Island, 994; Hahn, 992; Mud, 991; Altnow, 983; Titlow (1.2 miles, SW), 984. The lakes probably represent a shallow drainageway for meltwater from ice of the retreating Des Moines Lobe but Mud Lake is on tributary drainage from the west.

The average depth in the middle of Mud Lake is about 4 feet. At high water levels this lake has an outlet to the east, but this was not active during 1962-64. (During the high water period in 1965 water flowed in from the ditch but as more normal conditions were established there was a slight reverse outflow). The present owner reports the lake has been dry only during the severe drought year of 1936. There is a lush growth of marsh grass in shallow water areas near shore, with more or less underwater vegetation throughout.

A well at the farm home on the north side of Mud Lake is reported to be only 30 feet deep, but another well at the barn a few hundred feet south is 170 feet deep, as are most wells in the vicinity. The regional water table may be at a considerable depth in the area, although the lake levels given above suggest a very shallow local zone of saturation.

Test holes showed a black prairie topsoil with sandy clay below (figure 13). The water level in the holes slopes away from the surface level of the lake.

Table 19. Water levels of Mud Lake, Gaylord Quadrangle

September 18, 1962	992.6
December 20, 1962	992.1
June 20, 1963	992.6
February 12, 1964	992.05
June 26, 1964	992.25
August 17, 1964	991.69
September 2, 1964	991.94
September 23, 1964	991.92
March 24, 1965	992.23
May 1, 1965	993.19
May 20, 1965	994.48
July 7, 1965	993.47
August 8, 1965	992.47
September 15, 1965	992.23

The pond level was remarkably stable during the period from September 18, 1962 to March 24, 1965 which, with the exception of snow during the winter of 1964-65, was a period of low precipitation. Unfortunately, records were too scattered prior to the winter of 1964-65 to furnish much information on the water level when the lake was frozen over but there appeared to be little change.

From September 23, 1964 to March 24, 1965, however, the level rose slightly during a period when an ice cover prevailed much of the time, and a rise of about 1 foot occurred during the spring breakup.

Ga-2 Pothole. This long, shallow lake on the Arthur Koester land in the N½ of Sec. 17, T. 114 N., R. 27 W. Sibley County has an area of nearly 40 acres. It lies in typical prairie country on an almost level plain with shallow lakes to the east and west. The lake has a heavy growth of marsh vegetation and is shallow throughout. It was selected for comparison with Mud Lake (Ga-1) which is 5 miles to the southwest.

Test holes on the east side were in gray clay ranging to sandy clay. The water level in the holes on December 20, 1962 was near, but slightly below, the pond level with the surface soil frozen (figure 14). The water level in the pond seems remarkably stable, especially in view of dry periods in the summers of 1963 and 1964.

In December 1962, test holes were made on the east side of Ga-2, 35 feet and about 250 feet from the shore. (See samples 210 and 211, table 21.)

The record of water levels is too limited to draw firm conclusions regarding leakage; nevertheless there is an indication of the lack of any significant loss of water except by evaporation. The period September 18-December 20, 1962 was one of very little precipitation yet the level remained stable. Declines during the dry summers of 1963 and 1964 were moderate, and in view of deficient precipitation during both summers the decline was actually less than evaporation.

The nature of the bottom sediments is shown by the laboratory results cited for samples 173 and 174. Both are characterized by the lack of gravel. Number 174 has a large content of sand but probably sufficient clay and silt to eliminate much permeability. The silt and clay content of number 173 is practically 90 percent, which doubtless accounts for the relative stability of the water level. Soils data are given in table 21.

Table 20. Water levels of Gaylord (Ga-2) Pothole

September 18, 1962	1,002.0	
December 20, 1962	1,002.0	Ice level, Water 1001.5
June 20, 1963	1,001.95	
February 12, 1964	1,001.3	
June 26, 1964	1,001.11	
August 17, 1964	1,000.40	
September 2, 1964	1,000.71	
September 23, 1964	1,000.68	
March 24, 1965	1,002.55	
May 1, 1965	1,003.23	
May 20, 1965	1,003.03	
July 8, 1965	1,002.73	
August 3, 1965	1,002.3	

Gracelock Quadrangle

Gr-1 Pothole. The Gracelock potholes are located in western Minnesota. The first (Gr-1) is shown on the USGS Gracelock topographic map, with Gr-2 on the Gracelock S. W. sheet. Both potholes lie near the western edge of the till plain (ground moraine) of the Des Moines Lobe, which covers a large area in central and southern Minnesota.

Gr-1 pothole covers about 40 acres (Secs. 5, 21 and 28 T. 119 N., R. 39 W.) and lies in the midst of a marshy area, in which many temporary ponds form when precipitation is normal or above. The pothole has a heavy growth of marsh grass with a limited area of open water in the center. There are no creeks or ditches to carry water in or out of the depression. Gr-1 is considered to be a typical prairie pothole and is a wildlife management area.

Five test holes were made on the southwest side of Gr-1 and are shown in figure 15. The water level in the holes when excavated, July 18, 1963, were:

1 — 1,030.0
2 — 1,029.8
3 — 1,029.8
4 — 1,029.9
5 — 1,030.4

The pothole water surface elevation was 1,030.3.

The situation is complicated by a road ditch and high grade. Hole 1, north of the road and 7 feet from the ditch, was in black clay and encountered water at only 0.3 foot below the surface. Hole 2, 22 feet from the ditch, was

Table 21. Textural classification of samples from test holes at Gaylord (Ga-2) Pothole

No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
211	2	2.5-3.5′	0	20	24.8	55.2	Sandy clay loam
210	1	5-7.8′	0	24.1	37.5	28.4	Clay loam
174*	1W	3.8-6′	0	23.4	61.7	9.9	Silty clay loam
173*	1W	6-7′	0	13.7	29.1	57.2	Sandy loam

* Denotes bottom sediment.

Table 22. Textural classification of samples from test holes at the Gracelock Quadrangle

Pothole	No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
Gr. 1	86	4	0-4′	6	31.1	32.6	30.3	Clay loam
Gr. 1	87	3	2.5-3.5′	11	30.8	30.6	27.6	Clay loam
Gr. 1	88	5	3-8′	4	32.1	37.2	26.7	Clay loam
Gr. 1	169*	1W	3.6-4′	0	32.7	53.1	14.2	Silty clay loam
Gr. 2	79	3	1-11.5′	22	25.3	24.2	28.5	Gravelly clay loam
Gr. 2	192*	1-B	7.7′	9	32.5	32.8	25.7	Clay loam
Gr. 2	194*	1-B	20.3′	9	29.6	42.4	23.0	Clay loam

* Bottom sample.

in similar black clay soil and water was found at 1.4 feet. Hole 3, located 29 feet from the ditch, showed 2.5 feet of black clay and 1 foot of mottled gray clay with water at 1.7 feet. Hole 4, in the center of the road grade, cut 4 feet of black soil with water at 2.6 feet. Hole 5, in the center of the road and 35 feet from 4, is in similar clay loam and encountered water at 5.3 feet. The data on samples from holes 3, 4, and 5 are shown in table 22.

In March 1964 a test hole near the center of pothole Gr-1 produced a silty clay sample taken at 3.6 to 4 feet below the bottom of the pond. The laboratory classification is shown in table 22. A microscopic study of the sample showed an abundance of brown to black organic clay aggregates. Quartz was abundant as medium-sized silt grains ranging up to sand size. Skeletons of diatoms were numerous and proved that the deposit — devoid of gravel — was water laid. The combined clay-silt content of 85.8 percent doubtless accounts for the relatively stable water level of the pond.

It should be noted that from August 1963 to March 1964 the level was remarkably stable. There was very little precipitation during the fall of 1963, and Gr-1 was frozen from January to March when readings showed no change. Obviously there was little or no loss due to seepage during that period. During the winter of 1964-65 the pond froze solid.

A pothole located in section 21 is about 900 feet northwest of Gr-1, and its water surface is 2 feet lower than that in Gr-1. Two holes were excavated on the southeast side of the pond (figure 15). The first hole, located in a cornfield 14 feet from water, produced black to brown clay with the water level at 2.4 feet, or elevation 1,027.3 as compared with a pond level of 1,025.1. Hole 2, in similar soil, but 35 feet from shore encountered water at 1,027.6. This shows that the groundwater near the second pond slopes toward the pond and away from pond Gr-1.

Table 23. Water levels of the Gracelock (Gr-1) Pothole

September 11, 1962	1,030.5	
August 8, 1963	1,029.4	
January 2, 1964	1,029.4	
March 23, 1964	1,029.4	
June 18, 1964	1,029.96	
July 15, 1964	1,029.63	
August 12, 1964	1,028.99	
September 8, 1964	1,028.97	
October 10, 1964	1,028.57	
December 21, 1964	1,128.57	(ice level)
March 24, 1965	1,028.83	
May 1, 1965	1,030.98	
May 20, 1965	1,031.03	
August 5, 1965	1,030.16	
September 15, 1965	1,029.92	
October 15, 1965	1,030.18	

Gr-2 Pothole. This pothole lies about 6 miles slightly southwest of Gr-1 in Sec. 32, T. 119, N., R. 40 W., and Sec. 5, T. 118 N., R. 40 W. (roughly half in each section) with a total area of about 90 acres. Ernest Tosterson owns part of the land. The surrounding prairie is level, ranging in elevation from a low of 1,010 along Dry Weather Creek, 2 miles east, to a high of 1,050 on a low ridge 2 miles to the north. Gr-2 is a typical shallow prairie pothole with a heavy growth of marsh vegetation over much of the area, and during the drought of 1964 it was nearly dry.

Three test holes (figure 16) were made on the southwest side. The first, at 15 feet from the water's edge, showed that the soil consisted of black peat. In another located 35 feet from the pond, shallow peat gave way to bluish and brown clay with a thin layer of sand from 2 to 2.5 feet. The soil was largely brown clay in the third test hole, 50 feet from the water's edge. The water table slopes sharply away from the pond as the following data shows: Pond level on June 18, 1963, 1,030.5; Hole 1, 1,027.4; Hole 2, 1,024.7; Hole 3, somewhere below 1,018.4. The same levels on June 20, 2 days after sinking the holes were, 1,027.4, 1,026.4 and 1,021.0, respectively. A year later on July 15 these levels were 1,024.8, 1,027.6 and 1,025.5. A 10-minute infiltration test made on hole 3 showed very little movement of water into the soil for the first minute and essentially none thereafter. The textural classification of soil sample 79, from hole 3, is given in table 22.

When first investigated on September 11, 1962, the water level was high as shown by table 23. The practical stability of the levels from January 2 to March 23, 1964, when the pond was frozen over, shows that there was negligible water loss by seepage out of the bottom, in spite of the sharp decline of water surface away from the pond (figure 16).

We took advantage of the dry bottom in August 1964 to sample the bottom sediments. The log is given in table 24, with laboratory classification of samples (192, 194) given in table 22.

Table 24. Water levels of the Gracelock (Gr-2) Pothole

September 11, 1962	1,027.3	December 24, 1964	Dry
August 20, 1963	1,027.5	March 24, 1965	Dry
January 2, 1964	1,027.65	May 1, 1965	1,027.79
March 23, 1964	1,027.7	May 20, 1965	1,027.97
June 18, 1964	1,027.64	August 5, 1965	1,128.48
July 15, 1964	1,027.32	September 15, 1965	1,028.19
August 12, 1964	Dry	October 15, 1965	1,028.38
September 8, 1964	Dry		

LOG

Feet	
0-3	Black, fibrous peat
3-4.4	Silt and clay. Sample 191 at 4.4′
4.4-7.7	Silt. Sample 192 at 7.7′
7.7-13.1	Clay with gravel. Sample 193 at 10′
13.1-20.3	Gray, sandy clay. Sample 194 at 20.3′

The presence of gravel shows that the hole penetrated till at about 7.7 feet. A combined clay-silt content of 65 percent accounts for the impermeability of the soil. This would seem to agree with the infiltration test that the soil does not allow much water to seep out; although the water level is shown by the tests to slope away from the pothole at a sharp gradient.

Samples obtained from the hole in the middle of the dry pond permitted some detailed studies in the laboratory. Small portions of samples 191-194 were examined by a petrographic microscope. Sample 191 consists of a dark gray powder. Some organic matter and a few diatom skeletons were observed in this sample, indicating a water-laid sediment at 4.4 feet. Clay and silt aggregates were numerous and a small amount of carbonate was recognized.

The sample at 7.7 feet was light gray in color and contained no diatom skeletons. It consisted mainly of light-brown clay aggregates. To determine the clay minerals, we X-rayed a fraction of −2 microns with the following results as parts of 10: montmorillonite 3-4, muscovite mica 3-4, chlorite 1-2, and kaolinite 0-5.1.

Samples 193 and 194 were similar to 192 as revealed on microscopic examination. A preliminary examination of sample 194 showed that the pollen was largely of Cretaceous age, doubtless a result of incorporation of Cretaceous sediments in the till of the Des Moines Lobe.

Inver Grove Quadrangle

The Inver Grove Quadrangle covers an area in Dakota County immediately south of St. Paul and largely west of the Mississippi River, which runs along the east side of the quadrangle to Pine Bend where it turns east and off the map area.

This area is particularly useful in the study of permeability and seepage below lakes and potholes because the terminal moraine topography is well developed with roughly 200 potholes and 10 small lakes in the area of approximatley 50 square miles. Moreover, the Mississippi River is entrenched in a gorge so that most of the potholes are situated from 200 to 350 feet above the river. Of the potholes studied, the nearest is only 1,000 feet from, and approximately 200 feet above, the river (figure 17). A recent detailed study of the glacial geology of the area by Gelineau (1959) is particularly helpful in consideration of the area.

The part of the Inver Grove Quadrangle of most interest in this investigation is covered by the St. Croix Moraine, which was deposited by ice of the Superior Lobe and is predominantly red or brown. Locally the red drift is overlain by a thin deposit of gray drift deposited by thin ice along the east side of the Des Moines Lobe. This moraine was cut by a later drainageway eroded by water from the Des Moines Lobe and occupied by stratified drift, according to Gelineau. The potholes are largely confined to the area of the St. Croix Moraine. The color of the drift is dark brown rather than red, and ranges texturally from a sandy till to a very sandy or gravelly till. Gelineau sampled and found that all samples contained over 55 percent sand. Although many samples were mixed, three uncontaminated samples averaged 76 percent sand. Loess-like silt forms a thin discontinuous veneer over much of the area, and its presence in a pothole would tend to cut down water seepage to the sandy drift below.

Because of the large number of lakes and potholes, the presence of the Mississippi River along the east side, the nearness of headquarters, and the disparity of levels of the water surfaces, seven small bodies of water were selected for detailed work and later special studies were made on Hornbeam Lake in response to a local request.

In-1 and In-2. These potholes are in the SW¼, sec. 6, T. 22 N., R. 22 W., Inver Grove Township just south of St. Paul. A private road to the Shanahan home follows the north side of In-1, and a township road cuts off a small part of In-2. The distance to the Mississippi River is slightly over 4 miles. The site is in the midst of the St. Croix Moraine and many shallow potholes and small lakes exist in the surrounding area. In-1, with an area of 7.2 acres, has a well-developed border of marsh vegetation, and In-2 has 5.6 acres and is entirely occupied by a lush growth except in periods of high water. Both became nearly dry during extended droughts. When the area was first examined in 1962 a third pond of an acre or more existed a short distance north of 2. Observations were made of this pond in 1962 but discontinued early in the summer of 1963 when it dried up.

A series of test holes were dug during the late summer and fall of 1962. This was a period of normal or slightly below normal water levels. The water levels in the ponds were as follows on October 11, 1962: In-1, 887.6; In-2, 884.6; North Pond, 890.0. The groundwater level in a series of 14 test holes showed a variable relation to the levels of the potholes as shown by figure 8. On the northwest side of the North Pond the groundwater level in hole 13 was above pond level, between that and In-2 the slope was to 2 but between 2 and 1 the groundwater level was below that of both ponds. On the northeast tip of In-1 the water levels in the holes were close to that of the pond, but in holes 1 and 2 the level stood 0.9 foot below.

Late in 1954 when In-2 was largely dry, test holes near the west side showed that water in a peat-silt layer at a depth of 1.1 to 1.8 feet was under pressure and rose to within 0.3 foot of the top of the hole. Although the hole was only 2 feet from the water's edge and the top only .10 foot above water surface, the hole remained dry until the peat layer was struck. The variable relation of the water levels to the pond levels led to extensive testing by auger holes and by a peat sampler for holes in the bottom sediments. Many samples were collected and, as shown in table 25, 15 were classified in the laboratory.

As would be expected for drift of the St. Croix Moraine, the soils are generally light brown in color and are sandy with little, if any, carbonate. Such soils are rather permeable and a series of infiltration tests in holes 2, 5, 7, and 11 showed that water moved rapidly out of the auger holes and continued to move at a decreasing rate beyond the length of the tests, which ranged up to almost 2 hours. Holes 3 and 10 had a much lower rate but this was, at least in part, because the holes were shallow and the water was under low head. Staff gages were set in potholes 1 and 2 and records kept for 1963 and 1964 (figures 25 and 26). Original levels were determined with respect to a local benchmark established in 1962. It was found that the water level in both ponds was relatively stable over the winter of 1962-63. In fact the level of 2 was precisely the same on October 1, 1962 and on May 2, 1963. The levels rose during the spring, particularly 2, which rose 0.88 foot between May 2 and 9, largely due to runoff from the pavement along the south side. The levels remained stable during the spring rains, but the last heavy rain in the area occurred on June 10, 1963, after which precipitation was subnormal for the remainder of the year. Levels of both potholes slowly dropped during the period from June 10-December 31. In-1 dropped a total of 1.82 feet and In-2, 1.62 feet during this period. This decline appears to be well within the evaporation loss (table 4) measurements for the same period, based on U.S. Weather Bureau observation at Farmington a few miles to the south. During the winter of 1963-64 the levels were again remarkably stable. The water elevation for In-2 on December 26 was 885.99 and was the same elevation on April 9. Elevations for In-2 on the same dates were 884.09 and 883.34, indicating a small loss by seepage during ice cover.

A complete graph of the changes during 1964 is shown by figure 26. There was little snowfall during the winter of 1963-64, so the usual spring rise was slight in 1 and lacking in 2. Rainfall was deficient during the spring and early summer, so decline was continuous until heavy rains in late August and early September reversed the trend. The decline again corresponded roughly to the expected amount of evapotranspiration. Heavy vegetation, particularly in 2, probably meant that transpiration was important.

The water was so low during the winter of 1964-65 that the data on levels are considered to be of little value. Heavy snowfall and spring rains in 1965 raised the levels well beyond those at the beginning of the observations in 1962 and a new program was started.

Bottom Samples

As noted above, water levels in In-1 and In-2 were remarkably stable during the winter indicating that an insignificant amount of water was lost out of the bottom. Infiltration tests showed that water moved out rather freely from test holes on land. As shown in table 25, nine samples were collected from the bottom of the two potholes, some through the ice and others after the water had receded during the dry summer of 1964. The samples were collected to determine the difference between sedi-

Table 25. Textural classification of samples from test holes at Inver Grove (In-l and In-2) Potholes

Sample	Hole	Depth	Gravel	Clay	Silt	Sand	Class
3	6	3′	11	12.9	14.5	72.6	sandy loam
4	8	14′	13	9.0	20.3	70.7	sandy loam
5	9	2′	4	22.1	49.4	28.5	loam
6	12	3′-8′	22	11.0	17.1	71.9	sandy loam
125*	1W-64	1.6′	0	3.0	67.8	29.2	silt loam
126*	1W-64	3.0′	0	23.0	46.8	30.2	loam
153*	2W	4′	0	17.8	39.0	43.0	loam
154*	1W	2.9-5′	0	22.2	51.4	26.4	silt loam
196*	1S	7′	0	15.1	56.2	28.7	silt loam
198*	2S	2.8-4.1′	0	13.5	51.7	34.8	silt loam
200*	1S	9′	0	20.7	64.0	15.3	silt loam
202*	2S	3.3-4.5′	0	26.5	59.0	14.5	silt loam
203*	2S	4.5-4.8′	0	24.4	53.7	21.9	silt loam
212	3B	1.5-4.5′	18	8.2	18.3	73.5	sandy loam
213	3B	4.5-7.0′	18	7.0	18.5	74.5	sandy loam

* Denotes hole in the bottom.

ments on land and on the bottom of the ponds. Following are the logs of the bottom holes and the depth from which some of the samples in table 25 were taken:

Hole 2W, In-1, 100 feet+ of the east end on January 30, 1964

Feet

0.3 Ice
0-2.0 Peat, cobble stone at 2′
2.0-2.3 Sandy layer
2.3-4.5 Sandy clay, gray, sample 153 at 4′

Hole 1S, In-1, 15 feet east of low water's edge, 200′ west of normal shoreline August 25, 1964

Feet

0-1.5 Peat and top soil
1.5-2.0 Sand
2.0-2.8 Silt
2.8-6.6 Brown to very dark gray clay or silt
6.6-9.3 Greenish gray silt or clay, sample 200 at 9′
9.3-9.9 Mixed gray silt, sand, and pebbles

Hole 2S, In-1, middle of small, dry cattail pothole east end of In-1, August 26, 1964; connects with In-1 during high water

Feet

0-2.5 Dry, black organic soil
2.5-3.3 Gray, sandy silt
3.3-4.5 Brown and gray silt; dry, sample 202
4.5-4.8 Silt, sandy gravel; damp, not wet, sample 203

Hole 1W — 64 middle of cattail bay of In-1, January 14, 1964

Feet

0-1.8 Silty muck, sample 125
1.8-3.0 Silty clay, sample 126

Hole 1W, In-2, near middle end, west of the island, January 30, 1964

Feet

1.3 Ice
0-2.9 Peat
2.9-5.0 Black, organic, plastic silt and clay, sample 154

Hole 1S, In-2, middle of south bay on land August 25, 1964

Feet

0-0.5 Silt
0.5-1.5 Brown to black peat
1.5-1.9 Organic silt, water level at 1.6′
1.9-4.0 Brown silt plus fine sand
4.0-7.4 Gray silt, not wet, sample 196 at 7′
7.4 Gravel

Hole 2S, In-2, west side of north bay, 100 feet from high water line, August 25, 1964

Feet

0-.3 Top soil and peat
.3-1.2 Gray silt and fine sand
1.2-1.8 Brown, fibrous peat
1.8-2.8 Organic soil with silt
2.8-4.1 Silt with fine sand, sample 198
4.1-4.6 Coarse sand

If the results of laboratory tests of samples taken on land adjacent to the potholes are compared with those from holes on the bottom of the ponds, differences appear. The samples from holes on land have from 4 to 22 percent gravel and, moreover, numerous boulders occur on the adjacent land. In contrast, boulders and gravel are absent in the bottom sediments. The sand content of the land samples, after removal of the gravel, averages 65 percent, whereas the samples from the bottom sediment average only 27 percent. The combined clay and silt content of the land samples is 35 percent and for the bottom sediments 73 percent. As is probably normal for glacial sediments, the silt content is greater than the clay content, particularly for till derived from northeast sources. The nature of the bottom sediments doubtlessly accounts for the relative imperviousness of the potholes.

Microscopic Examination. The significance of the samples of bottom sediments led to a microscopic study of small portions of all samples collected, including some not classified in the soils laboratory. Most of the samples contained considerable amounts of organic matter that combined with the clay minerals to form black or brown aggregates. Within such aggregates were enclosed minute silt-size particles of quartz and, rarely, lesser minerals. A few grains of feldspar, amphilbole, pyroxene, and other minerals normally were present. Several of the samples contained abundant remains of diatoms, thus proving that the sediments were deposited in water. Silt-size particles of quartz was the most abundant single constituent. The clay minerals were predominantly calcium montmorillonite and muscovite plus lesser kaolinite.

In-3 Pothole. This pond is located on the Harry Schindeldecker farm in SW¼, SE¼, sec. 8, T. 27 N., R. 22 W., located in the midst of a well-developed part of the St. Croix Terminal Moraine. The topography of the area is shown on the Inver Grove, U.S.G.S. topographic sheet and is characterized by sharp depressions and hills with the relief in the area ranging in elevation from about 800 to 1,000. The Hastings Pool of the Mississippi River 2.5 miles to the east has a normal elevation of 687.

Pothole In-3 is oblong, with dimensions of about 200 by 400 feet, and the area covered by water at the highest normal level is about 1.5 acres. This pothole lies in a pronounced, crudely circular ice block depression with steep slopes rising as much as 100 feet. Part of the slopes are lightly wooded, but the more level areas are cultivated fields. The drainage area is limited, particularly where an elongated pothole (In-4) occurs only about 700 feet to the west and about 20 feet higher. The normal elevations of the potholes are approximately 870 and 890, respectively. Shallow gullies lead into In-3 from the southwest, southeast, north, and northwest. It seems evident that in periods of heavy rain or melting snow considerable water may run in, and there is some seepage on the west side. In normal or dry periods there is no surface run-in. When In-3 was first examined in the fall of 1962, there was a small amount of seepage at the west end a few feet above the water level in the pond. In the fall of 1963, a dry period, this seepage had completely disappeared and did not return during 1964. Examination of the pond and adjacent land on September 18, 1964 (after a series of heavy rains [2.69 inches between September 1 and 9]) revealed no evidence of run-in, largely due to the heavy cover of vegetation.

In contrast the winter of 1964-65 was a period of heavy snowfall followed by a wet spring. The ice level in the pond on December 31, 1964 was 869.19. By April 22, 1965 the water level had risen 6.69 feet to 875.88, by far the highest elevation reached during the project.

Test holes were dug at the southwest, southeast, east, and north sides. Figure 19 shows the relation of the test holes to the pond and the general nature of the soil, which is a red sandy clay. When the test holes were dug in the fall of 1962, the water level in the holes was below pond level except at the southwest side. The holes on the southwest side were located on a sort of alluvial fan at the mouth of a small gully which terminated upward at the edge of a cultivated field. The elevation of the water surface in the upper hole was 877.9 as compared with a pond level of 869.8.

The glacial drift in the holes around the pond was generally sandy, gray to brown in color, and contained pebbles, cobbles, and boulders. Samples were obtained from hole 3B at the southwest side with the laboratory analysis shown in table 26.

The log of the hole showed contrasting layers.

Hole 3B

Feet	
0-0.5	Topsoil
0.5-2.0	Sandy loam, sample 176
2.0-3.5	Mixed sandy loam and sand
3.5-4.0	Pebbles in clay or silt loam
4.0-5.3	Gray to brown clay or silt, sample 177 at 5-5.3 feet

We obtained records of the water elevation of the pond beginning October 1962 when the water surface stood at 869.8. On April 4, when we began the 1963 readings, the water surface had risen to 871.4. As shown by the graph of figure 25 there was a very gentle decline until June 10. Weather Bureau records show that there was very little rainfall in the Minneapolis-St. Paul area from June 10 for the remainder of the summer. This resulted in a pronounced decline (1.36 feet) in the water surface from mid-June to September 1. With the advent of cool weather and a normal rainfall, the water level declined only slightly from September 1 until the end of the year. During the winter of 1963-64 the ice level was practically the same from October to March, but the pond probably froze to the bottom.

Bottom samples were obtained by augering through the ice in January 1964. The logs of two holes, one in the middle and the second near the west end below the seepage area, observed in 1962, are shown below:

Hole 1	**Feet**
Ice	0.6
Peat grading to muck	0-3.1
Gray sandy clay	3.1-3.7
Similar sandy clay	3.7-4.4
Gray sandy clay	4.4-5.4, sample 155

Hole 2	**Feet**
Black, sticky clay	0-3.5
Greenish gray clay	3.3-4.5, sample 156 4-4.5
Sandy, greenish clay	4.5-5.0

It was observed that the greenish clay in hole 2 was not wet, but moist, whereas the sandy clay allowed the slow percolation of water into the hole. The level rose 1.7 feet in 3½ hours.

The samples from the bottom of the pond show a considerably higher clay content than does the drift on shore. The silt content is also high. In this respect the bottom sediment is not unlike sample 177 from hole 3. This suggests that silt, from silty layers in the drift, was carried into the pond from the surrounding steep slopes and the combined clay-silt content of 70 percent probably explains the ability of the pond to hold water.

Table 26. Textural classification of samples from test holes at In-3 to In-7 Potholes, Inver Grove Quadrangle

Pond	No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
In-3	176	3B	.5-2.0	16.5	1.8	15.3	66.4	Gravelly loamy sand
In-3	177	3B	5.0-5.3	7.0	27.3	50.5	14.8	Clay loam
In-3	156*	2W	4-4.5′	0	26.2	62.7	11.1	Silt loam
In-3	155*	1W	5-5.4′	0	39.6	36.4	24.0	Clay loam
In-4	116	1-63	3-5.5	trace	28.8	53.4	17.8	Silty clay loam
In-4	178	3E	3.2-4.5	3	10.3	36.5	50.2	Sandy loam
In-4	179	3E	7-7.8	4	17.8	52.0	26.2	Silt loam
In-4	157*	1	12.4-3.7	0	28.9	42.1	29.0	Clay loam
In-4	207*	2	9′	0	24.8	60.5	14.7	Silt loam
In-5	7	2	11′	17	3.8	7.5	71.7	Gravelly loamy sand
In-5	152*	1W	4-6.8′	0	28.3	37.4	34.3	Clay loam
In-5	204*	2B	6.5′	0	37.8	35.4	36.8	Clay loam
In-6	183	3	3.2	18	16.7	12.9	52.4	Gravelly sandy clay loam
In-7	23	2	1-4′	17	10.8	14.0	58.2	Gravelly sandy loam
In-7	127*	1B	1.0′	0	23.0	54.8	22.2	Silt loam
In-7	180	4E	0-5.5′	12	12.7	25.2	50.1	Gravelly sandy loam
In-7	205*	2B	1.6′	0	11.6	33.8	54.6	Sandy loam
In-7	206*	2B	4.8′	17	13.5	1.5	68.0	Sandy loam

* Denotes bottom samples.

Because of the importance of the bottom samples in this typical small pothole a microscopic study of the two bottom samples was made followed by an X-ray determination of the clay materials in sample 156. The clay fraction consists of three materials, with calcium montmorillonite forming 50 to 60 percent, muscovite mica 20 to 30 percent, and kaolinite about 20 percent. Calcium montmorillonite is the principal constituent of commercial nonswelling bentonite.

A microscopic study of samples 155 and 156 showed a complex mixture of organic matter, clay, silt, and sand grains. Most of the sand grains were sub-angular to sub-round and silt-size particles of quartz was the most abundant mineral. Fine, needle-like aggregates of the clay minerals reported by X-ray were abundant. As far as could be seen, diatom remains were absent, whereas in bottom samples of several other ponds they were abundant.

In-4 Pothole. In-4 is a long, narrow pothole in the SW¼, SE¼, sec. 8, T. 27 N., R. 22 W., and about 700 feet west of Pothole In-3. In-4's normal area is about 2.5 acres but ranges widely because the depth of water does not exceed 3 feet except during moist periods. The area is in the rough topography of the St. Croix Moraine and the long narrow depression with low, but steep banks that suggest an under ice channel. The pond is fairly well surrounded by a narrow border of timber on the steep banks, except at the southwest side where a field slopes toward the pond. Because of the shallow water, there is a wide zone of heavy marsh vegetation.

The first determination of the water level in the pothole was made on August 25, 1962 at 890.6 feet above sea level. By December 6 (a dry period) the elevation had dropped to 889.9. The first determination in 1963 was on May 14, when the level had risen to 891.35. The water surface elevation remained steady to June 11 at which time, because of below normal rainfall, a steady decline set in that lasted until September (figure 25). Some precipitation during September held the level nearly constant, but another decline occurred which continued until after freeze-up. On December 28 no water remained below the ice, which had a surface elevation of 888.11. The total decline was 3.14 feet between May 14 and sometime prior to December 26. While most of the decline occurred as a result of lack of precipitation and high evaporation, the decline after the freeze-up can apparently be explained only by seepage into the ground. Pothole In-3 is 700 feet to the east and about 20 feet lower than In-4. Seepage from the west into In-3, from the direction of In-4, does occur during moist periods.

Test holes (figures 20 and 21) were made at the north end, east side, and west side, in an attempt to determine the groundwater level in relation to the level of the pond. The water level slopes away sharply at the north end, slightly away on the west side, and generally toward the pond on the east side, although in hole 1 on that side the water level seems to be slightly below pond level. Hole 9 at the north end, 182 feet from the edge of the pond, was drilled to 16.5 feet in red sandy clay but did not reach water at a depth of 9 feet below pond level.

The test holes at the north end of In-4 were particularly surprising because of the sharp decline of the water level in the holes away from the pond. It seemed evident that water from the pond was not able to pass through the sandy clay soil rapidly enough to maintain the groundwater level near pond level.

Three samples were taken from test holes, one on the west side, and two on the east side. For comparison, two holes were put down in the bottom of the pond and the logs are given herewith. Laboratory results for bottom samples 157 and 207 are shown in table 26.

Hole LW. Taken about the middle of a long pond, January 30, 1964

Feet	
0.8	Ice
0-2.0	Black to dark gray silt
2.0-2.4	Thin layer of peat
2.4-3.7	Dark gray, sandy silt, Sample 157. Water entered at 3.6, rose to 2.9 after 24 hours.

Hole 1-64 — In south end in small isolated dry area. In center of deepest area, August 26, 1964

Feet	
0-2.4	Brown, organic silt
2.4-3.5	Black, decomposed peat
3.5-5.5	Dark gray silt, only slightly moist
5.5-9.6	Gray silt. Sample 207 at 9 feet
9.6+	Sand and pebbles, water

Sample 207 (table 26) with a combined clay-silt content of 94 percent doubtless forms a seal. But, as previously indicated, this is not entirely effective as a slow loss of water is shown by the record of levels during 1963 and 1964.

A microscopic study of the two samples showed that diatom remains were abundant in sample 157 and sparse in 207. Typical silt grains were composed mainly of quartz, but clay and several other silicates were observed. Organic matter was abundant in 157 and sparse in 207. Calcite grains suggested contamination from gray drift prevalent to the west.

In-5 Pothole. This pond was selected because of its perched position high above the Mississippi River. The elevations for In-5 and the river are roughly 853 and 687, respectively (figure 17). The pond is located on the line between Secs. 22 and 23, T. 27 N., R. 22 W. In-5 is small, about 3 acres at its highest level, and exists in a small depression in the rugged area along the west side of the river where it cuts through the St. Croix Moraine. In wet weather there is possible inflow from a limited area to the west, but several similar depressions to the north, west, and south catch much of any surplus water.

When first observed on July 18, 1962, In-5 appeared to be a fairly permanent pond with steep banks and a heavy growth of vegetation around the margin. However, later study showed it to be a shallow pond, and during the deficient precipitation starting in mid-summer of 1963 and extending into the summer of 1964, In-5 dried up almost completely. During the year 1963 a good record of the level followed a pattern similar to that of other potholes and small lakes in the area, showing that the steep gradient to the river has little effect upon seepage from the potholes.

The soil in the area is sandy and gravelly as shown in table 26. In 1963, the groundwater surface in hole 1, located near the water's edge, sloped toward the pond. Steep slopes and rocks prevented reaching water in a second hole and further work was abandoned. Infiltration tests in two holes showed fairly rapid movement of water into the soil, as would be expected from the character of sample 7.

In January 1964, a test hole was made in the middle of the pond where the ice was 1.2 feet thick. The log is as follows:

Hole 1W — Near center of pond. January 23, 1964

Feet	
0-1.2	Ice
1.2-3.6	Black, organic silt
3.5-4.0	Sandy silt, water at 3.6 feet in thin lense of sand
4.0-6.8	Black silt, sample 152

Hole 1S — 150 feet west of east end, 10 feet from edge of water — August 26, 1964

Feet	
0-0.5	Organic silty soil
0.5-2.5	Black peat
2.5-7.0	Black silt with fine sand. Sample 204 at 6.5′

The combined silt and clay content of 65.7 percent in sample 152 (table 26) differs sharply from sample 7, from Hole 2, on land which yielded only 13.6 percent silt and clay.

A microscopic study of sample 204 revealed an abundance of dark brown to black organic clay aggregates with fine and coarse quartz grains and numerous skeletons of diatoms, thus verifying that the deposit at 6.5 feet was water laid.

It is evident that the bottom sediments in the pond must inhibit seepage. Otherwise, in view of permeability of the adjacent soil (sample 7, table 26), the steep gradient to the river, and the shallow water, the pond would be dry in a short time. The graph of the water level from March to December 1963 (figure 25) shows that the principal loss of water was during the period of high evaporation during June, July, and August. However, there was a loss of 0.53 foot during the period October 24-December 20, 1963. This indicates some loss by seepage during that period of low evaporation and partial ice cover. This loss was verified by the fact that on January 23, 1964 the pond was frozen to the bottom, and a test hole reached water at 2.4 feet in a black organic silt.

In-6 Pothole. As with In-5 this pond was selected because of its location close to the top of the steep bluffs along the Mississippi River. In-6 is about 2,800 feet from the river and 90 feet higher than In-5 in elevation. It is small, about 2.5 acres, and does not fluctuate much in size because it is surrounded by steep banks on all sides, particularly on the west where the land rises about 100 feet. In-6 is surrounded by brushy woods, with no evident drainageways leading into it. The area is in the St. Croix Moraine where it has been modified on the east by erosion of the steep slopes down to the Mississippi River. The water is relatively shallow (6 feet maximum) but is sufficient to prevent complete freezing to the bottom.

The first determination of water level was on November 19, 1962. In relation to a benchmark on the railway bridge to the west the water level was recorded as 776.5. A stable level was indicated by the ice level of 776.3 on March 23, 1963. For fluctuation details see figures 25 and 26. The water level rose during the breakup of the ice and spring rains to 776.88 on May 16, 1963. As in most of the water bodies near the Minneapolis-St. Paul area, a decline occurred after the last heavy rain on June 10. In the case of pothole In-6 this decline was moderate during the dry months of July and August and then gentle for the remainder of the year. The decline from May 16 to December 20, 1963 was 1.62 feet, but from March 22 to December 20, 1963 the net loss was .9 foot. During the period December 20, 1963 to March 12, 1964 the loss was only .36 foot and from November 8, 1964 to January 9, 1965 the decline was .20 foot.

Test holes were made at the north and south ends (figure 23). But steep slopes and the presence of boulders prevented extensive determination of the adjacent water level, which coincides closely with the level of the pond.

Infiltration tests were made in three holes. Hole 1, only 12 feet from the water's edge, was in a gravelly, sandy soil and, as expected, infiltration was rapid. Holes 2 and 3 were in gravel, sand, clay, and silt (sample 183) and filtration was slow, especially after the first 5 minutes.

The reasonable inference from the above data is that there is little loss by seepage. Also, the rather stable water level during a period of high evaporation is probably aided by seepage during wet periods from the steep slopes into the pond, although no evidence of seepage was observed anywhere along the shore.

Bottom Samples. The permanent nature of this pond, with its particularly steep banks, makes the bottom samples interesting. The test holes on the south bank showed that the adjacent soil is predominantly sand and sandy clay or silt. As previously noted, gravel boulders, and cobblestones are numerous. Laboratory classification of sample 183, shown in table 26, is believed to be fairly representative of the glacial drift around the pothole.

A microscopic study of sample 129 revealed an abundance of angular quartz grains of silt size and also larger quartz of sand size (mainly angular rather than rounded). Organic matter formed brown aggregates, presumably with clay and enclosing small silt grains. Skeletal remains of diatoms were numerous and several accessory silicate minerals were recognized.

The work on Pothole In-6 showed rather clearly that the deposition of fine sediments had a sealing effect. Otherwise, this pond perched high above and just over one-half mile from the Mississippi River would not be a permanent body in glacial drift containing such a large percentage of sand and gravel.

In-7. Pine Bend Pothole. This pond lies in a small but abrupt depression less than three-eighths of a mile west, and almost 200 feet above the Mississippi River, in the Pine Bend area south of St. Paul. There is a steep bluff up from the river bank, but a narrow ridge at the top of the bluff separates the pond depression from the steep slope to the river. The pond is small (about 4 acres) and the drainage area is also small and the water shallow. Along the west side is a fringe of trees, but beyond is mostly meadow and pasture land. The pond is free of rushes, except at the east side.

Test holes on the west and east side produced sand and silt near the pond and a brown, sandy loam with gravel and cobblestones farther out. Laboratory analysis for a typical sample (23) from a test hole on the west side, and another on the east side (180) are shown in table 26. A laboratory classification of the samples showed that the fine-grained material in the deposits had a higher silt than clay content, which is true of much of Minnesota's glacial deposits, particularly the deposits of the St. Croix Moraine.

It seems evident from the above data that the pond does not control the water level adjacent to it. We concluded that at the May date there was some water moving in the soil from the ridge to the east. This was followed by a period of subnomal precipitation so the inflow soon disappeared and the pond continued to decline, as shown by the graph in figure 26.

An examination of the specific elevations of the staff gage reading and the graphs of that data shown on figures 25 and 26 indicates that the water in the Pine Bend Pond (In-7) is relatively stable during the winter when evaporation and run-in are largely, if not entirely, eliminated. For example, the ice level on November 20, 1962 was 877.5 and 4 months later, on March 22, 1963 it was 877.36. In the winter of 1963-64, the ice level was at 875.16 on December 20 and 874.90 on March 12.

As in the case of In-5 and In-6, this stability emphasizes the essentially sealed bottom provided by the fine-grained sediments. We noted repeatedly in the microscopic study of the bottom sediments of this and other potholes that organic matter and clay formed dark brown aggregates that enclosed silt and even sand particles. We believe this flocculated material is important in cutting down permeability.

The pond became nearly dry during the drought of 1963-64, but in 1965 heavy snowfall and early spring rains raised the level from elevation 874.26 on October 17, 1964 to 882.12 on April 22, 1965. This rise of 8 feet started a new cycle that is being studied.

A review of water level graphs of the Inver Grove and the St. Paul W. groups, shown in figures 25 and 26, reveals several significant points. First, the general shape of the graphs are similar. Those for 1964 are complete for the year and show that changes during the period of ice cover were small or in some cases almost nonexistent. In spring the water level rose in all bodies. Reference to table 7 shows that the snowfall for the Minneapolis-St. Paul area was below normal from January through March, but rainfall in April was 1.13 inches above normal. June and July 1964 had below normal rainfall and high evaporation, expressed in the graphs by a rather rapid drop in levels of all nine bodies being gaged. Late in August and September rainfall was about double the normal amount and this is expressed on the chart by rises of comparable amounts in all 10 ponds and small lakes. Figures 25 and 26 include 3 graphs of lakes in the adjacent St. Paul W. Quadrangle. Precipitation was below normal for the last 3 months of 1964 and the levels returned to approximately the August levels and changed only slightly, except Carlson Lake (Sp 3), which evidently lost a modest amount by seepage.

Isanti Quadrangle

The so-called Anoka Sand Plain covers a large area in parts of Anoka, Isanti, and adjacent counties. The water table is at a shallow depth over large areas and the soil is highly permeable. We believed this area would furnish a good comparison with other areas of the state where the soil is relatively impermeable.

A small pothole occurs in a private playground area called the Booster Club, located in the SW¼, SE¼, sec. 4, T. 33 N., R. 23 W., Anoka County about 25 miles north of Minneapolis. To the east about 4 miles a chain of small lakes extends from northeast to southwest. As shown by the topographic map, these are at only slightly different levels, thus indicating the general groundwater level. Another pothole occurs on the Grant Farm, about one-fourth mile west of Linwood Lake, in sections 7 and 18 of T. 33 N., R. 22 W., and to the northeast are additional small lakes.

These lakes and potholes were selected as representatives of the many water bodies in the area. Gages were installed and test holes made over a large area to determine the configuration of the water table. Because of their situation in a single environment these potholes and lakes can best be considered together, although the data on each is presented separately.

Is-1. Booster Club Pothole. This is a typical shallow pond located in a slight depression on a nearly level sand plain. Is-1 is surrounded by uncultivated grassland, and while it has no obvious surface drainage into it several ponds exist nearby. Test holes on the north side show that the groundwater level and the pond level nearly coincide, although the pond tends to be slightly perched (figure 27). A test hole at the road corner about 700 feet southwest of the pond shows that the groundwater level there is nearly the same. The soil to the depth tested consists mainly of fine sand. A small pond exists a short distance north of the Booster Club Pothole and beyond a low sand ridge. Differences between the water surface elevation in the pothole and water levels in test holes on the south side rarely exceed 2 feet. Laboratory test data of samples from the area are shown in table 27.

Table 27. Textural classification of samples from test holes in the Isanti Quadrangle

No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
29	Is1-1	0-1.8′	trace	2.2	3.4	94.4	sand
98	Is3-1	0-2.6′	trace	1.3	1.0	97.7	sand
25	Is4-2	0-5′	trace	3.8	3.1	93.1	sand
99	Is6-1	0-3.8′	trace	3.3	7.7	89.0	sand
56*	Is3-B		trace	0.5	0.5	98.0	sand
187*	Is1-B	3.0-5.5′	trace	5.3	2.5	92.2	sand

* Denotes bottom Sample.

As would be expected in such sandy soil, infiltration tests at first showed very rapid movement of water into the ground and this continued at a slowly decreasing rate. A test of 1 hour and 50 minutes indicated that movement out of the hole continues until the original water level in the hole is approached. In one hole a second test was repeated shortly after the first to determine if the sand would remain saturated or not. The results were much the same, but the movement of water out of the hole was somewhat slower during the second test.

A graph of the fluctuation of the water level in the Booster Club Pothole (figures 31 and 32) shows a remarkably stable level from April 4, 1963 to June 12, 1963, with a sharp decline occurring as a drought period developed during which evaporation was high. Water surface levels reached a nearly stable condition during the latter part of July, but heavy rains in the area in mid-August caused a rise of .2 foot. The level quickly dropped to the earlier level, however, and showed only a slight loss to the end of 1963. The total decline from the high point to the low point at the end of the year was 1.25 feet.

The elevation of the water surface during periods of low temperatures and ice cover are particularly important. For example, the ice level on December 28, 1962 was 910.33. On April 2, 1963, about the time of the breakup, the water level was 910.53. Again, in the winter of 1963-64 the water level on October 24 was 909.76 and on March 5, 909.63. In the following fall the record was October 28, 908.58 and January 1, 908.62.

Inasmuch as the pond is isolated from either inflow or outflow at the surface, test hole data show the pond level is governed by the groundwater level which naturally does not change much during the frost period. Groundwater levels decline slightly by the movement of water out througth Cedar Creek to the west.

Is-2. Grant Farm Pothole. This is a shallow pothole 4 miles east of Is-1, and 700 feet west of Linwood Lake (Secs. 7 and 18, T. 33 N., R. 22 W.). It is about 5 feet higher in elevation than Linwood Lake. The area of the pothole is about 35 acres and the depth only a few feet, as the border is covered by a heavy growth of rushes. The shore is rimmed by shrubs and trees, mainly oak. The soil is the usual sand of the area, but organic matter is abundant in the pond.

A graph (figures 31 and 32) of the staff gage readings shows the general modest fluctuation common to the Isanti area. A gage was established on April 2, 1963 when the water surface elevation was at 905.5. There was a very gradual rise until June 12, but it totaled only .25 foot, and the decline to the final reading on December 19, 1963 was to 904.6. The change in surface level between December 17, 1962 and April 2, 1963 was only .04 foot, which is within the limits of error of such determinations. Again, between October 24, 1963 and March 5, 1964 the change was a rise of only .06. The fact that the water level is 5 feet above Linwood Lake strongly suggests that the organic deposits quite effectively prevent its level seeking that of Linwood Lake.

Is-3. Linwood Lake. The area of Linwood Lake is about 567 acres according to a Minnesota Department of Conservation survey. Next to Coon Lake it is the largest of the chain of lakes and ponds extending northeast-southwest the length of the Isanti Quadrangle sheet. Is-3 comprises parts of sections 8, 9, 16, 17, T. 33 N., R. 22 W. and is irregular in shape, with its greatest dimension east-west, narrow at the west and over twice as wide at the east end. A small creek from Boot Lake to the south flows into Linwood, thence to Island Lake to the north and eventually to the West Branch of the Sunrise River via Martin Lake. The lake is therefore somewhat stabilized during higher levels by flow in and out. The relatively stable level is shown by the staff gage graphs of figures 31 and 32. The first reading in 1963 was on April 4 when the level stood at 900.0. There was a slight rise during the spring rains and then a slight drop in July. After that the level remained almost constant for the remainder of the year as controlled by a dam at the outlet. The change from the first determination of the lake's level on November 1, 1962 to the one on November 11, 1964 was a decrease of .55 foot.

Test holes at the west end of Linwood Lake showed that the groundwater table is close to that of the lake, but that it rises slightly toward Grant Pond, which is to be expected since the latter pond is higher. The bottom of the lake is largely covered by sand, as indicated by sample 98 in table 27. Test hole data taken June 25, 1963 showed a lake elevation of 900.4. Water elevations in test holes 29, 75, and 105 feet from shore were 900.4, 900.6 and 900.8, respectively. Linwood Lake is probably one of the controlling units in the water levels of the area as will be noted in the general discussion of the area after presentation of data.

Is-4. Mud (or Slough) Lake. About 4 miles northeast of Linwood Lake is a cluster of three small lakes. These are located in Secs. 27 and 28, T. 34 N., R. 22 W. and are called Fawn, Pet, and Mud Lakes on the U.S. Geological Survey topographic map. Locally, however, Mud Lake is known as Slough Lake. Under normal conditions Mud Lake and the others are not connected. In 1963 and 1964 Pet and Fawn were not connected because of low water but there is a shallow ditch between them.

Mud Lake is shallow and its borders are completely covered by a heavy growth of rushes. Shoreward from its marsh vegetation the pond is bordered by a fairly heavy scrub oak forest. Its area was about 24 acres at the 1963 level.

The graph of the water levels of Mud Lake parallels very closely that of the Grant Farm Pond except that in 1965 levels were read in a well point which produced unexplained irregularities. In 1963 the initial level, taken on March 25 while ice still covered the pond, was 894.64. It rose to 894.93 on June 12, then a decline occurred during the summer drought and period of high evaporation rate in late June and July. For the remainder of the year the decline was very slight so that the level was 893.95 on December 19. The total fluctuation for the year was almost exactly 1 foot.

Three test holes on the north side of Mud Lake and across the highway from Pet Lake were in the usual fine sand of the area and showed the water level to be near lake level. Test holes were made on November 29, 1962 with the lake level at 894.8, as shown on figure 28. The holes were 16, 27, and 34 feet from the water's edge and the water level stood at 895.03, 895.45, and 895.42, respectively. These were checked 2 years later on October 30, 1964 when the lake level was at 893.46, and the levels in the same holes were observed to be 893.66, 893.58, and 893.69. On the latter date Pet Lake stood at 894.33 so a slight inclination of the water table toward Mud (Slough) Lake is natural. The data show the close relation to the groundwater table and surface water level. The decline in the lake elevation between the above dates was 1.34 feet, and in hole 1, 1.37.

During the winter of 1962-63 the level stood at 900.1 on November 1 and 899.93 on March 25; on October 24, 1963 the level was at 899.83 and on March 5, 1964 at 899.82. During the winter of 1964-65 there was a small rise in the lake level as a result of heavy snow and a rain in February.

Is-5 Pet Lake. This small lake covers about 22 acres and during high or normal water levels connects by a ditch with Fawn Lake and fills a small swampy bay on the northwest side. It occupies the major part of the NW¼, SW¼ of sec. 26, T. 34 N., R. 22 W.

Test holes at the southwest side showed the usual sandy soil and, in conformity with the test holes near Mud Lake, the water table sloped slightly toward the south in the first hole 15 feet from the surface water, but was level from hole 1 to hole 3 (figure 29).

The water levels throughout the year 1963 show much the same variation as in Mud and Fawn Lakes (figures 31 and 32). The water level on March 3, while ice still covered the lake, was 895.75. It rose to 896.0 on June 12, declined moderately in late June and July, and dropped gradually until the low reading on November 21. The total decline was 1.2 feet or slightly more than for Mud Lake, although a reading on December 19, 1963 showed a slight rise after the freeze-up so the net decline was 1.07 feet.

The very slight change during the winter is shown by the fact that the first record after an ice cover showed the water at 894.81 on November 21, 1963 and on March 5, 1964 at 894.79. There was very little snowfall during the winter and subnormal precipitation during the spring and early summer of 1964. As shown by figure 32, there was only a slight spring rise followed by a decline in June, July, and August. This was reversed slightly in late August and early September. The relative stability of water levels in the sand plain is shown by the fact that the maximum difference in the surface level of Pet Lake for the year 1964 was only .70 foot.

The winter of 1964-65 was one of unusually heavy snow and rare winter rain in February. Consequently there was a rise of 0.67 foot from November 11 to March 3, a period of ice cover.

Is-6 Fawn Lake. This lake is somewhat larger than Pet Lake, and covers about 45 acres in the NW ¼, sec. 26, T. 34 N., R. 22 W. The soundings by the Minnesota Department of Conservation indicate a maximum depth of slightly over 30 feet. The surrounding area is a level sand plain with a growth of sparse scrub oak on which summer houses and lawns are located.

Test holes produced the usual brown sand with some sandy peat in one hole at a depth of 1 to 2 feet (figure 30). As would be expected the water level graph of Fawn Lake practically duplicates that of Pet Lake, although the lake is about 1 foot higher. The water surface in a hole through the ice was at 895.75 on March 25, 1963. It rose slowly during the spring with a peak on June 12 (figure 31) which resulted from a heavy rain on June 10. A moderate decline set in during late June and July. This was followed by a slow decline to the end of the year, interrupted by a slight rise in September as a result of a moderately heavy rain. The decline from high to low was 1.07 feet — very close to the decline in Mud and Pet Lakes.

As in the case of Pet Lake, the level of Fawn Lake was remarkably stable during the period of ice cover in 1963-64. The level on December 19, 1963 was 896.06 and on March 5, 1964, 895.96, a difference of only .1 foot.

As shown by figure 32, the fluctuation of the lake level in 1964 closely paralleled that of Pet Lake and was slight for the same reasons. The difference between the highest and lowest levels was .93 foot. As at Pet Lake, there was a small rise of .25 foot over the winter of 1964-65.

Discussion of Some Aspects of the Hydrology of the Isanti Area

If the yearly graphs of surface water levels of the six bodies in the Isanti area (figures 31 and 32) are compared with those of other bodies of water involved in this project, a striking difference may be noted. The general shape of the graphs is the same, but the fluctuation is much smaller for the Isanti area. In the case of Linwood Lake, this is explained by the fact that a small creek flows through it, and it is controlled at the outlet by a small dam. Other bodies are isolated from any continuous surface flow in or out. Therefore, fluctuations can be explained only by precipitation, evapotranspiration, and movement, either in or out of the ground. The year 1963 was a period of deficient precipitation in the region. The total precipitation for the year 1963 at the Minneapolis-St. Paul Metropolitan Airport was 5.21 inches below normal (24.76 inches). When normal or less, the precipitation for southern Minnesota is below the normal evaporation from open bodies of water. With the exception of Linwood Lake, there is little or no evidence of surface run-off into the ponds and lakes studied in the Isanti area. The relatively stable levels are a result of the very sandy and permeable soil.

Both the surface and groundwater level of a large area is controlled by flow into the headwaters of the Sunrise River, a tributary of the St. Croix River and to the west into Cedar Creek, a tributary to the Mississippi River. The fluctuation of the surface bodies of water is slight as compared with most other areas investigated. Thus it is a logical assumption that the surface levels of open bodies of water in the permeable sandy soil are maintained, in part, by contribution from the groundwater during periods of low precipitation and high evaporation such as the summer and fall of 1963 and 1964. This slight fluctuation is possible only in a highly permeable soil where water can move in and out of the groundwater and the lakes, ponds, and creeks, depending on which is highest.

In order to determine the relation of the water table and the surface water more definitely a number of test holes were put down over an area of approximately 70 square miles between Lindwood Lake, Booster Club Pothole, north to Lake Typo, and south to Coon Lake. More specifically, the area included the north two-thirds of T. 33 N., R. 22 W., the south one-half of T. 34 N., R. 22 W., and a matching strip 4 miles wide in T.'s 33 and 34 N., R 23 W. These tests show that the water table slopes consistently from west to east from a high at a point south of Fish Lake, toward Martin Lake at the source of the West Branch of the Sunrise River and a ditch or creek that drains through Rice and Boot Lakes to Linwood Lake.

At the west edge of the area the drainage is westward and the water table declines from elevation 918, at the southwest corner of Sec. 35, T. 34 N., R. 23 W., to 900 on the outlet of Deer Lake in Sec. 21, T. 33 N., R. 23 W.

The decline in the water level of the open bodies of water measured in feet during the period November 1962 to November 1964 was as follows: Fawn Lake, 2.2; Pet Lake, 2.05; Slough Lake, 1.4; Linwood Lake, 0.55; Grant Farm, 1.47; and Booster Club, 1.65.

In view of the low precipitation during part of the period (particularly low snowfall), the decline is modest. Linwood Lake is maintained by the relation of inflow, outflow, and an outlet dam, but the others do not have creeks flowing in or out. Their levels, therefore, represent a balance among precipitation, evapotranspiration, and contribution to or from groundwater.

Lake Elmo Quadrangle

The Lake Elmo Quadrangle lies in Washington County directly east of the city of St. Paul. The lake occupies parts of Secs. 13, 14, 23, 24, 25, and 26, T. 29 N., R. 21 W. and is in a depression that is apparently an old drainageway. Ice block pits are numerous in the till plain of Patrician drift west of the lake.

The drift is stony, sandy, and typically red to brown in color. Leverett (1932) noted that the matrix of the till is generally loose-textured so that water penetrates it quickly, and the ice-block basins rarely overflow their rims. The sandy, gravelly nature of the drift is clearly shown by results of laboratory tests on several of the samples from test holes made during the investigation. The considerable range in character of the till is also emphasized.

L.E. 1. Lake Elmo. Lake Elmo was selected for gaging surface fluctuations because of a group of 30 or more potholes lying between it and Eagle Point Lake, about a mile to the west. The potholes and Eagle Point Lake are somewhat higher than the surface of Lake Elmo, and two of the potholes were selected for detailed investigation (L.E. 2 and L.E. 3). The area lies in the northeast corner of the Lake Elmo Quadrangle. The town of the same name is located at the north end of the lake, which is 1.4 miles long. 0.5 mile in average width, and has an area of 292 acres. The lake is slightly over 120 feet deep in the middle. It is known to have extensive deposits of marl. A road along the east side is lined by homes, but the west side has a border of trees with farm land beyond.

Test holes installed in 1962 on the west side of the lake showed mainly marl near the lake, then marl and sand, followed by clay and sand at 172 and 184 feet from the water's edge. At the time the drilling was done (October 29, 1962) the water table sloped slightly away from the lake surface (1.3 feet at 184 feet from the water's edge) (figure 33).

Because of its depth Lake Elmo furnishes an important comparison with the potholes nearby, as it must be assumed that Lake Elmo is adjusted or controls the water table of its immediate area. The lake is comparatively stable in temperature because of the large volume of water compared to its surface area and, therefore, evaporation is lower than in the very shallow potholes nearby.

Figures 42 and 43 show a comparison of the graphs of the surface fluctuation of four bodies of water in the Lake Elmo Quadrangle. The shape of the graphs is similar, but there are differences in degree that will be discussed later.

The surface level of Lake Elmo was referred to a locally established benchmark on October 30, 1962 and stood at 870.0 above sea level. On January 7, 1963 the water level in a hole through the ice was 869.7. A staff gage was set on April 15, 1963, and the level was 869.85. Fairly heavy rains in May caused a rise to 870.25. The water level stayed close to the high until June 11 when a gradual decline set in during a period of practically no rainfall and high evaporation that persisted throughout the year. The level was 868.93 on December 10. From December 19, 1963 to March 12, 1964 the level was unchanged, but during the winter of 1964-65 the decline was .38 foot during the period Lake Elmo was covered by ice. The decline was noted at the end of a very dry period, and it is probable that the decline of this deep lake was in response to a decline in the regional water level.

As evidenced by infiltration tests, the soil around the lake — both above the present lake level and above the original shoreline — is highly permeable. In hole 2 (3 inches in diameter) water fell to the original water level of 3.5 feet in 12 minutes. The hole was refilled and used 3 gallons of water in 1.25 minutes. Hole 3 (in marl and fine sand with the original water level at 5.5 feet) declined 5.2 feet in 90 minutes when filled.

Hole 5 had the following log: 0-1.5 feet, sandy top soil; 1.6-2.0 feet, marl; 2.0-4.0 feet, heavy clay; 4.10-10.5 feet, sand. Hole 5 had an original water level of 9.1 feet. We found it impossible with the equipment at hand to completely fill the hole because of rapid water loss, so two tests were made starting at 4 feet from the top. Hole 5 was completely filled on the third run, due to soil saturation. But seepage was rapid and the water level declined 3.54 feet in 10 minutes—equivalent to a loss of 1.7 gallons.

During the winter of 1964-65 there was no decline in the water level during the period of ice cover but rather a small rise attributed to the heavy snow on the ice. The level on March 22 was 869.17. As a result of snow melt and heavy spring rains, the level rose to 874.95 by June 12 when the present project was terminated.

L.E. 2 is a shallow pond on the Koll farm in the north half of SW¼, sec. 23, T. 29 N., R. 21 W. and is 0.5

Table 28. Textural classification of samples from the test holes in the Lake Elmo Quadrangle

Sample	Location	Hole	Depth	Gravel	Clay	Silt	Sand	Class
8	Ria Lake	1	0-2′	14	5.9	9.5	70.6	Gravelly loamy sandy
9	Ria Lake	1	2-4′	trace	30.7	44.6	24.7	Silt clay loam
10	Ria Lake	3	0-8′	15	19.9	16.7	48.4	Gravelly sandy clay loam
11	Lake Elmo	3	5.5′	0	21.8	59.6	18.6	Silt loam
12	Lake Elmo	4	2-3.5′	3	32.6	52.0	15.4	Silty clay loam
13	L.E. 2	8	2-8′	5	14.9	24.1	56.0	Sandy loam
14	L.E. 2	8	8-13′	5	5.4	7.8	81.8	Loamy sand
15	L.E. 3	10	5-5.5′	11	2.1	6.6	80.3	Gravelly sand
16	L.E. 3	11	6-11′	13	10.4	14.6	62.0	Gravelly sandy loam
102	L.E. 3	11	3-4.2′	9	10.4	17.6	63.0	Sandy loam
107	Lake Elmo	1	Marl 88 percent					
144*	L.E. Pond	1W	4-5′	0	27.1	54.5	17.6	Silty clay loam
145*	L.E. Pond	1W	6.2-8.5′	0	10.4	18.8	70.8	Sandy loam
146*	L.E. 3	1W	3-4′	0	31.6	53.5	11.0	Silty clay loam
148-9*	Lake Ria	1W	8-10.8′	0	24.6	62.6	12.8	Silt loam
150*	Lake Ria	2W	4-4.5′	0	23.0	42.6	34.4	Loam
151*	Lake Ria	2W	4.5-5′	0	10.3	27.9	61.8	Sandy loam
189*	L.E. 3	1S	7.3-7.7	0	33.8	57.8	8.4	Silty clay loam
190*	L.E. 3	1S	8.0-13.1	0	35.6	56.3	8.1	Silty clay loam

* Denotes bottom sample.

mile west of Lake Elmo. It is in a rather sharp ice block depression just below the farm home and covers about 2 acres at the highest ordinary level. It is bordered on the northwest end by a road embankment and elsewhere by grassy pasture slopes, and lies near the east side of a group of 25 small ice-block depressions. Some are probably permanently occupied by water; others intermittently. These are all about 20 to 30 feet higher in elevation than Lake Elmo.

Two test holes at the southeast end of the pond penetrated a mixture of clay and sandy clay layers (see samples 13 and 14). Although we drilled 12 and 23 feet from the shore, we did not reach water in the first hole at 6.3 feet because a boulder stopped progress. The water level in the second hole stood at 9.2 feet from the surface (8.4 feet below pond level).

The detailed record of water levels for the pond started on April 15, 1963. Readings were made at intervals until December 20 and again from January 23 until the pond was dry on July 3, 1964. The usual rise occurred during the spring rains, but after June 10 a sharp decline set in which continued during July and August followed by a slight decline during the remainder of the year (figure 43). It seems probable that the larger part of the decline was a result of the very shallow water which permitted a relatively high evaporation rate. The spring rise was .34 foot, and the total fall, 1.66 feet. The original level of the pond was determined on September 12, 1962. Between that date and January 7, 1963, a period of little precipitation and low evaporation, the level ranged only from 896.8 to 897.0—the latter measured on the ice. This slight change would seem to show that there was little movement of water out of the pond by seepage. With the lack of snowfall during the winter of 1963-64, the pond showed only a slight rise in the spring of 1964 and with the summer period of high evaporation accompanied by negligible rainfall the pond was completely dry by July 3. The owner cultivated the pond bottom on July 11. With the rain in August a small amount of water accumulated and remained for the season. We discontinued further work because of low water.

L.E. 3. This pond is on the Koll farm about 1 mile west of Lake Elmo in the NE¼, NE¼ sec. 22, T. 29 N., R. 21 W. and has an area of about 2.5 acres. It lies in a low depression in a pasture and is largely occupied by rushes in summer. Eagle Point Lake, a large shallow lake, lies about 1,000 feet to the southwest, and several small depressions lie nearby just below elevation 900. The available area for run-in is small and so the pond is dry, or nearly so, during dry periods.

We dug three holes on the east side to determine the relation of the water table to the pond (figure 34). The soil proved to be clay and brown, sandy clay, grading downward to brown sand and sandy clay. Laboratory classification of three samples (15, 16, 102) are included in the tabulation given above (table 28). The water level in the test holes proved to be below the level in the pond despite the sandy soil. This indicates that the pond is isolated by the bottom sediments. An infiltration test in holes 10 and 11A showed that the clay and sandy clay had low permeability for the upper 4 feet of soil.

The graph of the staff gage readings (figures 42 and 43) shows the general rise and fall common to most of the ponds and lakes examined during this project, but a somewhat greater and sharper drop during the summer months. The water level through the ice stood at 888.24 on January 7, 1963. By April 15 it had risen to 889.06. The maximum was at 889.24 on May 13. Shortly thereafter a slow decline set in but was not significant until after June 12 when precipitation became subnormal and warm temperatures prevailed. By August 12 the major decline ended at 887.93, a total drop of 1.3 feet, and the decline for the remainder of the year was slight, making a total decline of 2.34 feet. A decline of .5 foot between November 5, 1962 and January 7, 1963 indicates some loss by seepage during a period of ice cover.

The interpretation of the fluctuation of the water level in this pond presents some uncertainties, but the general trends are not unusual, as noted above. The spring rise is normal, but the drop in summer is somewhat greater than normal. This may be attributed either to some leakage plus the usual evapotranspiration or just the latter. In view of the water level in the adjacent ground it seems probable that the major loss of water occurs as a result of excessive evapotranspiration abetted by very shallow water and consequent higher water temperature plus an excessive growth of pond vegetation. But a small loss by seepage is also probable as noted above.

Bottom Samples

Lake Elmo 3 seemed to be typical of many small potholes with a well-developed marsh growth and peaty accumulation although, as our records show, dry at times. The sediments in the bottom near the center were first sampled in January 1964 and again in August when the water had disappeared. The logs of the holes are as follows:

Hole 1W — January 23, 1964, middle of pond

Feet	
4	Ice
0-1	Black, mucky, fibrous peat, less fibrous near .5′
1-3	Black, clay-filled muck
3-4	Very wet black clay, sample 146
4-7.7	Black muck
7.7-8.2	Black clay grading to sandy gray clay

Hole 1S — Auger to water, peat sampler below. August 18, 1964

Feet	
0-1	Black peat, only moderately fibrous
1-4.3	Very fibrous, black to brown peat. Unusually fibrous layer at 1.5+
4.3-4.9	Rather sharp change to black organic clay or silt
4.9-6.2	Black organic soil. Water at 5.6 — 2 hours later at 5.3
6.2-7.7	Black sticky clay. Sample 189 at 7.3-7.9′
7.7-8	No sample (changed to peat sampler)
8-13.1	Stiff, black, organic clay (sample 190)

The laboratory classification of the samples is given in table 28.

Samples were collected from a hole drilled through the ice near the middle of a pond midway between Lake Elmo and L.E. 2 at the Koll farm buildings. The log and soil classifications are as follows:

Pothole No. 1 — Middle of pond on January 23, 1964

Feet	
0.2	Ice
0-4	Dark, plastic organic clay
4-5	Gray clay, somewhat oxidized to brown. Sample 144[*]
5-6.2	Gray clay and silt
6.2-8.5	Brownish sandy clay grading to sand Sample 145[*]

[*] See table 28 for laboratory classification.

Samples 144 and 145 are characterized by the absence of gravel, the high clay-silt content of 144, and the sand content of 145. This indicates a sorting action of water flowing into the depression, leaving boulders and gravel behind. The combined clay and silt content of 144 is 52.4 percent, which doubtless enabled the pond to hold water in the depression despite the fact that the water level slopes sharply away from the pond.

A microscopic examination of samples 144 and 145 showed the usual abundant silt particles and sand grains. The sand sizes include both very angular and rounded quartz grains with a few grains of various silicates. Brown aggregates of organic matter and clay minerals are common and clearly enclose minute silt grains. A careful search was necessary to reveal three rod-shaped grains believed to be diatom skeletons.

The combined clay and silt in samples 146, 189, and 190 is nearly 90 percent. On referring back to the tabulation of samples from the test holes of the drift taken on land in the Lake Elmo area, we found that the sand content ranges from 69.2 to 90.2 percent after removal of the gravel which ranged from 9 to 15 percent. Thus the proportions of clay-silt and coarser materials are practically reversed between land and bottom of the pond. Obviously a sediment with 90 percent clay-silt size material has a very low permeability.

Microscopic examination of the three bottom sediments 146, 189, 190) showed that all three samples have remains of diatoms and therefore were deposited in water. Organic matter and clay has flocculated, enclosing numerous silt-size particles of quartz. There are minor amounts of numerous silicate minerals as would be expected in a sediment derived from glacial drift.

L.E. 4. Lake Ria. This small lake was selected for its position high up on the east bluffs of the Mississippi River east of Newport in the W½, N¼, sec. 30 T. 28 N., R. 21 W. Washington County. As previously noted, Lake Ria lies in the southwest corner of the Lake Elmo Quadrangle. It lies in the St. Croix Moraine and at the west side of an extensive group of small depressions, many occupied by water during moist periods. Also about .25 mile to the east is a larger lake, locally called Lone Lake. L.E. 4 has no formal name but was called Ria Lake by long-time residents. The lake lies in a small depression that trends northeast-southeast, is long, irregular in shape, and receives drainage mainly from the northeast. Its area is approximately 11 acres, and the surrounding land is under several ownerships.

The glacial soil of the area is generally sandy, gravelly, and rocky but contains more or less silt and clay. Samples 8, 9, and 10 of the tabulation given in the general discussion of the quadrangle is indicative of the general character of the drift.

Test holes were made at the north and south ends, and the water table in all holes was below lake level (figure 35). This is not surprising in view of the sharp drop of the land to the west toward the Mississippi River. The topographic map shows that the elevation of Lake Ria is 947, and within a mile to the west at the east edge of Newport the elevation is 757. Lone Lake at 994 is nearly 50 feet above Ria.

We thought Lake Ria was a particularly favorable body of water for study of possible seepage into the ground. It is on the border in size between a pothole (pond) and a lake as defined by the Division of Waters, Minnesota Department of Conservation and, as previously noted, has a very sharp topographic gradient to the west. The record of the surface of the lake throughout the year is, therefore, of particular importance.

The earliest record of the level with reference to a locally established benchmark was 945.6 above sea level on October 25, 1962. On January 1, 1963 the water level through the ice was 945.2. A staff gage was set on April 15, 1964 with the level at 945.83. As was true of all the 1963 measurements in the area, the level rose during the spring rains, maintained a fairly good level until mid-June, and then declined steadily during the summer period of high evaporation. From mid-September on, the decline was very gradual (see figure 42). A significant rise of .44 foot occurred between April 15 and May 17, followed by a decline of 2.16 feet between May 17 and December 20. The graph and weather bureau records indicate that the greater part of the decline was due to evapotranspiration.

In order to verify the 1963 results, determination of water levels was continued throughout 1964 and into the spring of 1965 (figure 43). From December 20, 1963 to March 12, 1964 during a period of ice cover the decline was only .32 foot. The graph of the levels recorded during 1964 shows a slight decline (.80 foot) from January 23 to March 12 and a fairly pronounced rise to May 28 when a steady decline set in during a period of light rainfall that ended in mid-August. A small rise followed (see figure 43). From November 9, 1964 to January 9, 1965 (a period of ice cover) the decline was .17 foot. It seems, therefore, that loss by seepage is small. Between January 9 and April 22 (a period of heavy snowfall and spring rains) the level rose 5.84 feet and the lake was selected for a new detailed study.

Bottom Samples

Samples from the bottom of the lake were taken January 23, 1964 at two sites and subjected to laboratory analysis. The results are given in table 28.

The logs of the test holes in the bottom of the lake are as follows:

Hole 1W — Middle of Lake Ria, January 23, 1964

Feet	
4.4	Ice and water
0-8.0	Peat
0-8.7	Peat
8.0-8.7	Black organic clay or silt. Sample 148
8.7-10.2	No sample. Probably the same.
10.2-10.8	Black silt or clay. Sample 149

Samples 148 and 149 were combined for size analysis.

Hole 2W — At south end of ice, 25 feet north of normal shoreline

Feet	
0-2	Sand and peat. Probably contaminated from road grade
2-3	Peat
3-3.5	Black sandy loam
3.5-4.0	Black to gray, sandy clay
4.0-4.5	Gray, sticky clay, relatively dry. Sample 150
4.5-5.0	Gray sand. Sample 151
5.0-5.3	Gray sandy clay. Water level stable at 5.3.
5.3-9.3	Sandy clay grading downward to coarser sand and pebbles near the bottom.

Sample 151 is from a sand layer as shown by the log above. The others are probably more nearly typical bottom sediments, as shown by clay plus silt percentages of 85.2 and 64.8 and an absence of gravel that occurs in most samples taken from the shore.

A microscopic examination was made of small fractions of each bottom sample. Samples 148 and 149 from the middle contain abundant small angular quartz of silt-size grains, fairly abundant brownish organic clay aggregates, and many diatom skeletons. Sample 150 is a typical mixture of clay, silt, and sand size grains with quartz predominant, but the clay minerals include kaolinite, sericite, and montmorillonite. Complex silicates occur as sparse grains including feldspar, horblende, epidote, and sphene. Diatoms are present but rare.

Mankato East Quadrangle

M 1. Kimble Lake. This lake has an area of about 10 acres and is 8 miles east of Mankato on the Ken Kimble farm (Sec. 28, T. 109 N., R. 25 W.). Kimble Lake lies in the midst of a group of lakes, some of good size. Madison Lake, the largest, covers nearly 3 square miles (figure 36). The area is in a mild terminal moraine that extends along the eastern margin of the deposits of the Des Moines Lobe. The various lakes range in altitude from about 980 to 1,020 and do not appear to be adjusted to a normal water table level, although those to the west toward the Minnesota River Valley are naturally the lowest. The topographic map of the Mankato East 15-Minute Quadrangle shows the detailed situation. A survey on July 18, 1963 produced the following lake levels: Ballantyne 1,012.1; Duck 1,013.6; Kimble 1,018.6; Long 1,017.5; South Mud 1,007.0; North Mud 1,008.1.

Three test holes were made on the west side of the lake at intervals of 15, 45, and 65 feet from the water's edge on July 18, 1963. As shown by figure 37, the water level sloped sharply away from the lake level. Comparative levels were: lake, 1,018.6; hole 1, 1,018.4; hole 2, 1,015.9; hole 3, 1,014.3.

The soil adjacent to the lake (sample 78) has a large percentage of combined clay and silt as shown by the laboratory classification tabulated below:

Table 29. Textural classification of samples from test holes at Kimble Lake

Sample	Hole	Depth	Gravel	Clay	Silt	Sand	Class
78	3	2-10′	trace	35.5	40.5	24.0	Clay loam
166*	1B	3.5-8′	0	27.7	22.6	49.7	Sandy clay
215*	2B	10.8′	0	78.2	19.5	2.3	Clay

* Denotes bottom sample.

Sample 166 was taken at a depth of 4.5 to 4.7 feet below the lake bottom from a hole through 3.5 feet of ice and water. Sand was reported to have passed into blue clay at 7.5 feet but the sample was half sand. Later another test hole was made in slightly deeper water with the following results:

Feet
4.1 — Ice and water
0-4 — Peat
4-7.4 — Blue clay, sample 215 at 6.7 feet

As anticipated, sample 215 was an organic silty clay. Microscopic examination indicated that the clay minerals were predominantly montmorillonite and muscovite mica, usually referred to as illite in soils. An X-ray check of a small sample of minus 2 micron material yielded the following results:

Montmorillonite — Parts in 10-2.7
Muscovite Mica — Parts in 10-4.5
Chlorite and Kaolinite — Parts in 10-2.7

Table 30. Surface water levels of Kimble Lake

July 18, 1963	1018.6	October 10, 1964	1018.19
September 11, 1963	1018.7	December 21, 1964	1018.36
January 2, 1964	1017.9	March 24, 1965	1018.70
March 23, 1964	1017.7	May 1, 1965	10019.66
June 18, 1964	1018.00	May 20, 1965	1019.91
July 2, 1964	1017.8	June 6, 1965	1020.69
July 15, 1964	1017.88	August 3, 1965	1019.46
August 12, 1964	1017.48	September 15, 1965	1019.20
September 8, 1964	1018.38	October 15, 1965	1019.75

The relatively stable level during August and September suggests rainfall to balance relatively high evaporation. The fall of 1963 was a period of very low rainfall and a drop in water level resulted. During the period of January 2 to March 23, 1964, when the lake was frozen over, the level was nearly stable. The winter of 1964-65 was a period of heavy snowfall and one winter rain with the result that the water level rose slightly. In short, there is very little, if any, seepage to groundwater although the three drill holes show a steep slope of the water table away from the lake (figure 37).

The lake, reported to be about 60 feet deep in the middle, was at an average elevation of 1,018 in 1963. Such elevation places the lake 200 feet above the Minnesota River at Mankato, a distance of only 8 miles. Thus, a steep gradient in the water table must exist that would permit underdrainage if the bottom of the lake were permeable.

Marine Quadrangle

Ma 1. Johnson Pothole. The pothole Ma 1 is located in the NE¼, NW¼, sec. 25, T. 32 N., R. 20 W. Washington County on the Alder Johnson farm. It lies in a rolling upland at the head of a gully that extends to the St. Croix River 1.25 miles to the east. The normal water surface is at an altitude of about 968 and nearly 300 feet above the normal St. Croix River level of 680 (figure 41). The Johnson pothole is the farthest east of a series of potholes and lakes with Big Marine Lake 2.25 miles to the west. As shown by figure 38, there is a striking lack of adjustment of the water level of the various bodies of water to any common level. Lakes and ponds within about a mile of the Johnson pothole range from 8 feet below to 18 feet above its level as surveyed on June 4, 1963.

The area immediately surrounding the Johnson pothole is a pasture, and common swamp vegetation is largely lacking around and in the pothole. Local residents reported that the pond was dry during the severe drought of the thirties, but otherwise seems to be a fairly permanent body, although it freezes solid in late winter. The lack of swamp vegetation may be related to this long dry period and to the fact that cattle have access to the pond.

The Johnson pothole lies in the midst of cultivated fields that slope gently toward it. Shallow water drainageways show that in periods of heavy rainfall or melting snow a considerable amount of water runs into the depression, accounting for an abrupt rise in the water level, particularly in the spring. Within a few days during early April 1963 the water level rose a minimum of 2.87 feet at the time of the ice breakup. In the spring of 1964 (with very little snow cover the rise was a minimum of 2.47 feet by May 19. But during the same period Big Marine Lake and Sand Lake nearby rose only .45 and .38 feet, repsectively. In 1965 snowfall and rains at the breakup were both heavy, and the pond rose from 963.46 on January 1 to 972.15 by May 4. The only explanation that can logically be offered is the free run-off from cultivated fields as contrasted with the majority of the potholes studied, which have abundant sod, brush, and trees in the surrounding areas. Shallow test holes were made at the southeast side and north end (figures 39 and 40). In January 1964 a series of holes were also put down through the ice to sample the bottom sediments and determine the water level, as ice had formed to the bottom. The soil encountered in the holes at the southeast side was variable. Close to the water's edge, gray clay or silt occurred over black muck, but 17 feet further out top soil, gray, brown, and red clay, and silt extended to the bottom of a test hole at 8.5 feet. Still further out the soil was very sandy. At the north end of the pond the surface soil was mainly silt and clay and seemed impervious (figure 40). Near the water's edge a clay and pebble layer occurred from 1.5 to 2.5 feet and accepted water readily.

A second series of three test holes within 10 feet of the water's edge at the southwest side verified the existence of black muck below gray sand and silt which, it is assumed, had washed in from adjacent fields. Several samples of the soil were taken to permit size classification. The results are given in table 31.

The presence of sand, some gravel, and organic matter, in addition to the predominant silt and clay, indicates variable conditions of permeability. For this reason infiltration tests were made on all test holes drilled adjacent to the pond. These tests show the variability of permeability in various parts of the soil. Holes 1 and 2 at the southeast side, at 8 and 25 feet, respectively, from the water's edge allowed the water to seep out of the hole so rapidly that the water level approached the bottom of the holes within a short time. In contrast, six other holes showed comparatively slow seepage, especially below the upper foot of sod and top soil. In none of the six did the water level during the test approach the original water level in the hole or the bottom of the hole where water was lacking. The slowest seepage was a lowering of the water level .84 foot, and the most rapid 5.6 feet in 20 minutes.

The first determination of the water level in the Johnson Pothole was made on August 16, 1962 when the water surface was at an elevation of 965.76. By November 8 the water level had dropped to 966.97. On January 31, 1963 the water level was 965.56, and the ice surface 965.76. By April 4 the level had risen during the spring thaw to 968.63, and a staff gage was placed on that date. Readings were made at intervals for the remainder of the year and during 1964. The graph of figures 42 and 43 shows the fluctuations for 1963 and 1964. Moderate rainfall early in 1963 maintained the level fairly well until mid-May, then a steady decline set in, particularly after mid-June when precipitation was extremely low for the remainder of 1963. The total drop from April 4 to December 19 was almost exactly 5 feet. This is far above the evapotranspiration rate and can be explained only by seepage into the ground.

Conclusive evidence of seepage was obtained at an inspection of the pond on January 21, 1964. Eighty feet from the south end the ice over a rudely circular area 43 feet by 48 feet had collapsed. A well-developed circular crack separated the collapsed ice from ice on the remainder of the pond. There was no water below the ice and a test hole showed groundwater at 2.3 feet below the pond bottom. The test hole showed ice, 1.2; muck, 5; silt, 2.0; brown gritty soil, 0.5; and sand with pebbles, 0.3 feet. A test hole about 80 feet from the north end gave the following results: Ice, 1.2; muck, 3.2; gray silt and fine sand, 5; dark gray to black silt or clay, 1.0; brownish silt or clay plus pebbles, .5; and gray silt, 1.9 feet. There was no water in the hole to bottom at 8.4 feet.

A similar collapse of the ice occurred in the winter of 1964-65, but heavy snow obscured the features of the ice. There was a decline of 4.8 feet from the highest level in the spring of 1963 to the low on December 19.

Bottom Samples

The strong evidence of leakage from the bottom made the nature of the bottom sediments extraordinarily important. Logs of holes 3 and 6 show that the bottom sediments consist of silt with variable amounts of clay and sand as shown by the following tabulations:

Hole 6 — Middle of collapsed area of ice, January 21, 1964

Feet		
1.2	Ice	
0-.5	Muck	
0.5-3.7	Organic silt. Sample 138 at 0.5-0.8	
3.7-4.2	Brown, gritty soil	Sample 139
4.2-4.5	Brown, gritty soil with pebbles	

Hole 3 — 160 feet from north edge, January 21, 1964

Feet	
1.2	Ice
0-3.2	Black to brown muck
3.2-3.7	Gray silt and fine sand
3.7-4.7	Dark gray to black silt and clay
4.7-5.2	Brown silt and clay, pebbles
5.2-7.1	Gray silt, sample 140 at 5 to 6 feet

A comparison of the bottom samples 138, 139, and 140 with the samples from holes on shore failed to show any consistent differences. A microscopic study of sample 138 showed a typical silt with fairly abundant angular quartz grains of sand size but not rounded. Skeletons of diatoms are numerous, showing that sample 138 is a silt deposited in the pond. Sample 139, somewhat lower down, was taken from a layer in which pebbles were reported, and it is reasonably certain that this sample is a glacial deposit. The nearly 50 percent sand is also a point in favor of the glacial source. About all that can be concluded is that the sediments in the pond are not radically different from the glacial deposits on shore with perhaps some concentration of silt. Further examination of the bottom sediments is planned during a later project.

Ma 2. Morrison Pothole. On January 21, 1964 the positive evidence of seepage out of the Johnson pothole

Table 31. Textural classification of samples from test holes in the Marine Quadrangle

No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
Johnson Pothole							
18	1	2.5-4.5′	1	17.5	40.4	41.4	Loam
19	3	2.5-12′	16	7.1	13.5	63.6	Gravelly sandy loam
105	2(63)	5.7′	0	22.2	51.2	26.6	Silt loam
104	1(63)	0-3.5′	trace	16.0	61.0	23.0	Silt loam
103	3(63)	3.2-4′	trace	23.0	53.9	23.1	Silt loam
182	3	202.5′	0	25.4	28.3	46.3	Loam
138*	3	5-6′	0	9.4	62.2	28.4	Silt loam
139*	6B	5-6′	0	12.6	41.5	45.9	Loam
140*	3	5.2-7.1′	0	23.6	61.7	14.7	Silt loam
142*	1	2-2.4′	0	9.6	67.2	23.2	Silt loam
143*	1	3.7-4.2	0	27.6	56.0	16.4	Silt clay loam
100	Sand L, 1	2.5-3′	8	19.0	22.5	50.5	Sandy clay loam
58*	Sand L, 1B	9.3′	11	1.0	7.5	80.5	Gravelly sand
59*	Sand L, 1B	10.0′	0	5.0	42.5	52.5	Sandy loam

* Denotes samples from the bottom of the pothole.

was shown by ice collapse. It was then decided that observations were desirable on a nearby pothole for comparison. Fortunately, such existed on the Morrison farm across the highway and slightly over 1,000 feet somewhat west of north of the Johnson pothole. (NW¼, SW¼, sec. 24, T. 32 N., R. 20 W.). A water level had been determined for the pond on August 16, 1962 when the level was about at a normal high, that is 979.9. On January 21, 1964 the level had declined to 976.31. During the period January 21 to March 5 the level declined only 0.2 foot indicating only a small amount of seepage. As in the other lakes and ponds of the area there was only a moderate rise at the spring thaw. The pond is located in a pasture with gentle slopes on all sides and relatively free run-in may be expected during heavy rains or melting snow.

In 1964 the level rose from 976.31 on January 21 to a maximum of 977.31 on May 19, and declined rather consistently to 974.5 at the end of the year. The details are shown by the graph of figure 43.

Test holes were not made on the shore, as it was assumed the conditions were similar to those at the Johnson farm. To secure bottom samples a hole located at about the center of the pond was drilled through the ice in January 1964. The log is as follows:

Feet	
1.5	Ice
4.0	Water starts 0.2 below ice surface
0-0.7	Muck
0.7-1.2	Black, organic silt. Sample 141
1.2-2.4	Similar. Sample 142 at 2-2.4′
2.4-3.7	Lost sample
3.7-4.2	Gray clay or silt. Sample 143

A microscopic study of the three samples showed that organic matter is moderately abundant and with clay forms aggregates that appear brown under the microscope and frequently enclose minute grains of various minerals. Minute angular grains of quartz are abundant and make up much of the silt. These grains range from 0.005 mm to 0.3 mm. in diameter but average around .03 mm. Rod-shaped skeletons of diatoms are numerous in all three samples and prove deposition in water. In addition to quartz, there are several other minerals present, notably feldspar. The combined clay-silt content in these bottom sediments of 76.8 and 83.6 doubtless accounts for the water remaining in this depression.

The decline when the pond is at the higher levels indicates seepage, but during the period January 21, 1964 to March 5, 1964 the decline was only .20 foot during ice cover when the level was at 976.31, as compared with a June 1963 level of 979.81.

Ma 3. Sand Lake. The variable pond and lake levels in the area near the Johnson pothole made it desirable to have other detailed data for comparison of water levels. Sand Lake covers an area of 38 acres and lies 1 mile southwest of Johnson Pothole and west of the center of Sec. 26, T. 32 N., R 20 W. It lies on a gently rolling upland, but less than .25 mile to the east is the head of a gully that drops from an elevation of 950 to a terrace of the St. Croix River at 820.

Two test holes near the shore at the south end on the Lindgren farm showed that the soil ranges from silt or clay to sand with numerous boulders (sample 100). Soil size classification of sample 100 from test hole 1 is shown in table 31. During March 1963 samples of the bottom in 9.3 and 10 feet of water near the middle of the lake were also obtained (58 and 59).

Infiltration tests on two holes show a very slow rate in spite of the presence of sand. Hole 2 was dry 2.6 feet below lake level although only 38 feet from water.

From November 8, 1962 to January 31, 1963 the level declined .5 foot. The graph of water levels for the period March 26 to December 19, 1963, shows the same trend as most of the ponds and lakes under investigation (figure 42). A rise of about .6 foot occurred between March 26 and May 17. Then a slow but steady decline continued to September 1, followed by a slower decline as evaporation fell off and some rain compensated for evaporation. The decline from March to December was 1.65 feet, and from the high reading on May 17 to December 19 a decline of 2.49 feet was registered.

The trend of the levels of Sand Lake throughout 1964 (as of the other bodies of water in the area) show the effect of low snowfall, relatively light spring rains and a long summer drought that extended to mid-August (figure 43). The level on December 19, 1963 was 957.27 and declined to 956.62 on March 5, 1964. This suggests some loss by seepage, as the lake was frozen over during that period. The spring rise was only to 956.94 at the May 26 observation. A slow decline set in that continued to August 21, 1964. Late August and early September rains caused a small rise, but by mid-September the decline set in again as the rains ceased except for small showers that had little effect on the level. The decline from May 26 to the freeze-up in November was 2.17 feet which, allowing for precipitation, is somewhat more than a normal loss by evaporation. There was no decline over the winter of 1964-65, but this probably was a result of heavy snowfall and February rain. A tentative conclusion is that there is a small loss by seepage that may be related to the lake's location near the head of a gully leading to the St. Croix Valley.

Ma 4. Pitcher Lake. This pond or small lake was selected in the spring of 1964 for comparison with Johnson Pothole about 4.5 miles to the northeast. Johnson Pothole had proved to be the only example of large infiltration to the groundwater discovered to date. It seemed desirable to have another small body of water in the general area for comparison.

The pond is located in the NE¼, sec. 16, T. 31 N., R. 20 W., and is about 1,400 feet long, 400 feet wide at the widest place, and covers a little over 8 acres. Pitcher Lake has a slight eastward projection into section 15 on the Pitcher farm but extends mainly into the Olson and Sunberg farms. This small lake lies in the midst of a well-developed part of the St. Croix Moraine and is somewhat less than 4 miles west of the St. Croix River. The river is at an elevation of about 680 and the pond at about 950. Square Lake, about 1.5 miles southeast is at 871.

The glacial drift that makes up the St. Croix Moraine generally has a rather large content of sand, gravel, and boulders. The fine-grained material consists of silt rather than clay. In general, one would expect good permeability of the moraine as a whole. Lack of facilities prevented test borings on land, but all aspects of this pond and the adjacent area are being studied in a new program.

Water level observations are available from March 27, 1964 to August 2, 1965 and beyond in the new project. The general trend of the water level fluctuations coincides closely to that of Sand Lake to the north and Big Carnelian Lake to the south (figure 43). The original level determined on March 27, 1964 while ice still covered the lake was 859.02 with reference to a locally established benchmark. After the ice breakup, the level rose slightly to 959.22 in May 1964, but the absence of a snow cover and very light spring rains prevented a normal rise. A slow decline (figure 43) of 12.7 feet extended from May 19 to August 21 when above normal rainfall in late August and early September resulted in a small rise. The drop of 1.27 feet in the level was, without doubt, mainly due to very little rainfall during that period and relatively high evaporation. The level did not decline during the winter of 1964-65 because of heavy snowfall that, with heavy spring rains, raised the level 3.38 feet.

A test hole through the ice in 1964 and again in 1965 showed a considerable thickness of soft muck and peat. A summary of the two holes is as follows:

1964 water level through ice 959.02, middle of south part of the lake

Feet	
5	Water and ice
0.1-4.5	Soft muck followed by more compact muck with silty layers at 12-14.5′

1965 water and ice level 958.14. Located somewhat north of 1964 hole

Feet	
4.5	Water and ice
0-7.1	Soft muck
7.8-8.8	Firm muck
8.8-19.2	Peat, mainly brown and fibrous — sample 228 B at 16-17.4′
19.2-20.2	Brown sand with peat layer
20.2-22.5	Peat and muck. Sample 229 B at 19.8′

Future work will be done on this lake and samples 228 B and 229 were submitted for pollen studies to obtain an idea of the age and continuity of this small body of water. Details are given in the appendix of this report but this quotation from Barbara Sprose Hanson is pertinent here: "From this observtaion, sample 229 appears to be slightly older than sample 228 but still within the range of 8,000 to 10,000 years old on the basis of the C^{14} dates for the Cedar Bog Lake pollen diagram (Cushing 1963)." Cedar Bog is about 20 miles northwest of Pitcher Lake.

Ma 5. Big Marine Lake. Big Marine Lake lies mainly in the northwestern part of the Marine Quadrangle, but extends westward a short distance into the Hugo Quadrangle. This lake has an area of 1,577 acres and has extensive swampy areas bordering it. It occupies a shallow depression in the hilly upland about 4 miles west of the St. Croix River and 250 feet higher in elevation. Much of the lake is shallow, but near the south end a depression is fully 50 feet in depth. It was selected for detailed observation of the variation in level because of its size which we assumed had some control over the regional water table or, at least, was related to it in an area where several small lakes and ponds were being investigated. This lake also has a long history of declining levels and was at a very low stage when the project was started. Helped by heavy snowfall and spring rains in 1965, the lake rose to 3.67 feet above the reading on November 14, 1962.

The first determination of water level was on August 10, 1962, when it stood at an elevation of 936.10. On January 31, 1963 the ice level was 935.85, and the water level in a hole through the ice about 0.2 foot lower. Observations at frequent intervals began on March 26, 1963 when the ice level was 936.51. The graph on figure 42 shows the fluctuations from the above date to December 19. In response to the spring rains in 1963 the level rose to 937.10 feet. Then a slow decline set in during a period of low rainfall and high evaporation. The decline totaled 1.42 feet, which is judged to be within the surface loss by evaporation. Interpretation of the graph with the weather in mind does not suggest any significant loss to groundwater. The comparison with Johnson (Ma 1) Pothole is striking, as shown on figure 42.

Detailed observations of level were continued throughout 1964. It is significant that during a period of ice cover from November 21, 1963 to March 5, 1964 there was a gain of 0.1 foot. This is a small amount on which to base an actual gain in level, but there was no loss. (There was no seepage out as had long been supposed.) The graph of levels during 1964 (figure 43) has a normal pattern and the decline from May 5 to August 21 of 1.21 feet is doubtless due to a period of very low rainfall and high evaporation. There was a small rise from November 11, 1964 to April 1, 1965 when an ice cover prevailed.

Ma 6. Big Carnelian Lake. Big Carnelian Lake is located at the middle of the south edge of the Marine Quadrangle in Secs. 26 and 35, T. 31 N., R. 20 W. The lake has receded greatly in recent years, and it was reported that there was seepage to groundwater. As this was in the Marine Quadrangle, a gage was set and readings taken at intervals from November 14, 1963 to June 16, 1965. These data failed to verify any significant seepage during the period of ice cover. For example, from November 11, 1963 to March 5, 1964, the level declined only .19 foot. Again from November 11, 1964 to April 1, 1965, there was no decline but a gain of .33 foot. Perhaps more significant was a decline that preceded a period of heavy snowfall of .10 foot between November 11 and January 9.

The rise between April 1 and June 16 (a period of heavy snowmelt and rain) was only 1.65 feet.

The above facts lead to the tentative conclusion that the lake, at its recent level, does not lose an appreciable amount to seepage. It should be noted, however, that the shore where the lake has receded greatly is very sandy, and it is probable that higher water would be lost by seepage. Another important fact is that the lake has a small drainage area for its size, so it does not receive important amounts of water from the adjacent land under normal conditions.

Morgan Quadrangle

Mo 1. Lone Tree Lake. Lone Tree Lake is in the NE¼, sec. 9, T. 111 N., R. 33 W. about 6 miles east and slightly north of the village of Morgan in Redwood County. The adjacent land is owned by John Holtz. It lies in a typical prairie area underlain by ground moraine of the Des Moines Lobe and is only a mile southwest of the deep valley of the Minnesota River, which was eroded 200 feet down to bedrock by the torrents of Glacial River Warren.

Lone Tree Lake is shallow and weedy around the border but has a fair sized area of open water in the center. The total area is about 55 acres. In addition to Lone Tree Lake there are numerous shallow depressions in the general area, particularly 3 to 5 miles to the northwest. Two containing water when the project was started were examined briefly for comparison with conditions at Lone Tree Lake. Their locations are: SE¼, sec. 36, T. 112 N., R. 23 W. and NE¼, sec. 1, T. 111 N., R 34 W. At Lone Tree Lake three test holes were made on the south side at 15, 55, and 75 feet from the shore. These were in black sandy clay loam (figure 44 and sample 111). A sample from hole 3 (112) of section 36 pothole was in clay loam, as was a sample (113) from hole 2 at a pond in section 1. Laboratory classification indicated the following:

An infiltration test in hole 3 at Lone Tree Lake showed a fairly rapid movement of water out of the hole that continued at a decreasing but substantial rate for the 15-minute duration of the test. This is not surprising in view of the content of sand and the presence of organic matter. In contrast, a test in hole 3 of the section 36 pothole showed a small amount of infiltration during the first minute and very little thereafter. The presence of 40 percent clay doubtless accounts for the imperviousness of that soil. In contrast to the adjacent permeable soil, the bottom of Lone Tree Lake must be effectively sealed as shown by the water level stability during the winter of 1963-64 and again during 1964-65.

Bottom Sediments

A hole drilled through the ice of Lone Tree Lake in March 1964 furnished two samples that were examined in the laboratory. The soil classification is in table 32.

The absence of gravel and a very small amount of sand as compared with the 52.8 percent sand found in a sample taken from a hole on shore shows the high degree of classification performed by the water that carried the sediment into the lake.

A microscopic examination of sample 167 showed a considerable amount of organic matter which, with clay, formed dark brown aggregates that enclosed some of the coarser mineral grains. The clay is composed of at least two minerals. A few skeletons of diatoms verify the assumption that the sediment was deposited in water.

Table 33. Surface water levels of Lone Tree Lake, Morgan Quadrangle

September	11	1963	995.1
January	2	1964	995.01
March	23	1964	995.08
June	18	1964	994.94
July	15	1964	994.50
August	12	1964	994.19
September	8	1964	995.00
October	10	1964	994.23
December	21	1964	994.24
March	24	1965	994.42
May	1	1965	996.65
May	20	1965	996.65
July	8	1965	996.90
August	3	1965	996.70
September	15	1965	996.37
October	15	1965	996.73

Morris Quadrangle

Mor 1. A small lake with an area of about 25 acres lies 3 miles northeast of Morris in the NE¼, sec. 20, T. 125 N., R. 41 W. The area is underlain by nearly level till deposited by the Des Moines Lobe of the Lake Wisconsin Glacier. The Pomme de Terre River passes only about .5 mile to the west, but the lake is about 60 feet above the river and thus has potential underdrainage with a steep gradient. To the east, numerous shallow potholes and small lakes lie in a prominent glacial drainageway — evidently the ancestral Chippewa River.

There is a lack of accordance of water levels, indicating that the ponds and lake are independent of any existing regional water table that may exist. This situation led to the selection for investigation of the small lake with its location near the Pomme de Terre River. The farm on the east side of the lake is owned by Howard K. Olson, that on the west side by Telwar Harstad. Mor 1 has not been dry for over 20 years, but local residents report that it was dry during the severe drought of the thirties.

Test holes were made on the west side of the lake toward the river (figure 45). Hole 1, 30 feet from the water's edge on June 17, 1963, was in a coarse, sandy loam and the water level as drilled was 2.7 feet from the surface (elevation 1,146.60). Twenty-four hours later the water level had stabilized at 1,147.3. Hole 2 was 30 feet from shore in black clay loam for 4 feet, then a light gray

Table 32. Textural classification of samples from test holes in the Morgan Quadrangle

No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
111	3	2.5-4′	8	22.0	21.4	48.6	Sandy clay loam
112	3	1-2.5′	6	37.1	28.5	31.5	Clay loam
113	2	0-25′	trace	37.8	34.3	27.9	Clay loam
167*	1W	4.5′	0	33.2	46.8	14.0	Silty clay loam
168*	1W	7′	0	48.9	38.8	12.3	Clay

* Denotes bottom sample.

Table 34. Textural classification of samples from test hole in the Harstad farm, Morris Quadrangle

No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
77	2	4-4.5	15	21.9	24.0	39.1	Gravelly loam
216*	1B	8.5-9.5	0	25.2	44.7	33.1	Loam
217*	1B	9.5-10.5	0	19.0	32.6	48.4	Loam

* Denotes bottom hole.

to brown clay (sample 77). The water level was 3.45 feet (elevation 1,146.70) when drilled and 24 hours later had stabilized at 1,147.25. An infiltration test in Hole 2 showed fairly rapid movement of water out of the hole for 10 minutes, then slow but continuous movement for the 25-minute duration of the test.

Hole 2, August 20, 1963
Elevation of hole — 1,150.15
Elevation of water level in hole — 1,147.25
Elevation of lake level — 1,146.7

Hole 3 at 42 feet from shore was in black loam and light gray, sandy clay with the water level at 2.95 (1,146.60) when drilled and at 1,147.35 a day later (figure 45). The stabilized level of the lake on June 18, 1963 was 1,147.0. On the same day, the water levels in test holes 1, 2, and 3 were 1,147.3, 1,147.25, and 1,147.35, respectively.

The laboratory test results on the samples from test holes are given in table 34.

The water table appears to have a slight gradient toward the river. Lake levels at various dates were as follows:

Table 35. Water levels of the Morris Pothole

August 30, 1962	1145.2	September 9, 1964	1145.64
June 17, 1963	1147.0	October 11, 1964	1145.32
August 20, 1963	1146.7	December 22, 1964	1145.01
January 3, 1964	1146.15	March 25, 1965	1145.15
March 4, 1964	1146.26	August 5, 1965	1146.78
June 18, 1964	1147.22	September 20, 1965	1147.83
July 16, 1964	1145.96	October 14, 1965	1147.00
August 13, 1964	1145.41		

The January-March 1964 lake levels are particularly significant. During this time the lake was frozen over. Since this was a period of light snowfall, there was little to disturb the water level. The small gain is probably due to the small change that results from the relation of water and ice levels. The levels show, beyond reasonable doubt, that there is no significant seepage out of the lake to groundwater. The observations were repeated during the winter of 1964-65 with essentially the same results.

In December 1964 a test hole was made near the center of the lake with the following results:

Feet	
0-8	Ice and water
8-17.5	Silt, sample 216 at 16.5-17.5′
17.5-18.5	Sandy silt, sample 217

As shown by the tabulation above, the samples are a mixture of clay, silt, and sand and not much different from the sample from hole 2 on land near the lake. The samples were black with abundant organic matter and were selected for detailed study by microscopic methods.

The two samples contain skeletons of diatoms and therefore were water laid. Quartz of sand and silt size is abundant and clay moderately so. The principal clay mineral is montmorillonite as is generally true of clay in the till of the Des Moines Lobe. Calcite is present in small amounts, including one small shell fragment.

The thickness of the silt deposit with diatom remains indicated that a pollen analysis would be useful to determine the time of deposition of the silt at 9.5 to 10.5 feet below lake bottom. Details of this study are given in a separate chapter, but the following quotation of the report by Barbara Sprose Hanson is significant here:

> "Assuming that the pollen results from sample 217 most closely resemble a pollen assemblage from the *Pinus-Pteridium* subzone of the Thompson pond and Bog D pollen diagrams, it is possible to designate a relative date for the sample from Morris, Minnesota based on the C^{14} dates available for the Bog D pollen sequence. The C^{14} date for the lower boundary of the *Pinus-Pteridium* subzone for Bog D is 11,000 ± 90 years BP, and the dates for the upper boundary of the *Pinus-Pteridium* subzone is 8,560 ± 120 years BP. From the preceding data it is reasonable to suggest that sample 217 is between 8,000 and 11,000 years old."

New Brighton Quadrangle

The New Brighton Quadrangle covers an area of approximately 53 square miles directly north of Minneapolis and St. Paul. The glacial geology has recently been studied and mapped in detail by Stone (1965). The glacial geology is complex partly because the older deposits of the Patrician drift are lightly overlain by deposits of the Grantsburg sublobe and associated alluvial and aeolian deposits. Lakes and ponds are numerous with a considerable range in the water levels.

The two areas selected for detailed work are on opposite sides of the quadrangle, but both are located in areas of till named the Twin Cities Formation by Stone. These areas consist of a complex mixture of light gray till, reddish brown till, and other related drifts.

N 1. Stony Lake. Stony Lake is a small body of water (6 acres) in the northern half of Sec. 19, T. 30 N., R. 23 W., Anoka County 1 mile northwest of the village of New Brighton. Stony Lake is .5 mile west of Long Lake, a much larger body 60 feet lower in elevation. A small part of Stony Lake is cut off at the west end by Silver Lake Road. About 145 feet to the west and 13 feet above Stony Lake is a small pothole that measures 100 feet east-west by 125 feet north-south. This relationship was of particular interest in regard to the problem of seepage and both bodies were selected for study. The depth of Stony Lake at the time of bottom sampling in 1964 did not exceed 5 feet.

Test holes were made at the east end, at the west end of the part west of Silver Lake Road, and also between the small pothole (N2) and the lake, as will be described later. The test holes at the east end were made at intervals of 11, 25, and 42 feet from the shore and penetrated sandy clay loam soil. (See figure 46 and sample 24, table 36.) Sample 209 is from the bottom of the lake, 185 feet west of the east end.

The water level in the holes was at lake level in hole 1, 1 foot below in hole 2, and was not reached in hole 3 because of rocks. Road construction at the site prevented further tests, and as of August 1965 the lake had been so disturbed that further work was inadvisable.

In two test holes at the west side 18 and 33 feet respectively from the shore, we encountered boulders in a brown, sticky clay. Although both holes were sunk below water level in the lake, we encountered no water (figure 47). Infiltration tests showed that the soil in the vicinity of the lake and potholes had a low receptivity, except in hole 3 at the east side where an unusual increase in seepage occurred after 11 minutes. Unfortunately, grading of a street over the site occurred before a check could be made.

The first determination of water level of Stony Lake was made on August 8, 1962 when it stood at 923.2, with reference to the local benchmark established at the site. During 1963 observations were made at intervals using a staff gage. These are shown by the graph of figure 9. The water level in a hole through the ice stood at 922.59 on January 3, 1963 and at 922.12 on March 5 with the top of the ice at 922.30. The level rose somewhat irregularly until June 12. The last rain of any consequence in the area until September occurred on June 10. The level declined rather sharply during the warm, dry period of July and August, then very slightly to the end of the year. Total decline from June 12 to December 26 was 2.27 feet. Similar observations were made in 1964 and the graph (figure 10) shows a normal pattern. There was a slight decline during the period of ice cover from 920.65 on November 22, 1963 to 920.41 on March 12, 1964. A decline of only .24 foot in a period of nearly 4 months shows that seepage out of the lake is slight in spite of sandy soil in the area. The 1964 spring rise was small; the summer decline was fairly sharp as rainfall was deficient and humidity low. Heavy rainfall in late August and early September reversed the downward trend. The water level changed only .03 foot from November 11, 1964 to December 5 and actually gained .19 foot between December 5, 1964 and January 22, 1965.

Hole 1 — A test hole through the ice in the middle of the main lake and 135 feet east of Silver Lake Road resulted in the following log:

Feet	
0-4.1	Ice and water
0-1.2	Peat
1.3-3.9	Peat grading to muck
3.9-6.1	Sand
6.1-6.9	Coarse sand and fine gravel

Hole 2 — 185 feet west from the east end of the lake:

Feet	
5.1	Ice and water
0-3.1	Muck and peat
3.1-5.0	More compact muck and peat
5.0-5.7	Peat to silty muck to sand at bottom
5.7-7.6	No sample, probably soft muck
7.6-8.1	Sand grading down to a thin layer of silt and sand below
8.1-8.8	Coarse sand
8.8-9.4	Light gray silt and sand, sample 209

The logs indicate that below peat and muck the sediment in the bottom of the lake is sandy with thin layers. Sample 209 is predominantly sand but has considerable amounts of clay and silt (table 36). Microscopic examination of the sample shows that angular as well as rounded quartz grains are abundant. Organic matter with clay forms light brown aggregates in which the clay minerals

Table 36. Textural classification of samples from test holes in the New Brighton Quadrangle

No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
24	1	2-5′	5	25.3	17.6	52.1	Sandy clay
209	2W	8.8-9.4′	0	20.4	18.1	61.4	Sandy clay loam
26	4	0-5′	8	21.1	20.7	50.2	Sandy clay loam
161*	1W	4.0-4.3′	. .	37.6	39.2	23.2	Clay loam
159*	1B	10-11′	0	37.0	37.3	25.7	Clay
160*	. .	10.1-10.4′	0	40.8	36.0	23.2	Clay
121*	1B	5.5-7.5′	12	19.3	29.7	39.0	Gravelly loam
181	1	5.6-6.5′	8	19.9	13.9	58.2	Sandy clay loam
162-4	1B	8.4-15.5′	0	40.0	32.2	29.8	Clay loam

* Denotes bottom sample.

are flaky and needle-like in shape. Skeletons of diatoms are common and prove that the sand was deposited in the pond rather than by glacial waters.

In spite of the sandy deposit as shown by sample 209, there does not seem to be appreciable seepage out of the lake although the water level slopes away from the lake, and Long Lake — less than a mile to the east — is much lower, as noted above.

N 2. Stony Lake Pothole. As noted in the description of Stony Lake, a small pothole exists just west of Stony Lake, but about 13 feet higher with a ridge 145 feet wide between. This pothole, which probably had existed a long time, is only about 100 by 125 feet and when first observed contained between 2 and 3 feet of water. It was a favored home for a brood of ducks. The pond was mainly occupied by a heavy growth of rushes and allied aquatic plants and was bordered by a grove of scrub oak.

It seemed remarkable that this small pond could have existed with such a steep gradient to Stony Lake only 145 feet away. Moreover, it was evident that there was a considerable accumulation of peat in the depression. Later testing through the ice showed that the peat was, in fact, somewhat over 5 feet thick and a gray to black silt continued to 10.4 feet and contained an abundance of pollen. A remarkable feature is the very small area that could possibly contribute run-off to the pond.

At the time of testing, two test holes were made on the steep bank at the northeast side at 12 and 25 feet from the water's edge (figure 47). At 12 feet from the water's edge the water table was at pond level. At 25 feet the level was below pond level but at an undetermined depth because of boulders. The soil was brown sandy clay with oxidation decreasing downward.

Unfortunately, the shallow water of this small pond combined with below normal precipitation in 1963 resulted in its drying up in the late summer, thus preventing a complete record of water fluctuation. When first observed on August 8, 1962 the water surface was at 936.1. By November 11, it had decreased to 935.5, a somewhat modest decrease in view of the location and a very dry fall. In the spring of 1963 the water surface increased to 936.12 on May 15 and 936.10 on June 12. As was true on all water surfaces under investigation, a decline set in about mid-June and continued to August 27 when the pond became dry just below elevation 935. The total decline in level was 1.12 feet. About this time a street was graded along the west side, and its natural drainage was disturbed so that further observation of its water level was undesirable.

There is little doubt that Stony Lake Pothole is of glacial origin and presumably an ice-block pit. Although of very small size and situated on a hill, the pond has had remarkable persistence. To confirm this assumption the bottom was sampled at a central point with the following result:

Hole 1W. February 4, 1964

Feet	
0-5.1	Peat and muck
5.1-7.5	Black silt
7.5-10.1	Black silt with less organic matter, sample 159, auger, sample at 9.1-10.1
10.1-10.4	Gray sand and silt, sample 160. Core from Davis sampler

A sample of the silt at 7.5 was selected by H. E. Wright, Jr. for pollen analysis to determine where the flora fitted into the post-glacial ecology. The pollen laboratory of the School of Earth Science, University of Minnesota, reported an age of about 7,000 years for the sample. A sample (159) of the gray silt gave the size classification shown in table 36. The combined clay-silt content of the bottom sediments evidently represent the sorting action of inflowing water and acted as a seal to maintain the pond until organic matter added to the seal.

A microscopic examination showed that the fine-grained material consists of minute angular quartz grains and shreds and aggregates of clay. A few skeletons of diatoms show that the deposit at 10 feet was water lain. A detailed report on the pollen studies is given in an appendix to this report.

In order to compare the sediment in the pond with that on adjacent land a hole was put down through the ice in the middle of the pond with the results given below:

Feet	
0-2.2	Ice plus water to bottom
0-1.5	Muck and very plastic clay
1.5-2.1	Dark gray sand
2.1-2.7	Peaty and sandy muck
2.7-3.2	Clay or silt plus sandy layer
3.2-3.6	Plastic sandy clay
3.6-4.0	Stiff, sticky clay or silt
4.0-4.3	Stiff, black clay plus a pebble. Sample 161

Laboratory results on sample 161 are shown in table 36.

The combined clay-silt content of 76.8 percent doubtless accounts for the retention of water in the pond, although the normal water surface elevation is 7 feet above the lower lake only a few hundred feet to the north.

A microscopic examination of this bottom sample showed that the dark gray powder contained black to brown aggregates of clay and organic matter. Coarse, angular quartz grains are numerous, but extremely fine-grained silt is abundant. Diatom skeletons are numerous and prove that water-laid sediments are at least 4.3 feet thick in the pond.

N3-N5. New Brighton Quadrangle. In the vicinity of the intersection of Lexington and Victoria Streets north of St. Paul is a linear series of three small bodies of water (N3 to N5) at rather striking differences in elevation. The highest is in the NW¼, SW¼, sec. 23, and the others in the adjacent NE¼, sec. 22, T. 30 N., R. 23 W. The area has an irregular topography with several small lakes and numerous potholes.

When first surveyed in 1962 the three bodies had water surfaces at the following approximate elevations, 955.7, 935.1, 927.7. The upper pond is hemmed in by the grades of Lexington and Victoria Streets. Whether this is an entirely artificial situation or not is uncertain, but it is reported that a culvert once existed through the Lexington grade. Data obtained during this project shows that water does slowly seep out of the pond. The middle pond and lower lake appear to be permanent. During high water the middle pond overflows into the lower lake, but not much below elevation 935. The three bodies have an approximate acreage of 1.7, 1.4, and 15.2, respectively.

The upper pothole (N3) has rather steep natural banks on the south and east sides and partly road grade banks on the north and west. It is in a pastured field with minor marsh vegetation. Three test holes were made at the southwest side and a single hole on the northwest side as a check. The soil was mainly a sandy loam as shown by sample 26, table 36. The water level in the three holes on the southwest side was allowed to stabilize for 4 days and then stood as follows: 1-954.43; 2-954.3; 3-954.15. The pond was at 955.7. The elevation of the water surface was first determined on July 27, 1962 and stood at 955.7. Precipitation was normal or slightly above for the next few months and the level stood at 954.5 on December 3, 1962. It stood at 952.97 on January 4 and 954.12 on May 7, 1963. Beginning in May, 1963 readings were made at frequent intervals as shown by the graph in figure 9. Precipitation was good until June 10 and then was below normal for the remainder of the year. It became evident very soon after the last heavy rain on June 10 that this pond was losing water rapidly as compared with the lower pond and small lake. Contrary to all but one other pond under observation, the decline was at a practically constant rate from June 12 to December 26; the two readings are 954.24 and 947.82. In view of the artificial fill for the street grades, it was concluded that water was leaking through the road grade, although the supposed culvert could not be located. The graph of the elevation of the water surface is valuable for comparison with the many other graphs where no artificial factors are known to exist (figure 9).

The middle pothole (N4) west of the intersection of Lexington and Victoria has a high wooded hill on the south and west that contributes runoff in addition to that from the pavement of Lexington Avenue and the upper pothole. N4's maximum height is controlled by overflow along a small ditch at about elevation 936.

Test holes were made on the steep banks at the south and north ends. The pond level on August 26, 1962 stood at 935.1; the water level in the south hole was at 933.92, and the north hole at 933.34. The water levels in the holes were checked on May 21, 1964 and stood at 931.2 and 930.8, the pond level having declined meanwhile to 935.5. There seems to be no freedom of movement to groundwater. In fact, infiltration tests in two holes in the area showed that movement of water out of the holes was very slow. The water level fluctuation during 1963 in the middle pothole was similar to that of most of the water surfaces of ponds and lakes involved in the project during 1963 (figure 9). On May 7 the level was at 934.96. It rose to 935.14 by June 12 and then, due to dry weather, declined to 932.7 on December 26; most of the decline was in July and August, a period of little rainfall and high evaporation.

The level remained relatively stable during the winter of 1963-64 when the pond was frozen over. Specifically, the level was 933.06 on November 8, 932.70 on December 26 and 932.68 on March 13, 1964. The level, therefore, was essentially stable for two and a half months.

In accordance with most of the water levels under observation, there was only a moderate spring rise in 1964 (figure 10). The summer decline was moderately great as there was subnormal rainfall.

The lowest of the three bodies of water in the Lexington-Victoria area (N5) is a long, narrow lake 2,200 feet long with a maximum width of 400 feet. Its area is approximately 15 acres. It is held in on both sides by steep banks or slopes and doubtless is in a glacial drainageway with a southeasterly trend.

Test holes were made on the east side near the south end. Difficulty with rocks made impracticable completion of a good cross section showing the water table (figure 48). The soil is a red, sandy clay with pebbles and cobbles. When the original holes were dug in 1962, those at 34 and 69 feet from the water's edge failed to strike groundwater at 5.2 and 5.5 respectively. This was 2.5 below lake level. The same holes were checked on June 13, 1963, and water stood in hole 1 at 1.1 and in hole 2 at 3.1 feet. The water level in hole 1 was essentially at lake level, but in hole 2 it was nearly 2 feet above. Another check was made on May 21, 1964. The lake had declined to 926.6; the water in hole 1 stood at 926.8 and in hole 2 somewhere below 927.4, but a rock at the bottom prevented determining the level.

It appears from the available data that the water table near the lake fluctuates with the water available to the ground from rainfall. The graph of lake level readings for 1963 closely resembles that of most of the potholes and lakes involved in this project (figure 9). The level stood at 927.31 on January 4, at 927.14 on March 4, rose to 928.48 by June 12, and then declined moderately during July and August and very slowly thereafter to 926.73 on December 26. The total decline was within that expected of an excess of evaporation over precipitation, as the last half of the year was a period of deficient precipitation. The decline between December 26, 1963 and March 13, 1964 was .45 foot indicating slow seepage during ice cover.

The levels for 1964 were normal including a small rise in spring, a decline during a period of deficient rainfall from May to mid-August, then a small rise as heavy rains fell over a period of 3 weeks, followed by dry weather and a slow decline (figure 10). Under the influence of heavy snowfall and spring rains in 1965, the level rose 4.47 feet over that of the preceding November.

The bottom of the lake was sampled 200 feet from the south end. The log is as follows:

Feet	
0-3.1	Ice water
0-5.3	Soft, fibrous peat
5.3-10.7	Plastic clay or silt
10.7-11.3	Clay, somewhat sandy. Sample 163
11.3-12.4	Clay. Sample 164

The samples were combined for laboratory work with the results shown in table 36.

A microscopic examination revealed a large amount of brown aggregate material apparently consisting of clay and organic matter with entrapped silt particles. Quartz is abundant, some as coarse angular grains, many as very small grains. A few very small rods are remains of diatoms and an indication of a water laid deposit. The 70 percent of clay and silt doubtless accounts for the relative stability of this small lake that is in an area where the several lakes and ponds maintain divergent levels, ranging from a low of 876 or less to 944 or higher.

Solomon Lake Quadrangle—Willmar Area

The Solomon Lake Quadrangle lies directly north of Willmar in Kandiyohi County and includes a small part of the city. The eastern part of the quadrangle has a concentration of lakes of varied size that extend the full length of the quadrangle from north to south. Those to the south are connected by creeks and are at nearly the same level, but those to the north are at divergent levels. For example, Long and Point Lakes are only 900 feet apart (figure 49). But Long Lake is approximately 27 feet higher and Point Lake is 12 feet higher than Eagle Lake 700 feet to the east. Several potholes are scattered over the morainic area between the above lakes and Solomon Lake on the west side of the quadrangle.

The point of special interest in this quadrangle is the relation of the various ponds and lakes to each other, the water table, if any, and the reason for such diverse water levels in an area with a great deal of surface water. We might expect a near surface water table, although this does not seem to be the situation.

Test holes were made on the west side of Long Lake, between Long and Point Lakes, and also between Point and Eagle Lakes. The test holes on the west side of Long Lake, about a mile east of Pothole 1 showed the soil to be sandy and black plastic clay. The holes at 2, 15, and 45 feet west of the water's edge showed the water level in the holes to be .47, .52, and 1.76 feet below the lake level at 1,162.35. The lake is 35 feet lower than the pond (So 1) less than a mile to the west. It is thus evident that there is a lack of free circulation from the lake to ground and also within the ground. The divergence of water surface levels within very short distances does not correspond to a logical configuration of a water table. To learn more about the situation, additional shallow holes were sunk near the water along a nearly east-west line connecting the lakes as noted above.

On the east side of Long Lake, with Point Lake 700 feet to the east, the water surface slopes westward toward Long Lake in a sand and gravel soil. On the west side of Point Lake the slope is gently away from the lake (figure 50).

Point and Eagle Lakes are separated by a narrow neck of land, as shown in figure 49. The water surface close to Point Lake is level with the lake for about 75 feet and then within 30 feet dips sharply eastward. Across the neck of land near Eagle Lake the water surface is inclined gently toward the lake. Samples collected from the test holes proved to be sandy, as shown in table 37.

The level of Eagle Lake, which covers 855 acres, is controlled by an outlet to the south into Swan Lake and then into Willmar Lake and eventually southward to the Minnesota River. Point and Long Lakes lack outlets and excess water, if any, must move out underground. The lakes' normal levels are apparently a result of impervious bottom deposits. Otherwise we would expect them to seek a common level because they are separated by only 900 feet. Infiltration tests in holes at Eagle and Point Lakes and at the pothole show that water moves rather freely through the adjacent glacial sediments on the east side of Point Lake.

As shown in table 37, the most significant levels are those for the winter of 1964. During the period January 2 to March 24 (a period of ice cover and only minor snowfall) the fluctuations were small and showed that seepage was small or nonexistent. Point Lake received some water by inflow from groundwater. The period December 24, 1964 to March 3, 1965 was also one of an ice cover and essentially no evaporation, and the levels rose somewhat because of an unusual February rain.

So 1. Pothole. In the morainic area west of the lakes described above are several ponds (potholes), some at elevations considerably above the lakes. One of these designated So 1 was selected for investigation. It is crossed by the township road between Secs. 15 and 16 T. 120 N., R. 35 W., and is .5 mile northwest of the nearest point on Long Lake and 35 feet higher in elevation. So 1 has an area of approximately 1.8 acres, and the larger part is west of the road. But the east side was gaged because the lakes referred to above lie to the east. From Pothole So 1, a line oriented slightly south of east passes within 3 miles across Long, Point, and Eagle Lakes (figure 49). The respective elevations of the water surfaces on June 20, 1963 were approximately 1,197, 1,162, 1,138, and 1,124.

Table 37. Textural classification of samples from test holes in the Solomon Lake Quadrangle

Lake	Sample	Hole	Depth	Gravel	Clay	Silt	Sand	Class
Long	81	33	7-9′	4	22.1	33.6	40.3	Loam
Point (W)	82	3	5-7′	22	10.1	16.1	51.8	Gravelly sandy loam
Point (E)	83	2	0-3.5′	18	8.0	8.5	65.5	Gravelly loamy sand
Point (E)	84	3	7-9′	9	19.2	28.0	44.8	Loam
Eagle	85	3	2.5-3.5′	12	15.3	25.0	47.7	Gravelly sandy loam
Pothole So 1	80	3	3.4-5′	6	27.4	29.4	47.2	Clay loam
Pothole So 1	170*	1W	5.6′	0	27.2	28.6	44.2	Loam

* Bottom sample from center of the pothole.

The water level in test holes when drilled sloped slightly to the east toward Long Lake as shown by figure 51, but 2 months later as a result of dry weather the level of the pond had decreased .8 foot and the water levels in the holes were nearly the same as the pond level.

The water level in the pond fluctuates considerably, as shown in table 38, but available data indicates that winter loss was small. From January to March 1964 there was a small gain, mainly as a result of an early thaw of a light snow cover. From October 10 to December 24, 1964 the loss was .56 foot, in part from evaporation before the presence of an ice cover. A rise of over 4 feet in the spring of 1965 was the result of unusually heavy snowfall and spring rains. This was followed by a drop of 2 feet between May 20 and September 20. This tends to verify the fact, indicated by infiltration tests in holes on the land, that the soil adjacent to the pothole is permeable, but the sediment in the bottom is, at least, only slightly permeable.

Table 38. Water levels of three lakes and a pond, Solomon Lake Quadrangle

Date	Sec. 15/16 Pond So. 1	Long Lake	Point Lake	Eagle Lake
September 5, 1962	1,196.5	1,162.52	1,139.12	1,124.41
June 19, 1963	1,197.1	1,162.78	1,138.32	1,125.01
August 19, 1963	1,196.3	1,162.38	1,137.72	1,124.47
January 2, 1964	1,195.8	1,162.18	1,137.71	1,124.57
March 24, 1964	1,195.95	1,162.11	1,137.88	1,124.49
June 19, 1964	1,196.64	1,162.65	1,138.19	1,124.95
July 15, 1964	1,195.84	1,162.35	1,137.87	1,124.78
August 12, 1964	1,194.87	1,161.67	1,137.35	1,124.29
September 9, 1964	1,195.39	1,161.91	1,137.68	1,124.56
October 10, 1964	1,194.60	1,161.99	1,137.37	1,124.23
December 24, 1964	1,194.04	1,161.43	1,137.28	1,123.99
March 3, 1965	1,194.32	1,161.82	1,137.63	1,124.53
May 1, 1965	1,198.32	1,162.93	1,138.62	1,125.61
May 20, 1965	1,198.19	1,162.37		
August 5, 1965	1,196.80	1,164.10	1,138.96	1,125.02
September 20, 1965	1,196.26	1,163.99	1,138.84	1,124.75
October 15, 1965	1,196.54	1,163.97	1,138.99	1,124.94

St. Paul S.W. Quadrangle

The area of the St. Paul SW7½ minute topographic sheet includes a number of small lakes and literally dozens of potholes or ponds. Some depressions are permanently occupied by water; others, particularly the smallest, dry up in periods of low precipitation. The area had several advantages for the work of the "pothole project": (1) It is only a short distance across the Minnesota River from the Minneapolis-St. Paul International Airport where the official weather observations for the area are made. (2) The area is in a zone of pronounced terminal moraine topography so the various water bodies are at rather widely differing elevations. (3) The glacial deposits consist of red drift originating from the northeast, lightly overridden by gray drift derived from the northwest. (4) The Minnesota River gorge is deeply incised across the northwest part of the quadrangle with a normal water level at 690 above sea level, whereas some of the lakes are as high as 920; thus underdrainage is potentially good. (5) Professor H. E. Wright, Jr. and his students have made detailed investigations of the glacial and post-glacial history of a small lake (Sa 3 of this report) and a marsh in the area.

Sa 1. Brown Lake. This pond is located in the southest corner of Sec. 17, T. 27 N., R. 20 W. The area lies near the eastern margin of Mankato Drift of the Des Moines Lobe where the Mankato Drift overlies the St. Croix Moraine of Patrician age. This area was at one time a part of Blackhawk Lake to the east, but a ridge several feet high now separates the two bodies of water and evidently has done so for a considerable time.

At present the pond has an area of about 4 acres, and the water level is the same as that of Blackhawk Lake. The average depth of water in the middle is about 5 feet. The site is in a well-developed terminal moraine but only .5 mile from the bluffs along the Minnesota River Valley, which extends in a northeasterly direction. The river, as previously noted, is at an elevation of about 690, whereas the pond is at about 790. The suronding hills rise to 900. The area is partly wooded, two large lawns slope down to the water from the west, and there is a garden on the north side. The ridge between the pond and Blackhawk Lake is also cultivated during low water.

Test holes were made on the northwest and southeast sides with the results shown in figure 52. The water table slopes slightly toward the pond on the northwest side and away on the southeast. This is the reverse of what might be reasonably expected because of the steep gradient to the Minnesota River Valley on the northwest side, except for a high ridge near the pond.

The soil around the lake consists mainly of gray sand below the organic top soil, but there are local clay and sandy clay layers. Samples (20, 114, 115) of the latter from 3 holes on the southeast side of the pond gave the laboratory results shown in table 39.

Table 39. Soil analysis of samples from test holes in the St. Paul S.W. Quadrangle

Sample No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
20	5	5-5.7′	6	32.6	25.7	35.7	Clay loam
115	2A	3-5′	9	6.8	18.0	66.2	Sandy loam
114	1A	3-5′	trace	13.2	43.1	43.7	Loam
106	1	0-3′	12	4.0	12.8	70.2	Gravelly loamy sand
21	3	0-7.7′	14	9.6	7.3	69.1	Gravelly loamy sand

Infiltration tests in holes 1 to 5 showed that water moved freely through the soil, mainly through the sand layers.

Extensive gage readings of the water level were obtained for 1963 and 1964. With some allowance for variation in rainfall, the water level graphs for the 2 years are similar and have what appears to be a normal shape based on the results of this project (figures 25 and 26). There is only a minor change during the winter. From December 18, 1962 to March 14, 1963 the decline was .2 foot and from October 24, 1963 to March 9, 1964 .3. Again in the early winter of 1964 there was no change from November 9 to December 31. At the spring breakup in 1963, there was a rise of .67 foot and then a decline beginning in June, pronounced during the hot weather and very slight for the remainder of the year. The 1964 spring rise was slight, as there was very little winter's snow and low rainfall. A summer decline continued from mid-May to mid-August when heavy rains resulted in a rise of .5 foot. As in most of the ponds and lakes examined, there was a sharp rise of 5 feet in the spring of 1965.

When Brown Lake was first inspected in 1962 the low water level was thought to be a result of seepage to the steep slopes of the Minnesota Valley. A review of the gage records, however, showed that this was probably not so. Otherwise there would have been a pronounced decline all winter, which was not the case. The explanation of this situation probably lies in the combined silt-clay content of 80.8 percent obtained for a bottom sample. A microscopic examination showed that the sample contained abundant organic matter which formed black and brown aggregates with clay and silt. Diatoms remains were sparse but sufficient to show that the silt was deposited in the lake.

Sa 2. Kehne Lake. This small lake is located in the east half of Sec. 22, 8 27 N., R. 23 W., about a mile northeast of Carlson Lake. It has an area of about 12 acres and a peculiar shape with two elongated segments forming a near right angle. The St. Croix Moraine is rugged in the area with the lake lying in a deep depression. The lake is shown on the topographic sheet at elevation 817, whereas a broad, flat-topped hill .5 mile to the southeast is at 987. The average depth of the lake is less than 5 feet. The surrounding area is mainly wooded and the lake has a broad zone of rushes because of the shallow water near shore.

Test holes were made on the north and south sides of the southwest arm or bay. As shown in figure 53 the soil is predominantly sandy. A sample from test hole 3 (sample 21) gave the results shown in table 39. Infiltration tests in holes 1 and 2 showed rapid loss of water during the first 5 minutes and a continuous slower loss to the end of the test in hole 1 at 40 minutes. An average of three samples from a hole drilled in 5 feet of water gave moisture 60 percent and organic matter 17.7 percent.

The earliest observation of surface water level after establishing a benchmark near the lake was on August 29, 1962 when the elevation was 818.5. On November 13, 1962 the reading on ice was 818.8. The first reading in 1963 was on March 14 when the ice level was 818.65, a loss of only .15 foot in 121 days under ice cover. There was a sharp rise from March 14 to March 29 and a continuing irregular rise to June 3, 1963, as shown on figure 25. The sharp rise is presumably a result of run-in from the steep slopes around the lake. With the end of the spring rains on June 10 a rather sharp decline set in during July and August, then leveled off for the remainder of the year. The net loss from March 14 to December 23 was 1.10 feet; from the peak level on June 3 to December 23 the decline was 2.12 feet. These data show the large extent to which precipitation and evaporation control the lake level.

The 1964 record is somewhat similar as the graph shows (figure 26). A slow decline continued until mid-March when the usual spring rise set in ending in mid-May, followed by a long decline during a long summer drought. Rains in late August and early September caused a slight rise. The loss under ice cover during the winter of 1963-64 was greater than during the previous winter. In the winter of 1964-65 the lake was so low that reliable data on loss could not be obtained. In common with other bodies of water in the area, a large rise occurred in the spring amounting to 5.76 feet by April 22, 1965.

Available data indicate that there was a small to medium loss by seepage but more data is needed because of the difference in readings for two winters, as shown above. Additional samples of the bottom sediments are particularly desirable and will be obtained during a new project now underway.

Sa 3. Lake Carlson. Lake Carlson is a small body of water (about 9 acres) in the NW¼ of Sec. 27, T. 27 N., R. 23 W. This location is about 2 miles southeast of Brown Lake, a mile southwest of Kehne Lake, and about 14 miles south of Minneapolis in the midst of hilly St. Croix Moraine near the border of the Mankato Drift of the Des Moines Lobe. Wright, Winter and Patten (1963) suggest that the Lake Carlson depression may represent the location of a sub-glacial stream. The surrounding area is hilly and has many small depressions occupied by lakes, ponds, or marshes. There are 7 ponds and several marshes shown in section 27 on the topographic map of the St. Paul S.W. Quadrangle. The various bodies of water range considerably in elevation. For example, Jensen Lake, less than a mile southwest of Lake Carlson, is shown at 903 on the topographic map, whereas the Lake Carlson surface averages about 827.

Lake Carlson has a narrow sandy beach bordered by sedges and grasses with a zone of willows and poplar inshore. The adjacent area is mainly pasture land, and runoff finds little difficulty in reaching the lake, particulary along a drainageway from the west. The hills on the eastern and northern sides are covered by an oak forest. Details on the vegetation are given by Wright *et al.*

Test holes were made near shore on the southwest and east sides and the logs are shown on figure 54. The soil is predominantly sandy clay and loamy sand plus a variable amount of gravel. A typical sample (106) showed the classification given in table 39. The detailed investigation of the sediments beneath the lake by Wright *et al* showed a remarkable thickness of 13.2 meters (43.3 feet) of water-laid sediments above sand, presumed to be of glacial origin. The lake sediments consist predominantly of gyttja, a sapropelic black mud in which the organic matter is more or less characteristic of eutropic and oligotropic lakes. The common word muck is a suitable synonym for gyttja.

The first determination of lake level during the pothole project was made on December 4, 1962 when the ice level was at 827.15. Staff gage readings began April 1963 and continued at intervals to date. As shown by the graph of figure 25, there were only small changes during April, May, and early June, and the initial reading on April 9 was the high point. From June 9 on there was a steady decline during the summer months when evaporation was high and rainfall was negligible. During the remainder of the year there was a very slow decline as evaporation decreased, and an ice cover developed about December 1. Total loss during the period April 9 to December 23, 1963 was 1.92 feet, due mainly to evaporation.

Similar readings were made at intervals during 1964, as shown in figure 26. There was very little change in water level during the winter of 1963-64 (.1 foot from December 23 to March 12). The rise during the spring breakup was .85 foot because snow cover was thin. Rainfall was light during May and June and negligible during July and August. As a result a steady decline set in and amounted to 1.26 feet between April 28 and August 7. Rainfall totalling about 6 inches during late August and early September reversed the decline, but an extremely dry condition on the soil prevented any significant run-in.

From November 9 to November 21, 1964 the decline on a staff gage was .05 foot, which is probably a fair indication of the amount of seepage. As at Brown and Kehne Lakes, there was a sharp rise in the spring of 1965 from an ice level of 825.08 on December 31, 1964 to 833.65 (8.57 feet) on April 23, 1965.

New Brighton and St. Paul W. Quadrangles

S.P. 4. Cleveland-Roselawn Pothole. A small pothole northeast of the corner of Cleveland Avenue and Roselawn Street in Ramsey County is less than a mile north of the St. Paul Campus of the University of Minnesota and was selected as a testing ground for methods because it was only a mile from the Agricultural Engineering Shop. The Cleveland-Roselawn Pothole lies in the midst of rolling topography with several potholes and small lakes irregularly distributed over the area. A very small northern part of the pond lies at the southern end of the New Brighton Quadrangle, bounded on the south by the 45th parallel of latitude. The remainder of the pond is in the St. Paul West Quadrangle, specifically in Sec. 17, T. 29 N., R. 23 W.

The geologic situation according to Stone (1965) is similar to the other ponds and lakes studied in the New Brighton Quadrangle. Preliminary drill holes showed at once that the relation of pond level and groundwater levels was far from simple, and considerable testing was done as shown in part by figure 55. Unfortunately dumping of fill on the south and west sides was started shortly after the initial test holes were made, so it was decided to discontinue reading a staff gage but other observations were continued. The remarkable fact is that the pond level decreased only moderately in spite of sub-normal precipitation in late 1962, all of 1963, and most of 1964. Cessation of dumping permitted resumption of gaging in 1966.

One of the first tests was to dig a hole with a shovel about 3.5 feet from the edge of water in the pond. Surprisingly, the water in the pit remained below pond level after 5 hours. This situation was checked in November 1964 and the water level was again at 3.5 feet below pond level.

As shown in figure 55 a series of six test holes were made. All but the initial pit were dug by hand or machine augers. Hole 2 (20 feet from shore) was started 5.5 above pond level, sunk to 10.5 feet, and encountered water 5 feet below pond level.

Hole 3, at about the same level as hole 2 and 28 feet from shore, was sunk 20.4 feet where we struck a rock, but there was no evidence of water. Hole 4 was then sunk 11 feet from shore and just over 4 feet above water level stabilized at 7.8 feet or nearly 4 feet below pond level. Hole 5 was then located about 6 feet from water and slightly above the number 1 pit, and the water level proved to be about 1 foot below pond level. Hole 6 was then located 3 feet farther from the pond and nearly a foot higher than 5, and the water level proved to be over a foot lower.

The soil from all of the holes contained much sand and gravel but had enough clay and silt to cause it to cake into hard lumps when dry. (See soil analysis of sample 214 from hole 6.) Material excavated from a cesspool at a house 175 feet from the pond contained cobbles and small boulders. The color of the soil ranged from dark gray in the pit at the shore to red in hole 8, brown in holes 2 and 3, and gray in holes 4, 5, and 6.

In spite of the sandy and gravelly nature of the soil, it has rather low permeability as was shown by infiltration tests in holes 2, 4, 5, and 6.

Laboratory results of samples show the distinct difference between glacial drift (samples 214 and 216) and water-laid samples from the bottom of the pothole.

Table 40. Textural classification of samples from test holes at the Cleveland-Roselawn Pond

No.	Hole	Depth	Gravel	Clay	Silt	Sand	Class
224*	1B	5.9-6.9′	0	37.0	48.0	15.0	Silty clay loam
225*	1B	8.4-9.4′	0	32.9	57.6	9.5	Silty clay loam
226*	1B	16.2-17.2′	11	18.5	19.0	51.5	Gravelly silty clay loam
214	6	2.5-5′	14				
				16.9	25.6	43.5	Gravelly silty clay loam

* Denotes bottom sample.

Muck — A dark colored soil, commonly in wet places, which has a high percentage of finely comminuted organic matter.

The bottom sample from 16.2 to 17.2 feet is obviously from the glacial drift on which the water-laid deposits represented by samples 224 and 225 were deposited. The concentration of clay and silt in the bottom of the pond doubtless is responsible for the degree with which it is sealed from the adjacent sandy, gravelly soil.

A study of the pollen in sample 225 led Barbara Sprose Hanson to the opinion that the pollen assemblage was about 11,000 years old. Details are given in an appendix.

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Professors C. L. Larson and R. E. Machmeier read the manuscript and made many suggestions for its improvement.

Throughout the work, until his untimely death in February, 1967, Alden Domning supervised the field work and was responsible for construction and service of all mechanical equipment. His work and contribution to the project was invaluable.

George Schwartz is indebted to colleagues W. E. Parham, J. E. Stone, F. M. Swain, and H. E. Wright, Jr. of the Department of Geology, University of Minnesota, for many suggestions.

APPENDIX I

DATA ON LAKE SEEPAGE AND ICE SAG STUDIES

Abstracted From Data On File In Division of Waters, Minnesota Department of Conservation

1. **Instructions to gage readers.**
2. **Tabulated summary of water levels during ice cover, 1940-42.**
3. **Measurements of ice sag, 1939-40.**
4. **Copy of data sheet, ice sag measurements, 1939-40.**

STUDY OF SEEPAGE FROM LAKES

Instructions to Gage Readers

"Seepage from lakes is an important factor in almost every water conservation project. In projects for the utilization of water for power, water supply, sewage disposal, and navigation, seepage from reservoir lakes usually represents at least a partial *loss*. In projects for the storage of flood water and the retardation of runoff water on its way back to the sea, seepage always represents a definite *gain*.

The flow of streams in Minnesota during dry summers and during all winters consists primarily of groundwater or seepage flow. Direct surface runoff is conserved whenever it can be retarded and caused to seep into the ground to join the groundwater, from which it is gradually released to maintain stream flow during low water periods, particularly in winter.

"Very little is known about the seepage loss from most lakes. It necessarily varies somewhat from year to year. On some lakes the groundwater level around the lake is continually higher than the lake surface. Such a lake is supported by groundwater. If the groundwater level around the lake slopes upward at a relatively steep slope, then the lake is usually well maintained and shows comparatively little variation in level. If, on the other hand, the groundwater level around the lake is relatively flat, or even sloping away from the lake over a large portion of the area on the outlet side, then the lake will usually show large fluctuation resulting from substantial seepage loss during dry periods, particularly in winter.

"For the purpose of securing additional information on the seepage loss from some of our lakes, the following observations will be made this winter:

"1. As soon as the entire surface of the lake is covered with ice, so that the commonly observed 'steaming' of the lake just before it freezes up can no longer take place, the level of the lake will be determined by breaking the ice around the gage and reading the water level just as accurately as possible. If the gage is out of the water, it will be necessary to get the water level by using a long straight edge, carpenter's square, or rule, and carpenter's level for determining the equivalent gage reading. In some cases it may be possible to dig a small channel to let the water flow into the gage for the purpose of securing the reading.

"If the lake opens up again due to unexpected warm weather after the reading has been taken, a second level determination must be made. Record the exact time and, if possible, do the work when there is little wind blowing.

"2. Early next spring, *before the ice breaks up on the lake,* repeat the operation and secure another accurate water level. Chop a hole through the ice and proceed as instructed above. Record the date, the gage reading, and the thickness of the ice.

"The readings here requested will be substituted for the once-a-month readings that each gage reader previously agreed to make during the winter months.

"From the water levels observed in the fall and in the spring, and from the U.S. Weather Bureau records of precipitation recorded at the nearest stations between the dates on which the water levels were determined, and from the computed evaporation loss during the winter, we will determine the winter seepage loss from the given lake."

Adolph F. Meyer
Consulting Hydraulic Engineer

11/11/40

STATE OF MINNESOTA
DEPARTMENT OF CONSERVATION
DIVISION OF DRAINAGE AND WATERS

Nov. 11, 1940

INSTRUCTIONS TO GAGE READERS

Study of Seepage From Lakes*

"Seepage from lakes is an important factor in almost every water conservation project. In projects for the use of water for power, water supply, sewage disposal, and navigation, seepage from reservoir lakes usually represents at least a partial *loss*. In projects for the storage of flood water and the retardation of runoff water on its way back to the sea, seepage always represents a definite *gain*.

"The flow of streams in Minnesota during dry summers and during all winters consists primarily of groundwater or seepage flow. Direct surface runoff is conserved whenever it can be retarded and caused to seep into the ground to join the groundwater, from which it is gradually released to maintain stream flow during low water periods, particularly in winter.

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"The readings here requested will be substituted for the once-a-month readings which it was previously agreed each gage reader would make during the winter months.

"Record the readings in the gage height books and on a regular gage height report card. MAIL THE CARD AT ONCE. NO POSTAGE IS REQUIRED.

"Your cooperation will be greatly appreciated so that this study may be successfully completed and this essential information obtained."

Yours very truly,
S. A. Frellsen, *Hydrologist*
Div. of Drainage and Waters

Walter S. Olson, Director
By

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* Excerpts from Adolph F. Meyer, Consulting Hydraulic Engineer's memorandum dated November 11, 1940.

LAKE SEEPAGE STUDIES—DEPARTMENT OF CONSERVATION

K. M. Pederson
R. J. Owens

Lake	County	Date	Elev.	Date	Elev.	Diff.	
Lake Andrew	Kandiyohi	12-26-40	82.16	2-20-41	82.35	+ .17	
Bass Lake	"	12-31-42	94.58	3-25-43	95.14	+ .56	Thawing Inflow
Crook Lake	"	12-26-40	96.97	2-20-41	97.00	+ .03	
Diamond Lake	"	12-31-42	1161.73	3-25-43	1162.02	+ .29	
Eagle Lake	"	1-1-43	1125.36	3-15-43	1125.78	+ .42	
Florida Lake	"	12-26-40	88.78	2-20-41	88.96	+ .18	
" "	"	1-1-43	93.20	3-25-43	93.96	+ .76	Thawing
Games Lake	"	12-26-40	87.51	2-20-41	87.79	+ .28	
" "	"	1-1-43	89.58	3-25-43	90.28	+ .70	Thawing Inflow
George Lake	"	1-1-43	1159.64	3-25-43	1160.14	+ .50	Thawing Inflow
Henderson Lake	"	1-1-43	90.61	3-25-43	91.06	+ .45	"
Norway Lake	"	12-26-40	83.38	2-20-41	83.48	+ .12	
Big Lake	Sherburne	12-17-41	94.61	3-13-42	94.70	+ .06	
Chisago Lake	Chisago City	12-20-40	95.48	2-27-41	95.59	+ .11	
" "	"	12-18-41	96.47	3-3-42	96.32	— .15	
" "	S. Hy. 8 at Lindstrom	12-20-40	78.24	2-27-41	78.50	+ .26	
" "	N. Lindstrom	12-20-40	90.52	2-27-41	90.68	+ .16	
" "	"	12-18-41	91.43	3-13-42	91.32	— .11	
" "	N. Hy. 8	12-20-40	90.40	2-27-41	90.50	+ .10	
" "	"	12-18-41	91.89	3-13-42	91.60	— .29	
" "	S. Hy. 8 at Center City	12-20-40	91.16	2-27-41	91.01	— .15	
" "	"	12-18-41	92.90	2-13-42	92.27	— .63	
Clear Lake	Nicollet	12-28-40	94.32	2-19-41	94.38	+ .06	
" "	"	12-16-41	95.46	3-12-42	95.52	+ .06	
Clear Lake	Waseca	12-26-40	92.66	2-17-41	92.89	+ .23	
Clear Lake	Waseca	12-15-41	93.71	3-11-42	93.81	+ .10	
Coon Lake	Anoka	12-19-40	904.53	2-25-41	904.71	+ .18	
" "	"	12-17-41	905.71	3-13-42	905.63	— .50	Outflow
Crystal Lake	Blue Earth	12-27-40	94.19	2-18-41	94.79	+ .60	
" "	"	1-13-43	94.99	3-22-43	95.05	+ .06	
Emily	LeSueur	12-28-40	(986.51) 94.75	2-18-41	(986.93) 95.17	+ .42	
"	"	12-16-41	990.64	3-5-42	99.40	— .24	
Fox Lake	Rice	12-26-40	97.62	2-17-41	97.75	+ .13	
" "	"	12-15-41	97.23	3-10-42	97.21	— .02	
Francis Lake	LeSueur	12-27-40	1011.36	2-18-41	1011.20	— .16	
" "	"	12-15-41	1012.05	3-10-42	1011.92	— .13	
" "	"	1-12-43	1013.07	3-22-43	1013.02	— .05	
German Lake	"	12-28-40	1015.17	2-18-41	1015.25	+ .08	
" "	"	12-15-41	101.02	2-12-42	101.07	+ 05	
Green Lake	Chisago	12-20-40	87.91	2-27-41	88.06	+ .15	
Hanska Lake	Brown	12-28-40	96.32	2-19-41	96.43	+ .11	
Horseshoe Lake	Rice	12-27-40	100.72	2-18-41	100.93	+ .21	
" "	"	12-15-41	100.43	3-10-42	100.50	+ .07	
" "	"	2-10-43	100.97	3-22-43	101.38	+ .41	
Jefferson Lake	LeSueur	12-28-40	1013.14	2-18-41	1013.17	+ .03	
" "	"	12-15-41	101.01	2-12-42	101.03	+ .02	
Kansas Lake	Watonwan	12-27-40	98.98	2-18-41	99.33	+ .35	
Long Lake	"	12-27-40	96.52	2-18-41	96.44	— .08	
" "	"	12-16-41	96.89	3-11-42	96.62	— .27	
" "	"	1-13-42	101.35	3-23-43	101.57	+ .22	Outflow
Madison Lake	Blue Earth	12-27-40	1004.69	2-18-41	1004.78	+ .09	
" "	"	12-15-41	1007.92	3-11-42	1007.56	— .36	
" "	"	1-12-43	1010.81	3-22-43	1014.77	+3.96	

(Several others are given for 1943 but thawing made records of doubtful value.)

LAKE SEEPAGE STUDIES—DEPARTMENT OF CONSERVATION—(Continued)

Lake	County	Date	Elev.	Date	Elev.	Diff.	
Marion Lake	Dakota	12-26-40	90.27	2-17-41	90.09	— .18	
" "	"	12-15-41	91.99	3-10-42	91.55	— .44	
Mary Lake	Watonwan	2-27-40	98.19	2-18-41	98.50	+ .31	
" "	"	2-16-41	103.02	3-11-42	102.96	— .06	
" "	"	1-13-43	102.94	3-23-43	106.01	Inflow	
Mazaska Lake	"	12-26-40	92.86	2-17-41	93.04	+ .18	
" "	"	12-15-41	92.72	3-10-42	92.73	+ .01	
Mimard Lake	Anoka	12-19-40	95.28	2-25-41	95.30	+ .02	
Netta Lake	"	12-19-40	97.71	2-25-41	97.75	+ .04	
" "	"	12-17-41	903.78	3-13-42	903.52	— .20	
Norris Lake	"	12-19-40	92.77	2-25-41	92.86	+ .09	
" "	"	12-17-41	94.78	3-13-42	94.39	— .39	
Roberds Lake	Rice	12-15-41	100.70	3-10-42	100.73	+ .03	
St. Olaf Lake	Waseca	12-26-40	98.57	2-17-41	98.90	+ .33	
" "	"	12-15-41	99.95	3-11-42	100.14	+ .19	
" "	"	2-12-43	101.55	3-22-43	106.91	+5.36	
Sunrise Lake	Chisago	12-20-40	95.59	2-27-41	95.73	+ .14	
" "	"	12-18-41	96.71	3-13-42	96.62	— .09	
Twin Lake	Anoka	12-19-40	93.36	2-25-41	94.06	+ .10	
" "	"	12-17-41	94.93	3-13-42	94.98	+ .05	
Addie Lake	McLeod	12-19-41	94.86	3-13-42	94.88	+ .02	
Allie Lake	Renville	12-20-40	93.65	2-19-41	93.81	+ .16	
" "	"	2-19-41	94.88	3-13-42	94.90	+ .02	Inflow
Amelia Lake	Pope	12-27-40	91.81	2-25-41	91.92	+ .11	
" "	"	12-15-41	93.56	3-17-42	93.56	± 0	
Anna Lake	Ottertail	12-29-40	83.20	2-26-41	83.32	+ .12	
" "	"	12-16-41	83.44	3-19-42	83.50	+ .06	
Bass Lake	"	12-29-40	78.68	2-26-41	78.76	+ .08	
" "	"	12-16-41	78.58	3-19-42	78.57	— .01	
Belle Lake	Meeker	12-20-40	82.73	2-19-41	82.91	+ .18	
" "	"	12-18-41	83.10	3-12-42	83.13	+ .03	
Boon Lake	Renville	12-20-40	94.92	2-19-41	95.10	+ .18	
" "	"	12-18-41	96.42	3-13-42	96.36	— .06	
Brooks Lake	Wright	12-19-40	84.82	2-17-41	84.89	+ .17	
" "	"	12-18-41	85.09	3-12-42	85.11	+ .02	
Clitherall Lake	Ottertail	12-30-40	87.42	2-26-41	87.60	+ .18	
" "	"	12-16-41	87.80	3-18-42	87.19	+ .11	
Eagle Lake	"	12-30-40	87.01	2-26-41	87.12	+ .11	
" "	"	12-16-41	87.15	3-18-41	87.20	+ .05	
Fountain Lake	Wright	12-19-40	93.88	2-17-41	94.05	+ .17	
" "	"	12-18-41	95.09	3-12-41	91.15	+ .06	
Goose Lake	Pope	12-15-41	84.29	3-17-42	84.27	— .02	
Grove Lake	"	12-27-40	96.71	2-25-41	96.81	+ .10	
Howard Lake	Wright	12-19-40	79.05	2-17-41	79.24	+ .19	
" "	"	12-18-41	80.22	3-12-42	80.23	+ .01	
Jennie Lake	Meeker	12-20-40	85.52	2-19-41	85.71	+ .19	
" "	"	12-18-41	86.38	3-12-42	86.41	+ .03	
Lake Leven	Pope	12-27-40	93.27	2-25-41	93.34	+ .07	
" "	"	12-15-41	94.49	3-17-42	94.17	— .32	
Long Lake	Meeker	12-19-40	92.86	2-17-41	93.03	+ .17	
" "	"	12-18-41	93.47	3-12-42	93.43	— .04	
Loon Lake	Ottertail	12-30-40	90.04	2-27-41	90.19	+ .15	
" "	"	12-18-41	89.95	3-19-42	90.09	+ .14	
Manuella Lake	Meeker	12-19-40	96.11	2-17-41	96.50	+ .39	
" "	"	12-18-41	96.27	3-12-42	96.58	+ .31	
Maple Lake	Douglas	12-27-40	89.89	2-25-41	90.07	+ .18	
" "	"	12-15-41	91.61	3-17-42	91.72	+ .11	
Lake Mary	"	12-27-40	85.84	2-25-41	89.96	+ .12	
" "	Douglas	12-16-41	87.92	3-17-42	87.96	+ .04	
Minnie Bell	Meeker	12-20-40	78.61	2-18-41	78.75	+ .14	
" "	"	12-18-40	79.21	3-12-42	79.17	— .04	
Norway Lake	(25-133-41)	12-16-41	82.94	3-19-42	82.88	— .06	
Pickerel Lake	Ottertail	12-30-40	89.00	2-27-41	89.13	+ .13	
" "	"	12-16-41	89.52	3-19-42	89.62	+ .10	
Pleasant Lake	"	12-16-41	84.83	3-19-42	84.80	— .03	
Preston Lake	Renville	12-18-41	89.62	3-13-42	89.66	+ .04	
Reno Lake	Pope	12-27-40	76.33	2-25-41	76.40	+ .07	
" "	"	12-15-41	77.21	3-17-42	77.27	+ .06	

(Several others are given for 1943 but thawing made records of doubtful value.)

LAKE SEEPAGE STUDIES—DEPARTMENT OF CONSERVATION—(Continued)

Lake	County	Date	Elev.	Date	Elev.	Diff.
Ripley Lake	Meeker	12-20-40	87.84	2-18-41	87.98	+ .14
″ ″	″	12-18-41	88.55	3-12-42	88.62	+ .07
Smith Lake	Wright	12-19-40	91.16	2-17-41	91.25	+ .09
″ ″	″	12-18-41	92.52	2-12-42	92.59	+ .07
Spirit Lake	Ottertail	12-30-40	87.55	2-27-41	87.62	+ .07
″ ″	″	12-16-41	87.44	3-19-42	87.46	+ .02
Spring Lake	Meeker	12-19-40	80.11	2-17-41	80.30	+ .19
″ ″	″	12-18-41	80.35	3-12-42	80.37	+ .02
Stella Lake	″	12-19-40	87.48	2-17-41	87.83	+ .35
″ ″	″	12-18-41	87.62	3-12-42	87.83	+ .21
Sybil Lake	Ottertail	12-30-40	84.70	2-27-41	84.79	+ .09
″ ″	″	12-16-41	84.71	3-19-42	84.77	+ .06
Twin Lake	″	12-30-40	86.15	2-27-41	86.19	+ .04
″ ″	″	12-16-41	86.87	3-19-42	86.89	+ .02
Villard Lake	Pope	12-27-40	92.72	2-25-41	92.79	+ .07
″ ″	″	12-15-41	93.93	3-17-42	94.05	+ .12
Waconia Lake	Carver	12-21-40	87.28	2-21-41	87.44	+ .16
″ ″	″	12-19-41	88.70	3-13-42	88.76	+ .06
Washington Lake	Meeker	12-18-41	92.47	2-12-41	92.64	+ .17
Washington Lake	Meeker	12-18-41	93.53	3-12-42	93.54	+ .01
Whale Tail Lake	Hennepin	12-21-40	93.68	2-21-41	94.02	+ .34
″ ″	″	12-19-41	94.62	3-13-42	94.67	+ .04

(Several others are given for 1943 but thawing made records of doubtful value.)

SAG MEASUREMENTS

Sag of Ice in Middle of Lake as Compared with Border

* See Tabulation of Lake Seepage Studies

Lake	County	Freeze-Up	Date of Measurement	Sag
St. Olaf*	Waseca	12-15-39	3-5-40	.34
Beaver	Steele	12-1-39	3-5-40	.35
Fox*	Martin	12-15-39	3-6-40	.24
Long	Watonwan	12-15-39	3-6-40	.60
Kansas*	″	12-15-39	3-6-40	.22
Mary*	″	12-15-39	3-6-40	.35
Clear*	Waseca	12-15-39	3-7-40	.20
Emily*	LeSueur	12-15-39	3-7-40	.55
Big Kandiyohi	Kandiyohi	12-15-39±	3-8-40	.29
Ripley*	Meeker	12-15-39±	3-8-40	.19
Brooks	Wright	12-1-39±	3-8-40	.30
Buffalo	″	12-15-39±	3-8-40	+.16
German*	LeSueur	12-15-39±	3-11-40	.24
Jefferson*	″	12-15-39±	3-11-40	.15
Madison*	Blue Earth	12-15-39±	3-11-40	.20
Addie*	McLeod	12-15-39	3-12-40	.23
Little	Grant	12-1-39±	3-13-40	.05
Wall	Ottertail	12-15-39±	3-14-40	+.19
*Bass	″	12-15-39±	3-14-40	.40
West Battle	″	Late Dec.	3-14-40	.0
Twin	″	12-15-39±	3-14-40	.59
Horseshoe*	LeSueur-Rice	″	3-18-40	.0
Robaros	Faribault	″	3-18-40	.22
French	″	″	3-18-40	.30
Mazaska	Faribault	12-15-39±	3-18-40	.21
Cedar	Scott	″	3-19-40	.0
Pheasant	″	″	3-19-40	.19
Dora	LeSueur	″	3-19-40	.12
Elipian	Waseca	″	3-20-40	.30
Francis*	LeSueur	″	3-20-40	.72

Comments by George M. Schwartz

The lake seepage studies (measurements) by K. M. Pederson and R. J. Owens extend over a very large area and, therefore, represent lakes ranging greatly in size and their topographic situations. Of 143 measurements, not including those with inflow as a result of thawing or outflow, 109 show a usually small increase, and 27 a small decrease. The maximum loss was .44 foot for Lake Marion in Dakota County. Unusual gains are shown for Madison Lake, Blue Earth County, and St. Olaf Lake, Waseca County. These are not explained, but aside from those the maximum gain was .60 foot. The measurements show that most lakes have a very stable water level during the winter months. In general, it seems that there is more water added by inflow from the groundwater than is lost by seepage or in other ways.

APPENDIX II

POLLEN ANALYSES OF SELECTED SAMPLES OF LAKE-SEDIMENT CORES IN MINNESOTA

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Core samples were submitted by G. M. Schwartz for pollen analysis in an effort to determine the stratigraphic and chronologic position of the basal organic sediment in five small lakes in Minnesota. In each case about 300 pollen grains were counted, and percentages of pollen types were calculated on specific pollen sums (usually including pollen of trees and shrubs and wind-pollinated herbs) so that percentages could be compared with those of the nearest available standard pollen diagram (table 1). Inasmuch as the pollen assemblage represents primarily the regional pollen rain, correlation from site to site in a particular vegetational region is generally valid.

Most Minnesota lake basins originate as ice-block depressions; they are formed when a block of buried glacial ice melts out, often long after active glacier ice left the area. Thus the basal organic sediment in a lake basin may be much younger than the age of the moraine or other landform in which it is located. Detailed pollen studies of lake-sediment cores indicate that 1,000-2,000 years are commonly involved in this lag. During that period various changes in the regional vegetation may have occurred.

For the lakes in question, the Roselawn Avenue sample dates from the time of the spruce zone, about 11,000 years ago; samples from Pitcher Lake, Flensburg, and Morris date from the time of the pine zone, 11,000 to 8,500 years ago; and the sample from Stony Pond dates from the time of the prairie expansion into central Minnesota 7,000-5,000 years ago.

Some caution must be exercised, however, in concluding that the lakes in question did not come into being until the time indicated by the samples studied. We know enough about the early postglacial climate to doubt that the buried ice could survive in Minnesota as late as 10,500 years ago. It is possible that at several sites the basal pollen-bearing sediment was not sampled or perhaps not reached by the corer. The only way to determine this is by careful close-interval analyses of cores taken all the way to basal till or other glacial sediment.

Core 217

Mo-1, Morris Quadrangle, Stevens County, Minn., NE¼, sec. 20, T. 125 N., R. 41 W., is a small lake in the prairie near Morris.

The sample was taken from a depth of 10 feet in core segment 9.5-10.5 feet below the sediment surface. The material was organic silt with diatoms and low concentration of pollen. The pollen sum for calculation of percentages in table 1 excludes Cyperaceae as well as insect-pollinated herbs, aquatics, spores, and unknowns, for comparison with the percentages in the *Pinus-Pteridium* subzone at Thompson Pond in the prairie in Norman County 120 miles north of Morris (McAndrews, 1965). This subzone, where identified at Bog D Pond in the Itasca State Park, 40 miles east of Thompson Pond, is dated by radiocarbon analysis as about 8,500-11,000 years old. It represents the vegetation that succeeded the late-glacial boreal spruce forest all over Minnesota and adjacent states.

Core 223

F-2, Flensburg Quadrangle, Morrison County, Minn., NE¼, sec. 35, T. 129 N., R. 31 W., is a small pond in the deciduous forest region 1 mile southwest of Flensburg.

The sample was taken from core segment 5.9-6.6 feet below the sediment surface of a small pond. The pollen assemblage, when calculated in the same manner as the Morris sample, also compares most closely with that of the *Pinus-Pteridium* subzone at Thompson Pond, 140 miles northwest of Flensburg (McAndrews, 1965). Its age is thus in the 8,500-11,000 year range.

N-2, New Brighton Quadrangle, Ramsey County, Minnesota, Stony Pond, near Stony Lake, is in the deciduous forest region.

A sample of black sandy gyttja came from a depth of 7.90 feet at the base of the core. The pollen assemblage is marked by a very high percentage of chenopods, a group of weedy plants characteristic of disturbed ground. Such habitats are formed naturally when a prairie pond temporarily dries up (partially or completely), exposing bare ground for the invasion of weedy plants. The assemblage compares most closely with that of Zone C-b at Lake Carlson, in Dakota County, 25 miles south of Stony Pond, a zone deposited 5,000-7,000 years ago when prairie had expanded to the now-forested regions and when the incidence of dry years was probably much greater than today (Wright *et al.*, 1963). The upland prairie probably contributed the high percentages of grass pollen, and scattered oak trees added the few percent of oak pollen. The pond may have been completely dry much of the time, allowing inwash of sand from the slopes. Presumably underneath the sandy sediments at the base of the existing core are additional lake deposits formed during the earlier period when forest rather than prairie prevailed in the area.

Cores 225 and 226

S.P. 4, Cleveland and Roselawn Avenues, West St. Paul Quadrangle, Ramsey County, Minnesota is a small pond in the deciduous forest region.

Core 226 from depth 16.8 feet was sandy clay and yielded no pollen. Core 225 from 8.4 to 9.4 feet was peat with abundant pollen. The assemblage, with relatively high percentages of spruce, larch, birch, and *Artemisia,* closely resembles that of the *Picea-Larix* zone at Cedar Bog Lake, 30 miles to the north (Cushing, 1963), as well as at Kirchner Marsh, 30 miles to the south (Wright *et al.*, 1963). The high value of birch (12 percent) indicates that the sample came from the top of the zone, which is about 11,200 years old.

Cores 228-B and 229

Ma-4, Pitcher Lake, Marine Quadrangle, is in the deciduous forest.

Core 228-B came from a depth of 16-17.4 feet and core 229 from 19.8 feet. Core 228-B contained much more pollen. Its assemblage, with a high percentage of pine, indicates Core 228-B should be assigned to the *Pinus-Pteridium* zone of Cedar Bog Lake, 25 miles to the northwest (Cushing, 1963), deposited about 10,500 years ago. Core 229 has about equal percentages of spruce and pine and so can be assigned to the very base of the *Pinus-Pteridium* zone, deposited about 11,000 years ago.

Table 1. Comparison of pollen counts of core samples with those of certain pollen-assemblage zones in standard pollen diagrams in Minnesota.

a. Trees and Shrubs	Core 217 Morris	Core 223 Flensburg	*Pinus-Pterid.* Zone, Thompson Pond	Core N2 Stony Pond	Zone C-b Lake Carlson
Picea (spruce)	t	4	4-15	1.7	0-1
Larix (larch)	2.0	1	t		t
Juniperus-type (cedar)	2.5	2	t	0.3	
Betula (birch)	t	2	1-4	0.3	0-1
Alnus (alder)	2.0	2	1-2	0.3	0-1
Populus (poplar)		t	t-1		
Fraxinus (ash)	1.3		0-t		0-1
Abies (fir)		t			0-t
Pinus (pine)	32	6.4	15-35	2.7	2-12
Conifiers undiff.					
Ulmus (elm)		3	2-5	1.3	0-5
Quercus (oak)	2.5	3	1-5	5.5	2-30
Ostrya type (ironwood)		.7	0-2		0-3
Acer saccharum (sugar maple)	2.0	t	0-t		0-1
Tilia (basswood)		t			0-t
Salix (basswood)	4	l	t-1	0.3	0-4
Corylus (hazel)		l	0-t	2.4	0-1
Juglans (walnut)		t			0-t
Carya (hickory)		.7			0-t
Ephedra		t	0-t		0-t
Myrica		.7			
Eleagnus					
Shepherdia			0-t		
Total AP	49.4	50	35-55	15.2	6-71
b. Wind Pollinated Herbs					
Gramineae (grasses)	21	23	20-40	19.7	1-20
Cyperaceae (sedges))				6.5	2-10
Artemisia	9	15	7-11	3.1	2-10
Ambrosia (ragweed)	7	9	3-6	1.3	2-35
Iva ciliata		t	0-t		
Chenopodiineae	9	4	3-5	53.6	10-75
Sambucus					
Thalictrum			0-t		0-t
Sarcobatus		t	0-t		
Hymenoclea				0.3	
c. Other Herbs					
Cyperaceae	24	12	10-25		
Other Compositae	8	6	1-4	3.8	
Scrophulariaceae					
Cruciferae					0-t
Saxifragaceae					
Rosaceae			0-t		
Umbelliferae			0-t	2.7	0-t
Liliaceae				0.3	
Potentilla palustris					
Polygonum		3		1.7	
Gentiana					
Euphorbia					
Ranunculus		t	0-t		
Stachys		t			
d. Cryptogams					
Pteridium	2	7	t-2	t	0-10
Dryopteris-type		1	0-t	t	0-3
Sphagnum		t			
Equisetum			0-t		

Table 1. Comparison of pollen counts of core samples with those of certain pollen-assemblage zones in standard pollen diagrams in Minnesota.	**Core 217 Morris**	**Core 223 Flensburg**	*Pinus-Pterid.* **Zone, Thompson Pond**	**Core N2 Stony Pond**	**Zone C-b Lake Carlson**
e. Aquatic Plants					
Typha latifolia	3.2	t	t-4	t	0-t
Sparganium-type		1	0-t	3.1	0-t
Potamogeton-type			0-t		0-4
Nymphaceae				t	0-t
Nuphar		t	0-t		0-2
Myriophyllum			0-t		
Sagittaria		t	0-t	4.4	0-30
Alisma				1.7	
f. Unknown		5	t-2	11.0	2-10
Pollen sum	a, b (excel. Cyperaceae	a, b (excel.) Cyperaceae	a, b (excel.) Cyper-	a, b	a, b, c, d, e, f,

t = trace (<1%)

Table 1. Comparison of pollen counts of core samples with those of certain pollen-assemblage zones in standard pollen diagrams in Minnesota (continued). **a. Trees and Shrubs**	**Core 225 Roselawn Ave.**	*Picea-Larix.* **Zone, Cedar Bog Lake**	**Core 223-B Pitcher Lake**	**Upper part** *Pinus-Pterid.* **Zone, Cedar Bog Lake**	**Core 229 Pitcher Lake**	**Base of** *Pinus-Pterid.* **Zone, Cedar Bog Lake**
Picea (spruce)	32.5	30.48	t	t	16	20
Larix (larch)	3.1	1-4	0.5	t-1		2
Juniperus-type (cedar)	1.1	t-3	0.5	t	2	t
Betula (birch)	12.4	3-12	t	3-15	6	14
Alnus (alder)	3	1-18	1	1-3		4
Populus (poplar)	0.7	1-10		1-3		2
Fraxinus (ash)	3	3-20	1	2-4		3
Abies (fir)		t-2		t-1		1
Pinus (pine)	0.6	1-3	77	35-50	15	20
Conifers undiff.					13	
Ulmus (elm)	0.7	1-3	6	t-10	2	3
Quercus (oak)	5.5	3-6	2	4-8	3	3
Ostrya type (ironwood)	2.2	1-3	t	1-2		2
Acer saccharum (sugar maple)	0.6	t	0.5	t		t
Tilia (basswood)			t			
Salix (willow)	2.3	1-3		t-1	3	1
Corylus (hazel)	2.3	1-2		t-1	2	
Juglans (walnut)		t	0.5	t		
Carya (hickory)		t		t		
Ephedra				t		
Myrica						
Eleagnus	t					
Shepherdia	t	t				
Total AP	70	60-78	90	80-89	65	80
b. Wind Pollinated Herbs						
Gramineae (grasses)	2.6	1-4	2	1-10	7	1
Cyperaceae (sedges)	4.4	5-11		1-5	4	6
Artemisia	9.1	5-12	t	1-10	6	5
Ambrosia (ragweed)	1.1	1-4	1	1-2		4
Iva ciliata	t		t			
Chenopodiineae		1-2	1	t-1	3	1
Sambucus						
Thalictrum	0.4	t		t		
Sarcobatus				t		
Hymenoclea				t		

Table 1. Comparison of pollen counts of core samples with those of certain pollen-assemblage zones in standard pollen diagrams in Minnesota.

	Core 225 Roselawn Ave.	*Picea-Larix.* **Zone, Cedar Bog Lake**	**Core 228-B Pitcher Lake**	**Upper part** *Pinus-Pterid.* **Zone, Cedar Bog Lake**	**Core 229 Pitcher Lake**	**Base of** *Pinus-Pterid.* **Zone, Cedar Bog Lake**
c. Other Herbs						
Cyperaceae				2-4		
Other Compositae	0.7		t		4	
Scrophulariaceae			t			
Cruciferae	t					
Saxifragaceae						
Rosaceae	t	t				
Umbelliferae	t					
Liliaceae						
Potentilla palustris						
Polygonum	0.4	t				
Gentiana						
Euphorbia	t					
Ranunculus						
Stachys						
d. Cryptogams						
Pteridium		t-1	3	1-3		1
Dryopteris-type	0.6	t-1	1	1	2	1
Sphagnum	0.4				2	
Equisetum	t	t		t		t
e. Aquatic Plants						
Typha-latifolia		t		t		t
Sparganium-type	2.2					
Potamogeton-type		t				t
Nymphaceae						
Nuphar	1.3	t		t		t
Myriophyllum	t					
Sagittaria						
Alisma						
f. Unknown	1.7	t	1	t	6	t
Pollen sum	a, b, c, d, e, f	a, b, c, d	a, b, c, d, e, f	a, b, c, d	a, b, c, d, e, f	a, b, c, d

t = trace (<1%)

REFERENCES

1. Cushing, E. J., *Late Wisconsin Pollen Stratigraphy in East Central Minnesota,* 1963, Ph.D. Theisis, University of Minnesota.
2. McAndrews, J. H., *Post-Glacial Vegetation History of the Prairie Forest Transition of Northwestern Minnesota,* 1965, Ph.D. Thesis, University of Minnesota.

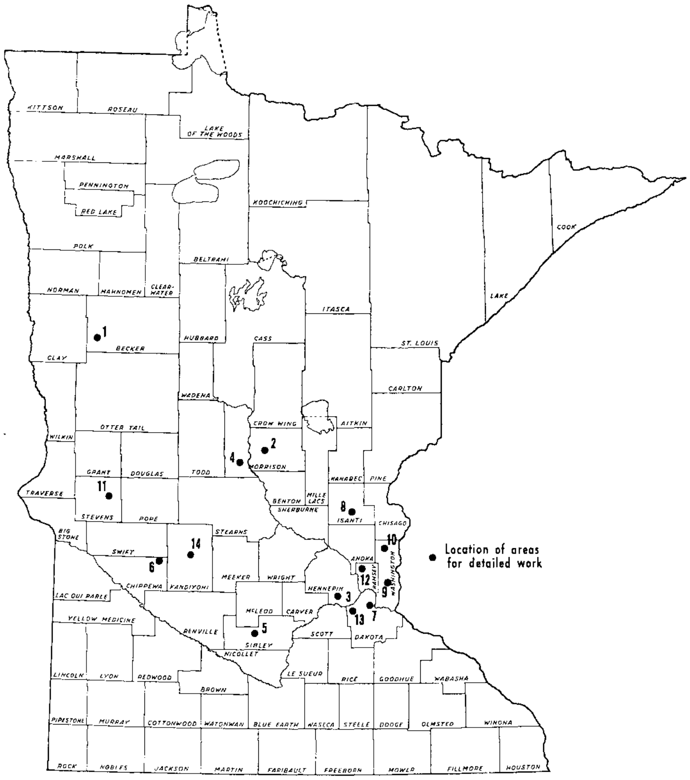

Figure 1. Map of Minnesota showing location of investigations.

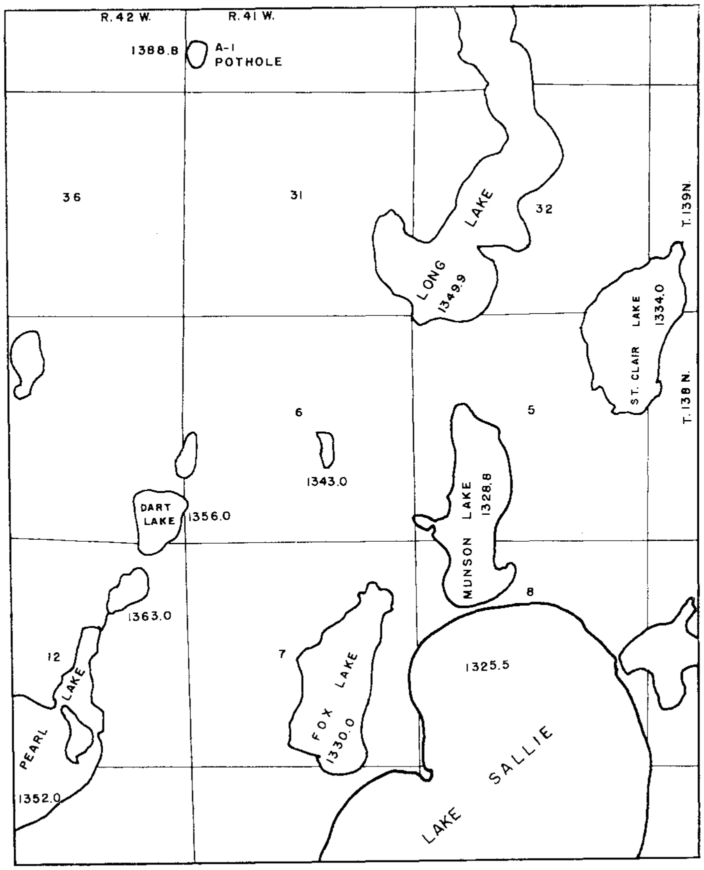

Figure 2. Map showing elevations of the surface of lakes and ponds in part of the Audubon Quadrangle.

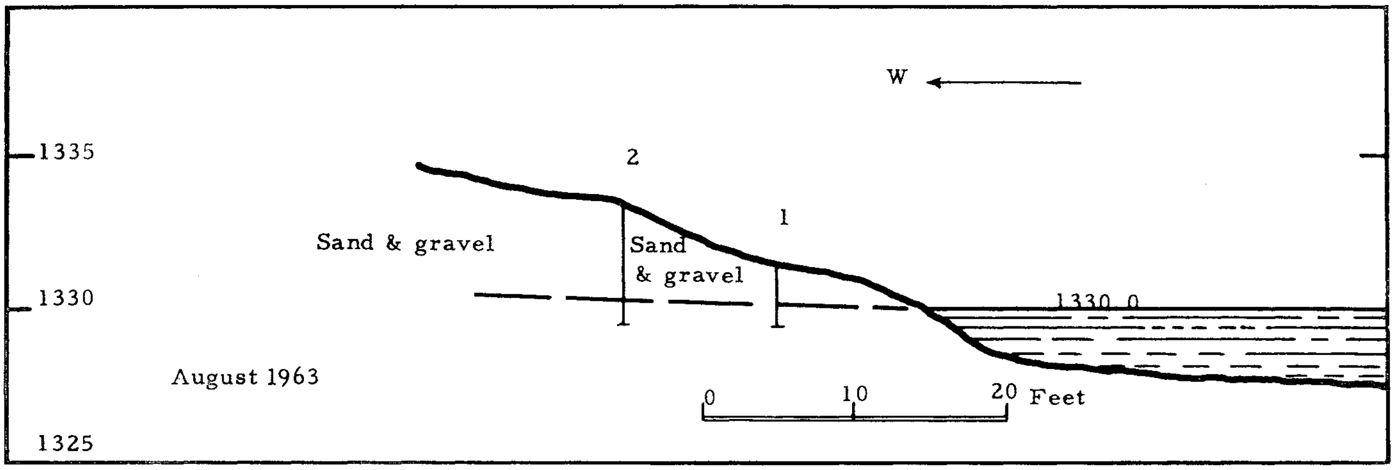

Figure 3. Cross-section showing test holes at Fox Lake.

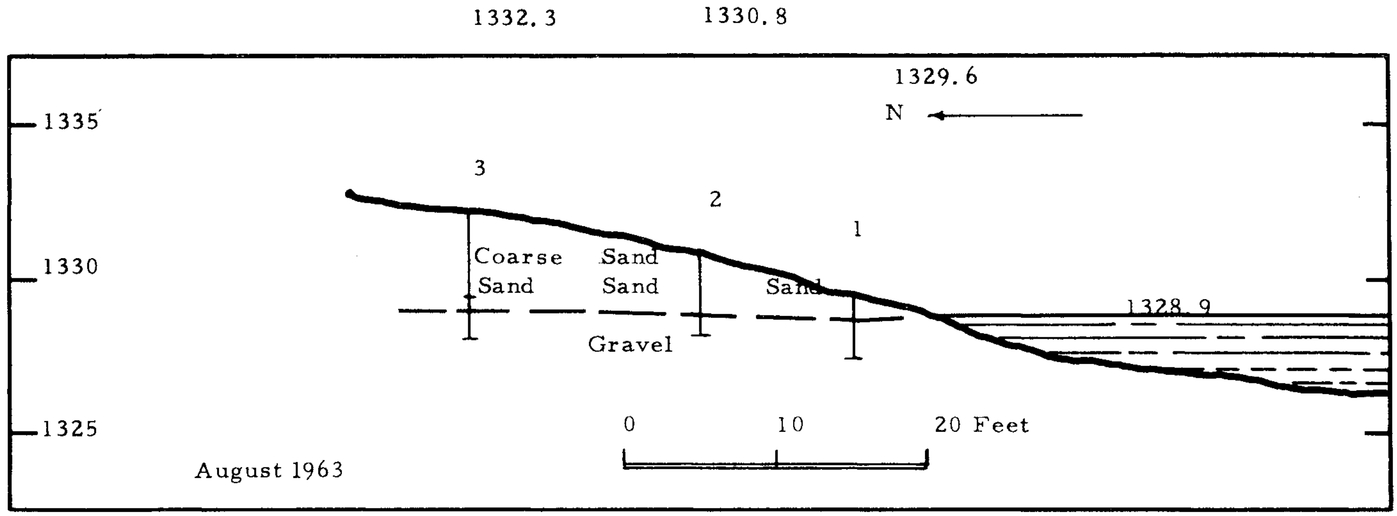

Figure 4. Cross-section showing test holes at Monson Lake.

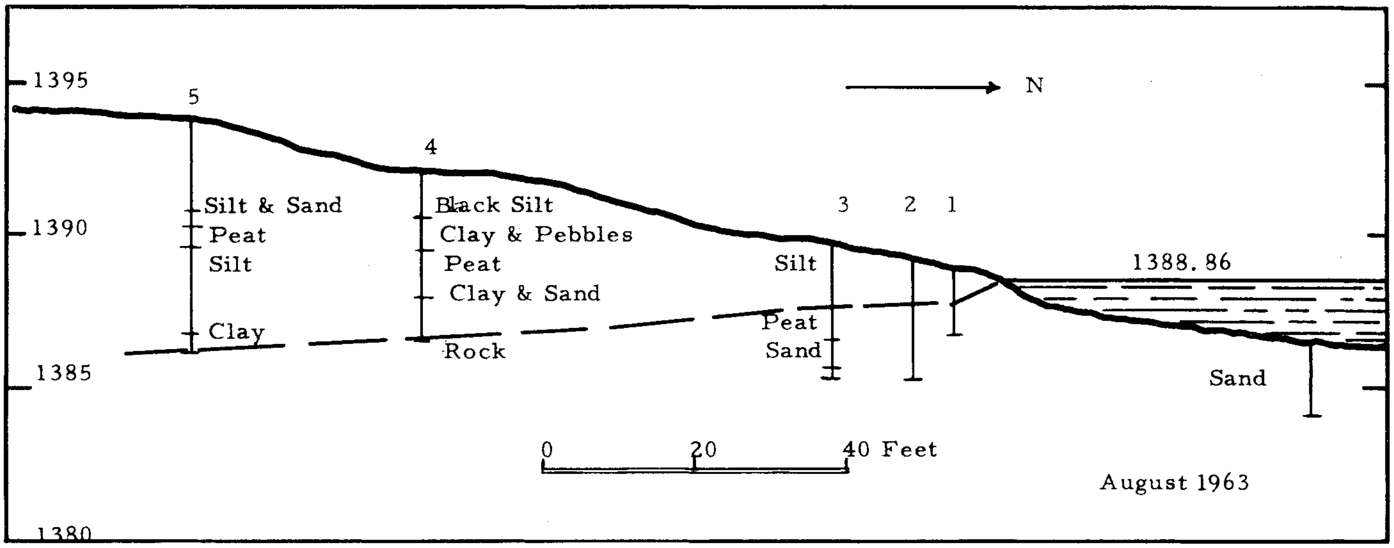

Figure 5. Cross-section showing test holes at A 1 pothole.

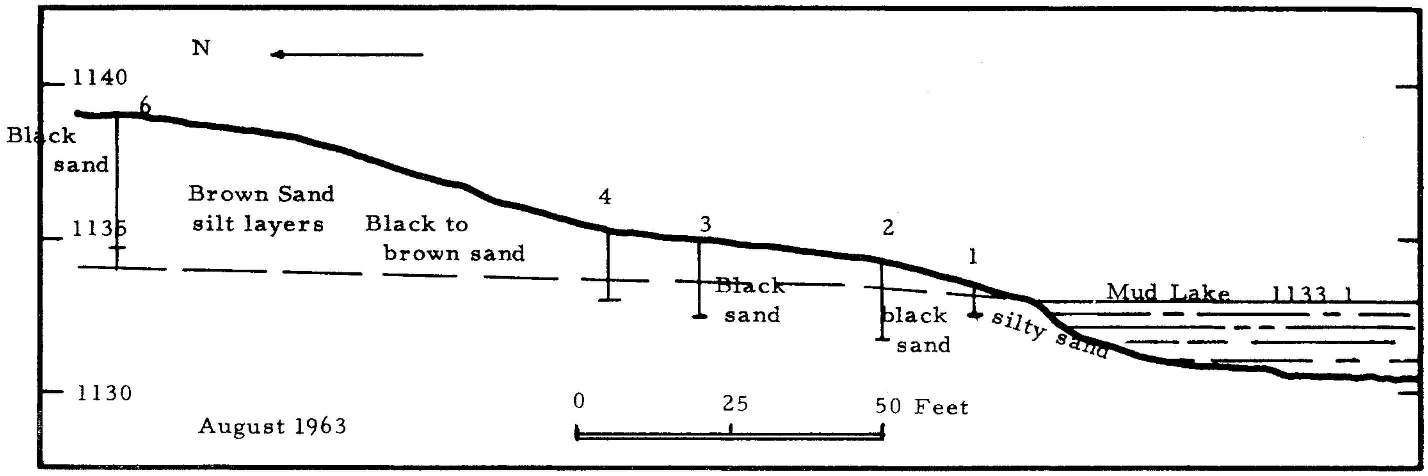

Figure 6. Cross-section showing test holes at Mud Lake, Belle Prairie Quadrangle.

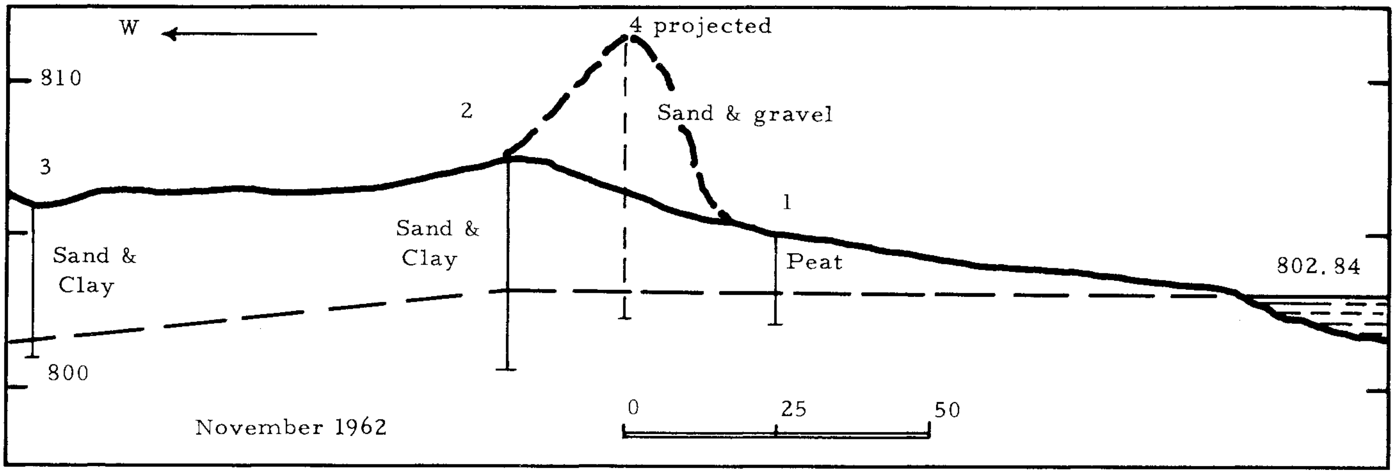

Figure 7. Cross-section showing test holes on the southwest side of BL 1 pothole.

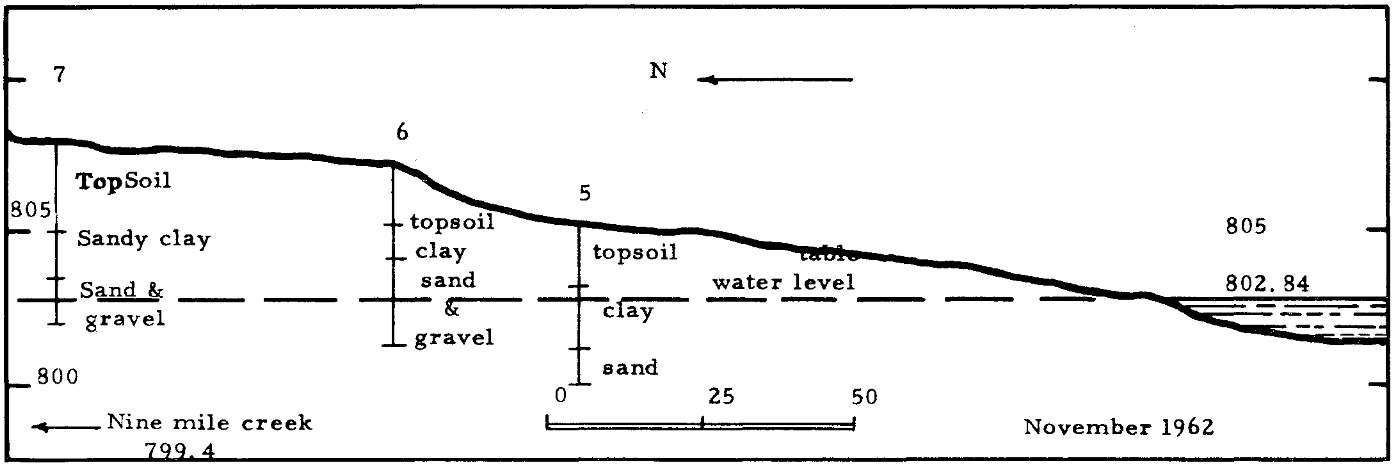

Figure 8. Cross-section showing test holes on the north side of BL 1 pothole.

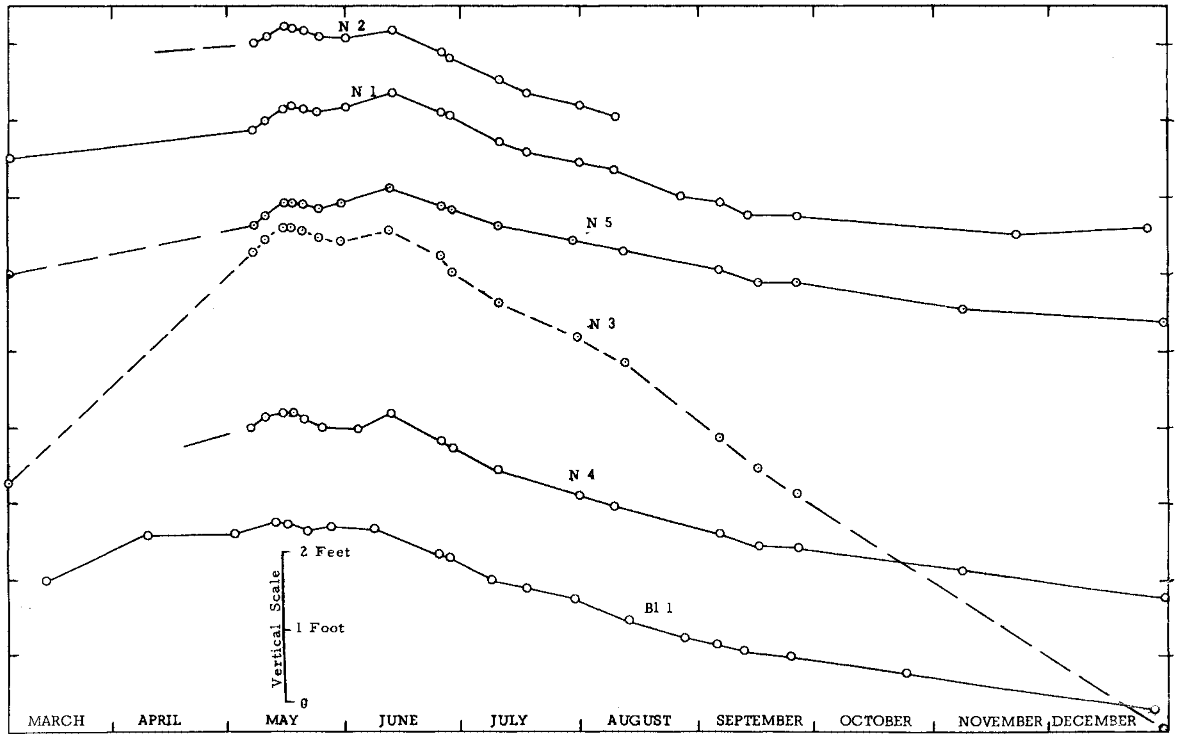

Figure 9. Graph of 1963 water levels for the Bloomington and New Brighton Quadrangles. Vertical scale .4 inch to 1 foot.

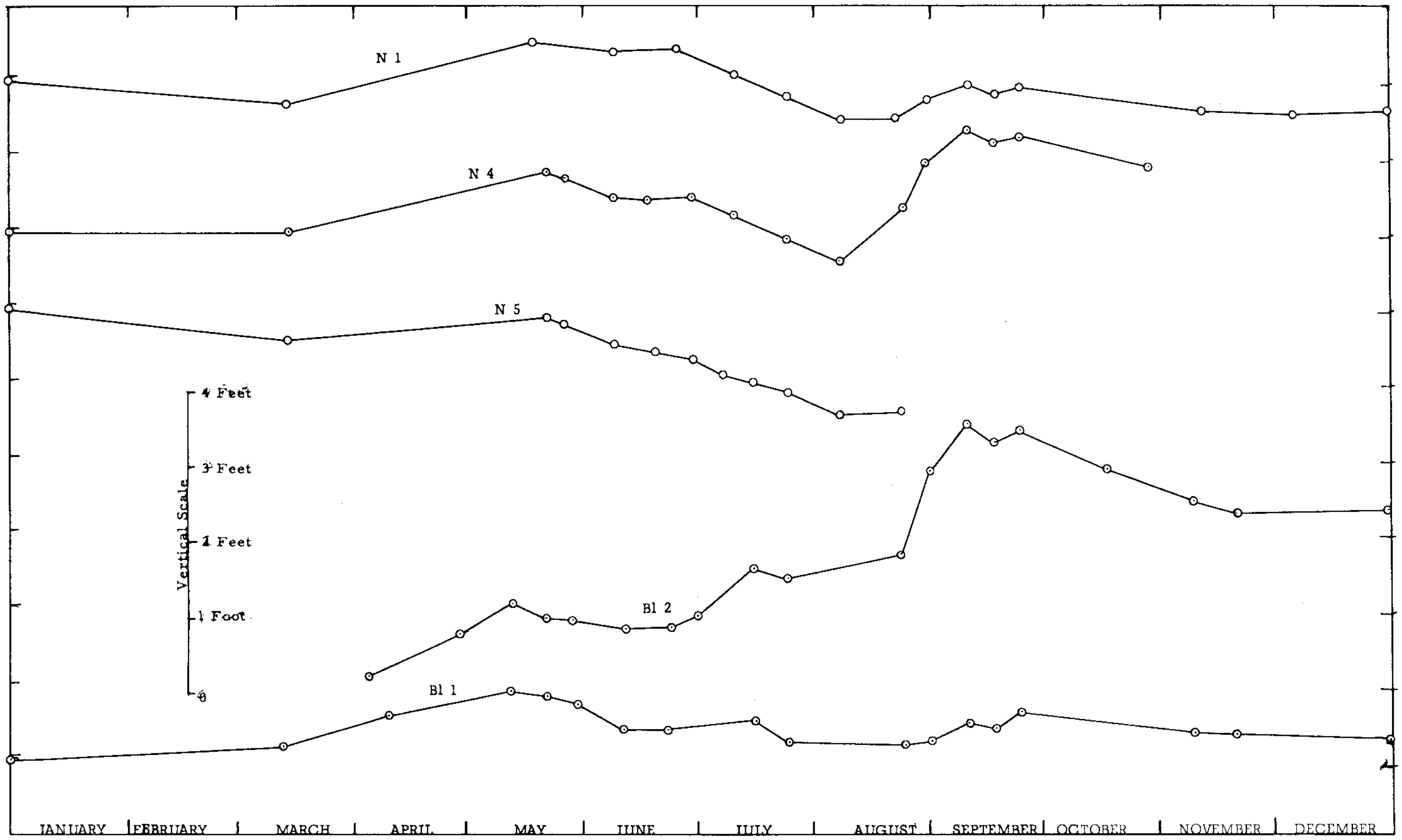

Figure 10. Graph of 1964 water levels for the Bloomington and New Brighton Quadrangles.

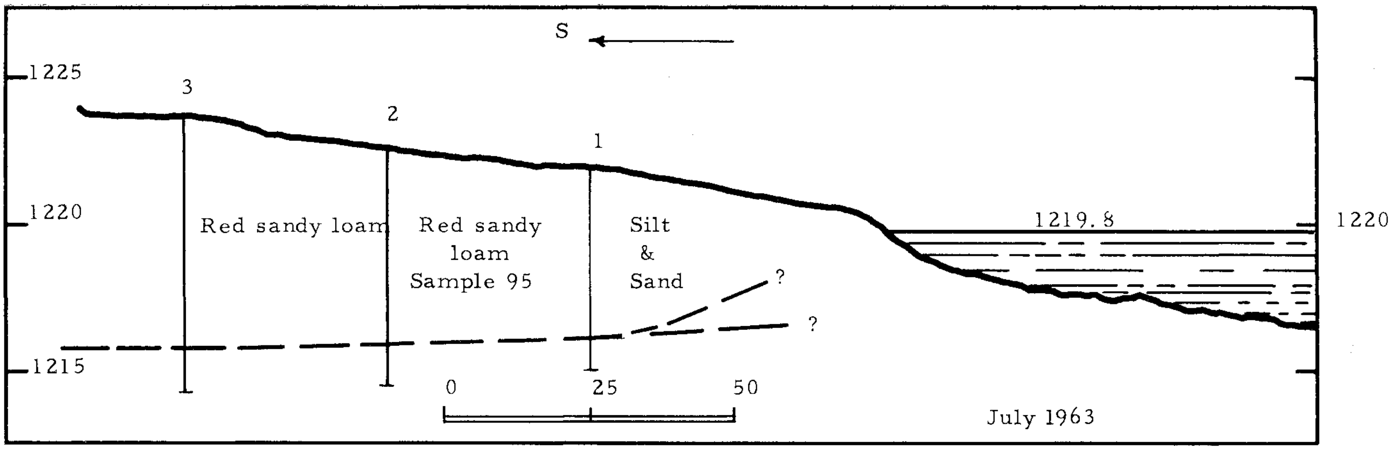

Figure 11. Cross-section showing test holes at Lake Beauty (F 1).

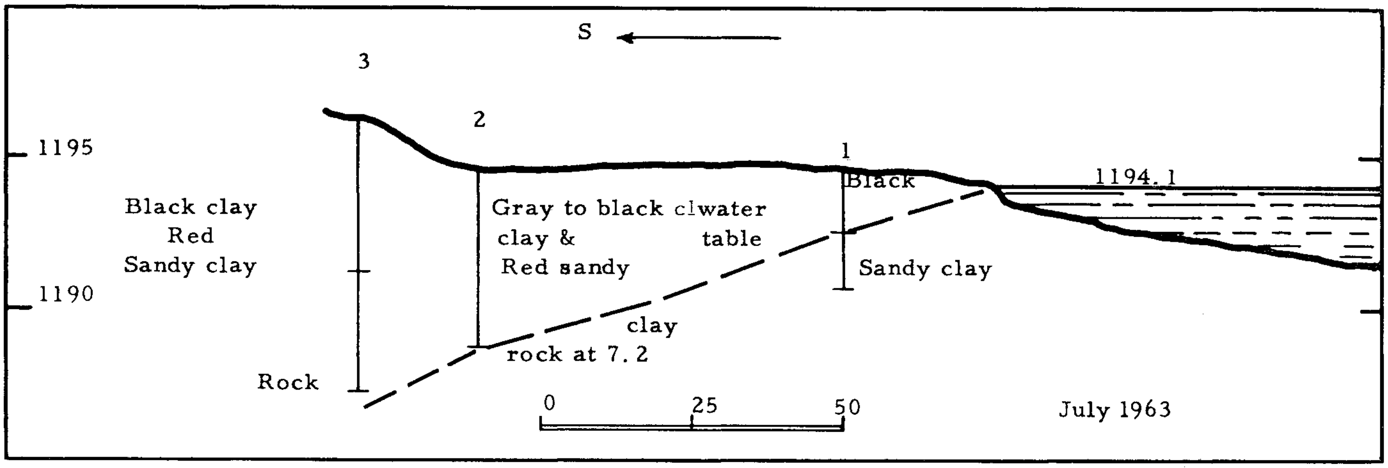

Figure 12. Cross-section showing test holes at Flensburg (F 2) pothole.

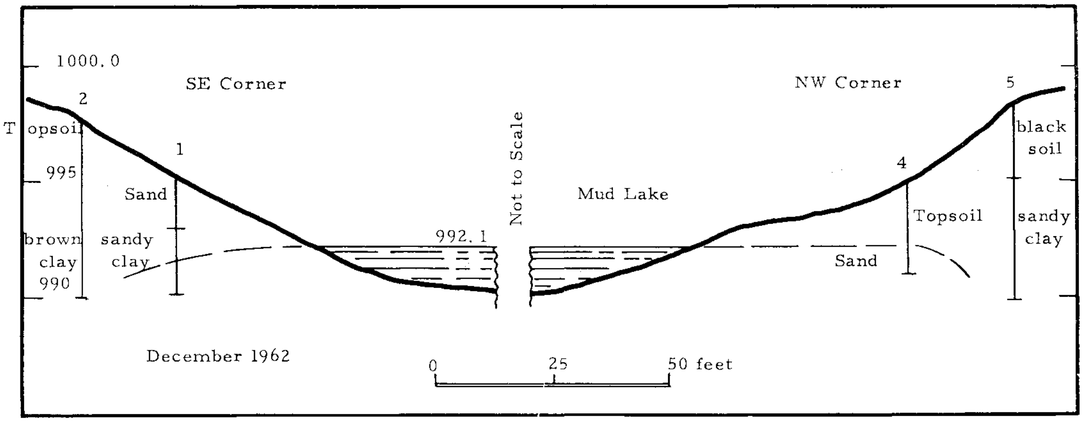

Figure 13. Cross-section showing test holes at Mud Lake (Ga 1), Gaylord Quadrangle.

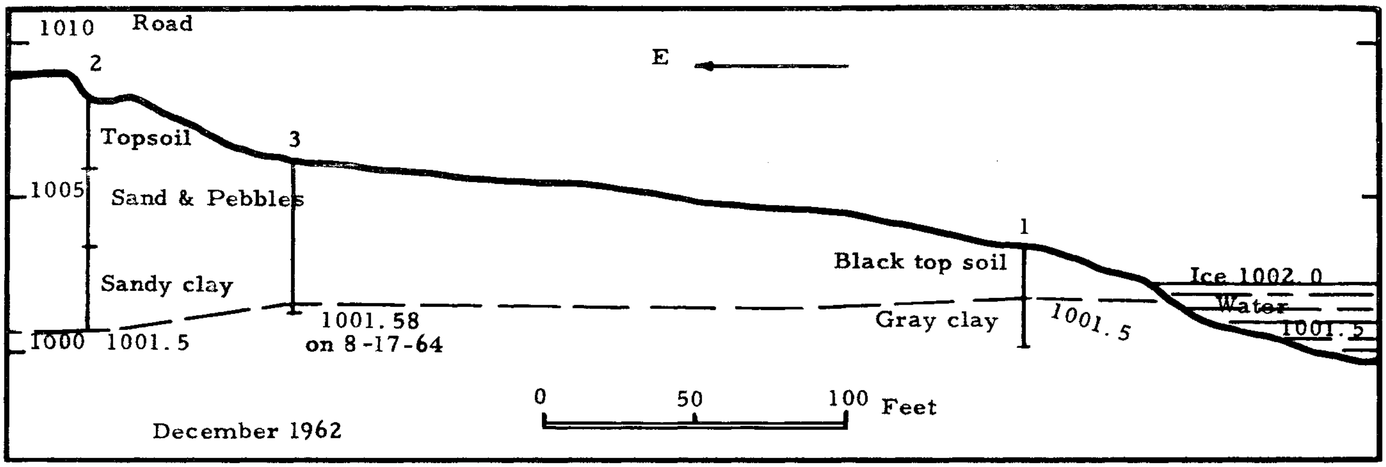

Figure 14. Cross-section showing test holes at Ga 2 pothole, Gaylord Quadrangle.

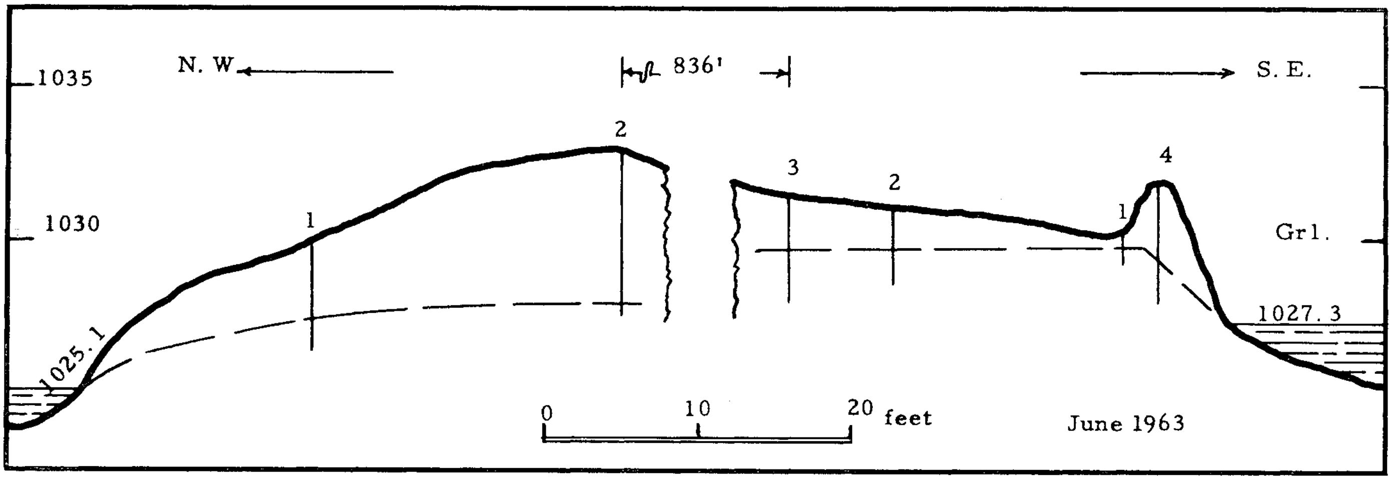

Figure 15. Cross-section showing test holes at Gr 1 pothole, Gracelock Quadrangle.

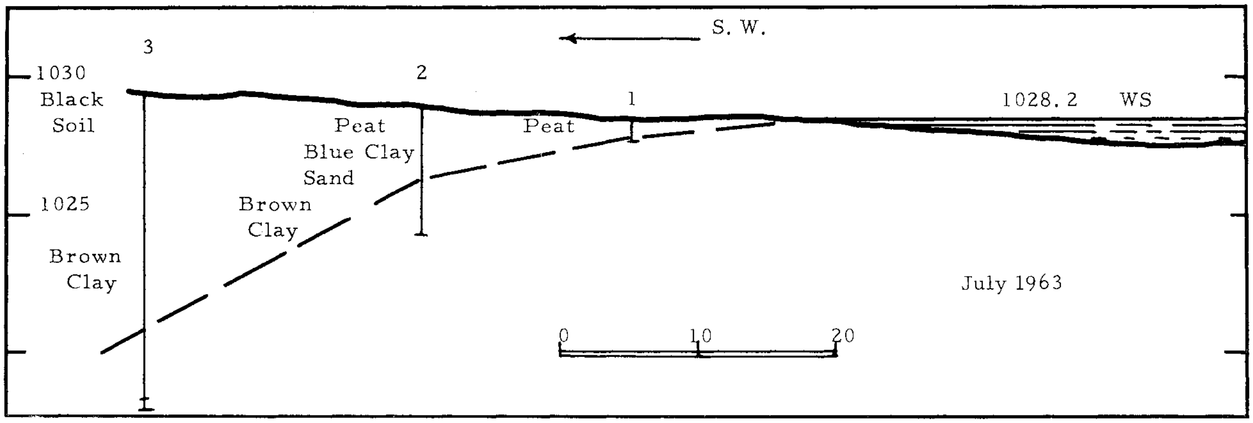

Figure 16. Cross-section showing test holes at Gr 2 pothole, Gracelock Quadrangle.

Audubon (Detroit Lakes)

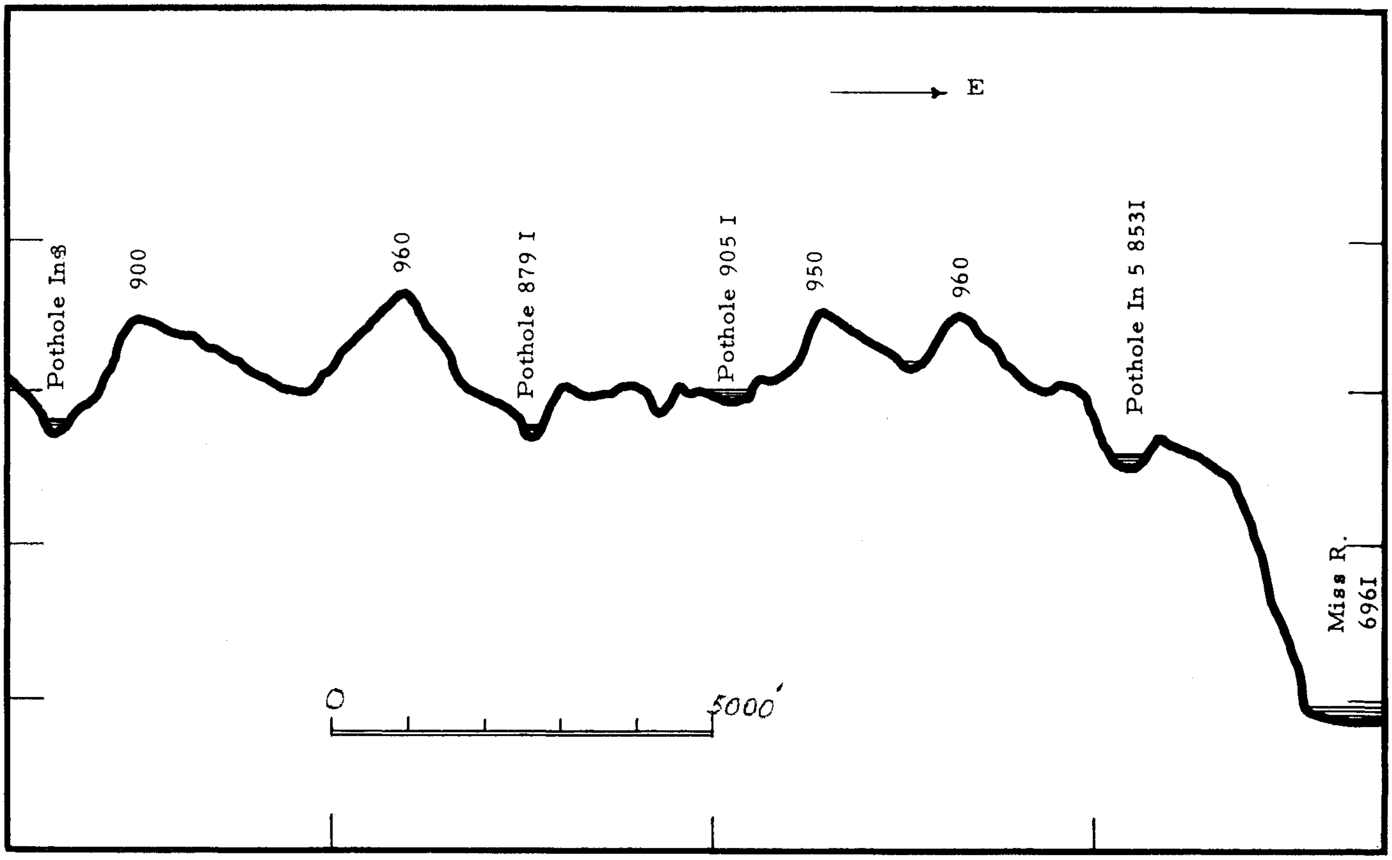

Figure 17. Profile showing the vertical relations of some Inver Grove potholes to the Mississippi River.

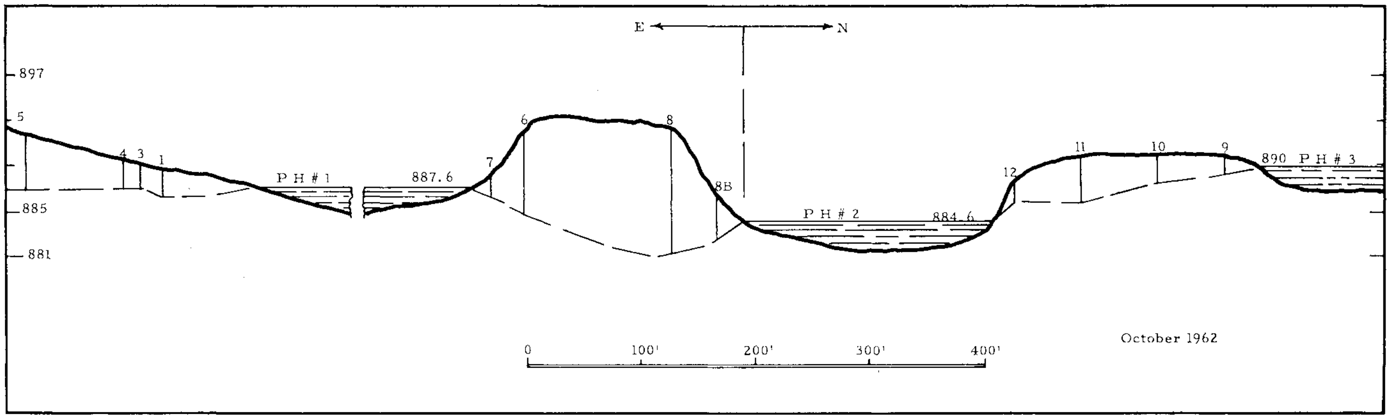

Figure 18. Cross-section showing test holes at In 1 and In 2 potholes.

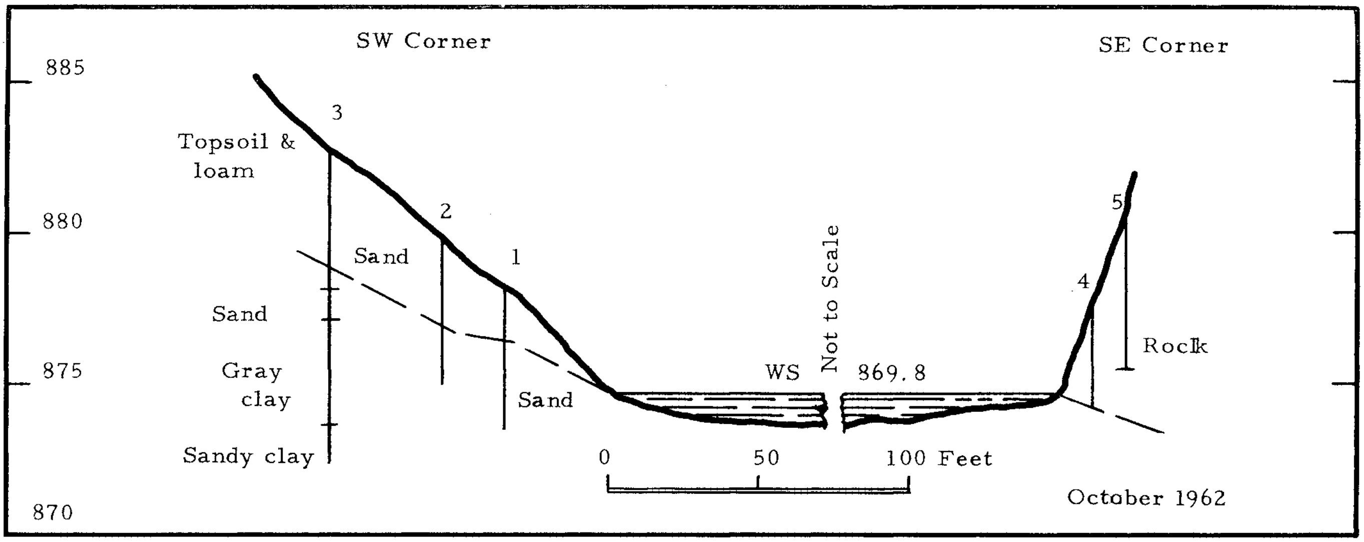

Figure 19. Cross-section showing test holes at In 3 pothole.

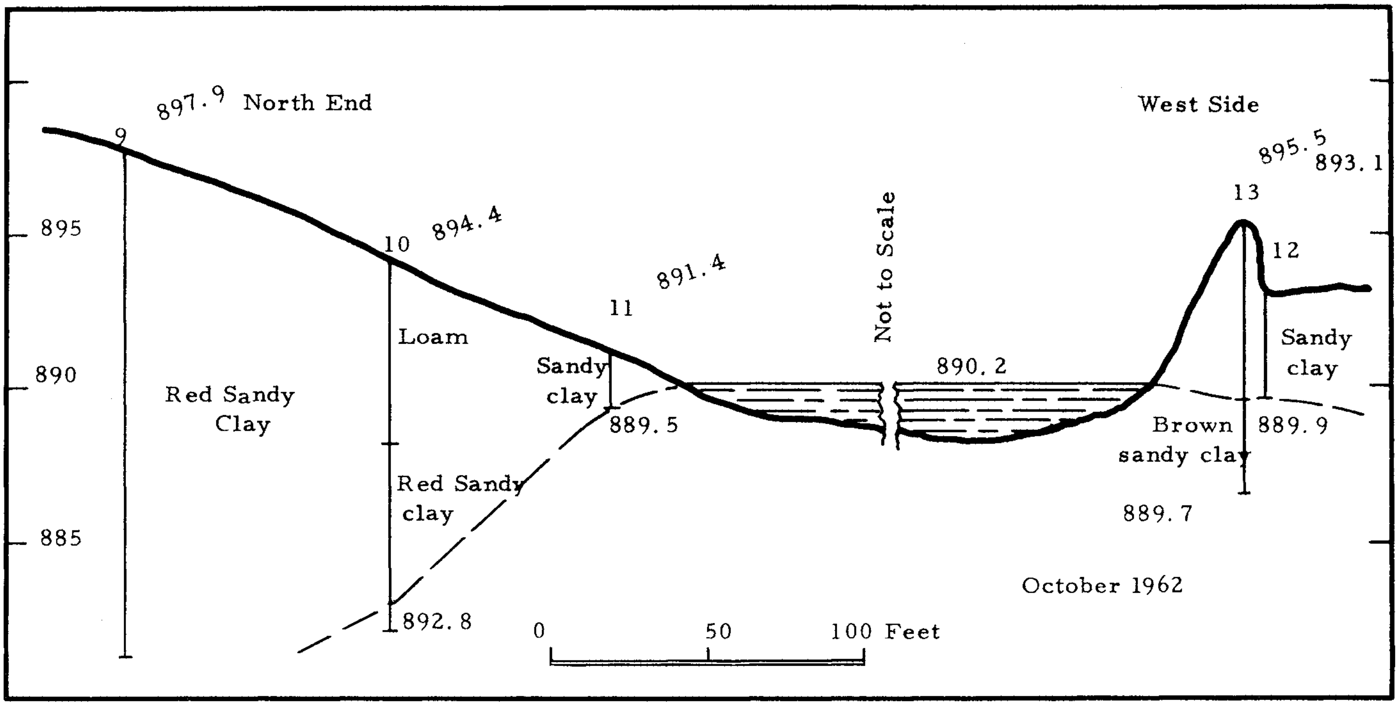

Figure 20. Cross-section showing test holes at the west side and north end of In 4 pothole.

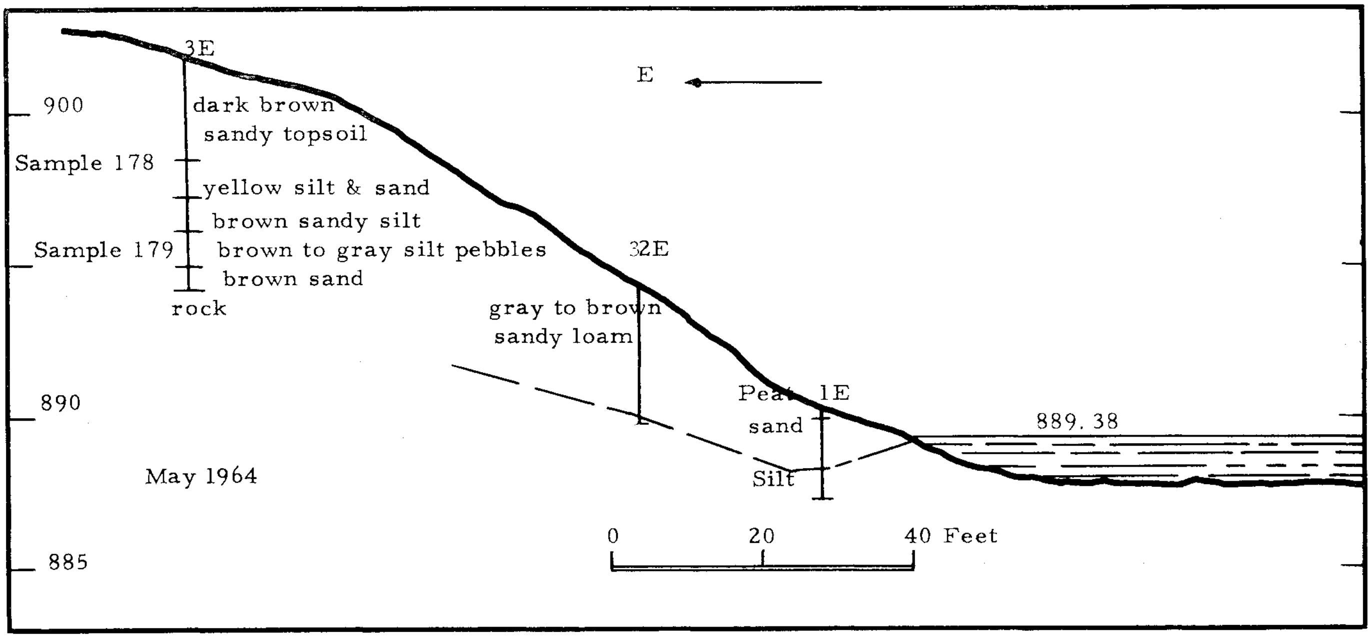

Figure 21. Cross-section showing test holes at the east side of In 4 pothole.

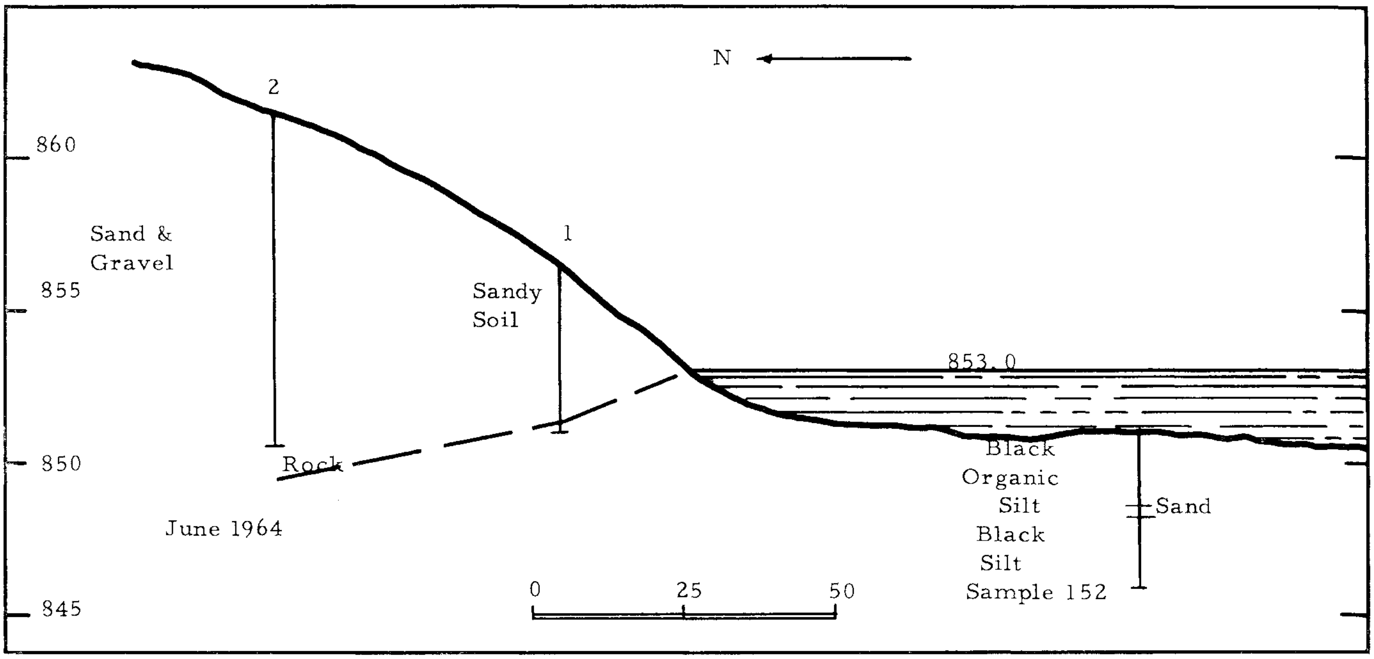

Figure 22. Cross-section showing test holes at In 5 pothole.

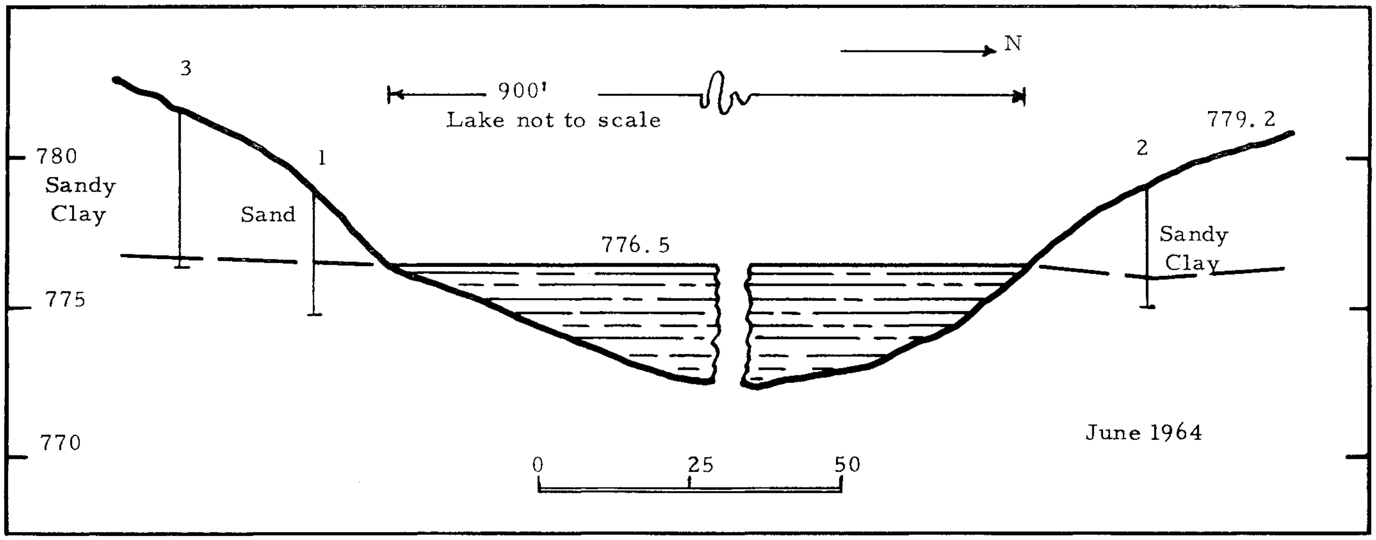

Figure 23. Cross-section showing test holes at In 6 pothole.

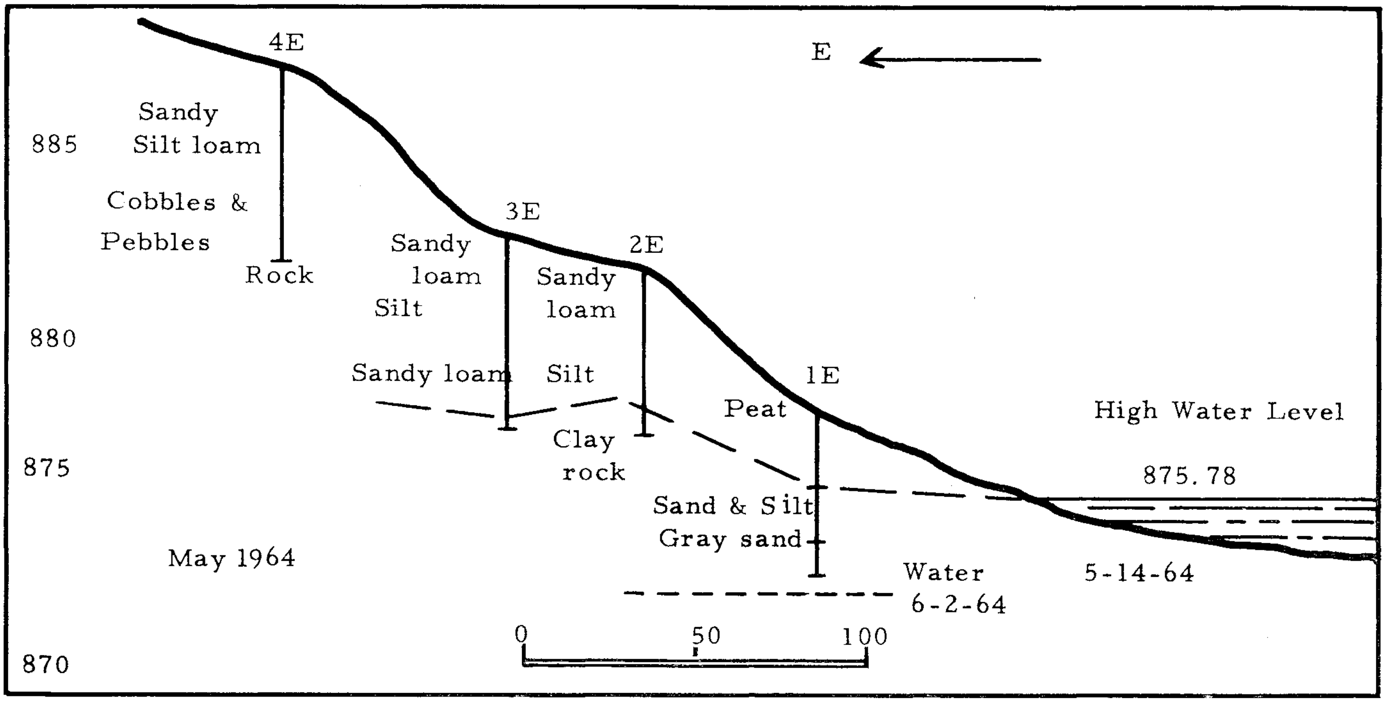

Figure 24. Cross-section showing test holes at the Pine Bend (In 7) pothole.

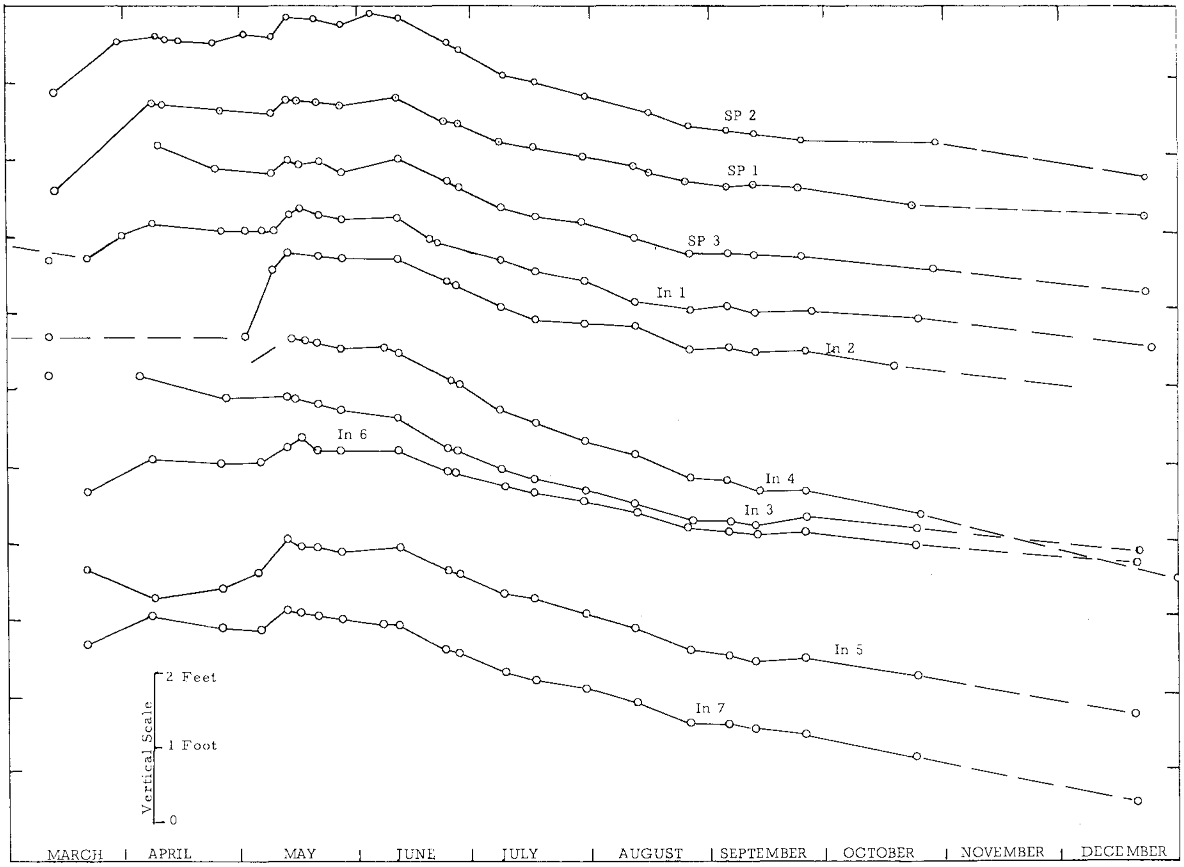

Figure 25. Graph of 1963 water levels for the Inver Grove and St. Paul S. W. Quadrangle.

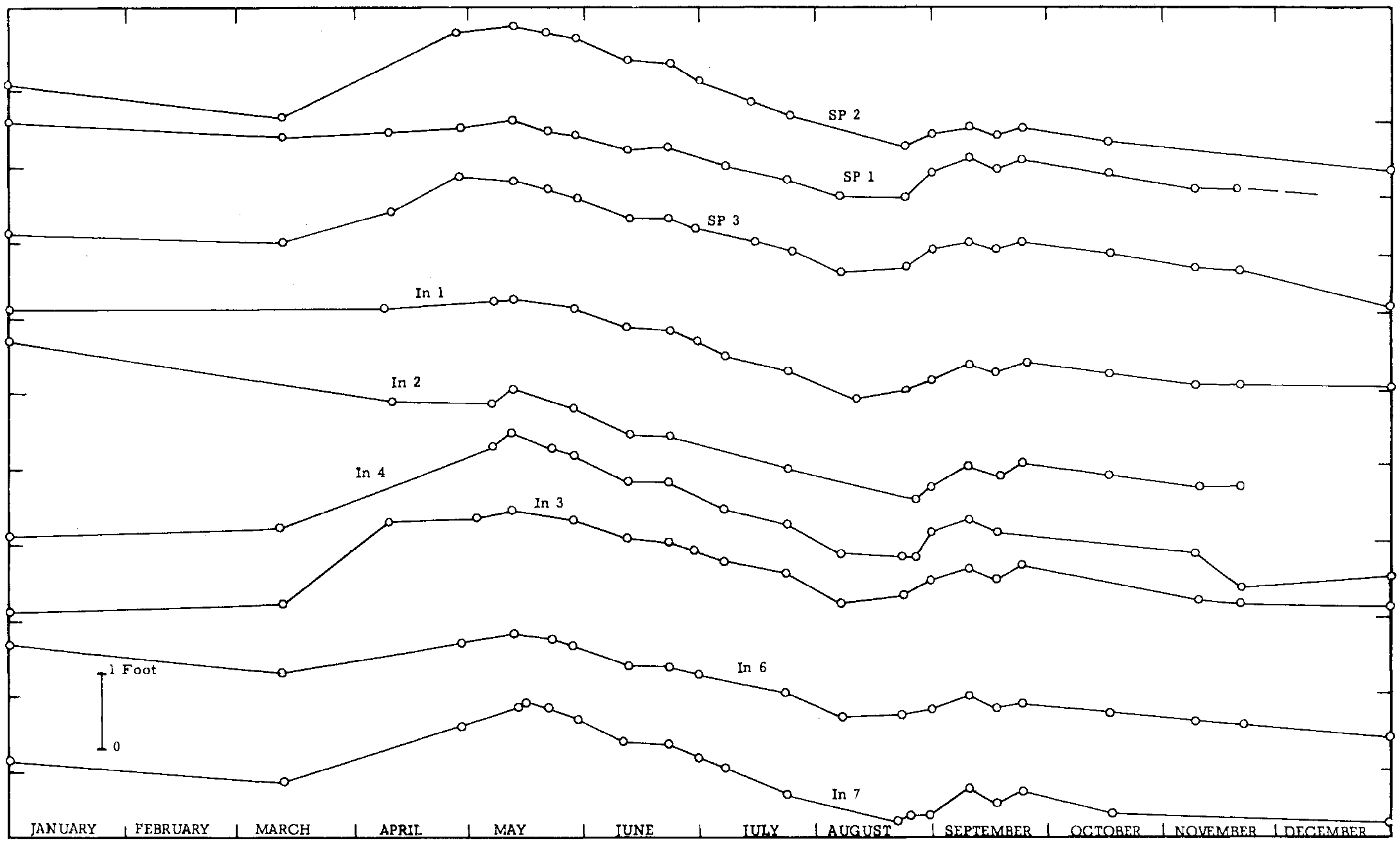

Figure 26. Graph of 1964 water levels for the Inver Grove and St. Paul S. W. Quadrangles.

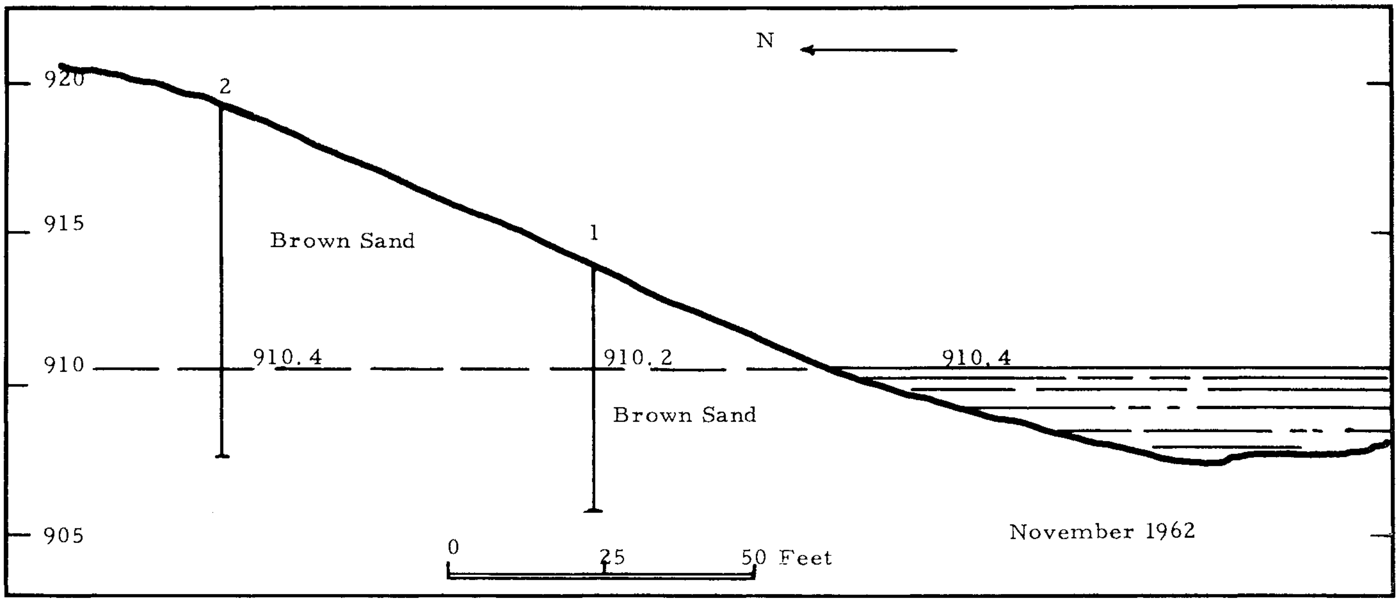

Figure 27. Cross-section showing test holes at Booster (Is 1) pothole.

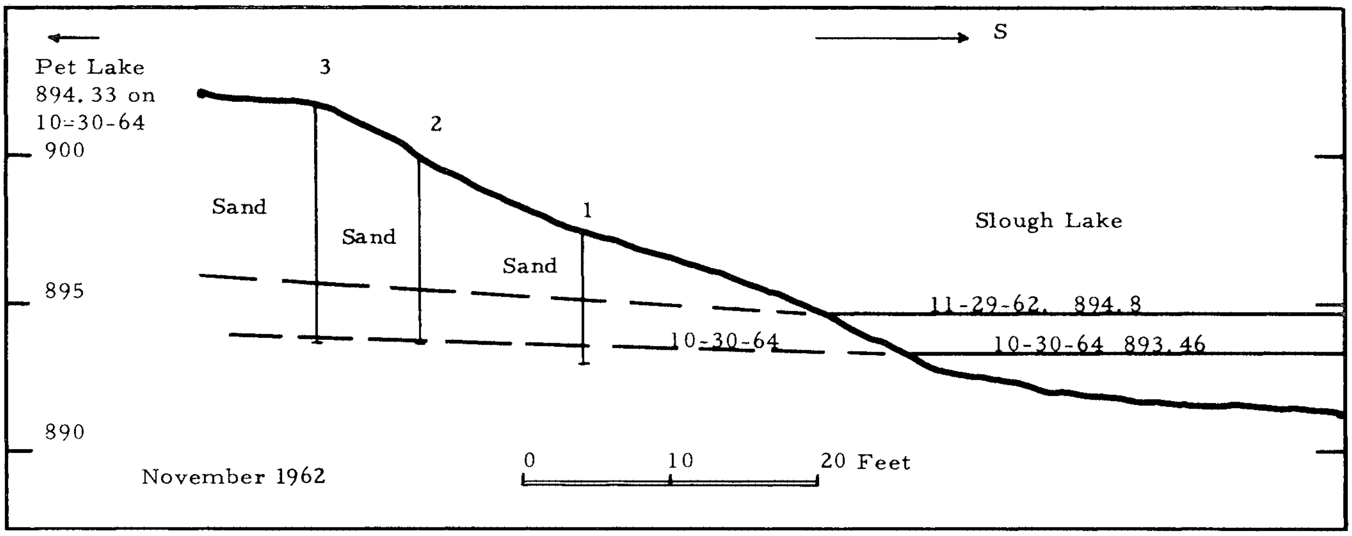

Figure 28. Cross-section showing test holes at Slough Lake (Is 4).

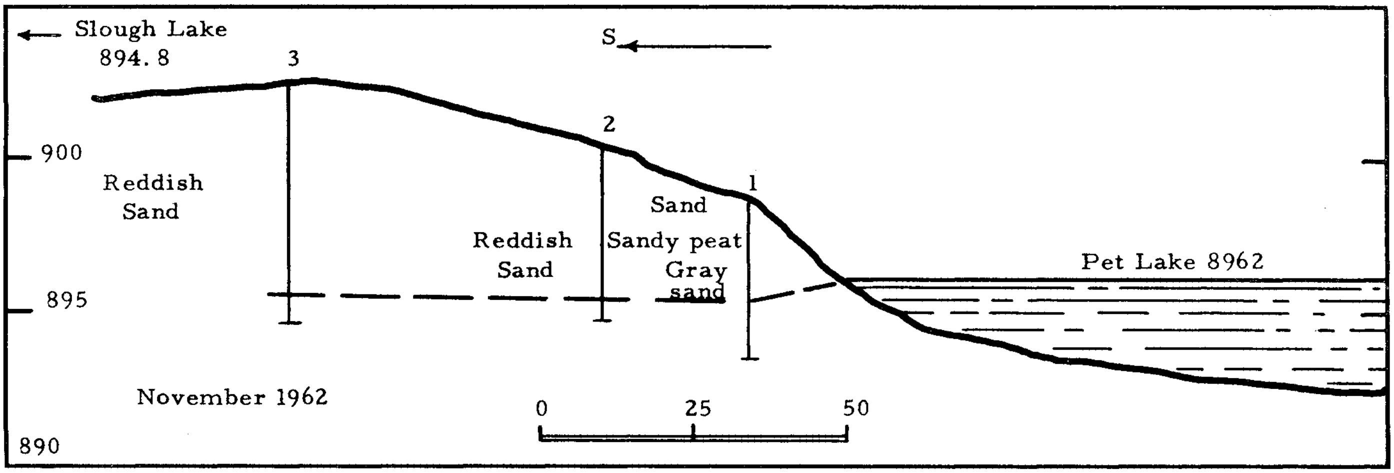

Figure 29. Cross-section showing test holes at Pet Lake (Is 5).

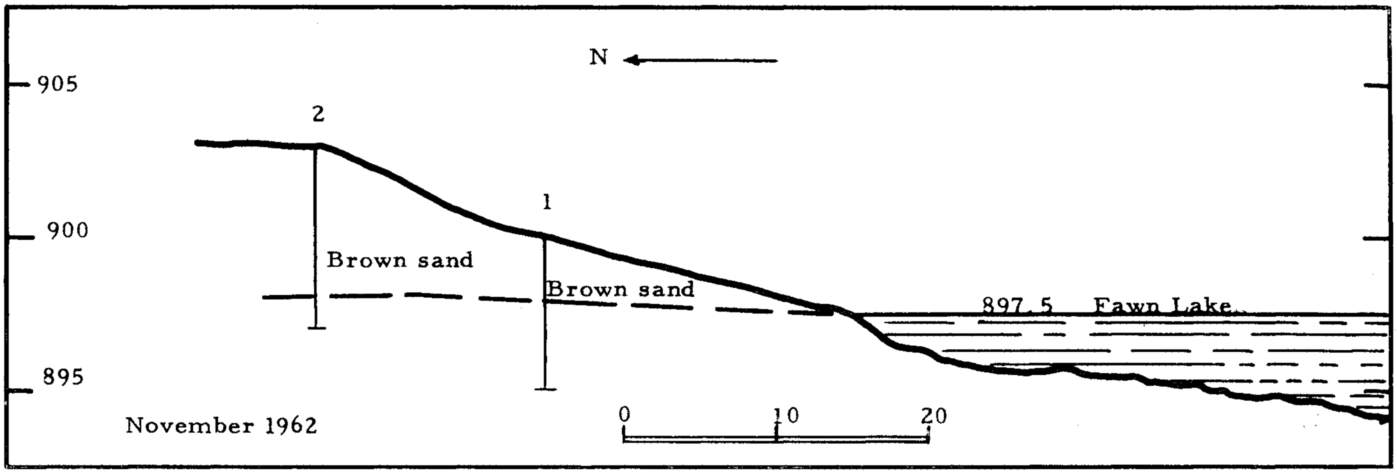

Figure 30. Cross-section showing test holes at Fawn Lake (Is 6).

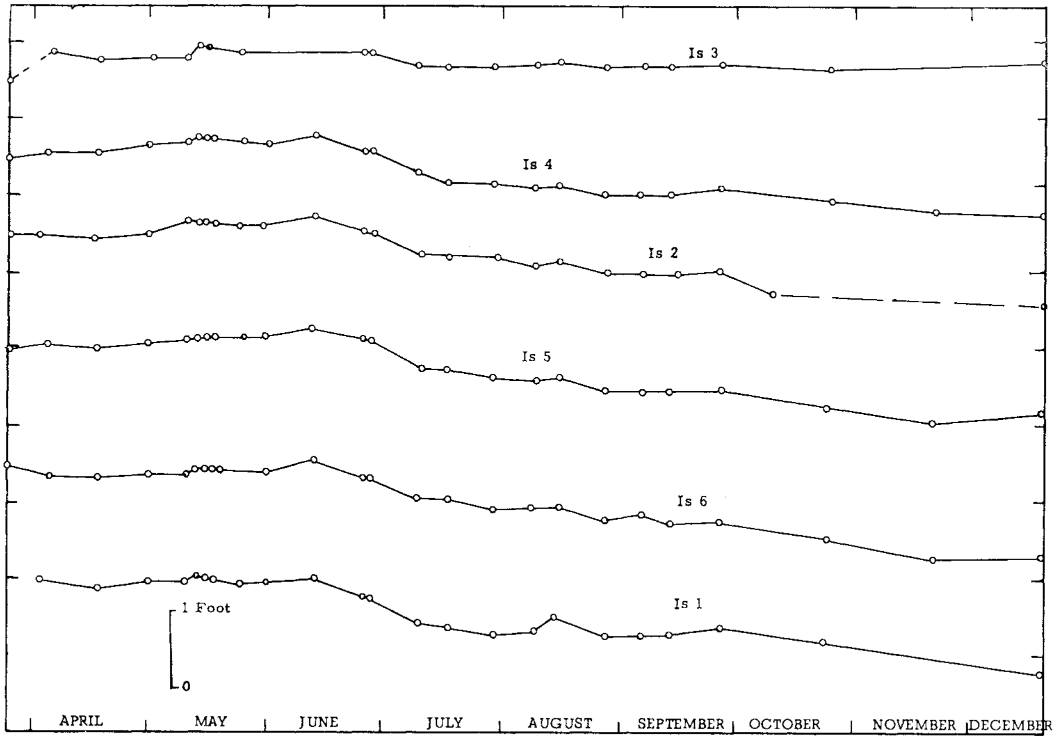

Figure 31. Graph of 1963 water levels for the Isanti Quadrangle.

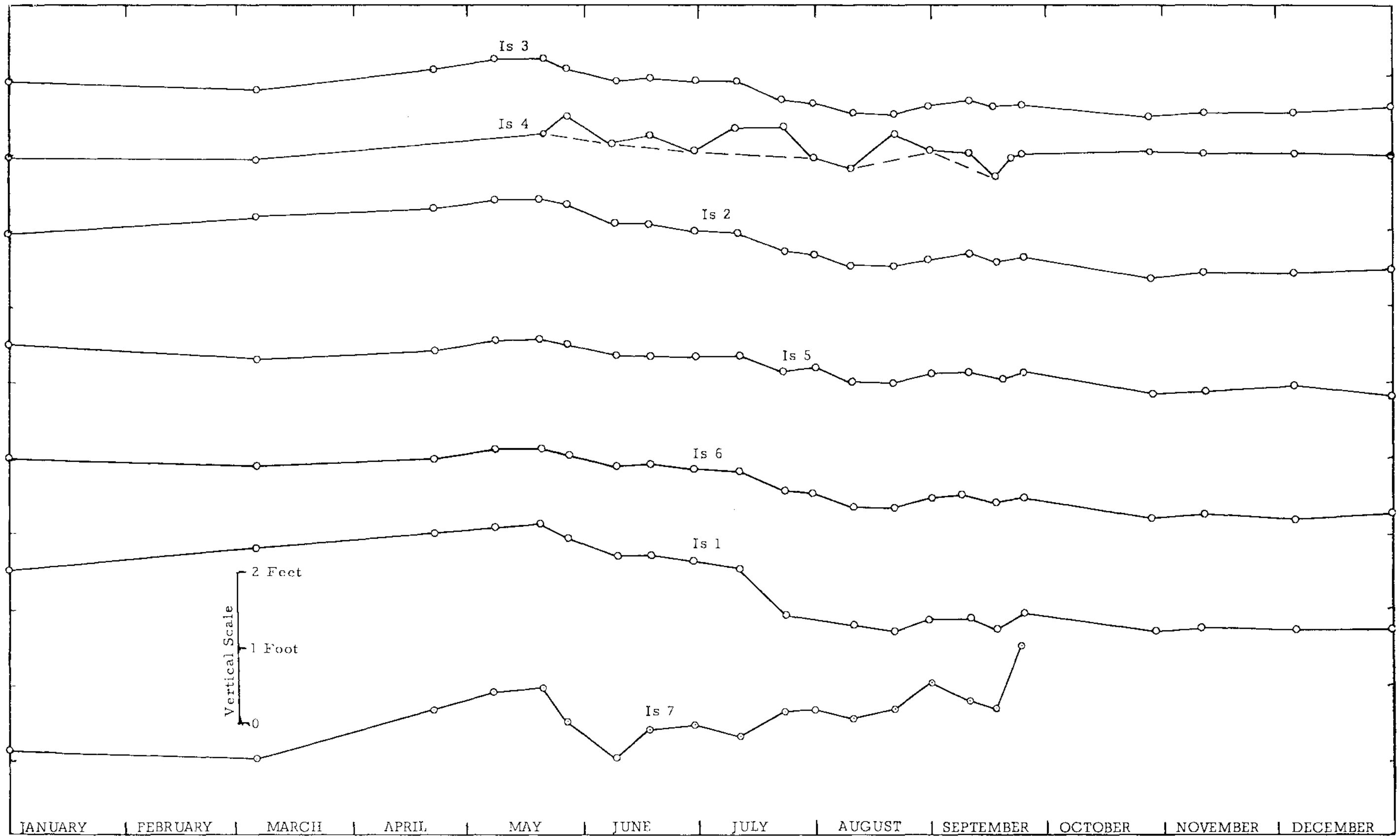

Figure 32. Graph of 1964 water levels for the Isanti Quadrangle.

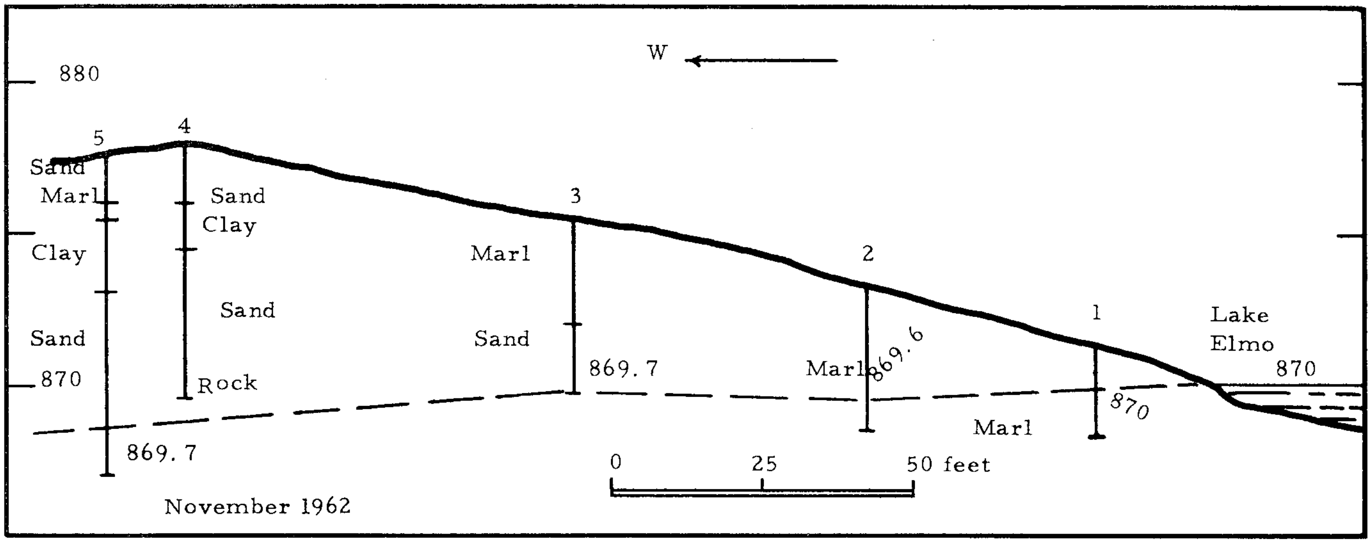

Figure 33. Cross-section showing test holes at the west side of Lake Elmo (LE 1).

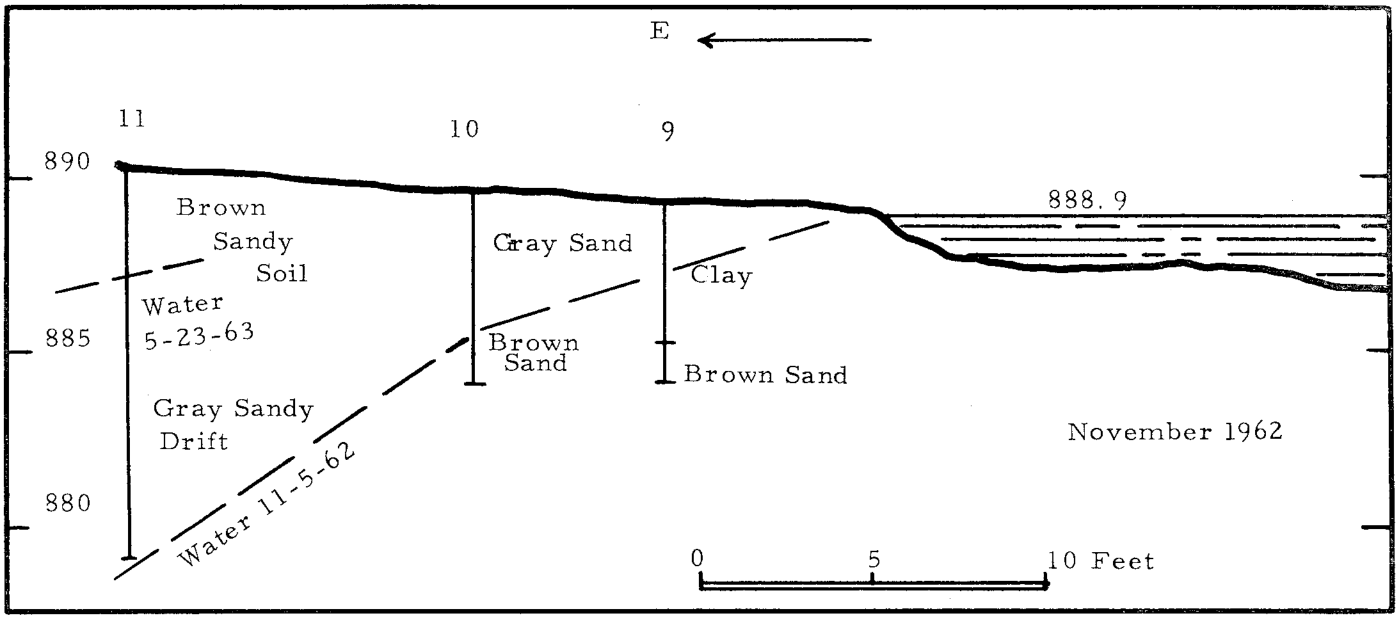

Figure 34. Cross-section showing test holes at LE 3 pothole.

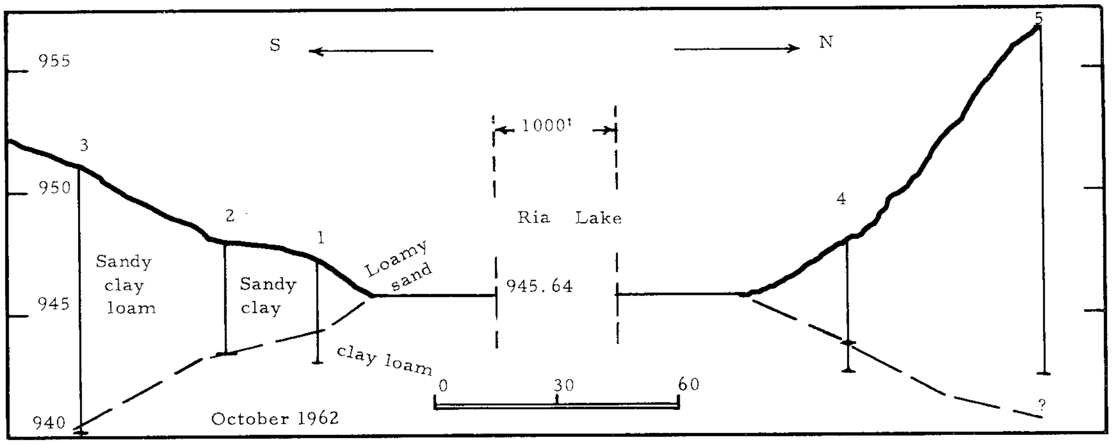

Figure 35. Cross-section showing test holes at Lake Ria (LE 4).

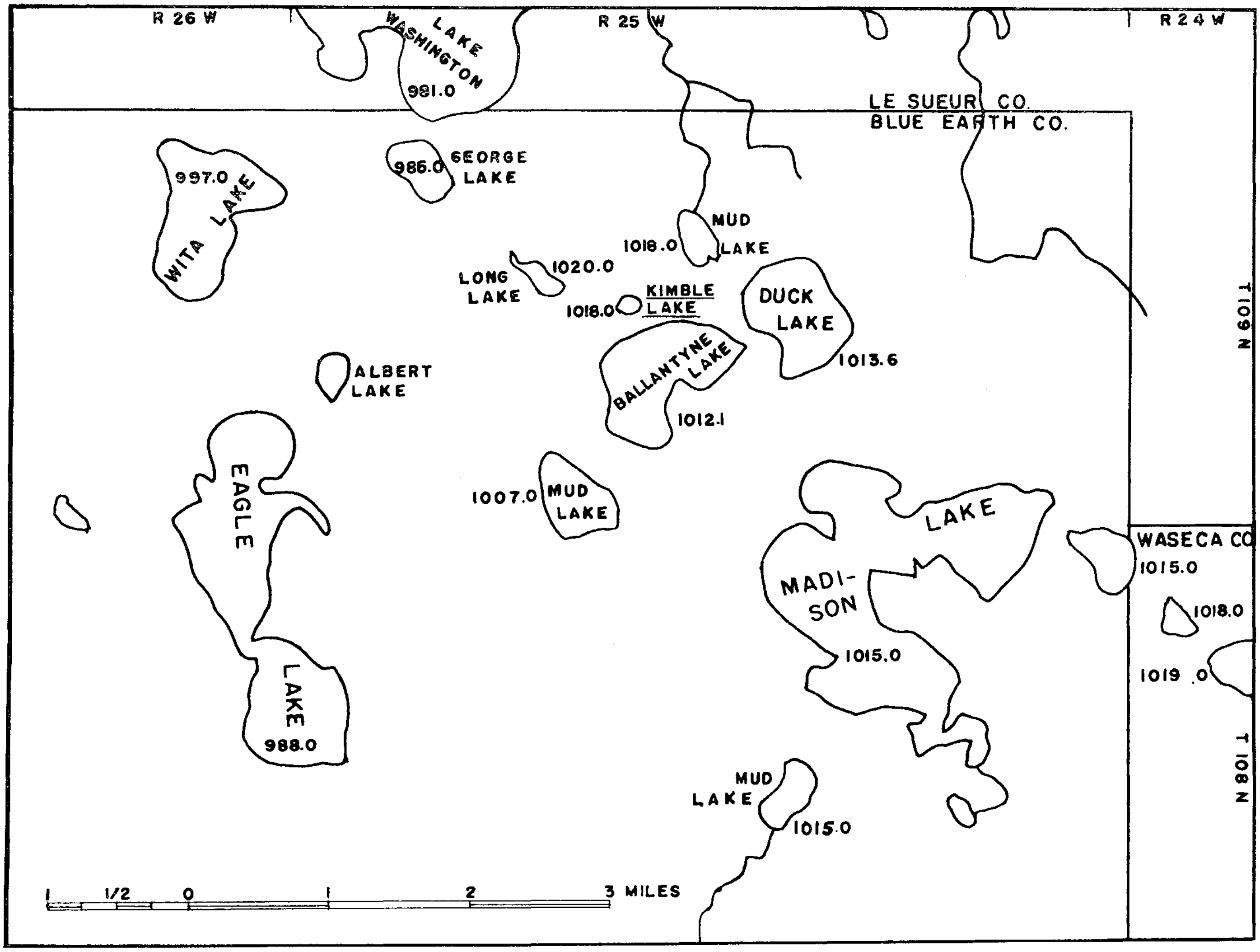

Figure 36. Map showing elevations of the water surface of lakes and ponds in part of the Mankato East Quadrangle.

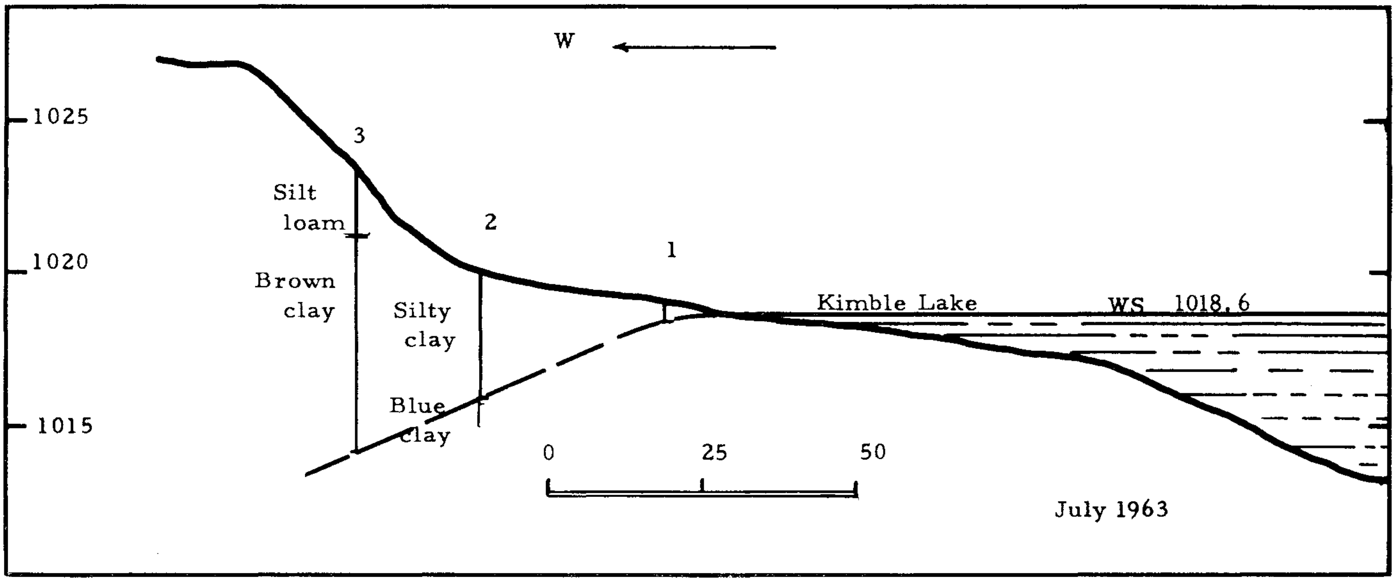

Figure 37. Cross-section showing test holes at Kimble Lake (M 1).

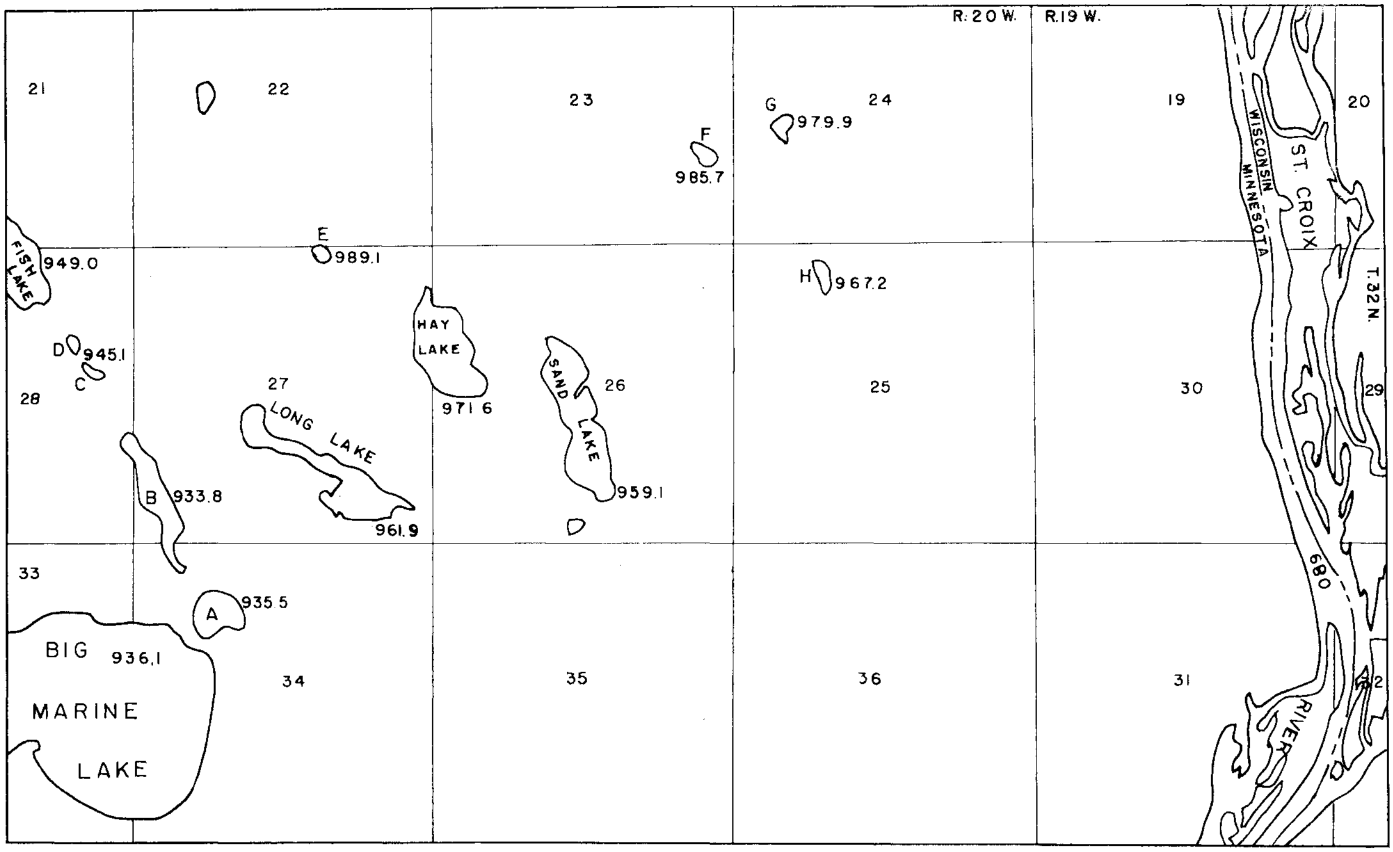

Figure 38. Map showing elevations of the water surface of lakes and ponds and the St. Croix River in part of the Marine Quadrangle.

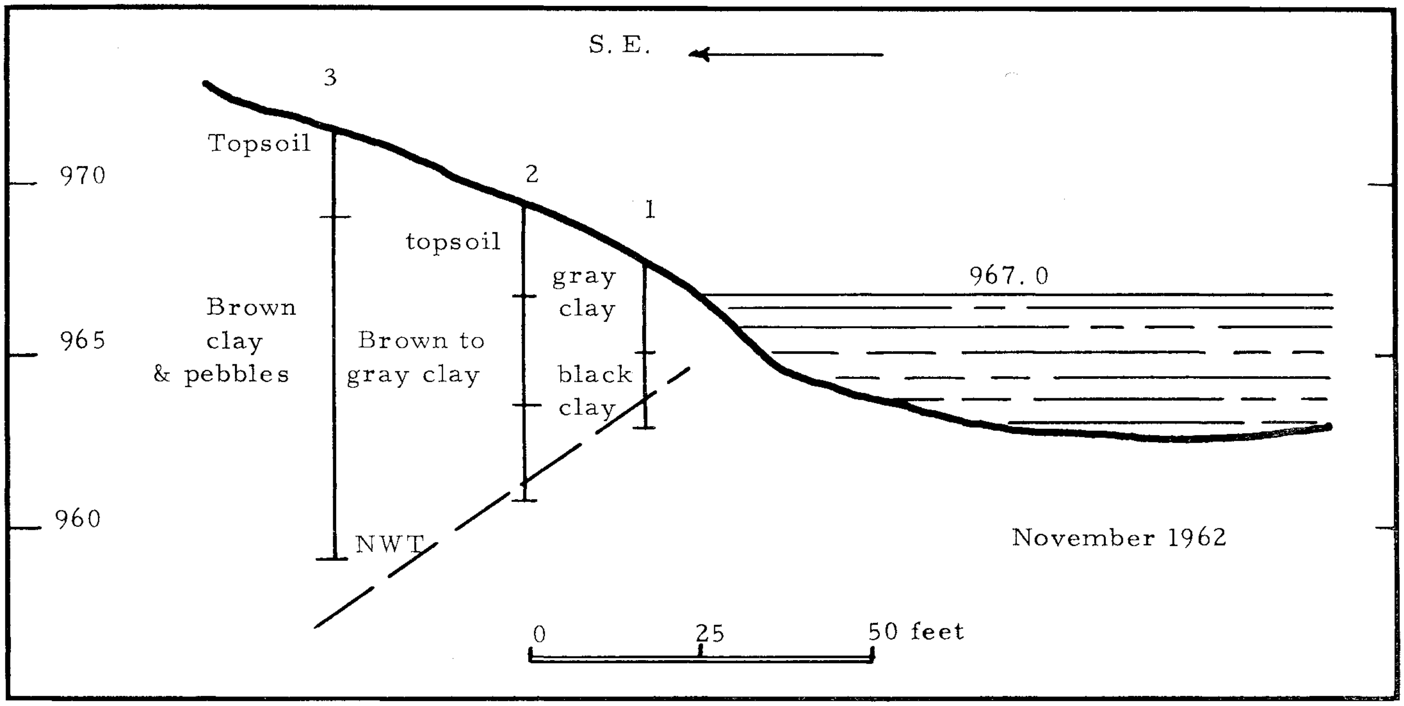

Figure 39. Cross-section showing test holes at the southeast side of the Johnson (Ma 1) pothole.

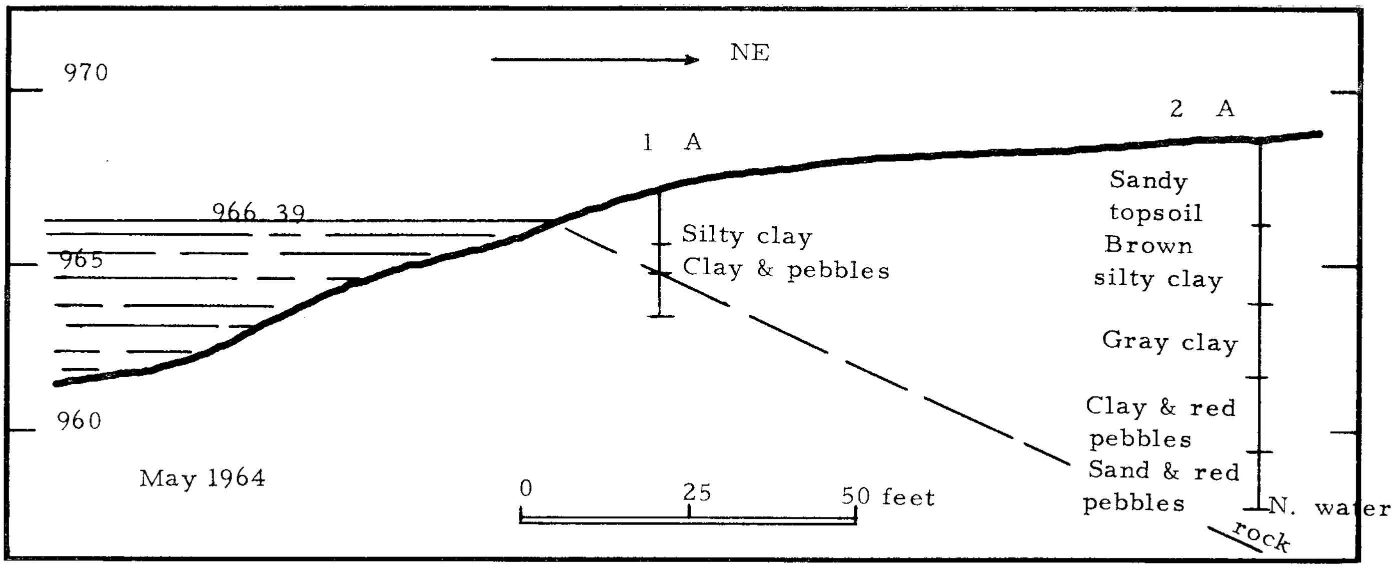

Figure 40. Cross-section showing test holes at the northeast side of the Johnson (Ma 1) pothole.

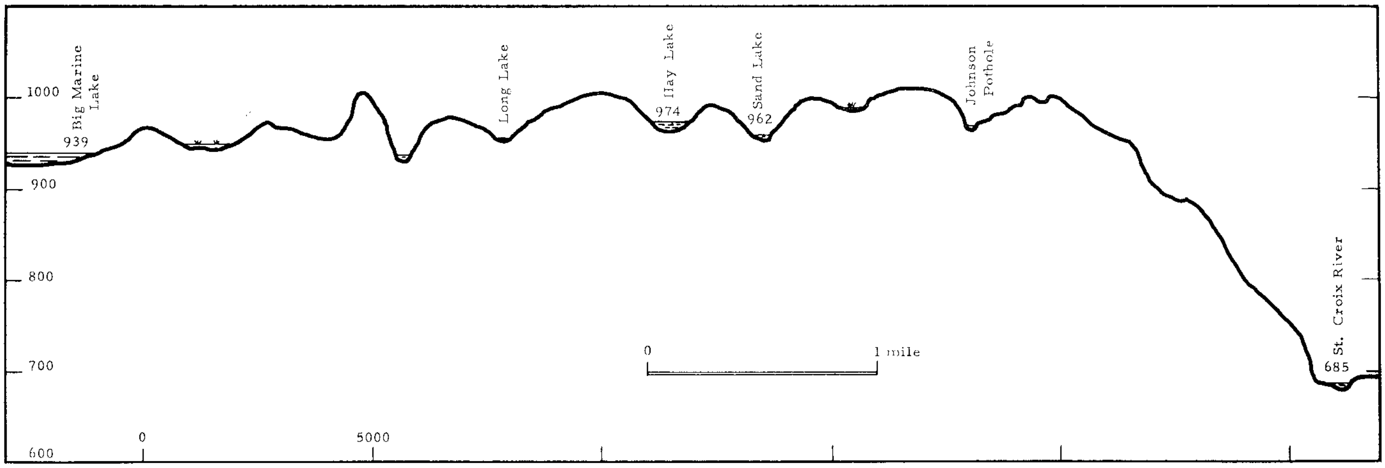

Figure 41. Profile showing the vertical relations of lakes and potholes to the St. Croix River in part of the Marine Quadrangle.

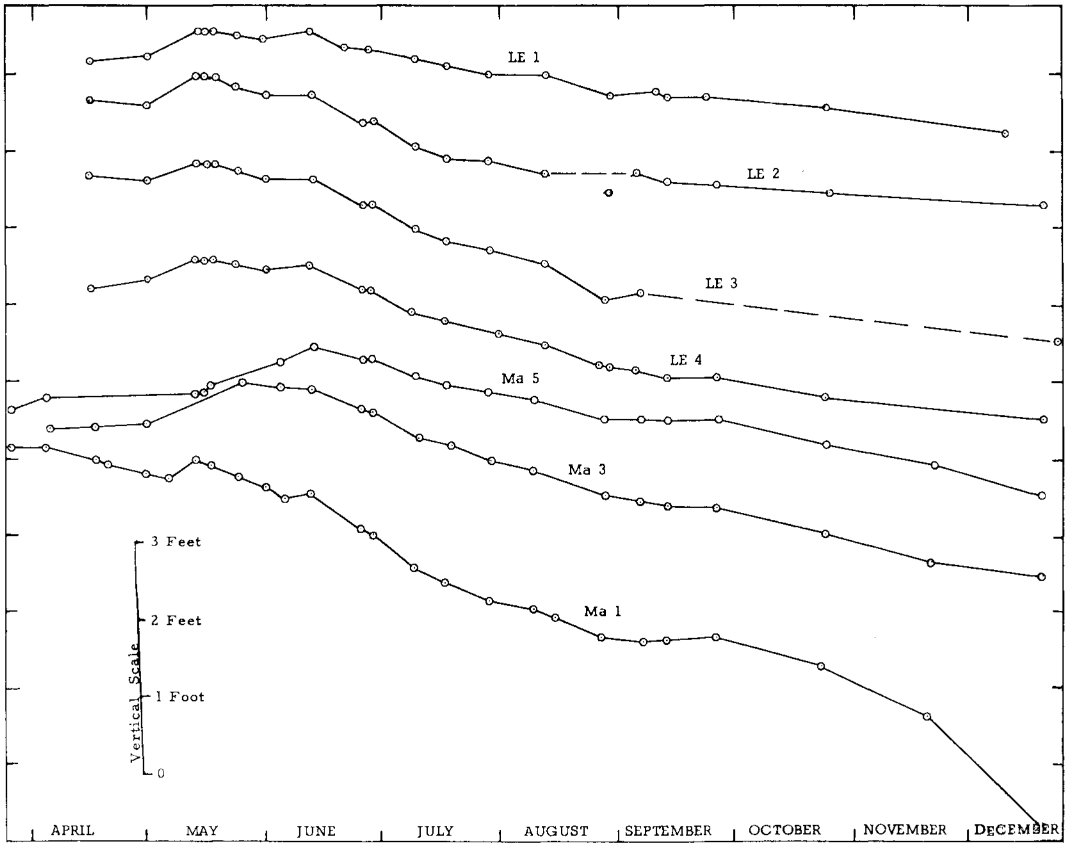

Figure 42. Graph of 1963 water levels for the Lake Elmo and Marine Quadrangles.

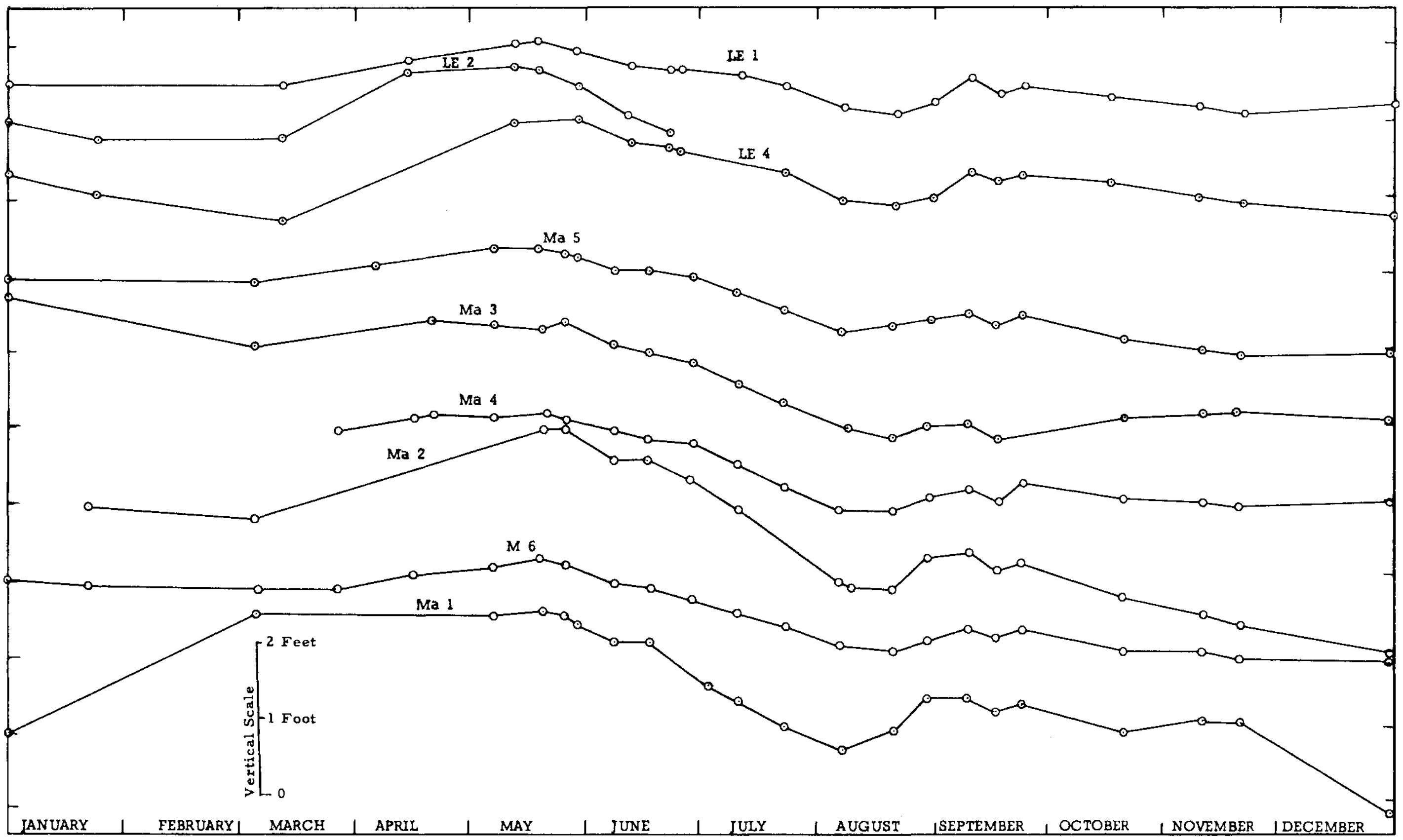

Figure 43. Graph of 1964 water levels for the Lake Elmo and Marine Quadrangles.

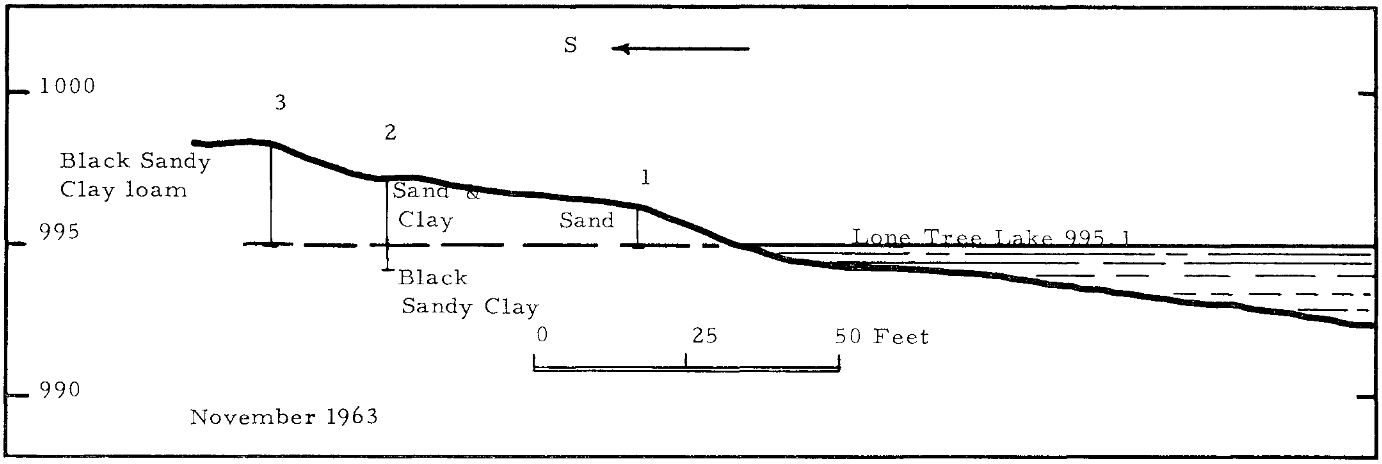

Figure 44. Cross-section showing test holes at Lone Tree Lake (Mo 1).

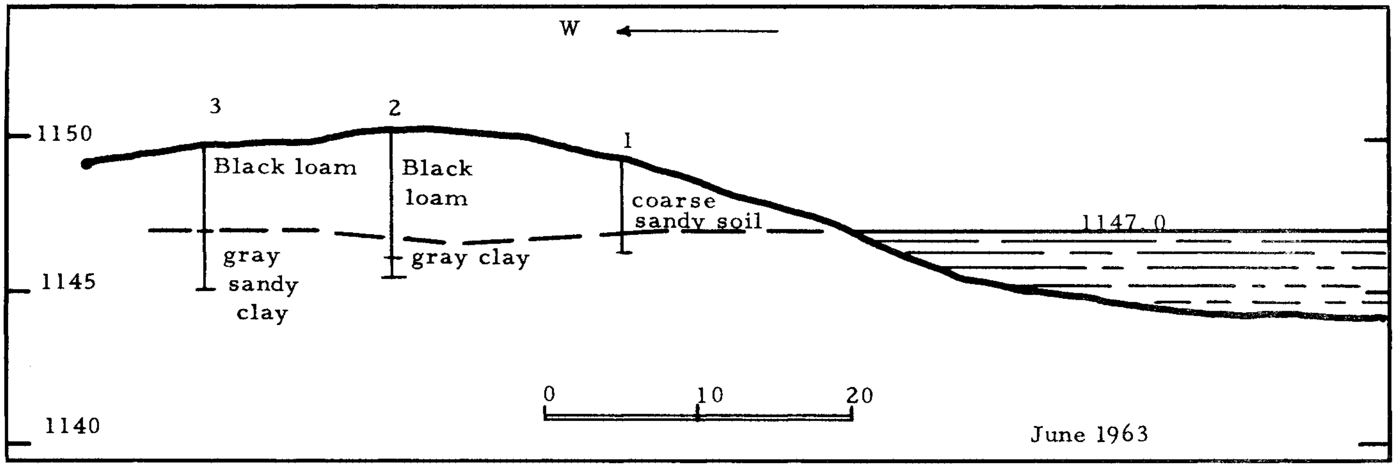

Figure 45. Cross-section showing test holes at Mor 1 pothole near Morris, Minnesota.

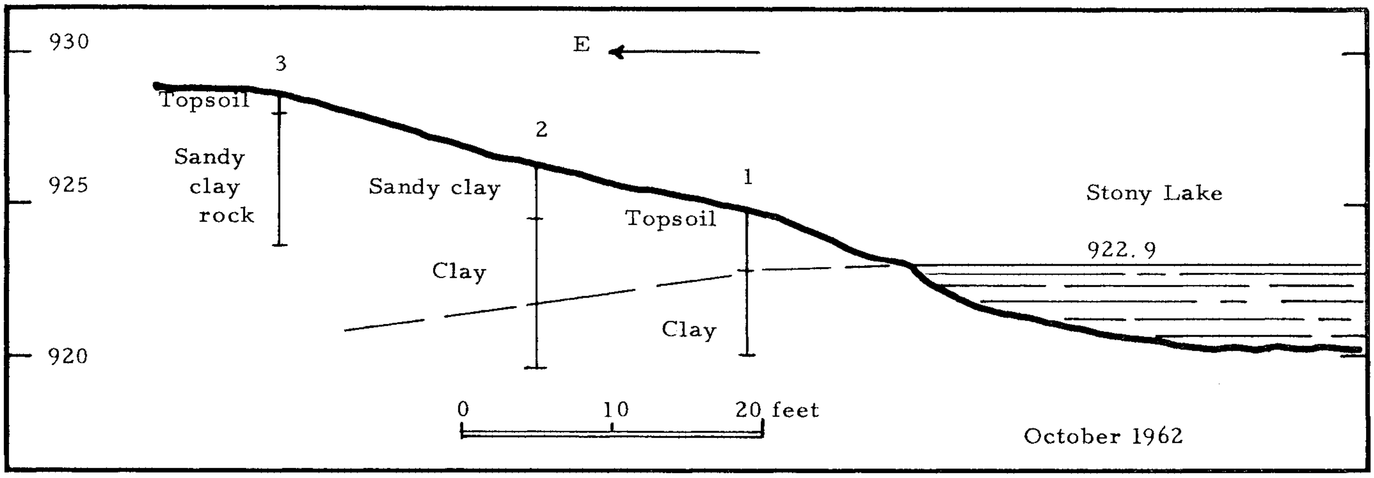

Figure 46. Cross-section showing test holes on the east side of Stony Lake (N 1).

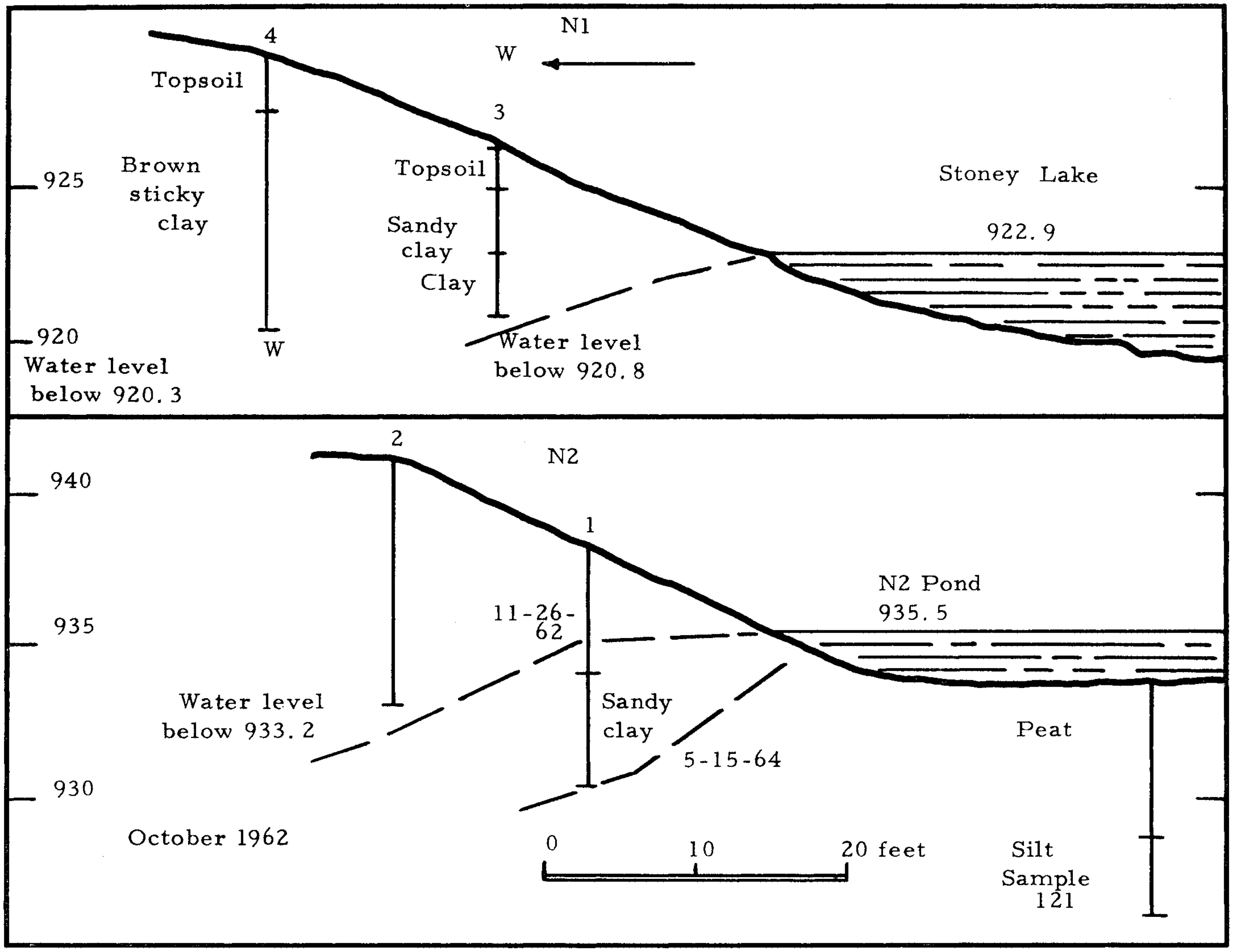

Figure 47. Cross-section showing test holes on the west side of Stony Lake and N 2 pothole.

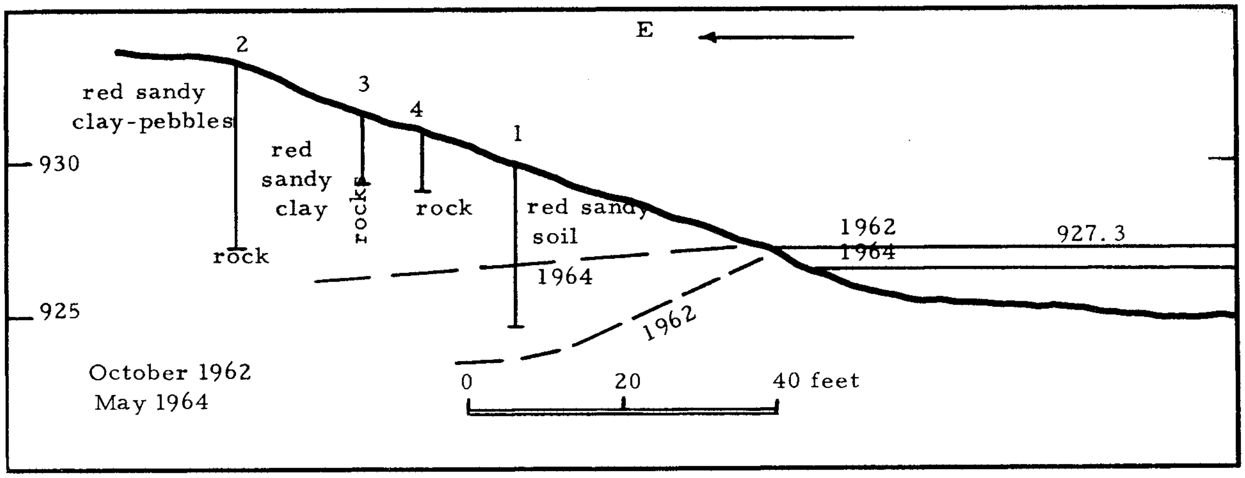

Figure 48. Cross-section showing test holes at the lower lake, near the Lexington and Victoria intersection (N 5), New Brighton Quadrangle.

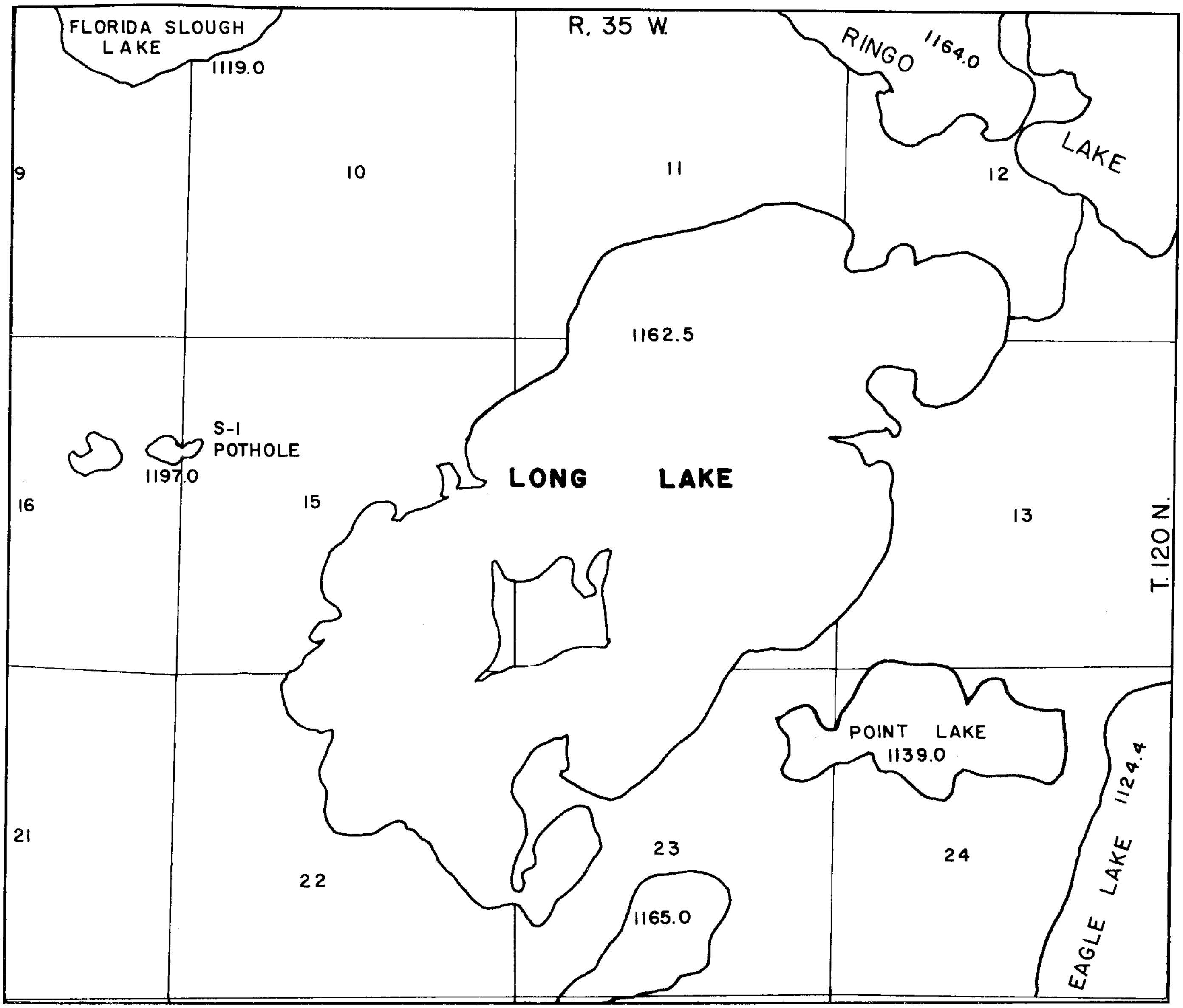

Figure 49. Map showing elevations of the water surfaces of lakes and ponds in part of the Solomon Lake Quadrangle.

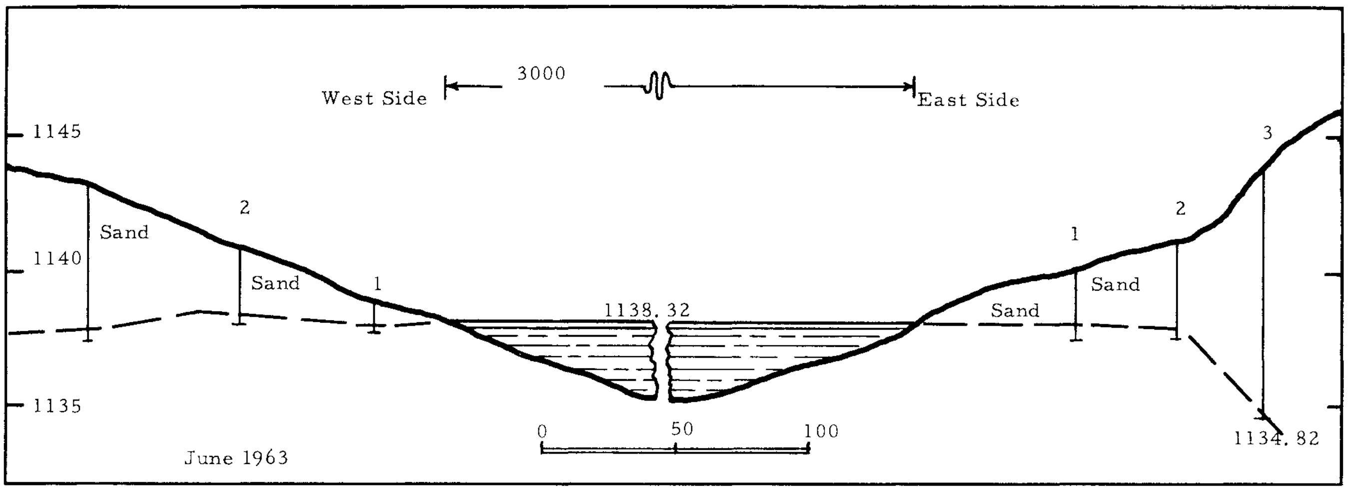

Figure 50. Cross-section showing test holes at Point Lake.

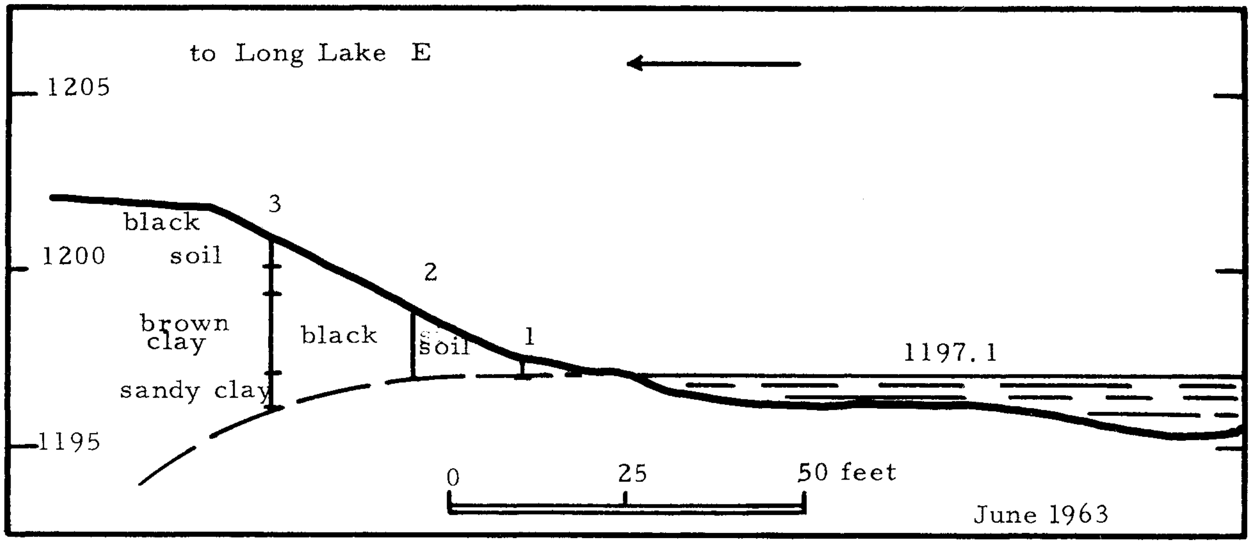

Figure 51. Cross-section showing test holes at So 1 pothole.

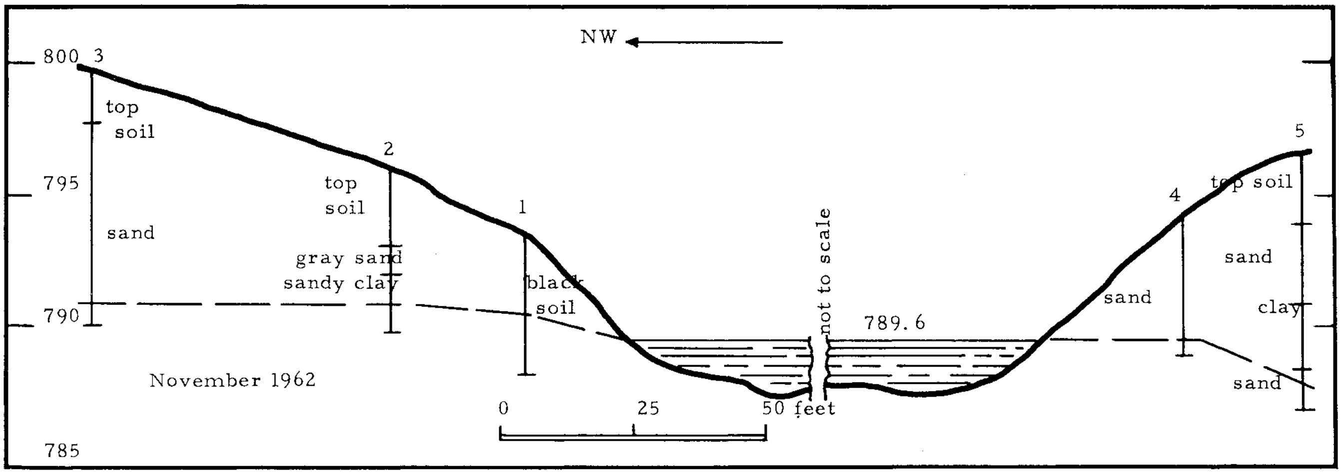

Figure 52. Cross-section showing test holes at Brown Lake (S.P. 1).

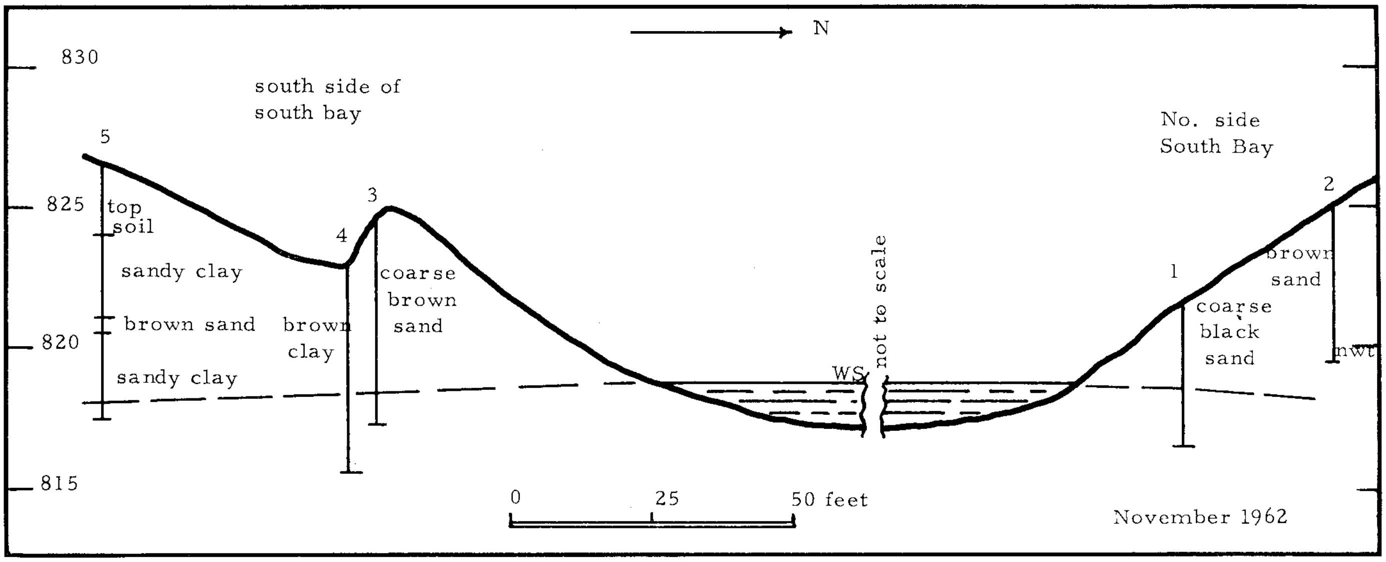

Figure 53. Cross-section showing test holes at Kehne Lake (S.P. 2).

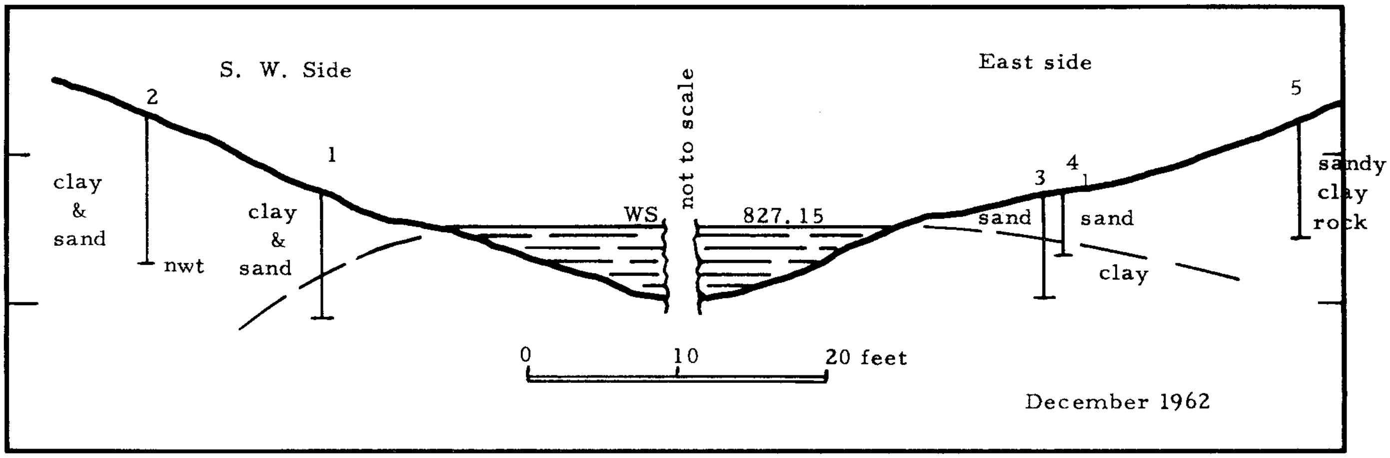

Figure 54. Cross-section showing test holes at Carlson Lake (S.P. 3).

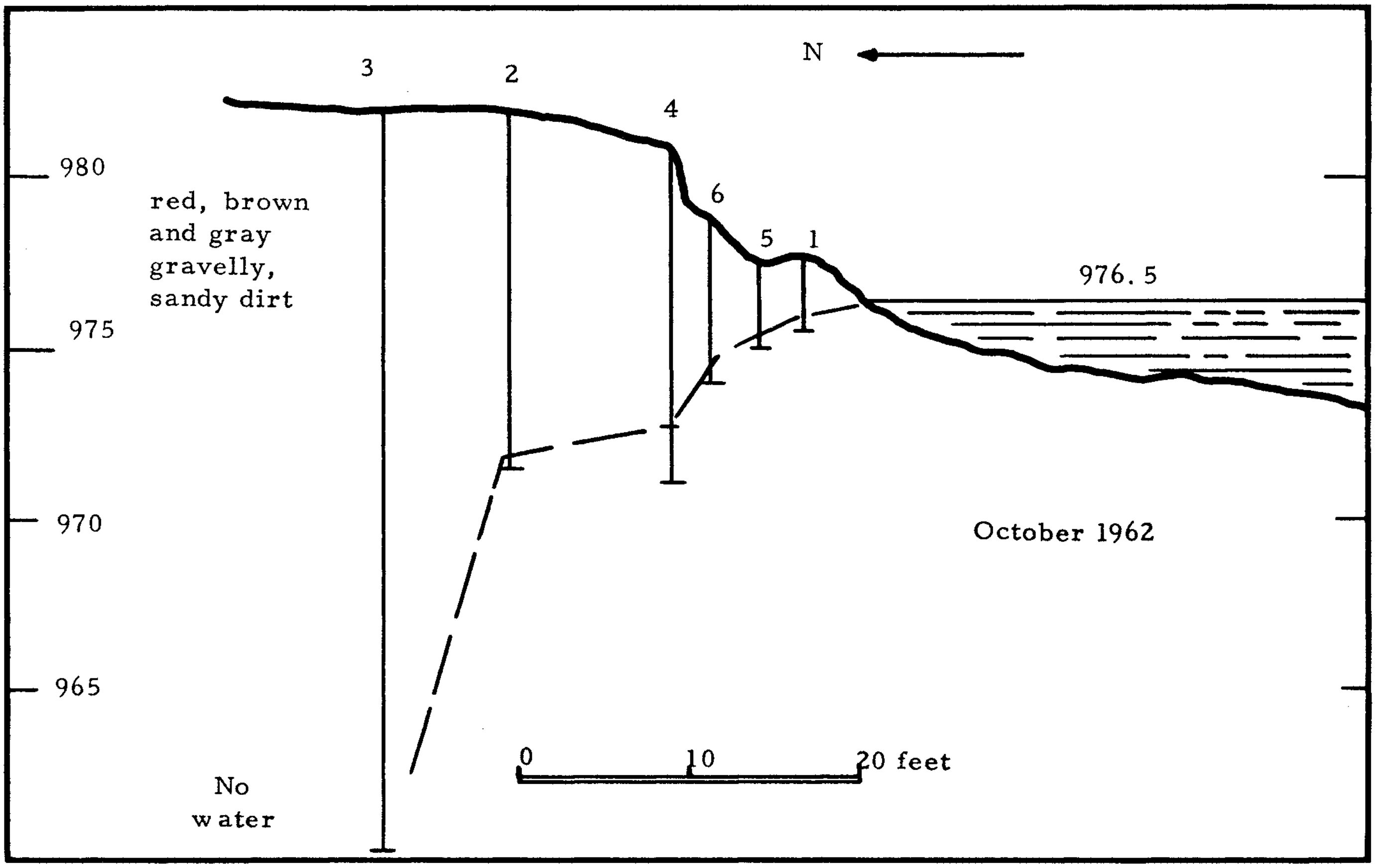

Figure 55. Cross-section showing test holes at Cleveland and Roselawn Pond (S.P. 4).

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