Hydrologic Investigations of Prairie Potholes in North Dakota, 1959–68

GEOLOGICAL SURVEY PROFESSIONAL PAPER 585-A

Prepared as part of the program of the U.S. Department of the Interior for the development of the Missouri River Basin

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Aerial view of prairie potholes on the Coteau du Missouri, May 1967. Water surfaces reflect the morning sun.

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By W. S. EISENLOHR, JR., *and others*

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PREFACE

This is the basic report on the Prairie Potholes Investigations of 1959–68. It contains the detailed descriptions of the potholes studied and of their setting and summarizes all the studies made as part of the total investigation. Thus, in this one report, all the significant results of the investigation are given.

At the start of the investigation, very little was known about the hydrology of prairie potholes. Immediate data on the amount of water lost from prairie potholes by evapotranspiration were needed. This phase of the investigation was given precedence, and results of it were presented by J. B. Shjeflo in 1968 in chapter B of this series. Chapter B also gives the most detailed description yet published of the instrumentation and computation procedures for using the mass-transfer principle to compute evapotranspiration losses.

As other hydrologic principles acting in and around the potholes were examined, many exploratory studies were made to ensure that all significant hydrologic factors were included in the investigation. Each study contributed to the total understanding of pothole hydrology. All this work is summarized in the present report, although the more important aspects of these studies are described in detail in other published reports.

The way in which vegetation affects transpiration rates and the method by which transpiration can be computed separately from evaporation are described in detail in papers by Eisenlohr, published in "Water Resources Research." C. E. Sloan gave a complete description of the ground-water studies in chapter C of this series. The detailed results from most of the other studies are contained in short papers published in "Geological Survey Research" and in technical journals, as noted throughout the text (and listed in "References").

Chapter D of this series presents the results of a study by R. E. Stewart and H. A. Kantrud, of the Bureau of Sport Fisheries and Wildlife, that calls attention to the importance of vegetation as an indicator of hydrologic conditions. Their report should have many practical applications.

Eisenlohr and Sloan have also published a generalized account of this investigation in Geological Survey Circular 558.

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HYDROLOGIC INVESTIGATIONS OF PRAIRIE POTHOLES IN NORTH DAKOTA, 1959–68

By W. S. EISENLOHR, JR., and others

ABSTRACT

A prairie pothole is a depression in the prairie, capable of storing water, that is the result of glacial processes. Years ago, there were many hundreds of thousands of prairie potholes in the North-Central United States, but large numbers of them have been drained for agricultural use. This report is limited to studies of prairie potholes in the eastern part of the glaciated northern Great Plains region in North Dakota—a rolling upland area covered with glacial drift, called the Coteau du Missouri. Potholes are wetlands that are the primary breeding area of migratory waterfowl in the United States. If production of waterfowl is to continue, suitable wetlands must be maintained, and even new wetlands created to offset those destroyed for agricultural use. The initial stage of the Garrison Diversion Unit calls for a normal annual diversion from Garrison Reservoir of 60,000 acre-feet of water for this purpose.

Many prairie potholes contain large amounts of emergent aquatic vegetation known as hydrophytes. Determining the loss of water by transpiration from emergent hydrophytes was one of the major objectives of the present study of the hydrology of prairie potholes. Other hydrologic factors were studied later, but the first part of the study was devoted almost exclusively to the determination of evaporation and transpiration losses at groups of potholes in Ward, Stutsman, and Dickey Counties. The mass-transfer method was used, and by determining the variation in the mass-transfer coefficient throughout a season, the losses by evaporation and transpiration were determined separately. Separate determinations were accomplished by relating the emergent height and the moisture content of the hydrophytes to the rate of transpiration, as determined by the mass-transfer coefficient.

Seasonal evaporation from the study potholes clear of vegetation was found to very nearly equal the generalized evaporation values published by the U.S. Weather Bureau. The effect of hydrophytes in potholes was twofold: their presence reduced evaporation from the water surfaces; and, at the height of the growing season, their transpiration rate, added to the reduced evaporation rate, frequently was greater than the evaporation rate from potholes clear of vegetation.

Net seepage outflow from potholes was generally very small—less than 0.01 foot per day per unit of water surface. This rate of seepage was not insignificant, however, because it often amounted to more than one-fourth of the total seasonal loss of water from a pothole.

The source of water supplying the evapotranspiration losses was primarily precipitation on the water surface of a pothole pond. Augmenting this supply was basin inflow—overland flow, flow in channels, and seepage inflow. Of these, overland flow was estimated to have been the largest by far; direct observations were not possible. Basin inflow was very erratic; it depended on combinations of events, such as antecedent soil moisture and rainfall intensity, or depth of snow at time of melting and concurrent rainfall. The occurrences of these combinations were such that, for a given season (October–March or April–September), the total basin inflow generally showed little relation to total precipitation. The greatest inflows were associated with late snowmelt flowing over frozen ground.

Following the evapotranspiration study, the effects of ground-water movement were investigated. All the study potholes were located in areas of glacial till in order to reduce the effect of seepage in the mass-transfer computations. Accordingly, ground-water movement was not a major factor in the water budget of the study potholes; however, it could be, in potholes located in areas of outwash sands and gravels, and in potholes in glacial till with only temporary ponds. Also, the direction of ground-water movement has a controlling effect on the water quality of a pothole pond. Where there is no seepage outflow or overflow, there is no mechanism for the removal of dissolved solids brought to the pond by basin inflow. Such potholes are saline—some even more so than sea water. Conversely, potholes that receive no seepage inflow generally contain fresh water and are usually not permanent. All conditions between these two extremes were found.

The permanence of water in a pothole (the extent to which the water body is permanent) and its quality were found to have a direct and significant relation to the species of vegetation that grows under those conditions. In fact, the species of vegetation are excellent indicators of water quality and permanence, and the report contains a table listing the com-

mon species used as indicators and the conditions that they indicate.

Many other facets of the hydrology of prairie potholes were investigated to ensure that no major factor was ignored, and the investigation results are described briefly.

INTRODUCTION

The prairie potholes have great economic significance in relation to the production of migratory waterfowl. Hunters pay more than $5 million annually in "duck" stamps alone, to hunt these birds. According to Smith, Stoudt, and Gollop (1964, p. 39), "The prairie pothole region makes up only 10 percent of the total waterfowl breeding area of this continent, yet it produces 50 percent of the duck crop in an average year—more than that in bumper years. This region covers about 300 thousand square miles in south-central Canada and north-central United States. It extends * * * across the border to include the western parts of Minnesota and South Dakota. There the Missouri River marks the western and southern border as it crosses western North Dakota and northern Montana * * *."

A prairie pothole is a depression in the prairie, capable of storing water, that is the result of glacial processes. According to Schrader (1955, p. 599), more than 660,000 potholes in North Dakota—and nearly as many in adjacent States—contain water in the spring of a normal year. (See frontispiece.) The name "prairie pothole" is unrelated to the specific geologic process by which it was formed. If a water body is larger than about a quarter of a square mile, the depression is not considered to be a prairie pothole; other than this, little more can be added to the definition. The modifier "prairie" should always be used (except to avoid undue repetition) to distinguish a prairie pothole from other kinds of potholes that are totally unrelated. The name is used extensively, both locally and in conservation literature. The name "slough" is commonly used in Canada for the same feature. In this report, the term "pond" refers to the water body in a prairie pothole and is used where it is desirable to distinguish between the two. Thus, when a prairie pothole goes dry, its pond disappears. The perimeter of a pond can be determined precisely, but the limit of a pothole—unless used as a synonym for the pond—is very vague and has no significance with respect to this study. The term "permanence" is used in this report as a measure of the degree to which a pond persists as a permanent water body.

This report describes studies in the eastern part of the region in North Dakota known as the glaciated part of the northern Great Plains physiographic province. This is a rolling upland area, covered with glacial drift, that is called the Coteau du Missouri.

The Coteau du Missouri (fig. 1) was defined by the U.S. Geographic Board (1933) as:

> A narrow plateau beginning in the northwest corner of North Dakota between Missouri River and River des Lacs and Souris River and running southeast and south, with its southern limit not well defined; and its western escarpment forming the bluffs of the Missouri.

Since then, many investigators (Winters, 1967) have sought to limit the extent of the feature called the Coteau du Missouri, or Missouri Coteau, as it is often called locally. The difficulty with other definitions is the lack of a suitable western boundary that is as well defined as the Missouri River. From hydrologic considerations, there is great merit in restricting the term to the eastern part of the area, which is covered with what is known geologically as collapsed or dead-ice moraine. This makes a relatively homogeneous hydrologic unit, and it is adequately delineated by Colton, Lemke and Lindvall (1963). (Fig. 9 shows virtually the same map.) The term "Coteau du Missouri" is therefore restricted to this area for use in this report.

The eastern part of the Coteau du Missouri as here defined has little or no integrated drainage systems and, thus, an almost complete absence of permanent streams. This region is also sparsely settled and has no large towns. These facts help to explain why, prior to this study, very little was known about the hydrology of the region. In the late 1950's, the need for more hydrologic information became apparent. Prairie potholes were being drained for agricultural use at an alarming rate, according to conservationists, who feared that continued drainage of these potholes would cause great depletions in the supply of migratory waterfowl as a result of the destruction of their breeding habitat. The impending Garrison Diversion Unit, which will eventually irrigate 1,007,000 acres [1] in the Dakotas by diverting water from Garrison Reservoir across the Coteau du Missouri, also threatened the destruction of additional waterfowl habitat. Therefore, that project includes a provision for creating new wetlands and enhancing existing wetlands, to compensate for those that will be destroyed. For this purpose, the initial stage of the Garrison Diversion Unit calls for a normal annual diversion from Garrison Reservoir of 60,000 acre-feet of water (U.S. Bureau

[1] U.S. Bureau of Reclamation, 1961, Project data book, Garrison Diversion Unit, p. 440.

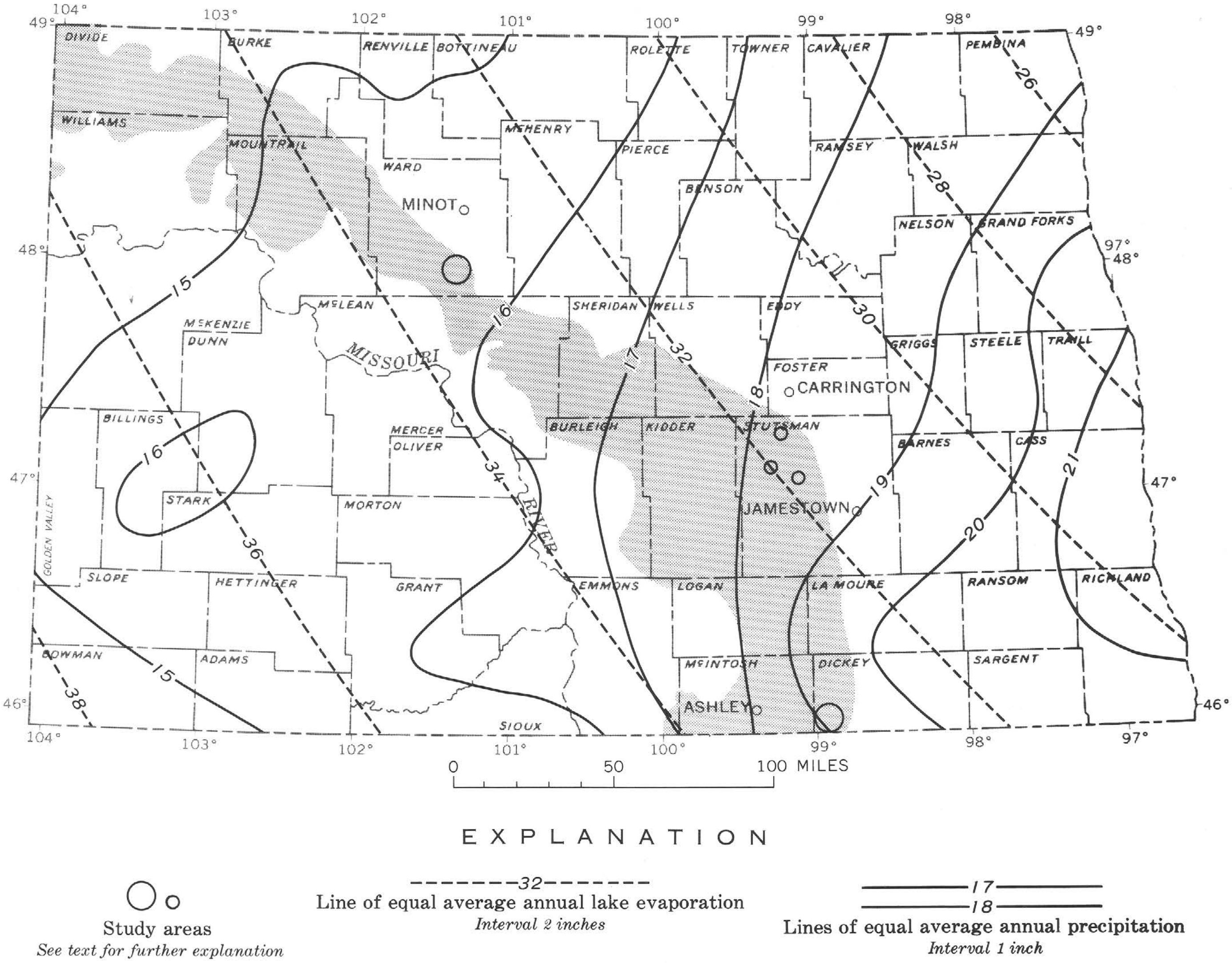


FIGURE 1.—Location of the Coteau du Missouri (shaded area), location of study areas (circles), average annual precipitation (data from the North Dakota State Water Conservation Comm.), and average annual lake evaporation (from Kohler and others, 1959).

of Reclamation, 1965, p. 7). Thus, the rate of water loss from prairie potholes is of economic significance.

Prairie potholes are individualistic. They can be classified in several ways by broad groups, but their individual characteristics make strict classification difficult. Furthermore, some of these characteristics change with changing hydrologic conditions, not only from year to year, but also within a year. Reasons for these individualistic and changing characteristics can generally be found in the hydrologic, geologic, topographic, and botanic factors that make up the environment, either natural or as modified by man. The relationships of potholes to these factors are summarized in this report.

The broad study of the hydrology of prairie potholes was under the technical supervision of G. Earl Harbeck, Jr., 1959–61, succeeded by William S. Eisenlohr, Jr., 1961–68. The evapotranspiration project was led by Jelmer B. Shjeflo, assisted by Roger A. Pewe, under the administrative direction of Harlan M. Erskine who first proposed the study and was largely responsible for its implementation. Early ground-water investigation, including consultation in the selection of potholes and the supervision of earth augering to explore subsurface materials, was done by Edward Bradley. The later ground-water project was led by Charles E. Sloan under the administrative direction of William S. Eisenlohr, Jr. Quentin F. Paulson succeeded Hans M. Jensen as consultant on the geologic and hydrologic aspects of the ground-water phases of the study. Special studies of the chemical quality of water were made (in order) by Hugh T. Mitten, Ben F. Leonard, Lester R. Petri, and James H. Ficken, and analyses of water samples were made in the U.S. Geological Survey's Lincoln, Nebr., laboratory, under the administrative supervision of Don M. Culbertson, followed by Kenneth A. MacKichan. Richard S. Aro and Lyle F. Lautenschlager made field studies of the vegetation, and Farrel A. Branson, acting as consulting botanist, made many professional contributions.

This report was prepared by the author from personal investigations, project data, and reports by other project personnel, as noted in the text. C. E. Sloan was especially helpful in this preparation, by compiling data and furnishing preliminary drafts of summaries of his work. The relation of this report to other reports resulting from this investigation is described in the "Preface."

Beginning in 1962, the U.S. Geological Survey worked in close collaboration with the research program of the Bureau of Sport Fisheries and Wildlife through the Northern Prairie Wildlife Research Center at Jamestown, N. Dak., Harvey K. Nelson, director. Robert E. Stewart, of that center, made botanic surveys for the study and furnished much useful data on aquatic vegetation.

Most of the aerial photographs of the prairie potholes and their surroundings shown in this report were taken by W. P. Sebens, executive secretary, North Dakota Soil Conservation Committee.

CHRONICLE OF THE STUDY

This study was begun as a result of the many questions that were being asked about the hydrology of prairie potholes. The most pressing question raised, because of the proposed Garrison Diversion Unit (p. A2) pertained to the rate of water loss from potholes as the result of evaporation, or evapotranspiration from potholes that are filled with emergent aquatic vegetation (fig. 2). A 5-year program of observations to answer this question was begun in 1959, when the first group of potholes was selected for study. The computations (Shjeflo, 1968) are for the growing seasons of 1960–64.

The potholes to be used in this program had to meet several requirements. The computation of

FIGURE 2.—Prairie pothole filled with emergent aquatic vegetation, Ward County, N. Dak. Instruments in foreground are for determining evapotranspiration.

evapotranspiration necessitated a complete determination of the water budget for each pothole. The selected potholes had to be both accessible and relatively unaffected by the activities of man. Some of the prairie potholes had to be those that were naturally filled with emergent aquatic vegetation, and others necessarily had to be those that were clear of vegetation. The pond in each pothole had to be as permanent as possible.

With many thousands of prairie potholes to choose from, the selection of study potholes presented a problem. Maps were of little use, other than to define likely pothole areas, and aerial reconnaissance was used to make initial selections of potholes. The search was then narrowed by making inspections on the ground, and final selection was made after drilling several test holes around each pothole to ensure that geologic conditions were favorable for low seepage rates. After considering several combinations, two groups of four potholes were chosen. In each group, one pond was clear of vegetation, and the other three ponds contained large stands of emergent aquatic vegetation. The first group (potholes 1–4), about 20 miles south of Minot, Ward County, was selected in the fall of 1959. A stilling well for the water-stage recorder was installed in each pond that winter (1960), while the ice cover was thick enough to support the material-handling equipment. A prospective group of potholes in Kidder County was rejected after test-hole drilling indicated unfavorable geologic conditions (fig. 3). The second group (potholes 5–8) was finally selected in July of 1960 in the extreme southwest corner of Dickey County. Stilling wells were installed in the banks of these potholes and were connected to the ponds with intake pipes. Instruments were not all installed until the following spring. Potholes 3 and 5 (fig. 4) were clear of vegetation.

These two groups of potholes were selected specifically for determining evaporation and transpiration losses (Shjeflo and others, 1962, p. 4) by a method (described on p. A57) that combines mass-transfer and water-budget techniques. This method is especially effective for water bodies, such as prairie potholes, in which evapotranspiration is the major factor causing a change in storage much of the time. All previous application of this method was work done on water bodies clear of vegetation and for which the coefficient was found to be a constant. In preparation for the present study, therefore, the possibility of a variable coefficient was given little thought. Instruments were selected on the basis that each computation period used in determining the coefficient would be of several days' duration so that the change in stage could be measured without appreciable error. Later, it was found that 6-hour computation periods had to be used, during which the change in stage was frequently so small that the water-stage recorder was barely adequate to measure the change. The diameters of the stilling wells prevented the substitution of larger diameter floats to increase the driving force on the water-stage recorder and, thus, the accuracy of the record.

Early in 1963, after more than 1 year of planning and reconnaissance, three new study areas were chosen in Stutsman County, and three additional potholes were selected for study in the Dickey County area. The areas in Stutsman County (fig. 1) were added to coordinate the research by the U.S. Geological Survey with that of the Bureau of Sport Fisheries and Wildlife; therefore, the numbering of potholes and the names of study areas in use by that Bureau were adopted by the Survey. The only change made in the numbering of potholes was the addition of an identifying letter for each area before the pothole number; "C" for Cottonwood Lake area, "M" for Mount Moriah area, and "W" for Woodworth area. As the potholes in the Woodworth area had not been numbered previously, those in which gages were installed were given numbers by the Survey. Staff gages (fig. 5) were placed in 14 potholes in the Mount Moriah area, four in the Cottonwood Lake area, and two in the Woodworth area. In addition, one pothole in the Cottonwood Lake area was equipped with instruments in the same manner as those in Ward and Dickey Counties. (For description, see p. A31.) A rain gage was also installed in each area.

The gages in Stutsman County were installed to determine the relative rates of water loss among the potholes. Assumption was made that evaporation rates would be about the same at all the study potholes, and that significant variations in water loss would be an index of the variations in seepage outflow. Such variations would aid in interpreting ground-water movement.

The three additional potholes in Dickey County were all very close to one already instrumented; hence, they were given the same number as the instrumented pothole plus an identifying letter. Pothole 5A is less than 100 feet from pothole 5, but it is filled with vegetation, whereas pothole 5 is clear. Pothole 5B is about 250 feet from pothole 5A and is at a much lower elevation. If pothole 5A

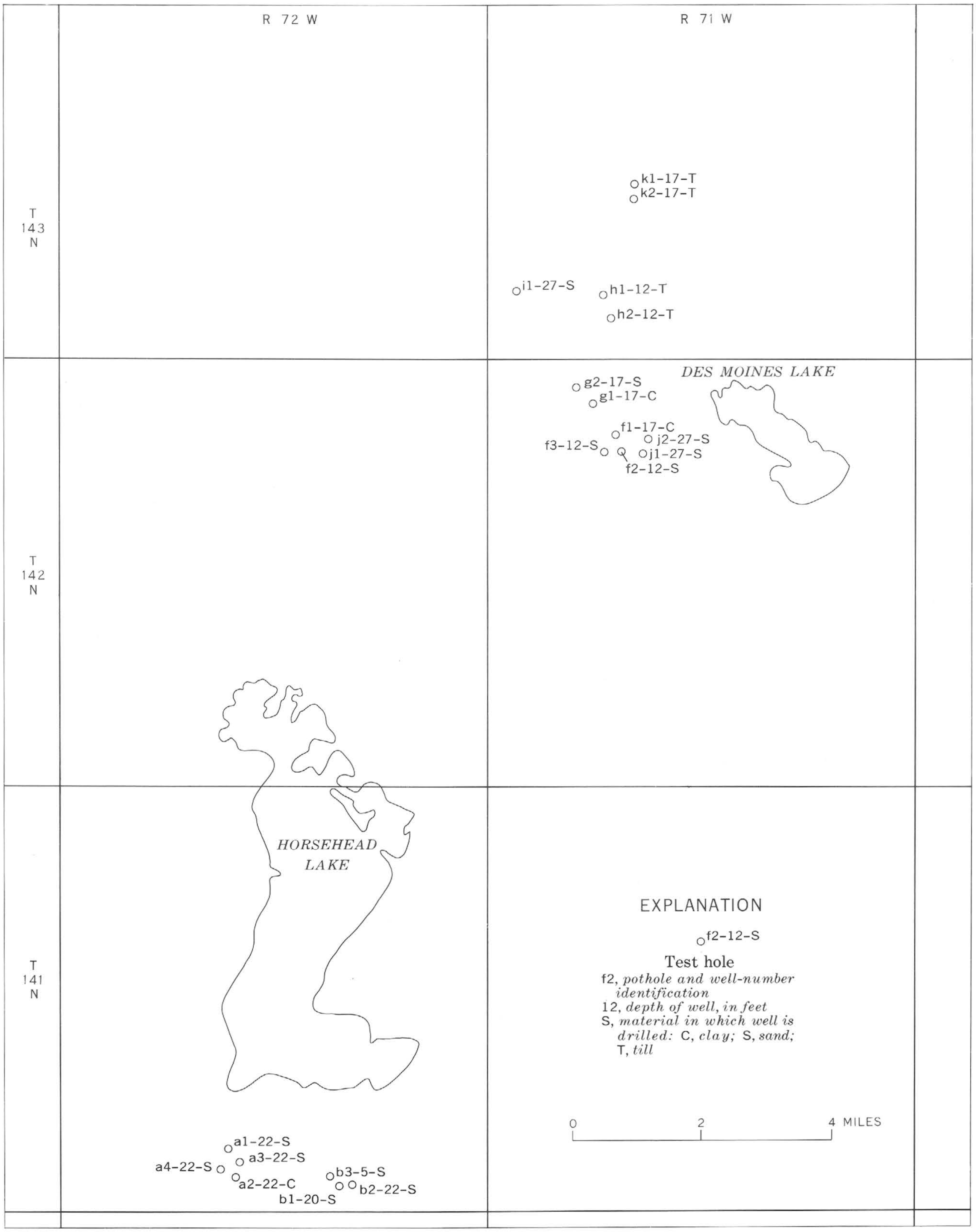


FIGURE 3.—Location of test holes in Kidder County.

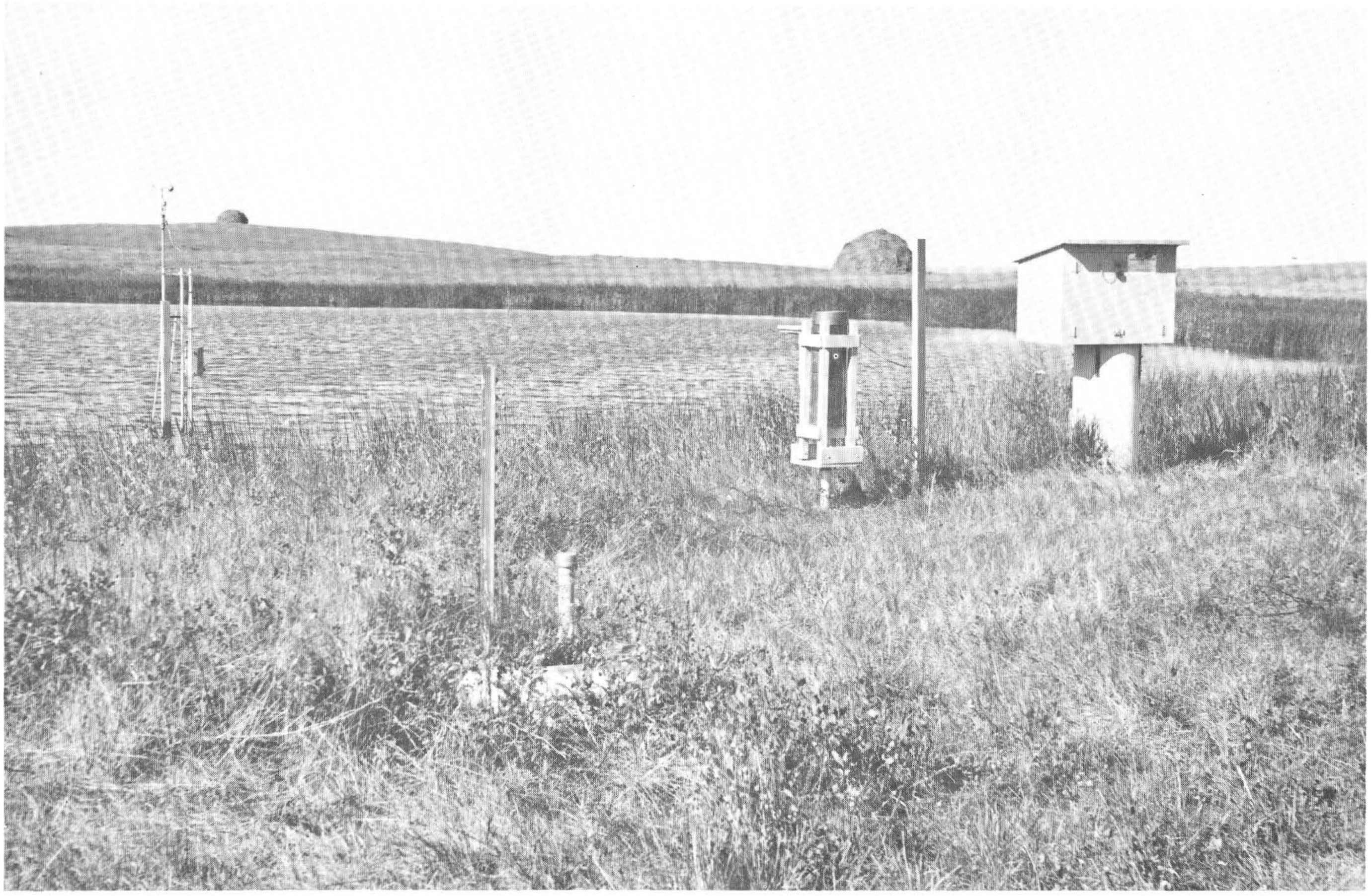


FIGURE 4.—Prairie pothole clear of vegetation, Dickey County. Instruments in foreground are for determining evaporation.

should overflow, it will drain into pothole 5B. The water in pothole 5B was much fresher than that in pothole 5, even though it was at a much lower elevation and only some 500 feet away. Pothole 6A was about 1,000 feet upstream from pothole 6.

These three additional potholes were selected to broaden the scope of the original study. They were particularly useful to the study in 1964, when high water levels interfered with the usefulness of potholes 6 and 7. Pothole 5A was used to supplement the vegetation studies in pothole 8, and the gage at pothole 6A proved to be useful in determining periods of possible overflow into pothole 6.

In 1963, with two full seasons of records collected, it became evident that evapotranspirtation could not be computed in the same manner that evaporation had been computed in other places. Although the volume per unit area of water surface could still be measured, the transpiration could not. Transpiration per unit area changed with the amount and activity of vegetation present. A new computation procedure was developed during the 1963–64 winter to take care of these variations in transpiration.

The following summer (1964), a botanist was employed on the project to make weekly observations of the vegetation. The observed data were used later to refine the computation procedures (Eisenlohr, 1966a). The work done in 1964 covered only the part of the season during which the vegetation grew to its maximum height and remained at maximum activity. It was not until the fall of 1966 that data were obtained to complete the analyses for the period during which the vegetation declined in activity. These studies showed that the estimated effects of vegetation, on which previous computations had been based, were sufficiently accurate for their intended purpose that no recomputations were warranted.

For the first 5 years of the study, most of the available funds were used to further the evapotranspiration project; hence, the studies of ground water and quality of water during this period were

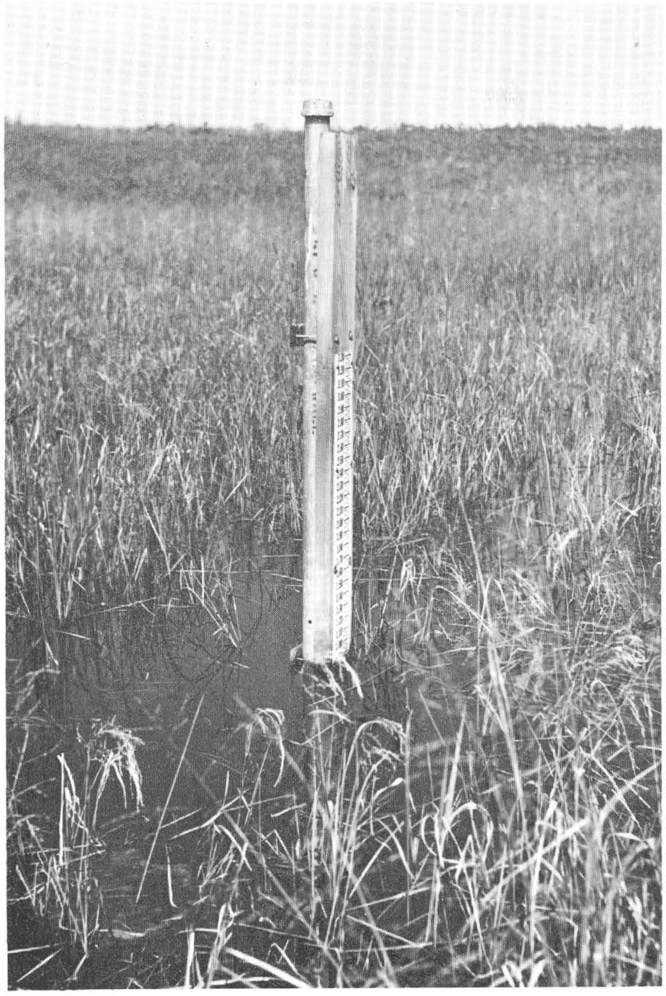


FIGURE 5.—Staff gage fastened to maximum-stage gage in pothole, Stutsman County.

very limited. Late in the summer of 1964, however, work on these two phases of the study was increased. At pothole C1, 40 observation wells were augered, not only to observe ground-water levels, but also to obtain samples of the well water for chemical analyses to determine whether changes in chemical quality would indicate the direction of ground-water movement. At several points, clusters of observation wells were installed, with each well finished at a different depth to determine the relation of hydraulic head to depth.

Originally, the evapotranspiration study had been scheduled to terminate at the end of the 1964 growing season, but, because the Dickey County potholes were not instrumented until the 1960 season was almost over, the instruments at all potholes were operated through the 1965 growing season. However, the heavy rains in 1964 and 1965 in Dickey County raised the water levels to their highest stages observed during the study. These high stages drowned the emergent vegetation in the potholes and caused the ponds in potholes 7 and 8 to coalesce with those in adjacent potholes, and produced extensive inflow and overflow at pothole 6. Thus, the Dickey County potholes (except for pothole 5) were no longer comparable with their previous condition, and the evaporation records for 1965 were not computed.

With the termination of fieldwork on the evapotranspiration project in 1965, a full-scale ground-water investigation was begun. Extensive augering of observation wells in the Mount Moriah area was done in the fall of that year, and much good information was obtained from these wells. The Mount Moriah area was chosen because of its preponderance of potholes—more than 100 potholes in 1 square mile. Regular observations of water levels in the observation wells were made until the spring of 1968. An inventory of all wells in a band across the Coteau du Missouri, extending from the vicinity of the Mount Moriah area southwestward to the Crystal Springs vicinity was made in 1967.

In 1967 an attempt was made to get some direct observations of seepage. A seepage meter was built to sample seepage rates at different places on a pothole bed. Construction of this seepage meter was based on the design described by McBirney (U.S. Bureau of Reclamation, 1961, p. 15), but it was modified in several ways to adapt it for use in a pond where change in stage was an important factor. Because seepage outflow rates were so low at the study potholes in North Dakota, another site was chosen. A prairie pothole was found in Minnesota where seepage rates were high enough that a prospect of success could reasonably be expected. An unanticipated difficulty arose, however, that could not be overcome. Whereas seepage rates measured in North Dakota were independent of the depth of water in the potholes, seepage rates at the Minnesota pothole were found to depend very much on the depth of water. Inasmuch as mass-transfer computations yield only average seepage rates, no way was found to compare the two methods of determining seepage. The work in Minnesota was benefited by services supplied as part of a prairie pothole investigation by the Agricultural Engineering Department, University of Minnesota, through the efforts of Prof. Evan R. Allred.

DESCRIPTION OF THE STUDY AREAS

Each study pothole was equipped with a water-stage recorder from which pond levels could be read to 0.001 foot, a tipping bucket rain gage that recorded each 0.1 inch of rain on one margin of the water-stage recorder chart, and an anemometer that recorded each 10 miles of wind movement on the other margin of the chart. A water-temperature recorder, from which the water-surface temperature could be read to 1°F, was installed close by. A recording hygrothermograph was installed near the center of each pothole group in Ward and Dickey Counties and at pothole C1 in the Cottonwood Lake area.

The stilling wells for the water-stage recorders in Ward County were erected in the potholes with access by an elevated walkway (fig. 2). The stilling wells in Dickey County were set in the bank and connected to the pothole by an intake pipe (fig. 4). Neither type was superior to the other. The Ward County installations were subject to large frost heave and did not settle back to a stable position until the end of May, about the same time that the intakes of the Dickey County installation were thawing out.

In addition to the foregoing instruments installed at all study potholes, thermistor probes were placed in potholes C1, 5, 5A, and 6, and in the ground near the gage shelter at C1. The probes consisted of four thermistors spaced 0.75 foot apart and encapsulated in a length of garden hose (fig. 6). The thermistors were protected by plastic and inserted in 0.22-caliber cartridge cases, the bases of which were flush with the outside of the hose. Complete readings of the thermistors were given by Shjeflo (1968, p. B11). The thermistors were installed to help determine when the ground thawed in the spring, and to aid in determining the effect of viscosity on seepage rates. No conclusive information on these subjects was obtained, but it was noted that the greater the depth below ground surface, the greater the lag in response to the seasonal changes in air temperatures. The thermistors also

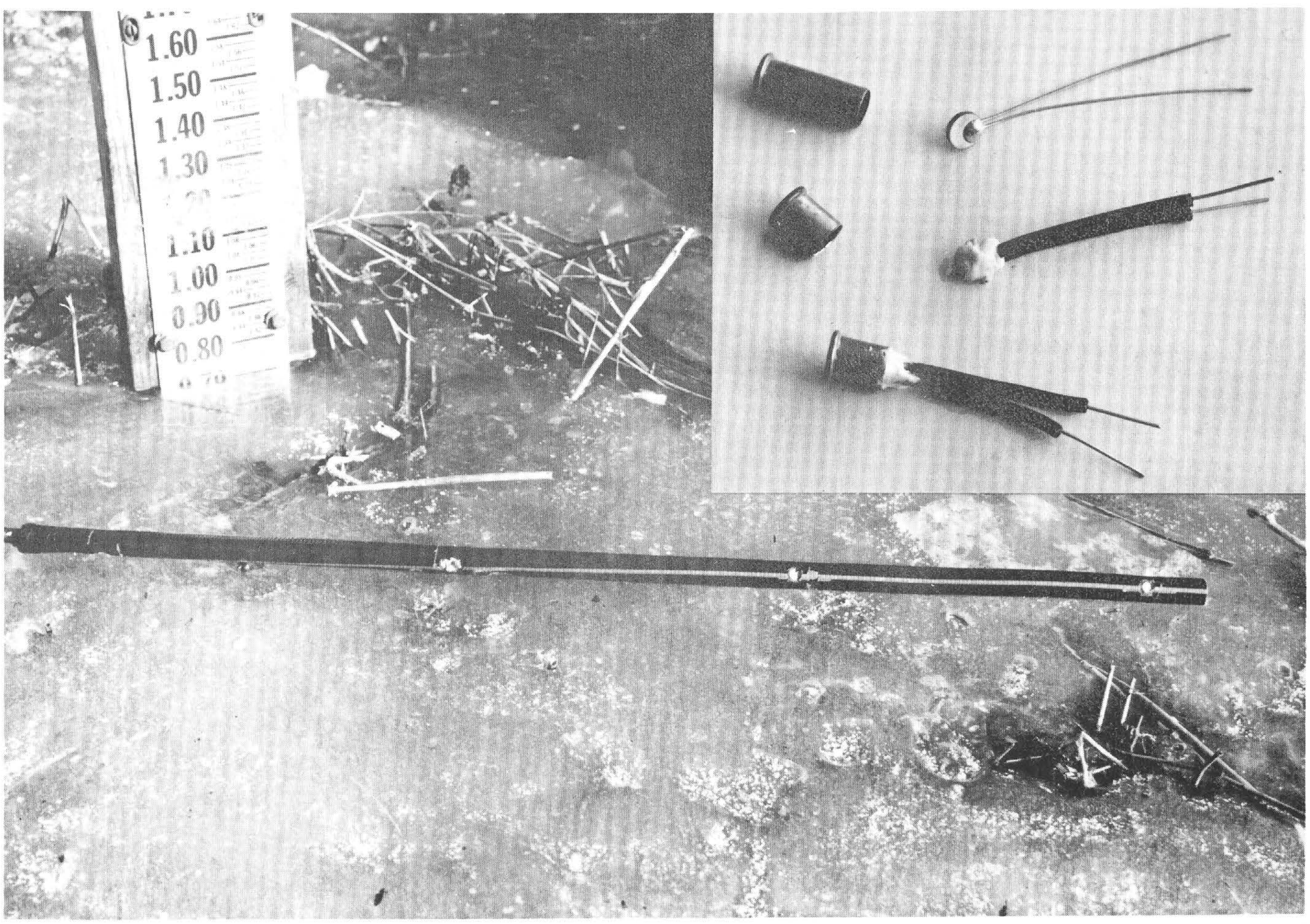


FIGURE 6.—Thermistor probe at pothole 5A in Dickey County. Probe was later inserted in nearby augered hole. Line through thermistors is a color stripe on hose. Steps in preparing thermistors for assembly in probe are shown in inset.

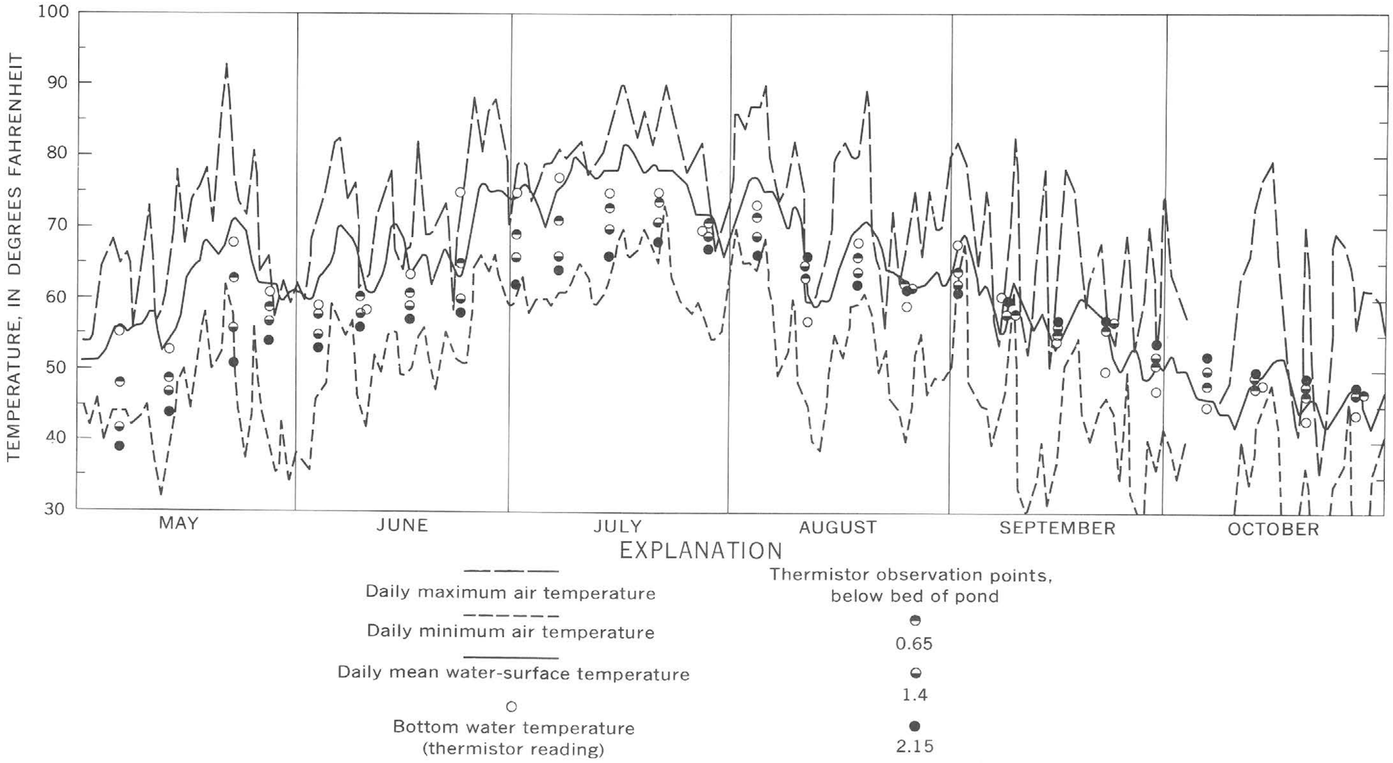


FIGURE 7.—Temperatures at pothole 5, 1964, Dickey County.

indicated that the ground thaws earlier in the season than other evidence had led the field men to believe.

The variations in temperatures at pothole 5 in 1964 (fig. 7) are believed to be typical of most of the potholes. Water-temperature surveys of the Ward and Dickey County potholes, made in August 1962, show a range in temperature within some ponds of as much as 10°F, but the distribution of these temperatures was such that the values from the temperature recorders are believed to give a reasonable average.

Potholes 1, 2, 4, 6, 7, and 8 were filled with vegetation, mostly hydrophytes of *Scirpus, Typha, Scolochloa,* and *Carex* genera, rooted in the bottom of the pothole, and emerging from the water surface to heights that for the taller species, may be as much as 6 feet. The vegetation ranged in density from 0 to more than 30 stems per square foot. In each of these potholes, two "vegetation gages" were installed (fig. 16). These height gages were simply vertical boards on which each foot of measure was painted alternately black and white. The top of each gage was set at 10 feet in Ward County and at 12 feet in Dickey County, pothole-gage datum. Every month, color photographs were taken of the vegetation surrounding each gage. The purpose was to record the height of vegetation. It was found, however, that the tops of the plants tended to bend over, so their heights could not be determined with sufficient accuracy for use in any correlation.

Several test holes were drilled in Ward and Dickey County near each study pothole to determine the subsurface geologic conditions. One of the test holes was cased and used as a ground-water observation well. An additional observation well was constructed in each of potholes 1, 2, 4, 7, and 8 when they went dry in 1961.

In the Mount Moriah and Cottonwood Lake areas (Stutsman County), 28 and 40 observation wells, respectively, were augered to help determine the nature of the water table and the ground-water-flow systems surrounding the potholes.

One of the basic objectives of the study was to determine the effect of vegetation in potholes on the rate of water loss. This was accomplished (without making use of the vegetation gages) by the method described in the section entitled "Effect of Vegetation on Evapotranspiration." To a much greater extent than was anticipated by Aro and Culbertson (Shjeflo and others, 1962, p. 7), vegetation was found to be very responsive to the effects of depth and quality of water on its environment. So much so, in fact, that the different species growing in these potholes can be used as indicators of the current hydrologic conditions in the ponds (mainly in relation to water quality) or of hydrologic conditions that existed within the past few months or years (mostly in relation to water depth and permanence). Because vegetative species are, thus, so important to the hydrology, tables listing the species commonly present in the individual potholes are given for each study group. The data for the tables were furnished by Robert E. Stewart, wildlife biologist, Bureau of Sport Fisheries and Wildlife. The usefulness of the tables is explained by Stewart and Kantrud (1971). The several zones used for each pothole at each time of mapping are used only to group those species found growing under similar conditions at that particular time and place.

Contour maps, on which the tables of area and capacity are based, are given in chapter B of this series (Shjeflo, 1968). The relation between each pothole and its drainage basin is shown on the maps contained in the present report. The broken lines delineating the drainage basins show the transit surveys along the drainage divides. All significant changes in direction are shown, and the straight lines were selected in the field to balance the areas inside and outside the basin. Errors in delineating the areas are believed to be approximately 1 percent.

The study potholes are in collapsed moraine consisting of glacial till, except for those in the Woodworth area in Stutsman County, where collapsed glacial outwash underlies most of the study area. Soils maps prepared by the Soil Conservation Service for the study areas show the soils to be the types that develop over glacial till. Differences in the soils result from slope variations that facilitate the removal or accumulation of the soil or that influence the degree of drainage in those soils subject to ponding. Test drilling, geologic reconnaissance, and mapping of soils all show the glacial deposits in the vicinity of the study potholes to be made up predominantly of glacial till.

Included in, and associated with, the glacial till are minor amounts of stratified or interlayered beds or lenses of silt, sand, and gravel.

The soils that develop on glacial till on the Coteau du Missouri are permeable and have a high infiltration and storage capacity. Soils that develop on glacial outwash are even more permeable and are areas of low runoff. Fluvial erosion is generally lacking on the Coteau. Thus, sedimentation rates have been very low in the potholes, and the landscape has been little modified since the stagnant glacial ice melted (Eisenlohr, 1969c, p. 62). The relative youth of the landscape and the geologically short time since the glaciers melted account, in part, for the lack of erosion; however, this is true only of the areas of uncultivated prairie. Where the prairies are farmed, significant erosion occurs during each heavy storm. All the study potholes were separated from any cultivated field by 100 feet or more of grassland, and no significant sedimentation was noted at any of the potholes during the study. C. E. Sloan observed that, although the drainage basins have been only slightly modified by erosion and creep, the pothole basins have undergone comparatively extensive modification by wave action. Modification of the pothole basins is due to the winnowing action of waves, which removes the finer sediment particles (the size of silt, clay, and fine sand) from the peripheral beach areas and carries these fines toward the center of the potholes. Remaining in the peripheral beach zone of most of the potholes large enough to sustain wave action is a residual deposit of sand and gravel and even some boulders (fig. 8). During development of this wave-cut platform, or residual deposit, a distinct nick-point, or change in slope, was formed at the strand line or high-water mark between the steeper, upland slopes and the gentle slopes of the beach area.

GEOLOGY

The rock formations in the study areas consist of glacial drift, underlain by the Tongue River Member of the Fort Union Formation of Tertiary age in

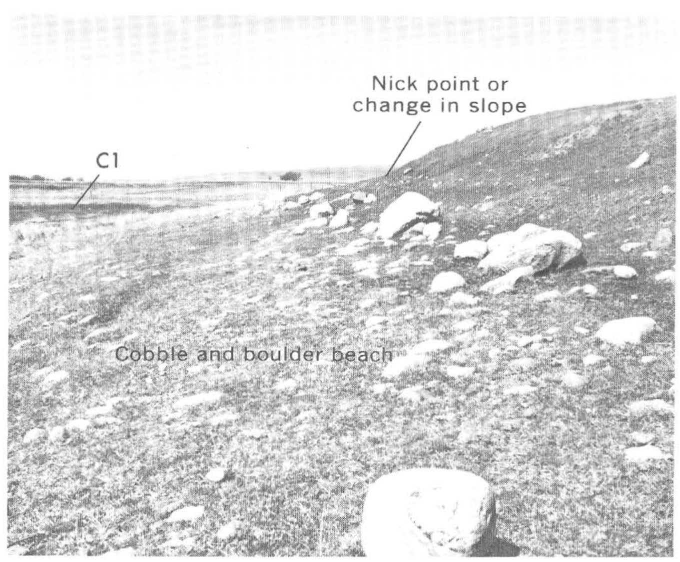


FIGURE 8.—Wave-cut platform at pothole C1, Stutsman County.

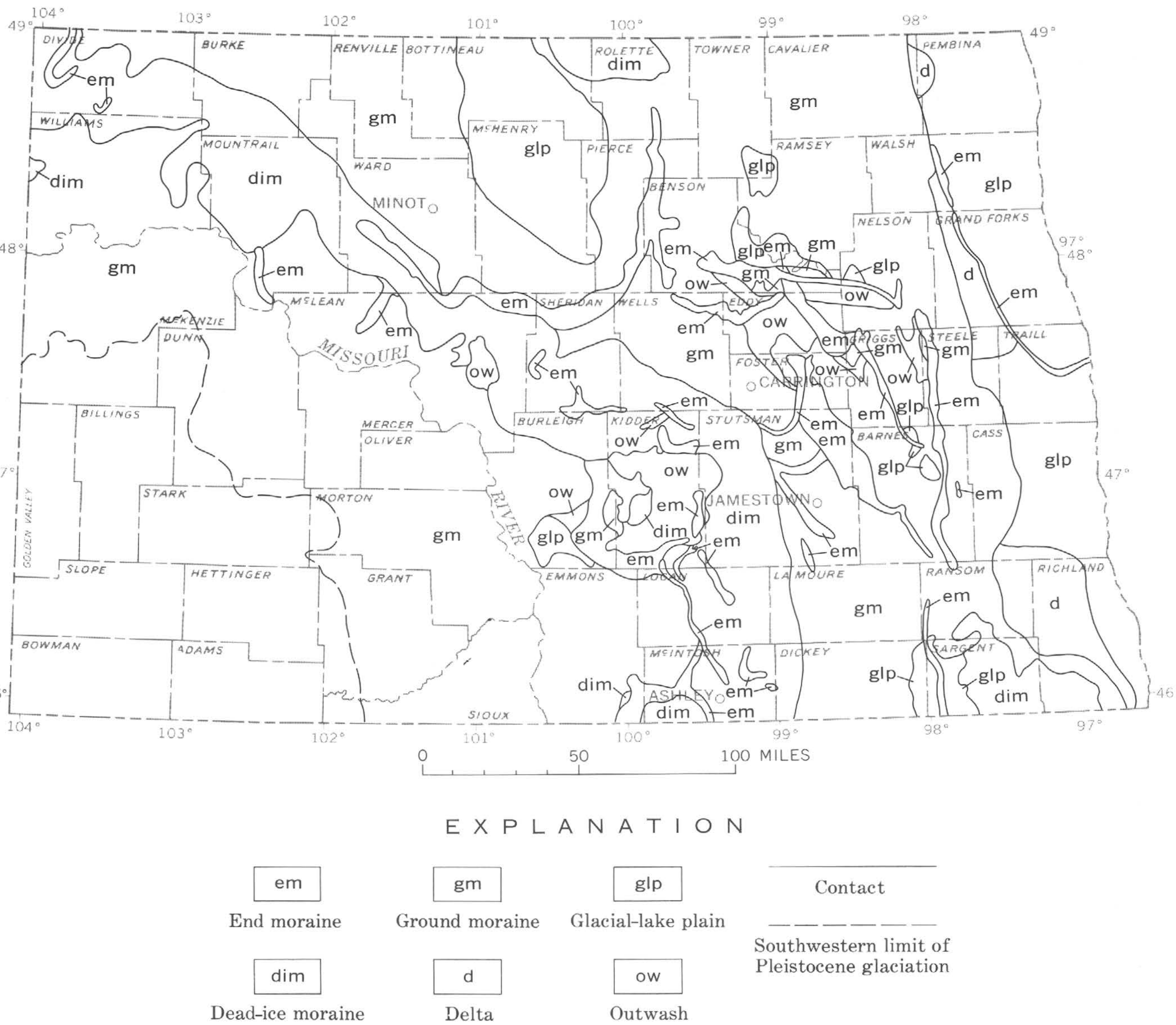


FIGURE 9.—Generalized glacial map of North Dakota. (Data from North Dakota Geol. Survey Misc. Map 9.)

Ward County, and by the Pierre Shale of Cretaceous age in Stutsman and Dickey Counties (figs. 9, 10).

"Glacial drift" (or "drift") is the general term used to describe all deposits of glacial origin. It is composed of any rock material transported by a glacier and deposited by (or from) the ice or transported in or by water from the melting of the ice (American Geological Institute, 1957). Till refers to nonsorted, nonstratified sediment deposited by the ice (American Geological Institute, 1957). Drift has often been sorted by melt water into deposits of gravel or sand; the most common of these deposits are known as outwash deposits. The finer grained materials are generally deposited in melt-water lakes and are known as lacustrine deposits.

The northeast-facing escarpment of the Coteau du Missouri rises 300 to 500 feet above the adjacent Central Lowland physiographic province. The Coteau du Missouri, in many places, owes much of its prominence to the topographically high underlying bedrock, which acted as a buttress against the advancing ice sheets and, thus, influenced the areal distribution and landform characteristics of the drift deposited on and beyond it (Lemke and Colton, 1958, p. 42).

About 90 percent of the Coteau du Missouri is covered with a type of drift known as dead-ice moraine, composed of till which consists of about equal parts of sand, silt, and clay, plus a small percentage of gravel. The clay-size fraction is domi-

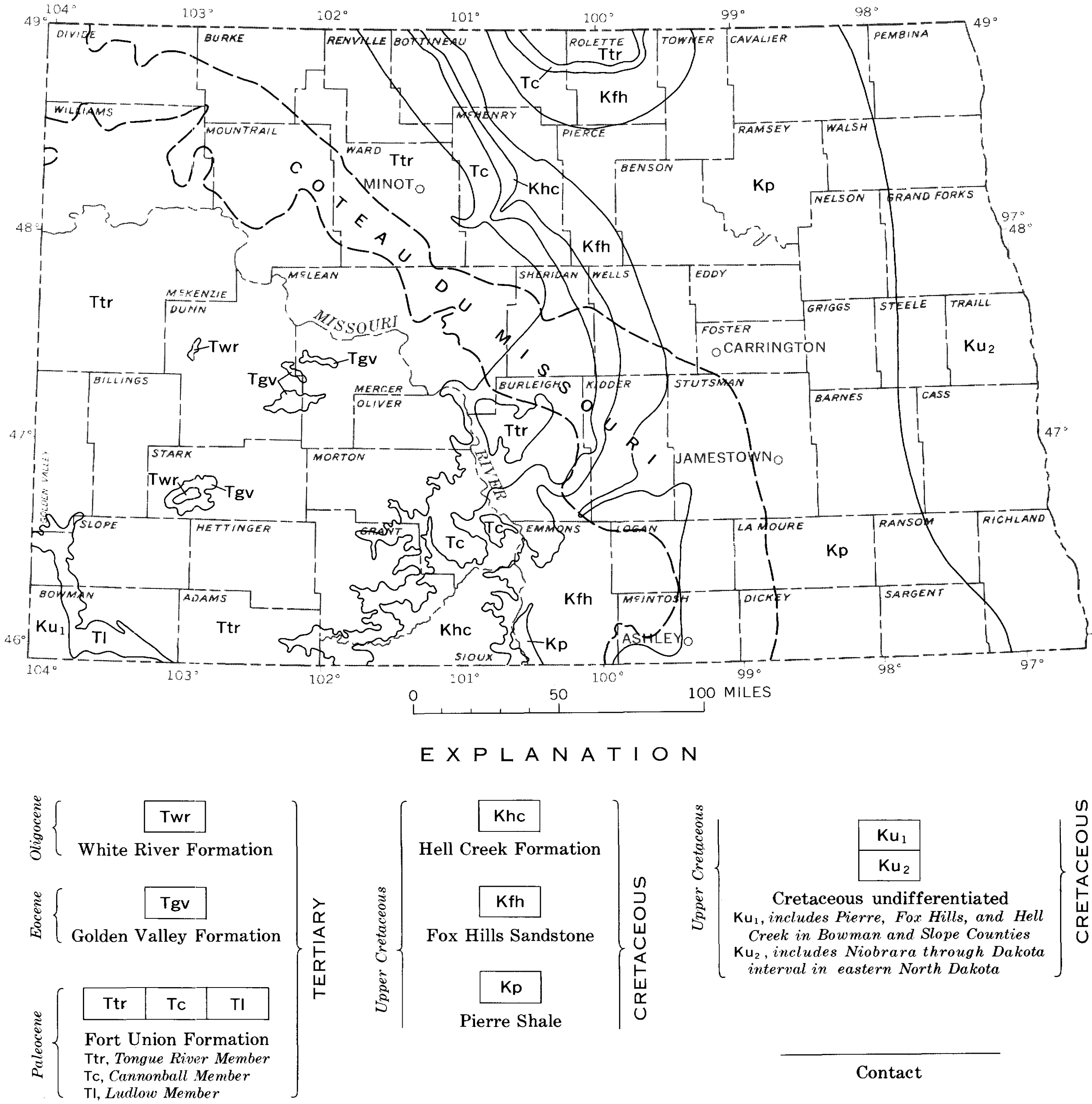


FIGURE 10.—Generalized bedrock map of North Dakota. (Data from North Dakota Geol. Survey Misc. Map 8.)

nantly montmorillonite (Clayton, 1967, p. 28–29). Other types of drift, such as end moraines, outwash deposits, and lacustrine deposits, are present on the Coteau but generally are not found in the study areas.

Dead-ice moraine is also known as stagnation or collapsed moraine (Colton and others, 1963). These latter terms seem to be more descriptive. As described by Clayton (1967), the glaciers on the Coteau du Missouri are believed to have remained after the northward retreat of the ice sheets because they were insulated by drift on the surface of the ice. As this ice melted over a period of about 3,000 years, the drift slumped or flowed to lower areas on the ice. Ice in these low areas, insulated by a thick layer of drift, melted more slowly, whereas the higher, newly exposed ice melted more rapidly. Thus, there were continuous inversions of the topography of the glacier, resulting finally in the hummocky topography so characteristic of the collapsed moraine deposits on the Coteau today.

The fine-grained material in the till is believed to have been derived from the local bedrock, although the larger rocks are thought to have been transported from Canada by the glaciers (Lemke, 1960, p. 53).

The till deposits in the study areas are believed to be at least 100 feet thick, and in several places may be several hundred feet thick. Soils that have developed on the till are very permeable, probably as a result of prairie grasses that develop root systems more than 3 feet deep (Lorenz and Rogler, 1967). The till itself is very permeable because of numerous joints, or cracks (Williams and Farvolden, 1967). According to Lemke, these joints can be 30 to 40 feet deep; they commonly produce columns whose cross section is about the same size and shape as the familiar mud plates in the dried sediments of a lake bed (fig. 16) (R. W. Lemke, oral commun., 1970). The ability of the joints in the till to store water is very great.

The wells augered in the Mount Moriah area ranged in depth from 14 to 67 feet, and averaged about 24 feet deep. Detailed descriptions and logs of some of these wells are given in the general description of the Mount Moriah area.

CLIMATE

The Great Plains of North Dakota are climatically dry subhumid to semiarid (Thornthwaite, 1941, pl. 3). Average annual precipitation ranges from about 21 inches in the southeast to less than 15 inches in the western part of the State (fig. 1). Generally, more than 75 percent of the annual precipitation falls during the warm season, April–September (Bavendick, 1941, p. 1053; fig. 11, present report). The average annual lake evaporation ranges from 26 inches in the northeast to 38 inches in the southwest corner of the State (fig. 1).

The permanence of ponds in prairie potholes, in a broad sense, is the result of the relation between precipitation and evaporation rates. These are the basic sources of inflow and outflow, respectively. The precipitation-evaporation ratio is given in figure 12, which shows that in the study areas the ratio ranged from less than 0.5 in Ward County to slightly less than 0.6 in Dickey County. This explains why, throughout our study, the potholes in Ward County generally contained less water than those in Dickey County. Because annual precipitation, on the average, is less than 60 percent of the

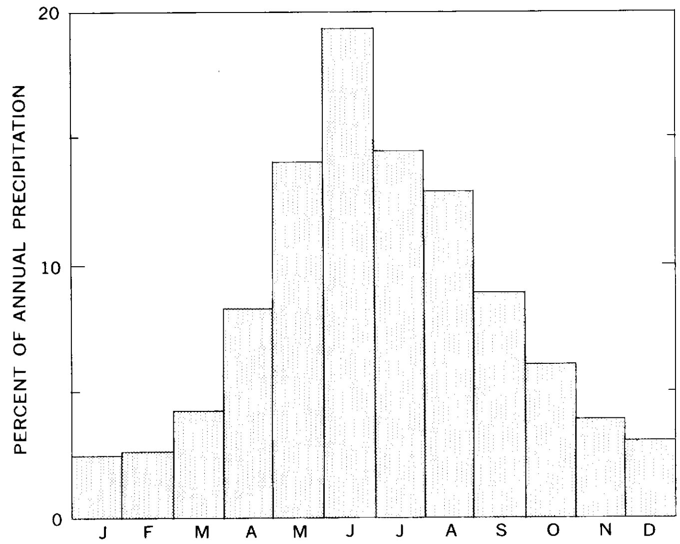


FIGURE 11.—Average monthly distribution of precipation for stations shown in figure 13. (From data compiled by Bavendick, 1941.)

annual evaporation, there is a strong tendency for ponds to disappear during those years when precipitation occurs only as scattered light storms. The difference between precipitation and evaporation is not so great, however, but that a wet year, during which precipitation is concentrated in a few intense storms and (or) the snowmelt runoff is heavy, can assure the persistence of pothole ponds for several years.

In 1950, as the result of the late melting of an abnormally heavy accumulation of snow during the winter, the potholes were reported to have filled with water to record-high stages. It is probable that these high stages provided extra carryover storage, so that at the start of this project in 1960, there were numerous potholes that had not yet gone dry since 1950. The following year, 1961, was a drought year, during which all but three of the eight study potholes became dry, some of them by early summer. Heavy summer rains in 1964 and 1965 raised water levels in the potholes, but in Ward County, the high stages of 1960 were not reached again during the study period (1960–64).

Long-term records show that annual precipitation has varied considerably from year to year at the four selected precipitation stations, as shown in figure 13. These stations were selected because of their long records and their proximity to the study potholes. Precipitation recorded in the highest year (fig. 13) is shown to be more than four times that recorded in the lowest year. However, as explained in the section "Variability of Water Supply," high

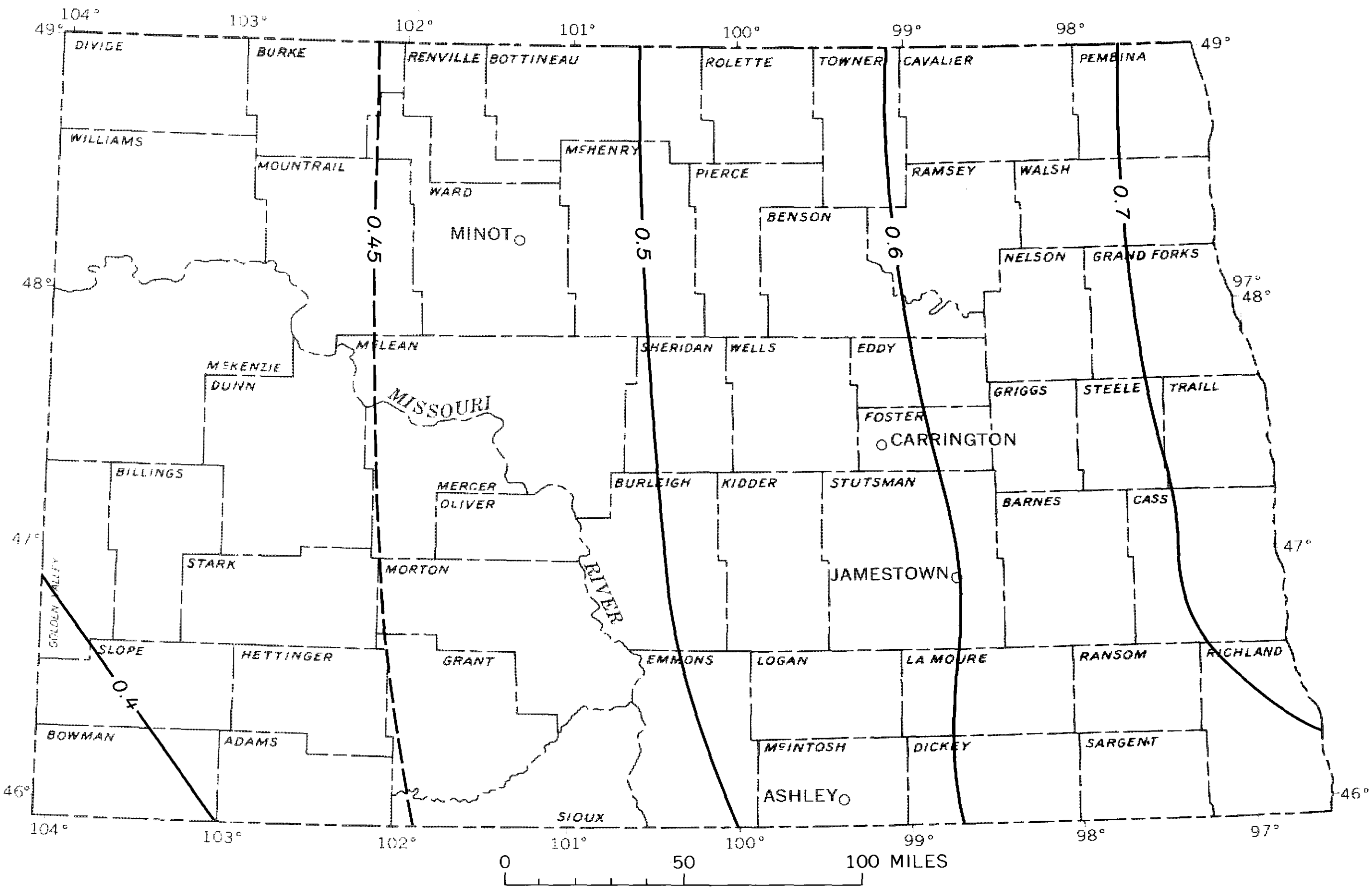


FIGURE 12.—Ratio of average annual precipitation to average annual evaporation, based on data in figure 1.

annual precipitation may not contribute any more to the water supply of a pothole than does precipitation that is only normal.

A partial explanation for such a phenomenomenon may lie in the fact that so much of the precipitation falls at times when the ground is unfrozen and the evapotranspiration losses are at their highest (fig. 11). There is, thus, ample opportunity for precipitation to be absorbed or dissipated rather than to become basin inflow.

Wind is an important climatic factor affecting evapotranspiration. Prevailing winds are from the northwest, and the average annual wind speed can be understood better when it is realized that the average wind speed of 10 miles per hour is the result of sustained strong breezes rather than occasional gales. At the potholes, winds of 25 to 30 miles per hour often last for 6 hours and have been known to last for as much as 15 hours. Winds of more than 30 miles per hour have been observed to last for more than 6 hours.

Temperature extremes range from below —40°F to more than 110°F. The average July temperature in the study areas is about 69°F. The daily range in air and water temperatures is rather large. Air temperatures often fluctuate as much as 30°F during a 24-hour period, and water-surface temperatures, as much as 20°F. Maximum water-surface temperatures tend to reach, and occasionally exceed, maximum air temperatures (fig. 7). Because water temperatures do not drop as low as the air temperatures during the night, the daily average water temperatures are generally higher than the air temperatures, sometimes by as much as 10°F or more.

The growing season for vegetation in the study potholes is short. The average number of days without killing frost is about 120—usually covering the period May 20 to September 20 (Bavendick, 1941, p. 1053).

The open-water season in a pothole is much longer than the growing season. The ice cover is generally melted by the second week in April, and it does not form again until early November.

Frost in the ground, however, persists beyond the last killing frost, usually lasting until the end of May. This conclusion is based on the observations

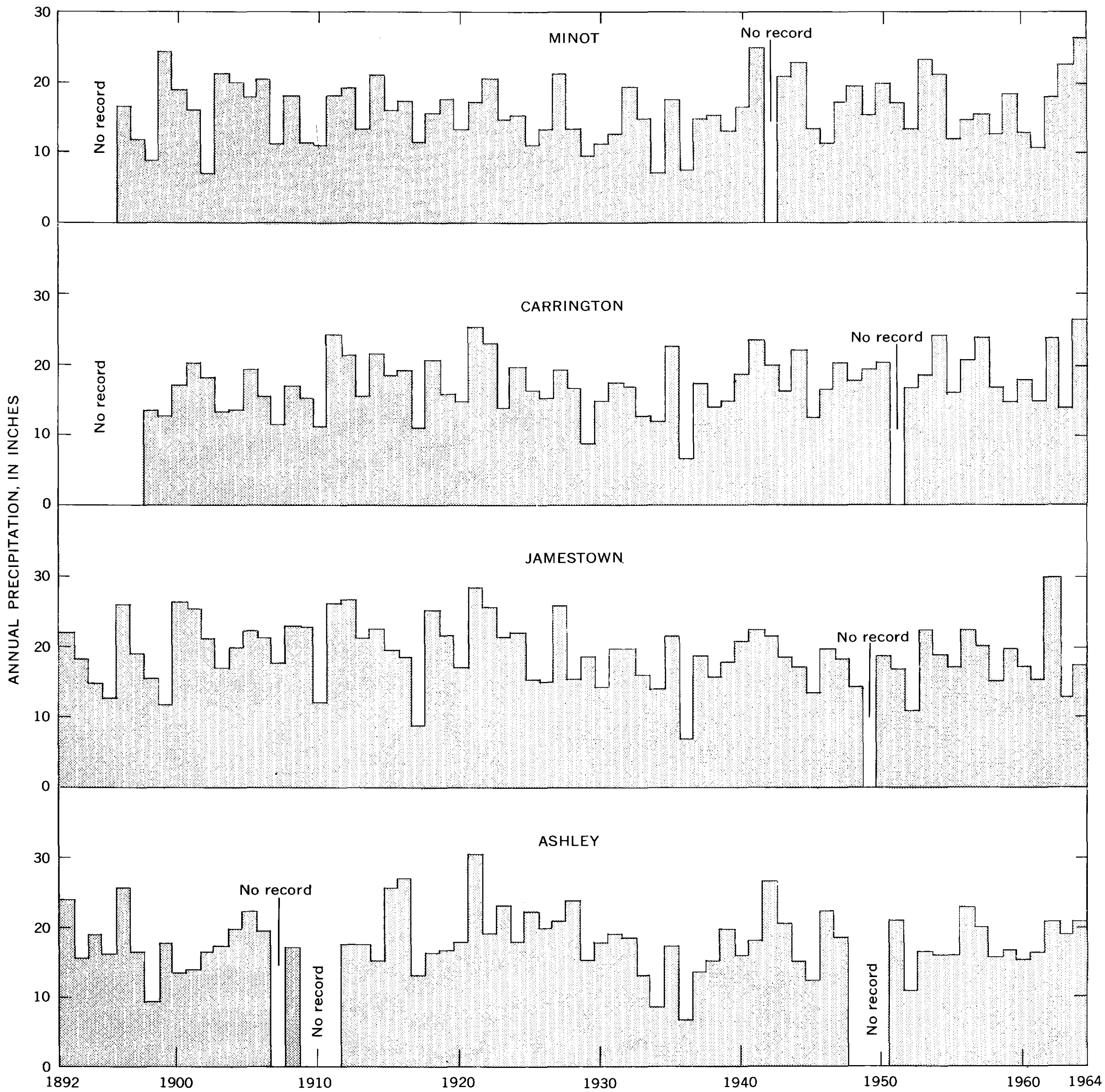


FIGURE 13.—Annual precipitation at four selected stations, 1892–1964.

of the technician who serviced the instruments installed at the potholes. Frequently in May and occasionally in June, he found ice in both the gage and observation wells and found the ground under the potholes to be frozen.

WARD COUNTY AREA

The locations of the four study potholes in the Ward County area are shown in figure 14. Their areas and capacities are given in table 1. The maximum stages at all four potholes were those occurring at the start of the project in the spring of 1960, and they were never again reached during the study period 1960–64.[2] The vegetation species that were

[2] Snow cover in the winter of 1969 was exceptionally heavy, with the result that total inflows to the potholes were far greater than those which occurred during the study period. The stages reaches in early May 1969 in relation to maximum stages that occurred during the study period 1960–64 were as follows: Pothole 1, +0.2 ft; pothole 2, −0.7 ft; pothole 3, −2.1 ft; and pothole 4, +0.4 ft.

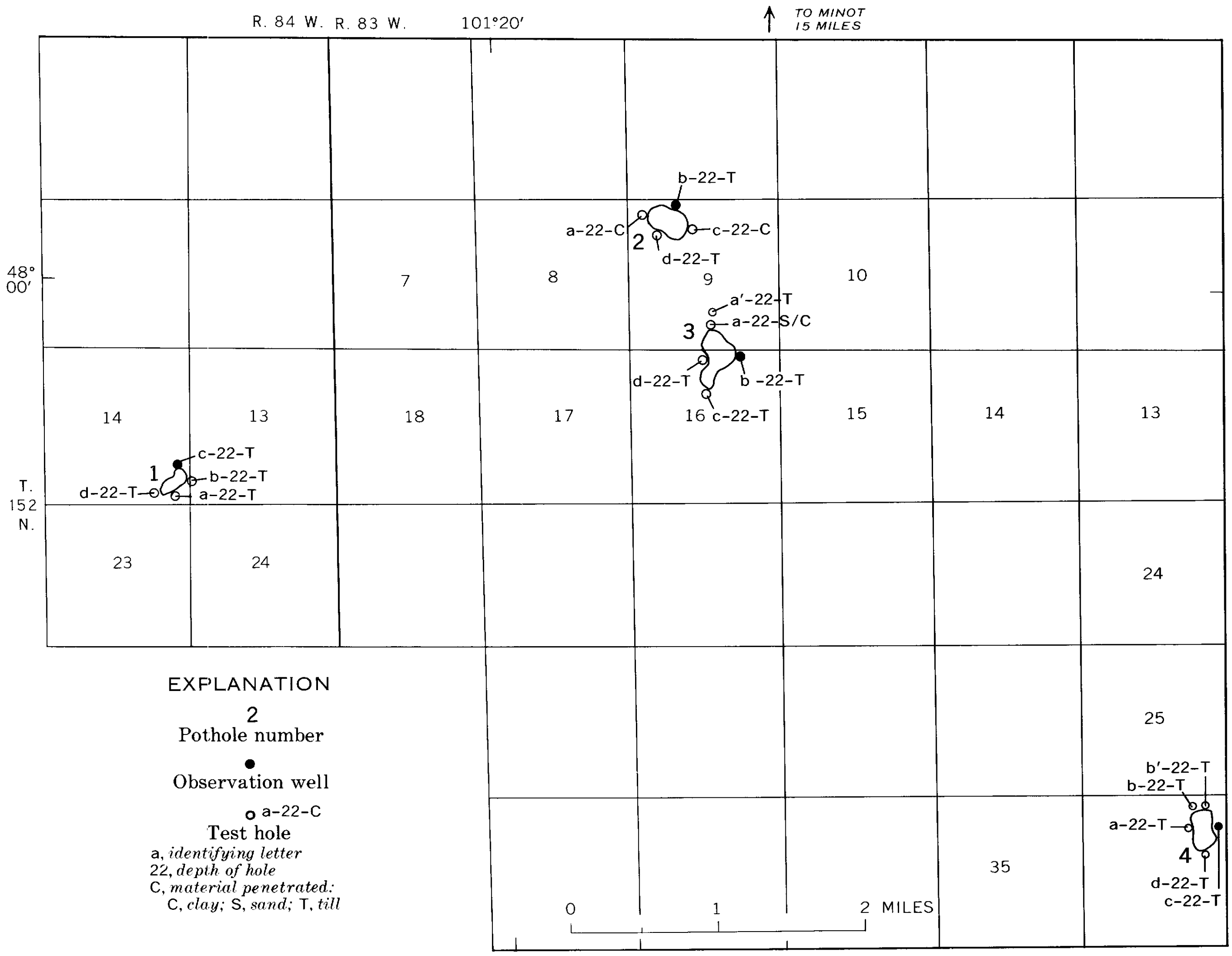


FIGURE 14.—Location of study potholes in Ward County, showing position of test holes and observation wells.

TABLE 1.—*Area and capacity of study potholes in Ward County*

Gage height (ft)	Pothole 1		Pothole 2		Pothole 3		Pothole 4	
	Area (acres)	Capacity (acre-ft)	Area (acres)	Capacity (acre-ft)	Area (acres)	Capacity (acre-ft)	Area (acres)	Capacity (acre-ft)
—0.7			0.0	0.0				
— .5			1.6	.1				
0.0			8.4	2.6				
.13							0.0	0.0
.5			15	8.6			6.0	1.1
.87					0.0	0.0		
1.0			20	18	2.8	.2	14	6.2
1.48	0.0	0.0						
1.5	1.0	.1			12.5	4.0	16	14
2	6.4	2.2	26	41	19	12	18	23
2.5	8.4	5.9			23	22		
3	9.4	10	29	69	26	35	22	43
4	11	21	32	100	31	64	25	66
5	13	33	35	133	34	96	27	92
6	15	46	36	169	37	131	28	120
7	16	62	38	206	40	170	29	148
8	18	78	39	245	46	212	31	179
9	19	97	41	285	54	262	32	210
10	20	116	43	327	60	319	34	243
Drainage area (including pond)	76		223		340		74	

present, to at least the extent of being fairly common, are listed in table 2; and zones used in 1964 are not necessarily the same as those used in 1961, although they may overlap to a great extent. The zones are delineated on the drainage-basin maps for each pothole.

The subsurface conditions at the study potholes were determined from 18 test holes that were drilled to a depth of 22 feet with a mud-rotary drilling rig during December 3–11, 1959. The locations of the test holes are shown in figure 14. Except for test holes 3a and 4b, which penetrated minor amounts of sand and clay, all the test holes penetrated till, only. Permeability of the till was judged to be low enough that ground-water movement would be negligible. One test hole at each pothole was made into an observation well by casing it with 16 to 18 feet of 1¼-inch galvanized steel pipe. The lower 10 to 12 feet of the pipe was slotted by use of a hacksaw and

TABLE 2.—*Emerged hydrophytes commonly present in study potholes in Ward County, July 1961 and October 1964*

[D, dominant; A, abundant; C, common; F, fairly common. Where no species is shown in a zone, that zone was mostly open water or no species was present in sufficient amount to be termed "fairly common." See maps for delineation of zones. Vegetation mapped by R. E. Stewart]

Species	Pothole 1										Pothole 2													Pothole 3			Pothole 4									
	1961 zones						1964 zones				1961 zones					1964 zones								1961 zones		1964 zones	1961 zones						1964 zones			
	A	B	C	D	E	F	A	B	C	D	A	B	C	D	E	A	B	C	D	E	F	G	H	A	B	AB	A	B	C	D	E	F	A	B	C	D
Alopecurus aequalis																								F												
Alisma gramineum		F																						C												
triviale		C																																		
Artemisia biennis																																			F	
Aster simplex																			A	C																
Beckmannia syzigachne																										C										
Calamagrostis inexpansa						F														C																
Carex atherodesi	C			D			D	F																												
praegracilis						C																														
Chenopodium rubrum													F																C	C						
Cirsium arvense														F					C																	
Distichlis stricta																															F					D
Hordeum jubatum																									C	D			F		C				C	
Juncus balticus						F									C					C						F						D				F
Kochia scoparia														F																						
Lotus americanus																										F										C
Phragmites communis																							D													
Poa palustris															C					F						F										
Polygonum lapathifolium	F																							F							F					
Potentilla anserina																																				C
Puccinellia nuttalliana																													C							
Ranunculus cymbalaria																													F		F					
Rumex occidentalis																			F																	
Sagittaria cuneata	F												F											C												
Scirpus acutus												D					D											D						A		
americanus																														F	C				C	
fluviatilis														F			F				D	F				F										
paludosus																														D				F		
Scolochloa festucacea			D				F	D						F				D																		
Senecio congestis																								F												
Sonchus arvensis						C									C				C												C					
Spartina pectinata																				C						F										F
Typha angustifolia													F									D														
glauca																	F																			
latifolia					D					D			D	D			F					D														

was gravel packed in the annular space around the perforated part of the pipe. Clayey till was back filled around the upper 4 feet of the pipe and was packed to provide a seal against surface inflow. Logs of the observation wells are shown in table 3.

POTHOLE 1

Figure 15 shows pothole 1, as photographed in September 1961. At the beginning of the study, pothole 1 was clear of vegetation, except for the round colonies (which can be seen in fig. 15) around the shore. A closer view (fig. 16) shows the round colonies behind the bare soil of the pothole that were characteristic in June 1961. By July 1961 new vegetation had started to grow over the entire pothole (fig. 17), and thereafter, pothole 1 was densely vegetated (fig. 18), mostly with an almost pure stand of *Scolochloa festucacea* (whitetop). The borders of this pothole were mowed in the summer of 1961.

The pothole shown at lower left in figure 15 probably did not overflow into pothole 1 during the study, but it may have done so for one or two short periods.

The outline of the drainage basin and the vegetation zones are shown in figure 19.

The maximum stage of pothole 1 recorded during the study period, 1960–64, was 4.33 feet on April 24, 1960. A slightly higher stage, 4.61 feet, was reached July 23, 1965. Pothole 1 became dry for the remainder of the season beginning about Oct. 25, 1960, June 1, 1961, September 5, 1962, August 10, 1963, and August 15, 1964, respectively. It did not go dry in 1965 or 1966.

The range in dissolved-solids content of the water is given in table 4.

TABLE 3.—*Logs of observation wells at study potholes in Ward County*

Depth (ft)	Lithology
Pothole 1	
0–2	Topsoil, black.
2–6	Clay, light-gray.
6–22	Till, yellow, fine to medium gravel.
Pothole 2	
0–1	Topsoil, black.
1–14	Clay, yellow, smooth.
14–22	Till, yellow, fine to medium gravel.
Pothole 3	
0–1	Topsoil, black.
1–5	Clay, light-gray.
5–22	Till, yellow, fine to medium gravel.
Pothole 4	
0–1	Topsoil, black.
1–22	Till, yellow, fine to medium gravel; contains shale pebbles and coal fragments.

TABLE 4.—*Approximate concentration of dissolved solids, in parts per million, in pothole 1, 1960–65*

Year	Early season		Midseason		Late season	
	Pond	Observation well	Pond	Observation well	Pond	Observation well
1960	250	-----	-----	-----	-----	-----
1961	800	-----	-----	-----	-----	-----
1962	300	1,300	300	1,100	-----	551
1963	400	-----	275	-----	-----	-----
1964	300	-----	450	-----	325	-----
1965	350	-----	-----	-----	-----	-----

POTHOLE 2

Figure 20 shows pothole 2, as photographed in September 1961. The western part of the pothole had been clear of vegetation until it became dry in August 1961. A month later, vegetation had begun to grow on the bare soil (fig. 20).

At low stages, the pond receded from the permanent gages, so temporary gages (fig. 21) were installed where the pond was deepest (fig. 20).

The outline of the drainage basin and the vegetation zones are shown in figure 22.

The maximum stage of pothole 2 recorded during the study period, 1960–64, was 3.7 feet, about April 25, 1960. Pothole 2 became dry on Aug. 20, 1961, and again on Oct. 1, 1962.

The range in dissolved-solids content of the water is shown in table 5.

TABLE 5.—*Approximate concentration of dissolved solids, in parts per million, in pothole 2, 1960–64*

Year	Early season		Midseason		Late season	
	Pond	Observation well	Pond	Observation well	Pond	Observation well
1960	550	-----	-----	-----	1,010	-----
1961	800	6,540	1,800	-----	-----	6,100
1962	900	6,000	1,200	7,500 [1] 3,460	-----	5,700 [1] 3,590
1963	1,700	8,520	1,600	-----	2,000	6,300
1964	800	-----	1,500	-----	1,500	-----

[1] Shallow cased well dug in lowest part of pothole to determine elevation of the water table after pond disappeared.

POTHOLE 3

Pothole 3 was considered to be clear because none of the vegetation species were emergent, with the exception of narrow bands along the shore. At times the pond was filled with submersed vegetation, parts of which protruded a few inches above the water surface. Transpiration from the protruding vegetation was considered to be enough to offset any reduction in evaporation that the presence of the vegetation might have caused.

The maximum stage of pothole 3 was 5.1 feet on April 25, 1960 and the pothole did not become dry until about Oct. 25, 1964. Temporary gages were used at several sites, however, as water levels receded.

Figure 23 shows pothole 3, as photographed in September 1961. (A corner of pothole 2 can be seen in the extreme upper-left corner of fig. 23.) Most of the drainage basin of pothole 3 can be seen above pothole 2 in figure 20.

The outline of the drainage basin is shown in figure 24. The vegetation zones, shown on this map, define the zones of shoreline vegetation, as mapped by Stewart in 1961. No map was prepared for 1964, presumably because all the vegetation was within the same two zones. The range in dissolved solids content of the water is shown in table 6.

TABLE 6.—*Approximate concentration of dissolved solids, in parts per million, in pothole 3, 1960–64*

Year	Early season	Midseason	Late season
1960	350	-----	500
1961	550	675	950
1962	650	600	725
1963	[1] 700	650	900
1964	800	1,400	2,400

[1] 943 ppm dissolved-solids concentration in observation well.

FIGURE 15.—Aerial view toward the south-southwest of pothole 1, September 1961. Photograph by W. P. Sebens.

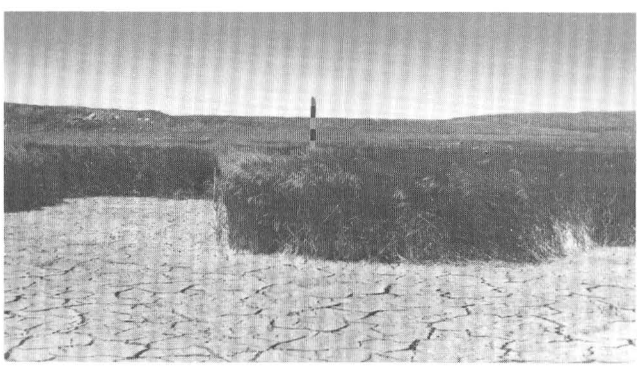


FIGURE 16.—Dry bed of pothole 1, June 26, 1961.

FIGURE 17.—New vegetation in bed of pothole 1, July 31, 1961.

FIGURE 18.—Vegetation in pothole 1, July 8, 1963, typical for the period 1962–1966.

POTHOLE 4

The drainage basin of pothole 4 was mostly virgin prairie at the beginning of the study. It was plowed during summer of 1963, and at least one small adjacent pothole was drained into pothole 4, thus increasing the drainage area slightly from that shown in figure 25. The vegetation zones are also shown in this figure.

A south-southwestward aerial view of pothole 4, taken in September 1961, is shown in figure 26. The numbers on the several potholes are the specific conductances (in micromhos per centimeter) as measured June 11, 1963. The regional drainage pattern, if the water should ever rise high enough for the ponds to overflow, would be from the northwest, through pothole 4, thence to the southwest (potholes with conductances of 140 and 1,600), and then southeast and south (potholes with conductances of 1,600 and 1,700).

Pothole 4 reached a maximum stage of 3.17 feet about June 1, 1960. It became dry for the season about July 10, 1961, Sept. 18, 1962, and Sept. 5, 1963, respectively. In 1964 the pothole became dry on Aug. 15, but was twice refilled by rains before it went dry for the season about Oct. 15. The range in dissolved solids content of the water is given in table 7.

TABLE 7.—*Approximate concentration of dissolved solids, in parts per million, in pothole 4, 1960–64*

Year	Early season		Midseason		Late season	
	Pond	Observation well	Pond	Observation well	Pond	Observation well
1960	1,600	------	------	------	4,100	------
1961	2,500	23,200	14,000	------	-----	14,300 [1] 41,500
1962	1,800	23,000	2,500	22,000	-----	16,000 [1] 7,000
1963	2,500	21,000	3,500	------	7,000	14,300
1964	2,000	------	5,000	------	8,500	------

[1] Shallow cased well dug in lowest part of pothole to determine elevation of the water table after pond disappeared.

STUTSMAN COUNTY

The study areas in Stutsman County were named by the Bureau of Sport Fisheries and Wildlife for the nearest prominent geographical feature. The three areas in which the U.S. Geological Survey also worked are known as the Mount Moriah area, Woodworth area, and the Cottonwood Lake area, and their locations are given in figure 27.

MOUNT MORIAH AREA

The Mount Moriah area, sec. 21, T. 144 N., R. 67 W., contains more than 100 potholes. It is on the edge of the Coteau du Missouri escarpment and, for this location, has a well-developed drainage system. Staff gages (fig. 5) were established in 14 potholes. These 14 potholes in the Mount Moriah area are designated with the letter "M" preceding the numbers 10, 12, 15, 23, 28, 34, 35, 40, 42, 43, 47, 55, 55A, and 56, respectively. The location of these potholes and the locations of the observation wells used to determine the elevation of the water table are shown on the topographic map (pl. 1). Figure 28 shows an aerial view of most of these potholes. A weighing rain gage was located in the center of the section. Vegetation in pothole 55A was not mapped. The species of vegetation found in the other study potholes are listed in table 8.

The relation between potholes M55 and M56 is shown in figure 29. The horizontal distance between the two water surfaces is about 80 feet at the nearest points. Pothole M55 did not go dry during the study, and the pond level in pothole M56 was never less than 2.5 feet lower than that of pothole M55. There was no significant overflow from M55 into M56 during the study prior to June 1964. The low concentration of dissolved solids in pothole M56 before this date and the much higher concentration after that date indicate strongly that there was no appreciable seepage from M55 into M56, despite their proximity. Even more significant is the fact that M56—the lower of the two potholes—went dry, but pothole M55 did not. Thus, any seepage from M55 to M56 was insufficient to prevent M56 from drying up.

Hydrographs for the study potholes, constructed from weekly staff-gage readings, are shown in figure 30. This figure shows that "M" potholes 10, 12, 15, 23, 28, 40, 47, 55A, 55, and 56 all overflowed.[3]

The concentration of dissolved solids in these potholes is given in table 9. Values, in parts per million, were obtained from chemical analyses of

[3] The other potholes in early May 1969 were all at stages between the maximums for 1965 and 1966.

TABLE 8.—*Emerged hydrophytes commonly present in study potholes in the Mount Moriah area, June 22–August 11, 1961*

[D, dominant; A, abundant; C, common; F, fairly common. Where no species is shown in a zone, that zone was mostly open water or no species was present in sufficient amount to be termed "fairly common." See map for delineation of zones. Vegetation was mapped by R. E. Stewart]

Species	M10						M12					M15				
	A	B	C	D	E	F	A	B	C	D	E	A	B	C	D	E
Alopecurus aequalis																
Aster simplex						C										
Beckmannia syzigachne																
Calamagrostis inexpansa											C					
Carex atherodes					D		D			D						
laeviconica						C										
praegracilis																
Chenopodium rubrum	C	C												C	C	
salinum		C														
Cirsium arvense																
Distichlis stricta																
Eleocharis acicularis																
palustris	D						D		C							
Glyceria grandis							C									
Hordeum jubatum																
Juncus balticus						C										C
Lycopus asper																
Lysimachia hybrida																
Mentha arvensis									C	C						
Poa palustris						D					C					C
Potentilla anserina																C
norvegica									F	C						
Rumex occidentalis																
maritimus							C									
Sagittaria cuneata																
Scirpus acutus				D				D					D	D		
americanus																C
Scolochloa festucacea																
Sonchus arrensis											C					
Sparganium eurycarpum																
Teucrium occidentale										C						
Typha latifolia			D												D	

Species	M23			M28					M34				M35				
	A	B	C	A	B	C	D	E	A	B	C	D	A	B	C	D	E
Alopecurus aequalis														F			
Aster simplex																	
Beckmannia syzigachne									F					F			
Calamagrostis inexpansa																	
Carex atherodes						F	D				D						D
laeviconica												C					
praegracilis		D															
Chenopodium rubrum									C				C		C	C	F
salinum																	
Cirsium arvense																	
Distichlis stricta			D														
Eleocharis acicularis									C								
palustris	C			C					C					D			
Glyceria grandis									F					F			
Hordeum jubatum	C	C									F						C
Juncus balticus								F									
Lycopus asper																	
Lysimachia hybrida																	
Mentha arvensis											C						
Poa palustris		C						C				C					
Potentilla anserina								F									
norvegica											C						
Rumex occidentalis																	
maritimus									C				D	F		C	
Sagittaria cuneata				F													
Scirpus acutus														F	D		
americanus																	
Scolochloa festucacea																	
Sonchus arrensis																	
Sparganium eurycarpum									F								
Teucrium occidentale																	
Typha latifolia					D	D				D						D	

Species	M40						M42			M43				
	A	B	C	D	E	F	A	B	C	A	B	C	D	E
Alopecurus aequalis							C							
Aster simplex														C
Beckmannia syzigachne														
Calamagrostis inexpansa														
Carex atherodes					D			D					D	
laeviconica														C
praegracilis														
Chenopodium rubrum	C	C	C	C	F					C	C	C		
salinum														
Cirsium arvense				F										
Distichlis stricta														
Eleocharis acicularis														
palustris		F	F				C				D			
Glyceria grandis														
Hordeum jubatum					C								F	
Juncus balticus						F								
Lycopus asper						F								
Lysimachia hybrida							C							
Mentha arvensis														
Poa palustris						C			C					
Potentilla anserina						F								
norvegica														
Rumex occidentalis			F											
maritimus		F								D				
Sagittaria cuneata														
Scirpus acutus			D											
americanus														
Scolochloa festucacea														
Sonchus arrensis													C	F
Sparganium eurycarpum														
Teucrium occidentale						F								
Typha latifolia				D								D		

Species	M47						M55				M56			
	A	B	C	D	E	F	A	B	C	D	A	B	C	D
Alopecurus aequalis														
Aster simplex														
Beckmannia syzigachne														
Calamagrostis inexpansa														
Carex atherodes					F								C	
laeviconica														
praegracilis														
Chenopodium rubrum			C						C					
salinum														
Cirsium arvense													C	
Distichlis stricta														
Eleocharis acicularis		F												
palustris		D									F	D		
Glyceria grandis														
Hordeum jubatum					F									C
Juncus balticus										C				
Lycopus asper														
Lysimachia hybrida														
Mentha arvensis					F								C	
Poa palustris					F	C								C
Potentilla anserina														
norvegica														
Rumex occidentalis														
maritimus														
Sagittaria cuneata														
Scirpus acutus								D						
americanus														
Scolochloa festucacea									C					
Sonchus arrensis										C				C
Sparganium eurycarpum				D					C				D	
Teucrium occidentale														
Typha latifolia			D						C					

TABLE 9.—*Concentration of dissolved solids, in parts per million, observed in study potholes in the Mount Moriah area*

[c, Specific conductance, in micromhos per centimeter. For relation to parts per million, see fig. 91]

Date	M10	M12	M15	M23	M28	M34	M35	M40	M42	M43	M47	M55A	M55	M56
May 1962		220c	1,350c		550c								1,180c	240c
June 1962			1,180c	450c			775c		72c	576c		1,450c	1,360c	204c
Aug. 1962		184c	1,100c	Dry	1,020c		660c		94c	422c			1,460c	169c
May 1963	1,020	354	774	1,260	277	433	581	463	254	809	340	1,670	849	
Oct. 1963			1,920		828			1,450			1,750		2,880	
July 1964						900c	1,150c		180c	1,100c			1,800c	1,330c
June 1966		264	974										1,170	

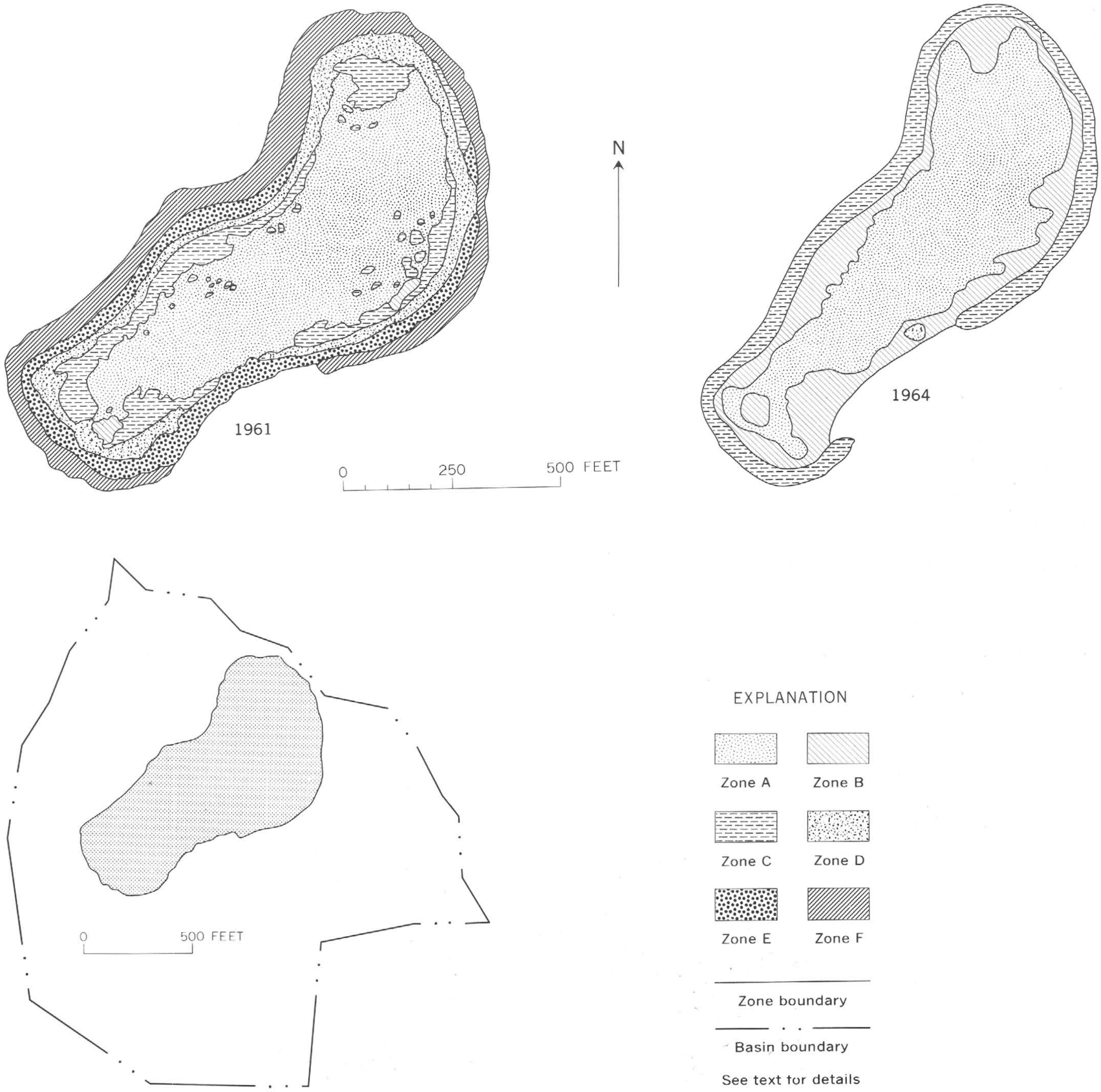


FIGURE 19.—Drainage basin of pothole 1, showing pothole vegetation zones in 1961 and 1964. Vegetation was mapped by R. E. Stewart. See table 2 for plant names.

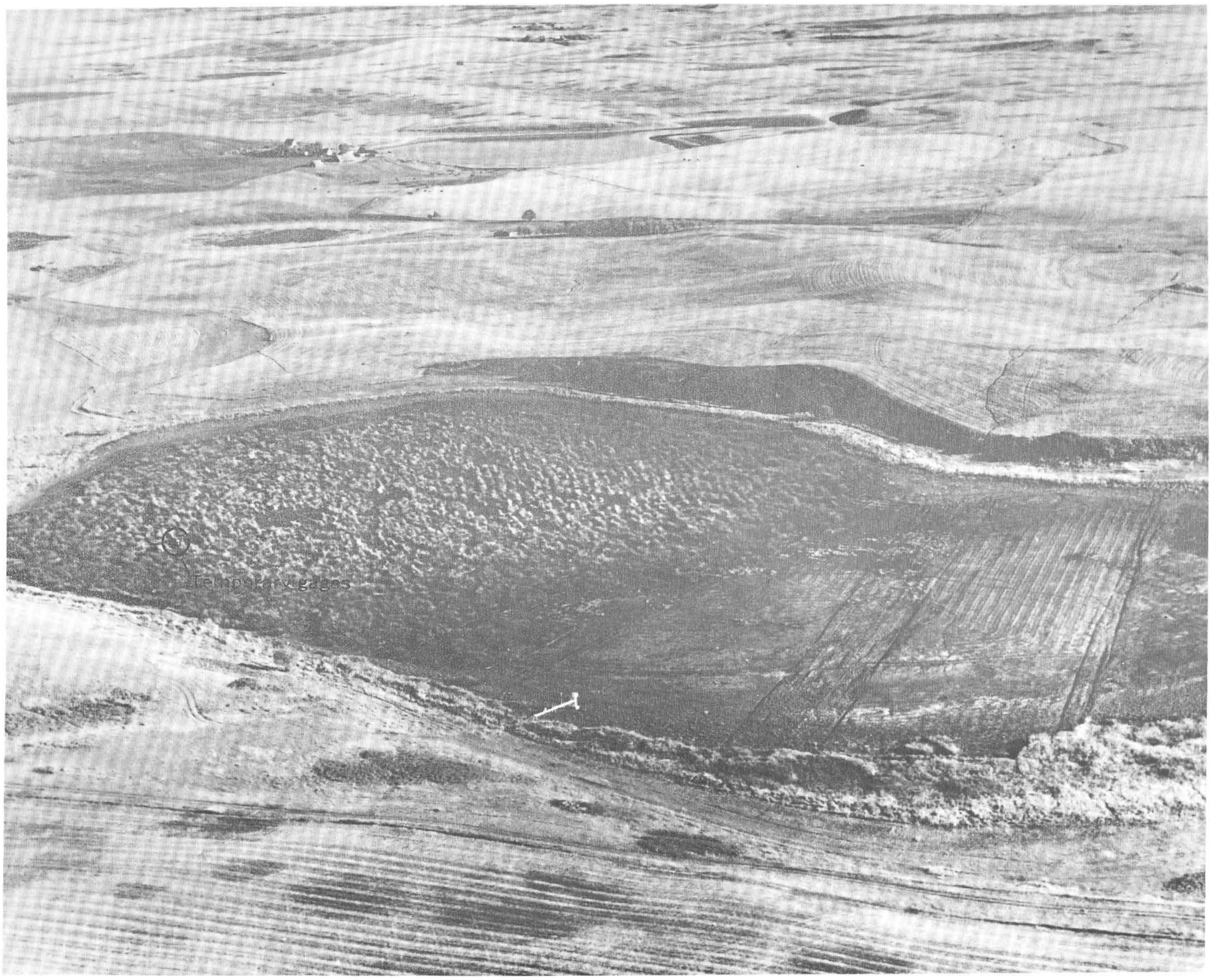


FIGURE 20.—Southeastward aerial view of pothole 2, September 1961. Pothole 3 is the large pothole just above pothole 2. Temporary gages are shown in circle. Photograph by W. P. Sebens.

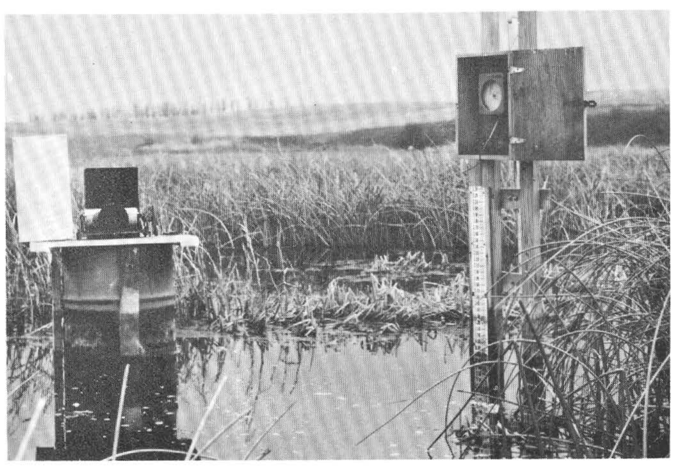


FIGURE 21.—Temporary gages at deepest part of pothole 2, April 27, 1963. Note dense stand of dead vegetation (foreground) remaining from previous summer.

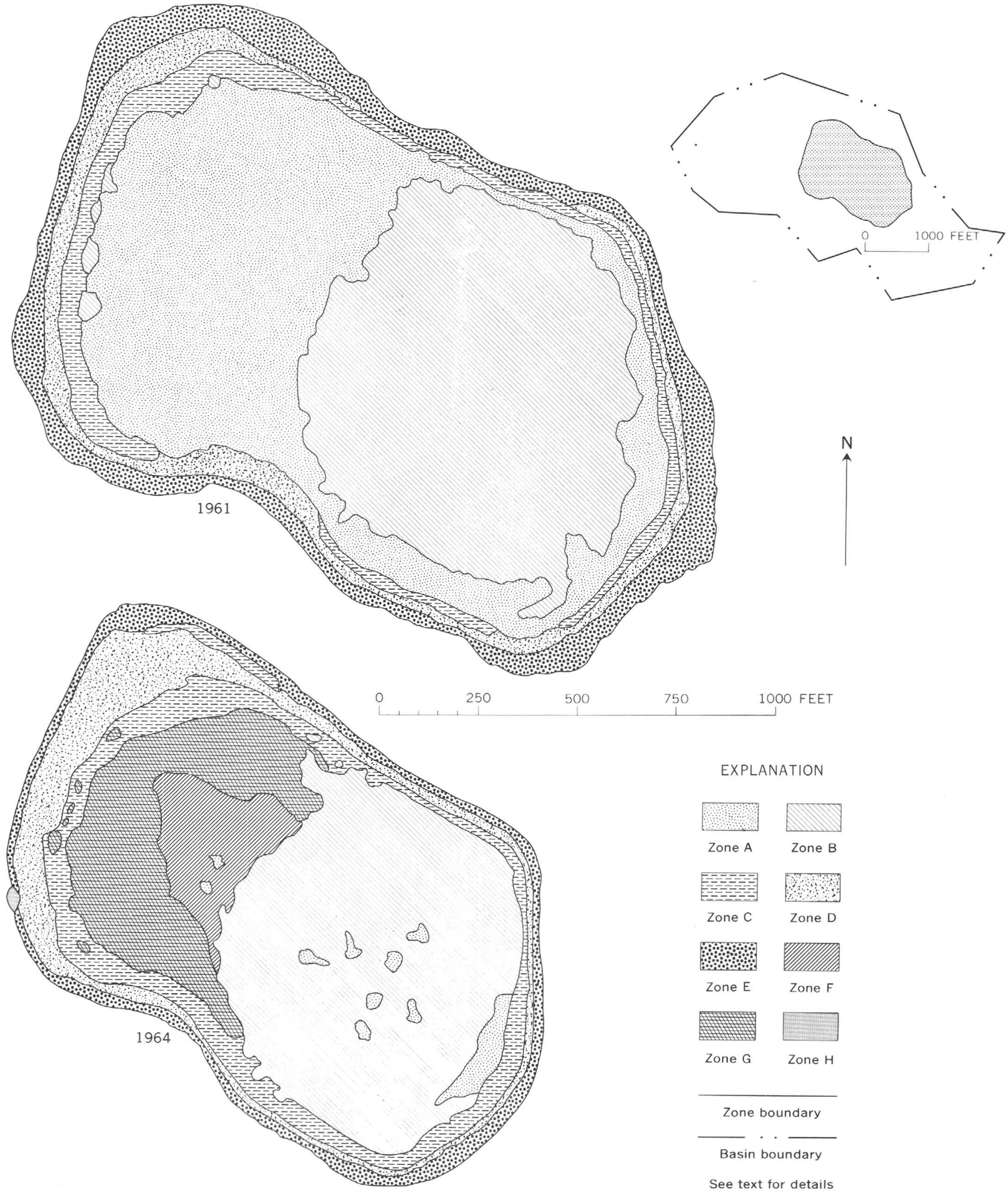


FIGURE 22.—Drainage basin of pothole 2, showing pothole vegetation zones in 1961 and 1964. Vegetation was mapped by R. E. Stewart. See table 2 for plant names.

FIGURE 23.—Northward aerial view of pothole 3, September 1961. Note corner of pothole 2 showing in the extreme upper-left corner. Photograph by W. P. Sebens.

the water samples. The specific conductances, in micromhos per centimeter, are the recorded observations made with a temperature-compensated conductance bridge. (The relation between micromhos per centimeter values and parts per million values is shown in figure 91.)

Twenty-eight observation wells (pl. 1) were augered in the Mount Moriah area during October 18–22, 1965. The wells ranged in depth from 14 to 67 feet. Some stratified material (including thin stringers of sand) was found in 21 of the 28 wells. Till was found in all the wells and was directly overlain by the soil zone in all but three wells. A buried oxidized zone occurred in one well at a depth of 43 feet. Only four wells were sufficiently deep to pass through the surficial oxidized zone. Depth to unoxidized till in these four wells ranged from 27 to 45 feet. A calcareous marl (thin zone) containing many small gastropods and pelecypods was found at a depth of about 12 feet in well M55–3. (See pl. 1.)

Water partly filled all but five of the wells immediately after drilling, and these became partly filled with water within a few hours. Depth to water ranged from 2.06 to 15.20 feet, and averaged 5.66 feet. Specific conductance of the water ranged from 425 to 18,000 μmhos (micromhos). Excluding the high and low values, conductance of 10 of the other samples averaged slightly more than 2,000 μmhos.

The 4-inch-diameter holes were cased with 1½-inch thin-walled aluminum conduit. The conduit was perforated (by cutting slots with a hacksaw) in the bottom 3 feet of pipe. Washed pea gravel was placed

FIGURE 24.—Drainage basin of pothole 3, showing pothole vegetation zones, 1961. Vegetation was mapped by R. E. Stewart. See table 2 for plant names.

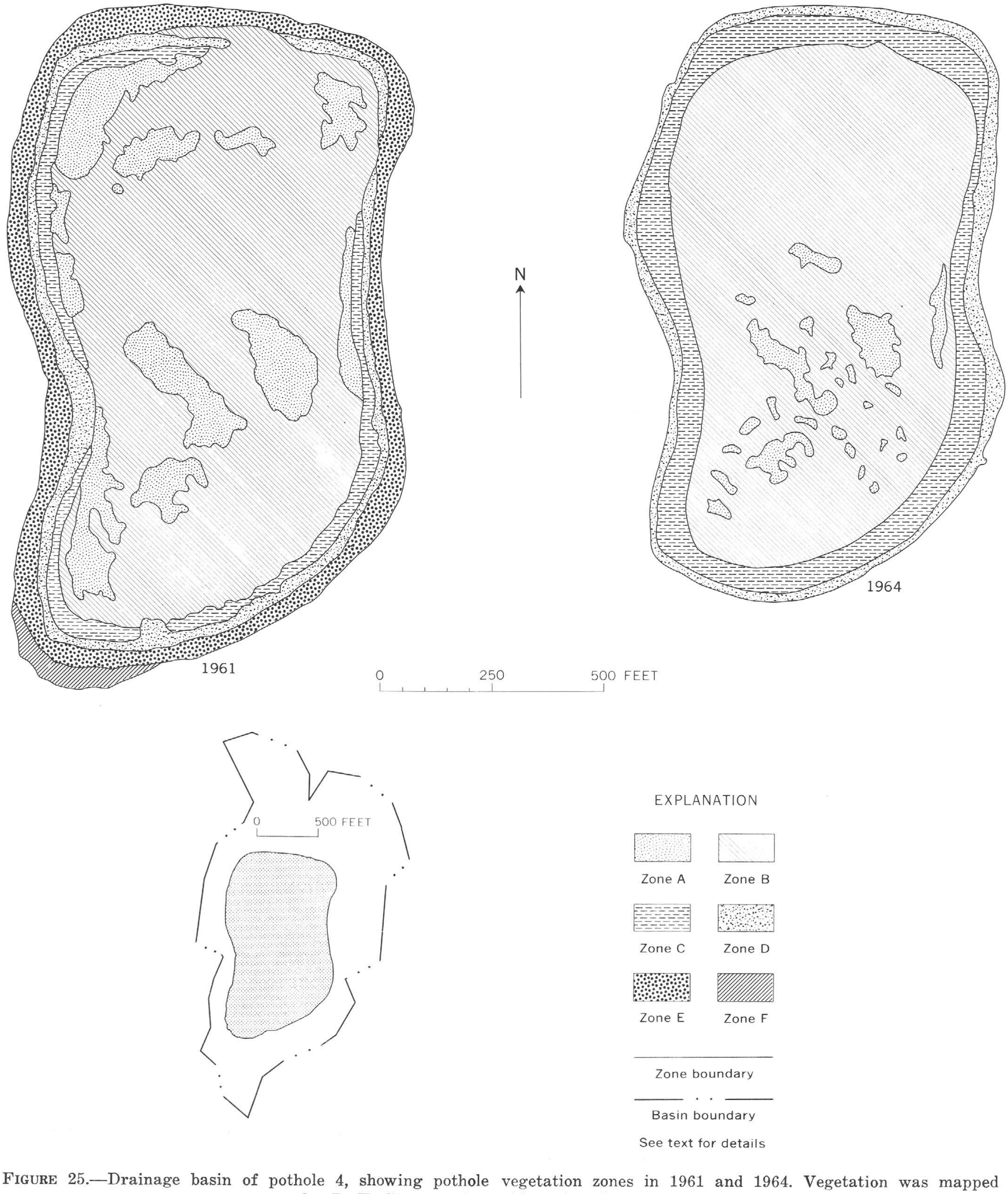


FIGURE 25.—Drainage basin of pothole 4, showing pothole vegetation zones in 1961 and 1964. Vegetation was mapped by R. E. Stewart. See table 2 for plant names.

FIGURE 26.—Aerial view of pothole 4, viewed toward the south-southwest. Numbers on potholes indicate specific conductances, in micromhos per centimeter, measured June 11, 1963. Photograph by W. P. Sebens, September 1961.

around the bottom few feet of perforated pipe to function as a stabilizing gravel pack, and till was packed around the top of the pipe to provide a surface seal. The pipes protruded above the ground surface from 0.25 to 1.75 feet and were covered to exclude precipitation. Wells with water in them at the time of drilling were pumped and developed with compressed air to promote free circulation of ground water into the well.

Logs of representative wells are shown in table 10.

COTTONWOOD LAKE AREA

The general location of the study potholes in the Cottonwood Lake area is shown in figure 27. The detailed location is shown on the topographic map (pl. 2), and all study potholes in the Cottonwood Lake area except pothole C1, which is to the left of the area shown, are shown in figure 31. The map (pl. 2) shows the locations of wells used in the general study of ground-water resources of Stutsman County, as well as those drilled especially for this study. It also shows the vegetation zones used in table 11 to show the species of emerged hydrophytes that were commonly present, as mapped by R. E. Stewart.

Ten test holes, designated 1 to 10, were augered in the Cottonwood Lake area from July 29 to August 5, 1961. The holes ranged in depth from 22 to 75 feet. Test holes 4, 5, 8, and 9 were entirely in till, whereas the remaining holes passed through significant thicknesses of interstratified sand and (or) gravel within the till. With the exception of

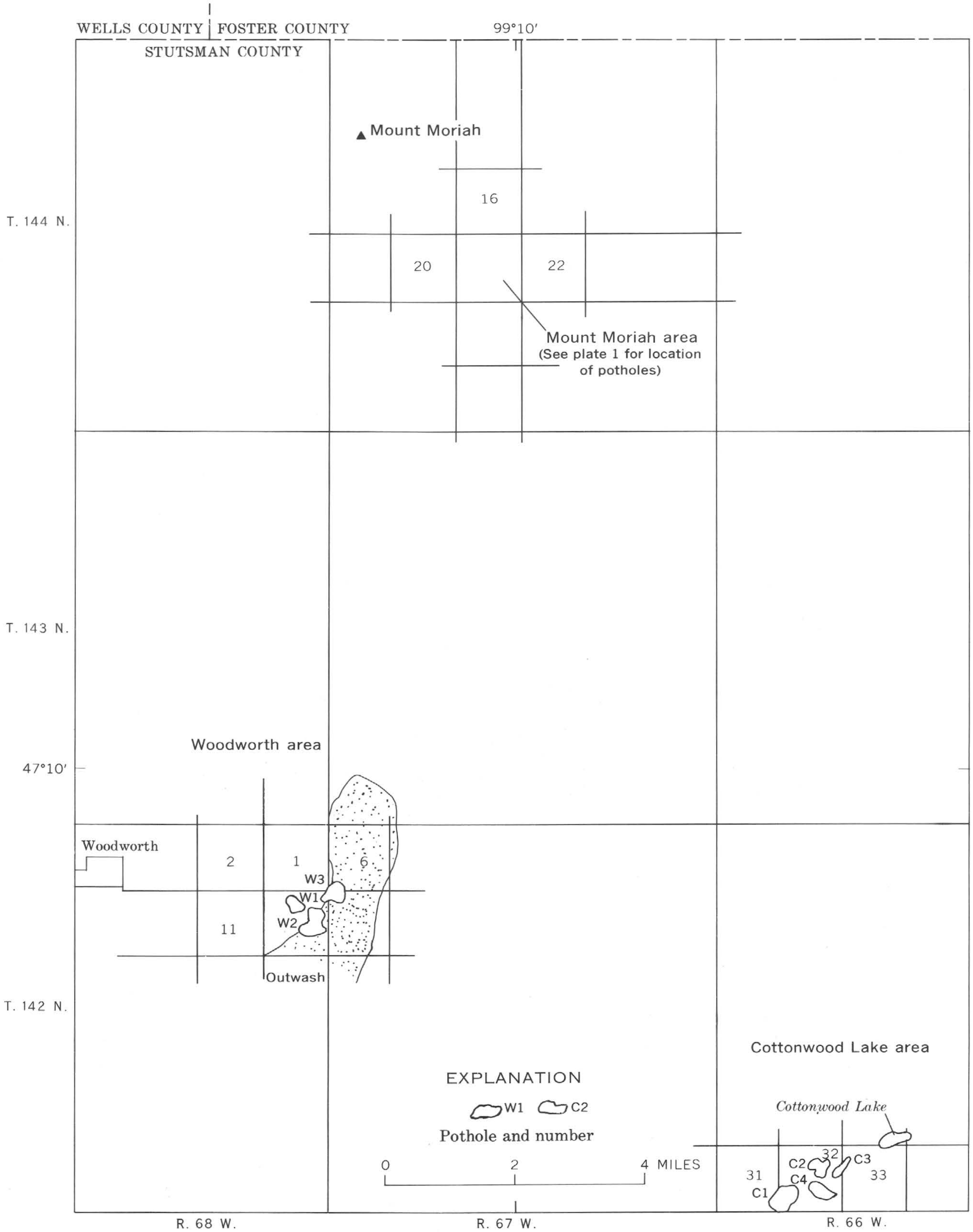


FIGURE 27.—Location of study potholes in Stutsman County.

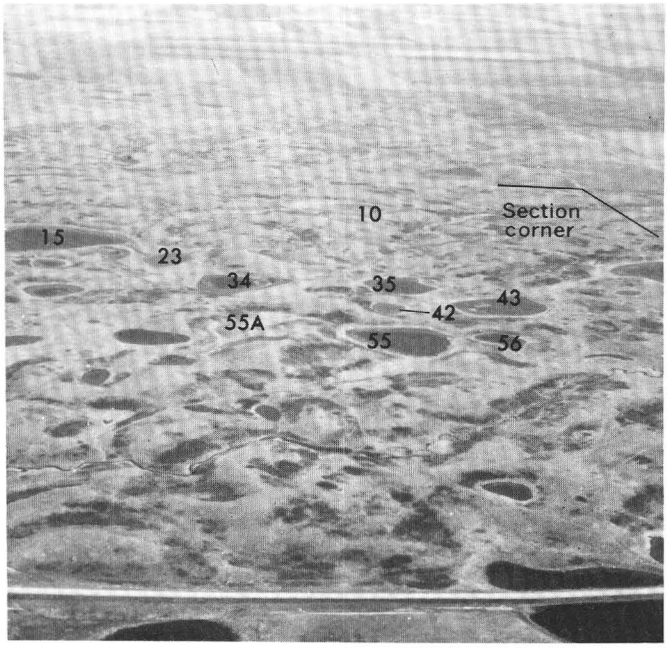


FIGURE 28.—Aerial view of the Mount Moriah area.

FIGURE 29.—Pothole M56 (foreground) and pothole M55 (beyond), June 27, 1964.

TABLE 10.—*Logs of representative observation wells in the Mount Moriah area*

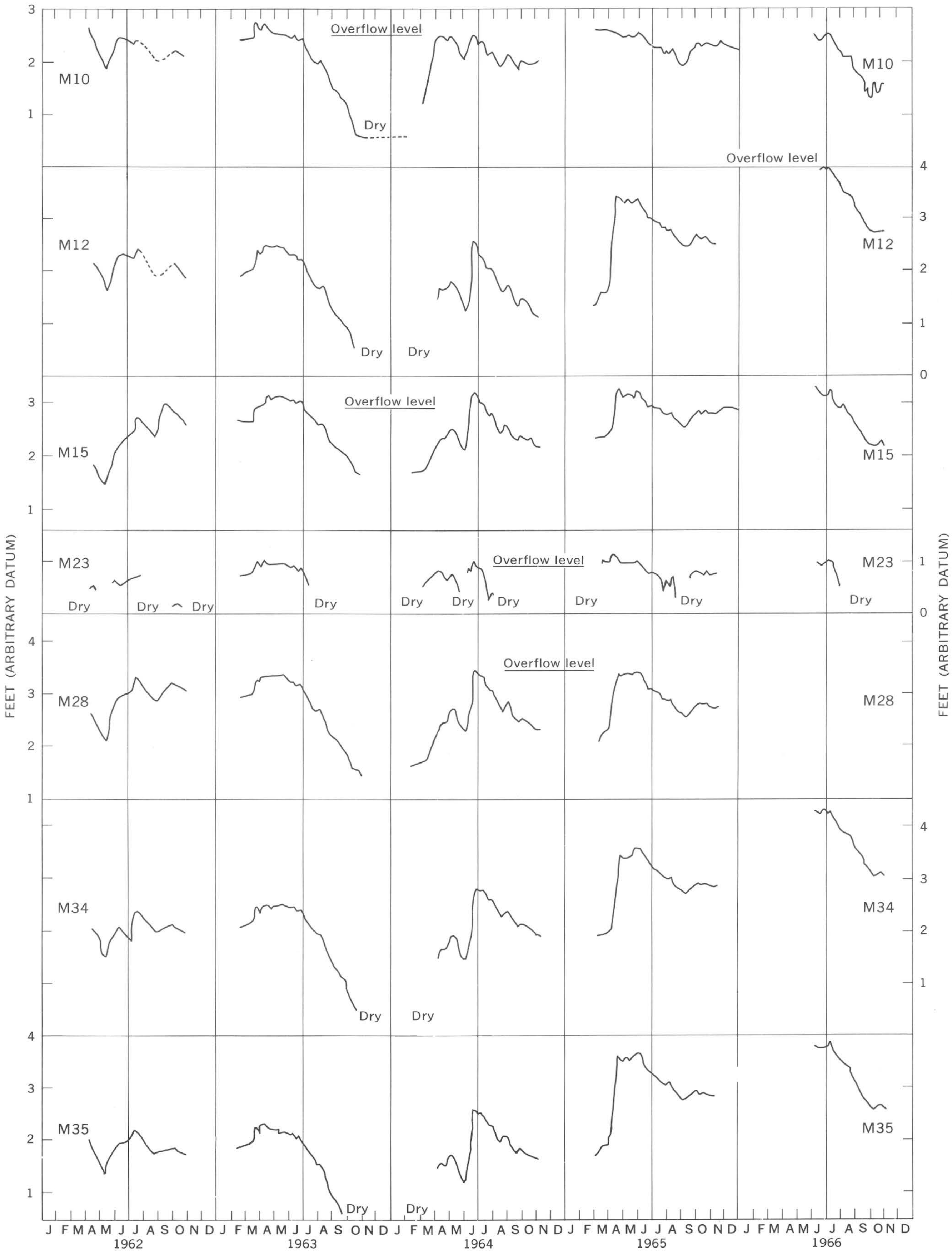
[For locations of wells, see pl. 1]

Well depth (ft)	Lithology
Well M4–1	
0–4	Soil, organic, brownish-black.
4–30	Sand, very fine to coarse, pebbly, silty, clayey, dark-yellowish-brown.
30–45	Sand; color change to dusky yellowish brown; slightly finer.
45–53	Sand; color change to olive gray.
53–55	Gravel.
55–67	Till, plastic, calcareous, olive-gray.
Well M15–1	
0–1	Soil, dark-gray.
1–15	Till, moderate-yellowish-brown.
15–27	Till; color change to dark yellowish brown.
27–42	Sand, fine- to medium-grained; gravel stringer at 37 ft.
42–43	Gravel.
43–45	Till, oxidized, moderate-yellowish-brown.
Well M56–1	
0–4	Soil, organic, brownish-black.
4–6	Clay, medium-gray.
6–15	Till, moderate-yellowish-brown; thin sand zone at 13 ft.

test holes 4, 7, and 9 (which were filled and abandoned), the test holes were cased with 1¼-inch- or 2-inch- diameter pipe and left as observation wells. The 1¼-inch- diameter pipes were finished with sand points, and the 2-inch- diameter pipes were perforated through the bottom 10 feet.

Logs of these test holes are given in table 12.

Because pothole C1 (shown in fig. 32) was large, relatively clear of emerged vegetation, and roughly midway between the Ward and Dickey County study areas, it was chosen for detailed study. Accordingly, it was equipped with water-stage recorder, tipping-bucket rain gage, anemometer, water-temperature recorder, and hygrothermograph. Originally, the water-stage recorder was driven by a bubble manometer because the shore is so flat that an intake pipe for a stilling well would have been too long. However the bubble manometer was not sufficiently sensitive. The drive was redesigned to give a 10:12 ratio on the recorder, but the light oil substituted for the mercury of the manometer lacked the force necessary to drive the float switch. The bubble manometer was abandoned, and temporary gage struc-


M10
M12
M15
M23
M28
M34
M35
Overflow level
Dry
FEET (ARBITRARY DATUM)
J F M A M J J A S O N D
1962
1963
1964
1965
1966

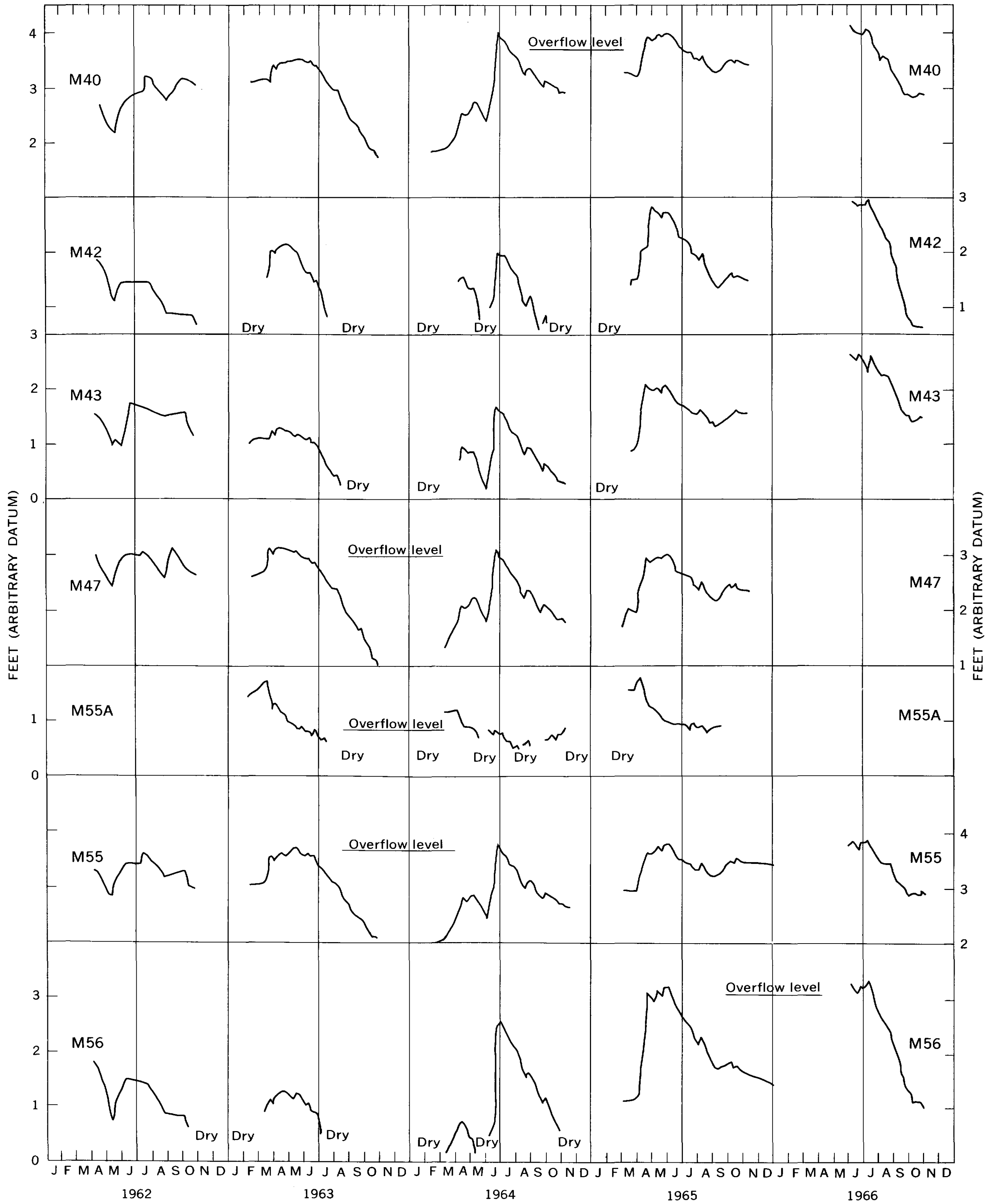


FIGURE 30.—Hydrographs of pond levels in potholes of the Mount Moriah area, based on weekly staff-gage readings. The 1962 data are from miscellaneous observations by the Bureau of Sport Fisheries and Wildlife.

TABLE 11.—*Emerged hydrophytes commonly present in study potholes in the Cottonwood Lake area, June 1961 and October–November 1964*

[D, dominant; A, abundant; C, common; F, fairly common. See plate 2 for delineation of zones. Where no species is shown in a zone, that zone was mostly open water and no species was present in sufficient amount to be termed "fairly common." Vegetation mapped by R. E. Stewart]

C1

Species	1961 zones A	B	C	D	1964 zones A	B	C	D	E	F	G	H
Alisma gramineum												
Beckmannia syzigachne												
Calamagrostis inexpansa									F			
Carex atherodes												
Chenopodium rubrum	C			C								
Cirsium arvense									C			
Distichlis stricta				F			A		C			A
Eleocharis palustris						C		A			F	
Hordeum jubatum				D			C		C			A
Juncus balticus							F		F			
Lycopus asper												
Muhlenbergia asperifolia												F
richardsonis												
Poa palustris												
Potentilla anserina												
Puccinellia nuttalliana				C			F					C
Ranunculus cymbalaria								F				
sceleratus												
Rumex occidentalis												
Scirpus acutus			F		A							
americanus				F		C					F	
paludosus			D									
Scolochloa festucacea								F				
Sonchus arvensis				C					C			
Spartina pectinata							C		C			
Typha glauca												
latifolia												

C2A

Species	1961 zones A	B	C	D	E	F	G	1964 zones A	B	C	D
Alisma gramineum											
Beckmannia syzigachne	C			C							
Calamagrostis inexpansa							C				F
Carex atherodes	C					D			A		
Chenopodium rubrum											
Cirsium arvense					C						
Distichlis stricta											
Eleocharis palustris	C		D		C						
Hordeum jubatum				C	D						
Juncus balticus											C
Lycopus asper											
Muhlenbergia asperifolia											
richardsonis											
Poa palustris											F
Potentilla anserina							C				
Puccinellia nuttalliana					C						
Ranunculus cymbalaria											
sceleratus											
Rumex occidentalis											
Scirpus acutus		D						A			
americanus											
paludosus											
Scolochloa festucacea	C						F		A		
Sonchus arvensis					C	C					
Spartina pectinata											C
Typha glauca										C	
latifolia										C	

C2B

Species	1961 zones A	B	C	D	E	F	1964 zones A	B	C	D
Alisma gramineum										
Beckmannia syzigachne										
Calamagrostis inexpansa										F
Carex atherodes								A		
Chenopodium rubrum			C	F		F				
Cirsium arvense										
Distichlis stricta						F				
Eleocharis palustris				D				F		
Hordeum jubatum						D				
Juncus balticus										F
Lycopus asper										
Muhlenbergia asperifolia										
richardsonis										
Poa palustris										C
Potentilla anserina										
Puccinellia nuttalliana						F				
Ranunculus cymbalaria				C						
sceleratus										
Rumex occidentalis										
Scirpus acutus	D	D	C	F			A	F		
americanus										
paludosus	D		D							
Scolochloa festucacea					D			F		
Sonchus arvensis										
Spartina pectinata										C
Typha glauca										
latifolia										

C3

Species	1961 zones A	B	C	D	E	F	G	H	I	J	1964 zones A	B	C	D	E	F
Alisma gramineum																
Beckmannia syzigachne																
Calamagrostis inexpansa													F			
Carex atherodes							C					D				
Chenopodium rubrum		C							C							
Cirsium arvense				C	C								F			
Distichlis stricta						F		D					C			
Eleocharis palustris						F	C					C				
Hordeum jubatum				C		D		F	C					D		
Juncus balticus							C						C			
Lycopus asper																
Muhlenbergia asperifolia																
richardsonis																
Poa palustris										C			C			
Potentilla anserina							C			C						
Puccinellia nuttalliana								C								
Ranunculus cymbalaria																
sceleratus		C														
Rumex occidentalis		C	C	C												
Scirpus acutus			D								D	F				
americanus																
paludosus																
Scolochloa festucacea		F		C	D		C					C				
Sonchus arvensis				C	C				C							
Spartina pectinata													C			
Typha glauca																
latifolia				D			F				F				D	C

C4

Species	1961 zones A	B	C	D	E	F	G	H	1964 zones A	B	C	D	E	F	G
Alisma gramineum		F													
Beckmannia syzigachne															
Calamagrostis inexpansa														F	F
Carex atherodes							C					F			
Chenopodium rubrum		C													
Cirsium arvense							C								
Distichlis stricta								D						C	A
Eleocharis palustris		C	C			C						A	A		
Hordeum jubatum		C				D		C							C
Juncus balticus								F						C	A
Lycopus asper															F
Muhlenbergia asperifolia															
richardsonis															C
Poa palustris															
Potentilla anserina															C
Puccinellia nuttalliana															
Ranunculus cymbalaria						C									
sceleratus															
Rumex occidentalis															
Scirpus acutus				D							A				
americanus								C				C	C		
paludosus															
Scolochloa festucacea			C				D				F	C	F		
Sonchus arvensis							C								
Spartina pectinata														C	C
Typha glauca										A					
latifolia					D				C						

FIGURE 31.—Aerial view of part of the Cottonwood Lake area, showing potholes C2–C4. Pothole C1 lies to the left of the area shown.

TABLE 12.—*Logs of observation wells drilled in 1961 in the Cottonwood Lake area*

[For well locations, see pl. 2]

Depth (ft)	Lithology
Well 1	
0–10	Silt, dusky-yellow-brown to dark-yellow brown; laminated by color in upper 7 ft; fairly cohesive; not too plastic; oxidized (upper 7 ft); calcareous. Till, silty to very sandy, dark-yellow-brown; slightly cohesive plastic.
10–20	Yellow mud, slightly oxidized, calcareous; very moist.
20–25	Till, olive-gray, calcareous; very cohesive.
25–32	Sand fine to coarse and fine gravel.
Well 2	
0–12	Till, very silty to sandy, moderate-olive-brown to dark-yellow-brown, noncohesive, oxidized.
12–16	Till, clayey, olive-gray; becomes darker with depth.
16–18	Rock or cobble.
18–40	Till, cobbly or pebbly.
40–42	Clayey sand to sandy clay with shale pebbles.
42–52	Sand, fine to coarse, and fine to medium gravel.
Well 3	
0–27	Till, brown; plastic with depth; cohesive, oxidized, calcareous; cobbles at 6 ft and 20 ft.
27–57	Till, olive-gray, very cohesive, plastic, calcareous; becoming darker. Cobble or pebbles at 56 ft.

TABLE 12.—*Logs of observation wells drilled in 1961 in the Cottonwood Lake area*—Continued

Depth (ft)	Lithology
Well 5	
0–20	Till, brown, cohesive, plastic, oxidized, very calcareous.
20–82	Till, olive-gray; same as above. Cobble and gravel at 29 ft.
Well 6	
0–7	Till, dark-yellow-brown, plastic, fairly cohesive, oxidized, calcareous.
7–32	Till, sandy to silty, grayish-brown; cobble gravel; at 22–23 ft olive gray, calcareous.
32–37	Sand, coarse.
Well 9	
0–5	Till, dark-yellow-brown, oxidized, weakly calcareous.
5–14	Till, silty, dusky-brown to dusky-yellow-brown, cohesive, fairly plastic, oxidized, weakly calcareous.
14–25	Till, dark-yellow-brown to olive-gray, strongly calcareous.
25–47	Till, dark-gray, cohesive, calcareous.
Well 10	
0–17	Till, brown to grayish-brown, slightly oxidized.
17–22	Till, olive-gray, plastic.
22–28	Till, olive-gray, plastic; pebbles sparse to abundant.
28–37	Gravel, fine to coarse.

FIGURE 32.—Pothole C1, showing instruments. Note wave action that made difficult the precise determination of pond level.

tures, as used in Ward and Dickey Counties, were installed. Pothole C1 went dry for the season in August 1961, and it reached its highest stage during the period 1962–64 of 4.2 feet, in June 1964, as shown in figure 35, successively higher stages were reached in 1965 and 1966.[4] The area and capacity of this pothole are given in table 13. The range in dissolved solids is given in table 14. A comprehensive network of observation wells was established around the pothole to study direction of ground-water movement.

TABLE 13.—*Area and capacity of pothole C1, Stutsman County, N. Dak.*

Gage height (ft)	Area [1] (acres)	Capacity (acre-ft)	Gage height (ft)	Area [1] (acres)	Capacity (acre-ft)
—0.2	0	0	2	36	53
0	7.8	.8	3	40	92
.5	21	8.2	4	43	133
1.0	28	21	5	46	178
1.5	33	36	6	49	225

[1] Drainage area, including pond, 243 acres.

TABLE 14.—*Approximate concentration of dissolved solids, in parts per million, in pothole C1, 1962–65*

Year	Early season	Midseason	Late season
1962	8,400	----------	----------
1963	1,800	2,600	3,600
1964	3,000	1,300	1,400
1965	1,000	----------	----------

Forty observation wells with depths ranging from 10 to 90 feet were augered near pothole C1 from September 15 to October 1, 1964. Minor amounts of stratified silt, sand, and gravel were penetrated in many of the wells, but glacial till was the predominant lothologic type.

A diamond-shaped array of five wells was drilled northeast of the pothole to obtain data applicable to the finite-difference equation for the analysis of recharge. The wells were drilled 50 feet deep and were spaced 75 feet from the well in the center. It was later found that the wells were too insensitive for their intended use.

The other observation wells were drilled in linear traverses radiating from pothole C1. At the traverse on the east side of C1, wells were drilled a few feet apart to different depths in clusters of three, to determine vertical hydraulic gradients. A cluster of two wells was also drilled in the northeast traverse.

Most of the wells were cased with 1½-inch-diameter galvanized-steel pipe, but two wells were cased with 4½-inch-diameter thin-walled metal casing. An 18-inch well point was attached to the lower end of the 1½-inch pipe to act as an intake, whereas slots were cut in the bottom 10 feet of the larger casings to allow inflow of ground water.

A lead plug with a paraffin seal was placed above the well point in the wells at the finite-difference array and in one well of each well cluster. This was to exclude water from inside the casings, so that they could be used as access holes for a nuclear moisture meter. When the nuclear meter was found to be unsatisfactory for determining water levels outside these holes, the plugs were pierced in order to use the holes as observation wells.

Logs of representative observation wells are given in table 15.

TABLE 15.—*Logs of representative observation wells at pothole C1*

Depth (ft)	Lithology
Well 17–A	
0–10	Clay; some sand, black (humic).
10–20	Till, sandy, olive-gray to dusky-yellowish-brown; numerous pebbles present; iron staining (streaking) noted.
20–30	Till, pebbly, olive-gray to dusky-yellowish-brown; somewhat more clayey than above; iron staining common. The till at this level was mealy in appearance as it came off the bit, in contrast with "clay strips or slabs." Gravel lens at approximately 23 ft.
30–40	Till, pebbly; color variation in this 10-ft interval. From 30–32 ft the till is grayish brown to olive gray; then the color changes to an olive gray to olive black in the interval 32–35 ft; from 35–40 ft the till is grayish brown to olive gray once again; and, finally, below 40 ft the till is again olive gray to olive black.
40–60	Till, pebbly, olive-gray to olive-black; some increase in moisture content (plasticity) at this depth (that is, the till is more uniformly a clay-silt material with fewer pebbles).
60–70	Till, clayey, olive-gray to olive-black. Similar to till above, except perhaps more clayey and somewhat less pebbly; also, this till is more plastic although not markedly so. Although pebbles are not so common in these clays as they were near the surface, many are, nevertheless, rather large in size. (Some at 70-ft depth were 1 in. in diameter or larger.)

[4] A stage of 7.4 feet was observed April 30, 1969.

TABLE 15.—*Logs of representative observation wells at pothole C1*—Continued

Depth (ft)	Lithology
Well 22–A	
0–5	Till, slightly pebbly, olive-gray to light-olive-gray; contains some fine sand in with the clay; some iron staining.
5–10	Till; similar to that above, except more clayey.
10–15	Till; also similar to that above, except it is somewhat darker, more an olive black. The interval appears to be transitional between the browner (weathered?) till above and the olive-gray to olive-black till below.
15–30	Till, slightly pebbly, olive-gray to olive-black, moderately plastic.
37–49	Sand, fine- and medium-grained, dark-gray to olive-gray; material is saturated; hence, samples from drilling are "soupy"; white sand grains (feldspar?) create speckled effect in the "liquidy" matrix.
49–52	Till, pebbly(?), olive gray to olive black(?). At the 49-ft level, drilling became more difficult after easy drilling in wet sand for 12 feet; because of the semifluid nature of the sand interval, it was not definite what was encountered at 49 ft, but some till was brought up from about the 52-ft depth on the drill pipe.
Finite-difference array, well W–1	
0–8	Clay; some sand, black (humic).
8–13	Clay, very sandy, light-olive-brown; somewhat moist.
13–15	Sand, clayey, light-olive-brown; mushy (sand is saturated); easy drilling at this level.
15–27	Till, sandy, olive-gray to olive-black; pebbles and lignite fragments common.
27–50	Till, same as that above, except somewhat more sandy; from the 15-ft level down, till found to be mushy.

Staff gages, as used in the Mount Moriah area, were installed in potholes C2, C3, and C4.

Pothole C2 (fig. 31) has a ridge across the middle, so that at low water there are two separate ponds, C2A and C2B, both of which had staff gages. The northwestern pond, C2A, normally would receive drainage from a larger pothole to the north by way of a surface channel connecting the two (fig. 34), but the upper pothole has been drained and is under cultivation.

A well was drilled in the northeast corner of C2A for use in the general ground-water study of Stutsman County (Huxel and Petri, 1963, p. 74). In June 1962 water flowed from the top of the casing, which extended about 1½ feet above the ground.

FIGURE 33.—Southwestward view of pothole C2B, June 26, 1962. Note that heavy stand of vegetation shown here is absent in figure 34.

Both ponds went dry for the season in May 1961. Vegetation was dense over most of both ponds in June 1962, as shown in figure 33. As the maximum pond levels rose each year, the two ponds coalesced and finally overflowed in June 1966. Figure 34 shows the pothole at the time of overflow and how the increased depth destroyed the vegetation. Hydrographs of the ponds are shown in figure 35.

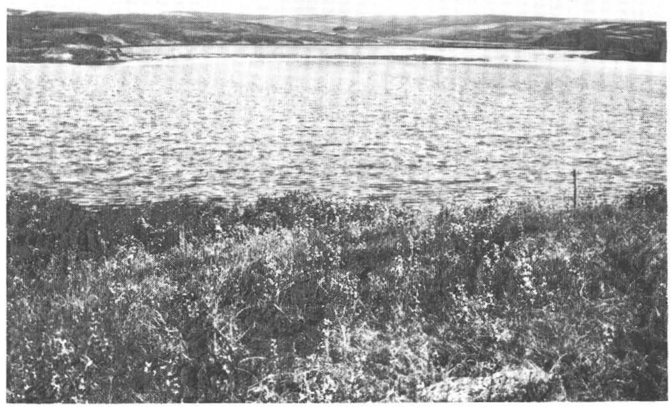


FIGURE 34.—Northwestward view of pothole C2, June 2, 1966. Pothole C2B is in foreground, and the dividing ridge between it and Pothole C2A (distance) is shown in the middle distance. Inflow channel enters the far shore (right of center).

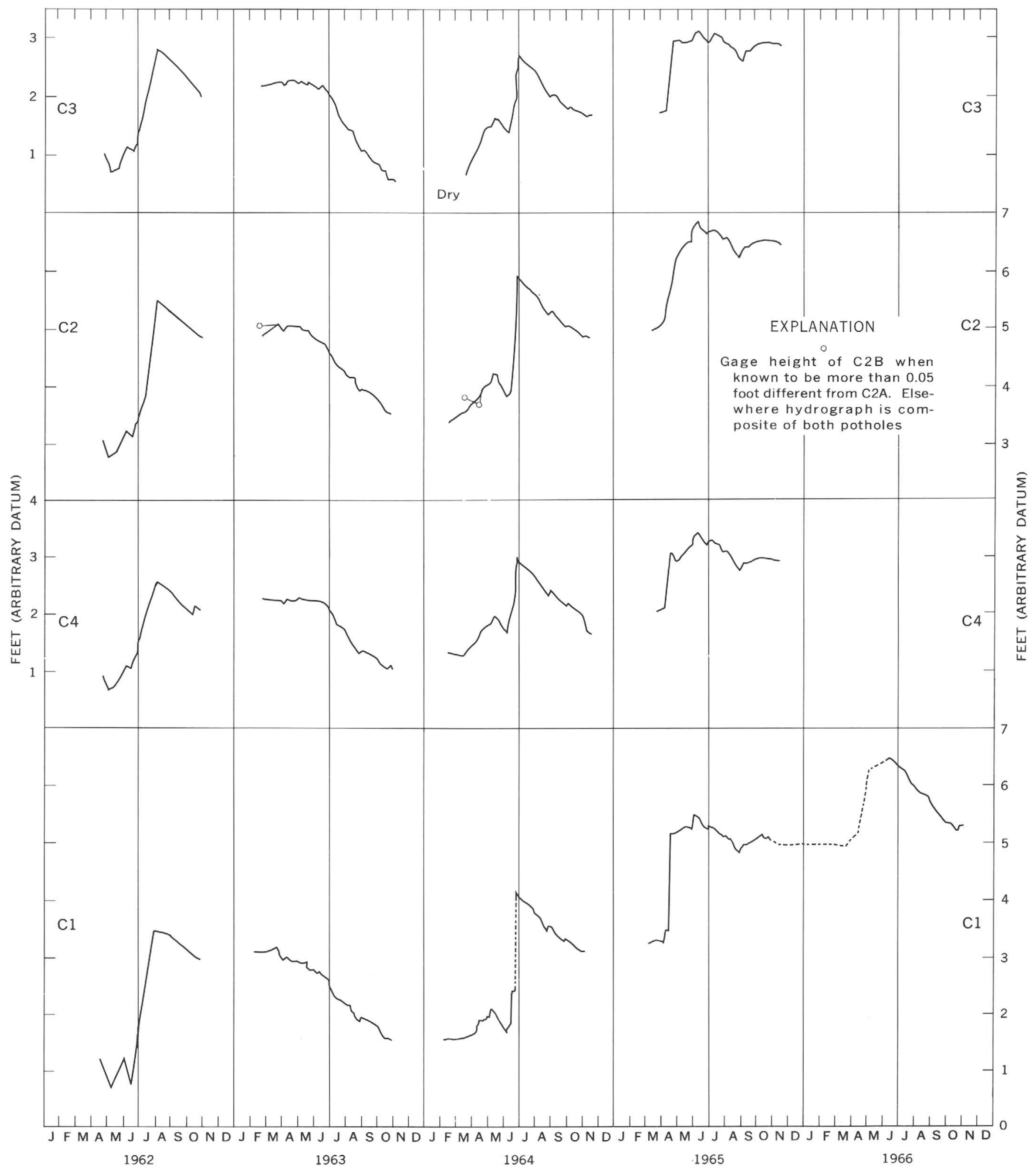


FIGURE 35.—Hydrographs of pond levels in potholes of the Cottonwood Lake area. Data for C1, 1963–65 from water-stage recorder; all other data 1963–66 from weekly staff-gage readings. The 1962 data are from miscellaneous observations by the Bureau of Sport Fisheries and Wildlife.

Dissolved-solids content of pothole waters ranged from 500 to 1,250 ppm. When C2B was separate from C2A its dissolved solids concentration was about one-third higher than that of C2A.

Potholes C3 and C4 also contained dense stands of vegetation in 1962 which had disappeared by 1966. Both potholes went dry for the season in June 1961, and reached their highest subsequent stage in June 1965; there are no records after 1965. The only water analysis was of a sample from pothole C4, obtained in May 1963. It contained 650 ppm of dissolved solids.

WOODWORTH AREA

The locations of the study potholes in the Woodworth area are shown in figure 27. Pothole W2 was chosen because it is in the area of outwash, and pothole W1 was included because it was known to overflow into W2. In 1965 the outflow channel of W1 was dammed to create a lake for the Woodworth Station, and pothole W3 was added to the group of study potholes. Selection of W3 for study was fortunate, for in that year W3 also overflowed into W2. The outwash area contains many gravel deposits, some of which are developed commercially.

During 1962–64 pothole W1 ranged in stage from 1.01 to 1.78 feet gage height; the stages in 1965 were not comparable, owing to the dam. Water was released through the dam occasionally; in April 1965 the release was estimated at 2–3 cubic feet per second. Pothole W2 ranged in stage from 7.37 to 8.67 feet gage height. Except for about a month and a half, including the entire month of July, pothole W2 overflowed from April to November, 1965. It also overflowed in April and May 1963, and in June and July 1964. During the period of record in 1965, pothole W3 ranged in stage from 9.42 to 9.81 feet gage height and overflowed from early August to November. Figure 36 shows Pothole W3 overflowing into Pothole W2 in May 1965, before the gage was established on pothole W3. Hydrographs of the potholes are given in figure 37.[5]

[5] All three potholes were overflowing at the end of April 1969.

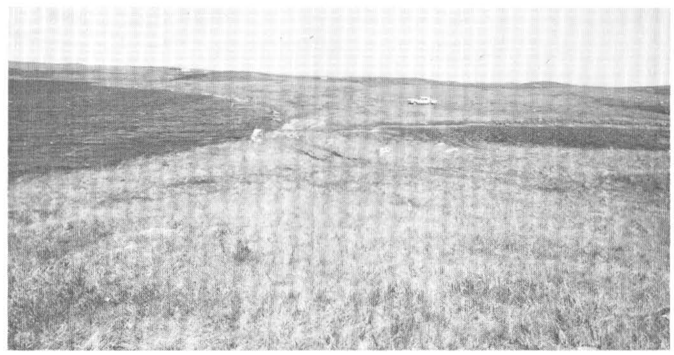


FIGURE 36.—Pothole W3 (right) overflowing into pothole W2 (left) May 1965.

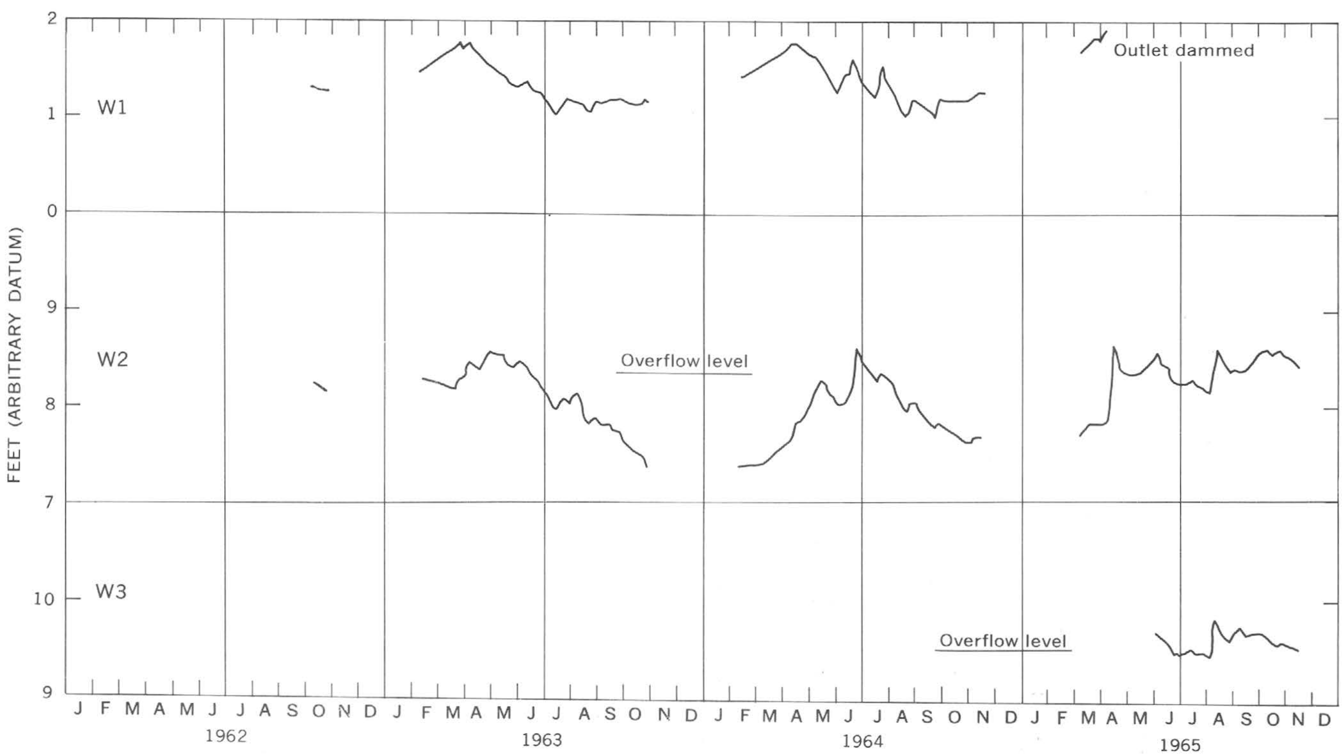


FIGURE 37.—Pond levels in potholes in the Woodworth area, based on weekly staff-gage readings.

Dissolved solids in potholes W1 and W2 in 1963 ranged from 740 to 800 ppm.

DICKEY COUNTY AREA

The locations of the study potholes in the Dickey County area are shown in figure 38. Their areas and capacities are given in table 16.

The maximum stages at all five potholes occurred in July 1964 as the result of a succession of heavy storms.[6]

The vegetation species that were present to at least the extent of being fairly common are listed in table 17; the zones are delineated on the map of each pothole.

The subsurface conditions at the study potholes were investigated by augering twenty-eight 4-inch test holes in their vicinity during the period July 25 to 28, 1960. The test holes ranged in depth from 13 to 27 feet and were in till, except for some small gravel, clay, and sand lenses in three of the holes. One test hole at each pothole was cased with 17 feet of 1¼-inch-diameter galvanized steel casing that was perforated throughout the bottom 8 to 12 feet and left as an observation well. A gravel pack was placed around the pipe in the perforated interval, and clayey glacial till was packed around the pipe near the surface to seal out surface water. Figure 38 shows location of the test holes, their depth, and dominant lithology. The logs of the observation wells are given in table 18.

[6] Much higher stages occurred in early May 1969 as a result of the extraordinary snowmelt that year. Stages in relation to the maximum for July 1964 were as follows: Pothole 5, at least 2.6 ft higher, at which stage it overflowed; pothole 5A, +0.4 ft; pothole 6, overflowed as in 1964; pothole 7, +1.5 ft; and pothole 8, +2.1 ft.

POTHOLE 5

Pothole 5 was considered to be clear of vegetation because there was no emerged species present, except for some in narrow bands along the shore. The vegetation zones and the drainage basin of pothole 5 are delineated in figure 39. Figure 40 shows pothole 5 in September 1961.

The pond in pothole 5 fluctuated between a low stage of 4.2 feet, in the fall of 1961, and a high stage of 7.7 feet, in the summer of 1964. It did not go dry during the study. Generalized variations in dissolved-solids concentration of the pothole waters are listed in table 19.

TABLE 16.—*Area and capacity of study potholes in Dickey County*

Gage height (ft)	Pothole 5		Pothole 5A		Pothole 6		Pothole 7		Pothole 8	
	Area (acres)	Capacity (acre-ft)	Area (acres)	Capacity (acre-ft)	Area (acres)	Capacity (acre-ft)	Area (acres)	Capacity (acre-ft)	Area (acres)	Capacity (acre-ft)
1.7	------	------	------	------	0	0	------	------	------	------
2.0	------	------	------	------	3.7	.7	------	------	------	------
2.44	0	0	------	------	------	------	------	------	------	------
2.5	1.8	0.1	------	------	5.3	3.0	------	------	------	------
2.97	------	------	------	------	------	------	0	0	------	------
2.99	------	------	------	------	------	------	------	------	0	0
3.00	9.4	3.1	------	------	6.1	5.9	.5	.01	.11	0
3.5	13	8.8	------	------	6.7	9.1	7.1	2.0	8.4	2.6
4.0	15	16	------	------	7.3	13	11	6.7	14	8.2
4.5	17	24	------	------	7.8	16	14	13	21	17
5.0	18	33	------	------	8.3	20	16	20	24	28
5.5	19	42	------	------	8.6	25	19	29	26	40
6.0	20	52	------	------	9.0	29	21	39	28	54
6.5	21	62	------	------	9.3	34	23	50	29	68
6.6	------	------	------	------	9.4	35	------	------	------	------
6.7	------	------	------	------	------	------	------	------	30	74
6.9	------	------	0	0	------	------	------	------	------	------
7.0	22	72	.03	0	------	------	24	62	------	------
7.5	23	84	.46	.10	------	------	26	74	------	------
7.8	------	------	------	------	------	------	26	82	------	------
8.0	23	95	1.0	.47	------	------	------	------	------	------
8.5	24	107	1.4	1.1	------	------	------	------	------	------
9.0	25	119	1.7	1.9	------	------	------	------	------	------
9.5	25	131	2.0	2.8	------	------	------	------	------	------
10.0	26	144	2.3	3.8	------	------	------	------	------	------
10.5	------	------	2.5	5.0	------	------	------	------	------	------
11.0	------	------	2.8	6.4	------	------	------	------	------	------
11.5	------	------	3.1	7.9	------	------	------	------	------	------
12.0	------	------	3.4	9.5	------	------	------	------	------	------
Drainage area, including pond	178	------	------	------	36	------	88	------	81	------

TABLE 17.—*Emerged hydrophytes commonly present in study potholes in Dickey County, July 1961 and October 1964*

[D, dominant; A, abundant; C, common; F, fairly common. Where no species is shown in a zone, that zone was mostly open water or no species was present in sufficient amount to be termed "fairly common." See maps for delineation of zones. Vegetation was mapped by R. E. Stewart]

Species	Pothole 5							Pothole 5A			Pothole 5B			Pothole 6							Pothole 7										Pothole 8								
	1961 zone				1964 zone			1964 zone			1964 zone			1961 zone			1964 zone				1961 zone						1964 zone				1961 zone			1964 zone					
	A	B	C	D	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	D	A	B	C	D	E	F	A	B	C	D	A	B	C	A	B	C	D	E	F
Alisma gramineum																					C																		
Calamagrostis inexpansa										F			C																				F			D	F		
Carex atherodes		F				C			A			A		C					A				C									C			F	D		A	
Cirsium arvense							F													C												F							
Distichlis stricta																																				C			
Eleocharis palustris			D						A															D					C			F					F		
Hordeum jubatum			C																						D								F						
Juncus balticus			C				C			A			A												C											D			
Lycopus asper													C																										
Poa palustris							F						C													C													
Polygonum coccineum																C			C																				
Potentilla anserina																										C													
Salix interior																		C																					
Scirpus acutus	D	F	F		A													C				D	D	F				C			D	F		F	F		C		
americanus																								C					C										A
fluviatilis					F										D			C	C																				
Scolochloa festucacea		D				C			F			C		D																		D			F				
Sonchus arvensis			C				C													F												F	F						
Spartina pectinata							C			C			C							C																			
Typha angustifolia																																		F					
glauca					A			A																										F					
latifolia											A																							F	F				

TABLE 18.—*Logs of observation wells at study potholes in Dickey County*

[For locations of wells, see figure 38]

Depth (ft)	Lithology
Pothole 5	
0–1	Black top soil.
1–22	Till, light-brown; high clay content.
Pothole 7	
0–1	Black top soil, boulders.
1–17	Till, light-brown, oxidized; high clay content.
Pothole 8	
0–1	Topsoil.
1–17	Till, light-brown, oxidized; high clay content.

POTHOLE 5A

Pothole 5A contained only water-stage and water-temperature recorders; the instruments on pothole 5 were close enough to provide the other data needed to compute the water budget (fig. 40). The observed stages ranged between 0.9 foot gage height, in the fall of 1963, and 3.6 feet, in the summer of 1964. A view of the pothole is given in figure 40, and the vegetation zones are shown in figure 42. The concentration of dissolved solids was less than 500 ppm.

TABLE 19.—*Approximate concentration of dissolved solids, in parts per million, in pothole 5, 1960–65*

Year	Early season		Midseason		Late season	
	Pond	Observation well	Pond	Observation well	Pond	Observation well
1960	-----	-----	-----	-----	2,500	-----
1961	2,500	6,120	3,800	-----	4,300	6,360
1962	1,700	6,100	1,800	6,650	2,100	6,600
1963	2,000	6,670	2,600	-----	2,900	6,680
1964	1,900	-----	1,700	-----	2,000	-----
1965	1,400	-----	-----	-----	-----	-----

POTHOLE 5B

Pothole 5B contained only a staff gage. It was included in the study because it was so close to pothole 5 and at a much lower elevation, yet the water, as indicated by the vegetation, was much fresher. Obesrved concentrations of dissolved solids in the pond ranged from 300 to 1,000 ppm. The observed stages ranged between 4.0 and 5.9 feet gage height, and some overflows are known to have oc-

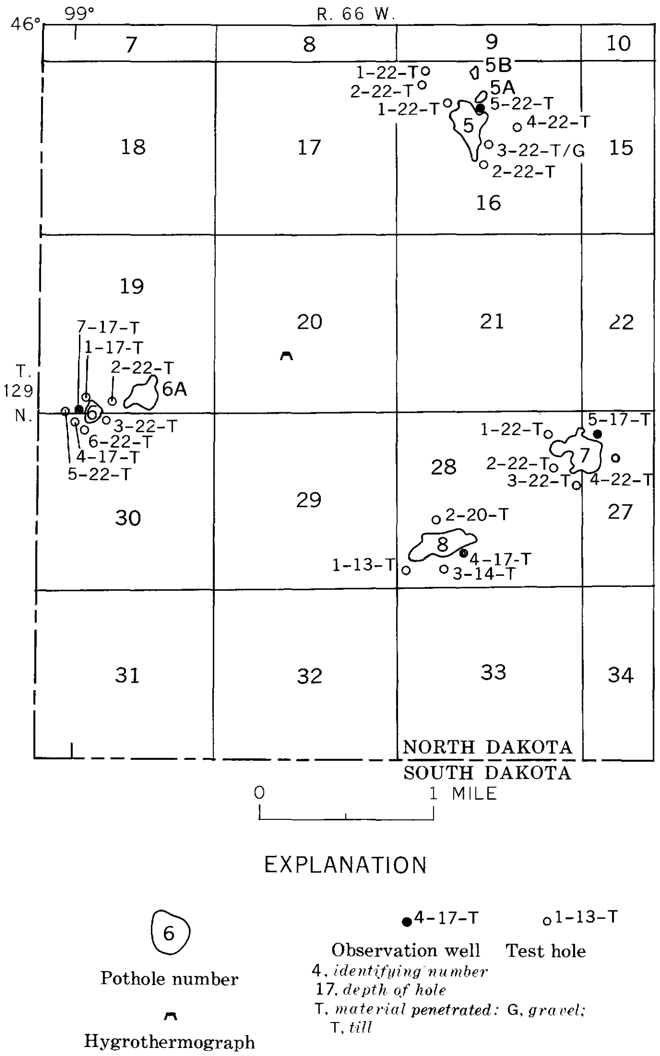


FIGURE 38.—Location of study potholes in Dickey County.

curred. The vegetation zones are shown in figure 39. A view of pothole 5B is shown in figure 41.

POTHOLE 6

Pothole 6 showed a dramatic change as a result of increase in water level. It did not go dry during the study, and the pond level ranged from 3.1 feet gage height, in the fall of 1963, to 7.3 feet, in the summer of 1964. The great increase in stage was from 4.0 feet June 16, 1964, to 7.3 feet July 8, 1964, at which time it was overflowing. The effects of this rise are shown by the vegetation maps and photographs. Figure 42 shows an outline of the drainage basin of pothole 6 and the vegetation as it was mapped in July 1961. Figure 43 is an aerial photograph of the vegetation in September 1961. The vegetation map for June 16, 1964, (fig. 44) shows a somewhat smaller open-water area than in July 1961.

The photograph, taken on June 10, 1964 (fig. 45), shows that there was indeed a dense stand of vegetation on that date. Less than 1 month later, the vegetation had been drowned, owing to the higher pond stage, and, as shown in figures 44 and 46, the pond was clear of vegetation except for that growing in a narrow band near the shore. The pothole was still clear when it was last observed in June 1968.

The 1964 rise in water level of pothole 6 was largely the result of inflow from pothole 6A, which has a far larger drainage basin than pothole 6 when 6A is not contributing. Pothole 6 overflowed in 1964, and again in 1965. The inflow and outflow channels are indicated in figure 44 and are pictured in figure 47.

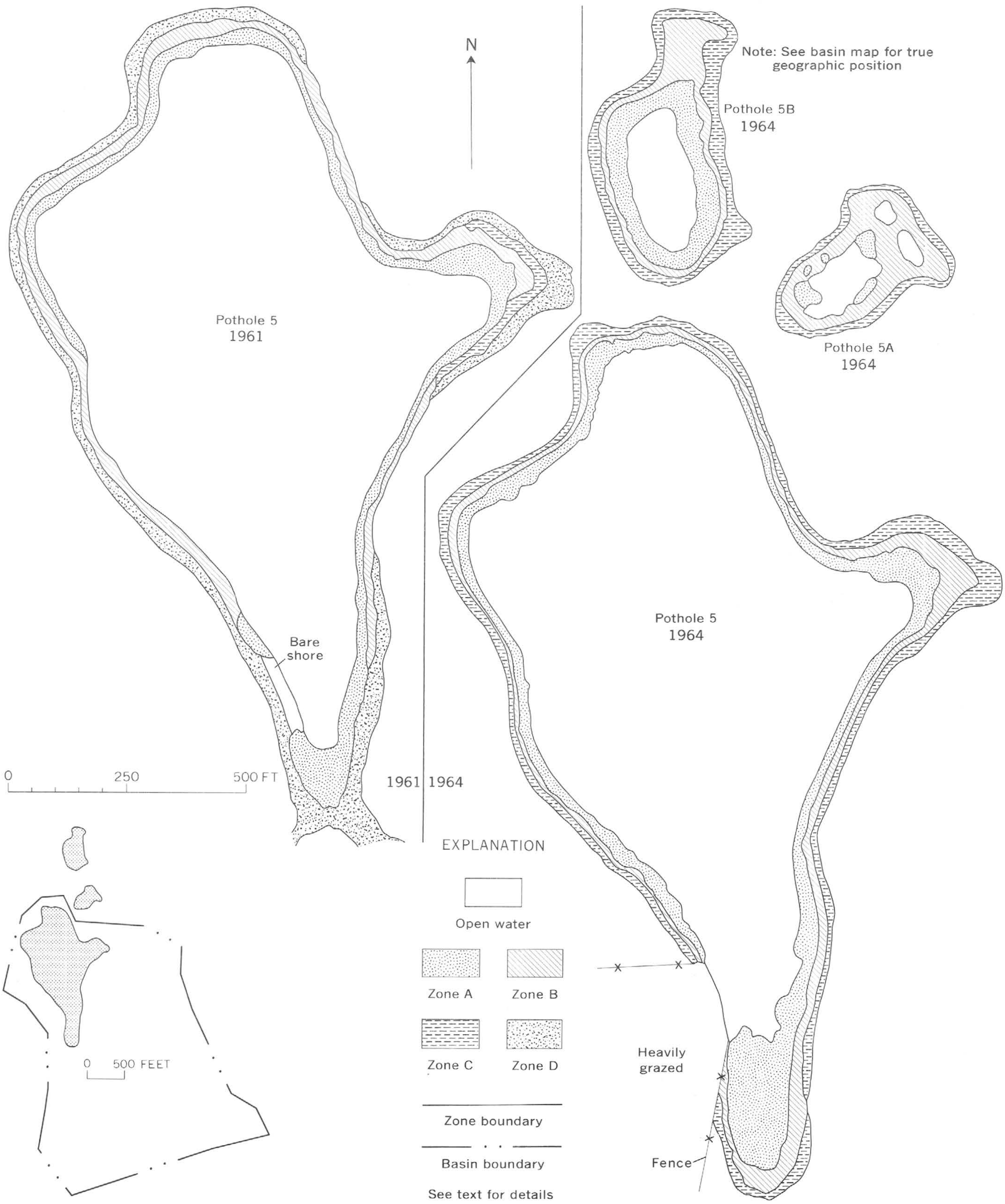


FIGURE 39.—Drainage basin of pothole 5, showing vegetation zones of pothole 5 (only) in 1961, and vegetation zones of potholes 5, 5A, and 5B in 1964. Vegetation was mapped by R. E. Stewart. See table 17 for plant names.

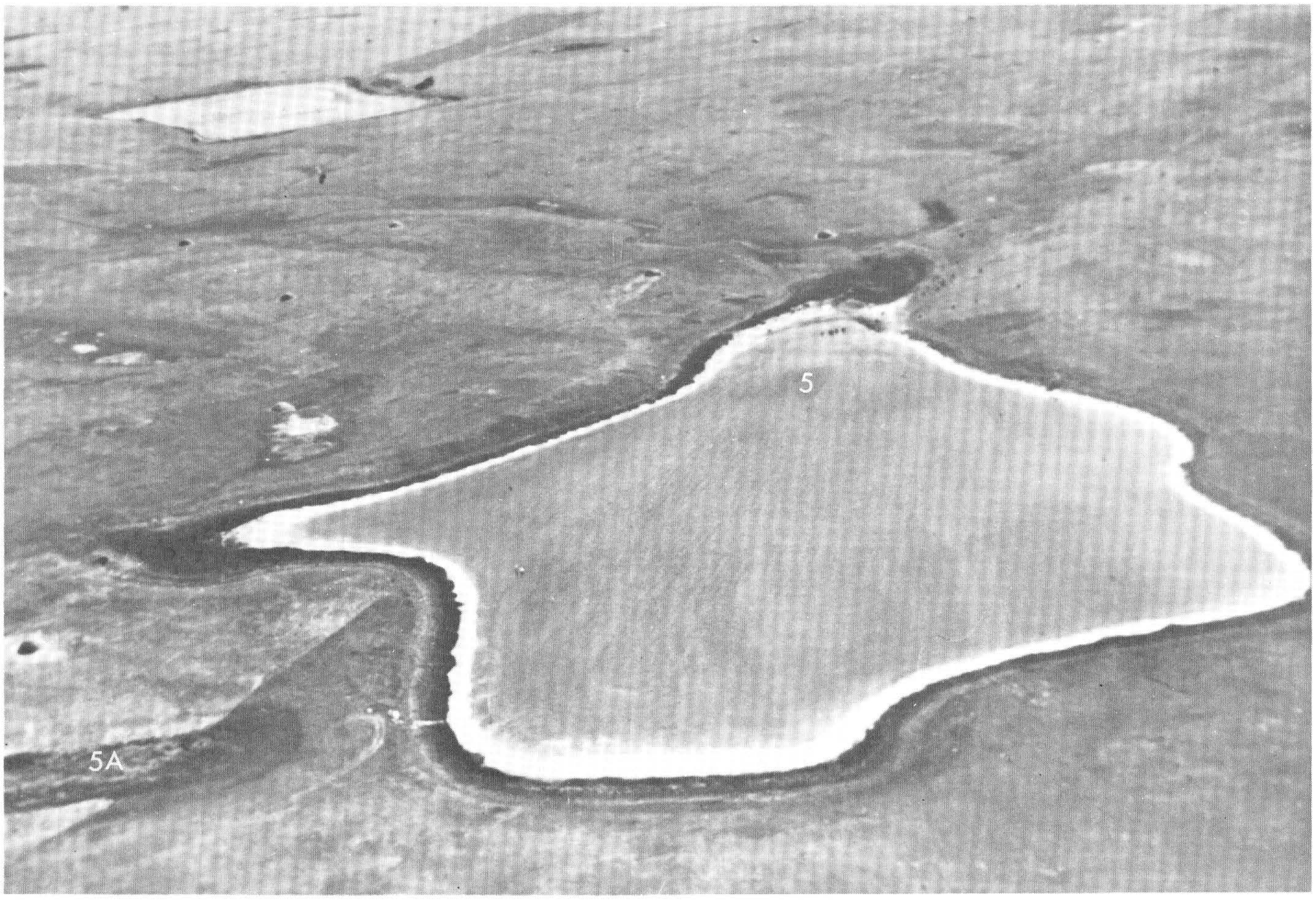


FIGURE 40.—Southward aerial view of potholes 5 and 5A, September 1961. Photograph by W. P. Sebens.

FIGURE 41.—Southward view of pothole 5B.

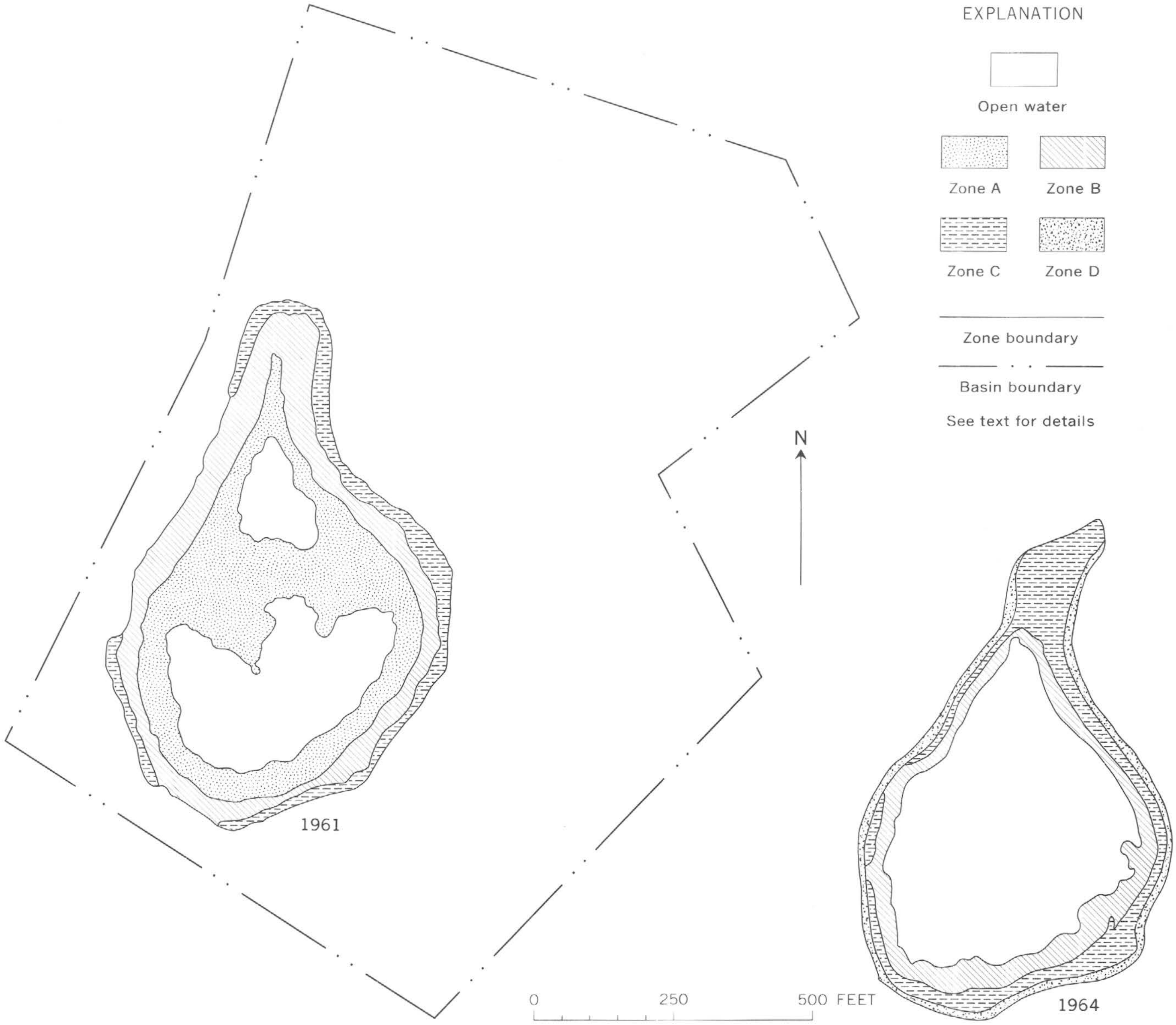


FIGURE 42.—Drainage basin of pothole 6, showing vegetation zones in July 1961 and October 1964. Vegetation was mapped by R. E. Stewart. See table 17 for plant names.

The variations in the concentration of dissolved solids in the pothole water are given in table 20.

TABLE 20.—*Approximate concentration of dissolved solids, in parts per million, in pothole 6, 1960–65*

Year	Early season		Midseason		Late season	
	Pond	Observation well	Pond	Observation well	Pond	Observation well
1960	-----	-----	-----	-----	450	-----
1961	450	3,170	500	-----	475	3,450
1962	275	3,050	370	3,700	380	3,600
1963	290	3,440	320	-----	350	3,370
1964	450	-----	575	-----	625	-----
1965	600	-----	-----	-----	-----	-----

POTHOLE 6A

Pothole 6A was clear of vegetation throughout the study. The staff-gage record was useful in interpreting the record of pothole 6, especially with respect to inflow. A view of the pothole is shown in figure 48, and its relation to pothole 6 is shown in figure 47. The pond levels fluctuated between 3.4 feet gage height, in the fall of 1963, and 6.0 feet, in the summer of 1964. The concentration of dissolved solids in the pothole waters averaged about 820 ppm in 1963. Daily variations of several constituents were measured by Mitten (1965).

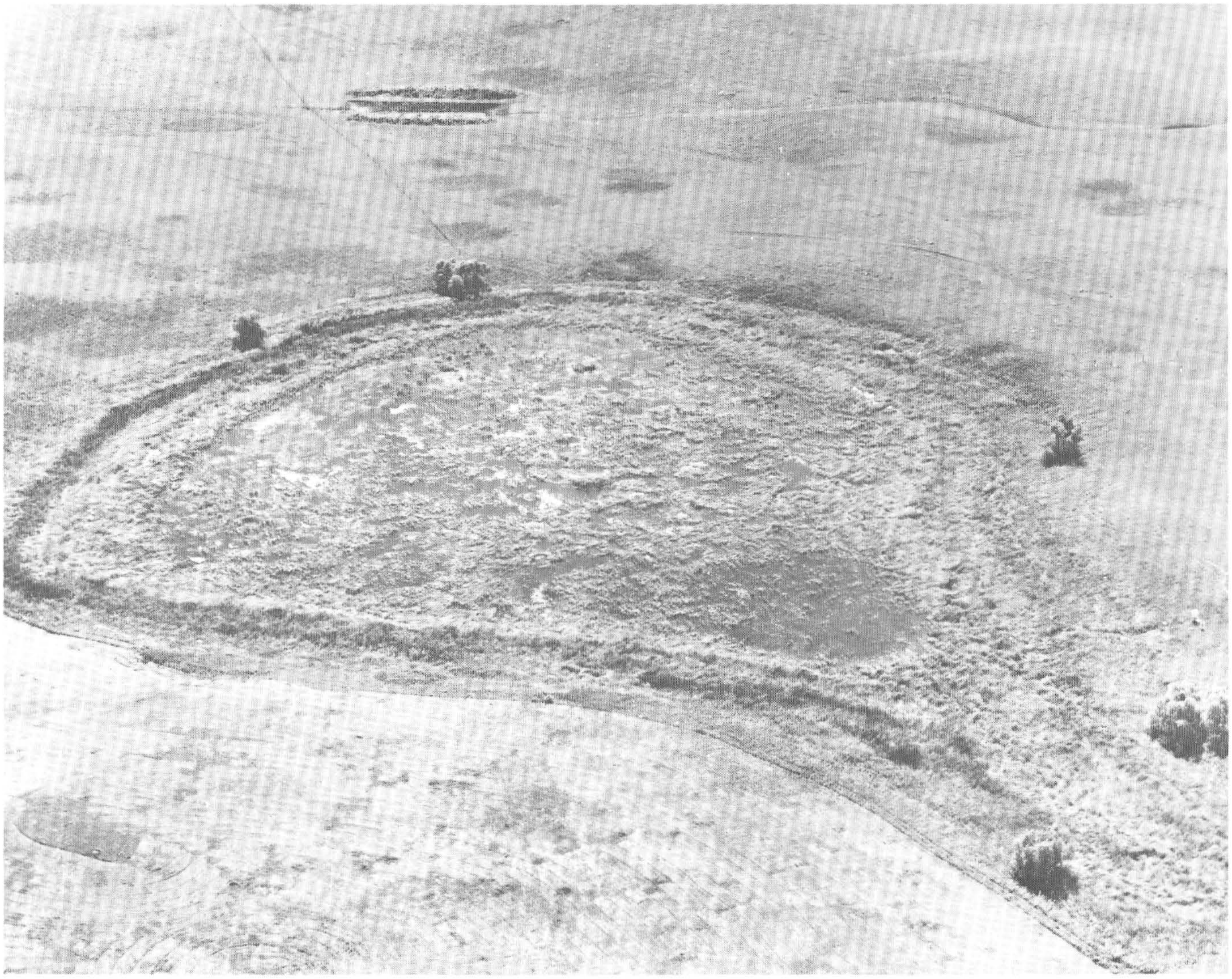


FIGURE 43.—Southwestward aerial view of pothole 6, September 1961. Photograph by W. P. Sebens.

POTHOLE 7

Originally, pothole 7 was heavily vegetated, which lasted to the summer of 1964, but by the fall of that year, most of the vegetation had been drowned, as indicated by the vegetation map, (figure 49). The pothole had the same appearance in August 1965 (fig. 50) and was still mostly clear when last observed in June 1968. Pothole 7 went dry in October 1960 (gage height, 3.0 ft) and was dry during most of 1961. The maximum stage, 8.4 feet gage height, was reached in July 1964. At stages above 7.5 feet, the pond in pothole 7 coalesced with the two to the south and west (fig. 51). At times, there was spring inflow at the northwest corner of the pothole. This inflow was measured in June 1965 and found to be equivalent to about a 0.0005 foot per day change in stage of the pond. The range in concentration of dissolved solids of the pothole waters is given in table 21.

TABLE 21.—*Approximate concentration of dissolved solids, in parts per million, in pothole 7, 1960–65*

Year	Early season		Midseason		Late season	
	Pond	Observation well	Pond	Observation well	Pond	Observation well
1960	-----	-----	-----	-----	1,600	-----
1961	950	5,100	850	-----	2,000	5,040
1962	900	4,600	750	4,600	750	4,730
1963	900	3,820	1,000	-----	900	4,660
1964	900	-----	900	-----	1,100	-----
1965	950	-----	-----	-----	-----	-----

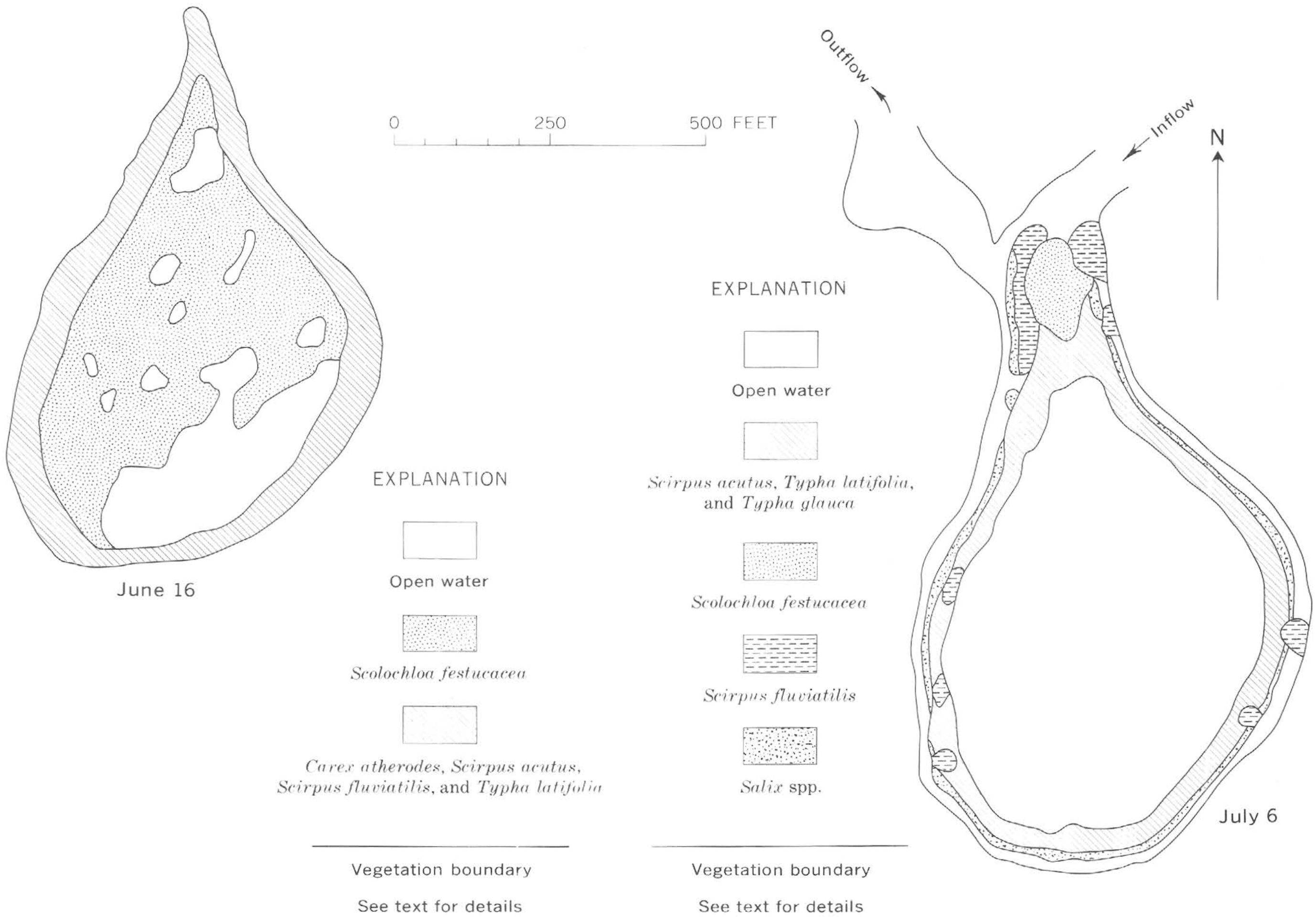


FIGURE 44.—Changes in vegetation from June 16 to July 6, 1964, in pothole 6. Vegetation was mapped by L. F. Lautenschlager.

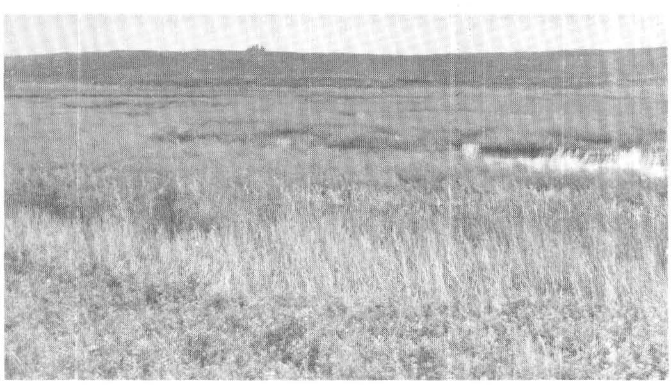


FIGURE 45.—View of vegetation-filled pothole 6, June 10, 1964.

FIGURE 46.—View of clear pothole 6, July 6, 1964.

FIGURE 47.—View of potholes 6 (right) and 6A (left-center background), the channel connecting them, and the outflow channel from pothole 6 (left foreground), June 1965.

FIGURE 48.—Pothole 6A, viewed toward pothole 6. Trees beyond pond are those shown in figure 43.

POTHOLE 8

Pothole 8 went dry for the season in October 1960 and July 1961; figure 52 shows the pothole when it was dry in 1961. It has not gone dry since (as of June 1968). The pothole was filled with dense stands of vegetation until the high stages of 1964 started the clearing process, presumbably by drowning; the maximum stage was 7.6 feet in July 1964. Beginning in 1965, the pothole was virtually clear of vegetation, except for that growing in a narrow band nearshore. The vegetation zones of 1961 and 1964 are shown in figure 53. During the high stages of 1964, the pond coalesced with the pond just to the north, which kept its vegetation while the vegetation was disappearing from pothole 8. Some surface inflow to pothole 8 occurred in 1964 and in 1965. The maximum observed stage was 7.5 feet, in July 1964. The range in dissolved-solids concentration is given in table 22.

TABLE 22.—*Approximate concentration of dissolved solids, in parts per million, in pothole 8, 1960–65*

Year	Early season		Midseason		Late season	
	Pond	Observation well	Pond	Observation well	Pond	Observation well
1960	-----	-----	-----	-----	500	-----
1961	900	-----	600	5,540	900	1,830
1962	600	-----	500	6,100	500	-----
1963	400	-----	450	-----	500	5,740
1964	500	-----	550	-----	650	-----
1965	650	-----	-----	-----	-----	-----

SUMMARY OF INVESTIGATIONS

VARIABILITY OF WATER SUPPLY

The number of migratory waterfowl available for hunting each fall is very closely related to the water supply of the prairie potholes. Unless waterfowl find sufficient pothole ponds for their needs, they do not breed. Pothole ponds can be classified roughly into two groups: those that tend to go dry because their source of water is almost all precipitation and runoff, and those that are relatively permanent because their water supply includes substantial seepage inflow. Potholes with substantial seepage inflow are generally found in outwash areas, and the inflow often comes from beyond the surface-drainage area. As such ponds are mostly permanent, they do not present much of a problem, other than the fact that they tend to be saline, as described in the section entitled "Ground-Water Hydrology." The water supply of the potholes in this group will not be considered further in the present report.

Precipitation is the basic source of water in potholes, as it reaches the pond by falling directly on its surface; also, it is the only source of inflow that is sure to occur from every storm. Runoff from the drainage basin is small and highly variable, but it is the key source that determines whether a pond will persist. Because seepage inflow is minor for potholes in the first group and can seldom be separated from runoff, the two (runoff and seepage) are usually considered together as basin inflow.

Precipitation on a pond varies appreciably from year to year (fig. 13), but seasonal replenishment of about 12–15 inches can be expected on the average. Average precipitation is far too small to meet the demands of evaporation. (See fig. 1.) Even in years of maximum precipitation, the average annual evaporation is greater. For a pothole to have a permanent pond, therefore, basin inflow must be large enough not only to meet all demands of evaporation not supplied by precipitation, but also to meet

FIGURE 49.—Drainage basin of pothole 7, showing vegetation zones in 1961 and 1964. Vegetation was mapped by R. E. Stewart.

all other depletions—especially that from seepage outflow.

As explained in the section "Climate," the ratio of average annual precipitation to average annual lake evaporation is a measure of the extent to which ponds will be present in the potholes over the years. Wide deviations from this precipitation-evaporation ratio occur in individual years. The effects of infiltration are such that precipitation during a single season or even a year may be completely unrelated to the basin inflow that occurs during that period.

Snowmelt flowing over frozen ground is believed

FIGURE 50.—View of pothole 7 in August 1965, showing pond clear of vegetation except for scattered plants of *Scirpus acutus*.

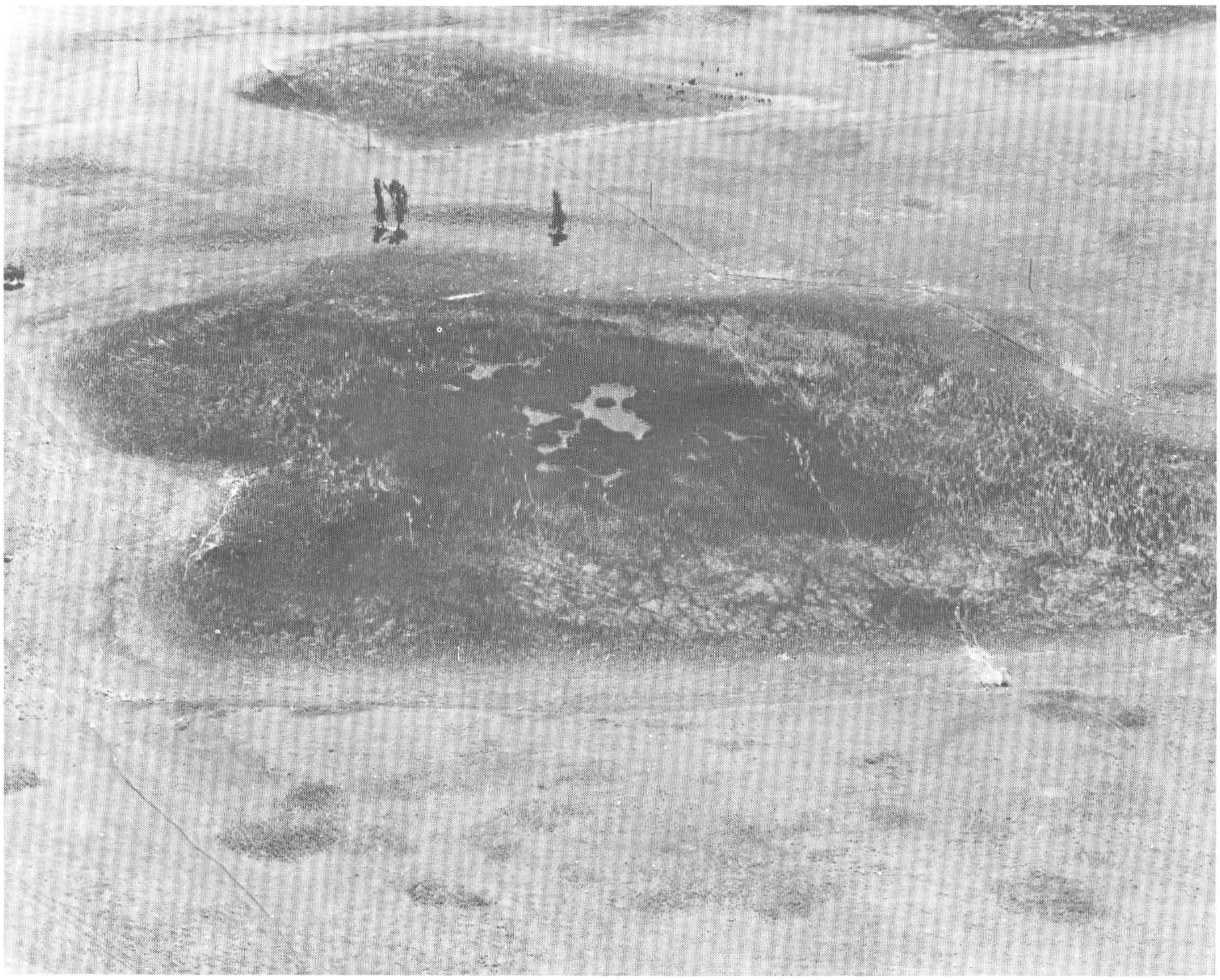


FIGURE 51.—Southwestward aerial view of pothole 7, September 1961. In 1964 the pond in pothole 7 coalesced with the two other ponds (shown at top of photograph). Spring inflow occasionally entered pothole 7 from the extreme right foreground. Photograph by W. P. Sebens.

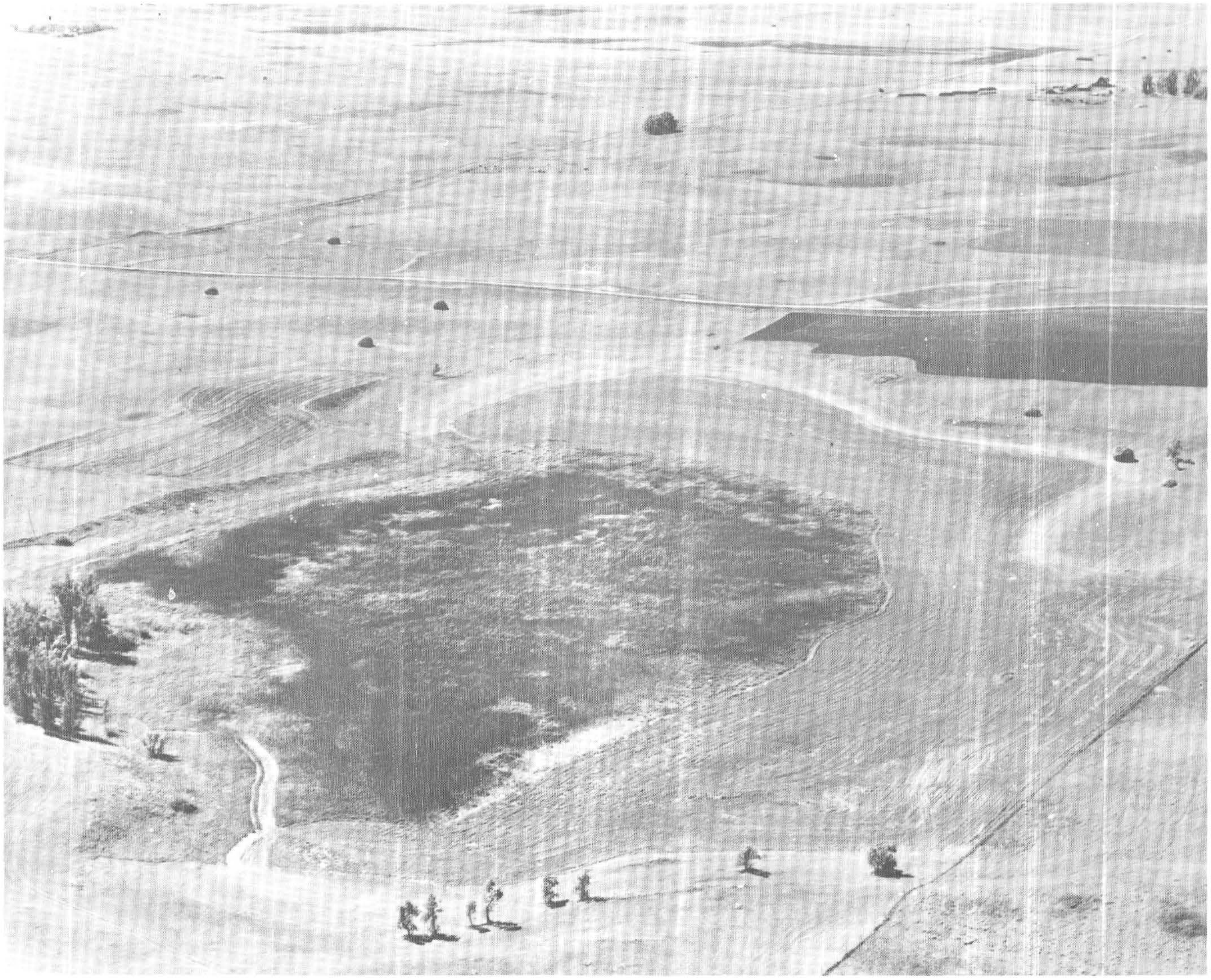


FIGURE 52.—Southwestward aerial view of pothole 8, September 1961. The pothole had been dry since mid-July, and the owner had mowed the grasses in the shallow-marsh zone. Photograph by W. P. Sebens.

by many people to be the largest source of water supply of prairie potholes. It does occur every year, but only infrequently does it contribute as much water as does precipitation. On the average, snowmelt inflow is equal to only 65 percent of the annual supplied by precipitation. Further, basin inflows that are great enough to offset the water loss not offset by precipitation and seepage inflow result about as frequently from summer rains as they do from snowmelt. Generally, large basin inflows from snowmelt are restricted to those years when the snow cover remains until spring, owing to persistent cold weather, and then melts rapidly while the ground is still frozen. A heavy snow cover is not essential. Such a condition occurred in Ward County in the spring of both 1960 and 1962. (See fig. 54, which shows the relation of seasonal precipitation to basin inflow at pothole 3.) During the preceding winters of both 1960 and 1962, there was less than normal seasonal snowfall, yet the basin inflows were the largest seasonal inflows during the study.

In contrast to these years, the year with the highest November–April precipitation (1961) had the lowest basin inflow for winter. The situation with respect to summer (May–October) rainfall is similar. The year of highest rainfall (1962) produced less basin inflow than the year of lowest rainfall (1961).

Even on an annual basis, there seems to be no correlation between precipitation and basin inflow.

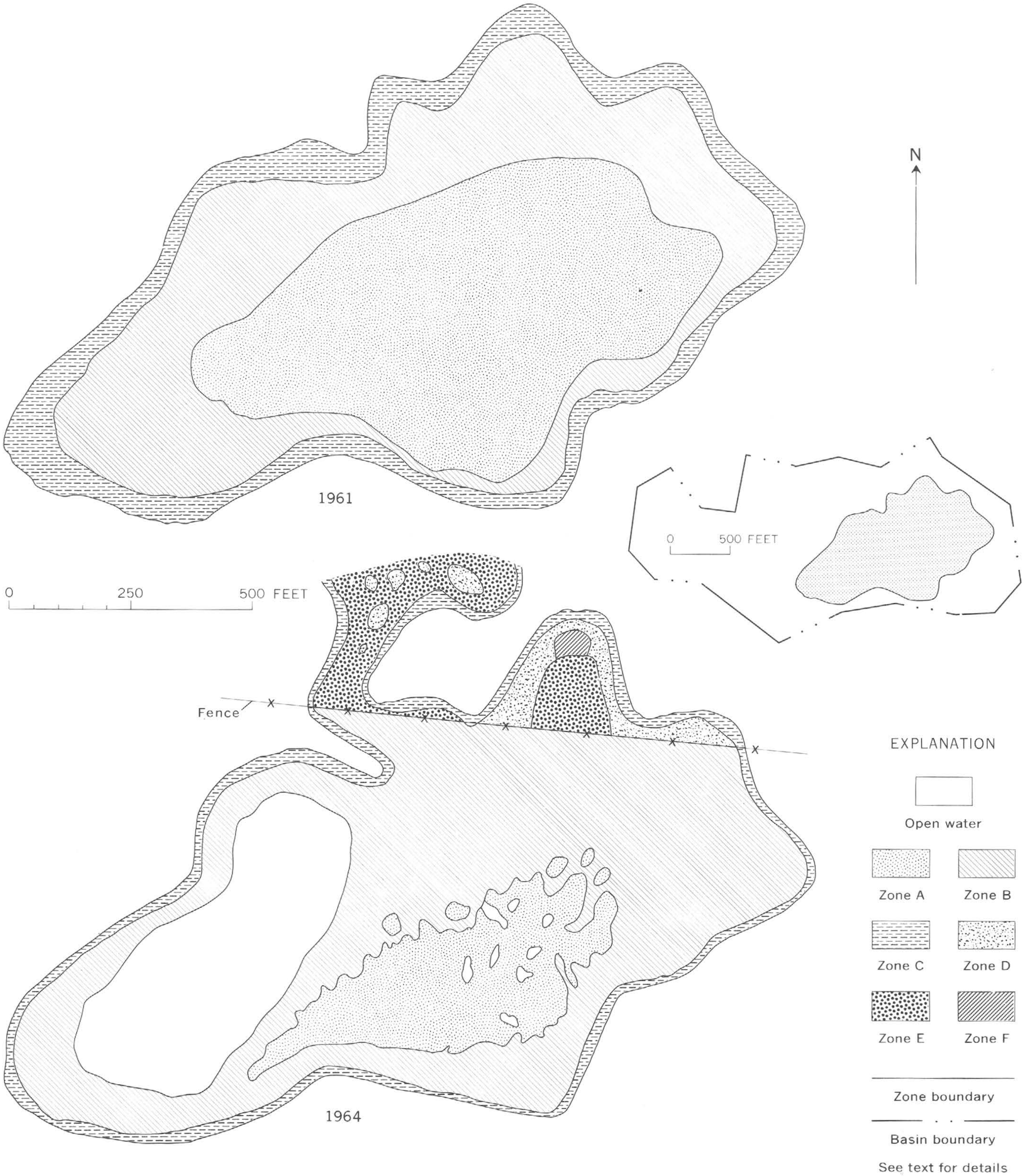


FIGURE 53.—Drainage basin of pothole 8, showing vegetation zones in 1961 and 1964. Vegetation was mapped by R. E. Stewart.

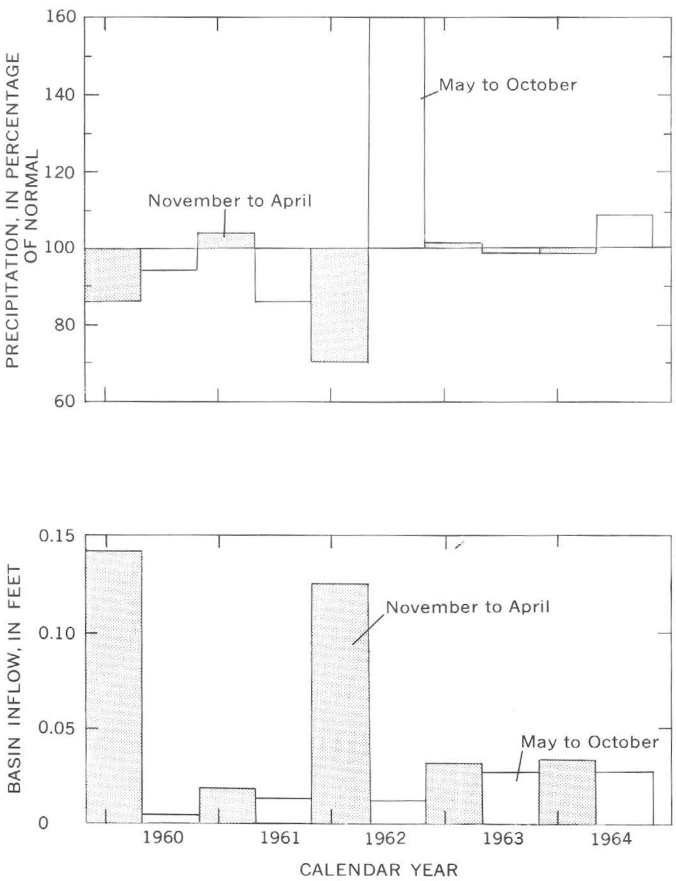


FIGURE 54.—Relation of seasonal precipitation to basin inflow at pothole 3.

The potholes studied in Dickey County are used for this example. During 1962–64 there was never as much as 0.1 inch of precipitation during the last half of September. By this time of year, the potholes have lost most of the water they will lose by evapotranspiration. Therefore, the last 2 weeks of the water year seems a logical time period to use for comparisons among years. Pond stages were averaged for these 2 weeks and compared with the precipitation records at Ashley (fig. 13). The precipitation gage is only 20 miles from the farthest pothole studied. Precipitation in 1964 was 0.05 inch less than that in 1962, yet pond stages were 1–2 feet higher than those in 1962. This condition probably occurred because the rains in 1964 were concentrated in a few weeks, and in 1962 the rains were spread over a much longer period. Also, precipitation in the year preceding 1962 was much less than that in the year preceding 1964. The general level of the water table is doubted to have had much influence because the well levels were generally below pond levels during this period.

The reason for these anomalies can be found in the variation in basin inflow from individual storms. As shown elsewhere (Eisenlohr, 1969b), the infiltration capacity of the soil controls to a very great extent the amount of overland flow. Channel and seepage inflow, the other factors in basin inflow, are minor factors and are not considered in this discussion.

Overland flow can occur only when the precipitation rate exceeds the infiltration capacity of the soil. It is convenient to describe the soil as saturated when this occurs. The term "Saturated" here refers to the inability of the soil to absorb all the water on its surface; however when the term is used with respect to infiltration capacity, it does not imply that all the pores in the soil are filled with water down to an impervious boundary.

When a soil is frozen, it is usually impervious. That is, for a soil to freeze, there must be sufficient moisture in the soil to form the ice that usually creates a barrier which prevents the vertical movement of water and of water vapor through the soil.

The infiltration capacity of an unfrozen soil may be highly variable, as a result of varying moisture content, especially if the soil contains an appreciable amount of montmorillionite clay. Such clays are present in the tills of the Coteau du Missouri.

The controlling effect of infiltration capacity is shown in the following examples. First, consider a pothole in Dickey County (pothole 5, fig. 55). This pothole received 0.18 foot of rain on July 5, 1964, and another 0.05 foot of rain about 24 hours later. There had been no previous rain at the pothole since July 1, when 0.07 foot of rain fell. Some drying of the soil undoubtedly took place in the 3-day interval, so the effect of soil moisture on producing basin inflow on July 5 is not known. It is known, however, that on July 5 the rainfall was very heavy, so heavy that it is not expected to occur at that rate and duration oftener than once in 10 years, on the average (U.S. Weather Bureau, 1955, p. 34). This storm raised the water level in the pothole by 0.385 foot. About 45 percent of this rise in level resulted from direct precipitation on the pond, and the other 55 percent resulted from basin inflow. The second storm was not especially heavy, but coming so soon after a heavy rain, the 0.05 foot of rain caused a rise in pond stage of 0.156 foot on July 6.

In contrast to these responses are those August 17–20—a little more than a month later—no rain had fallen for more than a week, and less than 0.04 foot had fallen since the first of the month. On August 17, 0.04 foot of rain fell in the morning,

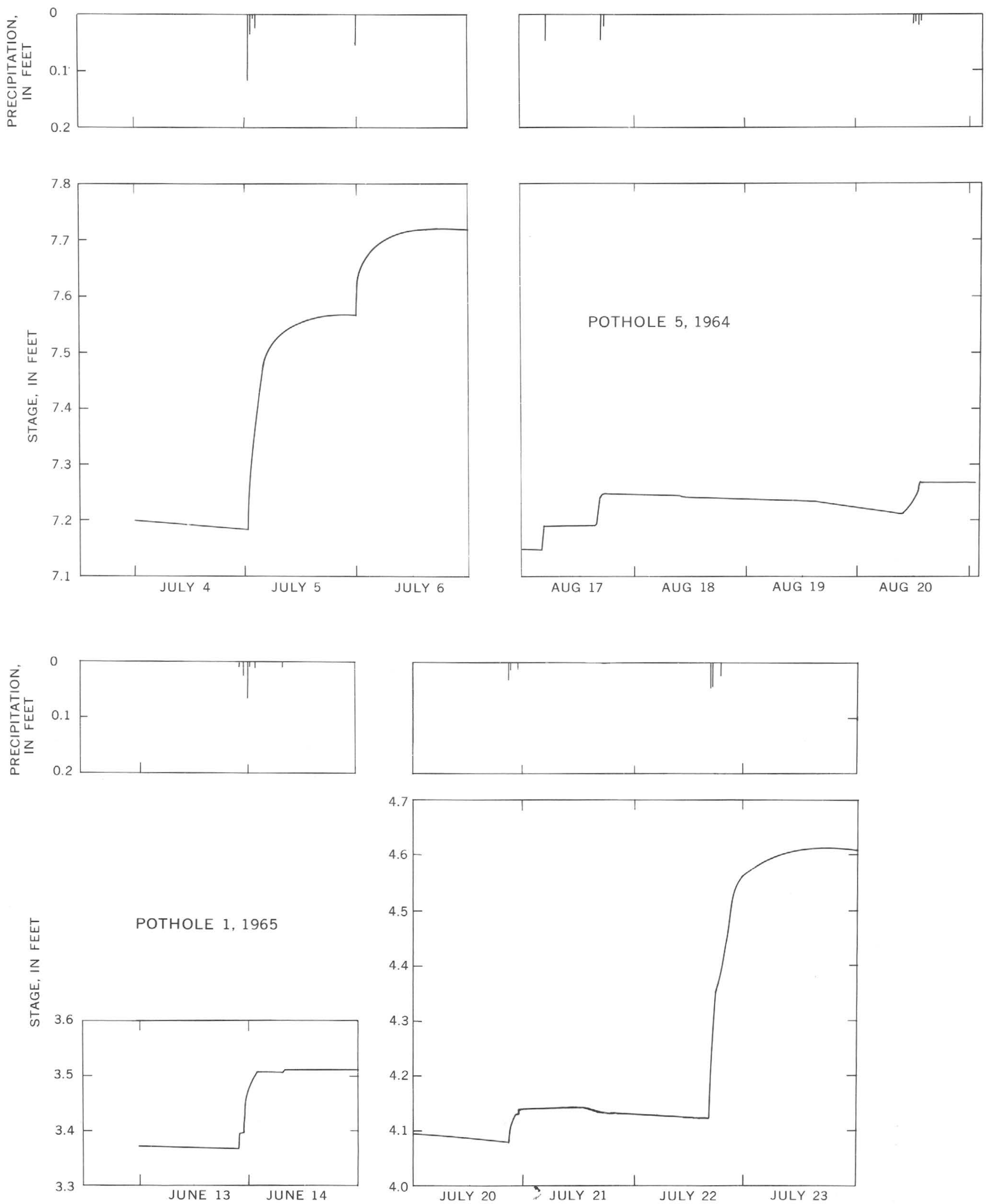


FIGURE 55.—Effects of high and low infiltration rates.

another 0.06 foot fell in the afternoon, and on August 20, 0.05 foot of rain fell about noon. No basin inflow resulted from any of these rains, and the first rain of 0.04 foot fell in about half an hour.

Compare, then, the two storms that produced 0.05 foot of rain each—one, on July 6, that produced basin inflow equal to twice the amount of rain that fell directly on the pond, and the other, on August 20, that produced no basin inflow at all. Note, also, that the 0.05 foot of rain that fell about midnight of July 5 was far more effective in producing basin inflow than was the 0.18 foot of rain that fell less than 24 hours earlier. Basin inflow equalled only 1.1 times the amount of precipitation from the first storm, but equalled 2.1 times the amount of precipitation from the second, smaller storm.

The lower part of figure 55 shows a second example (pothole 1) in which the time relationship is reversed. The chart for June 13–14, 1965, shows that rain of 0.125 foot produced a rise of 0.146 foot in the pond, 0.021 foot of which was basin inflow, or less than 0.2 of the amount of precipitation. Of the 0.125 foot of rain, 0.117 foot of this fell in 3½ hours, but there had been no rain for more than 2 weeks prior to that on June 13. The chart for July 20–23 shows that a rain of 0.108 foot on July 22, which fell within 3 hours, caused the pond to rise 0.495 foot, 0.387 foot of which came from basin inflow, or 3.6 times the amount of direct precipitation on the pond.

This last example shows the great influence that the condition of the soil has in controlling the amount of basin inflow. The rain of 0.05 foot on July 20 (only 42 hours before the rain on July 22) conditioned the soil such that overland flow was able to occur on July 22. In the example, the rainfall intensities are almost the same (0.117 foot in 3½ hours compared with 0.108 foot in 3 hours), so intensity of precipitation was not a factor. Thus, the fact that the second storm produced more than 3½ times the amount of basin inflow (0.495/0.138 = 3.6) than did the first storm must be the result of the antecedent rainfall July 20 prewetting the soil.

Prewetting seems to be the major factor in this phenomenon. It is postulated that drying of the montmorillonitic clays in the till causes vertical cracks. These cracks allow rapid penetration of water during a rainstorm until the moisture penetrates the dried blocks of clay, causing them to swell and close the cracks. Seemingly, this swelling is not rapid enough to take place during an individual rainstorm; hence, it is the effect of the preceding storm that produces these ground conditions.

That the prairie soils when dry can absorb large amounts of rain is indicated by two infiltrometer tests made in April 1963 at widely separated locations. They were made with a USGS microrainulator infiltrometer (McQueen, 1963) under the personal supervision of I. S. McQueen.

At a site in the Mount Moriah area, 0.23 foot of simulated rain was absorbed in an hour. A pit was dug near the instrument and soil samples were collected for the determination of moisture content. The appearance of the walls of the pit suggested that vertical cracking does occur. Although the top layer of the soil had a moisture content of 61 percent of the dry weight of the sample, the moisture content at depths below 0.5 foot was less than 25 percent. There had been no rainfall of much more than a trace since 0.01 foot of rain fell 6 days previously.

At a site adjacent to pothole 4 in Ward County, 0.24 foot of simulated rain (using distilled water) was absorbed in an hour. The last previous rain was about 0.02 foot, 10 days earlier. The soil-moisture content of the surface layer was 25 percent, based on the weight of the dry sample. It was 5 percent in the gravel layer (fig. 88), at a depth of 0.2 foot to 0.5 foot, below which depth it increased, as a saturated zone was reached at about 1.0 foot. An analysis of the water applied in excess of the infiltration capacity of the soil is given in table 32, which shows how rapidly water can dissolve minerals on the ground surface.

Basin inflow may sometimes depend on the configuration of the drainage basin. Some potholes that have large drainage basins may have areas that are noncontributing except in years of high basin inflow. In those years, however, runoff from normally noncontributing areas may overflow into the pothole and add enough water to assure a water supply in the pothole for several years.

This condition is believed to be the explanation of a sequence of events at pothole 3, which went dry in 1964, 3 years after other potholes around it had gone dry. When the other potholes received an appreciable amount of water in 1965 and 1966, pothole 3, although it has by far the largest drainage area, received little water, presumably because much of the drainage area did not contribute in those years.

Also, the known high basin inflows in 1950 are surmised to have kept many potholes from going dry until the drought of 1960–63. Thus, basin inflow can be considered as the key to permanence of water in a prairie pothole. Unfortunately, large amounts of basin inflow occur only sporadically and unpredictably. Shjeflo (1968, table 5) found that only in 1964—and then only at potholes 5, 7, 8, and C1—did basin inflow exceed the precipitation on a study pothole.

PREDICTABILITY OF WATER SUPPLY

Gains in the water supply of prairie potholes can be erratic and unpredictable, as described in the preceding section. (In contrast, the water losses from prairie potholes vary within narrow limits and are predictable.) The predictability of the midsummer water supply in prairie potholes 1 year in advance would be of great help in determining the allowable number of migratory waterfowl that can be hunted each fall. The number of birds to be taken each hunting season is regulated so that the remaining bird population, plus the expected production following the summer, will provide suitable hunting the following fall. The big unknown is "the production the following summer," which, in turn, is very largely determined by the pothole water supply. The changes in pothole water supplies appear to be so fortuitous that the only practical method of prediction is seemingly one based on probabilities.

The method of prediction to be described was first suggested in 1967 (Eisenlohr, 1969b) and then further developed in an administrative release to the Bureau of Sport Fisheries and Wildlife.

The water level in a pothole on September 30 (the last day of each water year) is probably the best base for predicting the water levels to be expected following summer. This date is chosen because, at that time, evapotranspiration losses are about over for the season, persistent ice covers are not yet established, and precipitation in late September usually is very low. Thus, September 30 water levels can be expected to be fairly stable and close to their minimums for the year. Water levels in potholes at the end of July are used as an index of the estimated waterfowl production in that year. Therefore, the change in water level of a prairie pothole between September 30 and the following July 31 would be a logical prediction unit. The basic requirement is a water-level record sufficiently long that the probabilities can be determined with reasonable accuracy.

Assuming such a record exists, it is necessary only to determine the increases in water level for the prediction periods, arrange them in order of magnitude, and plot them on probability paper. Then with a known water level on September 30, either of two values can be obtained: (1) the probability of having at least a given water level the following summer, or (2) for a selected probability, what water level will be reached. In either prediction, the change obtained from the plot on probability paper is added to the level on September 30.

Records from the Mount Moriah area will be used to illustrate the procedure. It is emphasized that the diagrams to be presented are for illustration only; the records on which they are based are entirely too short for satisfactory use. At least 10 years of record are needed before much dependence can be placed on the results.

Of the 14 potholes for which the hydrographs are shown in figure 30, only five could be used in a probability study because the others either overflowed or went dry too often. Those used were potholes M12, M34, M35, M42, and M43. The changes in water levels between September 30 and July 31 were computed for each year and arranged in order of magnitude. The probability of each value was computed as $p = m/(n + 1)$, in which m is the order number of each value, beginning with the largest, and n is the total number of values for each pothole. The data plotted on probability paper are shown in figure 56.

By using this diagram to show the method of application (despite the fact that it is not sufficiently well defined), it is found that the water

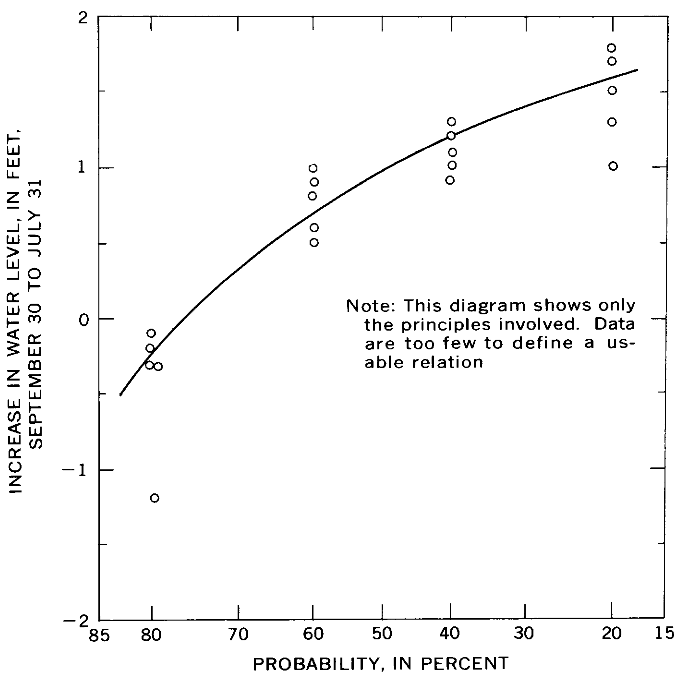


FIGURE 56.—Probability of change in pothole water levels, September 30 to July 31.

level in a pothole on July 31 of any year has a 75 percent chance of being as high as it was on September 30 of the preceding year, and a 50 percent chance of being as much as 1.0 foot higher. Viewed another way, if the desired water level on July 31 is 0.5 foot higher than the level of the preceding September 30, there is a 65 percent chance that this will occur. A study of the hydrographs in figure 30 shows that the years 1964–66 are in the beginning of a wet cycle, and figure 56 contains this bias.

For potholes that go dry in many years, another approach is necessary. A possible approach might be to relate the frequency with which a pothole goes dry to the "wetness" of nearby potholes that seldom, if ever, go dry. For this approach, probability will be measured in percent of time. Thus, a probability of 40 percent is equivalent to 4 years in 10. Suppose a pothole goes dry 6 years out of 10. This means that in 4 years out of 10, or 40 percent of the time, that pothole has water in it on July 31. Now, suppose a nearby pothole that usually contains water, has an average level on July 31 of 3.0 feet; suppose, also, that its level on September 30 is 2.0 feet. Then, if the curve in figure 56 were usable, one would find that, for a 50-percent probability, the rise in water level would be 1.0 foot. This would make the expected level 3.0 feet on July 31 for the pothole usually containing water. This is the average level for this pothole on July 31, and 40 percent of the time it contains that much water or more based on the diagram of figure 57, which is derived

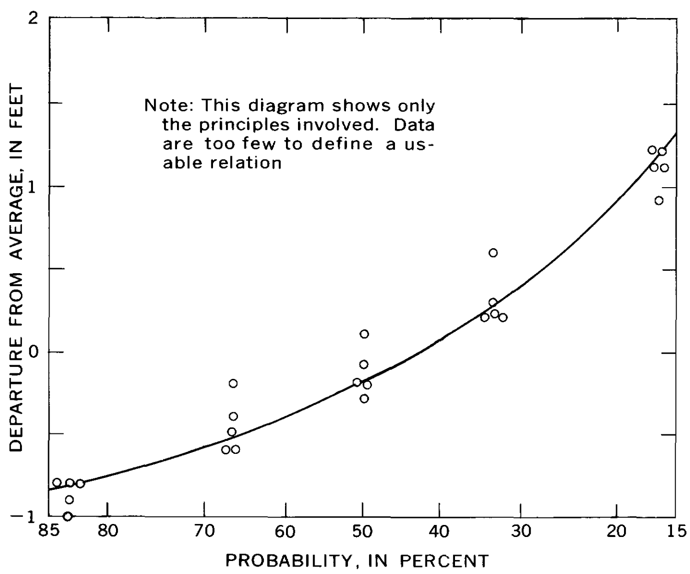


FIGURE 57.—Probability of departures from average water level on July 31.

from the same date used to plot figure 56. The same conditions are true for the pothole that frequently goes dry; 40 percent of the time it holds water on July 31. The tenuous conclusion is that the pothole that frequently goes dry has a 50-percent chance of containing water on July 31 in the year in question. Admittedly, such computations are somewhat conjectural, but for lack of a better method, and because of the economic need, perhaps they are of some value.

EVAPOTRANSPIRATION AND THE WATER BUDGET

The principal objective of the first part of this investigation was to determine the evapotranspiration losses from prairie potholes. The work was done by Shjeflo and published as chapter B (1968) of the present series. In summary, the procedures used followed the method first proposed by Langbein, Hains, and Culler (1951, p. 13) and subsequently described in detail by Harbeck (1962) for determination of evaporation losses from water bodies clear of emergent aquatic vegetation. The method was modified by Eisenlohr (1966b) for this study to also apply to water bodies filled with emergent aquatic vegetation. The basic equation is the simplified mass-transfer equation given by Harbeck (1962, p. 101):

$$ET = N\,[u(e_0 - e_a)], \qquad (1)$$

in which

ET = evapotranspiration;

N = a coefficient determined experimentally for a given lake and arrangement of measuring instruments;

u = wind speed at a fixed height above the water surface;

e_0 = saturation vapor pressure corresponding to the temperature of the evaporating and transpiring surfaces; and

e_a = vapor pressure of the air.

The quantity $[u(e_0 - e_a)]$ contains the meteorologic factors on which evaporation and transpiration depend. As described in the section entitled "Effect of Vegetation on Evapotranspiration," the transpiration by emergent aquatic vegetation is controlled by the same meteorologic factors that control evaporation.

According to the equation, evapotranspiration will be zero if either u or $(e_0 - e_a)$ becomes zero. In fact, if $(e_0 - e_a)$ becomes negative, it means that condensation is taking place. Often the point has been raised that the absence of wind does not indicate that no evaporation occurs; however, Harbeck (1962, p. 102) seemed satisfied that evaporation is negligible when there is no wind. The argument is based on the facts that (1) when there is no wind, the air becomes saturated, and no further evaporation can take place, and (2) evaporation by molecular diffusion is so small that it can be neglected. Convection currents do exist, but, seemingly, they are not strong enough to remove a significant portion of the "blanket" of water vapor that gathers above the water surface in the absence of wind. Thus, evaporation or transpiration occurs only to the extent that the air mass above the water surface can absorb and remove the water vapor released.

The coefficient N was evaluated by means of the water budget for each pond. A water budget of a pond is similar to any other water budget in that it shows the gains and losses from all sources. The gains are flows into the pond, the losses are flows out of the pond, and the change in amount of water stored in the pond is the item that balances the budget. Stated algebraically:

Outflow = inflow + decrease in storage.

Both inflow to and outflow from a pond can be divided into three groups, as listed below:

Group	*Inflow*	*Outflow*
Above the ground (or water surface)	Precipitation	Evaporation.
	Condensation	Transpiration.
On the ground	Runoff [7]	Overflow.
In the ground	Seepage inflow	Seepage outflow.

Transpiration would not be part of the water budget of most water bodies but needs to be included here for the prairie potholes that contain emergent aquatic vegetation, which removes water through the surface of the pond as transpiration.

Precipitation directly on a pond was measured in a tipping bucket rain gage at each pothole. It frequently produced the major increase in storage.

Condensation will occur under certain meteorologic conditions, but in our study those conditions did not occur to the extent that our instrumentation could identify them. Condensation will not be considered further.

Because the evapotranspiration studies were made on the Coteau du Missouri, where there are few or no integrated drainage systems, the runoff in channels produced only minor inflow—with the notable exception of flow from pothole 6A into pothole 6. Overland flow, although it produced practically all runoff, could not be measured directly. The total runoff, where large enough, was measured as an increase in stage of a pond in excess of the increase caused by precipitation on the pond surface and (or) as a decrease in stage less than that which takes place when it is known that there is no precipitation or runoff. Seepage inflow, if it occurred with runoff, could not be differentiated, so the term "basin inflow" is used in this report to designate all inflow to a pond from the drainage basin, as distinct from precipitation inflow directly on the pond surface.

Neither seepage outflow nor long-term seepage inflow at the prairie potholes studied could be measured directly but were determined together as net seepage outflow.

Seepage rates are subject to the influence of many factors. Fortunately, these factors seldom change rapidly, so that for short periods of time, seepage can generally be considered as a constant. In making the computations of evapotranspiration, no significant correlation could be found between seepage and any of the usual factors, so it was considered to be constant at all times. As a constant, seepage was evaluated as the residual in a water budget in which all other variables were measured.

Overflow at the study potholes in Ward and Dickey Counties occurred only at potholes 5B, 6, and 6A. No records were computed for the periods when overflow occurred.

The requirements of the water budget thus imposed certain restrictions on the choice of a pothole. A pothole chosen for study had to be one in which the pond seldom overflowed and in which basin inflow occurred only after heavy rains. Likewise, net seepage had to be very small, so that any errors in assuming it constant would have little effect on the determination of the coefficient N. (For definition of N, see p. A57.)

The working equation for the water budget of a prairie pothole, in units of feet per day per unit area of water surface, as used was

$$ET + S - P - B = H, \quad (2)$$

in which

ET = evapotranspiration;
S = net seepage outflow;
P = precipitation on the pond;
B = basin inflow; and
H = decrease in storage, measured as the decrease in stage of the lake.

[7] The term "runoff" is used rather broadly in this report to mean all water reaching a pothole on the surface of the ground. Runoff used in this sense includes flow in recognizable drainage channels and overland flow. Overland flow was generally the larger of the two.

Substituting for ET from equation 1, we have

$$N[u(e_0 - e_a)] + S - P - B = H, \qquad (3)$$

in which N contains a factor that gives ET in units of feet per day per unit area of water surface. The other units that determined the numerical value of N were miles per hour (u), and millibars (e_0 and e_a).

The value of N was determined by means of equation 3 for a computation period consisting of 15 to 30 computation units (of time) during which P and B were zero (Eisenlohr, 1966b, p. 95). Under these conditions, equation 3 can be rewritten as

$$N = \frac{H - S}{u(e_0 - e_a)}, \qquad (4)$$

Suppose, for the present, that $S = 0$. Then, if the values of H for the selected computation units are plotted against the corresponding values of $[u(e_0 - e_a)]$ in a diagram, such as figure 58, and an average line is drawn through the points, the slope of that line is the value of N.

If S were truly zero, as was just supposed, the line in figure 58 would have to pass through the origin to satisfy the equation. The line in figure 60 does not do so, but has a positive Y-intercept. This intercept is the value of S. As S was assumed to be constant, it has no effect other than that of determining the vertical position of a line of slope N. Unfortunately, there are seldom enough plotted points to define the slope of the line with high accuracy. Therefore, through the lack of adequate definition, rather than through any physical relationship, there is an interrelation between the determined values of N and S. This interrelation was eliminated in the following manner.

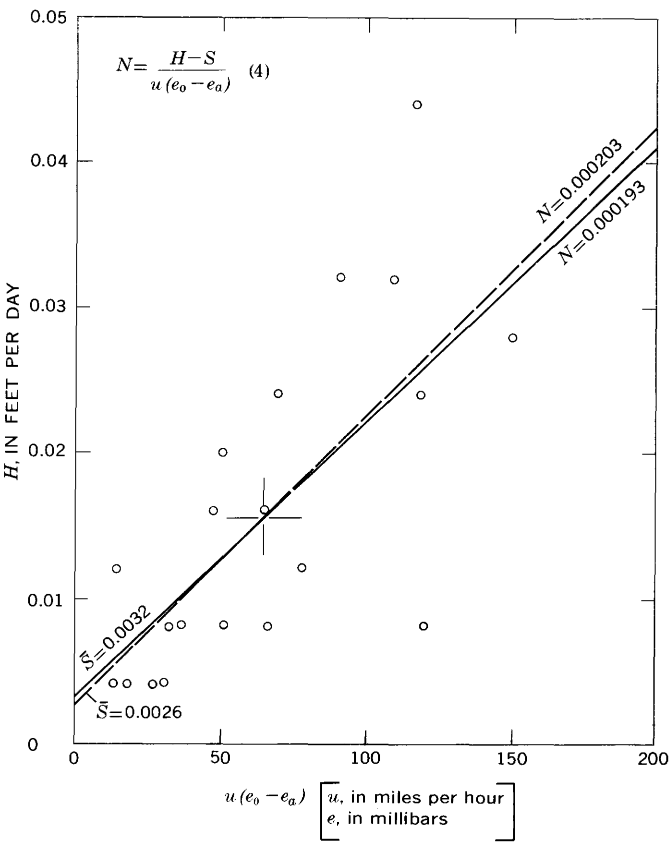


FIGURE 58.—Plot to determine mass-transfer coefficient, N, in a pothole filled with emergent aquatic vegetation. Pothole 8, August 15–19, 1963.

If 10 diagrams, such as figure 58, can be drawn for a single season, then 10 values of S will be obtained. If S is constant, as assumed,[8] these 10 values of S will be 10 estimates of the same value, and their average will be a much better estimate than any of the individual estimates. By using the average value, $\bar{S}$, the line in figure 58 was redrawn. Where originally it was drawn as a least-squares line (dashed line), it is now drawn as a solid line from an intercept of $Y = \bar{S}$, through the mean of the points (plus sign). This method yielded values of N that are much more consistent than the unmodified values.

The problem of determining as many as 10 values of N for a single season arises only for those prairie potholes that are filled with emergent aquatic vegetation. If vegetation is not present, evaporation is the only process by which water vapor is discharged to the atmosphere. Under such conditions, the coefficient N has been shown to be a constant (Harbeck, 1962), and the computation units (of time) and the computation period itself can be much longer. Figure 59 shows a determination of N that is based on a 4-year computation period. Such analyses have given satisfactory results in many parts of the United States for several years.

Evapotranspiration is computed by substituting the observed values into equation 1. The hydrophytes in prairie potholes are all herbaceous. Each spring they grow new stalks that die the following fall. The amount of plant material transpiring is, thus, continually changing throughout the growing season. In addition, the vegetation, by its presence reduces evaporation from the water surface by reducing wind speed, u, and by intercepting incoming radiation that would normally supply the energy for evaporation. The reduction in evaporation varies throughout the year, but within a fairly small

[8] See section entitled "Seepage Losses From Potholes," p. A76.

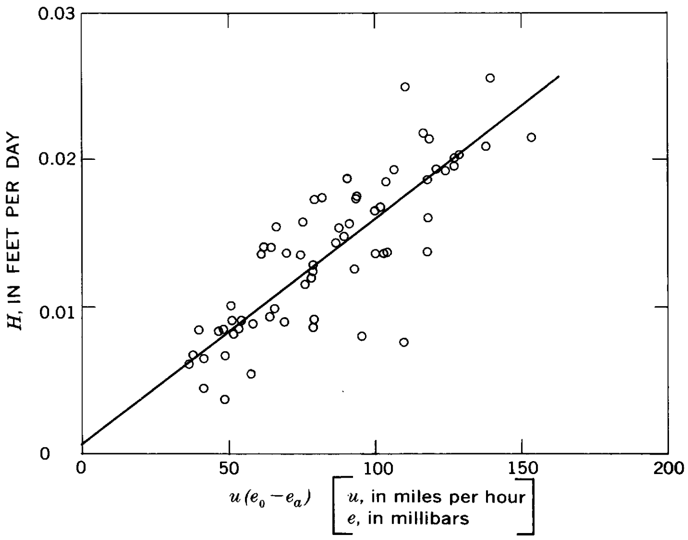


FIGURE 59.—Plot to determine mass-transfer coefficient, *N*, in a pothole clear of vegetation. Pothole 5, 1961–64.

range. Because of these effects, the coefficient *N* must also vary throughout the year. When the several values of *N* were computed for a given pothole and plotted against time in a diagram, as shown in figure 60, and as used by Shjeflo (1968, fig. 41), they define the variation in this coefficient for evapotranspiration.

If heavy rains are frequent, or if periods of record are missing from any one of the four instruments recording the basic observations, fewer values of *N* can be computed. The plotted points shown in figure 60 are all that could be obtained for pothole 8 during 1964. The smooth curve drawn by eye through the plotted points in figure 60 gives a value of *N* for any time, so that continuous computations of evapotranspiration can be made. Such computations are sufficiently accurate for many purposes, and were used by Shjeflo (1968) in making the computations for his report.

The computed seasonal evaporation (May–October) from potholes clear of emergent aquatic vegetation was found to be very close to the values given by Kohler, Nordenson, and Baker (1959) for lake evaporation. Kohler showed seasonal evaporation to average about 84 percent of the annual evaporation from lakes in North Dakota shown in figure 1 of this report.

The seasonal evapotranspiration loss from all potholes with emergent vegetation was less than the evaporation loss from the nearest study pothole clear of vegetation in every year, with only one exception. The average difference for all potholes in all years for which data are available is about 15 percent. The evapotranspiration losses that could be computed for a full month are given in table 23. The total volume of evapotranspiration can easily be computed, as shown by Shjeflo (1968, table 4, col. 26), making use of his tables of water-surface area.

EFFECT OF VEGETATION ON EVAPOTRANSPIRATION

At the start of this investigation it was anticipated by some that the evapotranspiration from potholes with vegetation would be so much greater than the evaporation from potholes clear of vegetation that transpiration data might be obtained as the difference between the two (Shjeflo and others, 1962, p. 4). Others recognized that the presence of vegetation could reduce evaporation from a pothole (idem, p. 10). It was also expected that transpiration rates might vary enough among species of vegetation that different rates could be identified with different species (idem, p. 7–8, 11). As shown in the preceding section, the difference in amount between the evaporation from clear potholes and the evapotranspiration from vegetated potholes was too small to make any such determinations.

In making the computations of evapotranspiration, it became clear that vegetation had a pronounced effect on the value of the mass-transfer coefficient, *N*. As shown by Eisenlohr (1966a,

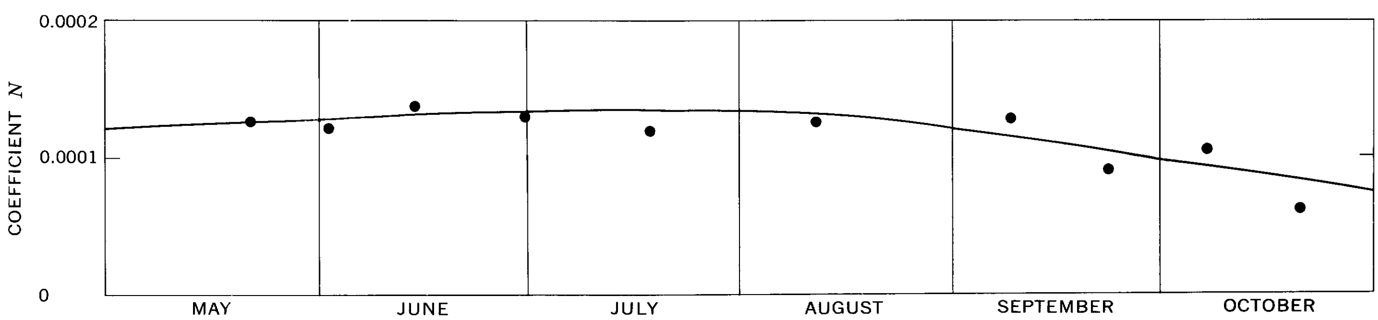


FIGURE 60.—Variation in coefficient *N* at pothole 8, 1964.

TABLE 23.—*Monthly evapotranspiration losses, in feet, from study potholes, 1960–64*

[Data from Shjeflo, 1968, table 5]

Month	Pothole									
	1	2	3	4	5	5A	6	7	8	C1
1960										
May	0.37	------	0.37	------	------	------	------	------	------	------
June	.30	------	.50	------	------	------	------	------	------	------
July	.49	------	.51	------	------	------	------	------	------	------
Aug	.45	------	.43	------	------	------	------	------	------	------
Sept	.26	0.31	.35	0.31	------	------	------	------	------	------
Oct	.13	.13	.15	.15	------	------	------	------	------	------
Season	2.00	------	2.31	------	------	------	------	------	------	------
1961										
May	------	.37	.42	------	0.42	------	0.31	------	------	------
June	------	.37	.51	------	.51	------	.39	------	------	------
July	------	------	.41	------	.44	------	.41	------	------	------
Aug	------	------	.59	------	.55	------	.47	------	------	------
Sept	------	------	.25	------	.30	------	.18	------	------	------
Oct	------	------	.15	------	.20	------	.04	------	------	------
Season	------	------	2.33	------	2.42	------	1.80	------	------	------
1962										
May	.27	.28	.24	.23	.28	------	.30	0.24	0.26	------
June	.36	.37	.34	.30	.38	------	.31	.40	.33	------
July	.36	.44	.36	.43	.40	------	.42	.34	.38	------
Aug	------	.50	.47	------	.57	------	.49	.60	.55	------
Sept	------	------	.28	------	.32	------	.28	.27	.29	------
Oct	------	------	.15	------	.19	------	.09	.07	.10	------
Season	------	------	1.84	------	2.14	------	1.89	1.92	1.91	------
1963										
May	.42	.38	.32	.21	.44	------	.29	------	.31	0.31
June	.47	.47	.49	.31	.48	------	.36	------	.36	.47
July	------	.69	.49	------	.55	------	.45	------	.41	.46
Aug	------	.47	.37	------	.51	0.53	.44	------	.44	.49
Sept	------	------	.31	------	.35	.25	.28	------	.22	.29
Oct	------	------	.24	------	.28	.14	.14	------	.12	.24
Season	------	------	2.22	------	2.61	------	1.96	------	1.86	2.26
1964										
May	.41	.33	.51	.32	.46	------	.38	.40	.36	.52
June	.28	.23	.35	.21	.42	------	------	.44	.43	.38
July	.50	.49	.55	.44	.49	------	------	.53	.42	.43
Aug	------	------	.48	------	.43	.48	.43	.49	.37	.42
Sept	------	------	.26	------	.27	.23	.22	.27	.22	.29
Oct	------	------	------	------	.23	.12	.11	.19	.11	.18
Season	------	------	------	------	2.30	------	------	2.32	1.91	2.22

1969a), the amount of vegetation largely determined the general level of the value of N, and the condition of the vegetation—height and moisture content—determined the variation in N throughout the growing season. These conclusions are based on the several studies of vegetation made as a result of the problems encountered in making the computations of evaporation.

Transpiration from pothole ponds comes from plants, known as hydrophytes, that emerge from the surface of the water. There are other types of hydrophytes, such as those that are completely submerged and those that seldom grow in water except during very high water stages. The simple term "hydrophyte" in this report refers to emerged hydrophytes only. The other types were not studied by the U.S. Geological Survey, but they are included in chapter D of the present series, by Stewart and Kantrud (1971). The scientific names are used to identify hydrophytes in this report to avoid confusion among conflicting common names and to identify species where a "common" name is not in common use. English names of the commonly occurring species are listed on page A97.

One of the major discoveries of the project was the fact that there was a very great variation in the amount of hydrophytes growing in pothole ponds. Ponds that were partly clear at the beginning of the study subsequently became completely filled with hydrophytes, and other ponds that initially were completely filled later developed large expanses of open water. Details of these changes are given as part of the description of individual potholes. The importance of the amount of hydrophytes growing in a pothole in relation to the mass-transfer coefficient can be seen in figure 70. The vertical separation among the curves in this figure is believed to be largely dependent on the amount of hydrophytes present.

Sudden changes in vegetation can take place when part of a pothole goes dry for the first time in a long period, or when the pond becomes much deeper than had occurred in a long period. These are the conditions that cause rapid regrowth of vegetation and rapid elimination of vegetation, respectively. Once a vegetation change has occurred, the new condition may persist for years before the opposite change takes place. Not all changes are sudden ones, however; slow changes also take place, and commonly the vegetation change lags several years behind the change in water permanence or depth. Reasons for such changes seem to be well established.

For rapid regrowth, Kadlec (1962) stated that "many emergent plants, including cattail and bulrush, must have a bare mud flat as a seedbed," and Harris and Marshall (1963) cited four other papers to the same effect. Excellent examples of rapid regrowth occurred at potholes 1 and 2 in 1961.

Rapid elimination of vegetation by drowning occurred at potholes 6, 7, and 8 in 1964. The change at pothole 6 was dramatic, some *Scolochloa festucacea* plants still growing in August 1964 had a total height of 5.2 feet. At that time, the maximum depth of water was more than 5.5 feet. Therefore, the water was too deep in the center of the pond for the vegetation to reach above the water surface, and it was truly drowned out.

Slow regrowth of vegetation has been observed by R. E. Stewart (oral commun., 1968) to occur by the slow outward expansion of perennial vegetation. This takes place by propagation from rootstalks. The exansion is limited by the depth of water that a species can tolerate or the rate at which the vegetation can spread in this manner, provided water depths are less than critical.

Harris and Marshall (1963) found evidence that emergent vegetation is limited by the depth of water and that it disappears if it is inundated continuously beyond a critical depth, which can be appreciably less than that required for rapid drowning. They cited many references to the effect that continuously inundated emergent vegetation seldom survives for more than 5 years and survived a much shorter time if subjected to increased wave action or greater depth of flooding.

With respect to the Coteau du Missouri, Stewart reported (oral commun.) that a pothole near Woodworth, N. Dak., had a rapid regrowth of *Solochloa festucacea* after going dry, but after the pothole vegetation had been inundated for 3 years with fairly stable water levels, the *Scolochloa* disappeared, and bands of *Scirpus acutus* grew near the shore.

Scolochloa festucacea is generally considered to be a shallow-water plant and is "commonly used for

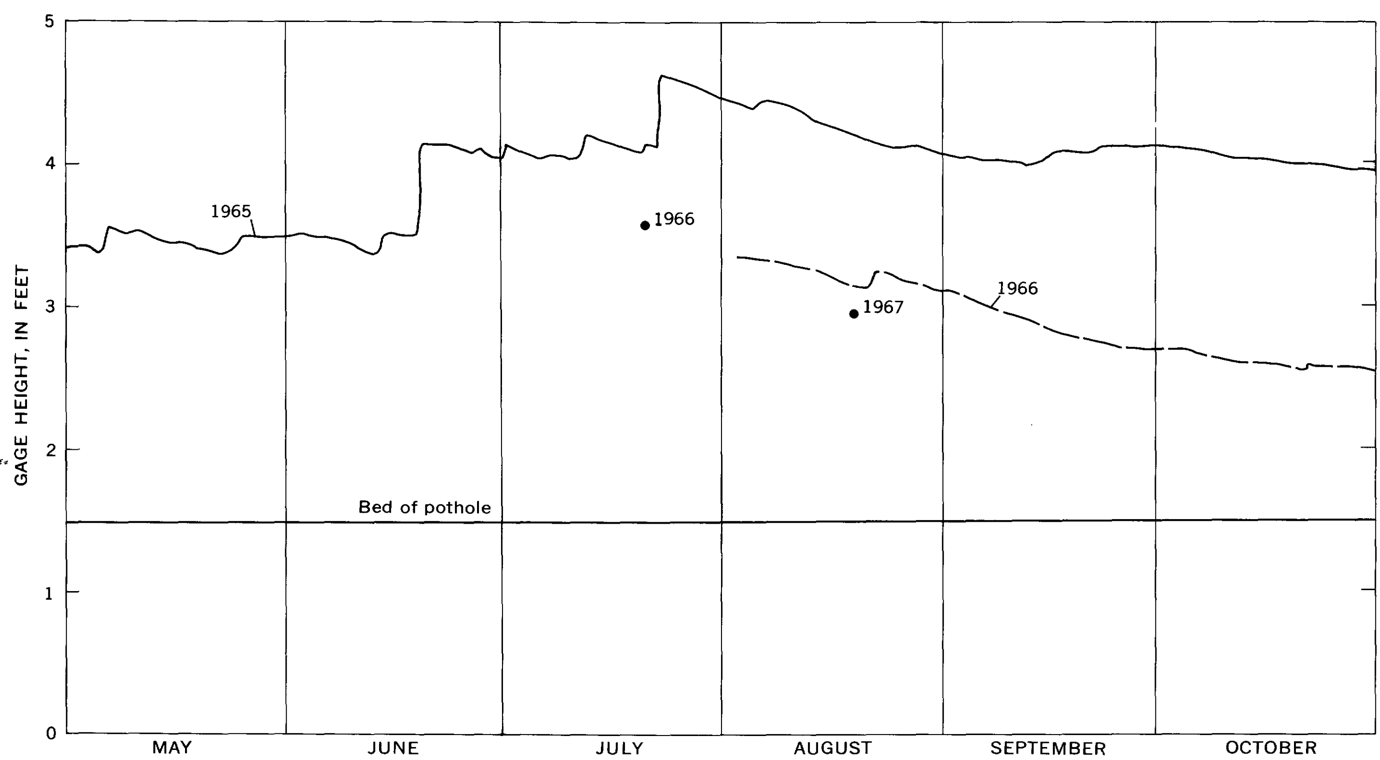


FIGURE 61.—Hydrographs of pothole 1, 1965–66.

hay" because "in most years the ground becomes dry enough so it can be harvested" (Stevens, 1950, p. 58). In pothole 1, however, the *Scolochloa* has persisted since its sudden appearance over the entire pothole in 1961. The pond in this pothole is believed to have been in continuous existence since early 1965. (See fig. 61.) A view of the vegetation in September 1968 is shown in figure 62.

Stewart reported also (oral commun.) that the hybrid cattail *Typha glauca* seems able to withstand greater water depths for longer periods than other emergent species of deep-marsh vegetation.

In computing seasonal evapotranspiration using values of N taken from a curve, such as the one in figure 60, the uncompensated errors are believed to be small. As evapotranspiration is computed for shorter periods, the smoothing effect of the curve in figure 60 introduces greater errors. It seemed possible that the variation in N could be a function of one or more properties of the hydrophytes. Intensive studies of the vegetation were made to investigate this possibility.

Samples of vegetation were collected in 1961 under the direction of R. S. Aro. Comprehensive samples were collected in mid-June and 6 weeks later, at the end of July. The results are summarized in table 24. Frequency is the ratio of the number of 9.6 square-foot sample plots in which a species occurred to the total number of sample plots. Aro considered the herbage yield (dry weight of stems) to be the factor that would correlate with transpiration, with reduction of evaporation by shading of the water surface, and with lowered wind velocities. However, he found that the nonuniformity of a natural stand of hydrophytes was so great that he was unable to obtain an adequate number of samples for his intended purpose.

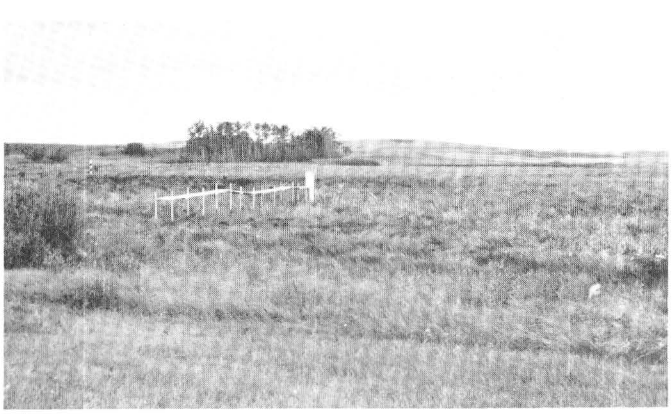


FIGURE 62.—View of vegetation-filled pothole 1, September 23, 1968.

Also, as part of Aro's work, weekly samples were collected of the emergent portions of several plants of each dominant species growing in each pothole. These species samples were used to determine the dry weight and moisture content, by species, as follows: Pothole 1, *Scolochloa festucacea, Typha latifolia;* pothole 2, *Scirpus acutus, Typha latifolia;* pothole 4, *Scirpus acutus, S. paludosus;* pothole 6, *Scolochloa festucacea, Typha latifolia, Scirpus fluviatilis;* pothole 7, *Scirpus acutus, Scolochloa festucacea;* pothole 8, *Scirpus acutus, Scolochloa festucacea, Typha latifolia.* Unfortunately, 1961 was the driest year of many years before and after, and, as a result, pothole 6 was the only one with vegetation that contained water throughout the season.

The variations in moisture content for pothole 6 are shown in figure 63.

Additional comprehensive observations of hydrophytes in four potholes (5A, 6, 7, and 8) in Dickey County were made in 1964. Grid lines were laid out in each pothole—75 feet apart in pothole 5A, 200 feet apart in pothole 6, and 300 feet apart in potholes 7 and 8. At each grid intersection, all vegetation above the water surface in four 9.6-square-foot quadrats was cut, separated into the several species, weighed, oven dried, and reweighed. From these data, the herbage yield and the moisture content of each species in each sample can be computed. The number of stems[9] of each species were counted to determine their relative abundance in the total number of stems in the sample. The samples were collected between July 13 and August 7, 1964. Similar samples were collected at potholes 5A and 6 during the period June 15–23; except that the number of stems of each species were not counted. Rising pond waters, as a result of heavy rains, prevented collection of samples at potholes 7 and 8 in June.

From early June to early September, weekly samples were cut from 10 randomly selected 0.96-square-foot quadrats in each of the four potholes. The moisture content of these samples gives the moisture distribution through the season (early June–early Sept.). Unfortunately, L. F. Lautenschlager, the botanist who collected and processed all the samples, was not available to continue the work beyond early September. The number of stems of each species in these samples was counted, beginning July 1. The dry weight per stem in these samples in relation to the average emerged height is shown in figure 64, and the seasonal variation in

[9] Stem is used here is the botanical sense of a principal axis of a plant. Many hydrophytes have several stems per plant. As the bases of hydrophytes are usually under water, plants are difficult to identify, but stems are not.

TABLE 24.—*Herbage yield and percent frequency of emergent vegetation at six potholes, June–July 1961*

[For common names of plants, see p. A97]

Plant species	Weight, second week in June (lb per acre)	Weight, last week in July (lb per acre)	Weight change in 6-week interval: Lb per acre	Weight change in 6-week interval: Percent	Percent contribution: June	Percent contribution: July	Percent frequency: July
Pothole 1							
All species	989	[1]	-----	-----	100	---	53
Scolochloa festucacea	863	-----	-----	-----	87	---	42
Carex sp	105	-----	-----	-----	11	---	15
Typha latifolia	21	-----	-----	-----	2	---	8
Pothole 2							
All species	133	520	387	290	100	100	33
Scirpus acutus	126	418	292	230	95	80	28
Typha latifolia	7	102	95	1,300	5	20	5
Pothole 4							
All species	456	853	397	87	100	100	67
Scirpus acutus	422	729	307	73	93	85	59
Scirpus paludosus	23	109	86	370	5	13	15
Hordeum jubatum	6	6	0	0	1	1	5
Puccinellia nuttalliana	5	9	4	80	1	1	5
Pothole 6							
All species	422	1,475	1,053	250	100	100	70
Scolochloa festucacea	417	1,134	717	170	99	77	60
Scirpus fluviatilis	4	291	287	7,200	1	20	15
Carex sp	1	34	33	3,300	---	2	5
Scirpus acutus	0	16	16	-----	---	1	5
Pothole 7							
All species	169	1,299	1,130	670	100	100	98
Scirpus acutus	110	1,083	973	880	65	83	81
Scirpus americanus	0	104	104	-----	0	8	27
Juncus balticus	3	58	55	1,800	2	4	31
Hordeum jubatum	38	37	−1	3	22	3	20
Potentilla anserina	11	9	−2	20	7	1	11
Distichlis stricta	7	8	1	10	4	1	8
Pothole 8							
All species	443	2,081	1,638	370	100	100	100
Scirpus acutus	149	1,281	1,132	760	34	62	82
Scolochloa festucacea	78	415	337	430	18	20	41
Carex sp	214	213	−1	-----	48	10	39
Typha latifolia	2	141	139	7,000	---	7	36
Eleocharis palustris	0	31	31	-----	---	1	14

[1] Pothole 1 was not sampled in July, owing to prior removal of vegetation by property owner.

the weighted dry weight per stem for all species is shown in figure 66.

Weekly observations also were made of the emerged heights of 10 marked plants of each species found in significant quantity in each pothole. The species were:

Pothole 5A. *Carex atherodes, Scirpus acutus, Scolochloa festucacea, Typha angustifolia, T. glauca,* and *T. latifolia.*

Pothole 6. *Carex atherodes, Phragmites communis, Scirpus acutus, S. fluviatilis, Scolochloa festucacea, Sparganum eurycarpum, Typha angustifolia, T. glauca,* and *T. latifolia.*

Pothole 7. *Carex atherodes, Scirpus acutus, Scolochloa festucacea, Typha angustifolia,* and *T. latifolia.*

Pothole 8. *Carex atherodes, Scirpus acutus, Scolochloa festucacea, Typha angustifolia, T. glauca,* and *T. latifolia.*

Because of the high pond stages following the June rains, the height records are not complete. Some plants were completely covered by water, some became inaccessible, and some lost their identifying markers (rubber balloons tied to the stems). Pothole 8 was the only one for which reasonably complete data are available. By estimating some of the missing records, seasonal estimates for pothole 5A were computed.

Aro's approach to the problem reflects the interest of botanists and agronomists in seeking data that can be applied generally to similar species of vegetation. The present study, however, was not concerned with the vegetation, per se, but with its effect on the hydrology of the pothole under study. New methods had to be developed to determine the effect of vegetation as a hydrologic factor in the water budget. In determining the water budget, each pothole must be considered as a unit and be calibrated "in place." If similar investigations are made elsewhere, the same procedures would probably have to be used there, also. Therefore, the general transferability of these data collected at

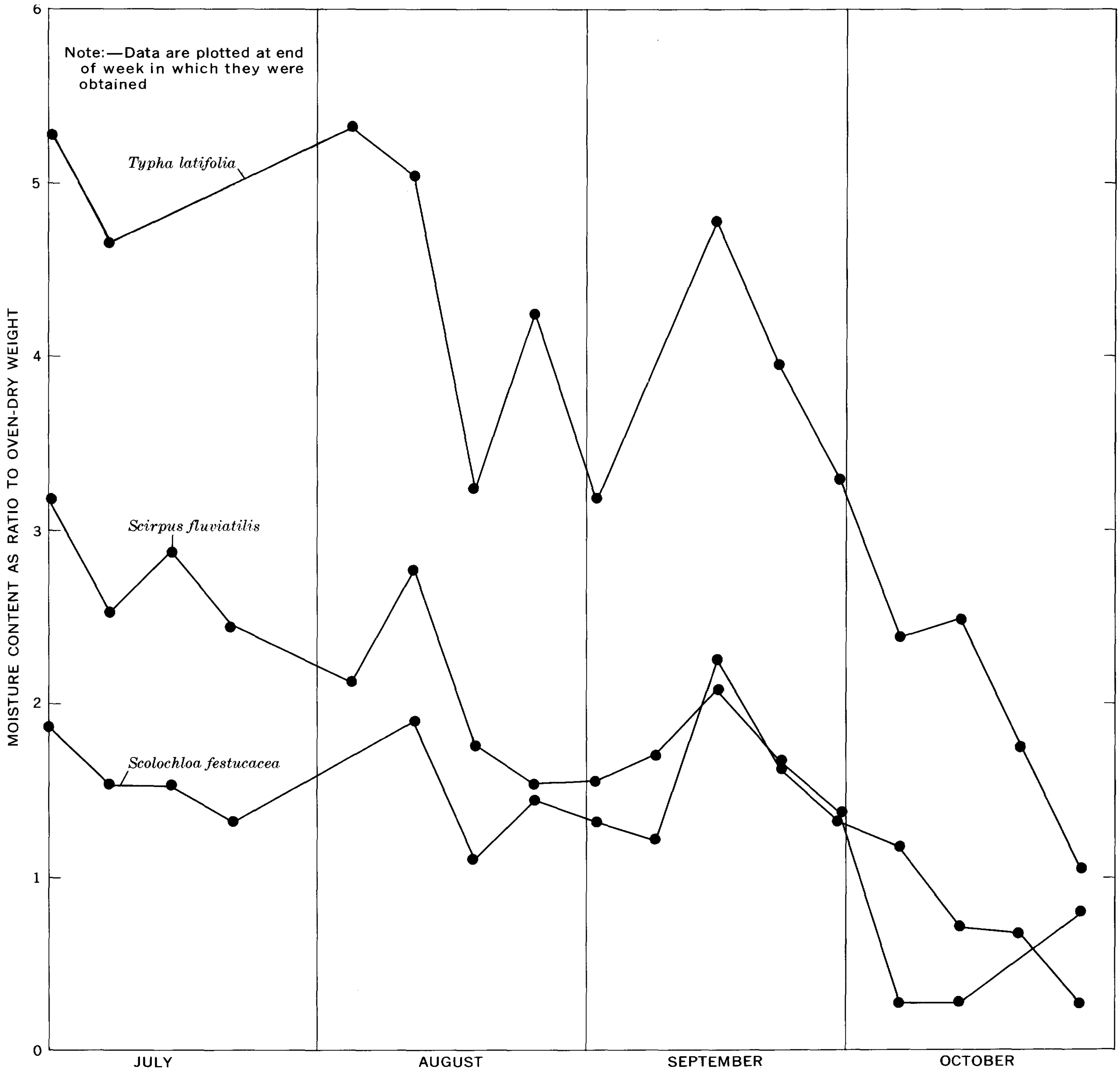


FIGURE 63.—Moisture content of hydrophytes in pothole 6, 1961.

any pothole becomes unimportant. Frequently, this is true where the variations in an observable parameter depend on many variables generally, but at a specific site, most of the variables can be considered as constants. In such situations, "in-place" calibration produces the best results. Fortunately, the unit approach also simplified the vegetative aspects of the study. Otherwise, as demonstrated by Aro in a statistical analysis of his data, the number of plots required for adequate sampling would have been prohibitive.

Transpiration is generally assumed to vary with the leaf area, or with the amount of herbage. To determine the leaf area of a natural stand of vegetation, or even to sample it adequately, is a nearly impossible task. It is not like a cultivated field that has been seeded uniformly. The distribution of stems of vegetation in the pond of a prairie pothole

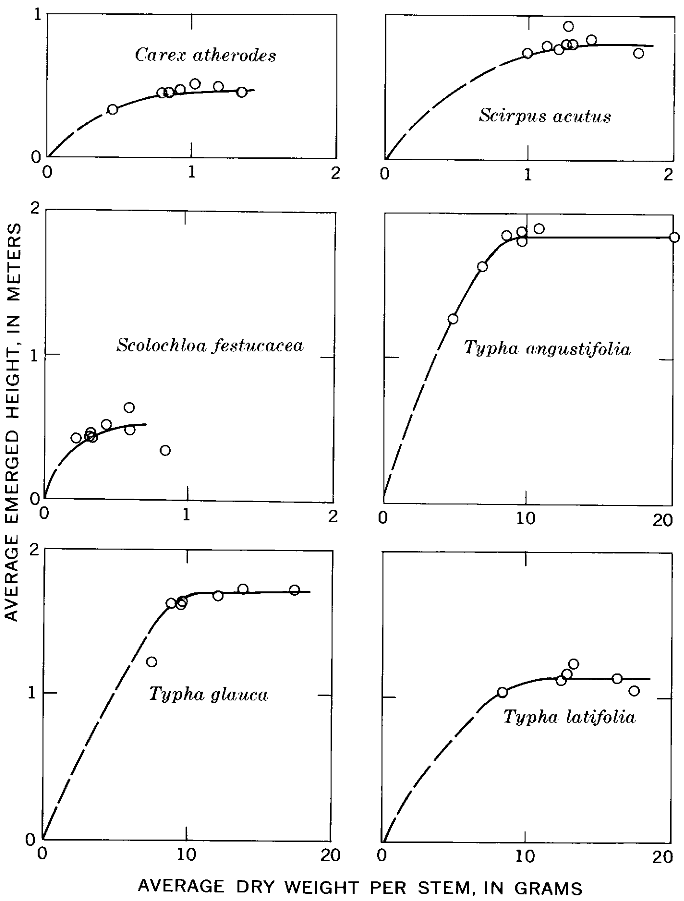


FIGURE 64.—Relation of dry weight per stem to emerged heights of several species of hydrophytes in pothole 8, July 1–August 26, 1964.

can be very erratic, as observed by Aro. (See p. A63.) Furthermore, the amount of emerged-leaf area is dependent on the water level, as well as on the stage of growth. Of these two, the water level is much more variable. Therefore, to be useful, a parameter of vegetation for correlation with transpiration must respond to changes in water level.

Transpiration losses could be determined only by using the entire pond as a unit; hence the rate of transpiration was computed as the average rate per unit area of water surface. In one way this was fortunate, for by assuming that for a given season in any pothole the number of emergent stems was essentially constant and, further, that the increase in leaf area of each stem of each species occurred at about the same rate, the emerged height, then, should be an appropriate measure of the total leaf area and, thus, the rate of transpiration from the entire pond. Therefore, a "height index" was determined as the weighted-average emerged height of all species of vegetation growing in a pond. As shown in figure 67, such an index provided a satisfactory measure of the coefficient of transpiration for the early part of the growing season when the vegetation was fully active.

The height index of each weekly sample obtained in 1964 was determined on the basis of the comprehensive samples. Some method was needed to weight the average heights of the different species. The comprehensive sampling was done within a 5-day period at each pothole, and the distribution of the dry weight among the several species was assumed to be in the same proportion throughout the season. Therefore, the average emerged height of each species was weighted by the ratio of the dry weight of each species in all samples to the total dry weight in the comprehensive samples. The height index of all species is the total of the weighted heights of each species sampled. These are the heights used in the correlation shown in figure 67. A sample computation is given in table 25.

Eisenlohr (1966a, p. 451) assumed that the growth pattern of hydrophytes is a conservative property and that the growth pattern and the density of hydrophytes in pothole 8 were the same in 1963 as they were in 1964. Comparable photographs indicate this to be a reasonable assumption. On this basis, height indexes at pothole 8 were also computed for 1963, using the data on vegetation heights from 1964. These indexes were used to compute tran-

TABLE 25.—*Computation of height index of vegetation in pothole 8, August 7, 1964*

Species	Weekly sample: Average height of 10 marked plants		Comprehensive sample		Height index
	Total (cm)	Emerged (cm)	Dry weight (g)	Ratio to total dry weight (weight)	Weighted-average height (weight × cm)
Carex atherodes	159.0	48.6	648	0.165	8.02
Scirpus acutus	192.1	78.9	1,204	.307	24.22
Scolochloa festucacea	153.1	47.1	959	.244	11.49
Typha angustifolia	303.8	186.7	628	.160	29.87
glauca	289.1	172.5	357	.091	15.70
latifolia	231.5	111.5	128	.033	3.68
Total	-----	-----	3,924	1.000	92.98

spiration for 1963. They were used only as corroborative evidence in defining the relation in figure 69.

To better understand the effect of hydrophytes on the hydrology of a prairie pothole, a separation of transpiration from evaporation is necessary. This can be done rather simply by considering the mass-transfer coefficient, N, to be composed of two parts—a coefficient of evaporation, (N_E), and a coefficient of transpiration, (N_T). Each coefficient is a measure of the rate of the related water loss in response to meteorologic conditions inducing the loss. The process is illustrated in figure 66, in which the coefficients of evaporation and transpiration for pothole 8 have been drawn to show the separate effects. The plotted values of N are the same as those plotted in figure 60.

There is a difference between evaporation and transpiration. Evaporation takes place from the water surface, but transpiration is from the hydrophytes above the water surface that discharge water absorbed by their roots. The root zone is below the real bottom of the pond, as can be seen easily when a pothole dries and one can walk through the vegetation on the "dry" ground (fig. 16). Thus, water reaches the root zone only as seepage, and what is transpired is really an abstraction by the roots from seepage. In all probability, however, a pothole containing a dense growth of hydrophytes will have a very permeable bottom layer of decaying vegetable matter and uncompacted sediments through which water flows easily. Deep seepage (relative to the root zone) under these conditions should be relatively unaffected by the water absorbed by roots. In order to avoid confusion with this use of shallow-seepage water, the effective bottom of the pond, at least as far as seepage is concerned, is defined for this report as a surface just below the roots of the plants.

The separation of coefficients is possible because hydrophytes can be considered as transpiring in response to atmospheric demand in the same way evaporation from a free water surface responds to atmospheric demand. The literature on transpiration contains many references to the fact that plants, when well supplied with water, exert little control on the transpiration rate per unit of plant material transpiring. For example, van Bavel, Fritschen, and Reeves (1963) stated, "We conclude that a full stand of sudangrass * * * in a highly evaporative environment * * * can transpire upon atmospheric demand."

Plants are thought by some to control transpiration through their stomata, but several investigators have shown that stomata have to be more than half closed before they exert any appreciable control on transpiration (Ehlig and Gardner, 1964; Kramer, 1959, p. 623; and Loftfield, 1921, p. 102). Loftfield (1921, p. 48) stated further than "such plants as *Scirpus validus* [giant bulrush], *Equisetum hiemale*, and *E. palustre* [horsetails], showed the stomata continuously wide open, and this seems to be their usual state." Presumably, other emergent hydrophytes have similar characteristics. Also, according to Visser (1965, p. 260), "The stomata regulate the loss of water to a value as nearly equal to the uptake of water by the roots as possible * * *. The explanation of the activity of the stomata cannot be found in the stomata of the plant, but in the moisture situation in the soil." Because hydrophytes grow in water, their roots are always supplied with all the water the plants can use; thus, their stomata presumably would not be called upon to restrict the flow of water. Such a relation further supports the idea that with hydrophytes, atmospheric conditions determine the water loss.

Some investigators may think that diurnal variation in transpiration is evidence that plants always control their transpiration, but, as shown in figure 65, it is evident that metorologic factors alone can

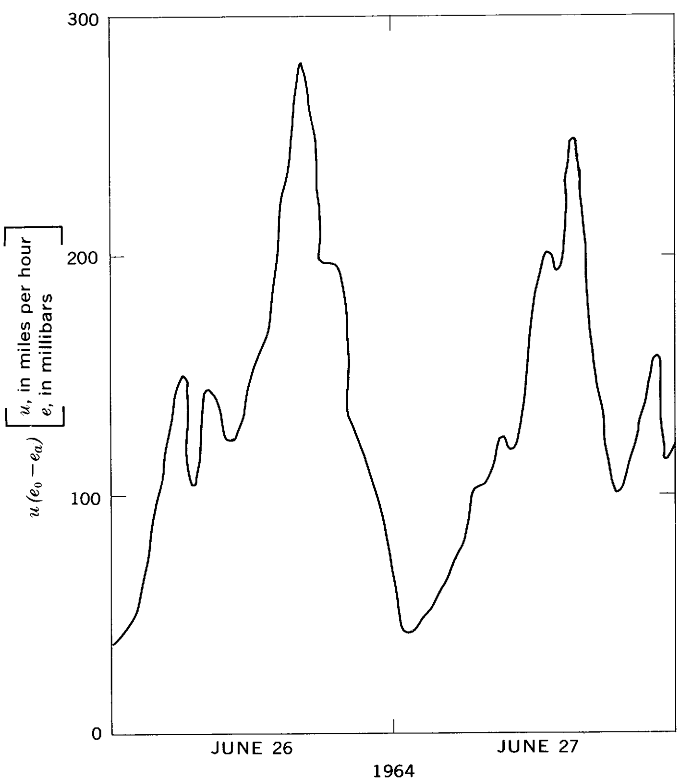


FIGURE 65.—Diurnal fluctuation of meterologic factors that control evapotranspiration.

produce the type of diurnal variation in transpiration frequently observed.

The coefficient of evaporation is not the same at a pothole filled with vegetation as it would be with no vegetation present, rather, it is much less, owing to the effects of the hydrophytes. Neither is it a constant, as the effects of the hydrophytes can change during the growing period.

Hydrophytes reduce evaporation by sheltering the water surface from the wind. An examination of the mass-transfer equation (eq. 1) shows that evaporation is directly proportional to wind speed. Hydrophytes, if they are sufficiently dense, can shelter a pothole enough that the wind speed is reduced to practically zero at the water surface, as shown in table 26. When this occurs, much of the mechanism for removing the water vapor as it forms is lost. However, buoyancy of the water vapor and convective currents seem to be able to transfer some water vapor upward above the vegetation, where it can be removed by the wind. This seems to be a different condition from that of no wind above the vegetation, as a significant amount of water is evaporated during the dormant season from a pothole filled with a dense stand of dead stalks of vegetation (fig. 21).

Hydrophytes can also reduce evaporation by shading the water surface; they intercept the incoming radiation, so that less energy reaches the water surface to cause evaporation. But much of the energy intercepted by the vegetation is used for transpiration.

TABLE 26.—*Effect of vegetation on wind speed, in miles per hour, at the water surface*

Date in 1964	Wind speed (mph)[1]		
	Just above vegetation	At water surface	
		In vegetation	Over open water
June 25	7	1	3
July 1	10	1	4
8	6	1	3
16	0	0	0
24	10	1	5
30	6	0	3
Aug. 7	8	0	4
13	8	0	6
19	10	1	5
26	20	4	14
Sept. 10	20	2	10

[1] Measured with hand anemometer, and read directly in miles per hour.

Thus, vegetation reduces evaporation in two ways —sheltering and shading—and neither way is confined to live plants.

The effect of vegetation in reducing evaporation is cyclic. As the plants grow above the water surface in the spring, they progressively stop the wind and shade the water, so evaporation should be reduced in accordance with this growth and reach a minimum at the time of maximum growth. For this study, maximum growth was assumed to coincide with maximum height (about July 23, fig. 66). Evaporation should then continue at the minimum rate until the vegetation has died and starts to break down as a result of weathering, especially by wind and snow. As the dead stalks are broken down, evaporation can be expected to increase, reaching a maximum about the time that new growth begins during the following spring. The breaking down of the dead stalks is a slow process, so that many potholes in spring are still filled with a dense stand of dead stalks (fig. 21), and the increase in the evaporation coefficient is small. For computed evaporation to vary during the season in accordance with these principles, the mass-transfer coefficient for evaporation, N_E, must vary in the same manner. Such curves were drawn in figure 66 for both 1964 and 1963. Note that N_E is the same as N except for the period when there was live vegetation above the water surface—about May 6 to October 20, 1964 (fig. 66). The variation in N_E is small; in fact, there was no variation in 1963. Therefore, the error in drawing such a curve should be very small.

The height index was chosen as a measure of the variation in transpiration from fully active vegetation. Figure 67 shows how the coefficient of transpiration, N_T, is related to the height index. The values of N_T were obtained by subtracting from each plotted value of N in figure 66, the corresponding curve value of N_E. As the values of N_E are fairly constant, this subtraction tends to increase the scatter of the N_T points. The height index was obtained by subtracting the gage height of the water surface from the gage height of vegetation (fig. 66).

The correlation in figure 67 is highly significant. Within the limits for which it is defined, the line is straight. It can be expected that under other conditions, such as higher or denser vegetation, the coefficient N_T would reach a maximum. The fact that in 1963 or 1964 there was no indication of such a maximum suggests that potential loss by transpiration from pothole 8 could be much greater than the amount observed during this study.

The relation shown in figure 67 was used to increase the accuracy of the distribution of N values. Height indexes were measured from the curves in figure 66 and applied to figure 67 to get the corresponding values of N_T. These values of N_T were

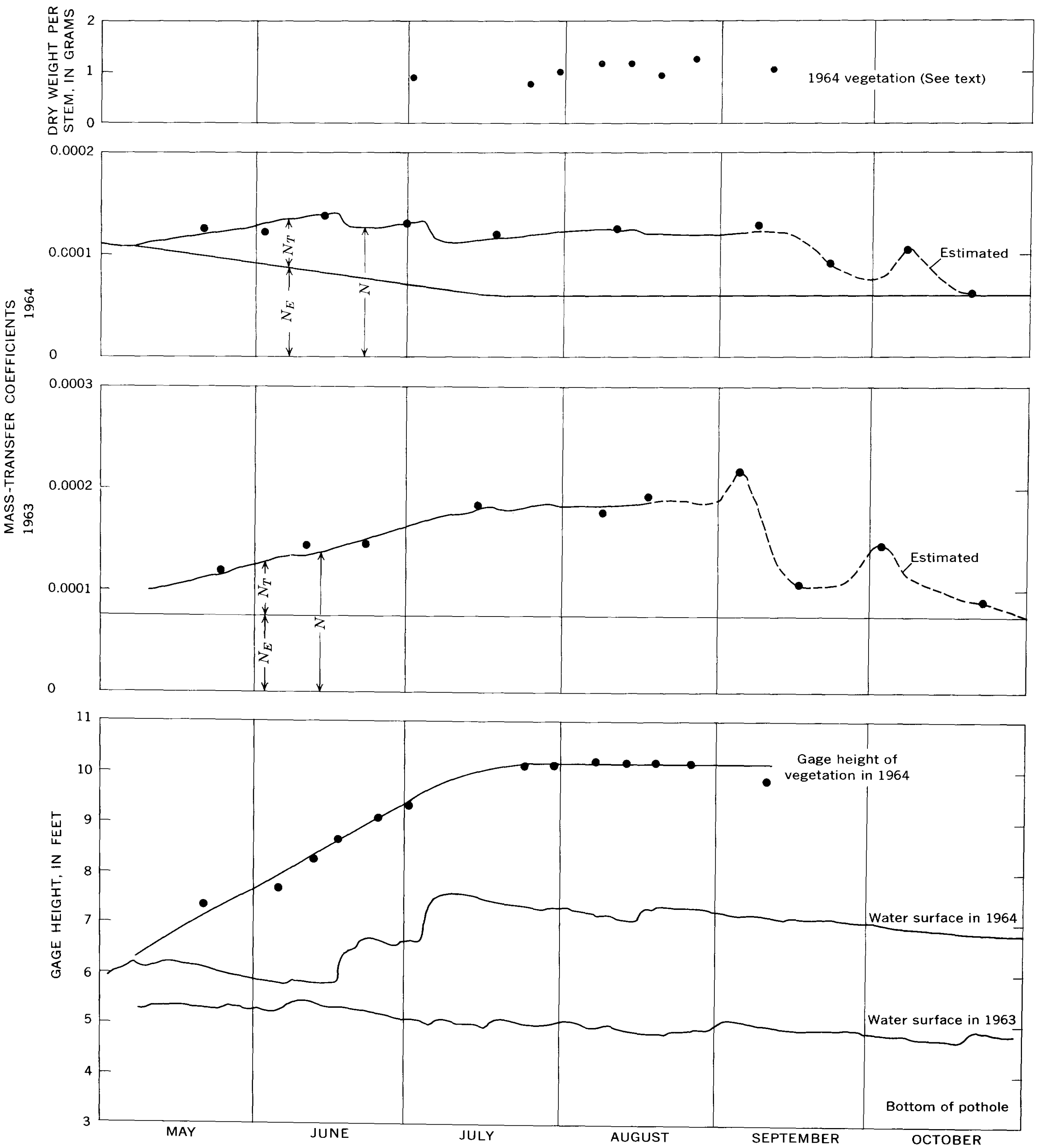


FIGURE 66.—Mass-transfer coefficients and heights of water surface and hydrophytes at pothole 8, 1963–64.

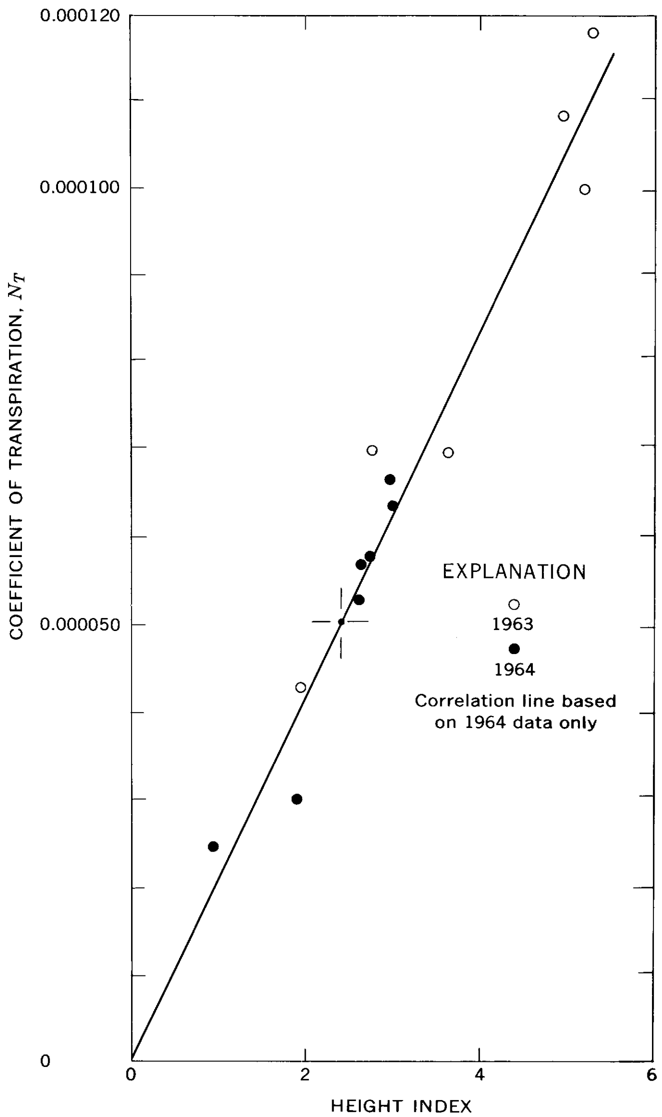


FIGURE 67.—Relation of height index to mass-transfer coefficient for transpiration, N_T, at pothole 8, 1963–64.

added to the N_E curves in figure 66 to get the distribution of N. We point out that once the N_E curve is drawn (fig. 66) and the relationship in figure 67 is fixed, there is no further leeway in drawing the curve for N through the plotted points.

The dashed part of the N curve is the part estimated for the period of declining activity of the vegetation, for which no data are available for 1963 or 1964.

On the basis of the vegetation studies made at pothole 1 in 1966 (fig. 68), it was concluded that the great variation in computed values of N during September and October represented real variations. Thus, the estimated lines were drawn through the computed points. The similarity between these variations in figure 66 and figure 68 should be noted. No computations were based on the curves in figure 66; rather they were drawn to illustrate the methods of analysis that were developed at the end of the project.

The transpiration rate at any stage of growth will depend on the product $[u(e_0 - e_a)]$, as does evaporation from the water surface. In this product, for the evaluation of transpiration, e_0 should be the saturation vapor pressure corresponding to the temperature of the vegetation. In this study, only unshaded water-surface temperatures were measured, and the use of water temperatures for vegetation temperatures may have introduced errors in the computed evapotranspiration. To some extent, the errors should be compensated by the method used for determining the coefficient N.

The height index was used as a measure of the amount of vegetation transpiring from the time when the vegetation first appeared above the water surface to the time when it started to decline in activity. The gage height of the water surface changes as the result of inflows and losses. The use of a height index as the measure of vegetation transpiring, thus, has the advantage that it responds directly to changes in water level. Such use has an additional advantage in that it provides a partial compensation for errors in measuring wind speed. The anemometers were kept at a fixed distance above the water surface. As the emerged height of vegetation increased, it reduced the effective height of the anemometer and tended to cause an increase in the coefficient N. This increase is believed to be small in relation to the effect of transpiration on N.

The height index is a useful parameter of transpiration only as long as the vegetation is fully active. Toward the end of the growing season, the activity of the vegetation declines. For want of a better term "activity decline" is used in this report to designate the period during which transpiration by vegetation shows a general decline from the summer high to dormancy in the fall. As will be shown later, the decline is not always continuous.

The relation between transpiration and the mass-transfer coefficient during the activity decline was investigated in 1966 (Eisenlohr, 1969a). The study was made at pothole 1, where the stand of *Scolochloa festucacea* was almost solid, and the water was 1 to 2 feet deep. The procedures used were the same as those used throughout the project. Weekly samples of vegetation were collected, weighed, oven-dried, and then reweighed. The losses in weight by drying are the moisture contents, and their ratios to the oven-dry weights were used as parameters of moisture decline. These ratios were compared with the mass-transfer coefficient (fig. 68).

The general trend of moisture content is downward. This trend suggests a general decline in activity of the vegetation and a corresponding decrease in transpiration. The curve for the mass-transfer coefficient shows a similar downward trend. This latter curve is really a curve of moving averages, as the data used to determine many of the points are common to two or more determinations. Any variation in the coefficient during this time of year is assumed to be caused by a variation in the ability of the vegetation to transpire.

The coefficient curve has two pronounced humps. The one in late August has a counterpart in the curve of moisture content. A hump in the moisture-content curve for late September is shown by a dashed line; this hump is an estimate based on the coefficient curve. In order to draw this hump, the data for the sample collected on September 26 had to be disregarded. The sample bag is believed to have had an unsatisfactory seal, which allowed moisture to escape before the sample was weighed several weeks later. A statistical analysis showed this observation to have less than 1 chance in 200 of being significantly related to the other observations. The rejection of this observation is supported by infrared photographs (Eisenlohr, 1969a).

The amount of infrared showing in transparencies made on Ektachrome Infrared Aero film, be-

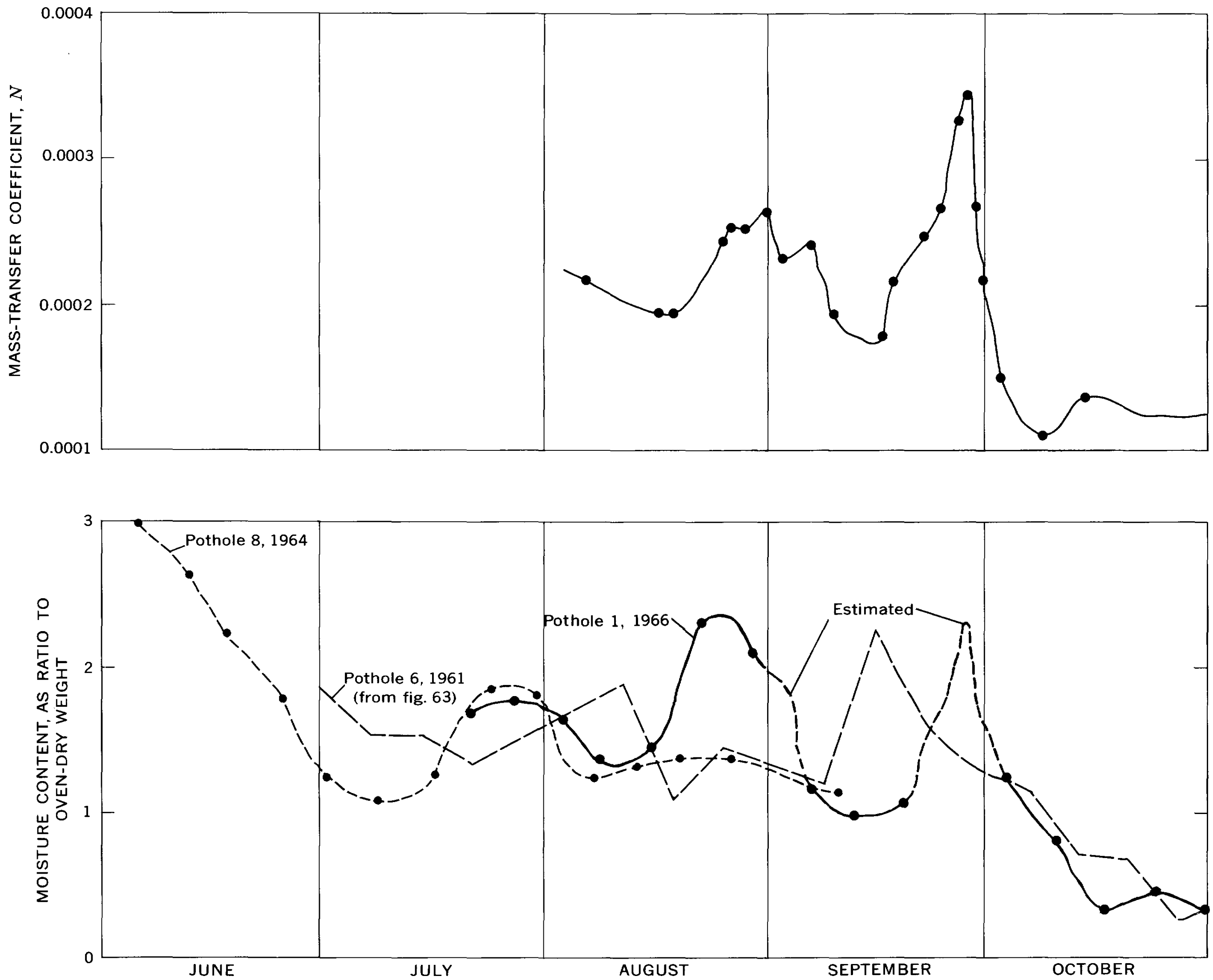


FIGURE 68.—Comparison of moisture-content ratios *(Scolochloa festucacea)* and mass-transfer-coefficient variations during activity decline, pothole 1, 1966.

tween the height of the growing season and dormancy in the fall, shows a general decline. There is one conspicuous exception—the photograph taken on September 26. This picture shows about as much red as the one taken July 27 and far more red than any other picture taken in September or October. The reason for the high infrared radiation on September 26 has not been determined. However, based on the fact that the photograph shows conditions similar to those in July and the mass-transfer coefficient curve shows a hump for the same time, a corresponding hump was put in the moisture-content curve.

These humps, better described as short-period fluctuations, seem to be real. They appear in figure 63, from which the data for *Scolochloa festucacea* are replotted in figure 68 for comparison. Also shown in figure 68 are the data for *Scolochloa festucacea* from pothole 8, 1964. In addition to this evidence of fluctuation in moisture content, the curves of N in figure 66 suggest similar short-period fluctuations.

From the vegetation studies of 1966, the ratio of moisture content of the vegetation to its oven-dry weight was selected as a parameter for the period of activity decline. The moisture-content ratio was plotted against the mass-transfer coefficient in figure 69. The coefficient N was used, rather than N_T, because all variations in the coefficient during this period were considered to be the result of variations in transpiration alone. Thus, it was unnecessary to make an estimate of N_E in order to compute N_T. In fact, figure 69 itself, through the Y intercept, provides an independent estimate of $N_E = 0.00012$, with a standard error of 0.00003. A value of $N = 0.00011$, for this pothole at the end of the activity decline ($N_E = N$) in 1960, was obtained from a diagram similar to figure 60. This consistency is gratifying in view of the large errors possible in such computations as these.

The correlation is significant, but it explains less than half the scatter for the points ($r^2 = 0.47$). The remaining scatter, other than that due to errors which may be large, possibly could be associated with the decline in moisture content during the summer, when there is no decrease in transpiration (for example, at pothole 8 in June 1964, fig. 68). If there were some way of measuring this general decline so it could be removed from the correlation shown in figure 69, then that correlation would probably give a much better explanation of the decline in transpiration.

The usefulness of the correlation in figure 69 is

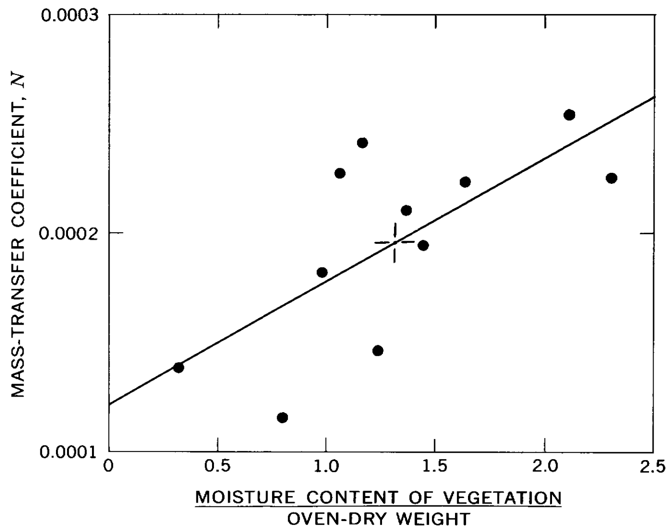


FIGURE 69.—Relation between moisture-content ratio and mass-transfer coefficient for pothole 1, August 3 to October 17, 1966.

limited by the short-period fluctuations that seem to occur in both the coefficient of transpiration and moisture content in the late summer (figs. 66, 63, 68). These fluctuations have not been adequately defined, so the moisture content, while explaining a cause of variation in N_T, is not much help in distributing the variations in N_T between computed values.

Two parameters of vegetation were found that correlate, to different degrees, with the rate of transpiration. The height index seems to be a very useful parameter during the period from the emergence of the first stems in the spring to some time after they reach their full height in summer. Moisture content, to the extent it can be used, seems to apply from early August to late October.

The decline in moisture content in June 1964 at pothole 8, certainly did not have any significant effect in reducing transpiration. Unfortunately, there was so little variation in observed moisture content later in the season at pothole 8 that it would have had little effect on the computed transpiration, regardless of the significance of any correlation. Therefore, the previous use of the height index until late August (fig. 66) was not changed. From the 1966 studies, however, it would seem that use of the height index should not be carried beyond the end of July. Curiously, at pothole 8, 1964, when the emerged height and coefficient of transpiration were practically constant (late July to early September, fig. 66) the dry weight per stem showed a slight general rise (fig. 66), and the moisture content showed a general decline (fig. 68).

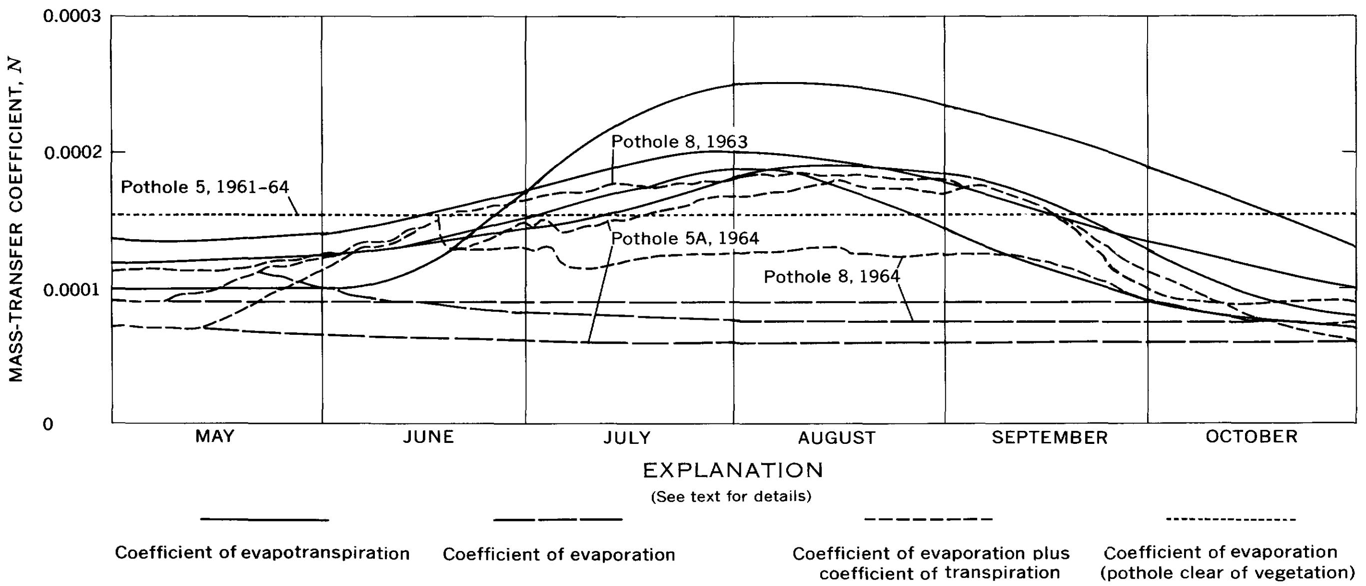


FIGURE 70.—Separation of the coefficient of evapotranspiration into its component parts.

Figure 70 shows the variation of N for several potholes in different seasons. The curves shown by short-dash lines are those obtained by computing coefficients for evaporation and transpiration separately. The fact that the coefficient N for these potholes, for the seasons shown, tends to be less than for the other potholes (solid lines), for which only evapotranspiration was computed, is the result of less vegetation transpiring, not of the method of computation. The variation in the amount of vegetation transpiring is caused by two factors—the density of the vegetation and the height of the plants above the water surface.

The variation in the coefficient for each pothole season shown in figure 70 represents the variation in evapotranspiration throughout that season. For the uniform conditions under which the curves were obtained, however, the vertical separation of the curves at the beginning and end of the seasons can be assumed to be caused by the way different amounts of vegetation in each pothole-season reduce the evaporation.

Some interesting inferences can now be drawn from figure 70, the first of which is the relation of the total seasonal evapotranspiration to what the seasonal evaporation would have been if no vegetation had been present. The long-dash line shows the coefficient for a pothole, clear of vegetation, in the same area as the other potholes. There is no reason to expect that the coefficients for the other potholes would be greatly different if they, also, were clear of vegetation. Therefore, the amount that other curves are below the dashed line at the beginning and end of the season is a measure of the amount that evaporation is reduced by the vegetation. The amount that each curve rises during the season is a measure of the transpiration.

The effects of the short growing season in North Dakota are evident in the short period during which transpiration takes place. In other climates where the growing season is longer, transpiration would have a much better chance of offsetting, perhaps by a substantial amount, the effect of evaporation reduction.

The spread in the curves during the height of the growing season, shown in figure 70, is considered as representing the effects of emerged height and density of the vegetation. If the amount (in terms of area) a curve is above the line for a comparable clear pothole is less than the amount it is below that line, then this indicates that the vegetation has probably reduced the total water loss to the air. If, however, the amount above the line is greater than that below, then it is assumed that the presence of vegetation has increased the water loss.

Table 27 gives the evapotranspiration from pothole 8 for 1963 and 1964. The process by which these data were obtained is such that large errors could occur. Despite this fact, the results seem to be consistent and reasonable. The magnitude of any quantity in relation to the magnitudes of other quantities should be fairly accurate. The data for pothole 5A for 1964 are included, as well as the evaporation losses at pothole 5, which was clear of

TABLE 27.—*Water losses, in feet, from May to October in clear and in vegetated potholes*

Year	Vegetated potholes: Average emerged height of vegetation during August (feet)	Evaporation loss	Transpiration loss	Total loss	Clear pothole 5 (evaporation loss)
	POTHOLE 8				
1963	5.2	1.1	0.7	1.8	2.6
1964	2.9	1.3	.5	1.8	2.3
	POTHOLE 5A				
1964	3.6	.9	1.1	2.0	2.3

emerged vegetation and about 3 miles from pothole 8. Also included in the table are the average emerged heights of live vegetation during August, which provide a measure of the relation between emerged vegetation and transpiration. This month was chosen because the vegetation at that time had approximately reached its maximum height, and 1 month is a sufficiently long period to average out fluctuations in water levels.

It could be expected that if the emerged hydrophytes had not been present in potholes 8 and 5A, the evaporation from each would have been about the same as that from clear pothole 5 (table 27). It can be concluded, therefore, that the presence of hydrophytes reduced the evaporation significantly, a reduction that for the two vegetated potholes listed was not offset by transpiration. In figure 70, pothole 8 shows the least seasonal increase in the coefficient of transpiration for any pothole compared. From the magnitude of this increase in coefficient at the other potholes, it would seem that transpiration can offset evaporation reduction in other situations. The fact that the seasonal increase in the coefficient is relatively small—and taking into consideration the curve in figure 67, which shows no maximum value of N_T—suggests that the density of growth in pothole 8 could be much greater, perhaps enough for the rate of transpiration to offset the reduction in rate of evaporation, or even more.

Continuous values of all items in the water budget were computed. Evapotranspiration from the potholes was also computed as the residual in the water budget (eq. 2). Precipitation was measured by a recording rain gage. The decrease in storage was obtained directly from the chart of a water-stage recorder. Basin inflow was scaled from the chart by extending the recession curve forward or backward from periods of no inflow and adjusting for precipitation. The net seepage-outflow rate was obtained from the intercept in the diagram for the definition of coefficient N (fig. 58). If there were periods of overflow, no computations were made for them.

The relation between the evapotranspiration computed by the mass-transfer equation and the values obtained from a water budget are shown in figure 71. These curves show the cumulative evapotranspiration from May 1. Where the two curves are parallel (constant vertical separation), the two methods give the same results. The vertical separation gives the total difference between the two methods, cumulative from May 1.

The two curves in figure 71 are only partly independent. Evapotranspiration by mass-transfer is computed as the product of N and meteorologic factors. The coefficient of N is dependent on the decrease in pond level, H, which is also one of the items in the water budget. Also, the seepage outflow used in the water budget is determined from the vertical intercept of the line defining the value of N (fig. 58). However, seepage was considered to be a constant, so the only way the water budget curves of figure 71 could be affected by errors in seepage would be by changes in the general slopes of the lines. That is, if the seepage were changed, the effect would be to pivot the curve about the left end so that the right end of the curve would fall on the new value of the total evapotranspiration for the season. There would be no change in the distribution of the evapotranspiration throughout the season. Therefore, the closeness with which the mass-transfer curves follow the changes in slope of the water-budget curves is a measure of the accuracy of the mass-transfer-coefficient curves in figure 66. Any major error in the way N was varied during the season would show as a significantly different slope of a mass-transfer curve in figure 71 compared with the corresponding water-budget curve.

The accuracy of the total evapotranspiration for the season is shown best by inserting the computed mass-transfer value of evapotranspiration in the water budget, as in table 28.

As no term in the water budget in table 28 is a residual, it could be expected that the budget would fail to balance. The fact that the residual error is zero is considered to be accidental because the starting time used for the beginning of seepage outflow in the spring was purely arbitrary; any change in this date would immediately throw the budget out of balance.

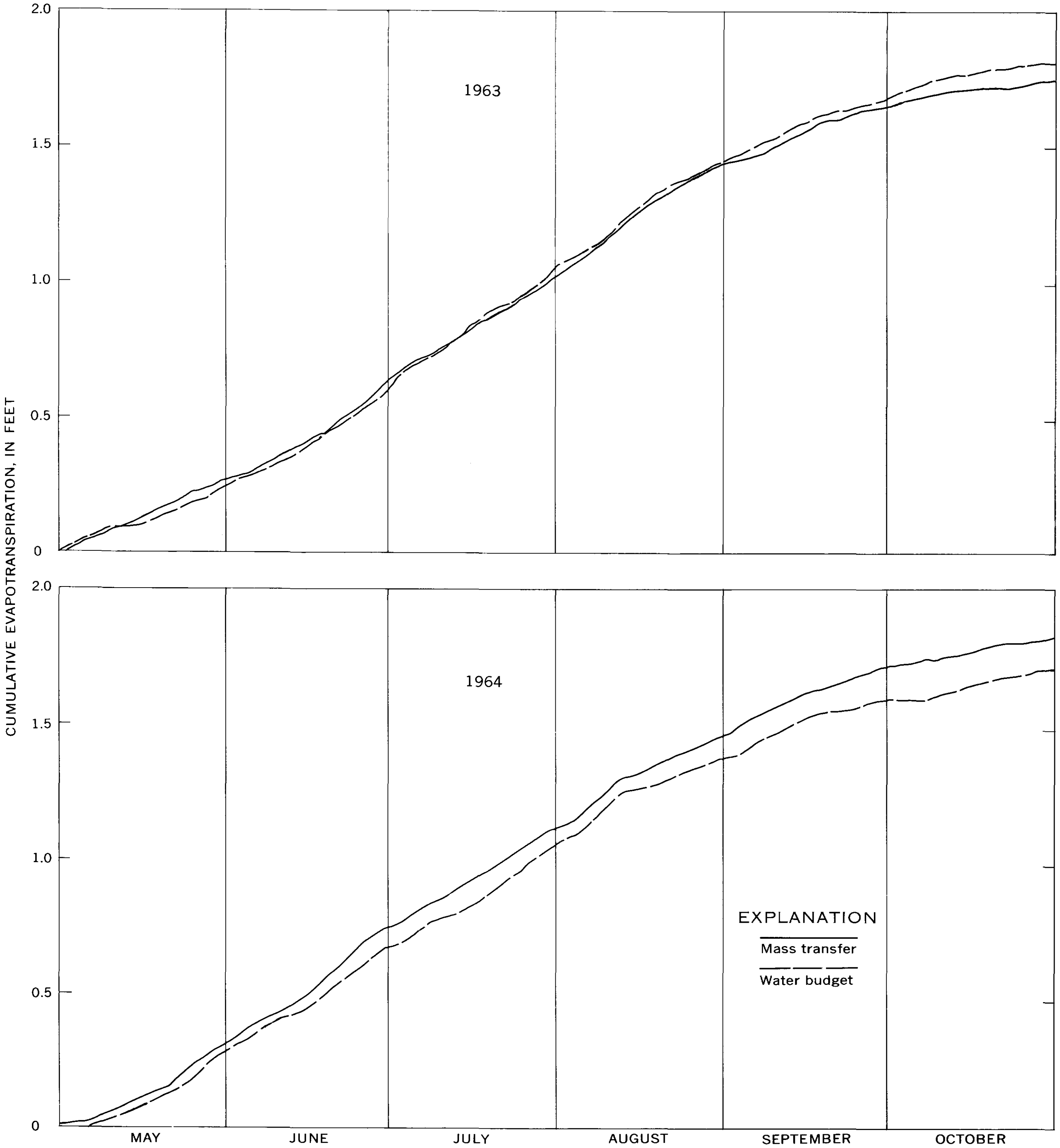


FIGURE 71.—Comparison of evapotranspiration quantities obtained by mass-transfer and water-budget computations, pothole 8, 1963–64.

TABLE 28.—*Water budget of a prairie pothole*

Component	May to October (feet)
Evaporation	1.09
Transpiration	.66
Net seepage outflow	.50
Total decrease	2.25
Precipitation	1.44
Runoff	.27
Total increase	1.71
Computed decrease in storage	.54
Measured decrease in storage	.54
Residual error	.00

Table 28 gives the water budget for pothole 8 for 1963 and shows evaporation and transpiration as separate items computed according to the preceding discussion. The total evapotranspiration, therefore, is not identical with that given in table 23, but the difference is not significant.

The residual error is a good measure of the general accuracy of the computations because less than 40 percent of the change-in-storage record was used in the definition of *N* and *S*, leaving the computations for more than 60 percent of the time as independent determinations.

SEEPAGE LOSSES FROM POTHOLES

In all the potholes studied, net seepage flow was an outflow item in the water budget and, thus, a loss of water from the pothole. Seepage inflow, when it occurred, only reduced the amount of this loss. Seepage was determined only as rate per unit area of water surface for use in the water budget. It was not used to determine any rate of groundwater movement.

Seepage in relation to a pothole is defined generally for this report as underground flow through the bottom of its pond. Specifically, it is underground flow across the imaginary warped surface that is roughly parallel to the bed of the pond, but is below the root zone of plants whose stems protrude through the water surface. (See p. A67.) Seepage is thus defined because transpiration must be measured with evaporation, yet the source of water for transpiration is water absorbed by the plant roots below the real bottom of the pond. The soil can generally be assumed to have little control over such water movement. In contrast, the water transpired by vegetation on the shore surrounding a pond, if supplied by the pond, must still move a sufficient distance through the ground that the hydraulic conductivity of the material through which it moves can have a controlling influence. This hydraulic conductivity could be high at those ponds that have wide, gently sloping shores with gravel and sand deposits of previous beaches just below their surface. (See fig. 88.)

The rates of seepage outflow were the subject of much investigation and discussion. They could only be determined as part of the computation of the mass-transfer coefficient, *N*. The process is such that large errors are possible in the computed values. A large range in values was found frequently. (For example, see Shjeflo, 1968, p. B39.) Are the variations in computed values real, or only the result of computational and observational errors? All computed net-seepage-outflow rates are low, seldom greater than 0.01 foot of water per day per square foot of pond area, and frequently less than half that rate. These flows are not negligible, however, because they often total more than one-fourth of the seasonal loss of water from a pothole.

Seepage rates are significant also because the value used has a direct effect on the determination of the mass-transfer coefficient, *N*. Especially because of this effect, it was deemed important to determine whether there is a measurable parameter related to the variation in seepage rates. All the usual factors were investigated without success: depth of pond, level in observation well, difference between pond and well levels, rate of decrease in well level, water temperature, and concentration of dissolved solids. For example, the plots for pothole 8, 1964, are shown in figure 72. Not every factor was investigated for every pothole, but any one that seemed promising for one pothole was tried for other potholes. No consistent relation between computed seepage and any other variable was found. On this basis, the variation in computed net seepage outflow was assumed to be due to error, and an average constant value was used in the computations. Average values for the study are given in table 29. Values of *N* computed on this basis seem to be more consistent than those resulting from using the variable rates of seepage computed.

From table 29 it can be seen that the average net seepage outflow from vegetated potholes is generally greater than that from clear potholes. Potholes 7 and 8 had dense stands of vegetation during the dryer years, became clear during the wet years, and were still clear of vegetation in 1968. Conversely, pothole 3 remained clear of emergent vegetation during the study, but toward the end of and after the study was practically dry each of several years, hence, this pothole may eventually be filled with vegetation unless large basin inflows occur.

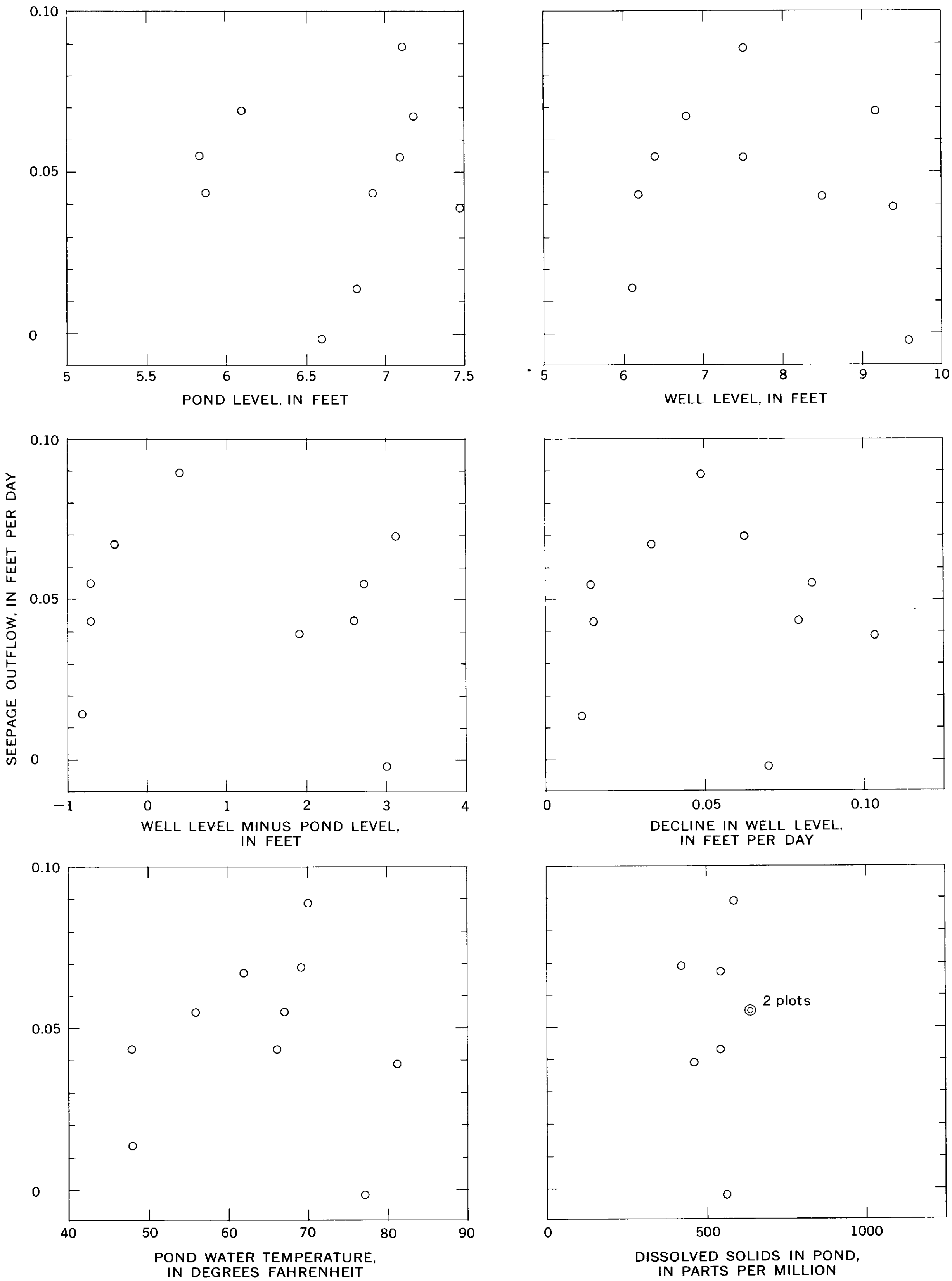


FIGURE 72.—Variations in seepage outflow compared with other factors, pothole 8, 1964.

TABLE 29.—*Average net seepage outflow rates from study potholes*

[From Shjeflo, 1968, p. B42]

Pothole	Seepage (ft per day)
VEGETATED POTHOLES	
1	0.0076
2	.0063
4	.0074
5A	.0088
6	.0053
7	.0035
8	.0033
Average	.0060
CLEAR POTHOLES	
3	0.0035
5	.0008
C1	.0015
Average	.0019

The three potholes just described have net seepage-outflow rates intermediate between those with high rates (which generally contained emergent vegetation) and those with low rates (which generally were clear). This fact, coupled with the fact that potholes need to go dry to reestablish vegetation (as described in the section entitled "Effect of Vegetation on Transpiration"), suggests that vegetation can normally be associated with high seepage-outflow rates. The high rates cause the more frequent drying of the pothole, which is needed to keep and (or) renew the vegetative growth.

Combining the seepage losses with those from evapotranspiration, the total water loss from potholes with vegetation can be seen to be significantly greater than that from potholes clear of vegetation.

At the close of the study, the subject was reexamined in the light of information obtained on ground-water flow systems (Sloan, 1972). The result is a persuasive explanation of at least some of the variations in net seepage-outflow rates. However, it is very doubtful that any recomputations on the basis of this explanation would signficantly affect previously published values of water loss.

It was early recognized that there is an extremely close correlation between pond levels and water levels in the nearby observation well. The relation is one that does not change when well levels go from above to below the plane of the pond surface (fig. 73). Furthermore, when pond levels rise as a result of precipitation and runoff, and there is no corresponding recharge to ground water, that relation

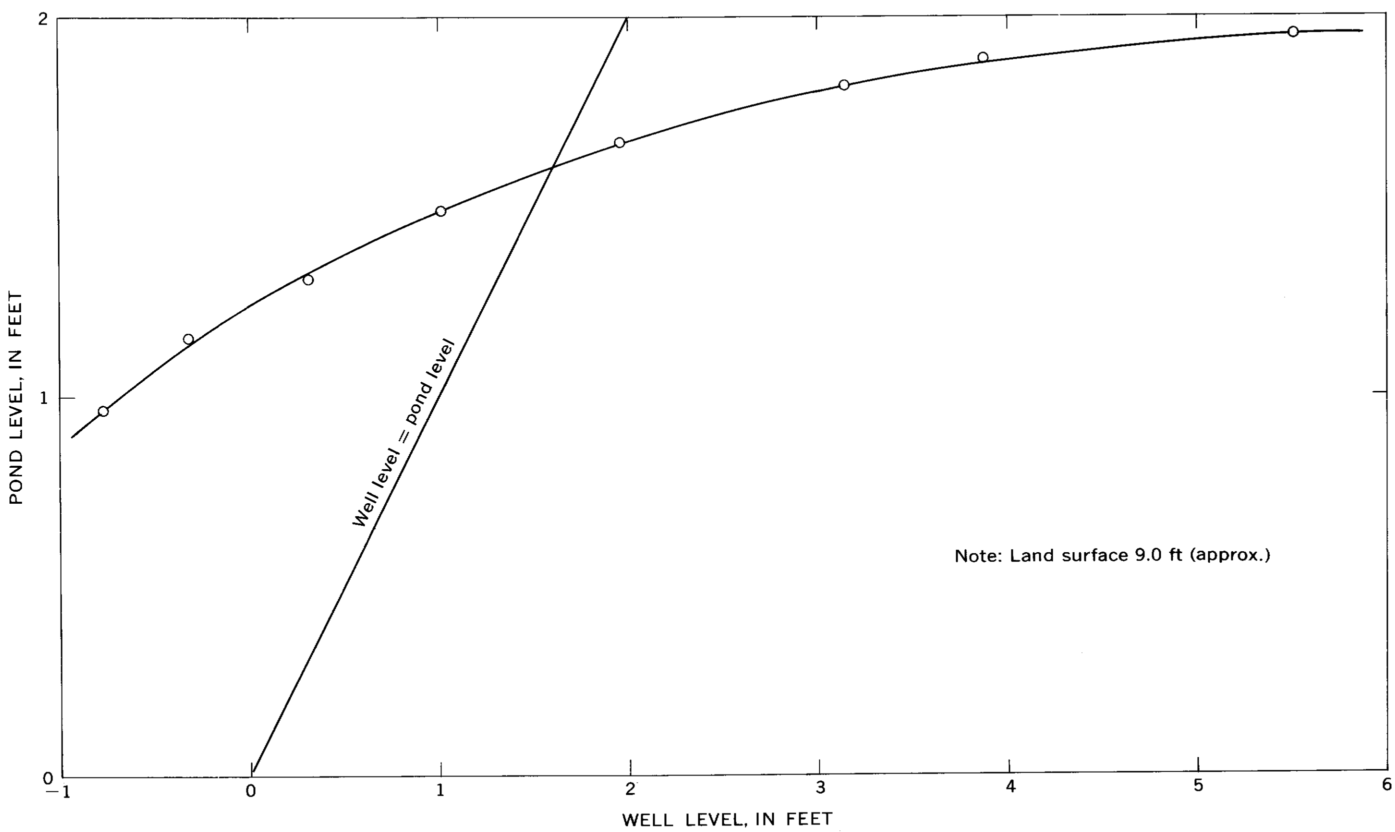


FIGURE 73.—Relation of pond level to observation-well level, pothole 4, June 22 to August 10, 1964.

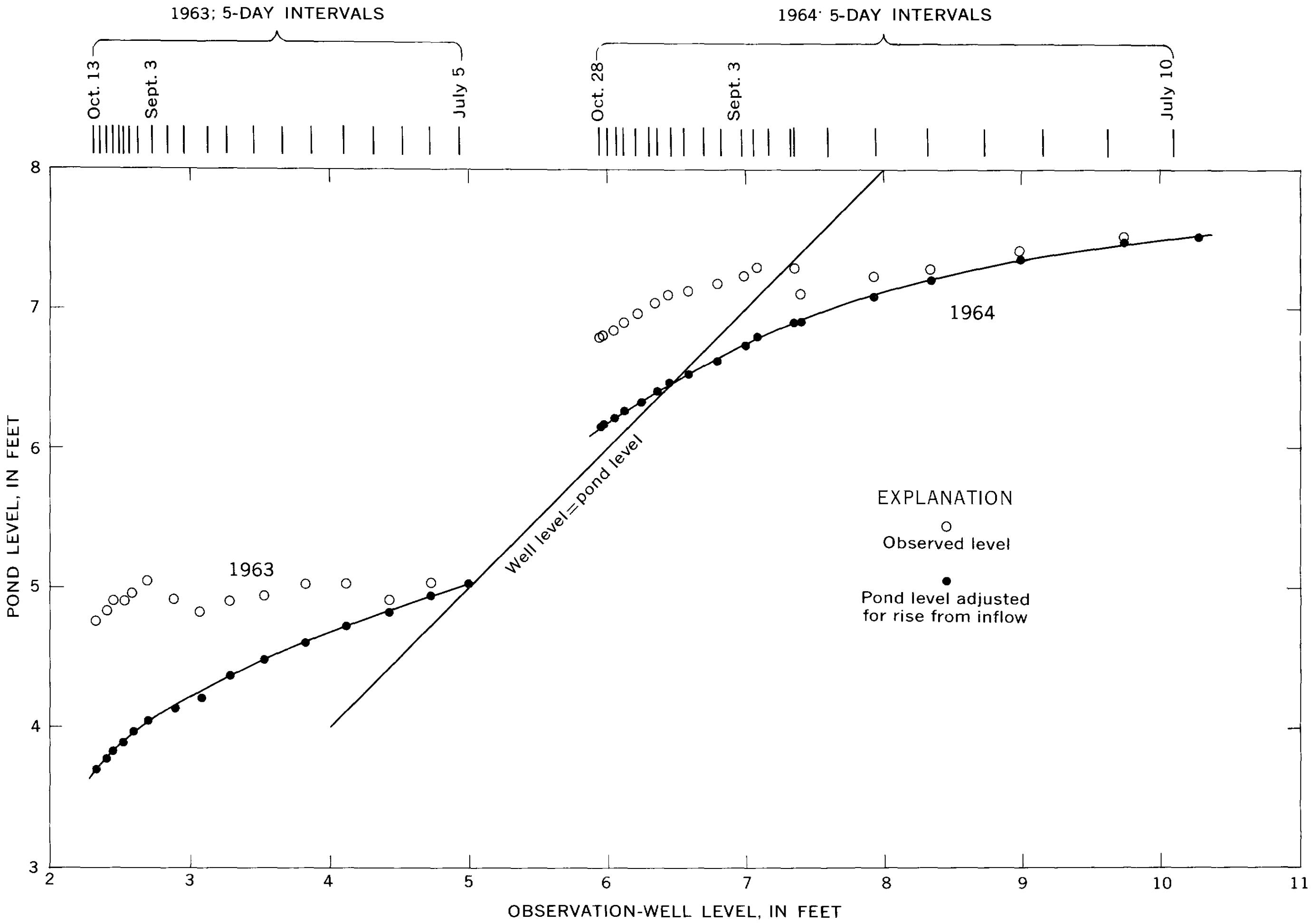


FIGURE 74.—Relation of pond level, adjusted for rise from inflow, to observation-well level, pothole 8, 1963 and 1964.

is displaced upward by the amount of the rise in pond level, but the slope of the relation curve remains unchanged. This is illustrated in figure 74, where pond levels are adjusted for precipitation and runoff that occurred within the period of the diagram. The large upward displacement of the graph for 1964 is the result of the large amounts of precipitation and runoff that occurred in the spring of that year.

An examination of the hydrographs in chapter B (Shjeflo, 1968) shows that the decline in well levels slows markedly in September, irrespective of the well's elevation or its relation to pond level. This is shown by the hydrographs in figure 75 and the 5-day-interval marks in figure 74. The slowed decline in water levels is explained by the decrease in transpiration by the vegetation surrounding the pothole ponds, where the water table frequently is not far below the land surface. Thus, the steeper parts of the hydrographs indicate an appreciable water loss by transpiration. Furthermore, the slopes of both hydrographs (fig. 75) are virtually the same in October, even though there was about 4 feet difference in their levels, which suggests that, in addition to transpiration, there is a general downward movement of water at a slow, but rather constant, rate.

Also, the rate of decline of water levels in wells when they were just below the pond levels was far greater in 1963 than in 1964, suggesting that the rate of decline in well level seems to be uninfluenced by the proximity of the well's actual level to that of the nearby pond.

During preparation of this report, a computer program became available for computing the covariances and correlation coefficients for many variables. Accordingly, for pothole 5, in 1964, the net seepage-outflow rate was compared with eight other variables. The highest correlation coefficient (0.76) was found to be with the decline in well level, in feet per day. (Fig. 76.)

The many observation wells drilled as part of the

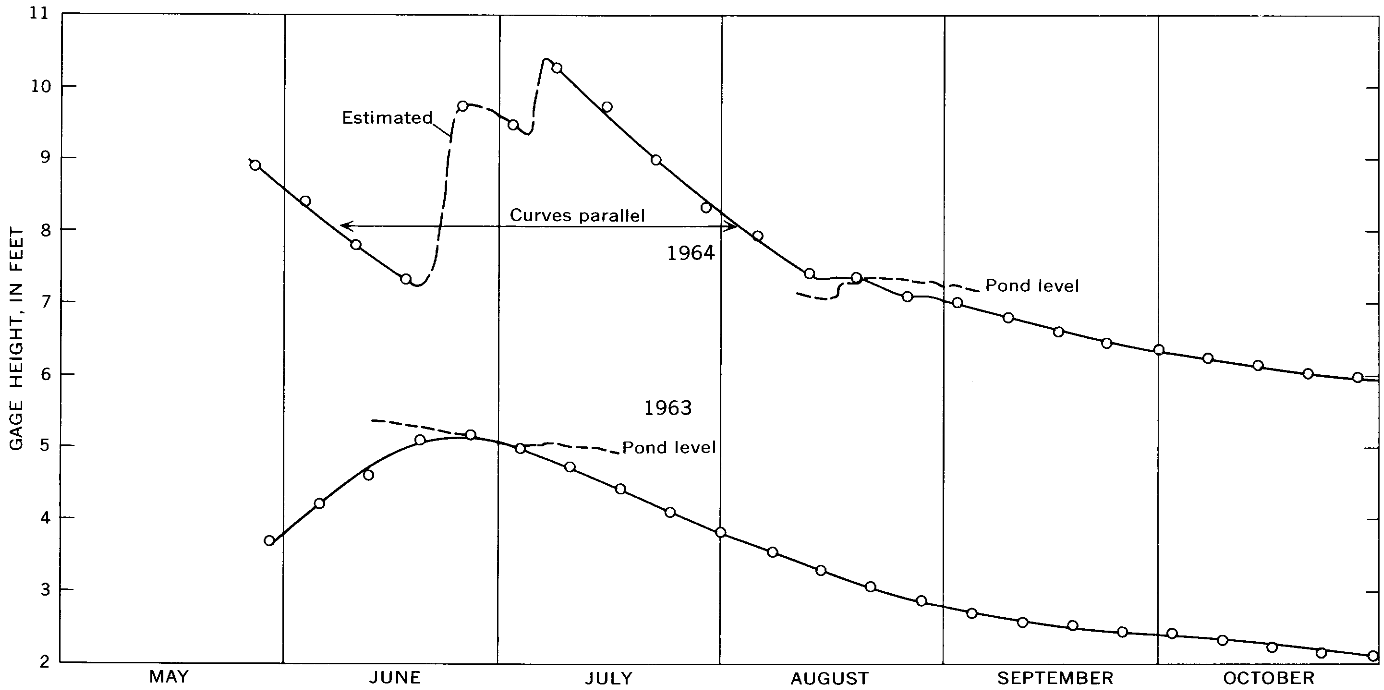


FIGURE 75.—Observation-well levels in pothole 8, June to October 1963 and 1964.

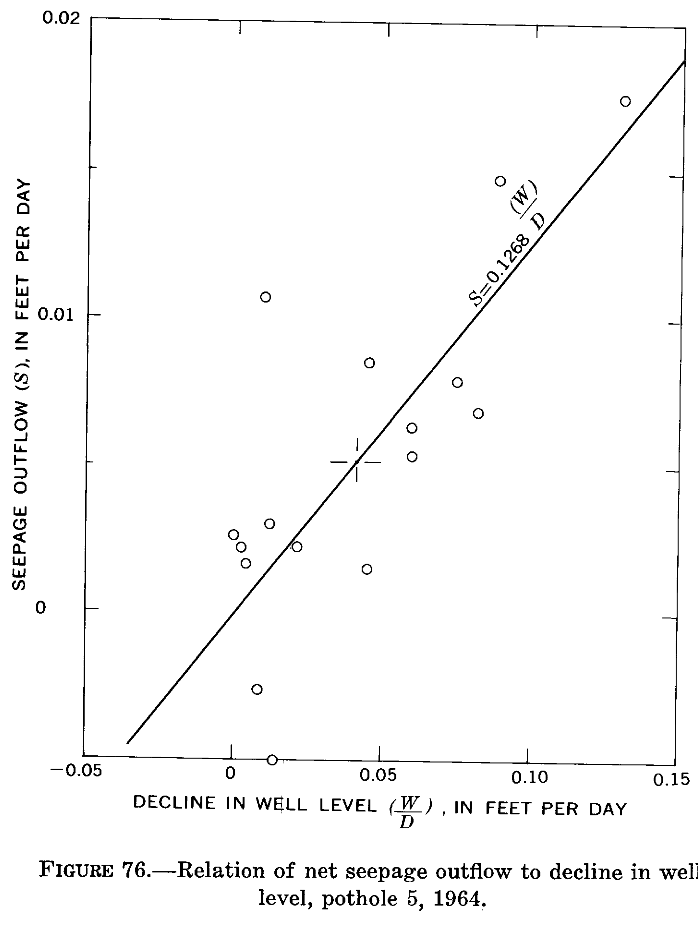


FIGURE 76.—Relation of net seepage outflow to decline in well level, pothole 5, 1964.

ground-water investigations showed rather conclusively that the water surface in a pothole is an "outcrop" of the water table. They showed also that the till below the frost line, and especially below the zone of oxidation, has very low premeability. Water at depth can be expected to move very slowly.

Putting these ideas together, we postulate that, as a part of the saturated zone whose surface at atmospheric pressure is the water table, the water lost by seepage from potholes is a part of the general decline in the water table. The much greater change in level observed in the observation wells is explained, in part, by the very low coefficient of storage for till. Flow through the till is slow, so it is difficult for pond levels to influence the levels in the observation wells, even as close as they are to each other. The decline in levels of pond and well are both part of an areal decline in the water table. Thus, water added to a pothole by precipitation has little influence on the general decline.

At a pothole where no evaluation of *N* has been made, a stage record alone can often provide useful information on seepage losses, if there are several other potholes nearby with similar records. The range in evapotranspiration losses is small compared with the range in seepage losses. Therefore, signficant differences in total losses within a group of potholes can generally be interpreted as variataions in seepage losses. Figure 77 shows how the records of

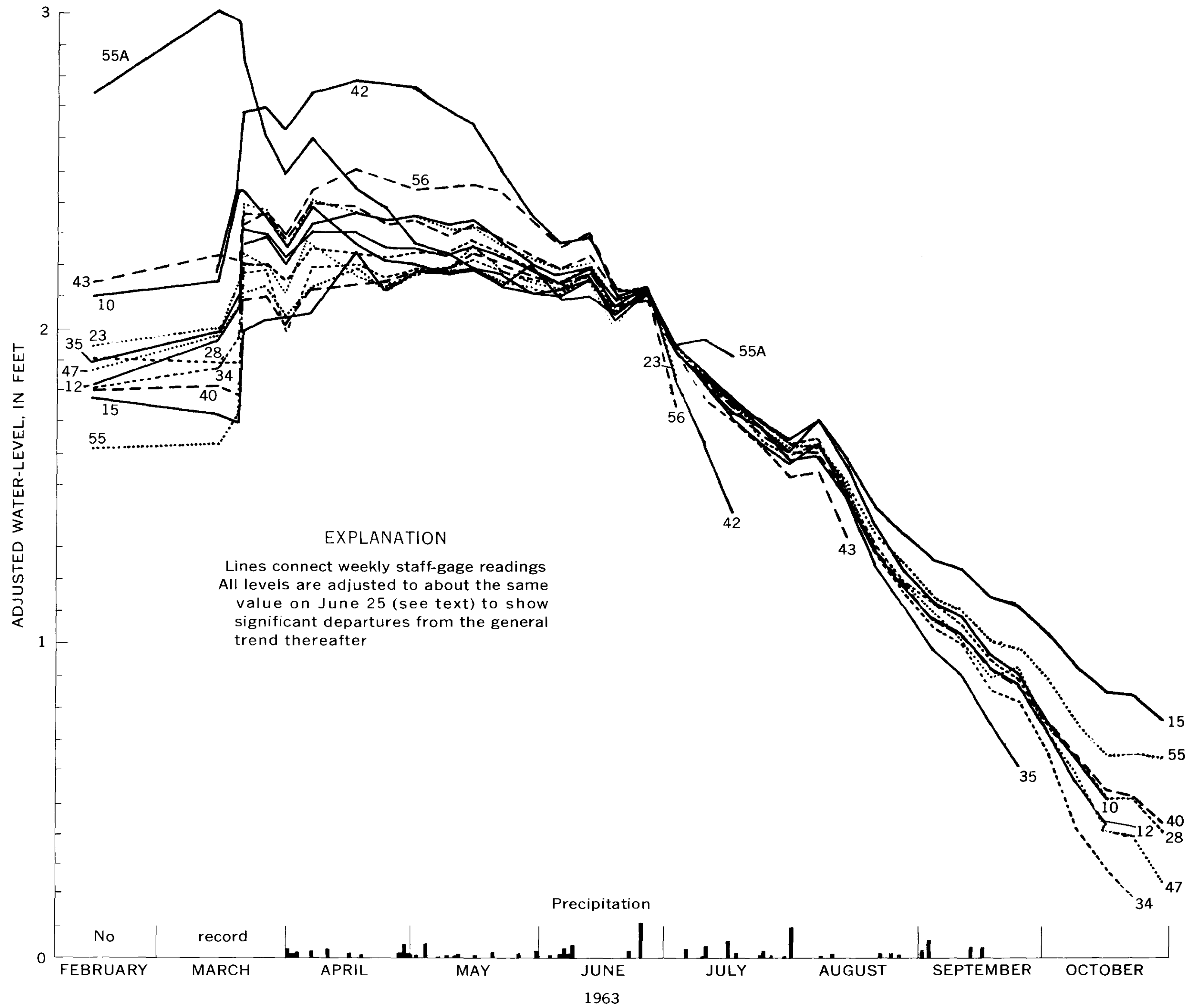


FIGURE 77.—Comparison of stage records for 1963 at potholes in the Mount Moriah area.

weekly staff-gage readings at the potholes in the Mount Moriah area were compared for 1963. In the spring, each pothole seemed to receive its own individual amount of basin inflow from each storm. In summer, however, basin inflow took place only from those storms that occurred when soil moisture conditions were favorable, and, then, the basin inflow showed far less variation among the potholes than in the spring. Following the rainfall of June 25, summer conditions seemed to prevail. An adjustment was therefore made in the gage heights for all potholes, so that the stage on June 25 would be very close to 2.15 feet. These adjusted gage heights are plotted in figure 77. The rate of total loss (evapotranspiration plus seepage) for most potholes falls within narrow limits, but a few potholes, M23, M42, and M56, show a much higher rate of loss, which is confirmed by observations in other years.

Pothole M40 was deemed to be about average for the Mount Moriah area potholes, so it was plotted (fig. 78) for comparison with the potholes in the Woodworth and Cotton wood Lake areas. In fig. 78 the gage heights were adjusted to 2.4 feet June 25. The losses indicated by the hydrographs after this date correlate rather well with other known or surmised facts about these potholes. Pothole W1 is known to be spring fed. Pothole W2 was selected originally because it was thought that it might be connected to the gravel beds in the area and have higher inflow seepage rates. The net outflow-seepage

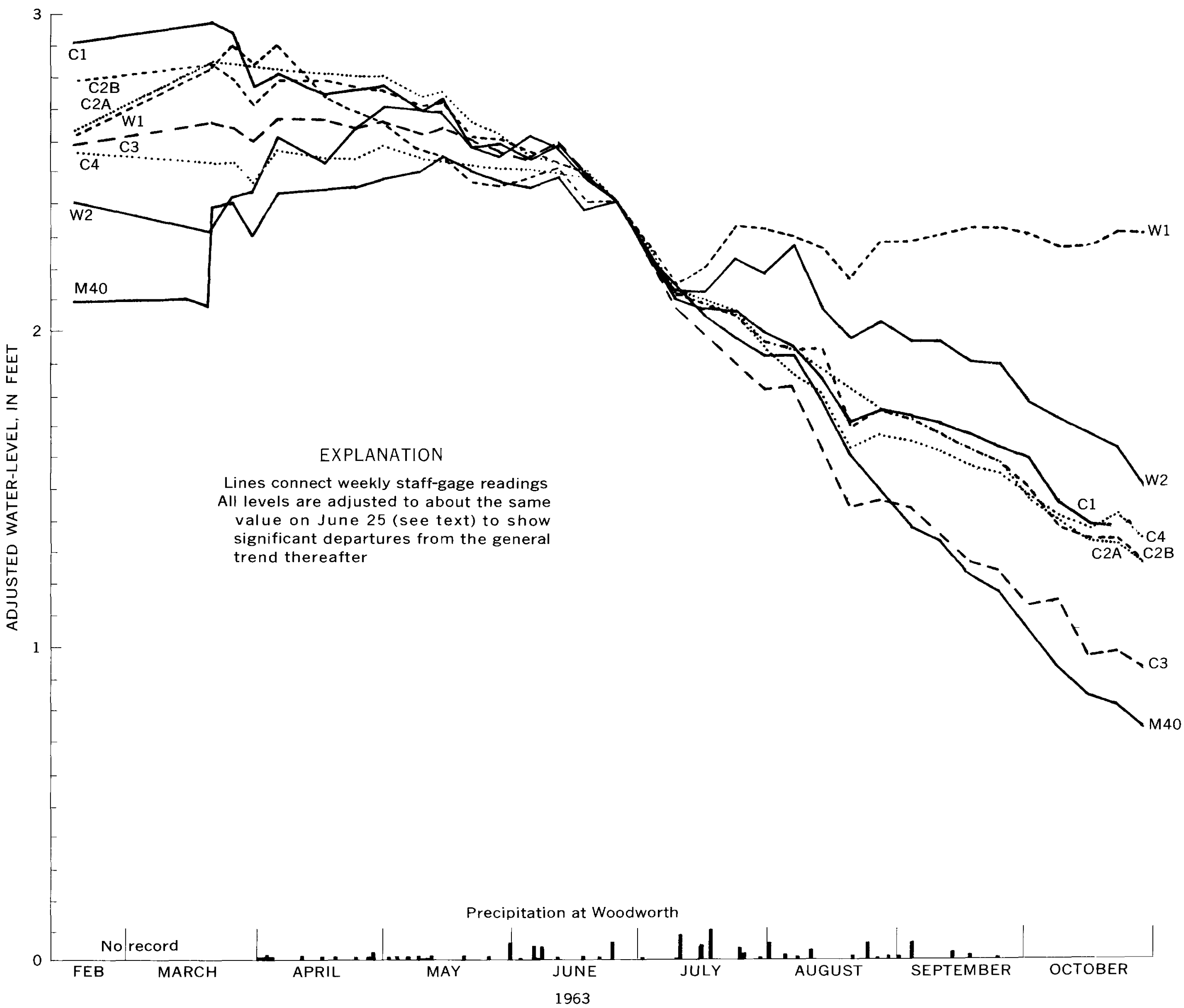


FIGURE 78.—Comparison of stage records for 1963 at potholes in the Woodworth and Cottonwood Lake areas.

rate from pothole C1, as shown in table 29, was very low, so it can be assumed that the rates at potholes C2 and C4 were also very low.

Thus, in an area where evapotranspiration rates are fairly uniform, stage records can be used to estimate relative net seepage-outflow rates.

GROUND-WATER HYDROLOGY

An intensive study of ground water near the study potholes, and in a broad profile across the Coteau du Missouri, was made by Sloan during the period 1965–68. Much of this section is a summary of his work, which is described in detail in chapter C of the present series (Sloan, 1972).

The ponds in priarie potholes, in effect, are "outcrops" of the water table. A water table is defined as "that 'surface' within the zone of saturation, at which the pressure is everywhere atmospheric" (Lohman, 1965, p. 92). In October 1965, 28 observation wells were augered in the Mount Moriah area to determine the position of the water table between potholes. (See "Destricption of the Study Area" and "Geology" sections.) Figure 79 shows a profile of the water table through several potholes, drawn on the basis of water-level observations in these wells.

The situation illustrated in figure 79 is believed to be typical of potholes on the Coteau du Missouri in which the ponds are relatively permanent. It should be evident that these ponds are not perched, or separated, from a regional water table by an

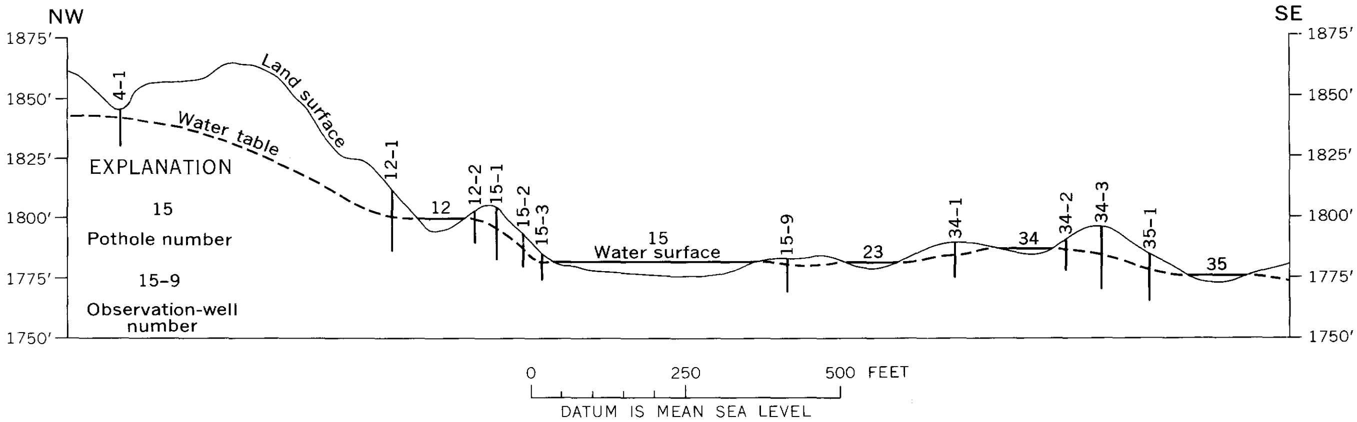


FIGURE 79.—Profile of water table and potholes in the Mount Moriah area. (From Sloan, 1972.)

unsaturated zone, as some previous investigators were led to believe. To understand the situation properly it is necessary to appreciate the effects of the very low hydraulic conductivity of the till in which the potholes were formed. In the more permeable outwash deposits, the water-table concept is much easier to understand.

Values of hydraulic conductivity ranging from 0.02 to 0.002 foot per day were measured in till surrounding eight observation wells at pothole C1. Hydraulic conductivity is the velocity of flow through a unit area of permeable material with a hydraulic gradient of unity. A common value for clay is 0.0002, and for a well-sorted medium sand, it is 100 feet per day.

Some of the observation wells in the Mount Moriah area appeared to be dry when they were augered, but water seeped into them and reached equilibrium within a few hours. Thereafter, these water levels fluctuated about the same as those in the other wells. The seeming "dryness" of these wells is explained as a result of the augering process. The till has a very low permeability, and the weight of the augering equipment can physically squeeze water out of the material being augered. Furthermore, the heat generated by the augering process probably vaporizes any remaining water in the material, because it is often brought to the surface hot and "steaming." Samples of this material appear dry and crumbly, although they may have been saturated and sticky when they were in place. Laboratory tests of samples from wells augered at pothole C1 gave an average hydraulic conductivity of only about 0.006 foot per day.

Figure 73 shows that the relation between well level and pond level did not change when the well level changed from above to below the pond level when the edge of the pond was only about 100 feet from the well. The hydraulic conductivity between the two points was simply too low to permit enough flow of water to modify the relation.

Figure 29 illustrates a relationship common on the Coteau du Missouri; two ponds close together with a relatively large difference in elevations of their water surfaces. (See text discussion with fig. 29 for data.)

Water levels in a cluster of wells cased to different depths are often markedly different. The difference in water level divided by the difference in depth of the bottom of the casing gives the gradient of vertical flow. As shown in figure 81, some of these gradients are steep.

The foregoing examples show situations which one might consider as evidence of perched ponds, if one did not take into account the very low hydraulic conductivity of till. Furthermore, the augering done during this study consistently showed a water table extending away from every pothole pond that was at least seasonal in permanence.

There are many truly perched ponds, but they last for very short periods. Commonly, a pond that forms above frozen ground disappears rapidly as soon as the ground thaws. Sloan (1972) measured a seepage-outflow rate of 0.5 foot per day (averaged over the area of the pond) in an ephermeral pond during the period April 11–16, 1969.

As a further check on the existence of a regional water table, more than 100 water wells were inventoried in a broad profile across the Coteau du Missouri, from the drift prairie in central Stutsman County to the outwash plain in central Kidder County (fig. 9). The water levels in these wells were

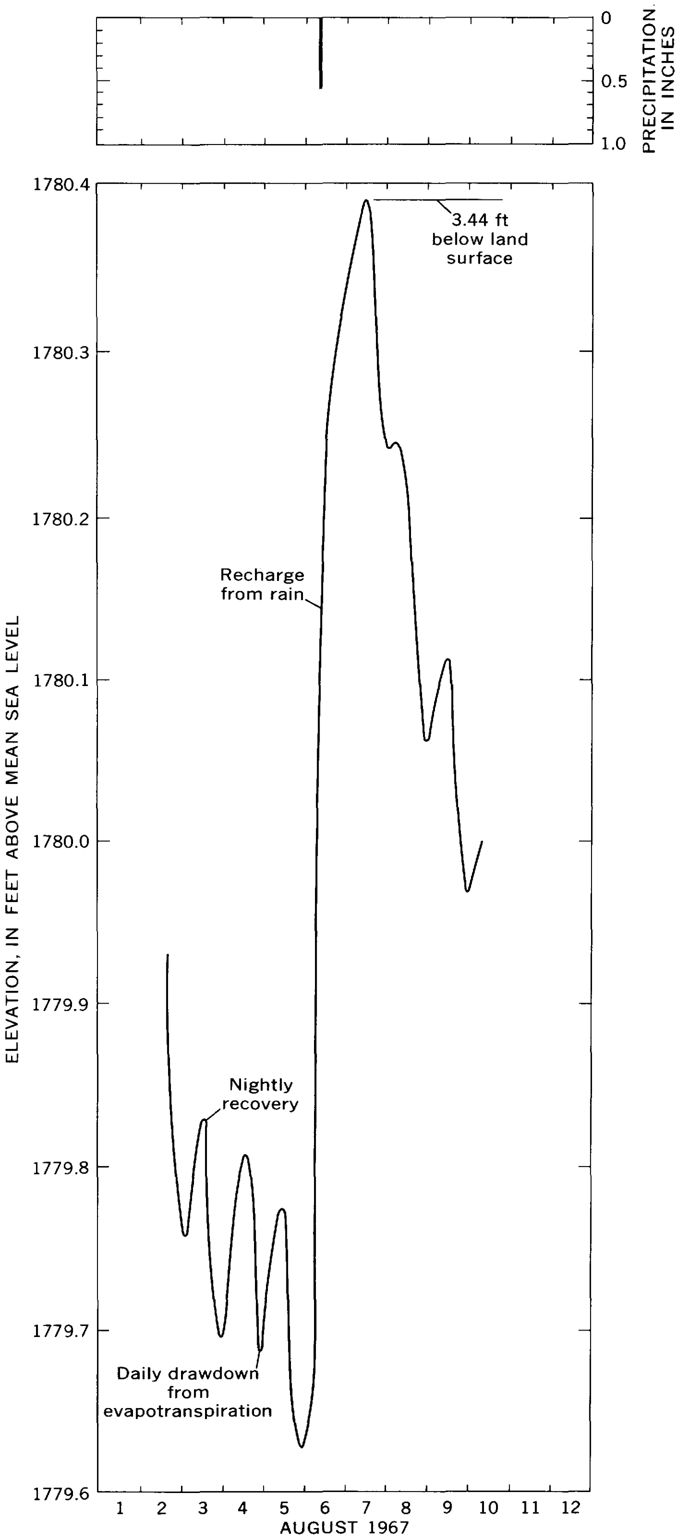


FIGURE 80.—Hydrograph of observation well 15–5 in wet-meadow zone of pothole M15. (From Sloan, 1972.)

very erratic, suggesting that they were more dependent on the depth of the well than on any regional water table. (See fig. 81.)

A water-table map of a part of the Mount Moriah area was prepared by Sloan on the basis of data from the ponds and observation wells. The water-table contours on Sloan's map are reproduced on plate 1. The contours show that the water table follows the general configuration of the land surface, but that it smooths the local irregularities.

The foregoing factors all point to the conclusion that ground-water movement near potholes in a till terrain is a local phenomenon. This may be explained, in part, by the vertical joints[10] that allow much more rapid movement of water vertically than horizontally. The work of Meyboom (Meyboom and others, 1966, and references cited therein) in Canada supports these conclusions. At least some of Meyboom' work was in a geologic setting similar to that of the present study (Meyboom and others, 1966, p. 11).

The preceding paragraph should not be interpreted to mean there is no horizontal movement of ground water through till. Good evidence indicates that, for a few tens of feet from the pond, there may be significant movement of water from the pond to supply the evapotranspiration losses from that area. This is especially true in ponds where there is a gently sloping bank underlain by a stratum from which the silt and finer particles have been removed. (See fig. 88 and its accompanying text discussion.) Sloan augered shallow wells along two profiles extending away from pothole C1. He found that the maximum lowering of the water table below pond level was 0.37 and 1.07 feet at distances of 21 and 12 feet, respectively, from the edge of the pond. This area is known as the wet-meadow zone because most of the vegetation consists of meadow grasses that tolerate a high water table and occasional inundation. Evapotranspiration fluctuates diurnally, and similar fluctuations in the water table beneath wet-meadow zones were observed. (Compare figs. 80 and 65.) This phenomenon may explain the partial correlation that Shjeflo (1968, p. B39) found between the mass-transfer coefficient and seepage rate at some potholes. It also shows how seepage from a pothole can be prevented from making a substantial contribution to ground-water recharge.

The clusters of wells on the east and northeast sides of pothole C1 clearly show a vertical hydraulic gradient. The difference in water level between any two wells in a cluster, divided by the vertical distance between their bottoms, gives the vertical hydraulic gradient between those two points. Water

[10] See the section entitled "Geology."

levels in the wells in four of these clusters on September 13, 1966, are shown in figure 81.

Hydraulic gradients measured at pothole C1 indicate slow downward flow beneath the uplands, and upward flow beneath the pothole and along its margins.

The chemical quality of pothole waters is closely related to the direction of ground-water movement. Details of chemical quality and range in total and selected dissolved solids are described in a succeeding section. For the present discussion the total dissolved solids or its practical equivalent—the specific conductance, in micromhos per centimeter (fig. 91)—is an adequate index of ground-water movement.

All water entering a pothole contains solids dissolved in it. The amount in rainfall is very small, but the amount in seepage inflow can be very large. Nonetheless, no significant amount of dissolved solids is removed from a pothole, other than in seepage outflow (ground water), except on those occasions (generally rare) when the pothole overflows. Evapotranspiration removes only pure water (as vapor), thus, further concentrating the dissolved solids in a pond. If a pond dries completely, some solids are precipitated on the ground, where some may be removed by the wind. Bacterial action may transform some dissolved solids into gasses that are lost to the atmosphere. Our study indicated that only minor amounts of solids are removed by either of these two processes.

Inasmuch as seepage outflow is the major controlling factor in removing dissolved solids from a pond, the rate of seepage outflow—in relation to the amount of water and dissolved solids brought into the pond—determines the salinity of the pond. At a pond where the rate of seepage outflow is high, the water will be relatively fresh. At a pond where there is no seepage outflow, the solids will accumulate, and the water can be anything from brackish to a brine. The total amount of seepage outflow is dependent on the slope of the water table (hydraulic gradient), the hydraulic conductivity of the bed material, and the part of the area of the pothole in which seepage inflow (instead of seepage outflow) takes place. The net result is that the salinity of a pothole water is a very good index of the direction of ground-water movement in the pothole's vicinity. Table 30 illustrates the relation between the direction of ground-water movement and the salinity of a pothole pond.

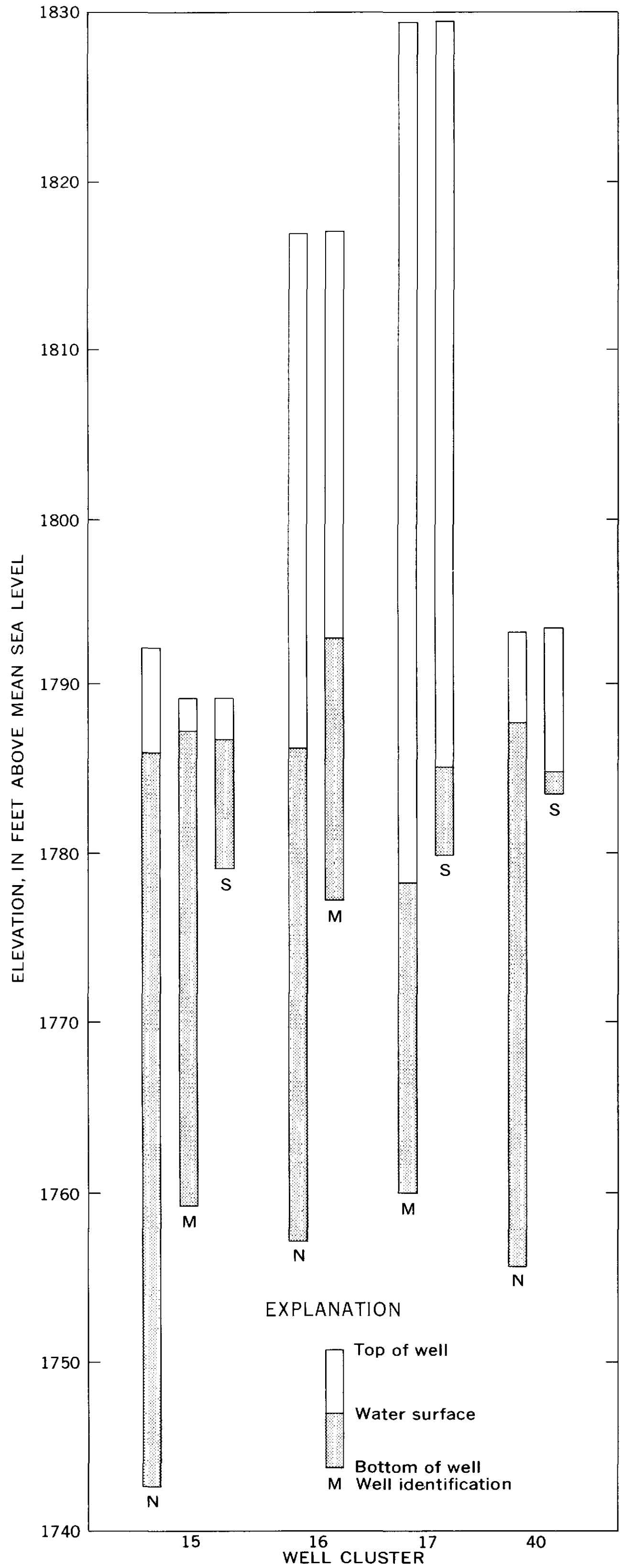


FIGURE 81.—Water levels in clusters of wells at pothole C1, September 13, 1966. Difference in water levels between adjacent wells divided by difference in their bottom elevations, gives the vertical hydraulic gradient. (From Sloan, 1972.)

TABLE 30.—*Relation between specific conductance and slope of water table at four potholes in the Mount Moriah area*

[From Sloan, 1972]

Pothole No.	Slope of water table from pothole	Specific conductance (μmho per cm)[1]
42	Steeply away	360
34	Gently away	775
12	Award and toward	1,100
15	Toward	3,000

[1] Micromhos per centimeter.

Just as the disposal of dissolved solids, left in a pothole as a result of water evaporating, indicate the direction of ground-water movement in relation to the pothole, so the solids dissolved in ground water, by their reactions with the soils through which they move, leave traces by which the direction of movement can be determined. This phenomenon was investigated at pothole 4, by Miller (1969).

Entering the southeast corner of pothole 4 (fig. 82) is a well-defined drainage course, which carries runoff when it occurs. There are several potholes along this course (P, H, G, F, fig. 82), but it is doubted that they overflow often. The course between pothole F and pothole 4 is much larger than it is above this reach. The vegetation here, especially near the outlet to pothole 4 (fig. 87), suggests an abundance of moisture, as though there was underflow.

In the reach between potholes F and 4, Miller (1969) took soil samples at two points to study the chemical evidence of underflow in the soil. The depth to the water table and the specific conductance were measured along a profile through these sampling points, with the results shown in figure 83. The high concentration of dissolved solids at two points higher than the pond indicates that enough soluble salts exist above pond level to supply the concentrations found in the pond.

As shown in figure 83, the upper point which Miller used for soil samples was about where pothole F would overflow. The vegetation for about 30 feet upstream from this point consisted of the usual prairie grasses. Little evidence was found of the types of vegetation that survive frequent inundation, which would have been present if the pond had risen frequently to its overflow level. The water table at this sampling point was 0.5 foot below the pond surface of pothole F.

The lower sampling point was about 200 feet downstream from the upper point, at a place where the water table was less than 1 foot above the pond level of pothole 4. It was below a fairly dense growth of shrubs, which filled the drainage depression, on the fan-shaped outlet of the drainage course (fig. 87).

The proportions and quantities of soluble sodium, calcium, and magnesium present in individual soil samples were measured by Miller to determine the patterns and modes of recurring moisture migration through the soil. He also measured the soil-moisture stress in each sample. Miller (1969) described how these data were analyzed to indicate the direction of moisture migration through the soil. He concluded that transpiration by vegetation and evaporation from the soil surface apparently caused an increase in salinity of the water flowing through the soil beneath the drainage course. Moisture moved vertically through the soil—upward, in response to evapotranspiration losses, and downward, in response to infiltration from precipitation. It also moved laterally, in response to the slope of the water table.

Miller (1969) found that lateral movement through the soil, in response to the slope of the water table, correlated with an increase of salinity. The increased salinity was caused by the concentration of salts as water, moving laterally, was depleted by evapotranspiration—the water being moved from the water table to the ground surface by plant roots, by capillarity, and as water vapor. The gradient for vertical movement under capillary stress was 0.01 meter for each 0.01 meter height above the water table (provided capillary equilibrium was reached) compared with a water-table gradient of only 0.01 meter in 0.50 meter. Figure 65 shows that evapotranspiration demand can be very low at night, a condition which allows capillary stress to approach equilibrium. The alternating high and low rates of evapotranspiration cause a cyclic vertical movement of moisture. The chemical analysis of the soil samples confirms this and serves as additional evidence that there is a higher rate of water movement vertically than horizontally in areas of glacial till.

The study potholes were chosen in till deposits, in order to meet the requirements of the method for determining evapotranspiration. In general, the till deposits occur on the higher parts of the Coteau du Missouri, where there is a knob-and-basin terrain. Outwash deposits, which are composed of eroded materials, generally occur as broad plains on the lower parts of the Coteau, where they are usually very permeable, and water-table conditions are

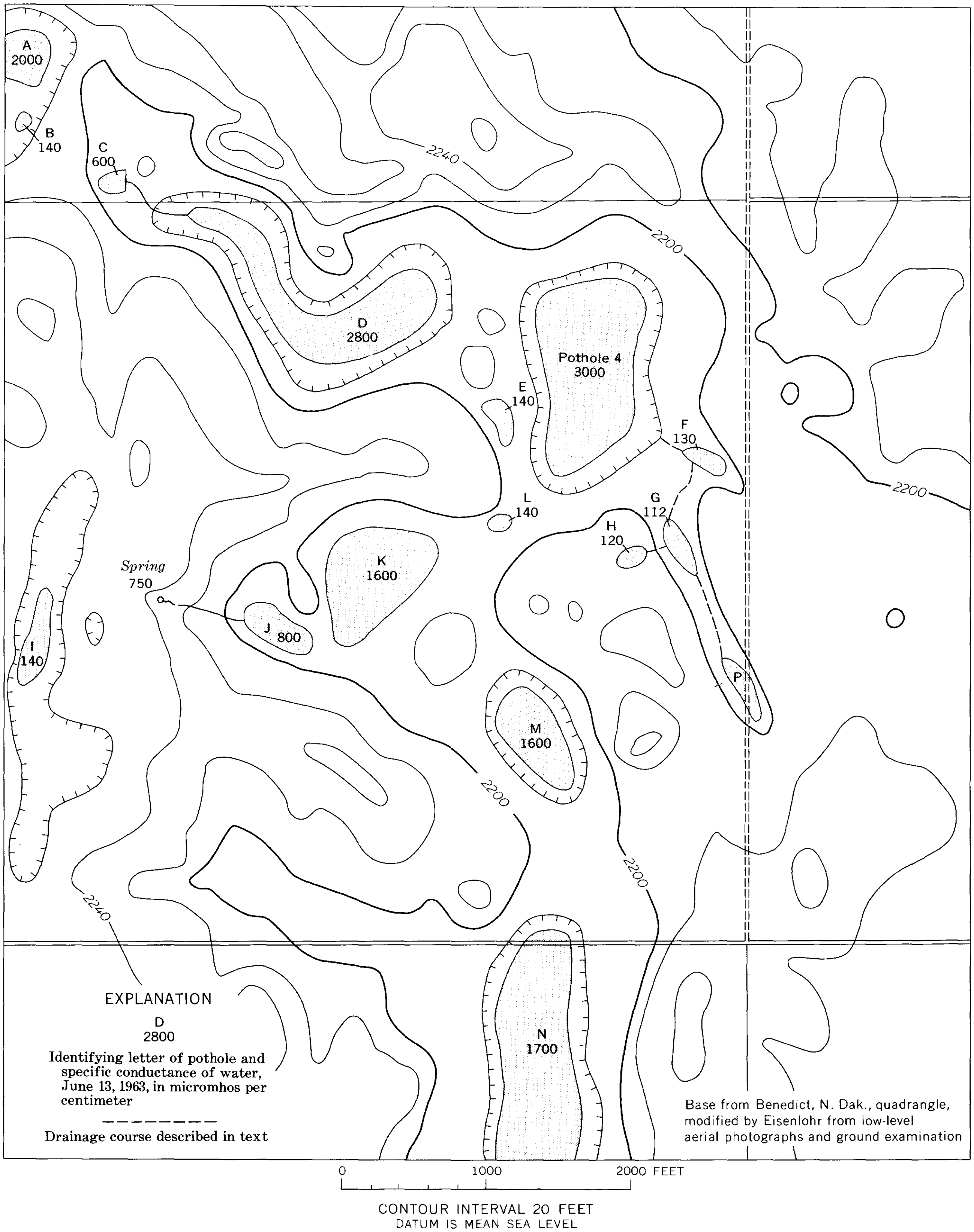


FIGURE 82.—Pothole 4 and surrounding potholes, in sec. 36, T. 152 N., R. 83 W.

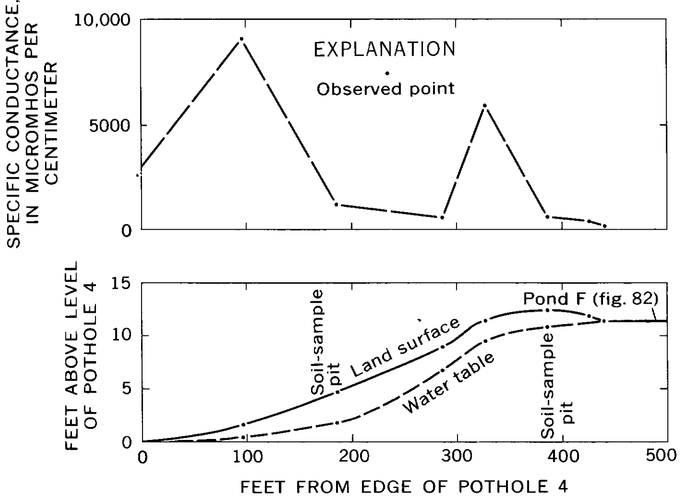


FIGURE 83.—Profile of water table and specific conductance beneath a small drainage course, tributary to pothole 4, June 13, 1963.

expected. Seemingly, an appreciable amount of seepage occurs as inflow to all ponds and lakes in outwash, but, commonly, there is also seepage outflow, except from the lowest pond or lake in any area. The higher proportion of seepage inflow in relation to precipitation and runoff into ponds in outwash tends to make them much more saline than ponds in till. Sloan (1972) found that Lake Alkaline in southwestern Stutsman County (SW¼ sec. 7, T. 139 N., R. 69 W.) had an average seepage-inflow rate of 0.0032 foot per day from August 9 to November 1, 1967. The range in specific conductance during this period was 18,000 to 22,000 micromhos per centimeter. The specific conductance of water from a spring discharging into the southwest corner of the lake was about 1,000 micromhos per centimeter.

CHEMICAL QUALITY OF POTHOLE WATERS

At the start of the study, the chemical quality of the water in the potholes was recognized as having an important bearing on other hydrologic factors. Accordingly, samples of water for chemical analysis were collected regularly from potholes and the adjacent observation wells. The analyses showed a large range in quality, not only among wells and potholes, but also with time at any individual well or pothole. The concentrations of dissolved solids in potholes in the study areas are shown in figures 84–86 and table 31.

The constituents analyzed and other properties of the water samples for the ponds have been published

TABLE 31.—*Concentration of dissolved solids in potholes sampled occasionally*

[Data are in parts per million, except as indicated]

Date	Dissolved solids
Pothole 5A	
June 26, 1962	[1] 712
May 9, 1963	362
Oct. 31, 1963	460
Pothole 5B	
June 26, 1962	[1] 420
Mar. 11, 1963	[2] 45
May 9, 1963	327
Oct. 31, 1963	1,010
Mar. 31, 1964	[2] 148
Pothole 6A	
June 26, 1962	[1] 756
May 9, 1963	679
Sept. 4, 1963	812
Oct. 31, 1963	776
Apr. 1, 1965	2,310
Pothole C2A	
May 7, 1963	532
Oct. 29, 1963	1,010
Pothole C2B	
May 7, 1962	[1] 3,690
June 26, 1962	1,600
Aug. 22, 1962	[1] 625
May 7, 1963	721
Oct. 29, 1963	1,220
Pothole C3	
Aug. 22, 1962	[1] 215
Pothole C4	
May 7, 1962	[1] 737
June 26, 1962	450
Aug. 22, 1962	[1] 485
May 7, 1963	656
Pothole M10	
May 8, 1963	1,020
Pothole M12	
May 8, 1962	[1] 218
Aug. 24, 1962	[1] 184
May 8, 1963	354
June 7, 1966	261
Pothole M15	
May 8, 1962	[1] 1,350
June 26, 1962	[1] 1,180
Aug. 24, 1962	[1] 1,100
May 8, 1963	774
Oct. 29, 1963	1,920
June 7, 1966	1,050
Pothole M23	
June 26, 1962	[1] 450
May 8, 1963	1,260
Pothole M28	
May 8, 1962	[1] 549
Aug. 23, 1962	[1] 1,064
Pothole M28—Continued	
May 8, 1963	277
Oct. 29, 1963	828
Pothole M34	
May 8, 1963	433
July 27, 1964	[1] 900
Pothole M35	
June 27, 1962	[1] 775
Aug. 24, 1962	[1] 660
May 8, 1963	581
Pothole M40	
May 8, 1963	463
Oct. 29, 1963	1,450
Pothole M42	
June 27, 1962	[1] 72
Aug. 24, 1962	[1] 94
May 8, 1963	254
July 27, 1964	[1] 180
Pothole M43	
June 27, 1962	[1] 576
Aug. 24, 1962	[1] 422
May 8, 1963	809
July 27, 1964	[1] 1,100
Pothole M47	
May 8, 1963	340
Oct. 29, 1963	1,750
Pothole M55A	
June 27, 1962	[1] 1,450
May 8, 1963	[3] 1,670
Pothole M55	
May 8, 1962	[1] 1,180
June 27, 1962	[1] 1,360
Aug. 24, 1962	[1] 1,460
May 8, 1963	849
Oct. 29, 1963	2,880
July 30, 1964	[1] 1,960
June 6, 1966	1,250
Pothole M56	
May 8, 1962	[1] 239
June 27, 1962	[1] 204
Aug. 24, 1962	[1] 169
July 30, 1964	[1] 1,330
Pothole W1	
June 26, 1962	[1] 1,180
Aug. 22, 1962	[1] 499
May 2, 1963	517
Oct. 29, 1963	740
Pothole W2	
June 26, 1962	[1] 1,120
Aug. 22, 1962	962
May 7, 1963	755
Oct. 29, 1963	796

[1] Specific conductance, in micromhos per cm.
[2] Runoff into pond.
[3] Almost dry.

elsewhere (U.S. Geological Survey, 1966). Data for representative samples are given in table 32 for these ponds, as well as for the adjacent wells. The end of August 1962 was chosen as a representative time for the Ward and Dickey County potholes, on the basis of figures 84 and 86, and where the

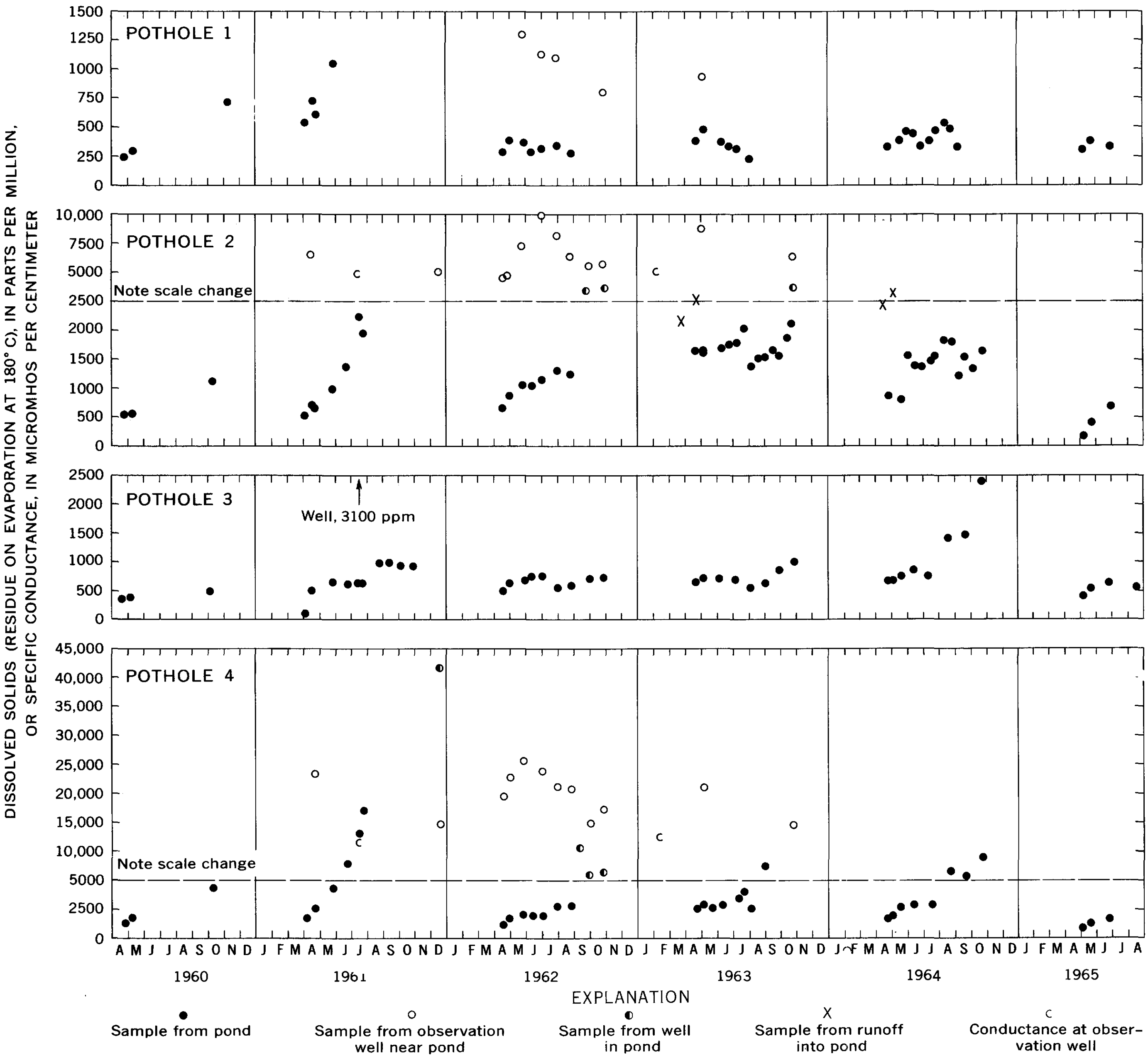


FIGURE 84.—Concentration of dissolved solids in Ward County potholes sampled frequently.

analyses listed are available for that time, they are given in table 32. June 1966 was the period chosen for representative samples in Stutsman County because comparable data for ponds and wells were available only at that time, with the exception of pothole W2. Analyses of miscellaneous samples are included where they are considered to be of unusual interest.

The general trend of water quality in any pothole was about what could be expected. The concentration of dissolved solids decreased as the volume of water increased, and the concentration increased as the volume decreased. This was not always true, however, and the opposites of both situations were observed.

The variation in salinity among potholes is largely explained in terms of seepage, as described under "Ground-Water Hydrology."

A good example of the effect of elevation in a chain of lakes is the Nelson-Carlson Lake system in Ward County (fig. 93). These lakes occupy a glacial meltwater channel that is filled with glacial-fluvial

TABLE 32.—*Selected analyses of water samples*

[Concentrations of dissolved constituents, dissolved solids, and hardness given in parts per million]

Location	Date of collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids (Residue at 180°C)	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Specific conductance (micromhos per cm at 25°C)	pH
REPRESENTATIVE SAMPLES																				
Pothole 1:																				
Pond	Aug. 27, 1962	21	0.34	0.00	36	19	5.0	26	234	0	8.0	1.8	.02	3.9	0.06	274	170	0	418	7.1
Well	May 6, 1963	----	----	----	32	134	99	5.3	654	0	295	2.3	---	----	----	943	629	93	1,380	8.1
Pothole 2:																				
Pond	Aug. 27, 1962	5.8	.08	.00	65	74	200	50	467	0	438	71	.7	3.8	.04	1,270	468	85	1,700	8.0
Well	Aug. 27, 1962	12	----	----	391	587	580	7.8	404	0	3,960	47	.7	.1	.21	6,260	3,390	3,060	5,940	7.9
Pothole 3:																				
Pond	Aug. 27, 1962	9.9	.04	.02	30	5.4	60	94	106	88	21	51	.8	7.2	.11	617	97	0	678	10.1
Pothole 4:																				
Pond	Aug. 27, 1962	26	.09	.19	82	252	370	57	506	0	1,540	22	.5	4.4	.40	2,830	1,240	825	3,270	8.2
Well	Aug. 27, 1962	11	----	----	458	1,880	2,920	26	718	0	14,100	62	.8	.9	.30	20,500	8,890	8,300	17,100	7.4
Pothole 5:																				
Pond	Aug. 25, 1962	37	.04	.00	143	249	108	33	272	0	1,300	12	.5	11	.27	2,260	1,380	1,157	2,460	7.6
Well	Aug. 25, 1962	8.9	----	----	449	756	343	28	258	0	4,780	15	.3	.1	.23	6,880	4,230	4,020	6,100	7.3
Pothole 6:																				
Pond	Aug. 25, 1962	4.0	.05	.00	45	35	13	22	284	0	61	2.0	.3	1.4	.01	375	257	24	581	7.5
Well	Aug. 25, 1962	16	----	----	492	300	110	10	236	0	2,330	13	.6	.1	.20	3,770	2,460	2,270	3,590	7.3
Pothole 7:																				
Pond	Aug. 25, 1962	11	.05	.03	73	72	27	26	308	0	275	14	.3	1.5	.06	720	479	226	985	7.3
Well	Aug. 25, 1962	9.3	----	----	448	499	171	36	241	0	3,190	11	.3	.0	.16	4,930	3,170	2,970	4,560	7.2
Pothole 8:																				
Pond	Aug. 25, 1962	45	.06	.08	66	37	15	24	288	0	113	6.3	.3	1.2	.06	502	316	80	672	7.6
Well	Aug. 25, 1962	8.2	----	----	440	674	260	18	268	0	3,890	14	.5	.1	.20	6,150	3,870	3,650	5,490	7.2
Pothole C1:																				
Pond	June 10, 1966	.7	----	----	51	110	177	38	432	31	552	27	.3	.3	.31	1,260	580	174	1,710	8.7
Well 15–2 (10 ft deep)	June 9, 1966	1.2	----	----	347	1,020	1,400	32	40	0	7,590	109	.7	.1	.21	12,200	5,080	5,050	10,400	6.9
15–3 (30 ft deep)	June 9, 1966	.9	----	----	340	171	238	20	59	0	1,910	55	.1	.0	.43	3,060	1,550	1,500	3,180	7.7
15–1 (50 ft deep)	June 9, 1966	.0	----	----	232	96	159	16	75	0	1,140	35	.1	.1	.61	1,890	976	914	2,200	8.1
Pothole M12:																				
Pond	June 7, 1966	2.1	----	----	34	16	17	11	163	0	57	4.4	.1	.9	.09	264	149	15	377	7.5
Well 12–2	June 7, 1966	14	----	----	81	31	10	5.1	389	0	25	4.7	.3	.4	.07	397	331	12	628	7.8
Pothole M55:																				
Pond	June 6, 1966	14	----	----	88	123	119	13	416	0	600	11	.4	.6	.26	1,250	725	384	1,600	8.2
Well 56–1	June 8, 1966	17	----	----	126	147	156	7.9	458	0	835	9.8	.4	6.3	.15	1,610	920	544	1,980	7.9
Pothole W2:																				
Pond	Oct. 29, 1963	----	----	----	17	97	69	29	221	49	326	20	---	----	----	796	441	178	1,070	9.1

Ward County group:																				
Maximum	May 1963	----	----	----	437	500	1,720	218	984	203	5,850	211	---	----	----	9,420	------	------	-------	----
Minimum	May 1963	----	----	----	7.5	5.2	1.4	11	94	0	7.2	.1	---	----	----	161	------	------	-------	----
Mean	May 1963	----	----	----	106	140	236	56	305	11	1,048	33	---	----	----	1,935	------	------	-------	----
Median	May 1963	----	----	----	77	98	51	40	246	0	540	10	---	----	----	1,115	------	------	-------	----
Stutsman County group:																				
Maximum	May 1963	----	----	----	269	187	133	58	448	10	1,180	48	---	----	----	2,290	------	------	-------	----
Minimum	May 1963	----	----	----	16	4.8	.9	5.5	66	0	5.2	.4	---	----	----	132	------	------	-------	----
Mean	May 1963	----	----	----	52	31	23	23	230	.3	122	11	---	----	----	445	------	------	-------	----
Median	May 1963	----	----	----	42	18	6.6	20	210	0	40	6.8	---	----	----	297	------	------	-------	----
Dickey-McIntosh County group:																				
Maximum	May 1963	----	----	----	316	1,510	6,260	577	955	110	16,280	2,560	---	----	----	29,000	------	------	-------	----
Minimum	May 1963	----	----	----	15	2.5	1.1	11	51	0	7.2	.2	---	----	----	107	------	------	-------	----
Mean	May 1963	----	----	----	82	196	401	60	382	8.5	1,349	146	---	----	----	2,612	------	------	-------	----
Median	May 1963	----	----	----	55	120	48	32	378	0	318	16	---	----	----	887	------	------	-------	----
MISCELLANEOUS NOTEWORTHY SAMPLES																				
Pothole 4:																				
Well in pond bottom (pond dry)	Dec. 18, 1961	18	----	----	458	4,660	4,180	23	1,490	0	27,600	188	1.7	2.5	.75	41,500	20,300	19,100	27,700	7.7
Runoff during infiltrometer test	Apr. 26, 1963	----	----	----	12	4.9	4.4	1.4	54	0	11	.8	---	.0	----	78	50	6	141	6.7
Pothole 8:																				
Water under ice cover	Apr. 1, 1965	48	----	----	287	254	95	73	1,590	0	685	28	.8	2.2	.08	2,410	1,760	456	2,830	7.7
Surface inflow	Apr. 1, 1965	10	----	----	23	6.5	1.4	20	84	0	35	4.5	.4	1.9	.16	211	84	15	242	6.9
Nelson-Carlson Lake system (pl. 3):																				
Lake 1	May 20, 1965	3.0	----	----	18	728	3,260	149	1,040	244	8,640	112	.1	.2	3.3	14,500	3,040	2,227	14,900	9.0
Lake 2	May 20, 1965	7.3	----	----	21	127	300	25	602	45	650	14	.3	.1	.49	1,560	573	4	2,150	8.8
Lake 3	May 20, 1965	15	----	----	20	92	142	15	450	39	296	5.8	.3	.2	.32	900	430	0	1,280	8.6
Lake 4	May 20, 1965	2.4	----	----	17	945	7,680	25	1,590	539	1,760	203	.0	.8	5.3	29,000	3,930	2,716	27,500	9.2
Lake 6	May 6, 1963	.9	----	----	19	900	25,000	443	1,410	724	54,100	886	---	----	----	85,300	3,750	2,714	65,000	9.2
Spring	Apr. 26, 1963	----	----	----	22	34	1,400	11	1,480	28	1,890	22	---	.2	----	4,240	196	0	5,570	8.4
East Chokecherry Lake																				
(T. 139 N., R. 69 W., Sec. 21)	July 20, 1967	16	----	----	157	4,740	81,100	2,070	1,380	0	177,000	10,100	.3	1.2	52	276,000	19,900	18,800	111,000	7.7
Do------Spring on shore	July 20, 1967	28	----	----	130	38	152	12	485	0	337	52	.3	0	.47	1,030	480	82	1,450	8.0

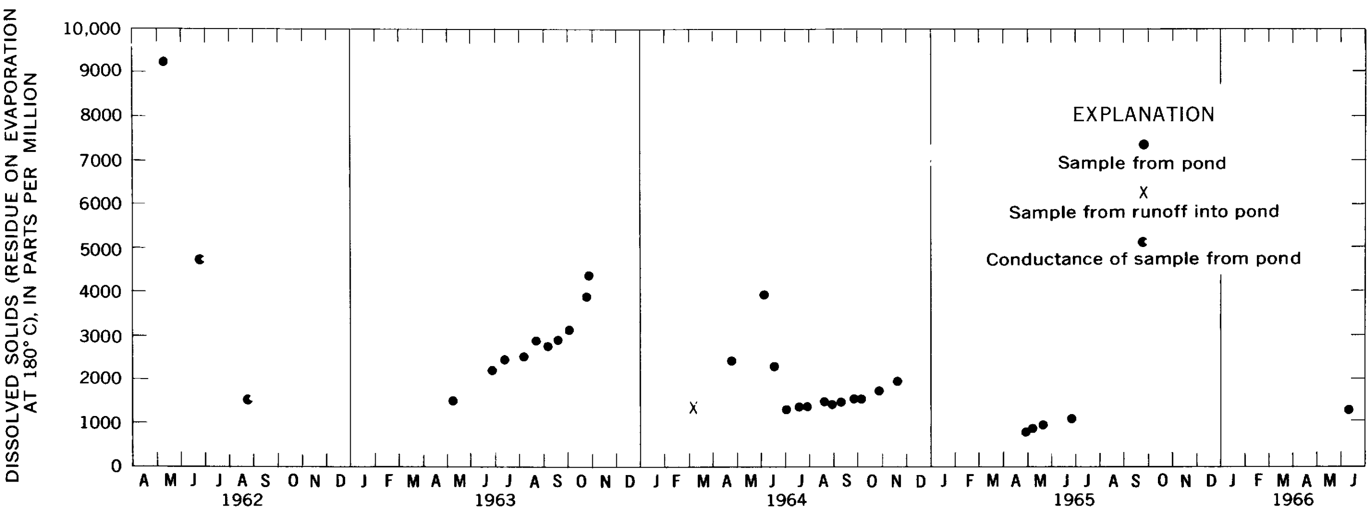


FIGURE 85.—Concentration of dissolved solids in pothole C1, Stutsman County.

sediments and lake sediments. There are no surface connections between them. The strong relation between elevation and salinity is evident from the data in table 33. Lake 6 in this table is the Douglas "A" Lake of Binyon (1952).

TABLE 33.—*Dissolved solids and water-surface elevations in Nelson-Carlson Lake system*

[c, Specific conductance, in micromhos per centimeter; for relation to parts per million, see figure 91. Data for 1966 from Sloan (1970)]

Lake No. (pl. 3)	Water surface Aug. 21, 1966 (ft, assumed datum)	Concentration of dissolved solids (ppm)	
		May 1965	August 21, 1966
1	100.0	14,500	21,400c
2	100.7	1,560	2,170c
3	103.1	900	1,300c
4	94.9	29,000	42,500c
5	92.4	35,000c	-------
6	83.9	[1] 85,300	-------

[1] May 1963.

The relative salinities of potholes in till also show a relation to elevation. This is illustrated in figure 82 which shows the specific conductance of the pond waters in potholes surrounding pothole 4, as measured June 13, 1963. The 2,200-foot contour outlines a depression that would be tributary to Oak Creek if the drainage system were fully developed. As it is, there is high ground between pothole 4 and potholes D and K—as high as 15 feet, which cannot be shown with the 20-foot contour interval on the map. There was no such high ground between potholes M and N.

The salinities of the various potholes seem to correlate very well with their relative elevation—except for pothole 4 and pothole D, which will be discussed below. The small ponds at high elevations contain fresh water, presumably because their source of water is precipitation, and they have enough seepage outflow to prevent the accumulation of dissolved solids. At lower elevations, the inflow, in addition to precipitation, probably includes seepage from higher potholes with its dissolved solids. Even the potholes at the lowest elevation presumably have seepage outflow which keeps down the concentration of dissolved solids in them. A good illustration is the spring between potholes I and J. The specific conductance of the effluent is much greater than that of the pond water above it on the hill (pothole I), but it is a little less than that of the pond into which it flows.

Pothole 4 has the highest concentration of dissolved solids of all the potholes studied, and pothole D had about the same concentration. These high values suggest that the seepage outflow was very low. In seeming contradiction to this situation, the seepage outflow at pothole 4 was about the highest of all those computed (table 29, present report; Shjeflo, 1968, p. B42). This is still a very low rate, well below 0.01 foot per day averaged over the pond surface. It is also explained easily. The shore is wide and slopes gently (fig. 87), and the pit dug for obtaining soil moisture (p. A55) penetrated a layer of gravel nearly 0.5 foot thick buried less than 0.2 foot below the surface (fig. 88). Thus, seepage outflow could have been dissipated by evapotranspiration losses from the shore of the pond, leaving the dissolved solids behind. White salt deposits are often found on the shore of this pothole (fig. 89) at elevations higher than the pond had been since the latest heavy rain that would have removed any

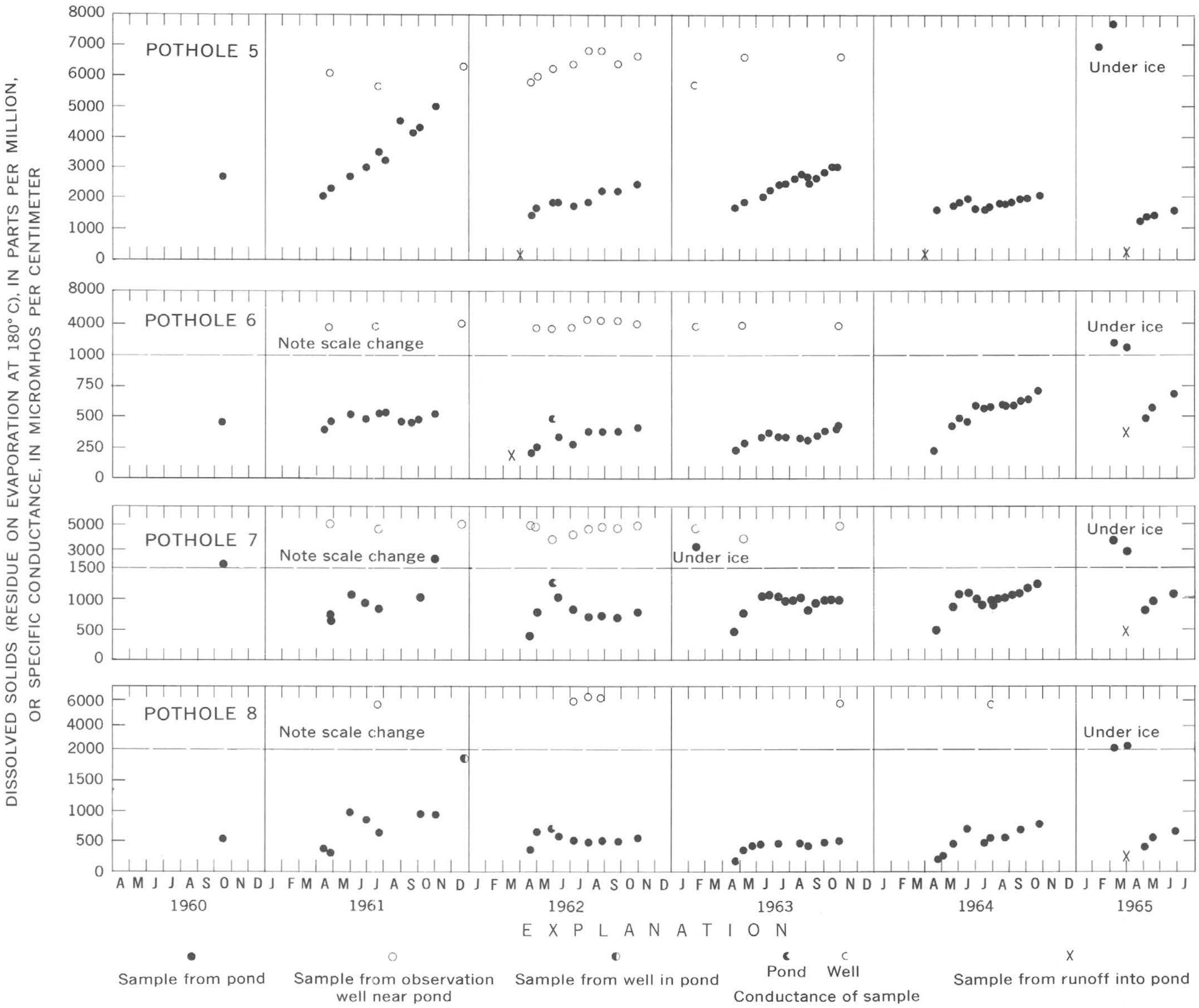


FIGURE 86.—Concentration of dissolved solids in Dickey County potholes sampled frequently.

deposit existing at that time and returned it to the pond. This indicates that salt deposits are the residues left by water brought to the surface by capillarity and evaporated.

That the salts remain in the pothole—stored in the soil when the pond dries and redissolved when the pond is recreated—is very likely. The mechanism is similar to the concentration of salts as the result of freezing described by Ficken (1967). (See p. A95.) In the fall of 1961 pothole 4 became dry. A shallow well was dug at the lowest part of the bed to obtain a record of water-table fluctuations below the bed. Chemical analysis of a sample from this well (table 32) showed a concentration of 41,500 ppm of dissolved solids. Thus, there are many indications that seepage from pothole 4 does not leave that basin, and none that show otherwise.

The general relation between salinity and elevation is illustrated in figure 90 (from data collected by Sloan, 1972).

The study potholes in Ward, Stutsman, and Dickey Counties constitute a very small sample of the potholes on the Coteau du Missouri. With such a small sample, there is always a good chance of bias of one type or another. To assure that there was no appreciable geographical bias with respect to chemical quality, two surveys were made in 1963 under the direction of Hugh T. Mitten.

Samples from 34 potholes in Ward County, 36 potholes in Stutsman County, and 36 potholes in

FIGURE 87.—View of pothole 4, showing wide, gently sloping shore. Heavy shrub growth in foreground is at outlet of drainage course mapped in figure 82. Man at center right is standing at the lower soil-sampling site.

McIntosh and Dickey Counties were collected during the period April 30 to May 3, 1963. The potholes selected in each area are about 3 miles apart in a grid pattern and generally are close to section-line roads. The concentration of dissolved solids in these samples, at their approximate locations, is shown on plate 3, and the maximum, minimum, mean, and median values are listed in table 32. The 39 percent of these potholes that contained water in the fall were sampled during the period October 28 to November 1, 1963.

Mitten found that when any single aspect of chemical quality of a sample was plotted against area, depth, or volume of a pond, no relationship was evident for any groups of potholes. He therefore compared averages and means among the groups. Mitten concluded that no aspect of the chemical quality of water was found that could be used to distinguish the prairie potholes in one area from those in another.

Mitten found, however, that the salinity of a pothole correlated generally with its size. The size of a pothole is often related to the direction of seepage around it. Potholes with net outflow seepage are generally smaller than those with net inflow seepage. Mitten's finding thus tends to substantiate the later work done by Sloan (1972).

Mitten (1965) also studied the ratio of the observed ion activity product for calcite ($CaCO_3$) to the commonly accepted solubility product (equilibrium) constant. He found his computed ratio correlated with the diurnal changes in pH, dissolved oxygen, water temperature, and carbonate-ion concentration.

Throughout the study, specific electrical conductance, expressed in micromhos per square centimeter per centimeter (micromhos per cm), was assumed to be numerically equivalent to the concentration of dissolved solids, expressed in parts per million (ppm). The true relationship, based on all data available for the potholes, is shown in figure 91.

The right-hand graph in figure 91 shows the upper end of the relation at reduced scale. Lines of a 1:1 relation between the two quantities show the variation in coefficient. The lowest coefficient for the conversion of specific conductance to parts per million is about 0.7 for the range up to about 2,000 micromhos per cm. Above that range, the value increases

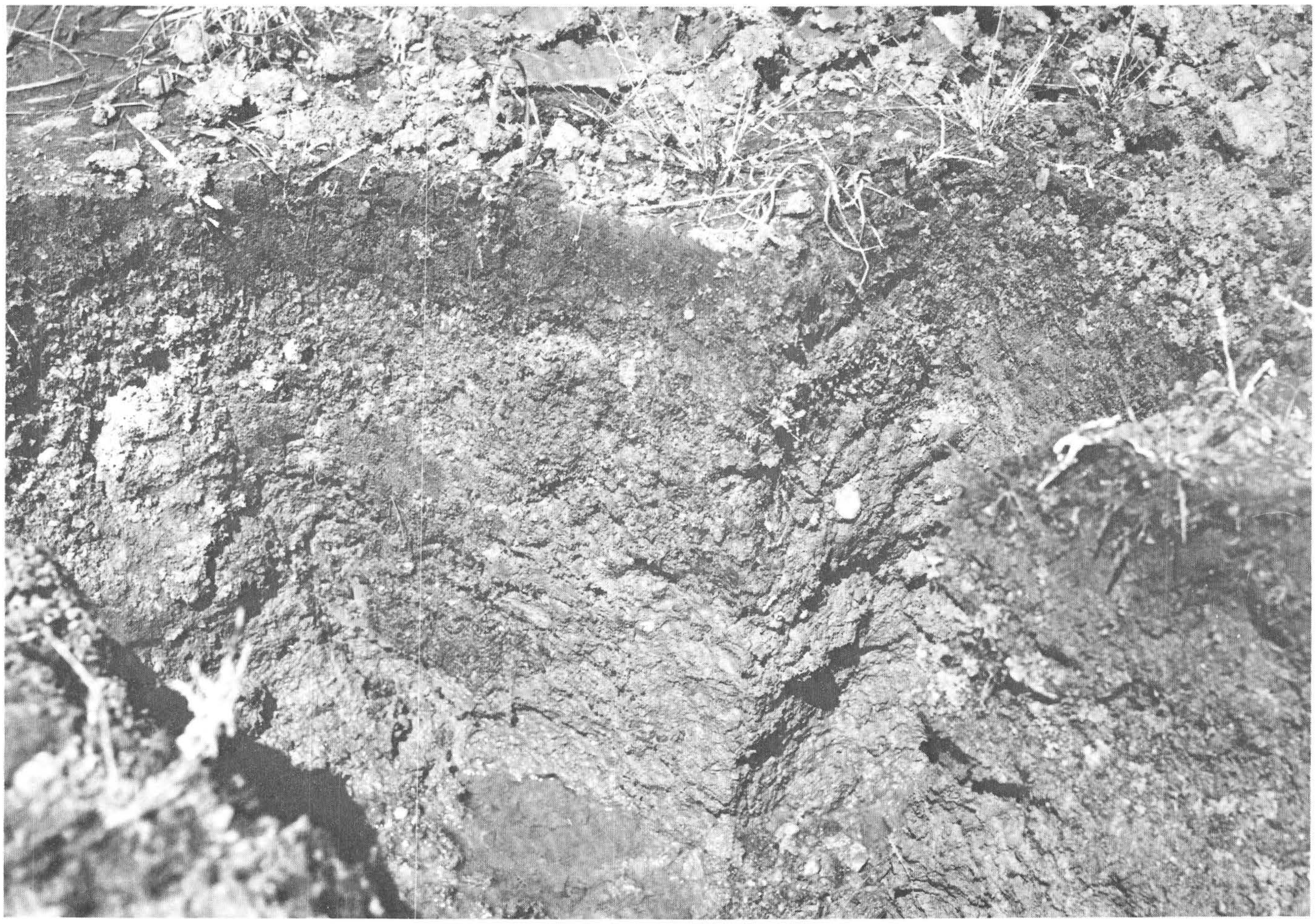


FIGURE 88.—Sample pit at pothole 4, showing gravel layer just below ground surface and white encrustations at ground surface.

rapidly to 1.0 at about 5,000 and remains close to 1.0 up to about 40,000. At about 60,000 micromhos per cm, the coefficient is more than 1.3. In view of the range of salinities found and the fact that generally only relative salinities were considered, the use of the number of micromhos per centimeter for the number of parts per million is considered to be satisfactory for the purposes of this report.

Ice is pure water. When the temperature of water that contains dissolved solids drops below the freezing point, ice crystals are formed. They form first at the surface and then downward as long as the freezing process continues. As the ice crystals form, they force much of the solute material into the solution below the ice, but some of the solute material is forced out of solution and trapped among the ice crystals. As the process continues, the solution below the ice becomes more concentrated, and greater portions of the solute material are trapped by the ice crystals.

The total effect of the above process in a pothole is to concentrate a large portion of the dissolved solids in the top layers of the bed material or as a precipitate on its surface. The effect is only temporary, however, because the dissolved solids stored in or on the bed return to the pond water.

This subject was studied in detail by Ficken (1967) at potholes 5 and C1 during the winters of 1963–64 and 1964–65. He found, from analyses of his samples, that the concentration of solids in the ice, in the water under the ice, and in the bottom sediment was distributed about as described above. He also found that immediately after the spring thaw, the concentration of dissolved solids in the pothole water was less than the concentration at freezeup the preceding fall. Within 2 months after the thaw, however, the quantities of dissolved solids in each pothole was about the same as they were before freezeup. Seepage outflow rates at both potholes were very low, so it is presumed that the dis-

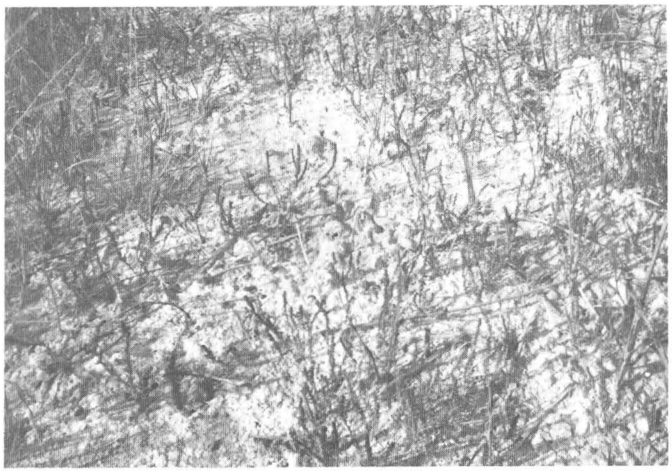


FIGURE 89.—White deposit on shore of pothole 4, left by evaporation of shallow ground water.

solved solids forced out of the pond waters by the freezing process were mostly all returned the following spring, rather than being carried away by seepage. The slow return of solute materials to the pond may be, in part, the result of their having been frozen in the bed in shallow parts of the pond, and thawing of the bed did not occur until several weeks after the pond ice had melted.

The species of hydrophytes that grow in a pothole seem to correlate very well with the average salinity and permanence of the water at the particular site of each species. The term "permanence" is used commonly in the classification of prairie ponds and lakes to indicate the extent to which such a water body is permanent. As used in connection with vegetation, it indicates the period of time (generally less than 1 year) that the ground on which the vegetation grows is submerged, or inundated. As this permanence and salinity are continually subject to change, so also are the species and densities of vegetation continually subject to change, but less rapidly. Thus, potholes frequently change from one classification to another. The ways in which permanence and salinity affect hydrophytes were stud-

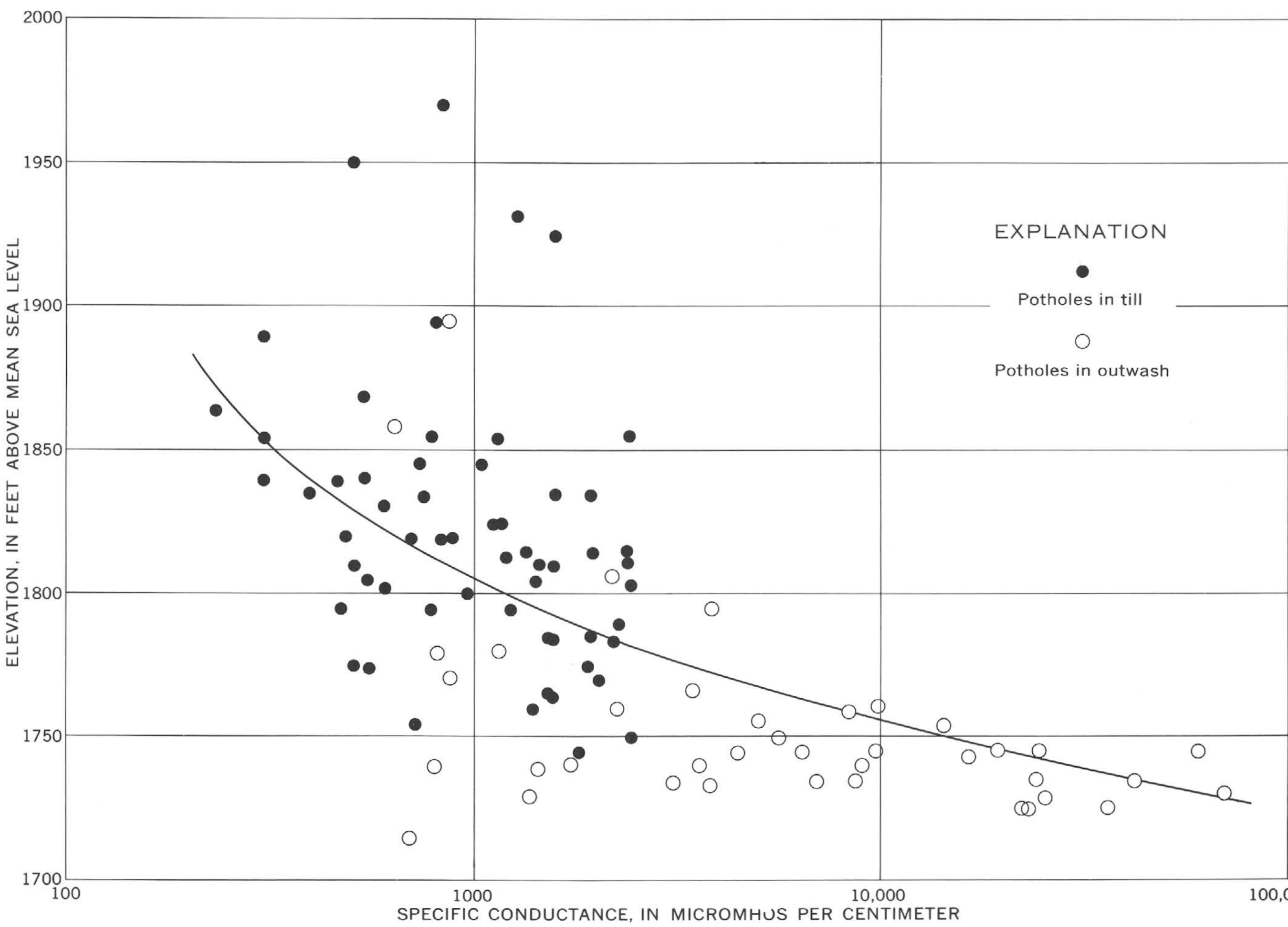


FIGURE 90.—Relation between specific conductance and elevation for potholes in till and outwash. From Sloan (1972).

ied by Stewart and Kantrud (1971). Their report is based on some 1,600 observations made during the period 1963–66. Table 34 is a brief summary of their work, prepared by Stewart for this report. Table 34 lists only those species that were found in enough potholes to be classed as "frequently common" or "abundant."

If the pothole vegetation is used as an index of conditions in a pothole, the possibility of areal variations or patterns should be considered. The most obvious pattern variation is the change in species composition from the shoreline to deep water with a corresponding increase in permanence. Another pattern observed in several saline potholes occurs where there is spring or seepage inflow of much fresher water. There is then a progression of plant species which exhibit growing tolerance to salinity in the direction of flow of this fresher water as it mixes with the main body of water and becomes more saline.

TABLE 34.—*Common species of emergent hydrophytes as indicators of permanence and salinity of water in potholes*

[Prepared by R. E. Stewart, Bur. Sport Fisheries and Wildlife]

Salinity of water and range in specific conductance [1] (micromhos per cm)	Permanence of water at site of indicated species [2]		
	Less than 1 month	1-4 months	More than 4 months
Fresh 0–500	*Aster simplex* *Boltonia latisquama* *Carex praegracilis* *Poa palustris*	*Alisma triviale* *Beckmannia syzigachne* *Carex atherodes* *Glyceria grandis* *Polygonum coccineum* *Sparganium eurycarpum*	*Scirpus heterochaetus*
Slightly brackish 500–2,000	*Aster simplex* *Calamagrostis inexpansa* *Hordeum jubatum* *Juncus balticus* *Spartina pectinata*	*Alisma triviale* *Beckmannia syzigachne* *Carex atherodes* *Eleocharis palustris* *Polygonum coccineum* *Scolochloa festucacea*	*Scirpus acutus* *Scirpus fluviatilis* *Typha "glauca"* [3]
Moderately brackish 2,000–5,000	*Calamagrostis inexpansa* *Hordeum jubatum* *Juncus balticus* *Spartina pectinata*	*Alisma gramineum* *Eleocharis palustris* *Scolochloa festucacea*	*Scirpus acutus*
Brackish 5,000–15,000	*Distichlis stricta* *Hordeum jubatum*	*Scirpus americanus*	*Scirpus paludosus*
Subsaline 15,000–45,000	*Distichlis stricta*	*Puccinellia nuttalliana* *Salicornia rubra*	*Scirpus paludosus*

[1] These ranges in specific conductance differ somewhat from those used by the U.S. Geological Survey, which are based on other needs, especially that of defining fresh water for domestic use.

[2] The time divisions used here are purely arbitrary; large deviations from them can be expected.

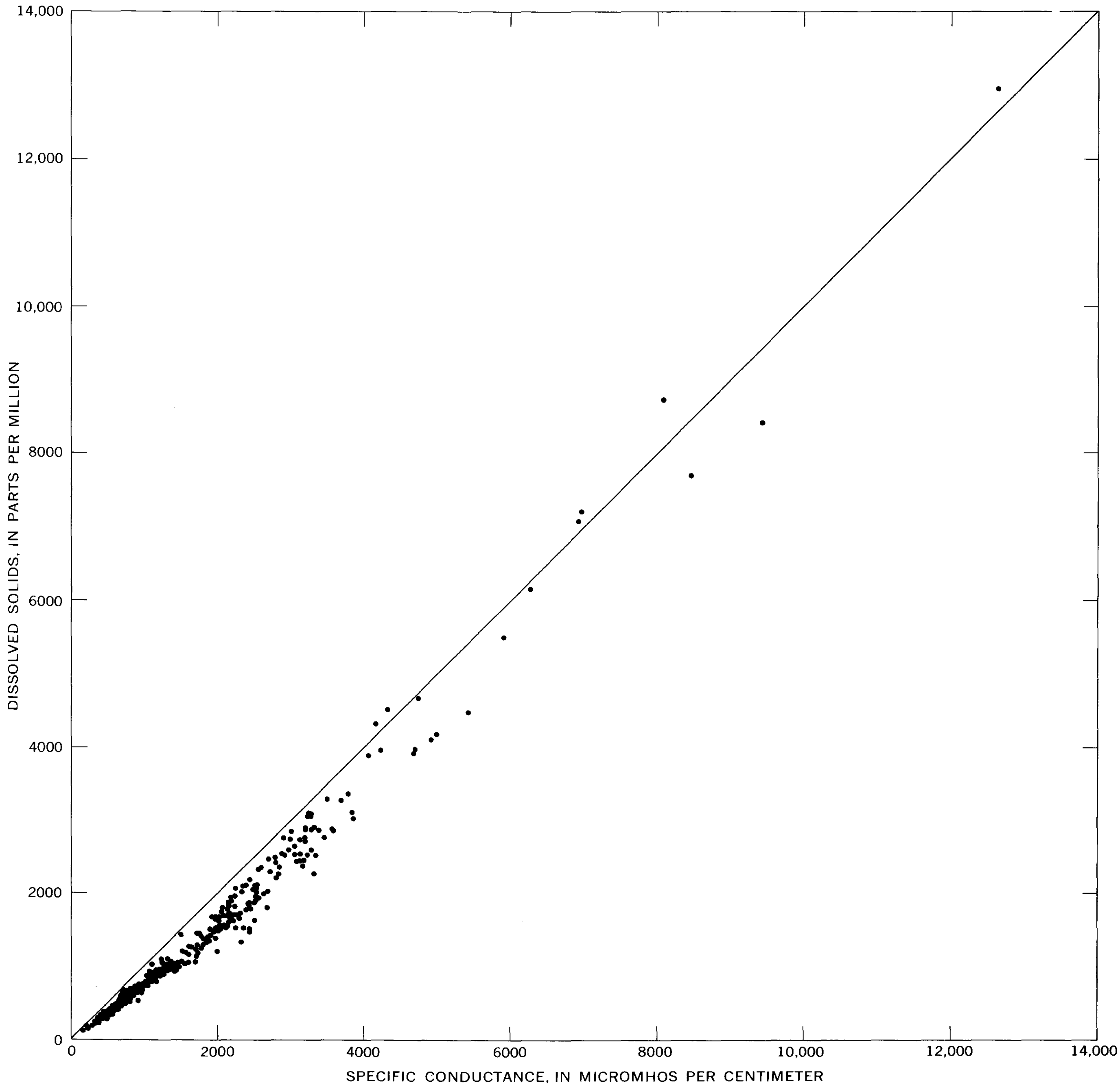
[3] Recent investigations show this species to be a hybrid of *Typha latifolia* and *T. angustifolia*.

Common names of the plants used in tables 24 and 34 are listed below:

Alisma gramineum, narrowleaf waterplantain
Alisma triviale, western waterplantain
Aster simplex, lowland white aster
Beckmannia syzigachne, sloughgrass
Boltonia latisquama, false-aster
Calamagrostis inexpansa, northern reedgrass
Carex atherodes, slough sedge
Carex praegracilis, sedge
Distichlis stricta, saltgrass
Eleocharis palustris, common spikerush
Glyceria grandis, tall mannagrass
Hordeum jubatum, wild barley
Juncus balticus, Baltic rush
Poa palustris, fowl bluegrass
Polygonum coccineum, marsh smartweed
Potentilla anserina, silverweed
Puccinellia nuttalliana, alkaligrass
Salicornia rubra, samphire
Scirpus acutus, hardstem bulrush
Scirpus americanus, common threesquare
Scirpus fluviatilis, river bulrush
Scirpus heterochaetus, slender bulrush
Scirpus paludosus, alkali bulrush
Scolochloa festucacea, whitetop
Sparganium eurycarpum, giant burreed
Spartina pectinata, prairie cordgrass
Typha "glauca," hybrid cattail
Typha latifolia, common cattail

Table 34 is very useful in making a first approximation of the salinity in any particular pothole. Vegetation in any pothole is generally composed of several species and is commonly grouped into distinct plant associations. Each species seems to be associated with a range of salinity to such an extent that it can be used to infer the salinity of the water in which it grows. Where species of different ranges in salinity are growing together, the salinity indicated is the range common to those species. For example, a pothole may contain both *Carex atherodes* and *Eleocharis palustris*. As shown in the table, *Carex atherodes* grows in fresh to slightly brackish water, and *Eleocharis palustris* grows in slightly brackish to moderately brackish water. Found growing together, these species would indicate that the pothole contained slightly brackish water.

As the water level in a pothole fluctuates it covers and uncovers vegetation on its shores. Therefore, vegetation that grows in the center of a shallow pothole can also grow near the shore of a deep pothole, where the permanence of water is about the same as that of the shallow pothole. In using the table to estimate the permanence of water, the user should be careful to apply it only to the site of the particular vegetation species observed, and to keep



in mind the persistence of a previous situation, as described in the section entitled "Effect of Vegetation on Evapotranspiration."

CONCLUSIONS

The most pressing question of this investigation was the amount of water lost from potholes by evapotranspiration (p. A4). This information was needed in connection with the wetlands to be supplied with water from Garrison Reservoir (p. A2). The total amount of water lost naturally from the study potholes during the season May to October is roughly 2.5 acre-feet per acre of water surface (Shjeflo, 1968, table 5). This water must be replaced if a pond is to be maintained. Precipitation on the pond surface averages about 1 foot (p. A48). This leaves about 1.5 acre-feet to be supplied from greater than average precipitation, basin inflow (runoff, including overland flow, plus seepage inflow), or some other source (such as Garrison Reservoir).

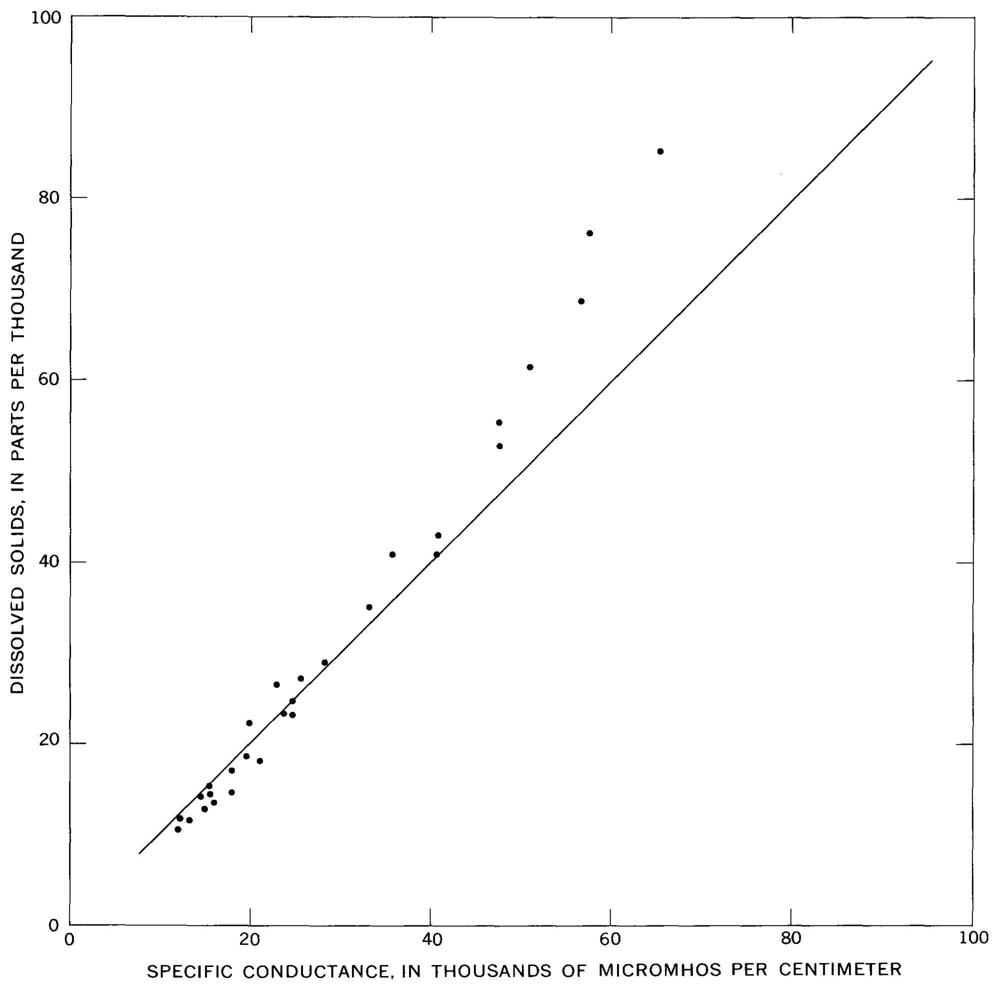


FIGURE 91.—Relation of specific conductance to concentration of dissolved solids for pothole waters. On facing page, in parts per million; above, at reduced scale, in parts per thousand.

Basin inflow for the season is an extremely variable quantity. It ranges from practically zero to several acre-feet per acre of water surface. Basin inflow is controlled largely by the infiltration capacity of the soil. This control is so effective that it can override the effects of seasonal precipitation in determining seasonal basin inflow (p. A48). For a specific pothole, however, a probability analysis would probably indicate the chances of an adequate natural water supply 1 year in advance, if adequate records are available for making the analysis (p. A56).

The ponds in prairie potholes are often assumed to be perched bodies of water (p. A83)—that is, the water is held in a pothole either by a sealed bottom or by an impermeable layer just below the bottom. Several facts are usually cited in support of this position: (1) Several ponds are commonly found to be very close together but to have large differences in water-surface elevation, sometimes with the highest pond being the deepest. (2) Wells drilled in till are frequently "dry." (3) Pond levels seem to be unrelated to ground-water levels. The till in which all the study potholes are located has such a low permeability that the above facts are not valid evidence of perched ponds. All evidence collected during our study indicates that the water table is at shallow depth and that this water table is continuous with the surface of pothole ponds that are at least seasonal in permanence.

Seasonal evaporation from study potholes clear of hydrophytes was very close to published regional values (p. A60). Hydrophytes, by their presence, reduce evaporation by sheltering and shielding the water surface. Sheltering reduces the ability of the wind to remove water vapor from just above the water surface. Shading prevents incoming radiation from providing the energy needed to evaporate water. The transpiration rate from hydrophytes at the height of the growing season, when added to the evaporation rate from the same pond, can give a total loss rate much greater than the evaporation rate from a pond clear of hydrophytes (p. A74). However, the growing season in North Dakota is so short that seasonal evapotranspiration is generally less than seasonal evaporation. In regions where the growing season is longer, the reverse would probably be true (p. A73).

The transpiration rate of hydrophytes during the period that plants were fully active was found to have a highly significant correlation with the emerged height of stem. By means of this relation, transpiration could be computed separately from evaporation by the mass-transfer method. During the period of activity decline in the fall, a significant correlation was found between the transpiration and the moisture content of hydrophytes. Large, unexplained fluctuations in moisture content during this period made the application of the correlation of little value other than to give a possible explanation for the fluctuations.

Some species of hydrophytes require bare soil for germination. Therefore, potholes that go dry often may be the ones that have the heaviest growth of hydrophytes. Also, potholes may go dry because of relatively high seepage outflow rates. This may explain why potholes filled with hydrophytes tend to have greater total loss of water (evapotranspiration plus seepage outflow) than those without hydrophytes (p. A76).

Seepage outflow from all study potholes was low —less than 0.01 foot per day when averaged over the pond surface. The actual maximum rate may be much higher, but confined to a narrow band around the perimeter of a pond. The shores of some ponds are underlain by ancient beaches from which all fine particles have been eroded. Water movement through such materials can be fairly rapid and provide ample water for evapotranspiration from the ground surface (p. A92). Most seepage outflow is probably dissipated in this way (p. A84). An observed tendency for the seepage outflow rate to vary with the mass transfer coefficient, N, supports this idea. Furthermore, J. B. Millar (1969, 1971) found in studies of Canadian potholes (sloughs) a highly significant correlation between water loss per day and length of shoreline per unit area of water surface. Millar was able to use this relation to estimate evaporation from his sloughs. There still remains, however, evidence of slow, relatively constant downward movement of water through the till (p. A79) which may reach lower ponds, especially in outwash areas. In computing seasonal water budgets, assuming the seepage outflow to be constant will probably introduce no appreciable error.

The flow of ground water through till is very slow. Till tends to develop vertical joints (p. A14) and ground water does seem to move vertically much faster than it does horizontally through till. Scattered through the till are lenses and stringers of sand and gravel that have strong local effects.

The most important effect of ground-water movement is the way the direction of flow controls the chemical quality of pothole waters (p. A85). All water entering a pothole contains dissolved solids. The only effective way for these to be removed are by overflow and seepage outflow. Evaporation and transpiration remove only pure water. Most potholes overflow rarely, if at all. If there is also no outflow seepage, the salts are concentrated in the pond, and the water becomes brackish to briney. If there is good seepage outflow, the waters may remain rather fresh, depending on the amount of dissolved solids in the inflowing waters. An intermediate quality of water indicates an intermediate relationship between inflow and seepage outflow.

The various species of hydrophytes found in prairie potholes have limited tolerance to the quality, depth, and permanence of the water in which they grow. The vegetation maps of the study potholes show the changes that occurred during this study. The tolerance of any species to a given quality of water is so marked that the species present at one time in a given pothole is an excellent indication of the quality of the water in which they are growing (table 34). This subject is explored fully in chapter D of the present series, by Stewart and Kantrud, wildlife biologists of the Bureau of Sport Fisheries and Wildlife.

This study has shown how various hydrologic factors determine the water supply of a group of prairie potholes. That is, we believe we can explain why in one season the potholes have a good water supply and in another season they do not. No attempt was made to find out, for any small area, which pothole was most likely to have a permanent pond and which pothole was most likely to become dry. These are important questions to be answered so that the best potholes for migratory waterfowl use can be preserved. The answer will most likely be found by studying individual prairie pothole basin characteristics.

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