Ground-Water Hydrology of Prairie Potholes in North Dakota

GEOLOGICAL SURVEY PROFESSIONAL PAPER 585-C

Prepared as part of the program of the 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, northern Stutsman County.

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By CHARLES E. SLOAN

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GROUND-WATER HYDROLOGY OF PRAIRIE POTHOLES IN NORTH DAKOTA

By CHARLES E. SLOAN

ABSTRACT

Prairie potholes (sloughs) are water-holding depressions of glacial origin in the prairies of the Northern United States and southern Canada. Water is supplied to the potholes by precipitation on the water surface, basin runoff, and seepage inflow of ground water. Depletion of pothole water results from evapotranspiration, overflow, and seepage outflow. Since potholes generally do not overflow, seepage outflow is the principal way in which dissolved salts can be removed. Salinity of pothole water is therefore a good indication of the seepage balance. Net seepage outflow results in fresh to brackish waters that constitute ephemeral to semipermanent ponds, whereas net seepage inflow results in brackish to saline waters that constitute semipermanent to permanent ponds.

Because the water table in the glacial deposits is continuous with the water surface in prairie potholes, the water-table gradient is adjusted to the water-surface elevation of the potholes. In cross section the water table is represented by a nearly straight line which connects potholes. The configuration of the water table around a pothole determines the direction of ground-water flow with respect to the pothole. Ground water flows toward the pothole if the adjacent water table is higher than the pothole water surface and flows away from the pothole if the adjacent water table is lower than the pothole water surface.

Prairie potholes were studied in North Dakota on the Coteau du Missouri, an area of stagnation moraine. About 90 percent of the glacial drift on the Coteau du Missouri is glacial till, and the remainder is largely glacial outwash and lake sediments. Ground-water movement in glacial till is controlled by its lithology and structure. This till, being a poorly sorted, largely unstratified mixture of clay, silt, sand, and gravel, is not highly permeable, so ground water moves most readily along the joints. Because joints in glacial till are most numerous near the land surface (owing to weathering effects), the most active ground-water flow systems are shallow and localized in the vicinity of potholes. As a result, local ground-water flow systems have a noticeable effect on pothole hydrology, particularly the salinity.

INTRODUCTION

Prairie potholes, or sloughs, are water-holding depressions of glacial origin that occur in 300,000 square miles of prairies in north central United States and south-central Canada (fig. 1). These potholes provide the most productive wetland habitat for waterfowl in North America. Although comprising only 10 percent of the continental waterfowl-breeding, the pothole region produces about 50 percent of the duck crop in an average year and much more in bumper years (Smith and others, 1964, p. 39). Potholes also furnish water for other wildlife and livestock.

The drainage of potholes for agriculture has reduced their numbers considerably throughout the

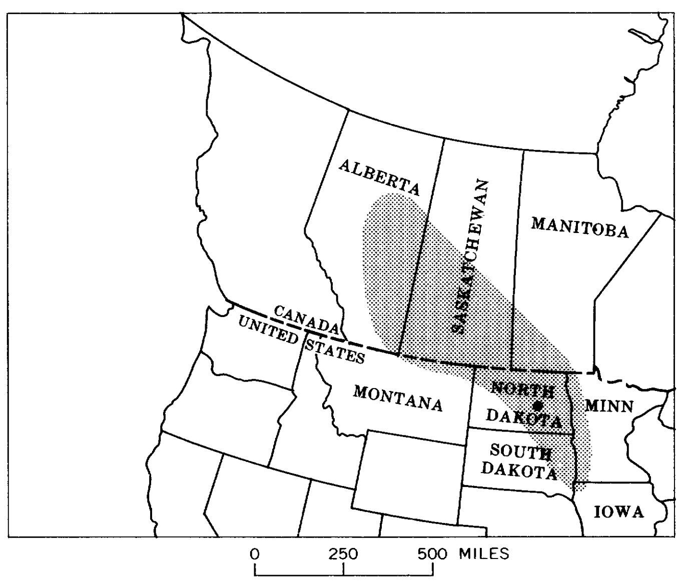


FIGURE 1.—Location of the prairie-pothole region (shaded) and study area (solid circle).

region. Because conservation and management of the remaining potholes require a basic understanding of pothole hydrology, the U.S. Geological Survey began an intensive study of the hydrology of prairie potholes in 1960, as part of the program of the Department of Interior for the development of the Missouri River basin. Since a short time after its inception, the prairie-pothole project has been directed by W. S. Eisenlohr, Jr.

The first phase of the project was an investigation of evapotranspiration in 10 prairie potholes on the Coteau du Missouri in North Dakota (Shjeflo, 1968). To minimize the effects of seepage, all the study potholes were in glacial till which, owing to its low permeability, allows little or no seepage outflow.

In the potholes he studied, Shjeflo found that direct precipitation and spring runoff from snowmelt were the major sources of water supply. Evapotranspiration was the major cause of water loss (Shjeflo, 1968, p. B46–B48). From May through October, the average evapotranspiration loss was 1.98 feet in vegetated potholes and 2.24 feet in clear pothole, roughly 2.1 feet for all potholes. These average evapotranspiration losses are close to the seasonal evaporation rate of 2.31 feet for lakes given by Kohler, Nordenson, and Baker (1959). Evapotranspiration did not vary a great deal among potholes or from year to year.

Seepage losses were found to be lower than evapotranspiration losses but were decidedly significant. The lowest seasonal seepage rate found was 0.0008 foot per day in pothole 5 in Dickey County, and the highest was 0.0105 foot per day in Ward County (Shjeflo, 1968, p. B48), some 13 times greater. The significant seepage losses made total water losses greater in vegetated potholes than clear potholes, even though evapotranspiration was less.

The primary objective of the ground-water project was to determine the influence of ground-water flow systems on the hydrology of prairie potholes. The ground-water project was begun in 1965. The studies were largely confined to the Coteau du Missouri in Stutsman County, N. Dak. Detailed studies of water movement in glacial drift were made in the Mount Moriah area, sec. 21, T. 144 N., R. 67 W., and at pothole C1, SW¼ sec. 32, T. 142 N., R. 66 W. General studies of ground-water hydrology and its relations to pothole hydrology were made in a profile across Coteau du Missouri, from its eastern edge in Stutsman County into the sand plain of central Kidder County. This report describes the ground-water investigations and their results. For descriptions of the study potholes and their setting, see the first report of this series (Eisenlohr and others, 1971).

Assistance provided by the staffs of the U.S. Bureau of Sport Fisheries and Wildlife, Northern Prairie Wildlife Research Center, at Jamestown, N. Dak., under the direction of Harvey Nelson, and the Woodworth, N. Dak., research station, under the direction of Leo Kirsch, is gratefully acknowledged. Frank D. Holland, III, provided able field assistance during the summers of 1966 and 1967.

CLIMATE

North Dakota, having a continental-type climate, has long cold winters and short summers. According to Bavendick (1941, p. 1054), the temperature reaches 90° F or higher an average of 14 days a year and 0° F or lower an average of 53 days a year.

Average annual precipitation is about 18 inches according to U.S. Weather Bureau records and average annual lake evaporation is about 32 inches (Kohler and others, 1959) at the pothole study areas in Stutsman County. About 75 percent of the annual precipitation and about 84 percent of the annual evaporation occur during the crop-growing season, April through September. As a result, most of the precipitation is absorbed in the soil and transpired or evaporated back to the atmosphere, and very little goes to runoff or ground-water recharge. The most effective season for runoff is in the early spring when snowmelt and precipitation rates generally exceed the potential for evapotranspiration.

GEOLOGY

The lithology and structure of the glacial drift underlying prairie potholes influence the movement of ground water and thereby affect their hydrology. Late Pleistocene (Wisconsin) glaciers in North Dakota deposited a mantle of glacial drift over all but the southwestern corner of the State. All preglacial drainage in North Dakota flowed into Hudson Bay in Canada, and the preglacial terrain sloped northeastward from the southwestern part of the State. Thus, the glaciers were advancing up the regional slope. The general effect of glaciation was to subdue the preglacial topography by filling the lows and planing the highs.

Glacial drift, or simply drift, is a general term used to denote all deposits of glacial origin. Drift includes unsorted ice-laid rock debris called till, sorted melt-water-laid sand and gravel called outwash, and fine-grained sediments laid down in lakes. Usually associated with drift are windblown deposits of silt and sand. For a general discussion of glacial geology in the northern Great Plains, see Lemke, Laird, Tipton, and Lindvall (1965).

The bedrock underlying the glacial drift in North Dakota is poorly consolidated and easily eroded. It consists largely of shale, siltstone, and sandstone of Cretaceous and Tertiary age (fig. 2). The glacial drift consists mostly of fine-grained sediments derived from the underlying bedrock. In addition some coarser material, mostly Paleozoic carbonates and Precambrian igneous and metamorphic rocks derived from the Canadian Shield and its margins, constitutes a small but conspicuous fraction of the drift.

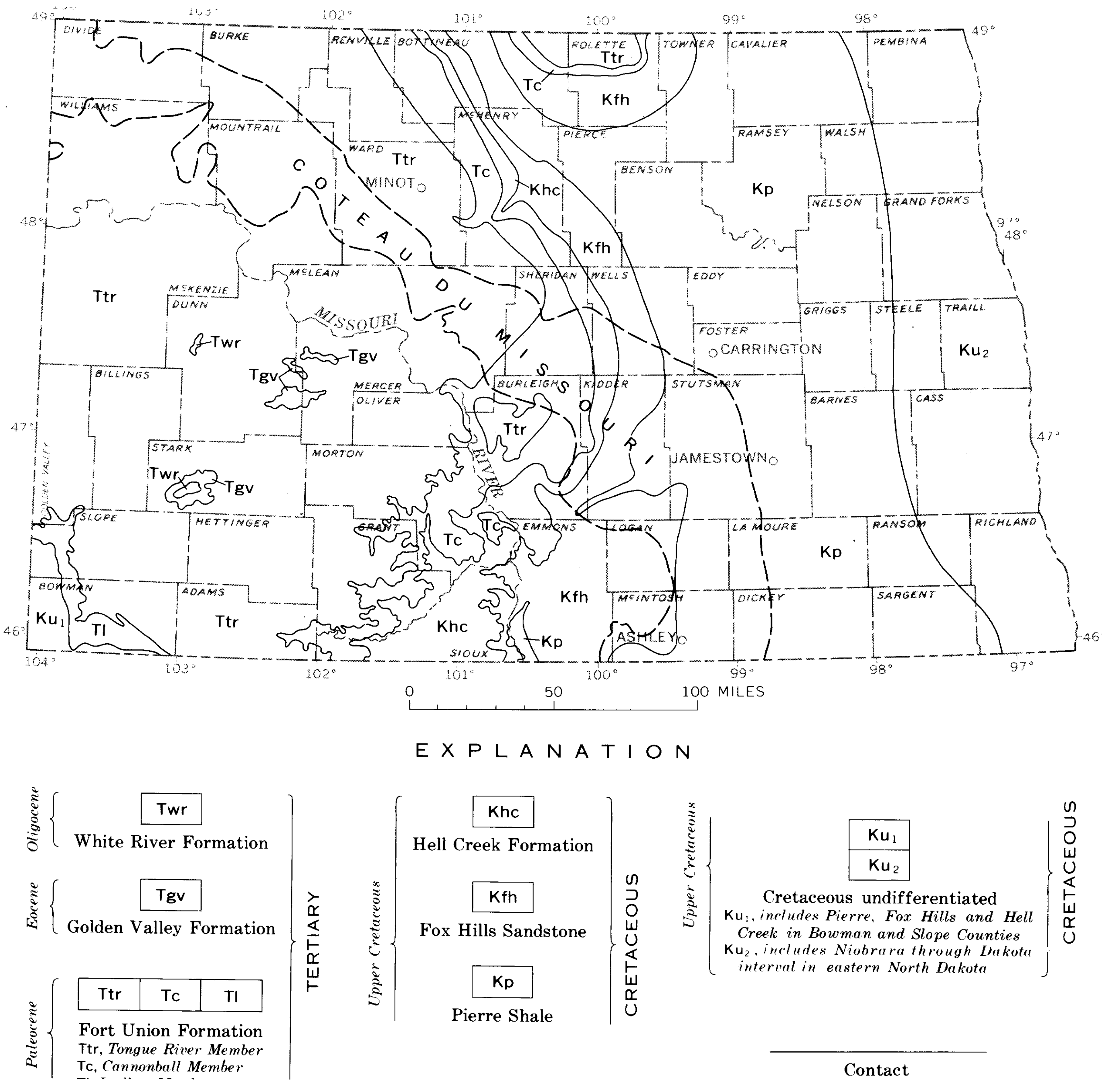


FIGURE 2.—Generalized bedrock map. Modified from North Dakota Geological Survey Miscellaneous Map 8.

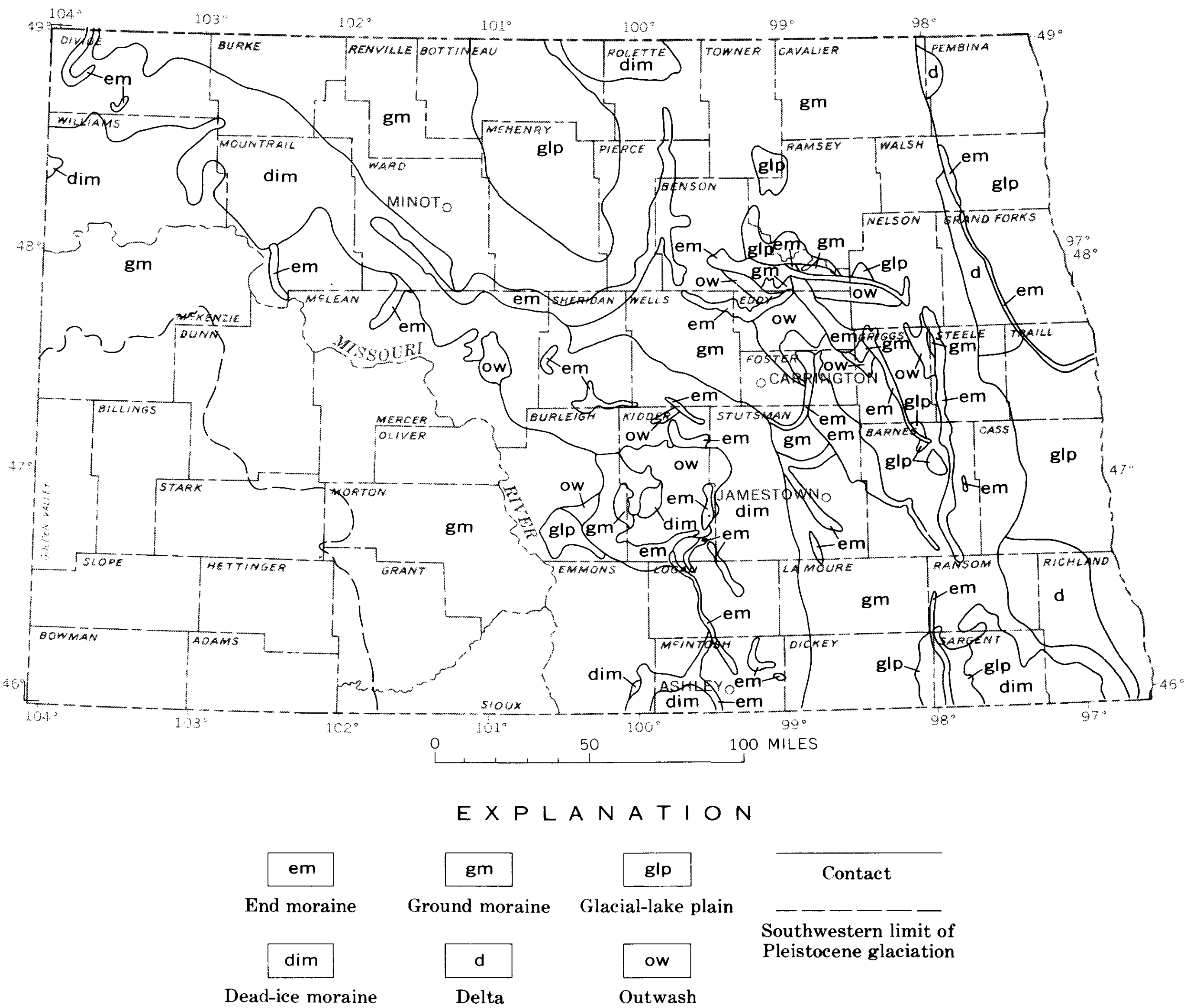


FIGURE 3.—Generalized glacial map showing area of well and pothole inventory (shaded). Modified from North Dakota Geological Survey Miscellaneous Map 9.

The composition of the drift reflects the lithology of the underlying bedrock (Lemke, 1960, p. 53), as shown by the following examples: (1) Till overlying the lignite-bearing Tongue River Member of the Fort Union Formation contains numerous lignite chips dispersed throughout, (2) till overlying the Cannonball Member of the Fort Union Formation is usually sandier and more yellow or tan than till that overlies the Tongue River Member, and (3) till that overlies the Pierre Shale contains numerous shale chips and has a darker gray color than the till that overlies either the Tongue River or Cannonball Members. A generalized glacial map of North Dakota (fig. 3) shows the distribution of some of the principal glacial deposits and land forms in North Dakota.

The most conspicuous glacial feature of North Dakota is the Coteau du Missouri, defined by the U.S. Geographic Board (1933) as a "narrow plateau beginning in the northwest corner of North Dakota between the 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." Winters (1967) discusses boundaries of the Coteau and other definitions that are in use. For this study the Coteau du Missouri is defined as that region of dead-ice moraine which lacks a well-integrated

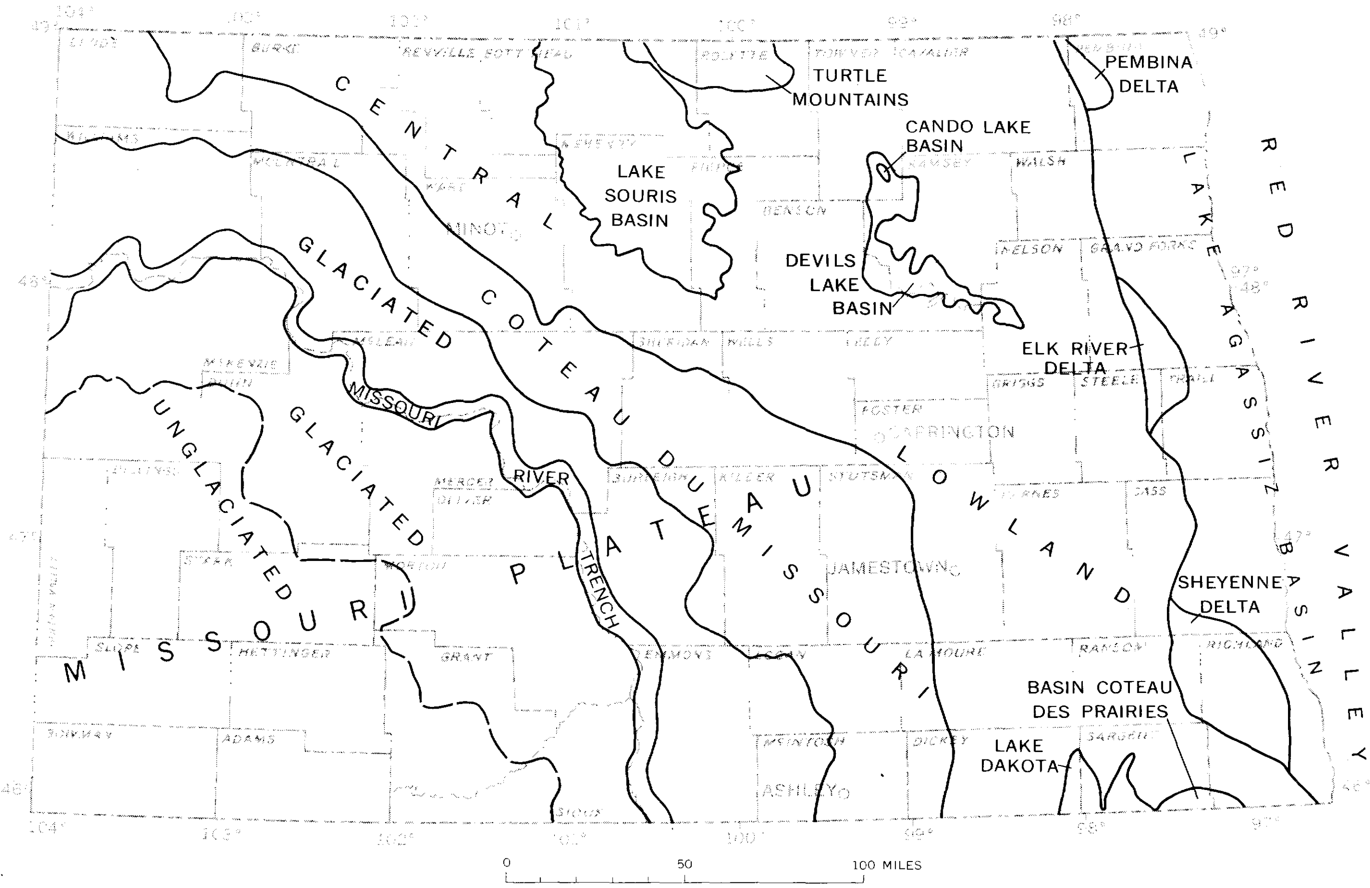


FIGURE 4.—Selected generalized physical subdivisions. Modified from Lemke and Colton (1958).

drainage system and lies between the Missouri escarpment on the northeast and the well-drained ground moraine adjacent to the Missouri River on the southwest. Figure 4 is a generalized map showing selected physical subdivisions of North Dakota including the Coteau du Missouri.

Glacial drift west of the Coteau du Missouri consists mainly of thin ground moraine that is discontinuous and patchy near the Missouri River. West of the Missouri River, the drift is very discontinuous and, in many places, consists only of scattered erratics.

GLACIAL DEPOSITS ON THE COTEAU DU MISSOURI

The Coteau du Missouri consists of dead-ice moraine that resulted from the extensive glacial stagnation that followed several advances of late Wisconsin glaciers. Most of the glacial drift on the Coteau has been dated by carbon-14 methods at less than 13,000 years before the present (Clayton, 1966). Stagnation occurred near the terminus of the glacial advances because of the insulating effect of thick superglacial drift that slowed the melting process. When the buried ice melted, a hummocky knob-and-kettle topography that did not have a systematic linear form or an integrated drainage system resulted. This distinctive terrain, filled with innumerable prairie potholes (see frontispiece), is commonly called dead-ice moraine (Clayton, 1967; Hansen, 1967; Lemke and others, 1965) or stagnation moraine (Colton, Lemke, and Lindvall, 1963; Winters, 1963; Gravenor and Kupsch, 1959). Owing to its youth and unique topography, the Coteau has been little modified by erosion or mass movement since its origin.

All the studies of prairie-pothole hydrology were made on the Coteau du Missouri in North Dakota. Most of the Coteau du Missouri is covered by dead-ice moraine of which about 90 percent is glacial till and the rest is small amounts of outwash and lake deposits. Superposed on the dead-ice moraine are a number of end moraines resulting from various ice advances. Outwash deposits, generally associated with these end moraines, extend away from them to the southwest as outwash channels or plains. Although much less extensive than till on the Coteau, areas of outwash contain important aquifers.

Glacial features associated with glacial stagnation on the Coteau du Missouri (Clayton, 1967, p. 31–34) include disintegration ridges, disintegration trenches, "doughnuts," collapsed outwash, ice-walled lake plains, and collapsed lake sediment.

Depending on the nature of the bedrock topography, drift thickness of the Coteau varies considerably. It is generally thickest over the main preglacial valleys, such as those of the Cannonball and Missouri, and thinnest over the bedrock highs. Drift thickness is generally greater on the Coteau than on the "drift prairie." In dead-ice moraine, drift thickness is related to topographic relief (Clayton, 1967, p. 37). In general, the drift is thick where the relief is high and is thin where the relief is low.

TILL

Glacial till on the Coteau du Missouri, which is very stony, consists largely of limestone, dolomite, quartzite, granite, and gneiss. Stones are conspicuous in the area because certain glacial processes have concentrated them into ridged zones, the winnowing action of waves in the beach zone of potholes uncovers and concentrates boulders along the shore line, and farmers gather and pile the stones to facilitate the cultivation of fields. Stones also occur in some glacial outwash so that their presence is not sufficient to distinguish between areas of outwash and till. The absence of boulders and stones, however, is fairly indicative that an area consists of glacial outwash or lacustrine beds, as stones are so common in till.

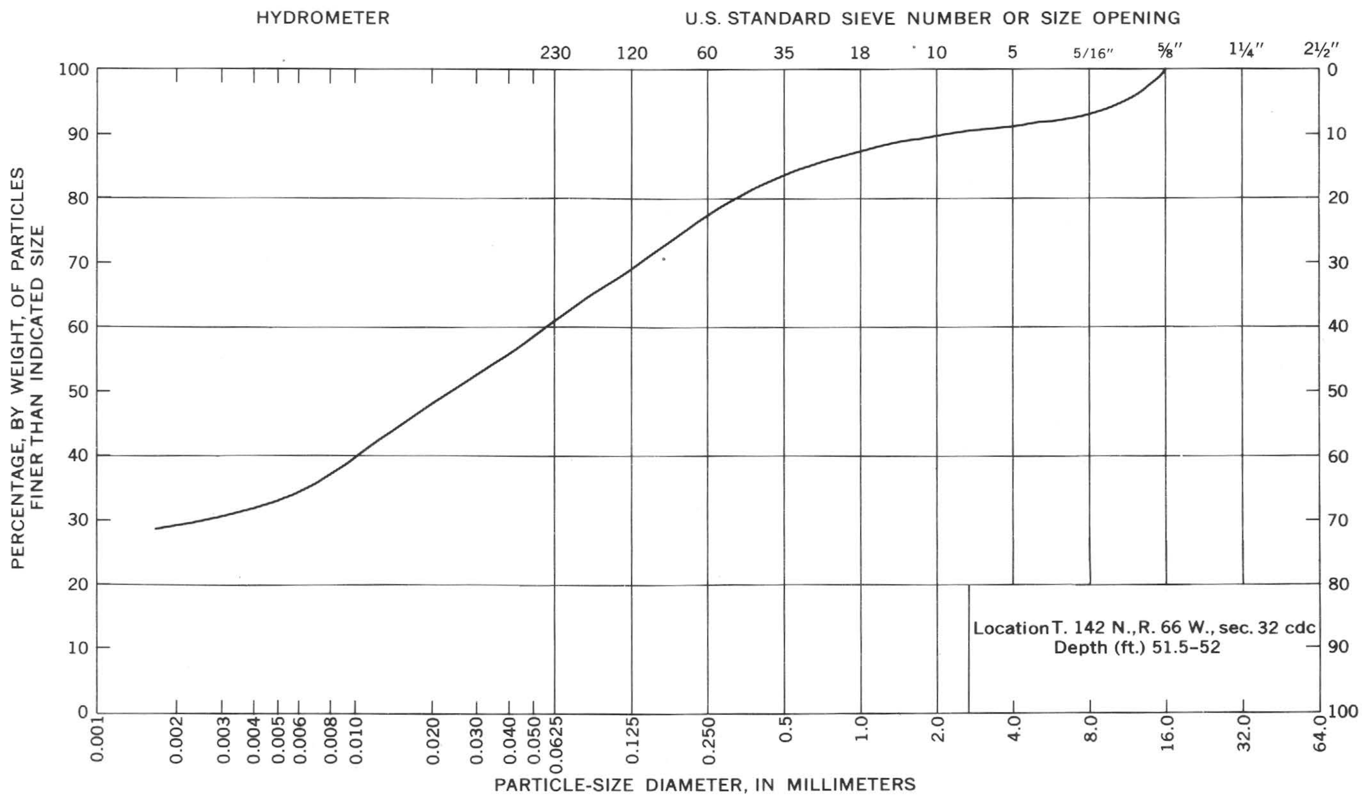
Water movement in glacial till is controlled by the lithology and structure of the till. Glacial till, also called boulder clay, is an unstratified unsorted heterogeneous mixture of clay, silt, sand, pebbles, cobbles, and boulders. Adjectives such as "clayey," "silty," or "sandy" can be used with the term "till" to denote the predominance of a particular constituent. The proportions of silt, clay, and sand are about equal in till on the Coteau du Missouri and usually constitute more than 90 percent of the till sample. The high clay content of glacial till makes it plastic when wet and very tough and hard when dry. Table 1 shows the percentages of clay, silt, sand, and gravel from selected cores at pothole C1. Although pebbles and larger stones are distributed throughout the till, they constitute a fairly small fraction of it. A grain-size analysis of glacial till taken from a borehole at pothole C1 in Stutsman County (fig. 5) is typical of much of the till found in the Coteau region.

TABLE 1.—*Percentages of clay, silt, sand, and gravel in selected cores at pothole C1*

Well	Core depth (ft)	Percentage of— Clay	Silt	Sand	Gravel
15S	11.0–11.5	33.2	33.9	28.0	4.9
17M	51.5–52.0	31.7	29.8	28.2	10.3
S–1	53.0–53.5	37.4	45.8	16.1	0.7
E–1	13.0–13.5	37.0	31.7	27.2	4.1
N–1	51.0–51.5	30.6	38.4	26.3	4.7
14M	30.0–30.5	27.5	32.7	35.9	3.9
15N	49.5–50.0	33.7	37.1	26.5	2.7
Average		33.0	35.6	26.9	4.5

Permeability as used in this report is a general term which refers to the ability of a material to allow a fluid to pass through it. The low permeability of the till is caused by the high percentage of silt and clay which normally constitutes more than 50 percent, and sometimes more than 75 percent, of the total detritus forming the till. Water movement in glacial till is controlled primarily by jointing. Glacial till is irregularly jointed. Near the surface, till commonly has a crudely horizontal imbricated jointing similar to a flaky piecrust. Joints in glacial till can extend to substantial depths as indicated by Meyboom, Everdingen, and Freeze (1966, p. 38). They state that, while drilling in Saskatchewan at two test holes in glacial till, drilling fluid was lost at 55 feet and 44 feet, respectively. At both locations, shortly after the beginning of the losses, drilling fluid (a mixture of water, aquagel, and wheat bran) started issuing from parallel "cracks" in the ground up to 20 feet away from the drill holes. Joints in glacial till show an adjacent oxidation zone that extends into the reduced part of the till. According to Williams and Farvolden (1967), these oxidation zones suggest that water in joints moves farther before losing its oxygen than does water moving through intergranular pore spaces. A relatively high permeability for the joints is thus indicated.

Enclosed within glacial till are numerous beds or lenses of stratified silt, sand, and gravel. Where they occur as isolated bodies, completely enclosed by till, such lenses or beds of sand and gravel have little effect on the gross permeability of a till unit. Local sand and gravel beds at shallow depths in glacial till can provide avenues for recharge or discharge of ground water if they intersect potholes. In general, sand or gravel in till has an effect on pothole hydrology only if it occurs at shallow depth and has good hydraulic continuity with potholes.



	CLAY SIZES	SILT SIZES	SAND SIZES					GRAVEL SIZES				
	<0.004	0.004–0.0625	Very fine 0.0625–0.125	Fine 0.125–0.25	Medium 0.25–0.5	Coarse 0.5–1	Very coarse 1–2	Very fine 2–4	Fine 4–8	Medium 8–16	Coarse 16–32	Very coarse 32–64
PERCENTAGE OF PARTICLES OF INDICATED SIZE	31.7	29.8	7.4	8.6	6.3	3.4	2.5	1.6	1.2	7.5	0	0

FIGURE 5.—Grain-size analysis of sample of glacial till pothole C1.

Soil-forming processes and weathering near the land surface make shallow till very permeable as compared with till at depth. Soils that develop from glacial till, when unfrozen or unsaturated, have a high initial infiltration capacity. Because till soils sustain an ample cover of vegetation under natural conditions, they are areas of low runoff.

Fluvial erosion, except where accelerated by cultivation, is generally lacking in the Coteau du Missouri, and sedimentation rates have been quite low in the potholes. Thus the landscape has been little modified since the stagnant glacial ice melted. Although the drainage basins have been only slightly modified by erosion and creep, many pothole basins have undergone extensive modification by wave action.

OUTWASH

Glacial outwash was deposited by streams fed by both glacial melt water and precipitation. Outwash consists largely of sand and gravel and has sorting and stratification that is characteristic of stream-laid deposits. Much of the outwash on the Coteau was deposited on top of the stagnant glacial ice and subsequently collapsed, forming a topography similar to collapsed glacial till. Outwash deposits, very coarse and bouldery near the source of melt-water discharge, grade into finer gravel and sand with increasing distance from the source. The distal margin of prominent end moraines is a common source of coarse detritus in glacial outwash.

Relative to adjacent till, most glacial outwash is topographically low because of its fluvial origin and generally has broader and more gentle landforms and less local relief. Outwash deposits, frequently confined to melt-water discharge channels, are less commonly in broad areas such as the sand plain in Kidder County, N. Dak. Surficial outwash may reach thicknesses as great as a few hundred feet but is generally much thinner. In many places outwash is a thin veneer overlying glacial till.

Soil developed on outwash has a high infiltration capacity and, consequently, little runoff or sediment yield. Ground-water flow has a greater effect on the hydrology of potholes in outwash than in till, because outwash is much more permeable. As a result, potholes in glacial outwash tend to have water levels that are comparatively stable, and the ponds are generally more permanent and saline than in glacial till.

Compared with glacial till, glacial outwash covers only a small part of the Coteau du Missouri. Large lakes and playas are common, and potholes are relatively scarce in glacial outwash on the Coteau.

LAKE DEPOSITS

Perched lacustrine plains are common on the Coteau du Missouri, but they have limited total area. Except where the lake beds have collapsed as a result of glacial stagnation, few prairie potholes occur in glacial-lake deposits because of their flat surfaces. Lake (lacustrine) sediments are poorly permeable; they consist primarily of clay and silt and contain minor amounts of fine sand. Fine laminations of alternating clay and silt beds called varves occur in some of the glacial-lake deposits.

DRIFT-PRAIRIE DEPOSITS

The central lowland east of the Coteau du Missouri is characterized by low relief and integrated drainage. Extensive glacial-lake deposits of silt and clay occur in the Agassiz, Souris, Devils Lake, and Dakota basins in this area. Most of the central lowland is covered by ground moraine, which consists largely of lodgement till deposited beneath the glacier by active ice. In contrast with the high-relief stagnation moraine on the Coteau, the ground moraine forms an undulating plain of low relief, locally called the drift prairie or drift plain (fig. 6). Prairie potholes in the ground-moraine area are less numerous and generally shallower than those in the

FIGURE 6.—The drift prairie, an undulating plain of low-relief ground moraine in central Stutsman County, near Jamestown.

Coteau region. The drift prairie has certain characteristic linear features, such as washboard moraines and elongate drumlins, which indicate the active-ice origin of these features. End-moraine loops of various ice advances occur within the drift prairie. These end moraines, consisting largely of till, stand out above the low-relief plain as elongate curvilinear ridges of moderate to high relief. Associated with many of the end moraines are deposits of sand and gravel in outwash channels and plains.

CHARACTERISTICS OF PRAIRIE POTHOLES

"Pothole" and "slough" are synonymous. Some objections to use of the term "pothole" have been expressed, particularly by geologists who may have associated potholes with quite different features. "The Glossary of Geology and Related Sciences," second edition, by the American Geological Institute gives six separate meanings to "pothole," none of which fit "prairie potholes." Because it is consistent with conservation and wildlife literature the compound term "prairie pothole" is used.

Most prairie-pothole basins resulted from the melting of blocks of buried glacial ice. As the ice melted, the saturated superglacial till settled and an inversion of topography took place, such that ridges and hummocks underlain by ice became depressions after the ice had melted. Ice-contact faces are common along one or more sides of the larger potholes.

The size of a prairie pothole ranges from a fraction of an acre to several square miles. Potholes larger than about 40 acres are arbitrarily called lakes by the U.S. Bureau of Sport Fisheries and Wildlife. Almost all pothole ponds are shallow; few are more than 5 feet deep, and most are less than 2 feet deep. The shape or outline of potholes is controlled by the glacial processes that produced the pothole depression and by the erosional and depositional processes that have affected the pothole since its origin. Some potholes are circular or oval, but most are irregular owing to their haphazard origins. In a typical large pothole, wave action has planed the shores, winnowing out the fine material and transporting it to the center of the basin. A wave-cut bench having a marked change of slope between the beach and upland (fig. 7) is produced, and a lag deposit of sand, gravel, cobbles, and boulders is left in the beach zone.

As a result, most pothole depressions are saucer shaped. Most potholes overflow at some stage in their history but many of these spill only during a wet cycle and then infrequently. A few potholes do not spill at all. The general absence of spill is evident by the lack of an integrated drainage system throughout the Coteau du Missouri. Potholes range in water permanence from those that contain water for only a few days following spring snowmelt, to those that contain water almost continuously.

FIGURE 7.—A prairie pothole having a pronounced wave-cut bench on the far shore.

The salinity of water in potholes is extremely varied, ranging from potholes in which the water is quite fresh to others containing brines that are several times more concentrated than sea water. Salinity is a measure of the quantity of total dissolved solids in water. The U.S. Geological Survey (Swenson and Baldwin, 1965, p. 20) considers that water containing less than 1,000 mg/l (milligrams per liter) dissolved solids is fresh and classes greater concentrations as follows:

Dissolved solids (mg/l)	*Salinity*
1,000–3,000	Slightly saline.
3,000–10,000	Moderately saline.
10,000–35,000	Very saline.
>35,000	Brine.

The upper limit for very saline (35,000 mg/l) is the average concentration of ocean water.

Stewart and Kantrud (1969) classified prairie potholes on the basis of the types of vegetation zones within the wetland:

Class 1.—Ephemeral potholes: low-prairie zone dominates central area of depression.

Class 2.—Temporary potholes: wet-meadow zone dominates central area of depression.

Class 3.—Seasonal potholes: shallow-marsh zone dominates central area of depression. Peripheral wet-meadow zone usually present.

Class 4.—Semipermanent potholes: deep-marsh zone dominates central area of depression. Peripheral shallow-marsh and wet-meadow zones usually present.

Different vegetation zones occur because of differences in water permanence or duration of inundation. Wet-meadow zones are in potholes, or portions thereof, that contain water of varying depths for only brief periods after spring snowmelt or immediately following heavy rainstorms. Shallow-marsh zones generally contain water through spring and early summer but often are dry from mid-summer through fall. In deep-marsh zones, water is ordinarily contained throughout the spring and summer, frequently extending into fall and winter.

Differences in salinity of water cause differences in the species composition within the various zones. The kinds and amounts of pothole vegetation are related to the permanence and salinity of pothole waters. Salinity and water permanence in a pothole fluctuate rapidly in response to inflow and outflow. Vegetation species change rather slowly in response to fluctuations in salinity and permanence so that they tend to integrate the short-term change and adjust to the seasonal, or even longer, hydrologic balance of a pothole.

GENERAL HYDROLOGY

Water enters the potholes by precipitation directly on the pothole surface, by runoff from the pothole watershed, and by seepage inflow. Outflow results from evapotranspiration, from surface overflow, and from seepage outflow.

Shjeflo has shown (1968, p. B48) that precipitation on the pothole surface is the main source of water supply to the pothole and that runoff from snowmelt is the next most important source of inflow. High runoff from snowmelt, which occurs infrequently, is generally a result of the rapid springtime melting of a snowpack having a high water content, producing water which runs off over frozen soils to the pothole. Such conditions existed in 1950 and again in 1969 when unusually high runoff occurred because a deep snowpack having a high water content persisted until late spring.

Runoff from summer precipitation is generally low and quite sporadic. Such runoff seems to be more closely related to conditions created by previous moisture than to the rainfall intensity itself (Eisenlohr and others, 1972). Prairie soils when dry have a high infiltration capacity and can absorb rainfall of high intensity. On the other hand, the montmorillinitic soils tend to swell when wetted, losing a great deal of their ability to absorb. Thus, closely spaced rainfalls of even low intensity can produce runoff.

Ground-water flow to and from potholes in glacial till is very slow but, quantitatively, is significant in that it increases or decreases the rate of pothole decline. The ground-water flow system around the pothole is quite important in its effect on pothole salinity.

All inflow processes carry dissolved solids into the pothole. The concentration of dissolved solids is extremely low in precipitation, moderately low in runoff, and relatively concentrated in seepage inflow. Dissolved solids in the pothole water can be removed by overflow or by seepage outflow. Evapotranspiration, because it removes water (as vapor) but not the dissolved solids, concentrates the salts in the pothole. Most potholes that overflow do so only infrequently, and many do not overflow at all. In the absence of overflow, outflow seepage is the only effective means of removing the salt load that is delivered to the pothole. The salinity of the pothole water is therefore a good index of the direction and amount of ground-water flow to and from the pothole.

The factors governing seepage inflow and outflow to and from potholes are the direction and magnitude of the hydraulic gradient toward and from the pothole, the permeability of the deposits which underlie and border on the pothole, and the water temperature in these sediments.

GROUND-WATER MOVEMENT

The flow of ground water through porous media depends on the hydraulic conductivity of the saturated material and the hydraulic gradient. Hydraulic conductivity is a physical property which equals the rate of flow under a unit hydraulic gradient through a cross section of unit area and measured at right angles to the direction of flow. It can be expressed in units of feet per day. Permeability is a general term that denotes the ability of a material to allow a fluid to pass through it. In this paper, the term "permeability" is used in the general sense to indicate relative degrees of permeability whereas the term "hydraulic conductivity" is used in a quantitative sense.

Ground-water movement relative to prairie potholes depends on the configuration of the adjacent water table and the hydraulic conductivity of the glacial drift. Ground water may move toward, away from, or parallel to the water table. In areas of ground-water recharge, such as topographic highs, ground water moves away from the water table. In areas of ground-water discharge, such as perennial streams or permanent potholes, ground water moves up toward the water table. Ground-water movement is essentially parallel to the water table in intermediate transmission zones where there is neither recharge or discharge. If the water table slopes toward the pothole from all directions (fig. 8A), there is a seepage inflow to the pothole. If the water table slopes away from the pothole in all directions (fig. 8B), there is seepage outflow from the pothole. For most potholes the water table slopes into some part of the pothole and away from the remainder (fig. 8C), thereby producing simultaneous seepage inflow and outflow (called through flow).

Figure 9 is a schematic diagram showing the continuous range of seepage conditions that exist and their relation to salinity. Potholes with total outflow are fresh, and potholes with total inflow are saline. Between the extremes of total outflow and inflow is a continuous series of through-flow conditions where salinity depends on the net seepage or seepage balance. Where outflow predominates, potholes are relatively fresh, and where inflow predominates, potholes are relatively saline.

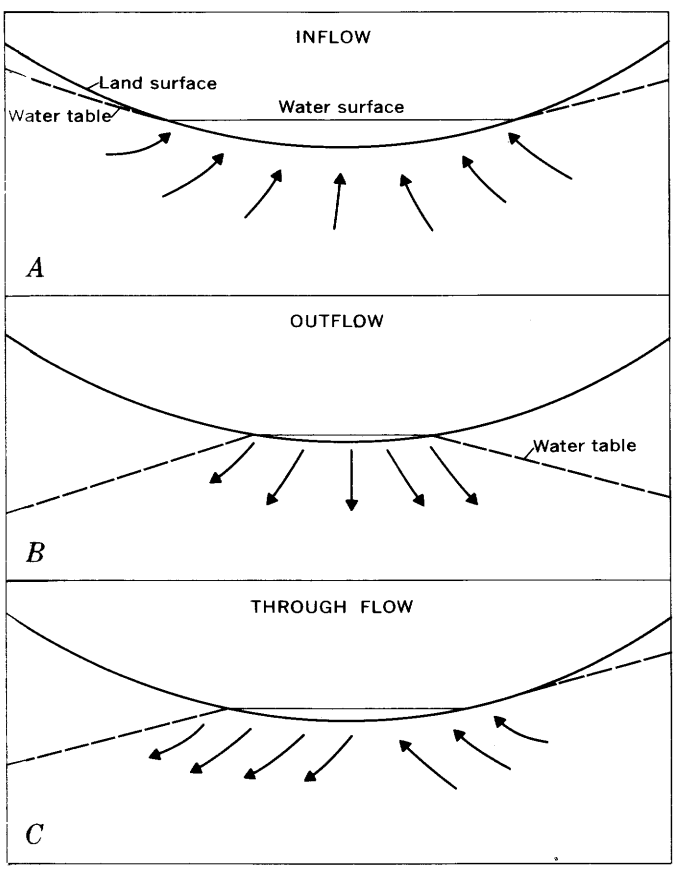


FIGURE 8.—Relation of the direction of ground-water flow (indicated by arrows) and water-table configuration.

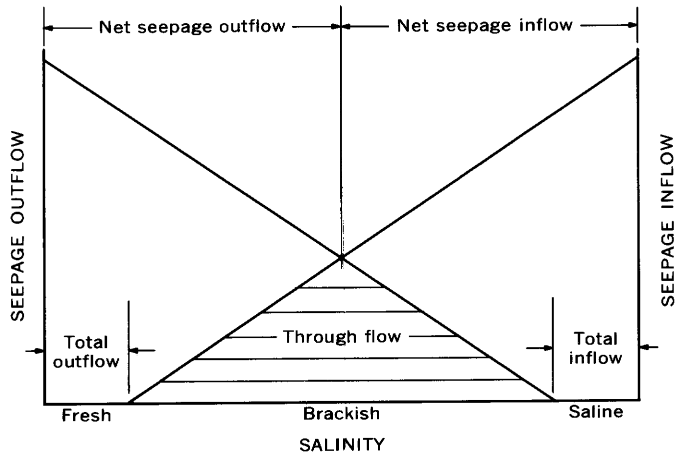


FIGURE 9.—Continuous range of seepage conditions and their relation to salinity.

Evaporation from the soil surface and transpiration by riparian vegetation creates a drawdown zone surrounding prairie potholes (see p. 15, 16.) The effect of the drawdown zone is to modify seepage by increasing seepage outflow or by decreasing seepage inflow. The drawdown effect also varies diurnally. Evapotranspiration throughout the day causes the greatest drawdown to occur during late afternoon or early evening. Evapotranspiration is greatly reduced during the night, and partial recovery of ground-water levels in the drawdown zone usually occurs. An observation-well hydrograph for the wet-meadow zone of pothole M15 (fig. 10) in the Mount Moriah area in Stutsman County shows daily drawdown and partial nightly recovery. The zone of shallow ground water surrounding a pothole is normally an area of profuse vegetation growth. According to Shjeflo (1968, p. B39), "Data for some of the vegetated potholes indicate that the seepage rates were highest when the mass-transfer coefficients were the highest, such as during the peak of the growing season in July and August." This effect was probably caused by increased seepage that resulted from drawdown in the wet-meadow zone surrounding the potholes and from the lowered viscosity of the water as temperatures increased.

Part of the water removed from the wet-meadow zone by evapotranspiration is supplied by the surrounding ground-water system. The proportion supplied by ground water versus that supplied by the pothole depends on the configuration of the water table and the permeability of the material surrounding the pothole. If the water table slopes

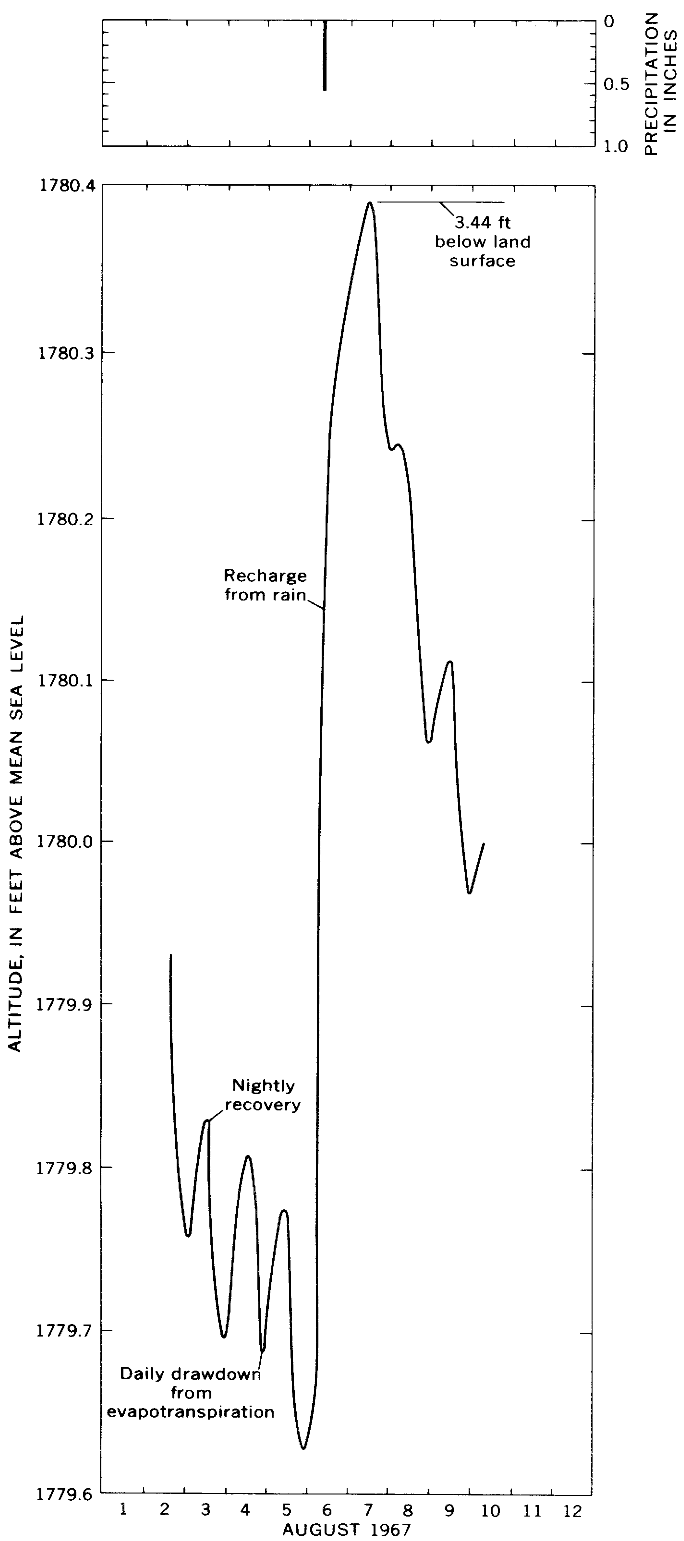


FIGURE 10.—Observation-well hydrograph for wet-meadow zone of pothole M15 (see fig. 16), Mount Moriah area.

steeply into the pothole on all sides, then most of the water evaporated from the wet-meadow zone is supplied by ground water. Conversely, if the water table slopes steeply away from the pothole on all sides, then most, if not all, of the water evaporated or transpired from the wet-meadow zone is supplied by the pothole. Usually, the water table slopes into some parts of the pothole and away from other parts, resulting in an intermediate balance between the ground-water and pothole supply to the wet-meadow zone. As evaporation increases, seepage tends to increase because of the effect of evapotranspiration from the wet-meadow zone surrounding the pothole. The net result is that apparent seepage outflow from the pothole does not result in total recharge to the ground-water system but is partly or, in some places, totally removed by evapotranspiration from the fringing wet-meadow zone.

Ground-water flow in the vicinity of potholes in glacial till is extremely slow, but is intensified in the shallow zone surrounding the pothole. In deeper glacial till, flow tends to be vertical and is very much slower. Therefore, localized shallow ground-water flow systems dominate the ground-water hydrology of prairie potholes.

Below the water table, water moves by gravity from regions of higher fluid potential toward regions of lower fluid potential. Fluid potential (total hydraulic head), sum of the hydrostatic pressure potential (pressure head) and the gravity potential (elevation head), may be determined from the static water level in wells. In materials of low permeability such as glacial till, the rate of water movement is extremely slow, even in tills having a high hydraulic gradient.

FIELD INVESTIGATIONS

Field studies were conducted at several sites on the Coteau du Missouri to determine ground-water conditions near various potholes. These included the following: An intensive study near pothole C1 in the Cottonwood Lake area to determine conditions near a typical prairie pothole, a detailed study of ground-water conditions as related to prairie potholes in the Mount Moriah area, and a reconnaissance study of a broad area extending from eastern Stutsman County to the sand plain of Kidder County.

COTTONWOOD LAKE AREA

Pothole C1 (fig. 11) is in the Cottonwood Lake area of the SW¼ sec. 32, T. 142 N., R. 66 W., about

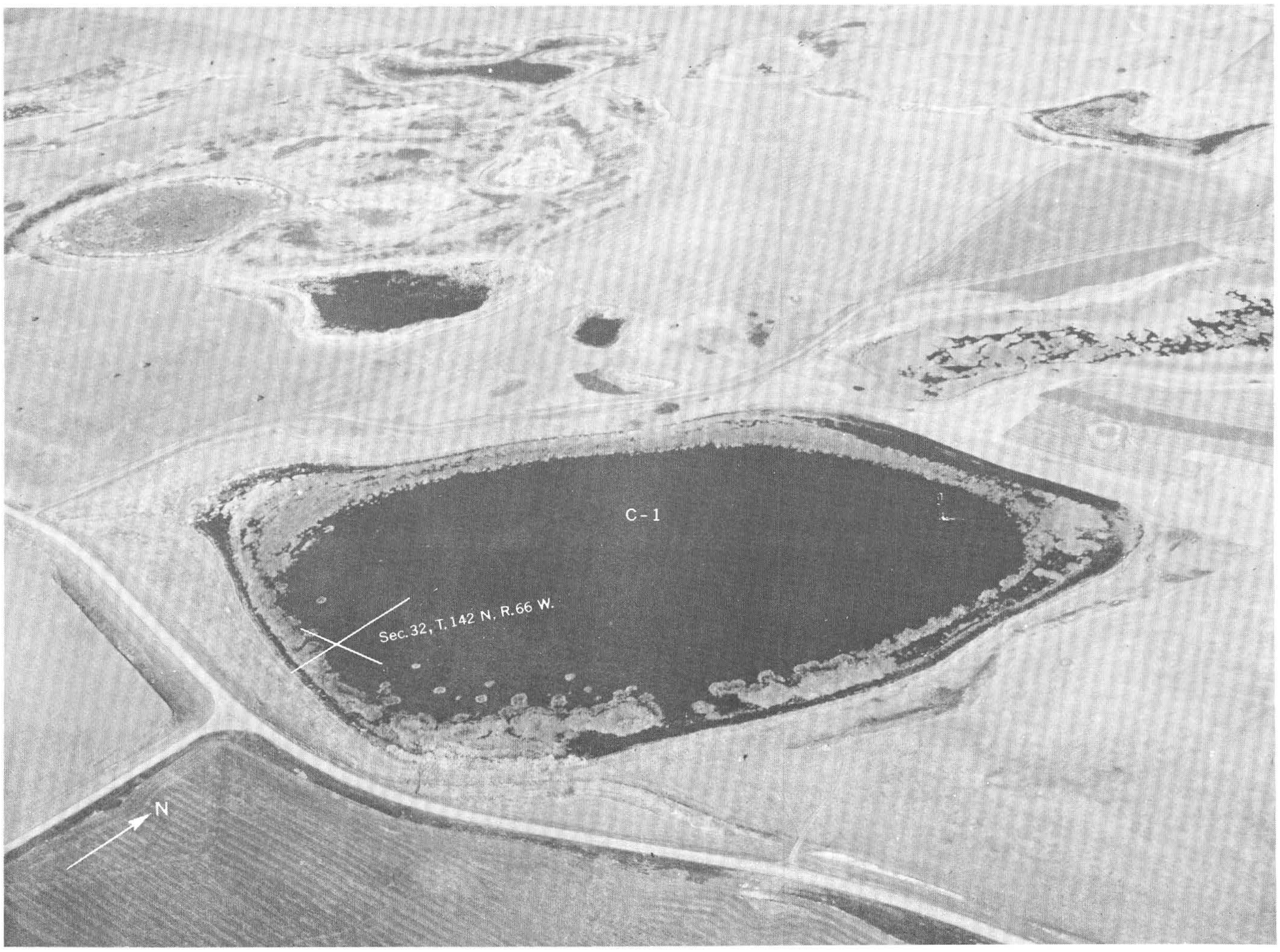


FIGURE 11.—Aerial view of pothole C1, near Buchanan.

12 miles west of Buchanan, N. Dak. Pothole C1 is surrounded by surficial glacial till in high-relief stagnation moraine. The pothole is in a deep basin that shows evidence of a high-water mark about 6 feet above the highest water level that occurred during the study. A well-developed wave-cut platform that is very stony surrounds the pothole. The pothole is brackish and semipermanent according to the classification of Stewart and Kantrud (1969).

In the fall of 1964, test holes were drilled at 42 locations around pothole C1 (fig. 12) to define ground-water conditions in the vicinity. The test holes were drilled along rays extending from the edge of the pothole to the adjacent uplands. Four groups of three test holes were drilled in a line extending east from the pothole. Samples were collected during drilling for lithologic description, size analysis, and moisture content. Selected cores were collected for a determination of hydraulic conductivity. The test holes were drilled with a 5-inch auger and cased with 1½-inch galvanized pipe. An 18-inch screen was attached to the lower end of the pipe, and a gravel pack was placed around the screen. The annular space between the outside of the pipe and the drill hole was filled with drill cuttings.

Soil temperatures were measured on the shore and beneath pothole C1 at periodic intervals in 1964 (Shjeflo, 1968, p. B11). Temperature beneath the pothole ranged from a low of 26° F on March 31, at a depth of 2.25 feet, to a high of 80° F on July 14, at the surface of the bed. Soil temperature on shore ranged from 21° F on December 2, at a depth of 0.25 foot, to a high of 77° F on July 14, at 0.25 foot. The bed of C1 thawed from the top down so that the ground remained frozen until April 29 at a depth of 2.25 feet.

The rate of ground-water flow is inversely pro-

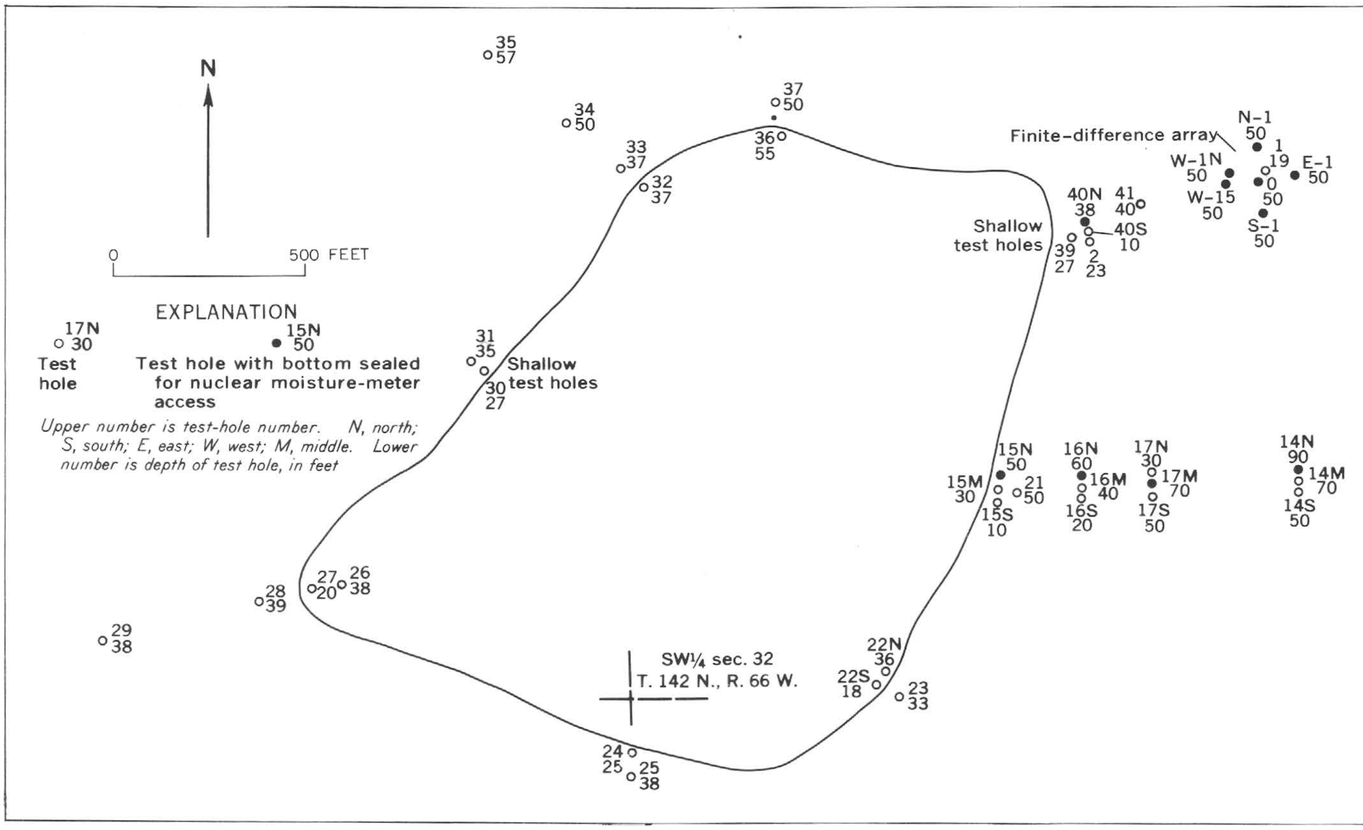


FIGURE 12.—Location of test holes at pothole C1.

portional to its viscosity, which in turn varies inversely with temperature. Between 32° and 77° F, there is more than a twofold decrease in viscosity and, thus, a corresponding twofold increase in the rate of flow, if other factors remain constant.

Pothole seepage occurs at very shallow depth where there are large variations in temperature (Shjeflo, 1968, p. B11) and, consequently, large variations in seepage rates. This shallow ground-water flow ceases when the ground beneath and adjacent to the pothole freezes.

Unweathered glacial till is poorly permeable. Weathering and soil-forming processes such as freezing and thawing, wetting and drying, biological activity, and movement of soil moisture tend to increase the permeability of glacial till. Because these processes are most active at or near the surface, the permeability of till diminishes rapidly with depth. According to Meyboom (1967, p. 133), surficial till is 10 to 100 times more permeable than deeper till. The hydraulic conductivity of glacial till surrounding eight piezometer screens at pothole C1 was determined by the Hvorslev method, used by Meyboom, Everdingen, and Freeze (1966, p. 42). Water was removed from the piezometers by a simple bailing device, and the time required to recover 90 percent of the pressure difference was recorded. The values of hydraulic conductivity thus derived ranged from 0.02 to 0.002 foot per day. In depth, the wells tested ranged from 27 to 60 feet. Laboratory permeater tests of till core samples from wells 15N, 16N, and 17N at depths of 11, 22, and 30 feet, respectively, gave an average hydraulic conductivity of about 0.0006 foot per day. The determinations were made with 1-inch cores in which appreciable squeezing occurred, thus accounting for the reduced hydraulic conductivity.

A diamond-shaped array of test holes was drilled northeast of the pothole to determine ground-water recharge by the finite-difference method (Stallman, 1956). One piezometer in each group and all five in the finite-difference array were plugged with a lead-paraffin seal above the screen to exclude water so that the casing could be used as an access hole for a nuclear moisture meter. Measurements made with moisture meters were not amenable to hydrologic interpretation because of the insensitivity of the moisture meter. The plugs were subsequently removed so that water levels could be measured directly.

Piezometers are commonly used in determining vertical fluid-potential gradients to distinguish between recharge and discharge areas. Erroneous conclusions can be obtained by comparing the head relationships between piezometers that have not stabilized. According to Lissey (1967), if the initial flow rate into or out of the piezometer is maintained after a pressure change in either the piezometer or the formation, the time required before stabilization recurs is called the basic hydrostatic timelag and is a measurement of sensitivity. Piezometers with low sensitivities, "large basic timelags," are never stabilized except at that instant when water levels reverse.

Thus, rapid ground-water-potential changes, even those of large magnitude, can go completely undetected by piezometers of low sensitivity. The sensitivity of a piezometer depends on two factors: (1) the diameter of the piezometer, and (2) the hydraulic conductivity of the surrounding materials. The lower the hydraulic conductivity, the lower the sensitivity, and the smaller the diameter of the piezometer, the greater the sensitivity. The sensitivity of the piezometers at C1 was extremely low because their diameters were so large in relation to the low hydraulic conductivity of the till. As a result, quantitative measure of recharge at the finite-difference array was impossible. Also, short-term changes in head could not be detected, though general trends were shown adequately.

FIGURE 13.—Type-F recorder in shelter at well 22N, pothole C1.

Water levels (a measure of fluid potential at the bottom of the casing) were measured weekly throughout the summer and less frequently during the winter on all the observation wells. Well 22N was equipped with a shelter containing a recorder (fig. 13) for continuous water-level measurements from 1964 to 1968. A portable shelter containing a recorder was used on many of the observation wells to monitor recovery from bailer tests.

Some of the piezometers near the edge of the pothole were inundated when the water level in the pothole rose. Wells 22N, 22S, 26, 27, 32, and 36 were under water during at least part of the study. Because water levels in those piezometers within the pothole were consistently above the pothole water level after the spring thaw, there must have been a zone of upward ground-water flow beneath the pothole. The upward fluid-potential gradient ranged from 0.009 foot per foot to 0.05 foot per foot beneath the pothole. Water levels in very shallow observation wells in study potholes in Ward and Dickey Counties, N. Dak., (Shjeflo, 1968, p. B10) were usually about 0.1 foot above pond level. Observation wells 24 and 30, on fairly steep banks near the edge of pothole C1, had water levels consistently above ground level. The fact that well 30 flowed over the top of the casing for extended periods of time indicates the existence of a strong upward-flow component along the immediate margin of the pothole as well as beneath the pothole.

Downward fluid-potential gradients ranging from 0.30 to 0.33 foot per foot were measured at piezometer groups 16 and 17 on the upland to the east of pothole C1. At piezometer group 15, near the eastern edge of pothole 1, there was a downward fluid-potential gradient of 0.015 foot per foot between depths of 10 and 30 feet and an upward gradient of 0.045 foot per foot between 30 and 50 feet. There is an upward gradient of 0.10 foot per foot between piezometers 40N and 40S near the northeast edge of C1. Figure 14 shows the distribution of fluid potentials at several piezometers near C1.

Two water-table profiles were obtained from shallow observation wells augered in the wet-meadow zone adjacent to wells 30 and 39 at pothole C1 (fig. 15). The drawdown observed at well 30C on July 5, 1967, was 1.07 feet below pond level at a distance of 12 feet from the pond. Drawdown in the more gently sloping profile at well 39 reached 0.37 foot below pond level at a distance of 21 feet from the pond. An upward fluid-potential gradient of 0.04 foot per

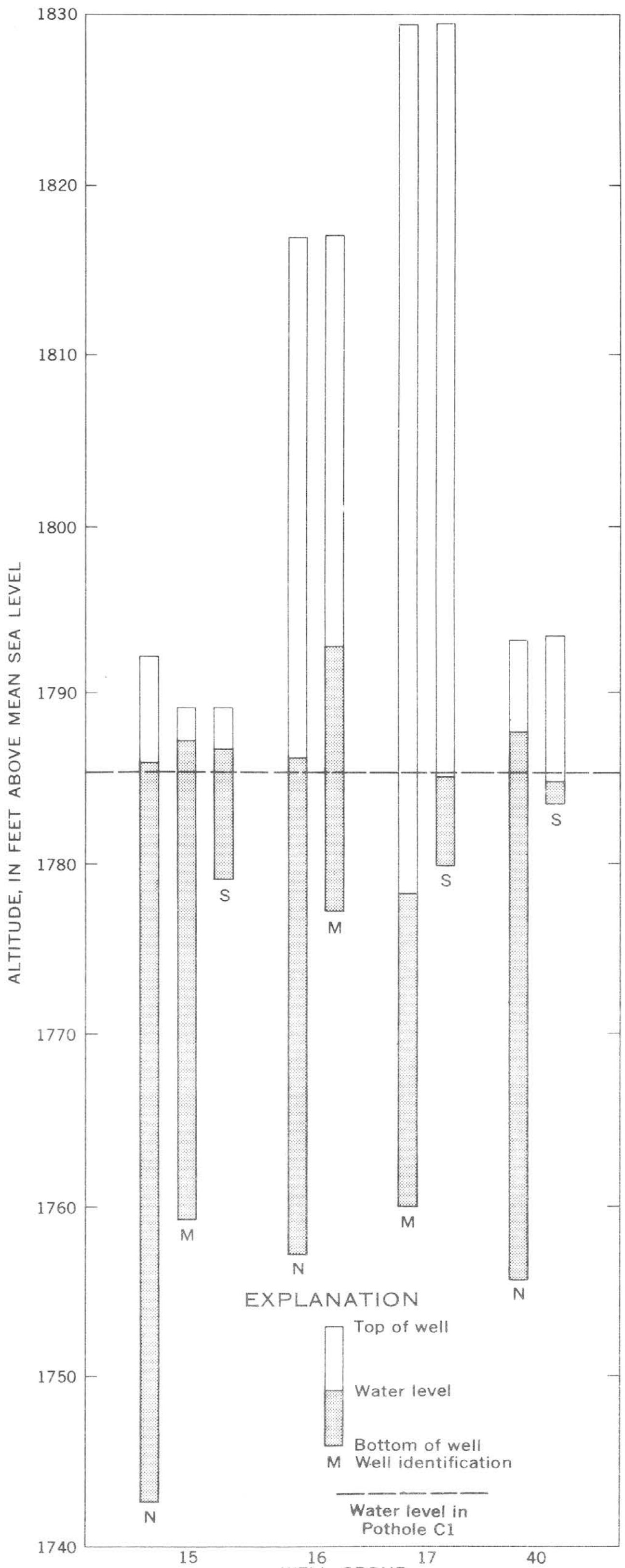


FIGURE 14.—Water levels in piezometers show vertical head, or fluid-potential, (vertical lines) for selected test holes, September 13, 1966. See figure 12 for location of well groups.

foot existed between well 30 (27 feet deep) and the water table.

Fluid potentials measured in piezometers at pothole C1 indicate slow downward flow beneath the uplands and upward flow beneath the pothole and along its margins. As drawdown by evapotranspiration in the wet-meadow zone adjacent to the pothole creates a potential for shallow seepage outflow, slow seepage to the pothole is occurring from ground-water flow systems beneath the pothole.

MOUNT MORIAH AREA

Studies in the Mount Moriah area of Stutsman County were designed to determine the relationship of the water table to the water surface in prairie potholes and the effects of these relationships on pothole hydrology.

The Mount Moriah area is sec. 21, T. 144 N., R. 67 W., on the poorly drained escarpment at the eastern edge of the Coteau du Missouri. There are 104 potholes in sec. 21, ranging in size from 0.01 to about 7.1 acres and in permanence from ephemeral to semipermanent.

The Mount Moriah area is in high-relief stagnation moraine that consists of surficial till except for the northeastern corner of the section where there is an outcrop of ice-contact stratified sand and gravel. The terrain slopes to the east from an altitude of 1,880 feet above mean sea level in the northwestern part of the section to 1,705 feet in the northeastern part of the section. Much steeper local slopes border most of the large potholes and drainage courses within the area.

Twenty-eight test holes were drilled in the Mount Moriah area (fig. 16) in October 1965 to determine the relationship of the water table to prairie potholes. The test holes, which ranged in depth from 14 to 67 feet, averaged 24 feet deep. Various thicknesses of stratified silt, sand, or gravel were penetrated in all but seven test holes. Glacial till occurred in all the test holes and comprised more than 80 percent of the total material augered.

The test holes were cased with 1¼-inch thin-walled aluminum conduit that was slotted throughout the saturated zone. Washed pea gravel was placed around the casing in the lower part of the hole, and till cuttings were placed around the casing in the upper part of the hole to exclude surface inflow. The casings were covered to exclude precipitation. The test holes were drilled only a short distance into the saturated zone so that the fluid potentials in the holes were very close to the water-table altitude. Water levels in the test holes show that the water table in

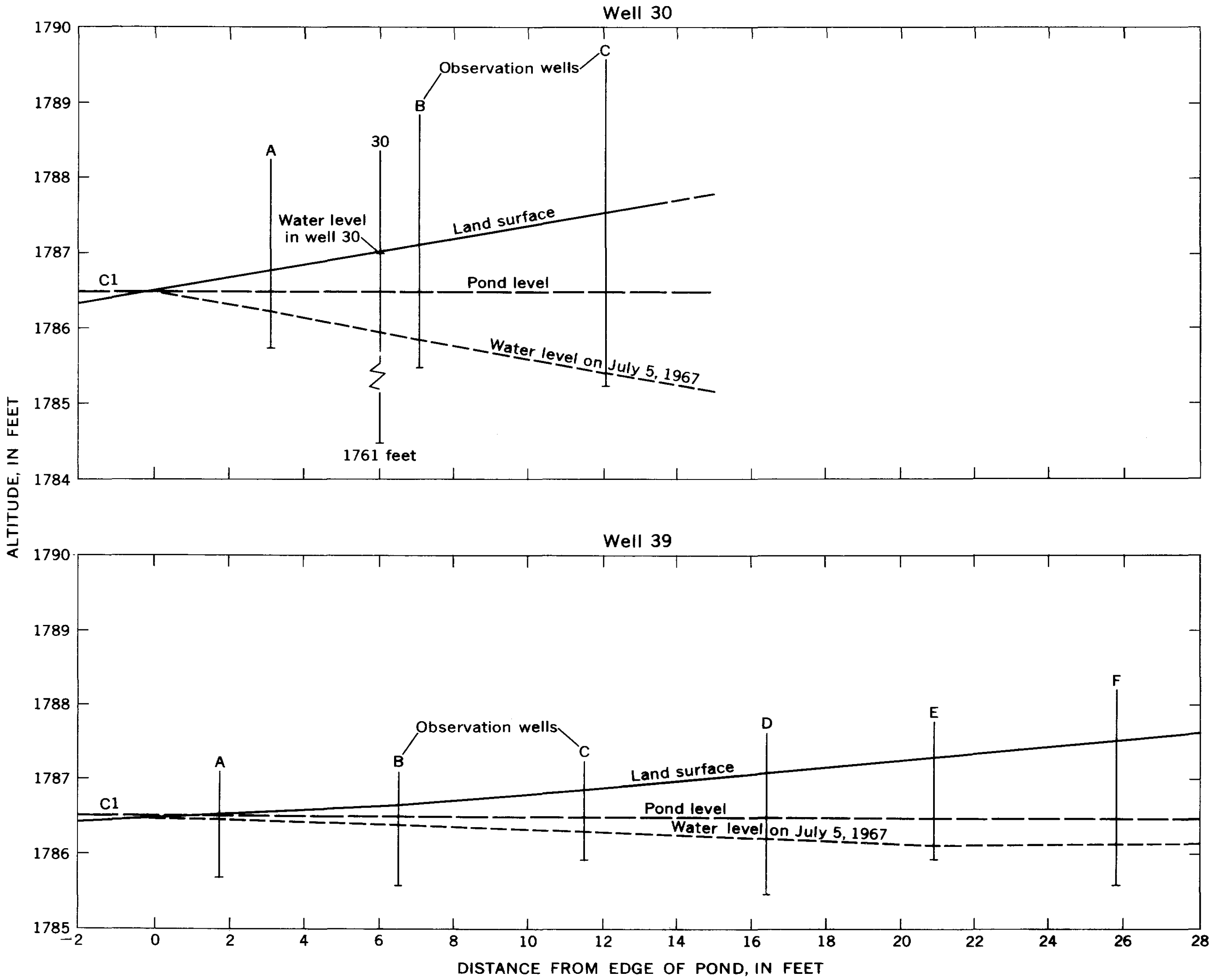


FIGURE 15.—Water-table profiles from wet-meadow zone adjacent to wells 30 and 39 at pothole C1.

cross section is almost a straight line connecting pothole water surfaces (fig. 17.)

The water table in the Mount Moriah area is a shallow subdued image of the general topography but, in detail, is a curved surface linking pothole water surfaces. A reasonably accurate representation of the water table can thus be obtained by using the altitudes of pothole water surfaces as control points for a water-table contour map. Following snowmelt runoff, frozen soil beneath potholes may cause ephemeral ponds to be perched above the water table. Because of the frost in the soil, perched water surfaces are not extensions of the water table. With this exception, altitudes of pothole water surfaces, determined at different times, can be used to show changes in the position of the water table. A water-table contour map (pl. 1) of the central part of the Mount Moriah area shows the conformity of the contours to the altitudes of pothole surfaces and water levels in wells.

Measurement of water depth and specific conductance were made in 71 potholes in the Mount Moriah area on June 8 and July 18, 1967. In accordance with the classification described under "Characteristics of Prairie Potholes," the potholes were grouped on the basis of the vegetation type in the deepest zone:

Class 1 (*ephemeral*).—About 20 potholes were examined, and all were dry on June 8 and for the remainder of the season.

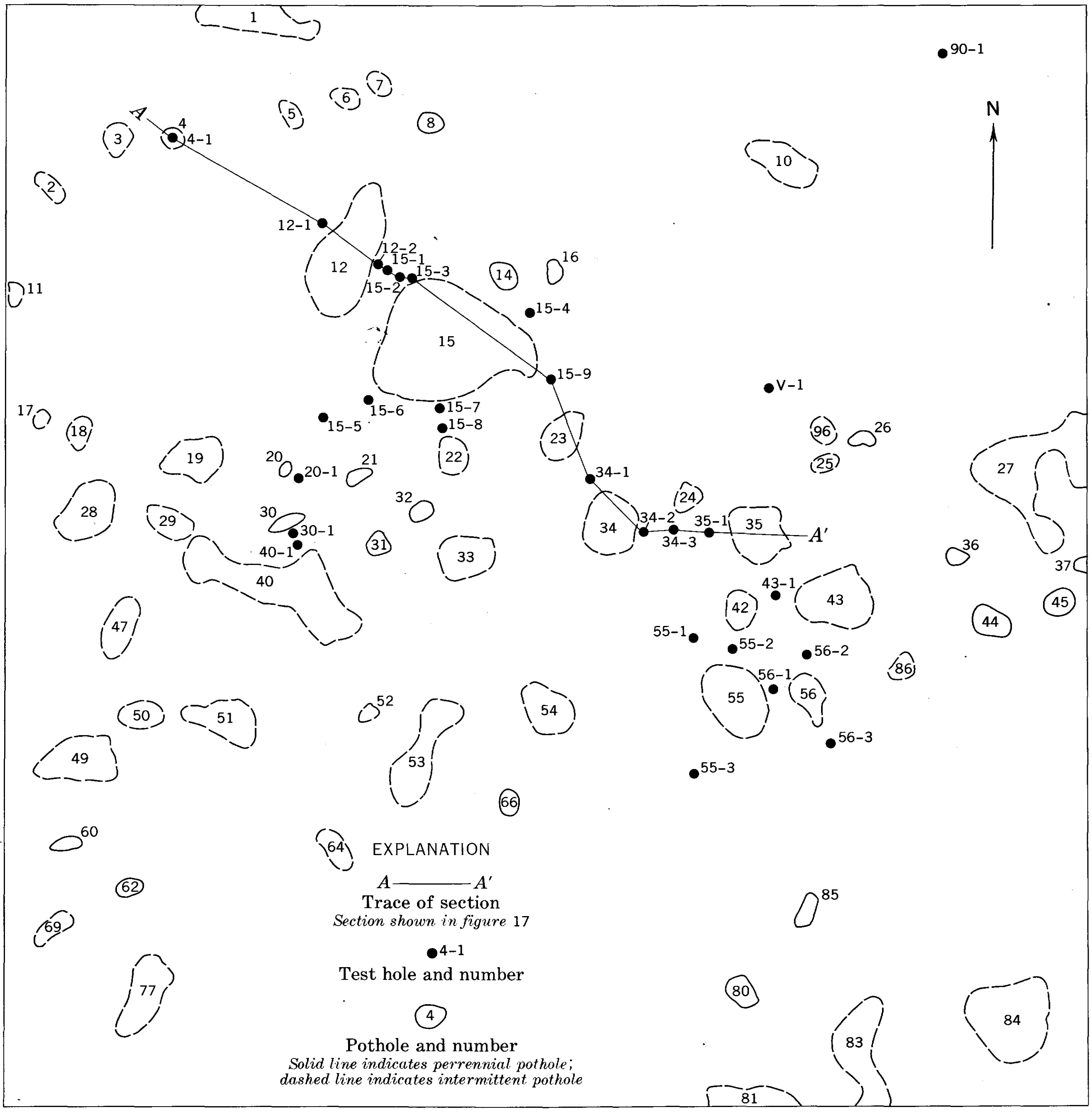


FIGURE 16.—Location of test holes in the Mount Moriah area, sec. 21, T. 144N., R. 67W.

Class 2 (*temporary*).—There were 22 potholes having an average depth of 0.76 foot on June 8, and all were dry by July 18. Six class 2 potholes showed evidence of ground-water discharge to their ponds and had an average specific conductance of 3,490 μmhos/cm (micromhos per centimeter), the highest of any group. In addition to ground-water discharge, the same six potholes had very shallow ponds (less than 1 foot in depth) that could not allow effective dilution by surface inflow. The remainder of the class 2 potholes had an average specific conductance of only 270 μmhos/cm.

Class 3 (*seasonal*).—There were 24 potholes which had an average depth of 1.9 feet on June 8 and an average specific conductance of 590 μmhos/cm. Their water levels declined an average of 1.25 feet between June 8 and July 18. All class 3 potholes were dry by August 29.

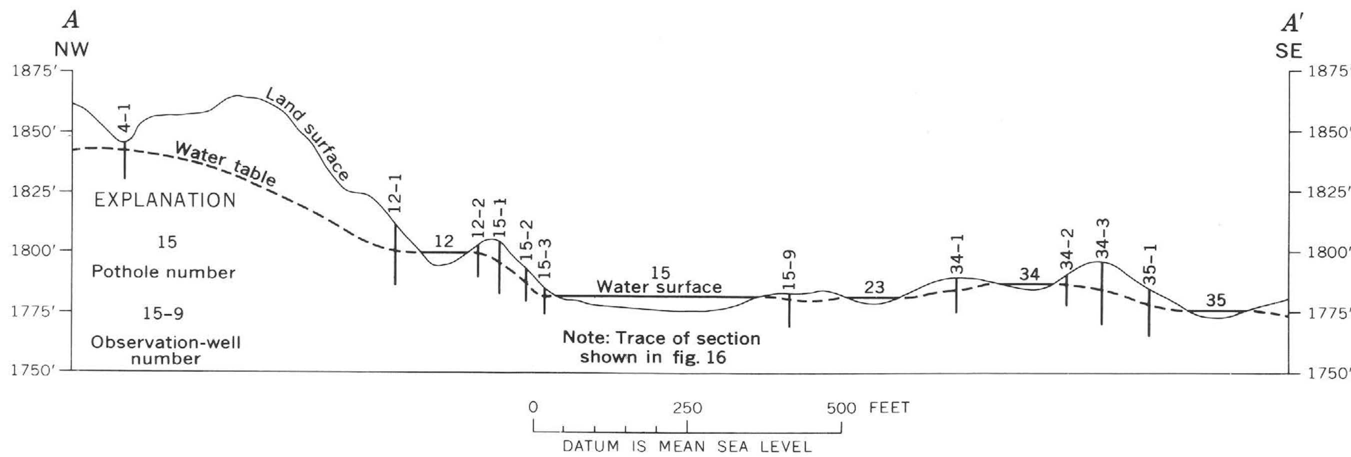


FIGURE 17.—Cross section of the water table and potholes in the Mount Moriah area. Trace of section in figure 16.

Class 4 (*semipermanent*).—The average conductance of 25 potholes was 1,320 μmhos/cm. Their average depth on June 8 was 2.6 feet, and their water levels declined an average of 0.75 feet between June 8 and July 18.

Although the results were affected by the drying out of class 1 and 2 potholes and by surface outflow from many of the class 4 potholes, the data in table 2 show an inverse relationship between conductance and rate of lowering of water level:

TABLE 2.—*Specific conductance and change of water levels in Mount Moriah potholes*

[Class: See discussion on "Characteristics of Prairie Potholes" in this report]

Class		Average water depth in feet (June 8, 1967)	Average specific conductance (μmhos/cm)	Decrease of depth in feet (June 8—July 18, 1967)
1	Ephemeral	Dry		
2	Temporary	0.76	270	>0.76
3	Seasonal	1.9	590	1.25
4	Semipermanent	2.6	1,320	0.75

Variations in the permanence and salinity of pothole water in the Mount Moriah area are related to the configuration of the water table surrounding the potholes (table 3):

TABLE 3.—*Rate of decline of water levels in relation to slope of water table near selected potholes in the Mount Moriah area*

Pothole	Class	Direction of water-table slope	Specific conductance (μmhos/cm)	Rate of decline (ft per day)
42	3	Away (steep)	360	0.042
34	4	Away (gentle)	775	.027
12	4	Away and toward	1,100	.025
15	4	Toward	3,000	.020

A series of shallow holes was hand augered between well 15–3 and pothole 15 on June 28, 1967, in the Mount Moriah area to determine the configuration of the water table upslope from the pothole. Test holes A, B, and C were 1 foot apart and 1 foot from the edge of the pothole, and test hole D was about halfway between the pothole and well 15–3.

Auger holes A, B, and D bottomed in a zone of silty sand and pebbles that was overlain by about 2 feet of dark clayey organic soil. Auger hole C bottomed in the overlying clayey zone. Water levels (table 4) indicate that water was moving through the sandy zone from 15–3 toward the pothole. Near the edge of the pothole, water was moving up from the sandy zone toward the surface. The sandy deposit may represent a beach zone formed at a higher pothole water level before the outlet was lowered to its present position. A high strand line is evident on the sides of the basin. The clayey soil developed over the emergent beach after the outlet was lowered.

Other auger holes northeast of pothole 15 penetrated zones of calcareous marl and lacustrine beds containing abundant fossil gastropods below the high strand line and above the present overflow level of pothole 15. Buried beaches thus may be

TABLE 4.—*Water levels in shallow test holes near pothole 15*
[*Altitude of pond surface, 1781.82 ft*]

Well	Depth (ft)	Altitude (ft)	
		Water level	Land surface
A	2.94	1,782.05	1,782.10
B	2.45	1,782.05	1,782.14
C	1.75	1,781.91	1,782.01
D	2.50	1,782.07	1,782.83
15–3	15.0	1,782.21	1,783.21

zones through which water is transmitted into potholes on their upslope side.

RECONNAISSANCE STUDIES

Water levels were measured in wells 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. 3), to see if any regional relationships could be discerned with regard to the water table and pothole hydrology. It was soon apparent that most wells in glacial till act as piezometers in that their water levels represent the total fluid potential at the intake to the well rather than the water table. As a result, the water table could not be defined using the water levels in existing wells. Because most of the wells are piezometers, an attempt was made to outline areas within the profile that were dominated by either ground-water recharge or discharge. Deeper water levels with increasing well depth indicate recharge, whereas shallower water levels with increasing depth indicate discharge. Although many closely spaced wells indicated local recharge or discharge, no large-scale flow patterns could be determined using the existing wells.

Detailed investigations of the water table in the Mount Moriah area demonstrated that the water table is continuous with the water surface of potholes (fig. 17; pl. 1). Thus, pothole water levels are excellent data points for construction of a water-table contour map. Studies at pothole C1 (fig. 14) shows that wells which act as piezometers show much variation in vertical gradients, both upward and downward, within a very limited area. With this in mind, a water-table contour map was constructed for the Goldwin SE 7½-minute quadrangle. Pothole water surfaces were used for control points (pl. 2). Shallow wells in the quadrangle fit within the contours but, in general, the deeper wells do not. No consistent pattern of recharge or discharge is apparent from the scattered wells. Although water levels in most of the deeper wells are substantially below land surface, some of the deeper wells flow. As a result, establishing regional flow relationships is difficult because the extreme local variations mask them.

Water-budget studies by Shjeflo (1968, p. B42) show that seepage rates vary significantly among prairie potholes in North Dakota. Average June-to-October outflow seepage during the period from 1960 to 1964 ranged from 0.0008 to 0.0088 foot per day in 10 study potholes. This tenfold difference in seepage occurred within a limited range of semipermanent and seasonal potholes. Observations of pothole water levels in several study areas in Stutsman County indicate that outflow seepage rates are much higher in ephemeral and temporary potholes. A seepage rate of 0.5 foot per day was observed in an ephemeral pothole pond in the NW¼ sec. 12, T. 142 N., R. 68 W., during the period April 11–16, 1969. Conversely, net inflow seepage of 0.003 foot per day was determined in Lake Alkaline, a saline lake in southwestern Stutsman County. A mass-transfer study of Lake Alkaline, in the SW¼ sec. 7, T. 139 N., R.69 W., was made during the period from August 9 to November 1, 1967. Lake Alkaline has an area of about 110 acres and is usually less than 2 feet deep. The specific conductance of the water in the lake ranged from 18,000 to 22,000 μmhos/cm during the period. Water from a spring discharging into the southwest corner of the lake had a specific conductance of about 1,000 μmhos/cm, and several seepage areas (fig. 18) are marked by dense colonies of hard-stem bulrush, cattails, and phragmites. Such flora indicates water of much less salinity than that in the lake.

Instruments for determination of evapotranspiration and seepage (fig. 19) were the same as described by Shjeflo (1968, p. B6). The study established that the seepage inflow is 0.00318 foot per day, a discharge to the pothole of about 80 gpm (gallons per minute).

It is likely that all intermittent and permanent saline lakes, and some brackish-to-saline semipermanent potholes, have net inflow seepage. In spite of the limited data pertaining to seepage, it is apparent that a wide range of seepage conditions prevails in the prairie-pothole region.

Potholes in till must depend almost totally on inflow from surficial processes, and thus their water

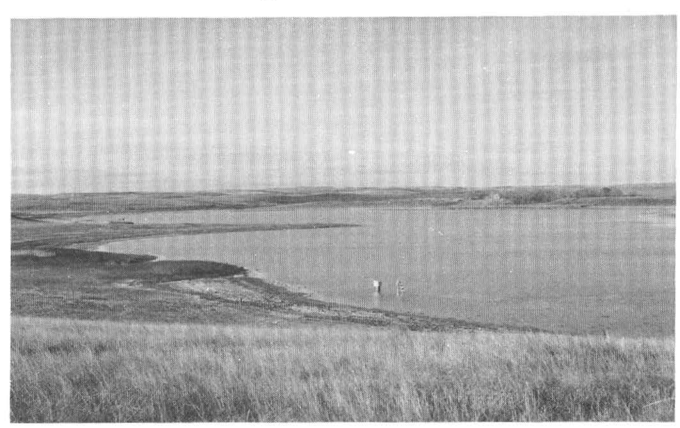


FIGURE 18.—A colony of hard-stem bulrush and phragmies (dark areas at left side of photograph) marking a seepage zone to Lake Alkaline.

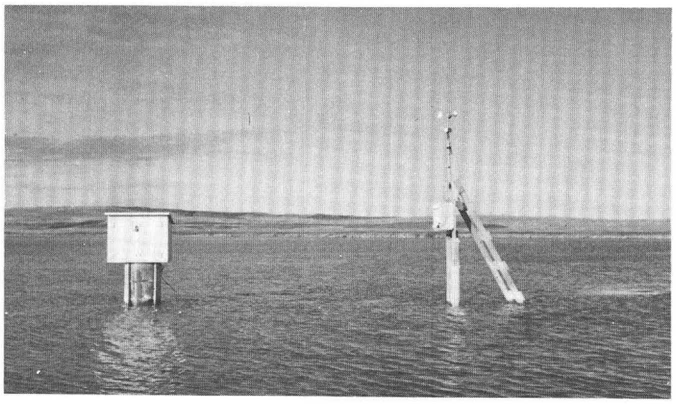


FIGURE 19.—Shelters and instruments for measuring and recording wind speed, water temperature, lake stage, and precipitation at Lake Alkaline.

levels are very dynamic and related closely to rainfall and runoff events. Ground-water seepage into the potholes does not usually occur at rapid rates and is not as quantitatively significant as surficial (precipitation and runoff) processes of water supply. However, ground-water flow systems provide the regulating system for seepage inflow or outflow and thus determine the salinity and, to a lesser extent, the permanence of potholes.

The rate of ground-water movement in glacial outwash is high compared with that in till because the outwash is more permeable. Ground-water flow tends to be more nearly horizontal, and through-flow conditions exist in most potholes in glacial outwash. Owing to the through flow in outwash potholes, the salinity of downgradient potholes is affected by those upgradient. Thus, where a chain of lakes occurs in an outwash channel, there is an inverse relationship between the altitude and salinity of potholes (fig. 20). Potholes in glacial outwash generally have more stable water levels than potholes in till because the ground-water reservoir acts as a regulator on water levels.

Ground-water discharge commonly prevails in areas of glacial outwash because of its low topographic position. As a result, saline potholes and lakes commonly occur in areas of glacial outwash.

QUALITY OF WATER

Water quality in prairie potholes in North Dakota varies with both time and place. Owing to shallow depth and wind action, there is little stratification in ponds from temperature or salinity so that the water quality within a pothole is generally uniform throughout. Exceptions to this include zones of ground-water inflow and stratification that result from freezing and thawing processes within the pothole.

The dissolved-solids concentration in a pothole is increased by evapotranspiration. The rate of concentration is determined by the seepage balance. During the winter months, as water in the pothole freezes, dissolved salts are concentrated in the solution at the base of the ice. If freezing continues to the bottom of the pothole, this concentrated layer will exist in the unfrozen bottom sediments (Ficken, 1967). Melting of pothole ice during the spring breakup and runoff from snowmelt usually occur simultaneously, so potholes are freshest in the early spring. Increasing salinity throughout the summer results from both evaporative concentration and diffusion into the pothole of the salts concentrated by freezing in the bottom muds (Ficken, 1967).

Table 5 shows a comparison of specific conductance of ground water and surface water in glacial till and outwash. Figure 20 shows the relationship between altitude and specific conductance for potholes in glacial till and outwash. Within the broad profile shown in figure 3, potholes in outwash generally occur at lower altitudes and are more saline than potholes in till.

TABLE 5.—*Comparison of specific conductance of ground water and surface water in glacial till and outwash*

	Number of samples	Specific conductance (µmhos/cm at 25°C) Range	Mean
Till:			
Ground water	80	300–27,000	1,800
Surface water	100	230–13,000	1,500
Outwash:			
Ground water	50	300– 1,200	500
Surface water	60	300–70,000	9,000

A general observation concerning water quality on the Coteau du Missouri is that water in potholes in glacial till is fresher than ground water in glacial till (table 7). In contrast, ground water in glacial outwash is fresher than water in potholes in glacial outwash. These conditions result because, in general, salinity increases in the direction of water movement. This is substantive evidence that in topographically high glacial till the water moves from the potholes into the ground, whereas ground water in topographically low glacial outwash discharges to the pothole.

Evaporative concentration increases salinity and causes the more insoluble constituents such as calcium carbonate to precipitate. The more soluble constituents such as sodium sulfate become concen-

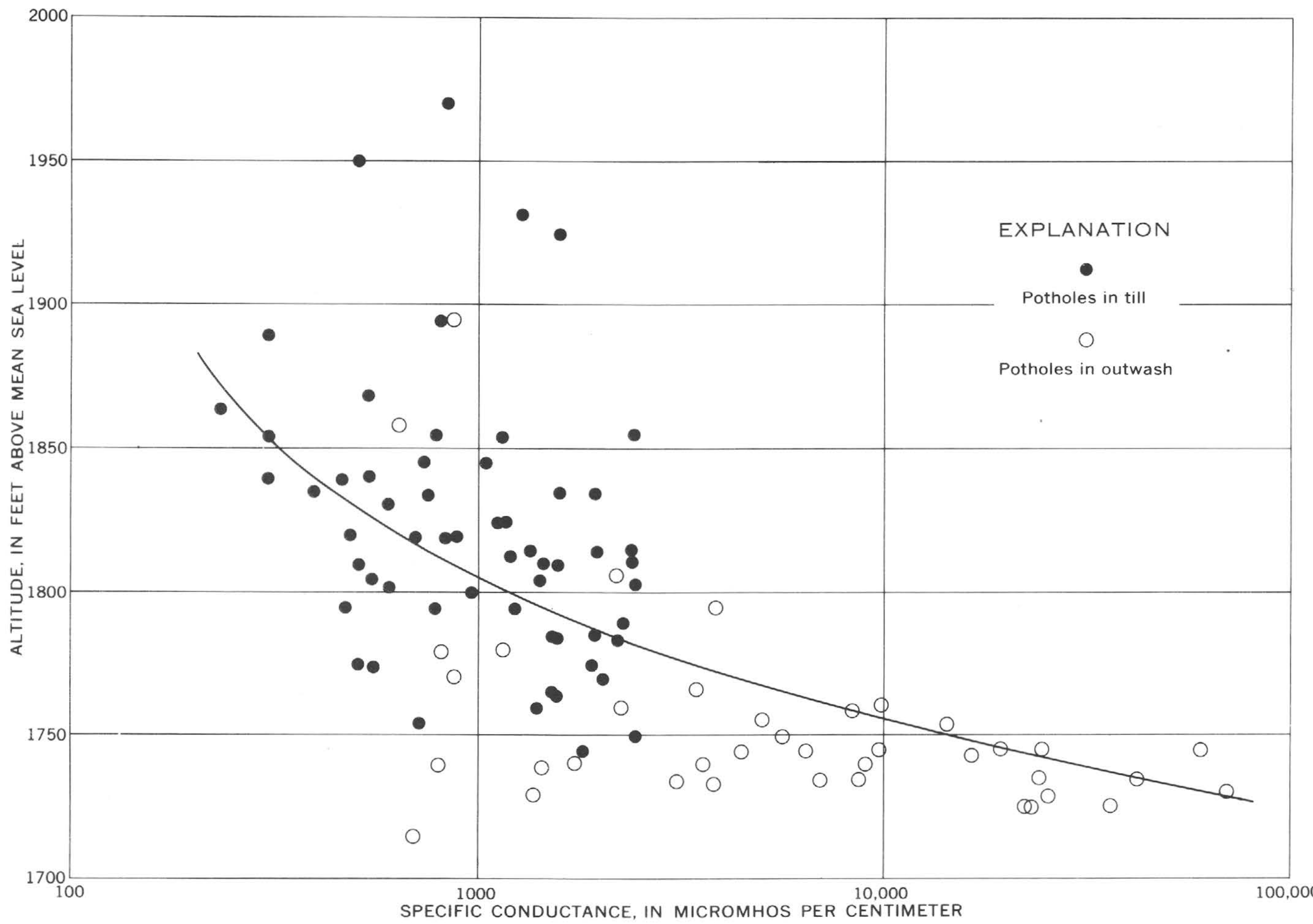


FIGURE 20.—Relation between altitude and specific conductance for potholes in till and in outwash.

trated by evapotranspiration. The natural sequence of waters in the pothole environment, from fresh to saline, is from waters rich in calcium bicarbonate through those that are rich in magnesium bicarbonate to waters rich in calcium sulfate and magnesium sulfate. The most saline waters are enriched in sodium sulfate.

Binyon (1952) observes that sodium sulfate deposits exist in closed depressions that contain seeps and springs marked by plant growth (fig. 21). He also notes that, within a group of lakes, a saline lake may be close to others that are fresh or only slightly saline. A lake containing concentrated brines is usually at a lower altitude than others in a group. The general factors common to sodium sulfate deposits are those of aridity and topography. The sodium sulfate deposits generally crystallize as mirabilite, which is $Na_2SO_4 \cdot 10H_2O$. When exposed to the air, as at the margins of the lake, the mirabilite effloresces and collapses to a white powdery anhydrous sodium sulfate called thenardite. Sodium sulfate occurs in undrained basins, usually in sandy or gravelly areas. In nearly all deposits, seeps are evident and artesian waters are commonly obtained near them.

The occurrence of sodium sulfate deposits in playa lakes in parts of North Dakota, Montana, and neighboring Canadian provinces has been explained in a variety of ways. Many observations about the occurrence of the salts are valid, but interpretations of their genesis have generally been needlessly complex and unsubstantiated by the observed facts. Most theories for the accumulation of sodium sulfate salts in North Dakota require a bedrock source of highly charged brines or saline water.

Grossman (1968) indicates that the deposits were derived from deeply buried evaporites in the Prairie Formation of Devonian Age; deeply circu-

FIGURE 21.—Springs, marked by vegetation, discharging to Spring Lake, a playa near Tappen in the Kidder County outwash plain.

lating ground water from the Rocky Mountains dissolved the evaporites and moved upward along fractures into large lakes in the Pleistocene deposits. Freezing segregated pure crystals of sodium sulfate that accumulated in meromictic lakes, and the residual brines, discharged into streams, drained southward into the Missouri River system. Rising temperatures and increasing aridity gradually disintegrated the drainage pattern in an area where the deposits are preserved beneath extinct or shrunken lakes.

Lemke (1960) stated that shallower bedrock, principally the Tongue River Member of the Fort Union Formation, is the source of the sulfate-rich water. Such theories ignore the abundant source of available salts in the drift surrounding the potholes. The drift is largely derived from, and differs little from, the underlying bedrock. Gypsum ($CaSO_4$) and pyrite (FeS_2) are abundant in the Pierre Shale and overlying Cretaceous and Tertiary rocks. These soluble constituents are leached by ground water and are discharged at only moderately concentrated levels into closed basins. There, sodium-sulfate-rich deposits form as a result of evaporation.

The occurrence of fresh potholes adjacent to saline ones is explained by their relative altitudes and the effect of water-table position on ground-water flow. Ground water flows from higher to lower potholes, particularly in glacial outwash where there is good hydraulic connection.

Specific conductance of lake water in glacial-outwash channels is inversely related to the altitude of the water surface of the lakes. Measurements of water-surface altitude and specific conductance were made at the Nelson-Carlson Lakes (fig. 22) near Douglas in southwestern Ward County on August 8, 1966. The Nelson-Carlson Lakes occupy a

FIGURE 22.—Nelson-Carlson Lakes near Douglas in Ward County. The lakes are identified by the letters A–E referred to in table 6.

glacial melt-water channel that is filled with glaciofluvial and lake sediments. A test hole in the melt-water channel (sec. 6, T. 151 N., R. 84 W.) penetrated 73 feet of sand and gravel before entering glacial till. Two other test holes in the melt-water channel (sec. 35, T. 152 N., R. 85 W.) penetrated about 20 feet of sandy and "lake" clays and 48 feet of sand and gravel before entering glacial till. The two closely spaced holes were cased with 1½-inch plastic pipe that was perforated at depths of 65 and 108 feet, respectively. The water level in the shallower well was 0.97 foot higher than that in the deeper well. A slight downward gradient of 0.0226 foot per foot exists at these wells.

The relation between altitude and specific conductance is shown in table 6. Relatively low specific conductance of water in the observation wells indicates that vertical flow is not appreciable. That there is inflow to the channel from the uplands on both sides is indicated by seepage zones on the lakesides marked by dense colonies of hard-stem bulrush and cattail.

A number of springs in Stutsman and Kidder Counties, and the lakes into which they discharge, were sampled in July 1967 for chemical analysis of water quality. Table 7 shows the degree of concentration effected by evapotranspiration of the lake waters. In the Crystal Springs area, a chain of

TABLE 6.—*Relation between the altitude and specific conductance of Nelson-Carlson Lakes in glacial outwash*

Lake (fig. 22)	Relative altitude (ft)	Specific conductance (μmhos/cm)
A	103.11	1,200
B	100.74	2,170
C	100.00	21,400
D	99.96	25,200
E	94.93	42,500

TABLE 7.—*Chemical analyses of spring and lake waters in Stutsman and Kidder Counties*

[Concentrations of dissolved constituents, dissolved solids, and hardness given in milligrams per liter]

Sampling site	Date of collection (1967)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Flouride (F)	Nitrate (NO_3)	Baron (B)	Dissolved solids (calculated)	Hardness as $CaCO_3$	Noncarbonate harness as $CaCO_3$	Sodium-adsorption-ratio	Specific conductance (µmhos/cm at 25°C)	pH
Spring at lake in SE¼ sec. 17, T. 139 N., R. 69 W	**July 20**	**24**	**78**	28	14	7.7	227	0	92	7.9	0.3	6.0	0.05	392	302	75	0.4	624	7.8
Lake in SE¼NW¼ sec. 17, T. 139 N., R. 69 W	do	10.0	30	725	2,100	325	691	29	5,750	905	.2	3.3	2.8	10,200	3,040	2,430	16	11,400	8.4
Spring at East Chokecherry Lake in SW¼NE¼ sec. 21, T. 139 N., R. 69 W	do	28	130	30	153	12	485	0	337	52	.3	0	.47	998	480	82	3.0	1,450	8.0
East Chokecherry Lake in SW¼NE¼ sec. 21, T. 139 N., R. 69 W	do	20	200	6,050	104,000	2,640	1,760	0	226,000	12,900	.3	1.3	66	352,000	19,900	18,800	250	111,000	7.7
Spring at Tweedy Lake in SE¼NW¼ sec. 24, T. 139 N., R. 69 W	**July 21**	**40**	**100**	**37**	24	24	427	0	80	19	.3	21	.09	555	402	52	.5	846	8.2
Tweedy Lake in SE¼NW¼ sec. 24, T. 139 N., R. 69 W	do	6.1	22	570	1,890	265	560	66	3,920	1,440	.1	.1	3.1	8,450	2,390	1,820	17	10,600	8.7
Spring at Widgeon Lake in SW¼NE¼ sec. 25, T. 139 N., R. 69 W	do	28	145	30	280	14	479	0	468	148	.4	3.3	1.0	1,350	486	93	5.5	1,980	8.1
Widgeon Lake in SW¼NE¼ sec. 25, T. 139 N., R. 69 W	do	10	120	170	636	90	373	0	1,500	413	.4	.5	2.1	3,120	998	692	8.7	4,480	8.0
Crystal Springs (north) in SW¼SE¼ sec. 1, T. 139 N., R. 70 W	**July 28**	**28**	**90**	**27**	**11**	4.5	345	0	77	4.1	.3	0	.04	412	336	53	.3	656	8.1
Crystal Springs (south) in NW¼NE¼ sec. 12, T. 139 N., R. 70 W	July 21	28	135	38	34	9.2	467	0	173	7.3	.3	0	.15	655	493	110	.7	982	8.1
Crystal Springs Lake in SE¼SE¼ sec. 1, T. 139 N., R. 70 W	do	35	55	81	72	19	376	8	288	20	.4	.7	.41	774	470	149	1.4	1,170	8.4
Middle Lake at Crystal Springs in SW¼SE¼ sec. 6, T. 139 N., R. 69 W	do	3.7	11	298	852	115	373	79	2,190	310	.2	1.1	1.5	4,000	1,250	812	10	5,470	9.0
Stink Lake at Crystal Springs in W½ sec. 5, T. 139 N., R. 69 W	do	3.4	95	3,800	20,900	1,860	1,020	0	48,200	8,180	.2	3.0	15	83,500	14,800	14,000	70	64,200	8.2
Spring at Lake Alkaline in NE¼NE¼ sec. 13, T. 139 N., R. 70 W	do	30	125	36	72	8.1	458	0	204	22	.3	0	.32	723	460	84	1.4	1,080	8.1
Lake Alkaline in NE¼NE¼ sec. 13, T. 139 N., R. 70 W	do	5.7	30	1,180	4,520	405	429	138	11,500	1,680	.1	.2	8.2	19,600	4,850	4,280	28	20,300	8.9
Spring at Salt Alkaline Lake in SE¼NW¼ sec. 16, T. 140 N., R. 70 W	**July 26**	**66**	**160**	**76**	299	16	797	0	468	176	.4	.5	.86	1,650	712	58	4.9	2,380	8.2
Pothole pond at Salt Alkaline Spring in SE¼NW¼ sec. 16, T. 140 N. R. 70 W	do	18	729	2,700	4,540	510	355	0	17,900	2,590	.1	.4	6.2	29,200	12,600	12,300	17	25,900	7.8

TABLE 7.—*Chemical analyses of spring and lake waters in Stutsman and Kidder Counties*—Continued

Sampling site	Date of collection (1967)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Flouride (F)	Nitrate (NO_3)	Baron (B)	Dissolved solids (calculated)	Hardness as $CaCO_3$	Noncarbonate harness as $CaCO_3$	Sodium-adsorption-ratio	Specific conductance (µmhos/cm at 25°C)	pH
Spring in middle of Spring Lake in SE¼NE¼ sec. 6, T. 140 N., R. 71 W	July 26	26	95	35	96	10	539	13	116	7.3	0.4	2.7	0.26	667	381	0	2.1	1,020	8.4
Spring at Stony Lake in NE¼-NW¼ sec. 17, T. 140 N., R. 71 W	-- do --	28	75	22	29	5.3	329	0	70	4.8	.3	0	.06	396	278	8	.8	628	8.2
Stony Lake in NE¼NW¼ sec. 17, T. 140 N., R. 71 W	-- do --	8.0	12	520	2,760	390	1,250	265	6,150	569	.1	.8	6.2	11,300	2,150	690	26	12,900	8.9
Spring at Pass Lake in SW¼-SE¼ sec. 30, T. 140 N., R. 71 W	-- do --	36	108	37	41	12	434	0	157	5.4	.4	.3	.18	610	422	66	.9	905	8.1
Pass Lake in SW¼SE¼ sec. 30, T, 140 N., R. 71 W	-- do --	1.3	32	760	3,300	440	347	158	8,750	640	.1	.2	4.2	14,200	3,170	2,630	25	14,900	9.2
Bird Lake in N½ sec. 32, T. 141 N., R. 71 W.	-- do --	4.3	6.3	315	3,990	335	1,460	268	6,850	1,020	.2	2.8	5.2	13,500	1,300	0	48	15,300	8.9
Mount Moriah Spring in NE¼-SW¼ sec. 16, T. 144 N., R. 67 W	July 20	28	110	37	60	10	437	0	197	4.4	.3	0	.20	662	426	68	1.3	656	8.1

lakes that have seasonal spill shows the increasing concentrations that occur with respect to altitude in closely associated lakes in glacial outwash.

SUMMARY

Ground-water flow systems surrounding prairie potholes influence the salinity and permanence of water in the potholes. Seepage is quantitatively low in glacial till, but ground-water flow in glacial outwash is sufficiently large to act as a stabilizing influence on pothole water levels. Ground-water flow in poorly permeable glacial till is extremely slow. Weathering increases the permeability at and near the surface, and, as a result, the highest flow rates and the most effective flow systems occur locally in the shallow zones marginal to potholes.

The water table is a shallow surface that is continuous with the water surface in prairie potholes. The configuration of the water table surrounding the pothole is quite important in determining the seepage conditions at a pothole. If the water table slopes into a pothole, ground-water discharge prevails, and the water is relatively saline and permanent. If the water table slopes away from the pothole, ground-water recharge occurs, and the pothole is relatively fresh and temporary. In most potholes, the water table slopes into some parts and away from the remainder, resulting in a condition called through flow. Where through flow exists, brackish conditions prevail, and potholes are semipermanent.

Evapotranspiration produces a drawdown zone that fringes most potholes in the summertime. This zone has a great influence on both seepage conditions into or from the pothole and on the distribution of fluid potentials in the surrounding ground-water flow system.

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