Geology and Ground-Water Resources of Nobles County and Part of Jackson County Minnesota

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1749

Prepared in cooperation with the Division of Waters, Minnesota Department of Conservation, and the city of Worthington

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By RALPH F. NORVITCH

ABSTRACT

The area described in this report is in southwestern Minnesota, about 130 miles southwest of Minneapolis and St. Paul. It includes Nobles County and the western tier of townships in Jackson County, a total of 864 square miles. Worthington, the Nobles County seat, is the largest city in the area, having a population of 9,015 persons (1960 census). Farming is the leading occupation, and food processing is the major industry. Critical water shortages have occurred in several parts of the area.

The climate is characterized by mild, subhumid summers and relatively long, severe winters. Mean monthly temperatures range from 15.1°F in January to 73.3°F in July. The mean annual precipitation is 26.75 inches.

The crest of the Coteau des Prairies, a broad highland belt, traverses Nobles County from northwest to southeast. Three glacial end moraines and their associated ground moraines trend south to southeast across the area. Altitudes range from about 1,820 feet on the crest of the coteau in the northwestern part of the area to about 1,390 feet above mean sea level in the Jack and Okabena Creek valleys in the northeast.

The Mississippi-Missouri River drainage divide crosses the area from north to east. The Cary outer end moraine trends southeast through central Nobles County. East of this moraine the land is poorly drained and contains numerous lakes and swamps; west of this moraine the land is well drained and contains few, if any, undrained depressions.

Within the area, granite and Sioux Quartzite of Precambrian age are overlain by Cretaceous strata, except locally in the northeast and northwest parts of the area where the quartzite is directly overlain by glacial drift. The Cretaceous strata are composed of interbedded shale, siltstone, and sandstone. The surface of the area is composed of Pleistocene deposits of glacial drift and some thin, patchy deposits of Recent age. Bedrock is not known to crop out in the area. The drift ranges in thickness from about 150 feet in the southwest and northeast corners to about 500 feet on the highest part of the Coteau des Prairies.

The Precambrian granite is not a source of ground water in this area. The Sioux Quartzite yields moderate supplies in adjacent counties to the north and west, but because of its sporadic occurrence it does not constitute an important water source in this area. The Cretaceous sandstone units are a secondary source of ground water and yield adequate supplies to at least 24 farm wells, which range in depth from 283 to 586 feet below land surface.

The primary source of ground water in the Nobles-Jackson County area is the glacial drift. Buried outwash deposits supply water to 7 of the 10 mu-

nicipalities and to most of the farms in the area. Two Worthington city wells, completed in a buried outwash deposit underlying East Okabena dry lake bed, were tested for short periods at 500 gallons per minute. The estimated coefficient of transmissibility for the aquifer at one of the wells was 70,000 gpd (gallons per day) per ft.

The buried outwash deposits may occur anywhere within the drift from about 15 feet below land surface to bedrock which is as much as 500 feet below land surface. The outwash ranges from a fraction of a foot to more than 25 feet in thickness where permeable; below the water table it generally will supply ample quantities of water to properly constructed wells.

Surficial outwash deposits fill the valley bottoms and form the terrace deposits associated with the present-day drainage channels. The thicker, more extensive, and continuous deposits occur in the proglacial stream channels that drained the fronts of the ice sheets rather than in those channels that now drain the backs of the moraines. The surficial outwash deposits generally are made up of sand, gravel and some silt and clay, and range in thickness from 0 to more than 60 feet; they range in width from a few feet in the narrow tributaries to about one mile in the larger stream valleys.

Four municipalities and many farms obtain part or all of their water supplies from surficial outwash. An Adrian municipal well, completed in this source, was pumped at a rate of 400 gpm. At the confluence of two streams which drain Ocheda Lake in southeastern Nobles County, the sand and gravel section is more than 60 feet thick in places. Results of a pumping test here showed an average coefficient of transmissibility of 150,000 gpd per ft. Coefficients of transmissibility may be as much as 500,000 gdp per ft in the thickest part of the deposit if the permeability of the sand and gravel is uniform.

Recharge to the surficial outwash deposits is relatively rapid; it is slower to the buried outwash deposits where the descending water must percolate through till of low permeability before entering the aquifers.

The quality of water in the Precambrian crystalline rocks, the Cretaceous strata, and the buried Pleistocene aquifers is poor. Chemical analyses of 22 water samples showed that dissolved solids ranged from 1,100 ppm (parts per million) to 3,050 ppm. Water from the surficial outwash deposits is good by comparison; dissolved solids in water from these aquifers ranged from 425 to 870 ppm.

INTRODUCTION

LOCATION AND EXTENT

This report describes an area in southwestern Minnesota, about 130 miles southwest of Minneapolis and St. Paul (fig. 1). Geographically, the area lies between lat 43°30′ and 43°51′ N., and long 95°20′ and 96°03′ W. It includes Nobles County and the western tier of townships in Jackson County; it occupies R. 38 W. through R. 43 W. and T. 101 N. through T. 104 N. The area is a rectangle, 36 miles long and 24 miles wide, and occupies about 864 square miles.

Worthington is the largest city and the Nobles County seat. The Minnesota-Iowa State border is the southern boundary of the area; the west, north, and east boundaries are Rock and Murray Counties, and the remainder of Jackson County, respectively.

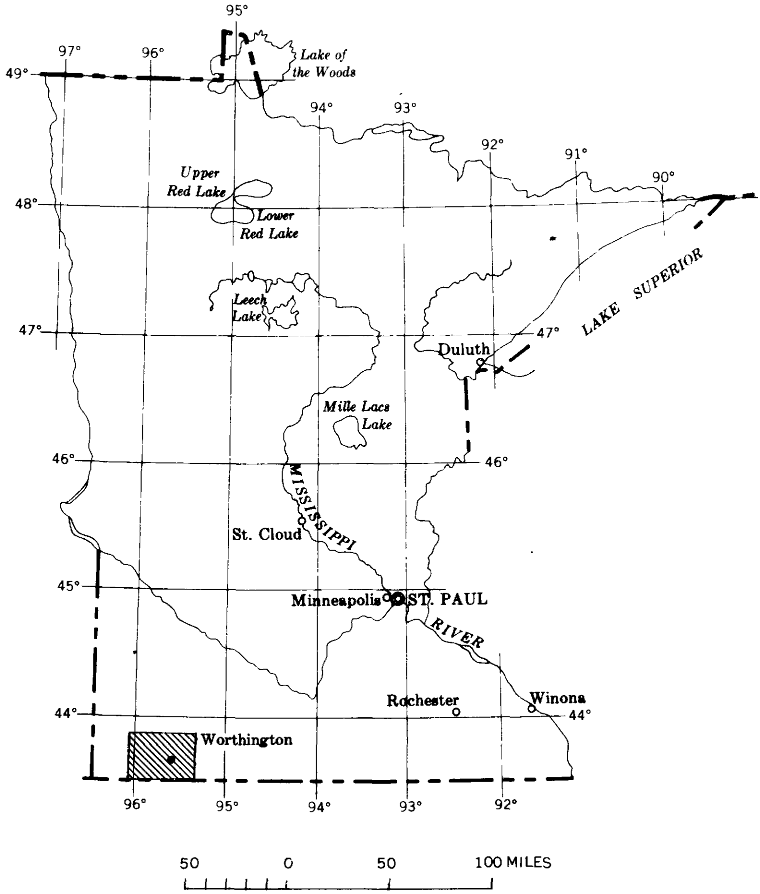

FIGURE 1.—Map of Minnesota showing location of area described by this report.

PURPOSE AND SCOPE

The investigation of ground-water resources in Nobles County and part of Jackson County was made by the United States Geological Survey in cooperation with the Division of Waters, Minnesota Department of Conservation, and the city of Worthington. This investigation is a part of the overall program for evaluating the water resources of the State and of the Country. Problems caused by near-drought conditions in southwestern Minnesota and a critical water shortage in the city of Worthington were factors in starting this investigation. Only by a thorough understanding of the water resources and their environment can water supplies be economically and completely developed.

In many parts of the area, available water and water consumption appear to be near balance. For this study, present water supplies have been evaluated, and areas where unused or little-used aquifers are present have been delineated. The report describes the geology in the area, the occurrence of ground water, the hydraulic characteristics of some of the water-bearing deposits, and the chemical quality of the ground water.

HISTORY AND METHODS OF INVESTIGATION

In the fall of 1955, the city of Worthington drilled 28 test holes and Survey geologists collected geologic data at these sites. Data on municipal water supplies were collected in the area during the winter of 1955–56. In 1956 and 1957, selected wells were inventoried to obtain data on well depths, water levels, construction, adequacy, and use. Where possible, depths of wells and water levels were measured. Some tests of water hardness were made using field-testing methods. During the same period, a reconnaissance was made of the surficial geology, and well drillers were contacted for subsurface geologic information. During the fall of 1956 and spring of 1957, samples were collected from 20 additional test holes drilled by the city of Worthington. As part of a Survey drilling program, two test holes were drilled in the fall of 1956 and 53 were drilled in the summer of 1959. An additional 43 shallow test holes were augered into the surficial outwash channel deposits in October 1959; a truck-mounted auger belonging to the Minnesota Iron Range Resources and Rehabilitation Commission was used.

Observation wells were established at four sites to determine fluctuations of water levels. Continuous water-level recorders were placed on three of these wells and the depth to water in the other was measured periodically. The stage of Okabena Lake was measured weekly after the middle of December 1956.

Geologic mapping was based primarily on the topographic expression of glacial features. Glacial boundaries were plotted in the field on aerial photographs. The surficial stream channel deposits were mapped on high altitude aerial photographs in the office and spot checked in the field.

Altitudes of 72 wells and test holes were determined with an alidade by a member of the Topographic Division of the Geological Survey. Other altitudes were estimated from an unpublished compilation map of the U.S. Army Map Service, Corps of Engineers, having a 50-foot contour interval.

Aquifer properties were determined in part by pumping tests of several municipal wells during which water-level drawdown and recovery measurements were made.

Comprehensive analyses of 22 water samples were made by the Quality of Water Branch of the Geological Survey. The remainder of the chemical data was furnished by the Minnesota Health Department.

ACKNOWLEDGMENTS

Many well owners allowed measurement of their wells and provided information concerning them. Special thanks are given the members of the Worthington City Council, Mr. Gordon S. Thompson, Worthington City Clerk, and Mr. Earl G. Smith, Worthington City Water and Heat Superintendent, for their cooperation.

The following drillers provided well logs and information concerning the drilling conditions in the area: C. E. Scott, M. Nienkerk, C. S. Eisele, E. Munson, and V. Johnson. In addition, Survey personnel were permitted to collect formation samples and run electric logs on selected holes drilled by the following companies: Frederickson Well Co., Hutchinson, Minn.; McCarthy Well Co., St. Paul, Minn.; and Tri-State Drilling Co., Wayzata, Minn.

PREVIOUS REPORTS

The general geology of Nobles and Jackson Counties was first described by Upham (1884). The area was included in Leverett's (1932) regional report on the Quaternary geology of Minnesota and adjacent areas in which the numerous glacial moraines were mapped, classified, and correlated. R. V. Ruhe[1] reclassified and correlated the glacial drifts included in this and adjacent areas.

Regional geology and general ground-water studies that include this area were done by Meinzer (Hall and others, 1911) and Thiel (1944). Both reports presented brief descriptions of the geology, occurrence of water, quality of water, and municipal water-supply data. A study of the Worthington water problem was made in 1955 by the Stanley Engineering Co. of Muscatine, Iowa; a report was compiled in which the present water supply was evaluated, possible future demands were estimated, and the economic aspects were considered in developing possible additional water sources.

WELL-NUMBERING SYSTEM

The system of numbering test holes and wells is based on the U.S. Bureau of Land Management's system of subdivision of the public lands. The area of Nobles and Jackson Counties is in the fifth principal meridian and base line system. The first segment of a

[1] Ruhe, R. V., 1950, Reclassification and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Thesis submitted to Iowa State Univ. for Ph. D. degree.

well or test-hole number indicates the township north of the base line, the second the range west of the principal meridian, and the third the section in which the test hole is situated. The lowercase letters a, b, c, and d, following the section number, locate the well within the section. The first letter denotes the 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract as shown in the diagram below. The letters are assigned in a counterclockwise direction, beginning in the northeast quarter. Within one 10-acre tract, consecutive numbers beginning with 1 are added, as suffixes.

The following sketch (fig. 2) of a township and section indicates the method of numbering a test hole. Thus the number 102.40.25-ccb1 identifies the first well or test hole located in the NW¼SW¼ SW¼ sec. 25, T. 102 N., R. 40 W.

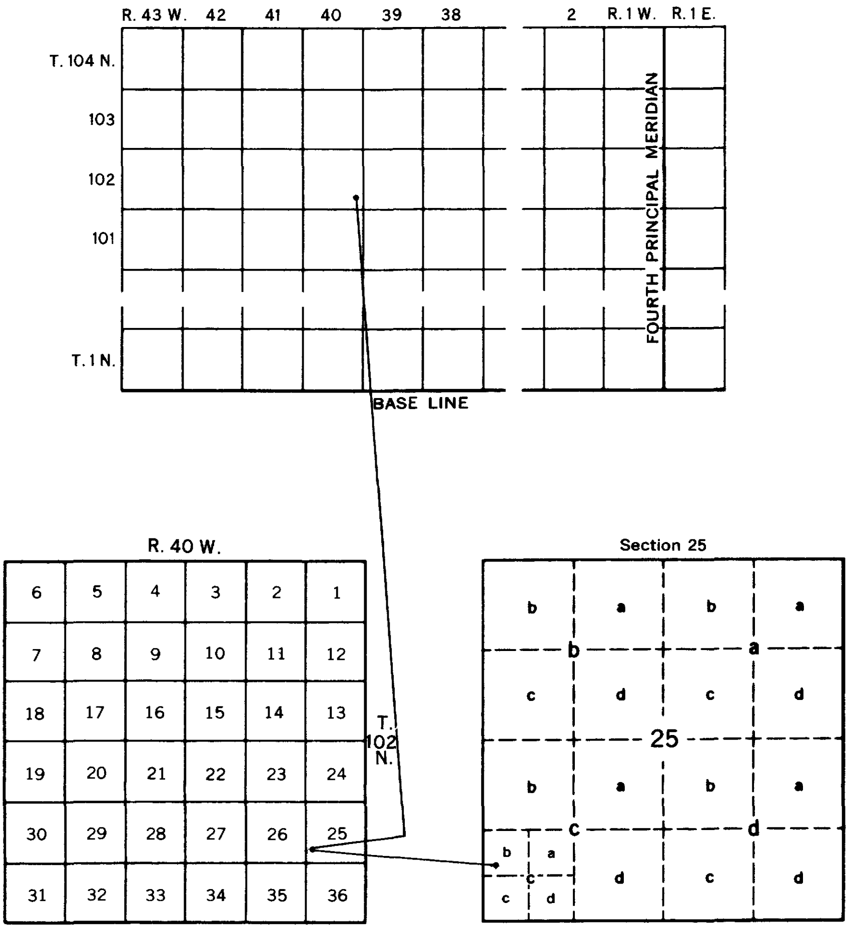

Figure 2.—Sketch showing well-numbering system.

GEOGRAPHY

CULTURE

The population of the area in 1960 was 25,106. Worthington is the largest city, having a population of 9,015 persons (1960 census). The area is served by Minnesota State Highways 60, 91, 264, and 266, and U.S. Highways 59 and 16. Three railroads traverse the area, the Chicago and North Western; the Chicago, Rock Island and Pacific; and the Chicago, Milwaukee, St. Paul and Pacific. North Central Airlines provides scheduled service at the Worthington airport.

Farming is the leading occupation. About 96.6 percent of the land area in Nobles County, or 440,238 acres, is in farms (1954 Census of Agriculture). It is assumed that the percentage of farmland for the part of Jackson County covered in this report is proportional to the Nobles County figure. The major crops are corn, soybeans, flax, oats, barley, alfalfa, and clover. The livestock are principally beef cattle, hogs, sheep, and poultry.

The largest single industry in the area is food processing. The Campbell Soup Co. operates a large canning plant in Worthington.

The Worthington Junior College provides a 2-year curriculum of accredited courses.

CLIMATE

The climate in the Nobles-Jackson County area is characterized by mild, subhumid summers and relatively long, severe winters. Abrupt changes in temperature and precipitation are common and are caused by low and high pressure systems (cyclones and anticyclones) that cross the area from west to east. Mean monthly temperatures (U.S. Weather Bureau, Worthington station) range from 15.1°F in January to 73.3°F in July. The average annual temperature is 45.1°F. The average growing season is about 145 days; the average for the State is 133 days. The number of years in 50 during which killing frost is likely to occur after April 20 is 49, after April 30 is 38, after May 10 is 24, after May 20 is 8, and after May 30 is 0. The number of years in 50 during which killing frost is likely to occur before September 20 is 7, before October 1 is 26, before October 10 is 36, and before October 20 is 44. The mean annual precipitation, including snowfall, is 26.75 inches. The mean ranges from 0.66 inch in January to 5.04 inches in June. The average annual class-A pan evaporation for the period 1946–55 was about 47 inches.

An average of one damaging or excessive rainstorm occurs during the summer season. Crop declines due to drought conditions may be expected about once in every 10 years.

TOPOGRAPHY

Physiographically the area is located in the Central Lowland province of the Interior Plains (Fenneman, 1938, p. 559–605). The part east of the outer border of Cary deposition (pl. 1) is in the Western Young Drift section and the part west of the outer border of Cary deposition is in the Dissected Till Plains section.

According to the topographic map (Army Map Service Fairmont quadrangle), the highest altitude in the area—about 1,820 feet—is 1½ miles northwest of St. Kilian in Nobles County. The lowest altitudes, about 1,390 feet, are in the channels of Okabena Creek and Jack Creek in the northeast part of the area. In the southwest corner of the area, the lowest altitude is about 1,430 feet in the Kanaranzi valley west of Ellsworth.

South- to southeast-trending glacial end and recessional moraines, ground moraines, and melt-water channels are the principal surface features. The Coteau des Prairies is the most prominent topographic feature in the region; it includes all Nobles County. According to Thiel (1944, p. 330), the crest of the coteau crosses the county from northwest to southeast between Worthington and Rushmore. It is a broad belt of highland whose crest trends southeastward from the northwest part of Nobles County and southward from the area between Worthington and Rushmore to the south-central border of the area.

DRAINAGE

The Mississippi-Missouri River drainage divide trends from north to east across the Nobles-Jackson Counties area as shown on Plate 1. Champepedan, Kanaranzi, and Elk Creeks (western Nobles County), Little Rock, Ocheyedan, and Little Sioux Rivers head on the west flank of the divide and drain into the Missouri River. Jack and Elk Creeks (eastern Nobles County), and Okabena Creek head east of the divide and drain into the Mississippi River.

The drainage through upper Okabena Creek northwest of Worthington is diverted in part into Okabena Lake through Whiskey Ditch (fig. 8), which was constructed in 1897 to maintain a stable lake level. The regular flow is to Heron Lake, about 2½ miles due east of where Jack Creek crosses the east boundary of the area.

The area west of the outer border of Cary deposition (pl. 1) is well drained, having few undrained depressions. The area east of this border is poorly drained and contains numerous lakes and swamps. The larger lakes in the area are Okabena and Ocheda Lakes in southeast Nobles County, East and West Graham Lakes in northeast Nobles County, and Round Lake in southwest Jackson County.

The drainage patterns of the streams are either rectangular or dendritic. Jack, Elk, and Okabena Creeks in the northeast part of the area have a rectangular pattern developed where the streams parallel the fronts of minor recessional ridges formed by the last waning ice sheet. Where Champepedan Creek flows through the Tazewell drift section, the tributaries also join the trunk stream at almost right angles. The remaining streams in the area are dendritic in pattern except perhaps in the upper reaches of Kanaranzi Creek where the tributaries emanating from the end moraine join the trunk stream at almost right angles.

Flow data are not available for any of the streams in this area. Probably during prolonged arid periods most of the streams go dry except perhaps the reach of Kanaranzi Creek south of U.S. Highway 16. Springs in this reach probably maintain base flow.

GEOLOGIC HISTORY

The granitic basement rocks and the quartzite in the Nobles-Jackson Counties area were formed during earliest geologic time, the Precambrian. Because of the thick drift cover, little is known about Precambrian history in southwestern Minnesota; however, in northern Minnesota the time was one of much igneous activity: lava was deposited under water and upon the surface, magmas intruded preexisting rocks, and a tremendous granitic mountain range (Giants Range) was formed. Part of the region was covered by seas in which sedimentary rocks, including the iron deposits on the Mesabi Range were deposited. Many of the rocks were metamorphosed by intense temperature and pressure as were those in contact with the Duluth Gabbro in the area west and northwest of Lake Superior. In southwestern Minnesota, after the formation of the granitic rocks, deformational forces must have been slight, for there has been very little subsequent change in the primary structure of the Sioux Quartzite since it was deposited.

In the report area, as in all southwestern Minnesota, no geologic formations represent the time between the close of the Precambrian and the beginning of the Cretaceous Period, roughly 400 million years. The hiatus may have been caused by a combination of periods of deposition and subsequent erosion or by a period of nondeposition. Large relief on the surface of the Sioux Quartzite indicates that deep valleys and buttes were carved by erosion sometime before deposition of the Cretaceous rocks.

The Cretaceous Period was characterized by repeated transgressions and regressions of inland seas in which sandstone and shale were deposited. Limestone was deposited locally but has not been found in the report area. The sediments were laid down in the valleys and other low areas cut into the underlying quartzite.

Another hiatus is present between the Cretaceous and Pleistocene deposits. The Pleistocene Epoch was marked by several advances and retreats of glaciers that covered most of Minnesota. Some drainage patterns were changed or completely obliterated, and others were little changed. Since the retreat of the last ice sheet, the topography has changed very little. Postglacial deposition has been confined mostly to lake and swamp deposits and to stream flood plains.

THE GEOLOGIC UNITS AND THEIR WATER-BEARING CHARACTERISTICS

The rocks underlying the Nobles-Jackson Counties area are of Precambrian, Cretaceous, Pleistocene, and Recent age. There are no outcrops of Precambrian or Cretaceous rocks in the area. The surface is composed of Pleistocene and Recent deposits. Plate 1 shows the surficial geology of the area, and table 1 briefly describes the geologic units and their water-bearing characteristics. The glacial morainal boundaries shown on plate 1 are modified from those mapped by Leverett and Sardeson (1932, pl. 2).

Meinzer (Hall and others, 1911, p. 286) suggests that Paleozoic rocks may underlie the area; however, there is no positive evidence of this.

PRECAMBRIAN

GRANITE

Granite was penetrated at an altitude of about 865 feet by two test holes in sections 23 and 24, T. 102 N., R. 40 W., where it immediately underlies Cretaceous sandstone and shale. The log of the test hole in section 24 suggests that the upper few feet of the granite may be weathered.

Logs of two test holes, one at Sibley, Iowa, about 8 miles south of Nobles County, and the other at the U.S. Air Force Chandler radar base about 3½ miles north of Nobles County on State Highway 91 penetrated Precambrian rock. The test hole at Sibley penetrated 8 feet of Precambrian rock (presumed to be granite) at an altitude of about 760 feet, immediately below Cretaceous sandstone, and the Chandler test hole penetrated gray granite at an altitude of about 690 feet. These two holes indicate that granite may underlie the Cretaceous in a large part of the area.

A geologic age more specific than Precambrian has not been determined for the granite in this area. Exposures of granite dated as

TABLE 1.—*Description and water-bearing characteristics of geologic units in the Nobles-Jackson Counties area, Minnesota*

System	Geologic unit	Thickness (feet)	Description	Water-bearing characteristics
Quaternary	Recent deposits	?	Clay, silt, sand, gravel, and peat. Recent deposits are not differentiated from underlying Pleistocene stream and lake deposits.	Undetermined.
	Pleistocene deposits	0-6±	Loess; windblown silt, buff to brown.	Not considered water bearing.
		0-7±	Minor deposits (include lake deposits of sand, silt, and clay) and interglacial deposits of brown and dark-gray clay considered to be buried soil zones.	Small yields obtainable locally from lake sands.
		0-60±	Outwash, poorly to well-sorted clay, silt, sand, gravel, and boulders. Occurs surficially as kames, terrace fill, and valley-bottom fill; in subsurface as isolated bodies of limited extent.	Small to large yields obtainable depending on grain size, degree of sorting, and extent of deposit. Major ground-water source in this area.
		500±	Till, unsorted, heterogeneous mixture of silt to boulder-size grains in clayey matrix. Buff in oxidized portions; various shades of gray in unoxidized portions. Calcareous throughout except in minor upper parts of oxidized zones where leaching has occurred.	Poor source of supply; very small yields obtainable locally from sandy layers.
Cretaceous	Shale	150±	Shale, but mostly gray and black; some pinkish-tan clay and siltstone; calcareous and noncalcareous; contains pyritiferous, lignitic, and gypsiferous zones.	Shale does not yield water. Very small yields obtainable locally from siltstone.
	Sandstone	275±	Sandstone, gray and tan, interbedded with shale and siltstone; drills as if partly cemented; predominantly fine-grained angular to well-rounded quartz grains.	Adequate yields for farms from deep wells; little information available.
Precambrian	Sioux Quartzite	1,060±	Quartzite, massive; gray in leached upper parts; pink, red, and violet at depth; contains shaley (catlinite) beds, conglomerate units, and loose sand zones.	Insufficient data for this area. Wells penetrating quartzite in counties west and north obtain small to moderate yields from fractures and loose sand zones.
	Granite	?	Crystalline basement rock------	No data.

Huronian or late pre-Huronian (Lund, 1956, p. 1476) occur 50 to 110 miles north of the area, in the Minnesota River valley between Ortonville and New Ulm. Several smaller masses have been dated as Keweenawan (middle Precambrian). Although there is no direct correlation of the Nobles County granite with the Minnesota valley granites, they are probably of the same granite series.

SIOUX QUARTZITE

The Sioux Quartzite lies directly beneath the drift near Kimbrae in the northeast part of Nobles County and in the vicinity of Lismore in the northwest part. (See fig. 4.) It reportedly underlies Cretaceous sediments at Ellsworth in the southwest part of Nobles County. The municipal well at Fulda, 1½ miles north of Nobles County, was reported to have penetrated 1,064 feet of Sioux Quartzite; granite was not penetrated.

The quartzite surface ranges in altitude from approximately 1,170 feet in the southwest part of the area to approximately 1,415 feet in the northeast part. A well in Lismore reportedly penetrated quartzite at an altitude of about 1,330 feet. Deep test holes at Worthington drilled through the Cretaceous formations directly into granite show that the quartzite is discontinuous in the central part of the area.

Detailed information on the Sioux Quartzite in the Nobles-Jackson County area is not available. However, the lithology of quartzite in other areas nearby is similar to that in the report area. The the most complete descriptions of quartzite in nearby areas are for the Corson area, South Dakota (about 26 miles west of the Nobles County border) by Beyer (1896); for Pipestone, Minn. (17 miles northwest of Nobles County), by Thiel (1944); and for eastern South Dakota in general by Baldwin (1949).

Pebble conglomerate and thin red shale (catlinite) are interbedded with the quartzite and can be seen in outcrops. Quartzite and the pebble conglomerate crop out in the SE¼ sec. 26, T. 104 N., R. 45 W., in Rock County, Minn. Red shale is exposed in the quarries in the SW¼ sec. 1, T. 106 N., R. 46 W., in Pipestone County, Minn.

The Fulda well has penetrated more quartzite than any other well in the State. Irving (1885, p. 200) estimates the full thickness of the quartzite to be 5,000 to 6,000 feet. Beyer (1896, p. 79) believes 1,500 feet a very liberal estimate.

Grout and others (1951, p. 1,051) have tentatively placed the age of the Sioux Quartzite between the Animikie Group and the Keweenawan Series in the Precambrian.

WATER-BEARING CHARACTERISTICS

None of the wells inventoried in this area obtained water from the granite. Unaltered granite is a compact, massive rock containing few, if any, interconnected pore spaces. Cracks and fissures in the upper part of the rock may contain some water; however, chances of tapping these openings are poor. Supplies of ground water are obtained from weathered zones of granite in some areas, but data on the extent and thickness of the weathered zone in the report area were not obtained.

In many parts of southwestern Minnesota, northwestern Iowa, and eastern South Dakota, small to moderate supplies of ground water are obtained from fractures and loose sand zones in the Sioux Quartzite. In the Nobles-Jackson Counties area a few farm wells reportedly are completed in the upper part of the quartzite, but it is not known how much of their yield is derived from this zone. The municipal well at Fulda, which obtains water from the quartzite, initially yielded 175 gpm.

Drillers have reported that after penetrating dense quartzite they have, on occasion, intercepted unconsolidated zones of sand. Baldwin (1949, p. 5), in a study of the Sioux Quartzite in eastern South Dakota, reports the following:

> * * * In some exposures and quarries it will be noted that the silica cement is not present. In such cases one can rub off the sand grains and rarely one can find patches where all the cement is gone and the sand is loose * * *. The absence of cement is probably due to weathering processes, which have locally removed the silica cement. In some cases it may be due to nondeposition of the cement * * *. By and large, the leaching and removal of cement is restricted to the walls of the joints or cracks in the rock, where surface water has seeped through and been channelized. It is not known to what extent the cement has been leached below the surface.

Theil (1944, p. 398) has written the following on water yield from the Sioux Quartzite in Rock County:

> * * * The yield of water from the quartzite depends upon the number and size of joints and the degree of cementation. Generally the joints or crevices are small and the beds are only slightly pervious. It is therefore necessary to drill relatively deep to bring the well in contact with many water-bearing openings and thus obtain an adequate supply. Furthermore, the increase in yield with depth appears to be in more than direct ratio. In some cases doubling the depth has increased the yield tenfold. There seem to be more porous beds at greater depth, and also the pressure with which the water enters the well increases with depth, thus increasing the yield.

The cost of drilling this hard rock formation is more than that for drilling softer formations; however, installation and maintenance costs are less because the wells generally are uncased through the quartzite and screens are virtually unnecessary.

It is not likely that a suitable water supply can be obtained from the granite, for crevices are uncommon near the surface and generally are not present at depth.

Because of the great depth and low permeability of the granite and the sporadic occurrence of the Sioux Quartzite, the Precambrian rocks are not considered a good source for future well development in this area.

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CRETACEOUS

Cretaceous rocks underlie the glacial drift in the Nobles-Jackson County area except locally in the northeast and northwest parts of Nobles County where Sioux Quartzite is in direct contact with the overlying drift. The Cretaceous rocks are composed largely of sandstone and shale but also contain siltstone and clay.

Few attempts have been made to correlate the Cretaceous sediments in this area with those in adjacent States. Meinzer (Hall and others, 1911, p. 286) has written the following description of the Cretaceous deposits near Nobles County:

> * * * Along Big Sioux River, northward from Sioux City, Iowa, there is a succession of exposures which together give roughly the following section, the total thickness of which amounts to several hundred feet:
>
> 4. Blue shale
> 3. Argillaceous limestone and chalk
> 2. Blue shale
> 1. Sandstone (buff to white)
>
> These rocks are Upper Cretaceous in age, as has been proved by abundant fossil evidence. No. 1 is referred to the Dakota sandstone and nos. 2, 3, and 4 to the Benton group. The nearest outcrop is about 30 miles southwest of this [Nobles] county.

SANDSTONE

The nature of the Cretaceous sandstone in this area is inferred from a few drill samples, electric logs, and observations of drilling action. The sandstone is apparently loosely cemented, interbedded with shale and siltstone, buff to gray colored, and made up largely of rounded to angular fine to medium quartz grains. Its contact with the overlying shale is easily detected on electric logs of test holes penetrating the formations.

Figure 3 shows histograms of grain sizes in three sand samples collected from different drill holes in Nobles County. A mechanical sieve analysis was run on each of the samples. The histograms show a wide range in grain-size distribution of the sand grains at the different localities. The percentages at the fine end of the scales are probably less than the actual percentages in the sandstone because the sand samples were collected from deep drill holes and, therefore, were subjected to some washing action. The larger percentage of coarse sand in the sample from well 104.41.36dcc1 may be due to a near-shore facies of deposition marginal to the Sioux Quartzite upland (subsurface) northeast of this well.

SHALE

A shale section ranging in thickness from 0 to about 150 feet overlies the sandstone in much of the Cretaceous area. Drill samples show that the shale is not highly indurated but has the consistency

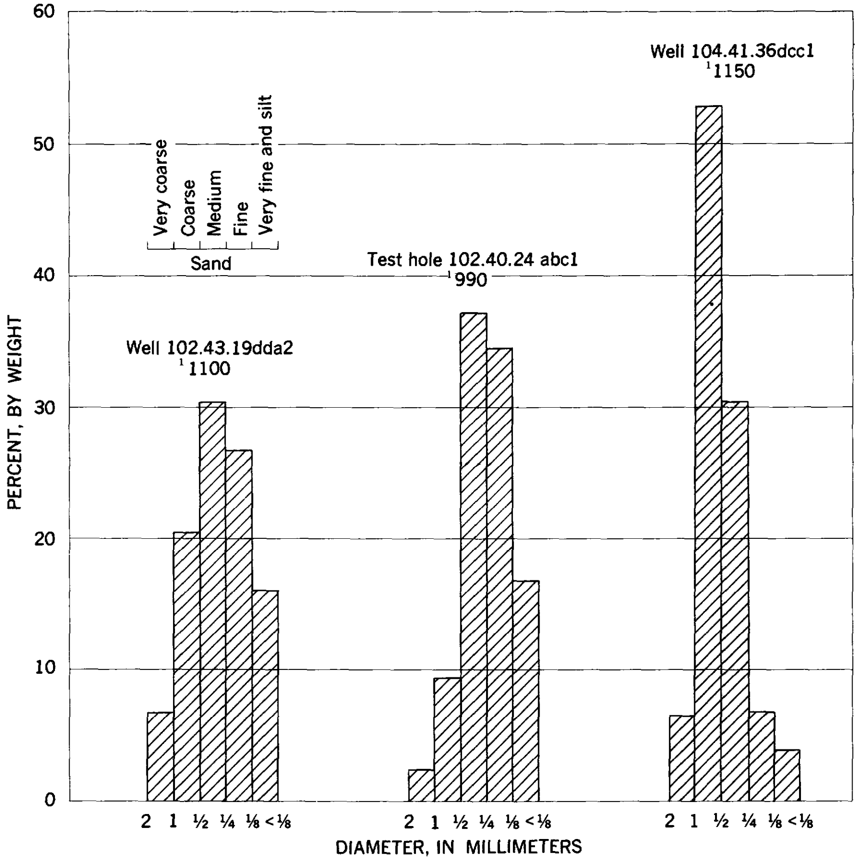

FIGURE 3.—Histograms for sandstone units of Cretaceous age, Nobles County. Numbers under well and test hole numbers indicate approximate altitude, in feet, of sandstone sample.

of a well-compacted clay. It ranges from pinkish-tan, at its top, to various shades of gray and black. Locally it may contain interbedded buff and gray siltstone. Macroscopic mineral constituents include pyrite, lignite, and some gypsum.

Subsurface contacts between the Cretaceous shale and the overlying drift are difficult to determine because of their lithologic similarities. The occurrence of a pinkish-tan clay (shale?) and gray clay mixture in drill samples from test hole 102.40.24abc1 (table 6) is believed to be the drift-shale contact. The top of the clay is at an altitude of about 1,245 feet. A similar occurrence of pinkish-tan clay was noted in test holes 101.40.28aab1, 101.40.33bcc1, 102.40.13aaa1, and 104.39.32dac1. The clay was penetrated at altitudes of 1,222, 1,260, 1.247, and 1,285 feet, respectively. Well 102.43.19dda2 entered gray shale directly below the drift at an altitude of about 1,265 feet.

Meinzer (Hall and others, 1911, p. 287) reports that a private well drilled in the village of Adrian penetrated green clay without grit between depths of 260 and 380 feet. The top of this clay is at an altitude of about 1,280 feet, which corresponds to the above-mentioned altitudes. Similarly, the log of the railway well at Ellsworth (Wilder, 1899, p. 108) shows blue soapstone (shale) at a depth of 190 feet (alt about 1,260 ft) to 240 feet. The meager data available show that the Cretaceous surface ranges in altitude from about 1,222 feet in test hole 101.40.28aab1 to 1,285 feet in test hole 104.39.32dac1, a regional relief of 63 feet. This range is typical of shallow-sea deposition or the relief developed by a long period of post-Cretaceous erosion.

WATER-BEARING CHARACTERISTICS

Twenty-four farm wells in this area are completed in Cretaceous rocks at altitudes ranging from about 1,070 to about 1,205 feet, and they range in depth from 283 to 586 feet. Most of these wells yield 3 to 10 gpm. The water is highly mineralized and has a high iron content. None of the wells was reported to be inadequate owing to water-level declines.

The city well of Sibley, Iowa (6 miles south of Nobles County), is 750 feet deep (about 765 ft in alt) and is completed in Cretaceous sandstone. It was constructed in 1947 with 115 feet of 10-inch-diameter screen and was test pumped for 8 hours at 565 gpm (gallons per minute); the drawdown of the water level in the well was 34 feet. The well was reported to be pumping sand.

Generally the Cretaceous water-bearing sands are fine grained and sand infiltration poses a serious well-maintenance problem, especially in large capacity (over 50 gpm) wells. The installation of newly developed screens having proper slot size on large capacity wells in the Cretaceous sands may reduce sand infiltration. Larger diameter screens would probably also decrease sand infiltration by increasing the total intake area of the well and thereby decreasing the entrance velocity of a given amount of water flowing into the well, for the ability of moving water to carry sediment is proportional to its velocity. Underreaming and gravel packing may also decrease sand pumping in some areas.

When drilling large capacity wells, it is advisable to penetrate the entire thickness of Cretaceous formations to locate the thickest and coarsest sections of sandstone. It is not necessary to penetrate the entire thickness when constructing farm wells, for supplies adequate for ordinary farm use may be obtained from the upper part of the sandstone.

Figure 4 shows the location of the wells in the Cretaceous rocks, well-completion altitudes, and generalized contours on the piezometric surface (static water level) in the sandstone. The wells are assumed to be completed in the first occurrence of Cretaceous sandstone. Therefore, by superimposing figure 4 on figure 5, a topographic map of the area, and noting the well completion altitude, it is possible to approximate the depth at which the sandstone is present in some areas and the height to which water will rise in a well in relation to the land surface. Most of the water levels used to construct the piezometric contours were reported.

The most permeable water-bearing strata appear to be in the north-central and eastern parts of the area. The occurrence of water-bearing strata in other sections is little known owing to the absence of data from deep drilling. An estimate may be made of the thickness of the Cretaceous sandstone formations from the data on figure 4. The difference between the altitude of the first occurrence of sandstone and the altitudes of the quartzite or granite gives the maximum possible thickness of the Cretaceous sandstone. The thicker the section the greater the probability of intercepting significant sandstone strata. The interbedded sandstone and shale section at Worthington is more than 250 feet thick; 2 miles east of Bigelow, it is more than 285 feet thick.

The Sibley, Iowa, well is the only nearby well in Cretaceous formations having a high yield. All the other wells in Cretaceous formations inventoried were used for domestic supply and did not pump the maximum quantity of water that the formation could yield.

The present withdrawal of ground water from the Cretaceous formations is small in comparison to the total amount available.

QUATERNARY

PLEISTOCENE DEPOSITS

During Pleistocene time, four continental glaciers invaded Minnesota. The glaciations are named, from oldest to youngest: the Nebraskan, Kansan, Illinoian, and Wisconsin. In Nobles and Jackson Counties deposits of the Wisconsin Glaciation (drift) are the only glacial deposits exposed at the surface. Older drifts have been identified in the subsurface from drill cuttings of buried soil zones, outwash deposits, and oxidized till.

The Wisconsin Glaciation is divided into four stades named, from oldest to youngest: Iowan, Tazewell, Cary, and Mankato.

The entire area, with the exception of a minor part covered by Recent alluvium is mantled by glacial drift and associated loess

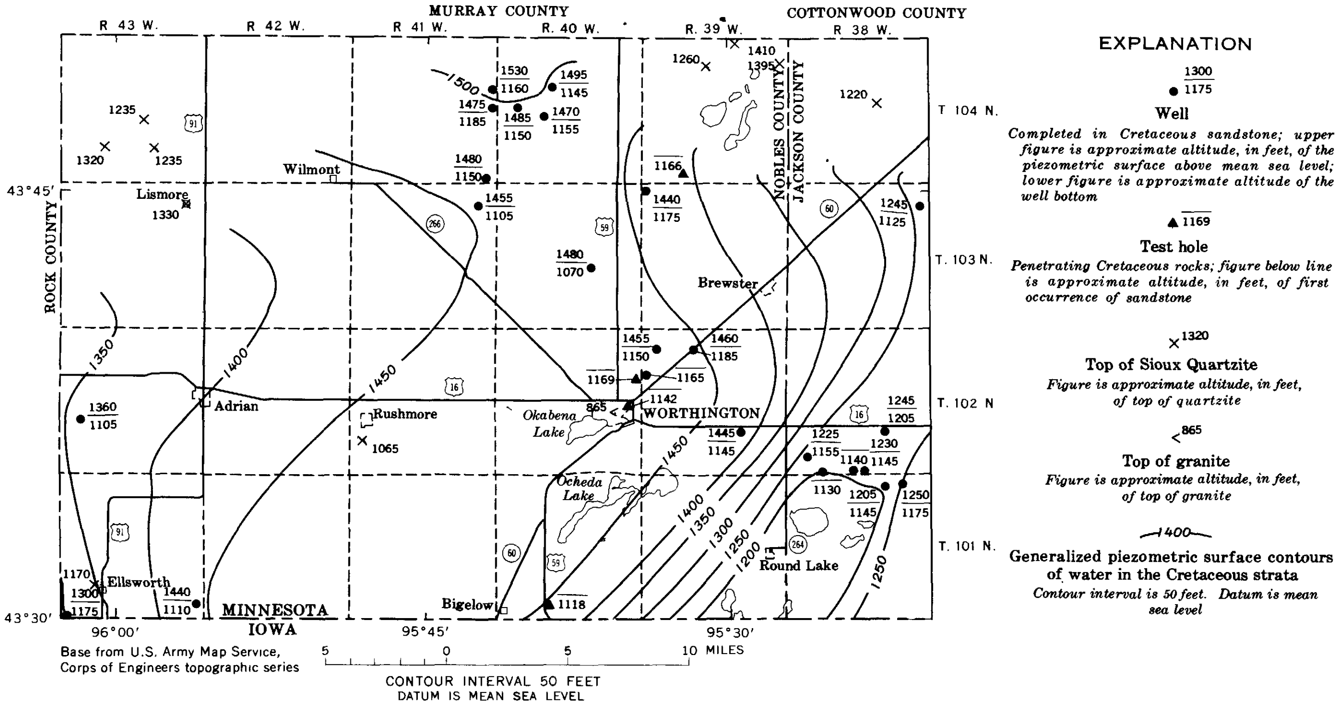

FIGURE 4.—Map of the Nobles-Jackson Counties area showing the location of wells and test holes penetrating the Cretaceaus sandstones and the approximate configuration of the piezometric surface of the water in the Cretaceous strata.

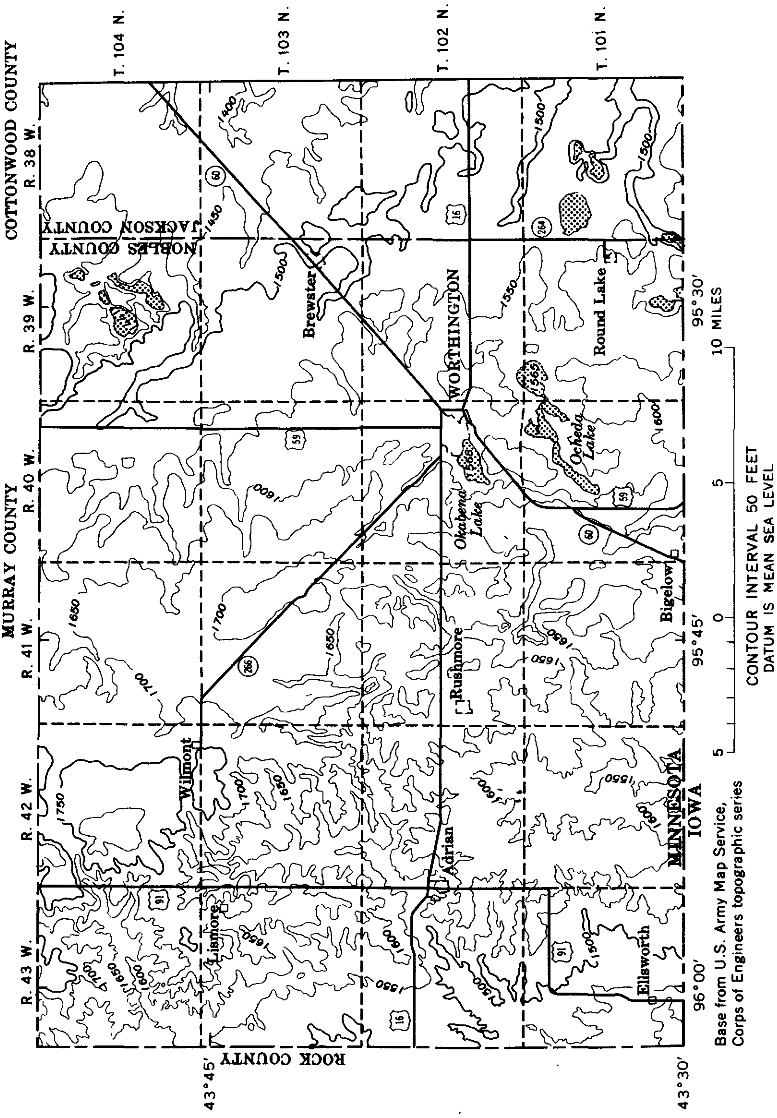

Figure 5.—Topographic map of the Nobles-Jackson Counties area.

(windblown silt). R. V. Ruhe (see footnote 1, p. 5) revised the drift classification used by Leverett (1932). Ruhe's classification is used in this report.

Glacial drift is composed of stratified and nonstratified materials ranging in size from clay to boulders. Stratified drift is termed outwash; nonstratified drift is termed till. Outwash is deposited by melt water flowing from the glacier; it is predominantly sand and gravel, but clay to boulder sizes may be included. Till is deposited directly from the ice and is composed of sand- to boulder-size grains imbedded in a silty clay matrix.

Loess is a windblown deposit of buff to brown silt derived from the outwash deposits associated with the glaciers. It is the parent material for much of the soil in the Iowan and Tazewell drift areas; it has a patchy occurrence in the Cary drift area.

Glacial drift can be further classified according to the topographic forms in which it occurs. End moraines are nearly continuous ridges or belts of generally rugged topography built up at the terminus of a glacier and usually dissected by melt-water streams. An end moraine is formed by the glacial ice melting at a rate equal to the glacier's advance. Ground moraines are extensive deposits having gently undulating surfaces, and are composed mostly of glacial till and minor amounts of stratified material. They are formed when glacial retreat is more or less uniform or when mass wasting of the ice occurs. The ground moraines in Nobles County grade into end moraines with the exception of the ground moraine of Iowan age which has no associated end moraine in this area. Kames are knobs or hills of stratified drift formed in contact with the ice and generally found in the area of end moraines. Kame terraces are benchlike deposits made up predominantly of sand and gravel that was laid down between the valley wall and an ice tongue occupying the valley at the time of the outwash deposition. Terrace fill and the lower valley fill deposits that are formed by outwash streams are not ice-contact features and thus differ from kames and kame terraces.

The thickness of the glacial drift in this area ranges from about 150 feet in the northeast and southwest corners, where surface altitudes are near 1,400 feet, to about 500 feet on top the Coteau des Prairies at an altitude of more than 1,800 feet. It may be thinner than 100 feet, locally, in the northeast part of Nobles County where the Sioux Quartzite is near the land surface.

MORAINES

Three end moraines and their associated ground moraines trend south to southeast across Nobles County (pl. 1). One is of Tazewell and two of Cary age. Leverett (1932) gave an Iowan age to the Tazewell moraine and called the Cary moraines Bemis.

Drift of Iowan age, largely ground moraine, is present at the surface in Nobles County to the west of the Tazewell drift border. Except for the melt-water channels traversing the Iowan, its surface has little relief.

The end moraines in this area are composed largely of till and have a subdued topographic expression. R. V. Ruhe (see footnote 1, p. 5) has written the following about the moraine of Tazewell age: "The most distinct Tazewell end moraine is located in northeastern Lyon County, Iowa, and southwestern Nobles County, Minnesota. It is not a knob and kettle type, but is characteristically a subdued, rounded knoll and sag terrain."

The occurrence of two end moraines of Cary age (Bemis of Leverett, 1932) in Nobles County is due to a splitting of one larger moraine in Murray County. Leverett (1932, p. 60) wrote about the bifurcation of the Bemis moraine:

> * * * From Chandler [Murray County] southeastward there are two slender moraines whose combined bulk is no greater than that of the one moraine north of Chandler, and which appear to be the continuation and equivalent of the Bemis moraine. They traverse the southern part of Murray County and run through central Nobles County in a general south-southeasterly course, having a narrow till plain between them. The outer moraine runs from Chandler to St. Kilian and is crossed by the Chicago, Rock Island, and Pacific Railroad just west of Wilmont. It is double for a few miles, from the southwestern part of T. 103 N., R. 41 W., southward to the Chicago, St. Paul, Minneapolis & Omaha Railroad [Chicago and North Western], where it crosses the Little Rock River east of Rushmore. There is a narrow gravel plain between the two members of the moraine where it has this double phase. South of the railroad it continues as a single moraine into Iowa, passing by the village of Bigelow.
>
> The inner moraine branches off from the Bemis moraine about 2 miles west of Iona (4½ miles north of Nobles County), runs south-southeastward to Reading, and crosses the Chicago, St. Paul, Minneapolis & Omaha Railroad (Chicago and North Western) directly west of Org Junction. It then swings eastward and runs into Iowa from a point near the southeast corner of Nobles County, Minn.

Of the moraine of Cary age, Ruhe (see footnote 1, p. 5) states: "From northern Nobles County, Minnesota, southward to northern Carroll County, Iowa, relief varies within the end moraine from 20 to 40 feet. Slopes range from 3 to 6 (locally 6 to 16) percent * * *. The Cary end moraine, in general, is a somewhat subdued knoll and sag topography with an abundance of undrained depressions."

The inner moraine of Cary age is difficult to trace. It is not continuous as is the outer moraine of Cary age and appears as a succession of discontinuous low-lying hills. Buried outwash deposits that were penetrated by drill holes in front of the inner moraine indicate that the topography may have resulted from the actions of ice in overriding an older moraine that had a series of melt-water channels at its margin. The following table lists test holes that are situated in front of the inner moraine. The thick sand and gravel deposits suggest the existence of a buried series of channels that roughly parallel the inner moraine of Cary age:

Test-hole	Approximate altitude of top of outwash body above mean sea level	Depth to top of outwash body (feet below land surface)	Thickness of outwash (feet)
103.41.4ccc1	1,560	134	12
102.40.7cba2	1,545	112	14
102.40.7ccc1	1,545	120	8
102.41.21ada1	1,520	129	14
102.41.22aad1	1,560	90	6
	1,520	132	14
102.41.22cad1	1,535	98	14

On the east flank of the outer moraine of Cary age is a system of five well-defined troughs separated by round- to flat-topped ridges that form the margin of the end moraine. (See pl. 1 and fig. 6.) East of the troughs is the ground moraine of Cary age. The troughs extend about 3 miles southeast from about half a mile southeast of the town of Wilmont. A few less well-defined troughs are present east of Wilmont. The troughs may have been formed by fracturing of the ice at its recessional margin and subsequent deposition of till in linear ridges between the ice slices, or they may have been formed by glacier-margin streams during deglaciation as explained by Flint (1957, p. 166–168). Troughs similar to the Wilmont troughs, but not as numerous, occur in the E½ sec. 5, T. 104 N., R. 42 W., and a series of less well-defined troughs are found in sections 30 and 31, T. 102 N., R. 40 W., and sections 26, 35, and 36, T. 102 N., R. 41 W. These features all trend southeast and lie in a line as shown on the map. All the troughs apparently were formed along the same recessional ice front.

STRATIFIED DRIFT

Stratified drift composed largely of silt, sand, and gravel is present at and below the surface in Nobles and Jackson Counties. The surface deposits occur in the form of terrace fill, valley-bottom fill, kames, and kame terraces. The terrace fill and valley-bottom fill deposits were laid down in proglacial melt-water

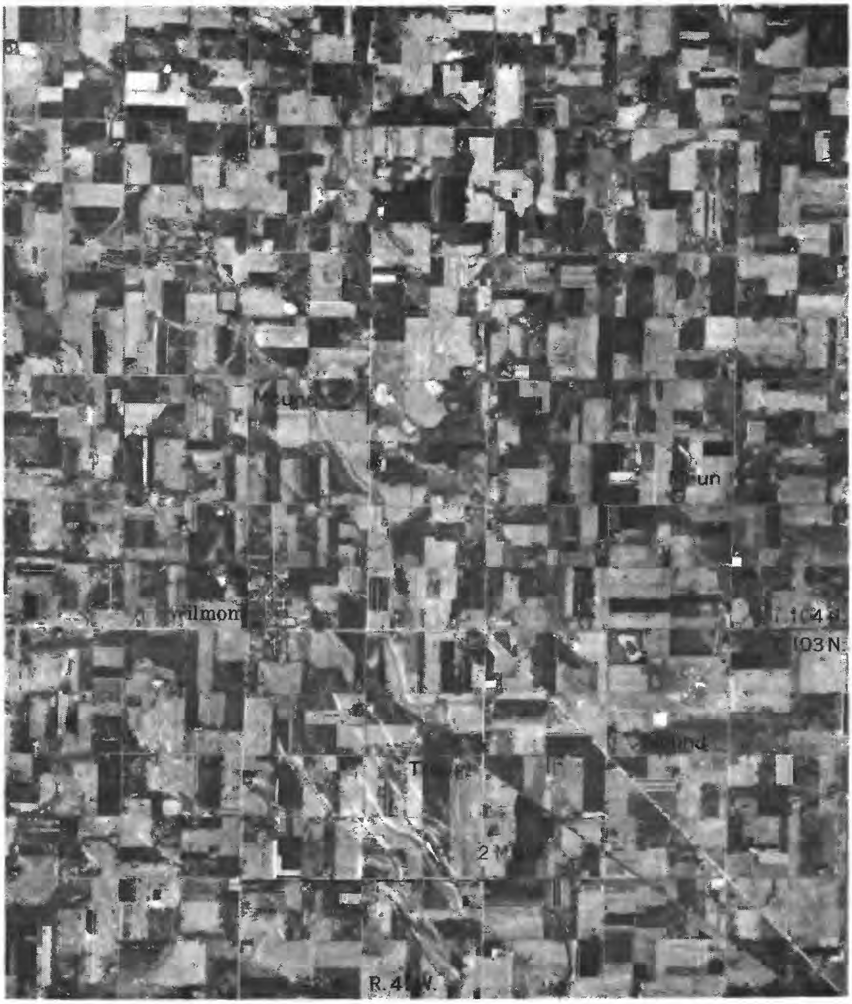

FIGURE 6.—Troughs and circular mounds in the vicinity of Wilmont.

streams during the Wisconsin Glaciation of Pleistocene glaciation with the exception of the deposits in Jack, Elk, and Okabena Creeks in the eastern part of the area, which may have formed during the northward retreat of the last ice front. The proglacial streams were probably overloaded with glacial debris and filled their valleys with outwash material. After the ice front retreated, the stream loads were smaller; the streams cut downward into the previously deposited valley fill. Through formation of meanders, the streams cut the terraces that are visible on the surface today.

The surficial outwash deposits may be overlain by a veneer of Recent alluvium (water-laid silt, sand, and gravel), which is confined to the stream beds and stream flood plains. Jack, Elk, and Okabena Creeks, as previously mentioned, drain the backs of the moraines. The size and shape of their valleys show that they did not have the volume of water nor the load that was available to the proglacial streams. Their channels, therefore, are relatively narrow and contain a lesser amount of alluvium except locally where conditions favored a large accumulation, as in areas of confluence of streams.

The surficial channel deposits were sampled by augering 43 test holes in them. The locations of the auger holes are shown on plate 1. Study of the test-hole logs shows that the deposits range in thickness from about 4 feet to more than 61 feet. The deposits range in width from a few feet in the narrow, shallow tributaries to about a mile in the Kanaranzi Creek valley southwest of Adrian and in the Champepedan Creek valley along the western border of Nobles County. (See pl. 1.)

On the basis of the positions of the terrace fill, three former stream levels are discernible in the proglacial channels; a high-level terrace, which may represent a fourth level or may be of ice-contact origin, is discernible in the channels west of the end moraine of Tazewell age. (See pl. 1.)

A surficial deposit of buff-colored, very fine to coarse-grained sand is in the southwest corner of the area in the drift section of Iowan age. The deposit is a high-level terrace fill having a linear extent of about 9 miles and a maximum width of about 1½ miles. It forms the east bluff of the Kanaranzi Creek valley and apparently has been dissected by the southwestward-flowing tributaries of that creek. The surface of the sand accumulation is fluted in a general northwesterly direction as shown on the aerial photographs of the area. The fluting is possibly due to deflation; however, the coarseness of the grains (about 15 percent is more than 0.5 mm) and the areal extent of the deposit indicate stream rather than wind deposition. An auger hole was drilled near the edge of the deposit in SW¼SW¼SE¼ sec. 19, T. 101 N., R. 43 W. The results showed 2½ feet of soil (loess) overlying about 15 feet of brown sand, underlain by gravelly sand to about 60 feet below land surface. Because of meager drill-hole data, the range in depth of the sand is not known. The approximate limits of the more pronounced accumulation of the sand have been delineated on plate 1.

Kames and kame terraces are numerous in the area of the end moraine belts and along bluffs of the major outwash valleys. A kame deposit is exposed in a gravel pit in SE¼SE¼SW¼ sec. 20, T. 103 N., R. 42 W. The range in grain size of the material in the deposit typifies that found in many kames. The northwest corner of the deposit is a poorly sorted conglomeration of sand to boulder grains which grade to bedded sand layers in the south side of the deposit. The east half of the deposit contains crossbedded sand and gravel lenses. The gravel screened from the deposit contained many grains more than 1¼ inches in diameter. A kame terrace exposed in a gravel pit in SW¼SW¼ sec. 3, T. 102 N., R. 41 W., extends into the NE¼SE¼ sec. 4, T. 102 N., R. 41 W. The grain size in this deposit ranges from sand to boulder. A large part of the deposit has been mined. A few other places where kame or kame terrace deposits occur are in E½NE¼ sec. 4, T. 101 N., R. 41 W.; SW¼NW¼ sec. 21, T. 102 N., R. 43 W.; and NW¼NE¼ sec. 32, T. 102 N., R. 43 W.

More than 200 circular mounds, which may be genetically related to kames, occur throughout the part of the report area covered by drift of Cary age. The mounds have no apparent orientation and range from about 0.05 to 0.5 mile in diameter. Because of their low relief these features are inconspicuous at ground level; however, they are noticeable on aerial photographs. (See fig. 6.) Generally the mounds have light-colored perimeters and display a vestige of former drainage around part of their base.

Several mounds studied in the field apparently are composed of either stratified drift or reworked till. The stratified drift is composed largely of sand or silt, and the reworked till is largely a mottled buff and gray clay containing lime concretions. The origin of the mounds can only be postulated. The mounds are too large to be attributed to frozen ground activity although some distortion may have occurred within them owing to freeze action during their early formation. The mounds probably were formed by meltwater deposits that flowed into holes in the ice during the last waning phase of glaciation when thin segments of ice still covered the area. Lemke (1960, p. 79) noted similar features in the vicinity of Flaxton, N. Dak., and described them in some detail. The only apparent difference between the mounds in the two localities is that the mounds near Flaxton are generally mantled by till; the mounds in this area generally are not.

Stratified drift occurs in the subsurface in deposits similar to the surficial deposits, but they have been covered and altered by subsequent glacial advances. Their presence is detected from well and test-hole cuttings. Plate 2 shows three test-hole sections of Nobles County in which the stratified drift is shown as sand and gravel and possibly silt. The sections show that the individual subsurface stratified deposits are generally thin and of limited areal extent.

Section *B–B′* shows one of the more extensive subsurface stratified deposits penetrated during the test drilling; however, well data on either side of the line of section show that even this deposit has little apparent lateral extent.

INTERGLACIAL DEPOSITS

Paleosols (buried soils), generally composed of dark-brown or dark-gray silty clay, were noted in cuttings from a few of the test holes drilled during this investigation. These soils mark interglacial or interstadial periods between successive ice sheets. One such deposit crops out in a road cut in E½NE¼NE¼ sec. 29 and W½ NW¼NW¼ sec. 28, T. 104 N., R. 43 W., Nobles County. The road running northward traverses the terminal moraine of Tazewell age. In four measured sections on the west side of the cut, shown on figure 7, the paleosol was found from about 6 to 10 feet below the surface. The general section, from the surface down, is a modern soil zone, an oxidized (yellow-brown in color) till, a thin layer of either sand, gravel, or silt, a noncalcareous brown silty loam (paleosol), a light-gray till, and an underlying oxidized till. The uppermost oxidized till is of Tazewell age. The paleosol may represent an interstadial period between the Tazewell and Iowan(?) substages, or it may represent an older Tazewell surface covered by

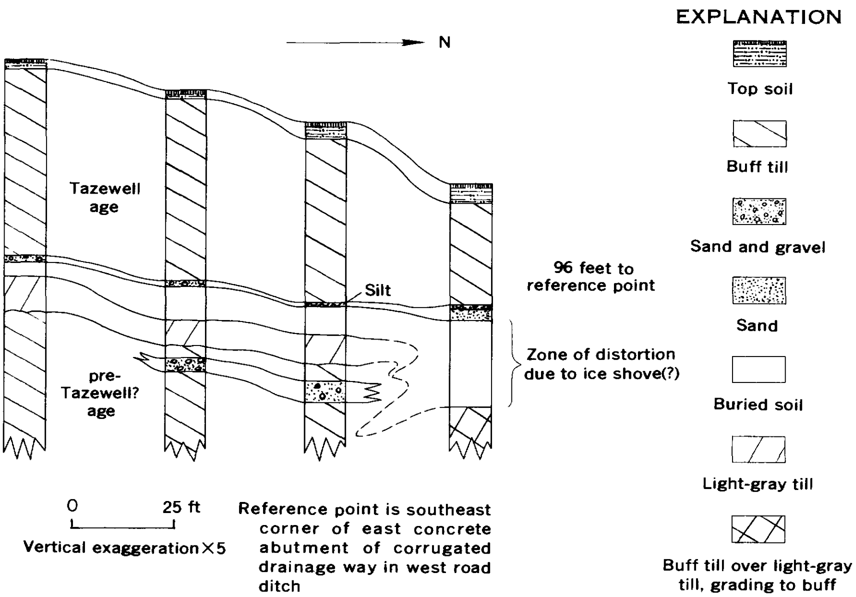

FIGURE 7.—Paleosol section in E½NE¼NE¼ sec. 29, T. 104 N., R. 43 W., about 4 miles northwest of Lismore.

a readvance of Tazewell ice. Evidence for the latter is the poor development of the soil. The overlying veneer of silt, sand, or gravel on top of the paleosol may be outwash deposited during the Tazewell advance. The light-gray till immediately below the paleosol is much lighter in color than the blue-gray unoxidized till found throughout the area. The light-gray color may have been formed in a reducing environment at the time of deposition or at the time of soil formation. The lower oxidized till may be of either Tazewell(?) or pre-Tazewell(?) age.

The hill in which the road cut was made forms a bluff of the Champepedan Creek valley. The surface of the paleosol is quite flat, and its thickness decreases from north to south away from the present valley.

A similar occurrence of light-gray till underlying a possible paleosol was noted in test hole 102.41.18dcc1. The paleosol(?) was penetrated 315 feet below land surface at an altitude of about 1,353 feet. The altitude of the paleosol exposed in the road cut is about 1,630 feet. Should these two paleosols represent the same surface, there is a difference in relief of about 280 feet in about 15 linear miles.

LAKE DEPOSITS

Lake deposits make up a small part of the surficial deposits in Nobles and Jackson Counties. Most of the deposits are fine grained and consist of clay, silt, and sand. Several of the former lake basins are shown on plate 1; their boundaries have been inferred from studies of aerial photographs. The basin with the largest extent is that in the vicinity of Bigelow near the Minnesota-Iowa border. It occupies a sag in the terrain immediately in front of the outer terminal moraine of Cary age. An early part (Cary?) of the drainage of this lake was to the east, probably through the narrow outlet beginning in the SW¼SE¼ sec. 19, T. 101 N., R. 40 W. Drainage in Recent time was to the south. The surface of this deposit is underlain, at least locally, by sand and may yield small quantities of water to domestic wells in the area. The extent and depth of the sand deposit in this basin were not determined. Several smaller lakes in the area have an origin similar to the Bigelow lake. East Okabena dry lake basin (pl. 3) is underlain with as much as 7 feet of black clayey silt containing numerous shell fragments. This basin as well as most of the basins in the area has gone dry in Recent time.

WATER-BEARING CHARACTERISTICS OF THE STRATIFIED GLACIAL DRIFT

Water-bearing deposits (aquifers) included in the glacial drift in Nobles and Jackson Counties are classified as: (1) buried outwash and (2) surficial outwash. Water is also contained in the till; however, till is relatively impermeable and is not considered an important aquifer in this area.

The locations of selected wells and test holes inventoried during this investigation and the location of test-hole sections are shown on plate 1. Figure 8 shows similar data for the Worthington area.

STRATIFIED DRIFT

A buried outwash aquifer is a deposit composed of glacial outwash and overlain by one or more sections of glacial till. Buried outwash is the major source of ground water in the area. Seven of the ten municipal water systems have wells completed in the buried deposits. Most of the farm supplies come from this source. Two wells owned by the city of Worthington were tested for short periods at a pumping rate of 500 gpm from the buried deposit underlying the East Okabena dry lake (pl. 3).

Buried outwash deposits do not exist everywhere within the drift. Wells have been drilled through the drift into the Cretaceous or Precambrian strata without penetrating water-bearing material in the drift. However, buried deposits, where present, may be found at various depths within the drift ranging from about 15 feet below land surface to the bottom of the drift (about 500 ft in places). They occur as isolated bodies of limited extent and as narrow, seemingly discontinuous channels which are difficult to trace by test drilling. It is conceivable that the buried deposits are continuous but so sinuous that the test holes did not show continuity. No large, continuous, buried outwash sheets have as yet been found in this area.

To delineate the buried deposits, test holes were drilled about ¼ to ½ mile apart. (See pl. 1.) From the results obtained, it is apparent that close correlation of beds between test holes would require that test holes be drilled closer than a quarter of a mile apart. Favorable areas for ground-water exploration are where thick sections of sand and gravel (10 ft or more) were penetrated and where records of farm wells indicate the existence of an aquifer at a comparable depth in the vicinity.

The areas listed below appear to be best suited for future exploration.

1. Northeast of Ocheda Lake along section line *B–B′* (pl. 1): the test-hole section of this area is shown on plate 2. Subsequent to the test drilling, two test wells were drilled by the city of Worthington—one at the site of test hole 102.39.29dad3 and the other about 200 feet east of test hole 102.39.32add1. Water

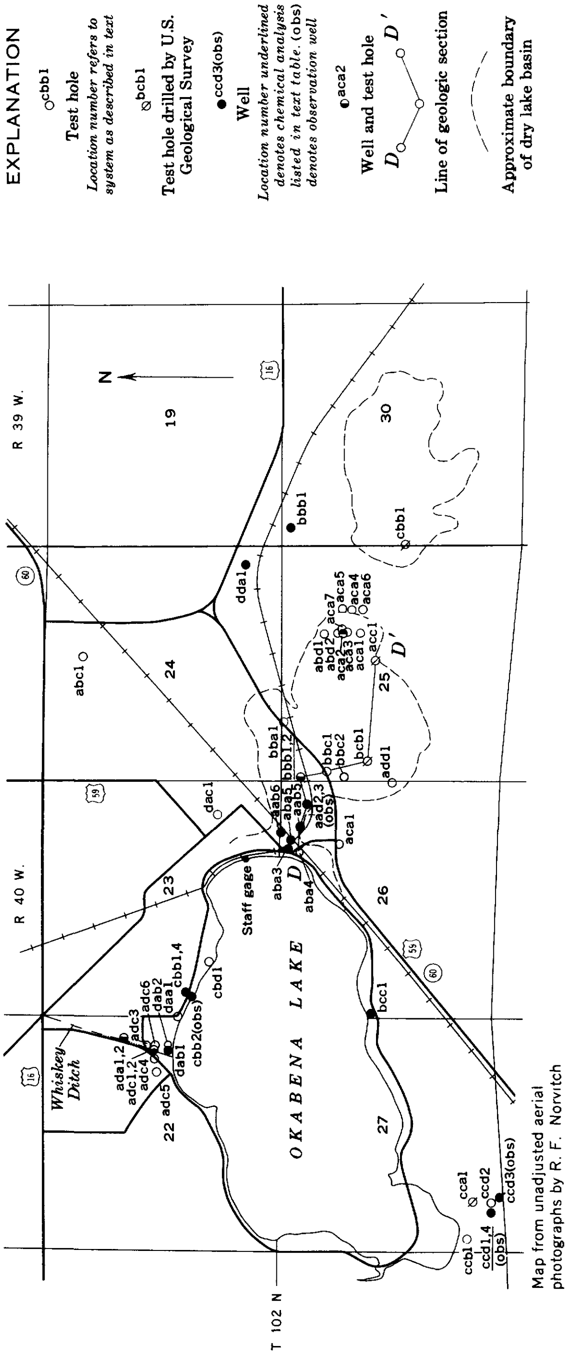

FIGURE 8.—Map of the Worthington area showing location of selected wells, test holes, and line of geologic section.

from buried outwash at these sites was reportedly pumped at rates of 100 gpm and 40 gpm, respectively. Because abrupt changes in depth, thickness, and permeability of outwash may occur in short distances, a well near the site of test hole 102.39.32add1 may show a better yield than the above wells.

2. Four miles northwest of Worthington in the W½ sec. 7, T. 102 N., R. 40 W.: Two test holes, 102.40.7cba2 and 102.40.7ccc1 (table 6), penetrated buried outwash at depths of 112–126 feet and 120–128 feet below land surface, respectively. Additional test holes were drilled to delineate the buried outwash in this area; however, they did not delimit the full lateral extent of the outwash. The location of these test holes is shown on plate 1. Test pumping was not attempted in this area.
3. About 5 miles west of Lake Okabena in a low area near the center of sec. 22, T. 102 N., R. 41 W.: Test holes 102.41.21ada1, 102.41.22aad1, acc1 and 2, and cad1 (pl. 1 and table 6) show sand and gravel accumulations which may be continuous. Test holes 102.41.22acc1 and 2 were drilled only to 97 feet below land surface owing to the collapse of the sand and gravel sections. This collapse may be indicative of coarse, permeable material, and the area may warrant further investigation.
4. Two and a quarter miles due east of Ransom near a tributary to the Little Rock River: The thickest and deepest buried outwash deposit penetrated during the investigation was found in test hole 101.41.22bab1 (pls. 1, 4). Four additional test holes drilled to delineate the outwash in this area met with little success. The location of these test holes is shown on plate 1. The fact that several farm wells in the vicinity of test hole 101.41.22bab1 apparently tap the buried outwash indicates that the deposit is relatively extensive.

The final evaluation of any outwash deposit is dependent on the rate at which it yields water to a pumping well. It is advisable to use extreme care in developing wells in the outwash deposits because of the wide range in grain size. Faulty well construction could easily cause a satisfactory water-bearing deposit to be disregarded as a possible source of supply.

Recharge to the buried deposits is slow; the water must percolate through till of low permeability before reaching the aquifers. Generally, the deposits are fully saturated and permeable enough to supply local farm demands. Some of the smaller municipalities (population less than 600) have succeeded in obtaining their entire supply from the buried outwash; however, a city the size of Worthington must augment its supply with water from other sources.

Surficial-outwash aquifers occur from the land surface down to the first till strata. They are melt-water features and consist largely of channel deposits made up of clay, silt, sand, gravel, and some till contributed as slope wash and talus. Also included as surficial outwash are kames and kame terraces. The upper and larger part of the kames generally is above the water table; however, the lower part may be saturated.

The channel deposits, delineated on plate 1, are the most important surficial aquifers in the western half of the report area. The channel deposits in the eastern half of the area may contain local accumulations of sand and gravel; in some places they consist only of alluvial clay and contain no permeable material. As defined in this report, channel deposits include all the material associated with the present stream valleys, including outwash from proglacial streams as well as alluvium of Recent age.

The grain size of the channel deposits is extremely variable. A well-sorted sand and gravel section may grade laterally and vertically into much finer sediments in a very short distance. Many of the deposits are poorly sorted, and exposures show a mixture of grain sizes from silt to coarse gravel; therefore, construction of large capacity wells should be preceded by careful test drilling, and wells should be so constructed as to assure maximum yields. Development should be extensive, and such methods as surge blocks, water jets, detergents, variable-rate pumping, or air pressure should be used.

The villages of Adrian, Ellsworth, and Lismore obtain their municipal water supplies from wells finished in surficial channel deposits. One well at Adrian, 102.43.13add2, was test pumped at 400 gpm (additional hydraulic data for this well is listed in table 2). The city of Worthington has six wells completed in surficial channel deposits. Well 102.40.27ccd4 at Worthington was test pumped at 200 gpm. The width of the filled outwash channel at the well site is about 500 feet. A pumping test was made in the vicinity of auger hole 101.40.26ccc1; the test well was pumped at 200 gpm for 24 hours. An analysis of the test is given later in this report.

Several farms also obtain part or all of their water supplies from the surficial deposits. Ordinary farm-well requirements, 3 to 10 gpm, may be obtained almost anywhere from saturated sections of the alluvium. In auger holes in the surficial channel deposits, water levels average 7 feet below the land surface.

The surficial outwash is recharged from precipitation. The recharge is quite rapid because the aquifers are at or near the land surface.

A separate report (Norvitch, 1960) describes the surficial channels in Nobles County.

DIFFERENTIATION OF SUBSURFACE GLACIAL DEPOSITS

The successive drift sheets in the report area are very similar in lithology. This similarity, the complex mode of glacial deposition, and the alteration of the surface overridden by the ice make subsurface correlations difficult. However, with sufficiently close control, tentative correlations may be made in some areas. The following techniques are offered as aids for subsurface correlation in glaciated regions where conditions are similar to those in Nobles and Jackson Counties.

When the author compiled geologic sections using information from the written log of a drill hole, stratigraphic breaks were drawn on the discernible buried soil zones, on the occurrence of oxidized till sections underlying unoxidized till sections (in this area oxidized till is yellow brown or buff colored; unoxidized till is gray), on sections of outwash of appreciable thickness, and on contacts between glacial material and bedrock. Plate 3 is a cross section through East Okabena dry lake bed. Test drilling was done in this basin to delineate a buried-outwash deposit that is reflected at the land surface by the surficial lake trend. The test drilling showed the deposit to be extensive and the city of Worthington subsequently installed additional water wells in this area. Subsurface correlation lines shown on plate 3 were drawn by using the above-mentioned criteria.

Most wells completed in outwash deposits were bottomed close to buried drift surfaces. Well-completion depths obtained from the well-schedule data were plotted in conjunction with test-hole logs and well logs to show drift surfaces and outwash bodies. When several wells in a given area had similar completion depths and logs were available to show that an aquifer or surface occurred at about the same depth, the wells provided an additional means for tracing the extent of the aquifer or surface. It should be noted, in using well-completion data, that some wells were measured when partly filled with sediment, that some were completed below the aquifer to provide a reservoir, and that some, completed within the till, may obtain water from seepage alone.

Where most of the available data consists of well-completion depths, it may be possible to trace aquifer extents or drift surfaces statistically. By plotting the well data and by grouping wells of similar depths according to their frequency of occurrence, aquifers of significant extent may be shown.

If the data used and the surface control are reliable, favorable well sites may be located by these techniques; however, correlations are not positive because of the complex patterns of glacial deposition.

ELECTRIC LOGGING

The electric-logging equipment used in this investigation consisted of a single-electrode logger having a continuous-recording stylus. The electrical properties of resistivity and spontaneous potential of the formations traversed were measured. The minerals, except metallics, that constitute the solids in a sand, clay, or indurated rock are good electrical insulators when dry, but they behave like electrolytes when the intergranular spaces are filled with mineralized water. Resistivity of these materials is the reciprocal of the electrical conductivity and is measured in ohm-meter units. The electrical resistivity of a formation is related to the nature, quantity, and distribution of the formation water (Guyod, 1957). The spontaneous potential (S.P.) is a measure of the electrical-potential drop along a drill hole and is affected, among other things, by the thickness and resistivity of the beds traversed (Doll, 1948). Other factors that affect electric-logging results are drill-hole diameter, salinity of drilling mud, and depth of penetration of drilling mud into permeable formations. Suitable electric logs can be obtained only in uncased drill holes.

Qualitative determinations, other than the permeability or impermeability of a formation, were not the major purpose for using electric logs in this area. Breaks between permeable and impermeable strata were selected and comparison with the sample log of a drill hole provided an additional means for determining the correct depth at which such breaks occurred.

Plate 4 shows an electric log of test hole 101.41.22bab1. The strip log, in the center, is taken from the sample log and is adjusted slightly to conform with the electric log. The inflection of the curves opposite the sand and gravel bed from 360 to 387 feet below land surface is a typical response of resistivity and potential curves in a coarse permeable saturated formation.

RECENT DEPOSITS

Clay, silt, sand, gravel, and peat make up the deposits of Recent age in the area. They were laid down in lakes and on flood plains of streams. Peat deposits, formed where vegetation gradually filled up lakes or ponds, are of organic origin. Peat deposits in this area have been mentioned as a fuel source by Winchell (1873, p. 104), but they are of small extent and of no appreciable economic importance at present. The Recent sand and gravel deposits in the stream channels are in contact with Pleistocene outwash deposits and are practically indistinguishable from them. It is assumed that they are quite thin, except locally, and of minor extent.

GROUND WATER

Ground water, as defined by Meinzer (1923, p. 22), is "* * * the water in the zone of saturation * * *." The zone of saturation is the zone that contains ground water under pressure equal to or greater than atmospheric pressure. The water table is the upper surface of the zone of saturation. All voids or interstices of rocks below the water table into which water may percolate are filled with water.

Rocks that lie above the water table are in the zone of aeration. Surface water entering the zone of saturation must percolate through the zone of aeration except where the zone of aeration is absent.

In passing through the zone of aeration, some of the water is held to the walls of the pore spaces by molecular attraction. A moist zone immediately above the water table that contains only water held by capillary action is termed the capillary fringe. Water in the zone of aeration is not available to wells, but where it is near the land surface it may be used by plant transpiration and soil evaporation. Soil moisture requirements and requirements for the zone of aeration must be satisfied before water will percolate into the zone of saturation.

Because the till is permeable, any unconsolidated deposit of sand and gravel below the level of the regional water table will be saturated.

Many swamps in this area are formed by the intersection of the land surface with the water table, but some may contain perched water, which is a localized water table held up by relatively impermeable silt or clay that is underlain by unsaturated deposits. Swamps that hold water for long periods after the spring thaw and after heavy rains but which later dry up are probably perched water-table swamps.

PRINCIPLES OF OCCURRENCE

An aquifer is a part of a formation or group of formations that will yield sufficient water to be considered a source of supply. Porosity is the property of a rock of containing interstices and is the ratio of the total volume of the interstices to the total volume of the rock, usually stated as a percentage. Permeability is the capacity of a rock to transmit water under pressure. A porous rock is not necessarily very permeable. Permeability is dependent upon the interconnection of passageways of capillary and supercapillary size between the openings. Permeability measured in Meinzer units is defined as the rate of flow of water, in gallons per day, through a cross-sectional area of 1 square foot, under a hydraulic gradient of 100 percent, at a temperature of 60° F. The specific yield of a saturated rock is the ratio of the volume of water it will yield by gravity to the volume of the rock. A fine-grained deposit such as silt or clay may have a high porosity and contain a large volume of water when saturated, but the interstices are so small that most of the water is held by molecular attraction and very little can pass through. A sand or gravel deposit may have a fraction of the porosity of clay, but its interstices are relatively large, transmit water freely, and yield large amounts of water to wells.

Ground water occurs under either water-table or artesian conditions. Ground water connected with the atmosphere either directly or through the zone of aeration is under water-table conditions and is unconfined ground water. Under artesian conditions the aquifer is overlain by a confining layer of lower permeability. Water in the aquifer is under sufficient pressure to rise above the base of the confining bed in a well or an open hole. The level to which the water will rise is independent of the water table and is called the hydrostatic head. The imaginary surface represented by the static water levels of several wells tapping the same aquifer is called the piezometric surface.

The water in the Precambrian crystalline rocks and in the Cretaceous sandstone is under artesian pressure. The water in the buried-outwash deposits also is artesian in most places. The permeability of the overlying till is so low in comparison to the outwash that it acts as a confining bed. The water in the surficial-outwash deposits is under water-table conditions, except locally where the deposits are fully saturated and are overlain by a relatively impermeable layer of Recent alluvial deposits of silt or clay. If the water levels in surficial-outwash deposits decline below the confining layer, because either prolonged pumping or natural discharge exceeds recharge, the artesian conditions become water-table conditions. Both conditions can prevail concurrently in the same aquifer.

SOURCE AND MOVEMENT

The source of all ground water available to wells in the report area is precipitation in the form of rain or snow. Part of the precipitation becomes surface runoff, part is evaporated, part is consumed or transpired by vegetation; the remainder seeps into the subsurface and recharges the ground-water reservoir. The glacial-drift aquifers are recharged locally. Surficial-outwash deposits are recharged principally from direct precipitation. Water recharging the buried-outwash deposits must percolate through thick sections of till of low permeability.

The Cretaceous aquifers are recharged from (1) water percolating through overlying beds, (2) lateral movement of water from pervious zones in the Sioux Quartzite where the beds of Cretaceous age lap against quartzite highs, and (3) downgradient movement of water from areas where the aquifers crop out at or are near land surface. Movement from the outcrop appears to be the least important source of recharge in this area.

Water moves down the hydraulic gradient from areas of recharge to areas of discharge; therefore, the highs on the piezometric surface, represented by the 1,450- and 1,500-foot contours shown on figure 4, roughly delineate areas of recharge to the Cretaceous aquifers. The area between the 1,450-foot contours that cross the central section of the map is possibly controlled in part by a topographic high, the crest of the Coteau des Prairies, through this area. The water table along this crest is higher than that of the land to the northeast and southwest; it therefore transmits greater hydrostatic pressures to the underlying deposits.

The 1,500-foot contour is in an area where the Cretaceous strata are in lateral contact with the Sioux quartzite (at Fulda in Murray County the quartzite is 236 feet below land surface or at an altitude of about 1,300 feet). Evidently the vertical permeability of the fractures and of loose sand zones in the quartzite exceeds that of the surrounding glacial drift and facilitates the movement of water into the beds of Cretaceous age; it thereby forms an area of greater recharge to the Cretaceous aquifers. High contours on the piezometric surface of the Cretaceous aquifers, therefore, should parallel Sioux Quartzite outcrops and buried quartzite highs where they are in lateral contact with Cretaceous aquifers.

Recharge to the Precambrian rocks is partly from percolation through overlying beds and partly from direct precipitation where Precambrian rocks crop out. The period of maximum recharge to all the aquifers is during the spring thaw and during heavy summer rains.

As previously mentioned, ground water moves from areas of recharge, in the direction of the hydraulic gradient, to areas of discharge. It discharges into surface-water bodies through springs, seeps, and effluent flow. The water table is a subdued model of the surface topography; it may be assumed, therefore, that direction of ground-water movement is similar to that of the present-day drainage and that the surface drainage divides are roughly coincident with ground-water divides. Because the regional surface-drainage divide—the Mississippi-Missouri—crosses this area, most water is moving away from the area.

EFFECTS OF PUMPING

The following discussion is based largely on a paper by Theis (1938) in which he discusses the significance of the cone of depression in ground-water bodies.

Before the introduction of wells, an aquifer is in a state of near equilibrium, that is, natural recharge is approximately equal to natural discharge. When additional discharge is imposed upon the aquifer by pumping, the balance is disturbed and either natural recharge must increase, natural discharge must decrease, or water storage must decline. Upon pumping a well, a cone of depression, whose apex is at the well, is formed in the vicinity of the well. Actually, it is not a true cone, but for purposes of explanation it is best to consider it as such. The lateral extent of the cone is dependent upon the transmissibility and storage coefficient of the aquifer, the length of time of pumping, and the location of discharge and recharge boundaries. The vertical extent of the cone is dependent upon the transmissiblity and rate of pumping.

In water-table aquifers, the initial growth of the cone is hundreds to possibly thousands of feet per day. As the area influenced by the cone is increased, the lateral growth of the cone cuts down to a few feet or tens of feet per day.

In the artesian aquifer where the storage coefficient is much smaller than in the water-table aquifer, the initial spread of the cone is from thousands to tens of thousands of feet per day. As the cone deepens, the hydraulic gradient of the moving water in the aquifer is increased and, in effect, water influenced by the cone is funneled into the pumping well.

As the pumping well discharges more and more water, the cone of depression expands. Initially water comes from storage in the aquifer and water levels decline. When the cone extends to areas of recharge or natural discharge or both, the draft on storage is decreased and the cone tends toward equilibrium. One source of discharge that may be intercepted is in areas of rejected recharge where the water table is above or near the land surface. A water table near the surface may promote the growth of vegetation and result in discharge of water by evapotranspiration. Where the water table is above land surface, it forms surface-water bodies from which discharge takes place by evaporation. Lowering of the water level or pressure surface in a rejected recharge area provides room for water to enter into the ground-water reservoir. Another source of natural discharge that may be affected is surface flow out of an area. If a stream falls under the influence of a cone of depression, the water that ordinarily would flow out of an area is diverted to the pumping well. In some areas the partial interception by the cone of ground water discharging to an effluent stream causes a decrease in the rate of discharge of ground water to the stream.

Where the cones of two pumping wells intersect, each well obtains water from the same area; the total output of the wells is thereby reduced and the rate of decline of the water level in each of the wells is increased. For maximum economic development, the extent of the cone of depression of each well should be known. Predictions can be made on the approximate lateral extent of the cone of depression for future dates at selected pumping rates through the use of information gained from field pumping tests and Theis' formula (1935).

HYDROLOGY

WATER LEVELS

During this investigation five observation wells were maintained to measure fluctuations in water levels. The wells were all within a quarter of a mile of Lake Okabena. Three observation wells (102.40.26aad2, 102.40.27ccdl, and 102.40.23cbb2) were equipped with continuous water-level recorders; one 2-inch well (102.40.27ccd3) was measured periodically with a steel tape, and a staff gage was installed at the city of Worthington filter plant (NE¼SW¼SE¼ sec. 23, T. 102 N., R. 40 W.) to record lake levels. (See fig. 8.)

The hydrographs in plate 5 were drawn by plotting the low reading for each week and connecting the points. The hydrographs together with precipitation and pumping data provide a basis for analyzing the causes of water-level fluctuations in the aquifers.

The cumulative departure from normal monthly precipitation at Worthington has been plotted on the monthly precipitation graph. This departure curve was constructed by adding the monthly departure from normal, from U.S. Weather Bureau records, to the cumulative total obtained for the previous month. The accumulation of departures, as drawn on plate 5, begins at zero and is only for the period of record shown on the graph; therefore, it is independent of the accumulated record of previous years. The cumulative departure curve is roughly parallel to the hydrographs shown on the figure and indicates the close relationship of local precipitation to ground-water levels.

Water-level fluctuations may be grouped under three headings: short-term, seasonal, and long-term. Short-term fluctuations may last from a few seconds to several days and may be caused by loading phenomena, pumping, precipitation, evaporation, and transpiration. The last three items cause greater fluctuations in the shallow water-table aquifers than in the deeper artesian aquifers. It may take an appreciable time for precipitation to affect the water level in an aquifer underlying a till sheet by addition to the storage in the aquifer; however, the additional weight of the precipitation upon the land surface may impose a load upon the structure of the aquifer that causes the water level to rise. Evaporation directly from the water table or transpiration from phreatophytes (water-loving plants) results in large water losses from shallow water-table aquifers. In an artesian aquifer, changes in pressure at one point are transmitted to all other points in the aquifer at high velocity and with little diminution in magnitude. Thus, loading phenomena such as atmospheric-pressure changes, earthquakes, earth tides, passage of railroad trains, or large floods are discernible in wells equipped with continuous water-level recorders, and they represent adjustments in the structure of the aquifer rather than an addition to or a reduction from storage.

Seasonal fluctuations are caused by changes in rates of recharge and discharge during the year. In the report area, maximum recharge occurs during the spring and summer. There is virtually no recharge during the winter months because the ground is frozen. Some recharge may occur on the few days when the temperature rises above 32°F.

Long-term fluctuations are due to temperature and precipitation cycles. Extended periods of above-normal temperatures and below-normal precipitation result in long-term water level declines because of increased evapotranspiration and increased pumpage. The reverse is true during periods of below-normal temperatures concurrent with above-average precipitation.

The effects of transpiration are shown by the hydrograph of well 102.40.27ccd1 (pl. 5), completed in a water-table aquifer. Almost immediately after the first killing frost in the fall of 1957 the water level begins to rise owing to the cessation of transpiration. According to Schneider (1958), the formation of the annual frost layer draw water from the ground-water body because water moves in response to the thermal gradient, and accretion to the frost layer takes place from below. This effect tends to lessen the rise of the water level. In December of 1957, water levels began to decline because discharge exceeded recharge, and they continued downward until the spring thaw in 1958 when mean daily temperatures rose above 32°F. At this time, water levels began a rather abrupt rise because of replenishment of the ground-water supply with melt water and increased rainfall.

In the fall of 1958, normal conditions did not occur. Rainfall was at a minimum, city consumption was at a maximum, and the mean daily temperature did not go below freezing until the middle of November. The results of this set of circumstances are clearly reflected on all the hydrographs.

A study of the hydrographs shows that the shallow water-table aquifer (well 102.40.27ccd1) responds more quickly to recharge than the deeper, artesian aquifer (well 102.40.26aad2).

Several times during the spring thaw and after heavy rainfall, the shallow deposits are fully saturated; water remains on the surface as rejected recharge and is eventually lost through evapotranspiration and surface runoff. To obtain the maximum quantity of water under such circumstances, pumping from these shallow aquifers should be increased and at the same time pumping from the deeper aquifers should be reduced. This procedure would allow a longer time for water levels in the deeper aquifers to recover to near static conditions, and water that would otherwise be lost through natural means could be recovered.

AQUIFER TESTS

The hydraulic characteristics of an aquifer are best determined by field pumping tests. Although the results obtained from pumping tests are approximations, they are useful in evaluating the hydraulic performance of an aquifer. The coefficients of transmissibility and storage may be computed, hydrologic boundaries located, and future effects of pumping predicted by using data obtained from these tests. The coefficient of transmissibility (T) is the term used to denote the number of gallons of water that will pass in 1 day through a vertical strip of an aquifer 1 foot wide extending the saturated height of the aquifer under a unit hydraulic gradient. The coefficient of storage (S) is the term used to denote the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

One of the accepted methods for evaluating the hydraulic characteristics of an aquifer is the nonequilibrium formula developed by Theis (1935). By using the observed amount and rate of change of the water level in a well affected by pumping, the following formula of Theis may be applied.

$$s=\frac{114.6\,Q}{T}W(u)$$

$$\text{where } W(u)=-0.577216-\log_e u+u-\frac{u^2}{2.2!}+\frac{u^3}{3.3!}-\frac{u^4}{4.4!}\cdots$$

$$\text{and } u=\frac{1.87\,r^2S}{Tt}$$

where s=drawndown, in feet, at observation well,
Q=discharge, in gpm,
T=coefficient of transmissibility, in gpd (gallons per day) per ft,
r=distance, in feet, from observation well to pumped well,
S=coefficient of storage,
t=time, in days, since pumping began.

In the derivation of the formula the following assumptions were made: (1) the aquifer is homogeneous and isotropic, (2) the aquifer has infinite areal extent, (3) the discharge or recharge well penetrates and receives water from the entire thickness of the aquifer, (4) the coefficient of transmissibility is constant throughout the aquifer, (5) the diameter of the pumping well is infinitesimal, and (6) water removed from storage is discharged instantaneously with decline in head. The foregoing assumptions are never quite satisfied under natural conditions and particularly not in aquifers occurring in glacial material; however, orders of magnitude for values of T and S may be attained.

In applying the nonequilibrium formula, the field data are plotted on logarithmic coordinate paper and a curve is drawn connecting points of drawdown plotted against the square of the distance from the pumped well over the time since pumping started or stopped. The resultant curve is matched with a type curve developed by Theis. Where the drawn curve deviates from the type curve, a boundary is assumed to exist. The initial departure above the type curve is a discharge boundary; the initial departure below the type curve is a recharge boundary.

During the period May 10–12, 1960, a pumping test was made in the outwash channel deposit in the SE¼SE¼ sec. 27, T. 101 N., R. 40 W., Nobles County—called the "Lake Ocheda-south" pumping test. Continuous water-level recorders were installed on observation wells 1 and 2, 35 feet and 109.5 feet, respectively, from the pumping well. A third well was drilled 195 feet east of the pumping well and was equipped with a continuous recorder; however, because water-level changes in this well were not in accord with water-level changes in the other two wells, drawdown and recovery data from this third well were not included in the computations. Figure 9 is an arithmetic graph of the drawdown and recovery curves of the water levels in the observation wells during the period of the test. Water-level measurements taken prior to pumping showed a slight downward trend in the observation wells.

Values of T ranged from about 220,000 gpd per ft in observation well 1 to about 100,000 gpd per ft in observation well 2. The difference in the T values at the two sites was expected, for the thickness of the aquifer at well 2 is about one-half that at well 1. (See definition of transmissibility, p. 40.)

The average permeability (P) of the material is equal to T/m where T is the transmissibility and m is the saturated thickness. The average P for the two sites is about 8,000 gpd per sq ft. Subsequent drilling showed that the aquifer is thicker to the east where more than 60 feet of water-bearing material has been penetrated. Therefore, if the permeability remains constant, T values may be as much as 500,000 gpd per ft. Because of the differing thicknesses of the aquifer, average T values apply only for the area covered by the pumping well and the observation wells.

A T value of 150,000 gpd per ft, an average S value of 0.004, and a Q of 200 gpm were used to compute theoretical curves for the relation of drawdown to time (fig. 10) and drawdown to distance (fig. 11) for constant well discharge of 200 gpm. An examination of the Theis formula shows that the drawdown is directly proportional to the pumping rate. Therefore, to find the drawdown for a well pumping 600 gpm, the values computed on figures 10 and 11 should be multiplied by three.

Boundary conditions were not explained in the predicted drawdown graphs; both recharge and discharge boundaries may be expected if pumping is continued for long periods. Recharge boundaries will tend to lessen the water-level declines and discharge boundaries will tend to increase them.

The test was made at a time when the aquifer was fully saturated and water levels were near their maximum height. Locally the aquifer in this area is overlain by 5 to 8 feet of clayey silt which acts as a confining layer; thus, the water occurs under artesian conditions. After a long period of discharge through pumping and by natural means, water levels are expected to decline to a level below the overlying confining layer, and water-table conditions will result. Estimates as to the time at which this condition may occur at a specific discharge rate may be obtained from the theoretical curves on figures 10 and 11. If this condition is reached, these

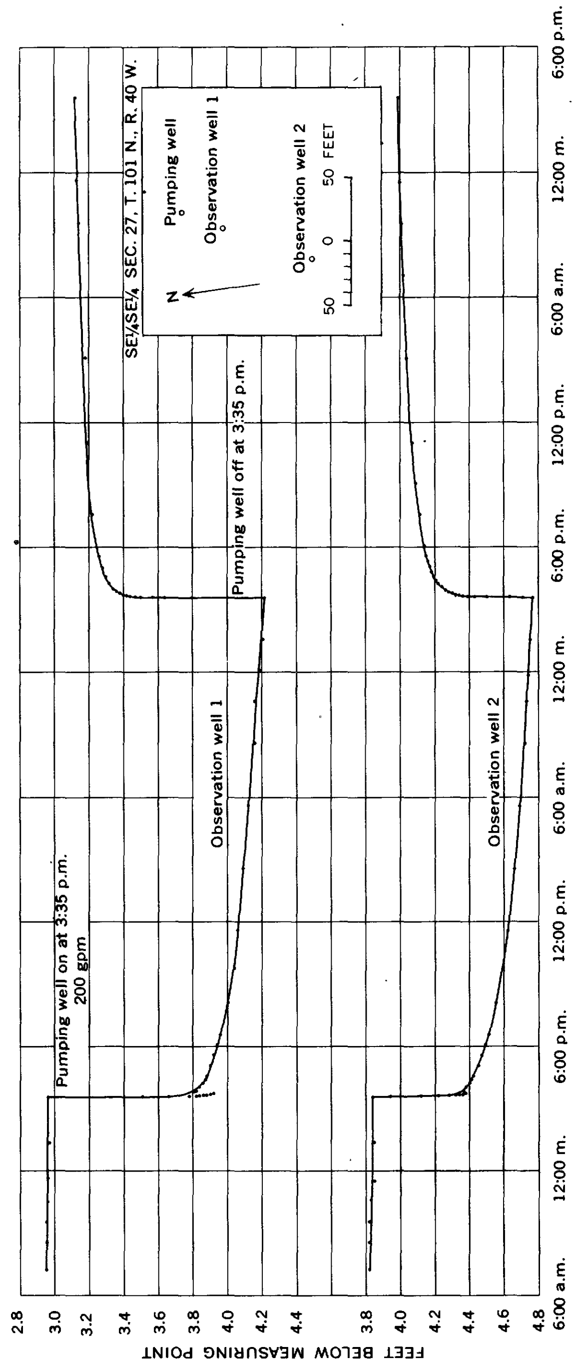

FIGURE 9.—Water levels in observation wells 1 and 2 during Lake Ocheda-south pumping test, Nobles County.

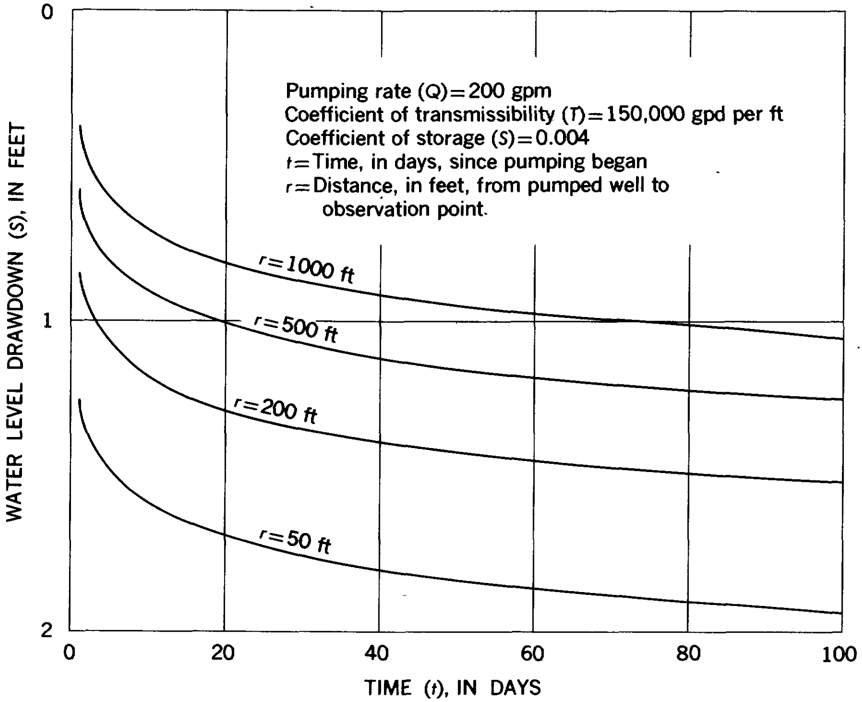

FIGURE 10.—Drawdown versus time since discharge began in the aquifer underlying the site of the Lake Ocheda-south pumping test (not adjusted for boundaries).

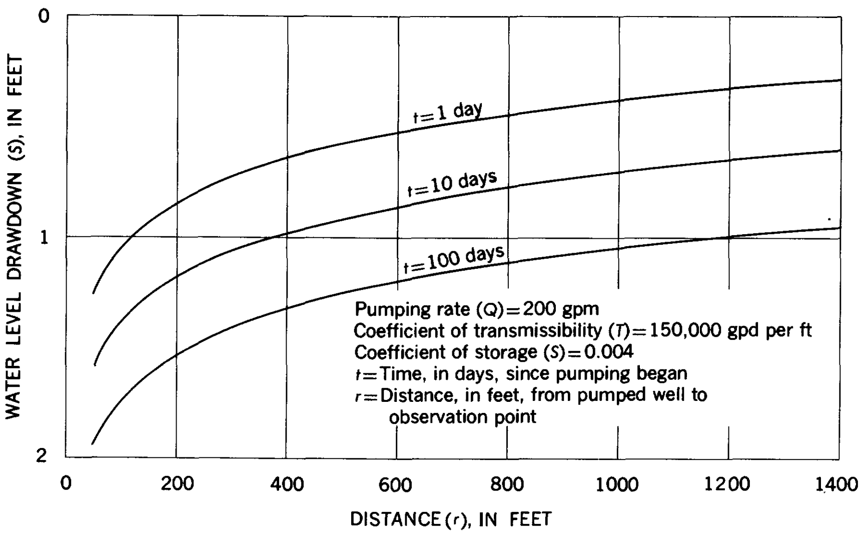

FIGURE 11.—Drawdown versus distance from pumped well in the aquifer underlying the site of the Lake Ocheda-south pumping test (not adjusted for boundaries).

curves will not be applicable. It is estimated that under water-table conditions, S values will approach 0.2.

In some areas, pumping tests to determine the hydraulic characteristics of an aquifer are impractical. In these areas, approximate values of transmissibility may be determined by using the specific capacity of the pumping well. The specific capacity of a well is the yield in gallons per minute per foot of drawdown. For example, a well pumping 100 gpm for an appreciable time and having 5 feet of drawdown has a specific capacity of 20.

In 1941 Theis (Theis and others, 1954) devised a method for computing transmissibility from specific-capacity data for water-table aquifers. At a later date, R. H. Brown (Theis and others, 1954) adapted Theis' method to fit artesian conditions. The computed values of the coefficients of transmissibility obtained by the above-mentioned methods are listed in table 2.

TABLE 2.—*Coefficients of transmissibility estimated from specific-capacity data for wells in Nobles County*

Well	Specific capacity (gpm per ft)	Approximate coefficient of storage	Computed coefficient of transmissibility (gpd per ft)
101.40.31 bdc 1	7.3	0.00004	18,000
102.40.23 cbb 4	14.6	.003	25,000
102.40.25 aca 2	7.5	.0002	16,000
102.40.25 bbb 2	33.0	.0002	69,000
102.40.26 aab 6	25.8	.0002	55,000
102.43.13 add 2	[1] 23.5	.2	30,000

[1] Pumping test was run during a torrential rainstorm; well may have received recharge.

PRESENT WELL DEVELOPMENT

The total withdrawal of ground water through all types of wells in Nobles County was estimated to be about 3 mgd (million gallons per day). Table 4 lists the average daily pumpage by the municipalities in the county, which is about 39 percent of the total withdrawal. The city of Worthington pumps about 1 mgd or about one-third of the total ground water used in the area. Industry consumes an estimated 1 percent of the total withdrawal of ground water, not including industrial use of the Worthington municipal supply. The estimate of rural consumption, 60 percent of the total withdrawal, is based on 40 gpd per person, 30 gpd each for milk cows, 12 gpd each for beef cattle, 2 gpd per hog, 1½ gpd each for sheep and lambs, 4 gpd for each 100 chickens, and 5 gpd for each 100 turkeys. The livestock numbers used for the estimate were taken from the 1956 Minnesota Agricultural Statistics publication compiled and issued by the State-Federal Crop and Livestock Reporting Service.

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It is assumed that the rural consumption in that part of Jackson County that is covered by this report is proportional to the rural withdrawal in Nobles County, about 0.37 mgd for all farms in R. 38 W., Jackson County.

Table 3 lists 74 wells considered to be representative of more than 3,000 wells visited during this investigation.

FARM WELLS

Most of the farm wells are bored or drilled; few dug wells and only one driven well were inventoried.

The bored wells range in diameter from about 8 to 72 inches; the casing is commonly concrete in the newer wells and wood in the older wells. The drilled farm wells range in diameter from about 3 to 6 inches; casings are usually steel.

In areas where the available aquifers transmit water slowly, the large diameter hole of bored wells provides a reservoir. Most wells of this type are finished at the very top of the aquifer. Some are bored below the water-bearing deposit to insure a larger reserve.

Many drilled wells for domestic and stock use penetrate only the upper part of the water-bearing deposit because some drillers consider it unnecessary to penetrate the entire deposit to obtain a suitable supply. The wells are finished with either an open-end casing or a screen.

Several wells completed in the glacial drift in the Jack Creek and Elk Creek drainage systems in northeastern Nobles County and a few wells within the Kanaranzi Creek drainage in western Nobles County either flow or reportedly flowed at one time. Those in the northeast range in depth from 80 to 220 feet; most of those in the west are about 70 feet deep. The flowing wells are located on both sides of the crest of the Coteau des Prairies. The surface relief ranges from more than 1,800 feet altitude on top the coteau to about 1,450 feet in the creek valleys to the east and about 1,550 feet in the valley to the west where the flowing wells are situated. The wells to the east probably flow because they are at a low altitude, sufficient head (hydraulic-pressure differential) being gained from the higher water table in the drift of the bordering uplands. The wells to the west may intercept outwash deposits associated with a former drainage channel, which underlies the present Kanaranzi Creek valley and originally headed on top of the coteau. The higher head gained in the recharge area is sufficient to cause the wells downvalley to flow. The flows are not large, and the aquifers are not a major source of ground water.

TABLE 3.—*Records of selected wells*

Type of well: B, bored; D, drilled; Du, dug
Type of pump: P, piston; J, jet; C, centrifugal; S, submersible; T, turbine

Use: D, domestic; S, stock; PS, public supply; I, industrial; U, unused
Adequacy: A, adequate; B, barely adequate; I, inadequate

Well	Owner	Depth of well below land-surface (feet)	Approximate land surface altitude above mean sea level (feet)	Diameter of casing (inches)	Type of well	Type of pump	Date of well completion	Depth to water below land surface (feet)	Date of measurement	Use	Adequacy
Jackson County											
101.38.13acd1	Mrs. Ballhorn	184.85	1,520	5	D	P		138.35	10-3-57	S	A
101.38.22bcc1	Robert Burns	54.02	1,500	18	B	P		25.55	10-28-57	D, S	A
102.38.15adc1	Johannes Onken	151.2	1,475	36-16	B	S	1955	48.2	10-3-57	D, S	A
102.38.21ccc1	Edward Janssen	56.8	1,505	28	B	P		25.2	10-17-57	D, S	
102.38.31aad1	Lila Habeck	345.91	1,505	5	D	P		276.3	9-25-57	S	A
103.38.12bad1	John Sievert	67.5	1,405	30	B	J and P	1950	23.9	10-23-57	D, S	A
103.38.32abc1	Florian Kunerth	33.85	1,500	36	B	P		4.32	10-3-57	S	I
104.38.10aca1	Richard Rostomily	164.35	1,430	5	D	P	1955	34.35	10-9-57	D, S	A
104.38.31daa1	Paul Bieser	60.45	1,430	24	B	S		22.82	9-26-57	D, S	A
Nobles County											
101.39.7aba1	Harold Hallstrom	73.65	1,585	32-28	B	J		42.85	7-20-56	D, S	A
101.39.17ccd2	Jim Thompson, Jr.	17.15	1,605		Du	P		10.67	7-26-56	D	I
101.39.20cbc1	Sudie Langseth	162.2	1,610	6	D	P	1952	80.66	7-27-56	S	A
101.39.33daa2	A. L. Feltman	27.6	1,570	20	B	J	1946	14.99	7-30-56	D	B
101.40.13ccb1	P. G. Nystrom	10.63	1,575	36	B	J	1955	6.78	7-19-56	S	A
101.40.18aad1	Ed Larson	30.4	1,670	20	B	C		23.42	8-29-56	D	I
101.40.23bcb1	Orville Thompson	115.5	1,600	34	B	P	1955	42.15	7-24-56	D, S	A
101.41.3aad1	George Henning	51.86	1,670	26	B	P		10.8	8-31-57	U	I
101.41.14aad1	Rancy Bents	296.31	1,700	5	D	P		142.85	9-6-57	S	A
101.41.18dda1	George Bents	345.96	1,630	6	D	P	1956	142.25	9-4-57	S	A
101.42.11aba1	W. B. Boldt	30.46	1,605	24	B	P		19.99	10-19-56	D	I
101.42.13add1	Ernest Tiesler	116.51	1,605	36-30	B	P	1952	72.1	10-15-56	D, S	A
101.42.35bbd1	John Odens	65.15	1,535	30-16	B	J		39.74	9-28-56	D, S	I
101.43.3dcc1	Leo Scheitzer	51.41	1,540	30	B	J		46.7	9-17-57	D, S	A
101.43.11cdd1	Frank Seitz	26.61	1,515		B	P		22.3	9-17-57	D, S	A
101.43.31cdc1	Edward McGuire	295	1,470	3	D	P	1927	168		S	A
102.39.2bcb1	C. L. Williams	60.88	1,550	24	B	J	1930	44.83	8-9-56	D	I
102.39.5ccc1	Louis Hibma	237	1,570	6	D	P		90.82	8-20-56	S	A
102.39.20bcc1	Minnie Hinrichs	182.75	1,605	5	D	P		70.49	7-24-56	S	A
102.40.3cdc1	Lloyd Standafer	140.5	1,630	6	D	P		61.82	6-17-56	D, S	A
102.40.7cba1	E. Herlein and others	112	1,665	26-16	B	P		33.05	5-31-56	S	A
102.40.20ddc1	Ray Cave	56.79	1,645	24	B	P		49.85	6-20-56	S	I
102.40.26aab1	Campbell Soup Co.	64.82	1,575	16	D	T	1949	44.33	8-13-56	I	A
102.41.1bad1	Roy Moss	224.65	1,685	6	D	P	1943	97.96	6-6-56	D	B
102.41.7ddb2	H. Boomgaarden	449	1,700	4	D		1956				
102.41.14add1	Art McCuen	149.7	1,700	5	D	P	1945	68.95	6-14-56	S	A

TABLE 3.—*Records of selected wells*—Continued

Well	Owner	Depth of well below land-surface (feet)	Approximate land surface altitude above mean sea level (feet)	Diameter of casing (inches)	Type of well	Type of pump	Date of well completion	Depth to water below land surface (feet)	Date of measurement	Use	Adequacy
Nobles County—Cont.											
102.41.36aac1	Gerrit Toussaint	96.5	1,700	33–24	B	P	1954	63.74	8–31–56	D, S	A
102.42.5dcc2	Henry Honermann	31.85	1,550	24	B	P		12.19	11– 7–56	S	A
102.42.10ada1	Nick Schutz	366	1,640	4	D	P		104		D, S	A
102.42.35bbd2	Roy Fletcher	162.57	1,595	6	D	P	1951	35.5	10–25–56	S	A
102.43.13add2	Village of Adrian	39.2	1,530	24–12	D	T	1957	8.7	8–23–57	PS	A
102.43.27daa1	Mary Hotz	102.95	1,530	28	B	P		54.35	9–24–57	D, S	I
102.43.36dda1	Gilbert Metz	240.45	1,575	5	D	P		138.45	9–27–57	S	A
103.39.13bbc1	Louisa Mankin	45.53	1,475	24	B	P		25.69	6–20–57	D, S	A
103.39.20bbb1	Henry Peil	148.59	1,530	5	D	P	1952	16.57	9–11–56	S	A
103.39.30abc1	Ray Larson	195.84	1,555	5.5	D	P	1950	47.23	9– 7–56	S	A
103.40.5abb1	Carl Spillman	160.11	1,645	36	B	P		132.09	5– 1–57	D, S	B
103.40.13bcb1	Edwin Smith	45.52	1,555	24	B	J	1947	33.79	4–23–57	D, S	I
103.40.29ddd1	Church of the Brethren	249.18	1,650	4.5	D	P	1950	92.38	9– 3–56	D	A
103.41.1ccd1	Milford Davis	586	1,695	6	D	S	1956	240		D, S	A
103.41.17aab2	Wilbur Miller	108.73	1,660	26	B	P		74.31	7– 1–57	S	A
103.41.24baa1	Herman Miller	26.03	1,705	24	B	P		19.59	5– 7–57	D	I
103.42.3baa1	Ed Krell	55.0	1,755	24	B	P		28.35	7–19–57	S	I
103.42.12abd1	Al Balster	167.95	1,705	26	B	P		34.5	7– 4–57	S	A
103.42.28aab2	Melchert Wagner	111.5	1,645	30–24	B	P	1955	55.35	11–13–56	S	A
103.43.2ada1	R. E. Knips	396	1,705	6¼–5⅝	D		1952	200			
103.43.21dda1	Bertha Sargent	16.04	1,575	26	B	P		2.32	9–16–57	D, S	A
103.43.35add1	Fred Gruis	38.86	1,620	26	B	P		14.11	9–13–57	S	A
104.39.1bab1	Chas. Christensen	80	1,450	36–32	B	J	1955	18		PS	A
104.39.15bcd1	Ted Halvormann	68.55	1,450	5	D	P		30.84	7–22–57	D, S	A
104.39.25aab2	F. E. Haberman	257	1,450	4	D	P	1923	50		S	A
104.40.8dcd1	George Gunderman	163.11	1,565	5	D	P	1948	25.19	7–29–57	S	A
104.40.15aad1	Ben Homfeld	89.11	1,550	5	D			11.8	8– 1–57	U	I
104.40.18ddd1	Catherine Pfingsten	460	1,610	5	D	P	1953	126		D, S	A
104.41.4baa1	George Onken	149.81	1,675	5	D	P		72.9	8–21–57	D, S	A
104.41.13ddd1	Emmanuel Lutheran Church	466.21	1,635	6	D	P		159.2	8–13–57	D	A
104.41.22bcb1	C. M. Ferguson	41.38	1,690	26	B	P	1936	8.6	8–23–57		I
104.41.36dcc1	Frank Johnson	514	1,660	6	D	P	1956	180		D, S	A
104.42.2bba1	William Eyres	118.98	1,760	26	B	P	1935	61.11	8–21–57	D, S	
104.42.8cdb1	Earl Larson	291.76	1,800	6	D	P		118.6	9– 7–57	D, S	A
104.42.20abd1	John Burkhard	42.51	1,810	26	B	S		25.28	8–10–57	D, S	A
104.42.35aab1	John Kremer	82.69	1,750	20	B	P		24.93	8– 2–57	D, S	B
104.43.3bbc1	Mrs. H. VanDyke	410	1,790	6	D	S	1956	200		D, S	A
104.43.24ddd1	Mrs. Ed. Pank	74.09	1,705	24	B	P		40.87	9–23–57	S	A
104.43.36dda1	T. B. Fehring	29.74	1,650	20	B	P		4.44	9–20–57	S	I

The size of livestock herds on many farms has been curtailed by water shortages. Some farmers report that they would increase their stock if sufficient water were available. Most farms have two or more wells from which they obtain their supply.

Where the water is available, a shallow well, 30 feet or less in depth, is used to supply domestic needs because most shallow water is less mineralized than water obtained from the deeper aquifers.

MUNICIPAL SUPPLIES

All municipalities in the Nobles County area obtain their water supplies from wells (there are no municipalities in the part of Jackson County covered by this report). Table 4 gives data concerning the municipal water supplies. The village of Adrian has two dug wells; Lismore, Ellsworth, Dundee, and Brewster have bored wells; Adrian and Brewster have both drilled and dug wells. The city of Worthington, as previously mentioned, filters water from Lake Okabena for industrial purposes, but does not pump this water into the public supply system.

TABLE 4.—*Selected data on municipal water supplies in Nobles County*

Municipality	Population (1960)	Source of information	Wells	Average pumpage (gpd) (1956)	Storage (gallons)	Number of customers (1956)	Treatment	Remarks
Adrian	1,215	W. E. Marston, secretary of water and light commission.	4	[1] 84,200	150,000	400	None	New well drilled August 1957; 2 drilled wells, 2 dug wells; chemical analysis. Elevated storage tank.
Bigelow	256	Edward Silvis, village clerk	1	[2] 15-20,000	15,000	[4] 57	do	Elevated storage tank. Chemical analysis; system initiated September 1958.
Brewster	500	Henry Weaver, village clerk	4	[3] 40,000	65,000	120	do	1 well is a shallow, hand-pumped well not connected to system; chemical analysis.
Dundee	148	Charles Christensen, private owner of well.	1		375	28	do	Chemical analysis.
Ellsworth	634	John D. Miller, village constable	1	[3] 14,000	35,000	162	do	Storage tank underground; chemical analysis.
Lismore	306	Lee Krogman, village clerk	1	[3] 30,000	50,000	70	do	Chemical analysis.
Round Lake	449	Irwin Menk, city clerk	1	[3] 20,000	50,000	60	do	Do.
Rushmore	382	Jerry Engelkess, village clerk	1	[3] 26,500	50,000	78	Chlorination, iron removal.	Do.
Wilmont	473	Herman Voss, village constable	2	[3] 20,000	45,000	105	Chlorination (twice a year), filtration.	Wood storage tank; chemical analysis.
Worthington	9,015	City records	18	[2] 900,000	1,000,000	[1] 2,250	Chlorination, $CaCO_3$ stabilization.	Three storage tanks. Chemical analyses.

[1] 1955. [2] Estimated 1959. [3] Estimated. [4] 1959.

QUALITY OF WATER

The chemical quality of ground water is dependent upon its geologic and hydrologic environment. Ground water takes minerals into solution as it percolates through deposits containing soluble salts. The amount of solution that takes place depends principally on the stability of the rock constituents, the size of the rock particles, and the length of time of contact. Chemical analysis may be an important tool to the hydrologist as an aid in determining the source and movement of ground water.

Table 5 lists the chemical analyses of the various waters in the area. The dissolved mineral constituents listed in the table are reported in parts per million, a unit weight of a constituent in a million unit weights of water. Parts per million may be converted to grains per gallon by dividing by 17.12.

Figure 12 shows a graphical representation of chemical water analyses by means of patterns (Stiff, 1951). Patterns for water from 12 wells of different depths are shown. The dissolved solids are shown on the patterns in equivalents per million. An equivalent per million is a unit chemical combining weight of a constituent in a million unit weights of water, and it may be obtained by dividing the concentration of the constituent in parts per million by the chemical combining weight of the constituent. Comparison of the patterns is a rapid visual method for determining similarities or dissimilarities between the different waters. The analysis of water from the Fulda well in Murray County was included in figure 12 and table 5 because no positive source of water from the Sioux Quartzite was known within the report area.

The water contained in the drift is generally very hard owing to a high calcium and magnesium content. It is also high in dissolved solids. There is a definite relationship between the geologic position of the aquifer and the dissolved solids content. Table 5 shows that water from shallow water-table aquifers having no overlying till strata contains from 425 to 870 ppm calculated dissolved solids. Water from aquifers overlain by till contains from 1,100 to 3,050 ppm dissolved solids.

The higher concentration of dissolved solids in water from aquifers overlain by till is probably due to (1) longer period of contact (because of the low permeability of till, percolating water descends very slowly; hence, there is ample time for chemical reaction) and (2) greater area of contact (because till is composed largely of clay and silt particles, percolating water comes in contact with a much larger area for solution than it would in a coarse media). Fine particles have much more surface area exposed per unit of volume than coarse particles.

TABLE 5.—*Chemical analyses of ground water in Nobles*

[Analyses by U.S. Geological Survey;

Location	Date of collection	Depth of well (feet)	Temperature (° F)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Strontium (Sr)	Sodium (Na)	Potassium (K)
Round Lake:												
101.39.24bbd1	6-10-58	154	50	32	0.1	4.8	2.3	484	92	1.3	195	13
101.39.33daa1	6-23-59	120	49	3.7	------	24	.94	366	92	------	72	14
Bigelow:												
101.40.31bdc1	6-24-59	86.9	48	4.8	------	11	.00	337	111	------	38	12
101.41.15ccd1	6-23-59	375	49	6.1	------	17	.72	306	117	------	138	8.2
101.41.18dda1	6-23-59	345.96	49	2.1	------	45	.94	417	150	------	169	13
101.41.23cdc1	6-23-59	283.1	48	6.0	------	[1] 8.6	.00	240	90	------	142	9.8
Ellsworth:												
101.43.20dbd1	6-23-59	19	47	6.4	------	.0	.00	82	31	------	11	1.6
102.39.7ccc4	6-24-59	412	52	14	------	3.7	.94	353	133	------	130	12
102.40.7cba1	6-23-59	112	48	6.7	------	.68	.00	183	61	------	39	4.9
Worthington:												
102.40.25bbb2 (well 22)	6-10-58	58.5	49	32	.2	4.5	1.2	272	88	.9	63	9.8
102.40.27ccd4 (well 21)	6-10-58	30	46	30	.0	1.2	1.2	118	37	.1	13	1.0
102.40.33ddd1 (well 16)	12-2-55	40-45	49	32	.9	.46	.18	131	40	------	26	1.0
Rushmore:												
102.41.19ddb1	6-10-58	375	50	36	.0	7.1	1.5	328	112	.8	163	6.4
102.41.30bad1	6-23-59	378	50	3.8	------	28	.35	412	130	------	158	13
Adrian:												
102.43.13add2 (well 4)	6-10-58	39.2	50	32	.1	.01	.80	118	40	.1	19	2.6
Brewster:												
103.39.25bda1	6-24-59	132	50	7.1	------	6.2	.94	476	69	------	93	9.8
103.40.31ccb3	6-24-59	123.9	49	8.6	------	6.7	.00	237	71	------	65	13
Lismore:												
103.42.7aab1	6-22-59	26	46	4.4	------	1.8	.00	145	50	------	16	3.4
Dundee:												
104.39.1bab1	6-22-59	80	50	4.8	------	6.6	.17	280	98	------	109	10
104.41.36dcc1	6-22-59	514	49	6.2	------	6.5	.00	245	88	------	133	11
Wilmont:												
104.42.36cbc1	6-22-59	350	50	6.1	------	6.1	.00	400	159	------	171	15
Fulda (Murray County)	3-27-57	1300	51	19	.1	.30	.66	280	90	------	168	9.4

[1] Fe in solution = 0.04 ppm.

All raw water in the Nobles-Jackson area is considered hard by ordinary standards. Calcium and magnesium are the principal constituents that cause hardness. Other substances, such as aluminum, iron, manganese, strontium, zinc, and free acid also cause hardness; however, except possibly for iron and manganese, most of these are not present in sufficient quantities to have a great effect on the hardness of water in this area.

The hardness of the ground water tested in the Nobles-Jackson County area ranges from 332 ppm in the well in the village of Ellsworth (101.43.20dbd1) to 1,660 ppm as $CaCO_3$ in well 101.41.18dda1. The weighted-average hardness of raw water from public supplies for the larger cities in Minnesota is 275 ppm (Lohr and Love, 1954, *County and the Fulda municipal well, Murray County*

results expressed in parts per million]

Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids		Hardness as $CaCO_3$		Percent sodium	Ignition loss	Specific conductance (micromhos at 25° C)	pH	Color
						Calculated sum	Residue at 180° C	Total	Noncarbonate					
279	1,750	4.0	0.3	0.0	0.09	2,710	------	1,590	1,360	21	------	2,930	7.1	------
544	979	4.8	.0	.2	------	2,120	------	1,290	846	------	230	2,070	7.3	5
532	938	.5	.1	.2	------	1,990	------	1,300	862	------	176	1,980	7.1	4
480	1,100	4.5	.2	6.5	------	2,250	------	1,240	851	------	313	2,150	7.4	5
390	1,680	8.8	.2	.4	------	3,050	------	1,660	1,340	------	318	2,790	7.2	5
392	942	2.5	.0	.8	------	1,870	------	969	648	------	250	1,940	7.5	5
333	60	5.8	.1	8.6	------	425	------	332	59	------	------	657	7.5	5
424	1,350	5.0	.0	.3	------	2,520	------	1,430	1,080	------	237	2,380	7.2	5
392	450	8.8	.4	.6	------	1,100	------	708	386	------	134	1,190	7.4	5
388	812	15	.2	.0	.00	1,480	------	1,040	722	12	------	1,830	7.0	------
328	184	8.0	.3	.7	.00	------	552	446	178	6	------	825	7.2	------
390	213	6.0	1.8	.3	6.0	------	659	492	172	10	------	930	7.7	2
454	1,190	2.0	.4	14	.00	2,070	------	1,280	907	22	------	2,420	7.0	------
320	1,610	6.5	.1	.3	------	2,840	------	1,560	1,300	------	324	2,650	7.2	4
311	183	24	.3	22	.66	------	603	459	204	8	------	894	7.3	------
418	1,310	1.5	.3	.7	------	2,500	------	1,470	1,130	------	235	2,290	7.3	4
382	703	3.0	.0	.5	------	1,490	------	884	570	------	170	1,610	7.6	6
344	307	6.5	.0	.6	------	870	------	568	286	------	98	1,000	8.0	5
328	1,030	5.5	.2	3.2	------	1,950	------	1,100	832	------	200	1,980	7.7	5
356	924	8.0	.0	4.0	------	1,860	------	974	682	------	233	1,930	7.4	8
346	1,710	3.2	.0	6.1	------	3,050	------	1,650	1,370	------	386	2,750	7.3	4
405	1,030	6.0	.3	1.0	------	1,800	------	1,070	736	25	------	2,190	7.4	------

p. 20). Minnesota Department of Health records show that water from Worthington well 4 (102.40.23cbb4) had a hardness of 370 ppm as $CaCO_3$. The well is about 190 feet north of Lake Okabena, and the relatively low hardness may be due to infiltration of lake water of lower concentration (less than 250 ppm) into the adjacent aquifer. Similarly, city wells 6 (102.40.22ada1), 7 (102.40.22adc6), and 8 (102.40.22dab1) show total hardness values of 730, 870, and 720, respectively. These wells are all within 1,200 feet of Lake Okabena and also may be receiving some recharge from the lake.

Two types of hardness are carbonate (temporary) and noncarbonate (permanent) hardness. The bicarbonates of calcium and magnesium cause carbonate hardness; sulfates, chlorides, and nitrates cause noncarbonate hardness.

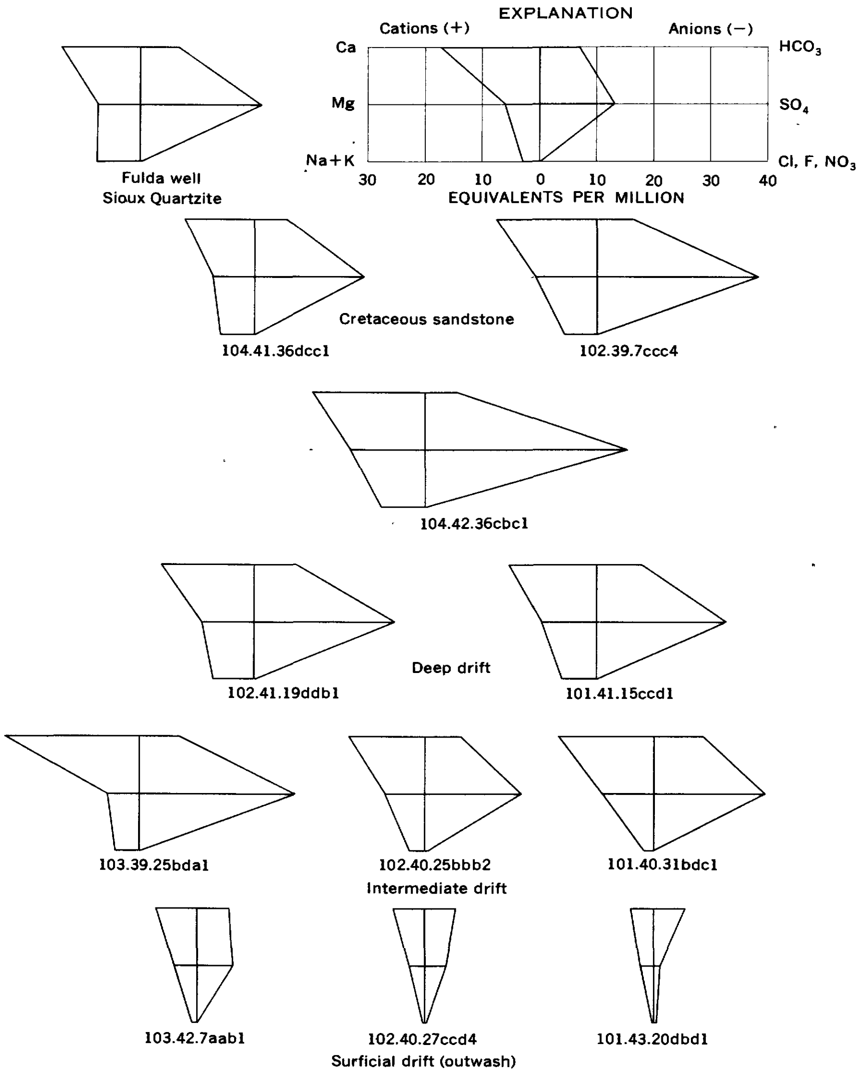

FIGURE 12.—Chemical characteristics of water from different aquifers in Nobles County and the Fulda municipal well, Murray County.

Calcium, magnesium, and silica contribute to the formation of boiler scale and deposits in hot-water heaters and pipes. Excess iron causes reddish-brown stains on porcelain fixtures and clothing. Manganese causes dark-brown to black stains on porcelain fixtures and on clothing. All these constituents contribute to incrustation on well screens and clogging of well systems.

"Iron bacteria" are troublesome in water containing excess iron. The bacteria utilize the dissolved iron in their life process, changing it to an insoluble form that produces a slime and may plug water systems and water-bearing formations in the vicinity of the well. The bacteria also impart a bad taste and odor to the water. Chlorine is effective in the removal of such undesirable organisms.

Following are some of the recommended limits for proposed chemical drinking water standards of the U.S. Public Health Service (U.S. Department of Health, Education, and Welfare, 1962):

	Element content (ppm)
Iron (Fe)	0.3
Manganese (Mn)	0.5
Magnesium (Mg)	50
Sulfate (SO_4)	250
Chloride (Cl)	250
Fluoride (F; must not exceed 3.0)	1.0
Detergents (as alkyl benzene sulfonate, ABS)	0.5
Total solids	500

Nitrate in drinking water in excess of 44 ppm (expressed as nitrate nitrogen, 10 ppm) may cause the condition in infants known as methemoglobinemia ("blue babies"). In some wells, excess nitrate in water is due to contamination by sewage or other organic matter.

SUMMARY AND CONCLUSIONS

The principal sources of ground water in the Nobles-Jackson County area are the outwash deposits included in the glacial drift of Pleistocene age. The drift and Recent alluvial deposits of minor extent mantle the entire area. The drift ranges in thickness from about 150 feet in the northeast and southwest corners of the area to about 500 feet along the highest part of the Coteau des Prairies. Drift aquifers in the area are classified as buried outwash and surficial outwash. The buried outwash supplies water to wells of 7 out of 10 of the municipalities and most of the farms in the area. The known deposits range in thickness from a fraction of a foot to more than 25 feet. Undoubtedly greater thicknesses will be found as more test holes are drilled in the area. The buried outwash occurs at depths from about 15 feet below land surface to the bottom of the drift. They are not extensive in area; holes have penetrated the entire drift thickness without passing through an outwash body. Where the deposits are below the water table and permeable, they will yield small to large quantities of water to properly constructed wells. Some wells completed in these deposits have yielded 500 gpm for short periods. Wells for ordinary farm use, 3 to 10 gpm, may be completed almost anywhere in the buried deposits.

Test drilling is the best method available for delineating these buried deposits. Because they are mostly narrow, sinuous, and of limited extent, accurate mapping will require test holes drilled closer than a quarter of a mile apart.

The most important surficial outwash deposits are in the channels of the proglacial streams that flowed from the morainal fronts. The deposits generally range in thickness from 0 to about 60 feet. They lie in the stream channels as valley-bottom fill and terrace fill and range in width from a few feet to about 1 mile.

A well completed in a channel deposit at Adrian was tested at 400 gpm. Four municipalities and many farms obtain part or all of their water supplies from the channel deposits, which can be recognized by their unique topographic expression. Satisfactory supplies can be obtained at low cost because the water table is near land surface and shallow wells penetrate adequate saturated thickness.

The assortment of grain sizes in both the buried and surficial outwash deposits is extremely variable. Well-sorted sand and gravel sections may grade laterally and vertically into much finer sediments in very short distances, and the grain sizes in any particular section may range from silt to coarse gravel. In most areas satisfactory water supplies can be obtained only from properly constructed wells that have been thoroughly developed by surging, pumping, backwashing, and similar methods. In any development of large water supplies, tests should be made by qualified hydrologists to assure that a well is yielding the maximum amount obtainable from the aquifer that it penetrates.

A secondary source of ground water is the deep-lying Cretaceous sandstones. Several farms, mostly in the north-central and eastern part of the area, obtain ample supplies from wells completed in sandstone at depths ranging from 283 to 586 feet below land surface. The Cretaceous formations are widespread, except in the northwest and northeast parts of the area where the Sioux Quartzite lies directly beneath the glacial drift. The thicker the Cretaceous section the better the chance of intercepting water-bearing sandstone. However, where the Cretaceous sandstone and shale are underlain by Sioux Quartzite, they may be quite thin.

Cretaceous sandstone in this area is generally fine grained; sand infiltration, therefore, poses a serious problem to wells. Modern well construction techniques may be used to combat part of this difficulty.

Most of the ground water in this area is highly mineralized. The best quality ground water is in the surficial outwash deposits having dissolved solids that range from 425 to 870 ppm. All other ground water has dissolved solids of 1,100 ppm or more.

SELECTED TEST HOLE AND WELL LOGS

Table 6 contains 26 selected test hole and well logs from a total of 195 test-hole and well logs collected during this investigation. Many of the test holes and wells in the table are referred to in the text. Those test holes, shown graphically on illustrations in the report, are not included in the table. Whether the listed log refers to a well, test hole, or U.S. Geological Survey drilled test hole is indicated under the location number. The remaining 169 logs not listed in table 6 are on file at the U.S. Geological Survey, Ground Water Branch Office, St. Paul, Minn., 55101.

TABLE 6.—*Selected test hole and well logs*

101.40.11baa2

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, black	0.5	0.5	Till, silty, sandy, pebbly, gray	8	49
Clay, gray and tan; contains pebble-size limey masses	.5	1	Sand, fine, medium, coarse; fine, medium gravel; gray till; layered	8	57
Till, silty, sandy, pebbly, yellow-brown	7	8	Till, silty, sandy, pebbly, gray, compact	24	81
Till, silty, sandy, pebbly, gray-brown	10	18	Sand; gravel; gray till; bouldery	6	87
Till, silty, sandy, pebbly, gray	18	36	Till, silty, sandy, pebbly, bouldery, gray	24	111
Sand, fine, medium, coarse; many shale grains	5	41			

101.40.11bda1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Till, silty, sandy, pebbly, yellow-brown	8	8	Till, silty, sandy, pebbly, bouldery, gray	12	95
Till, silty, sandy, pebbly, grayish-tan	13	21	Sand; gravel; till; boulders	2	97
Till, silty, sandy, pebbly, gray	12	33	Till, silty, sandy, pebbly, gray; contains some thin sand and gravel layers	29	126
Sand, very fine, fine, medium; contains many shale grains	6	39			
Till, silty, very sandy, pebbly, gray	41	80			
Sand, fine, medium, coarse; fine gravel; angular to subrounded; contains many shale grains	3	83			

TABLE 6.—*Selected test hole and well logs*—Continued

101.40.27ddd1

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, silty, sandy, brown	0.5	0.5	Clay, sandy, gray-brown, soft	6	47
Sand; fine gravel	4.5	5			
Sand, fine, medium, coarse; fine, medium, coarse gravel; contains many shale grains	36	41			

101.40.28aaab1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, black, humic	5	5	Sand	2	185
Clay, dark-gray	2	7	Till, silty, sandy, pebbly; mostly yellow-brown, some light-gray	72	257
Clay, light-gray	4	11	Till, silty, sandy, pebbly, yellow-brown to gray, compact	15	272
Till, silty, pebbly, yellow-brown	5	16	Clay, silty, dark-gray, compact	7	279
Till, silty, pebbly, gray-brown	28	44	Till, silty, sandy, yellow-brown and gray; becomes mostly gray at about 305 feet	76	355
Till, silty, gray; few pebbles	24	68	Sand, fine to coarse	3	358
Sand	2	70	Till, silty, sandy, pebbly, yellow-brown and gray; compact	2	360
Till, silty, bouldery, gray	70	140	Clay, pinkish-tan, compact	17	377
Gravel, fine, angular to subrounded; mostly shale and limestone grains	1	141			
Till, silty, gray	36	177			
Till, silty, sandy, pebbly, light-gray, compact	6	183			

TABLE 6.—*Selected test hole and well logs*—Continued

101.40.33bcc1

[Test hole]

Material	Thickness (feet)	Depth (feet)
Soil, sandy, brown; some pebbles	1.5	1.5
Clay, sandy	1.5	3
Till, sandy, pebbly, light-brown to brown	29	32
Till, sandy, pebbly, bluish-gray	41	73
Sand; gravel; contains some silt and clay	5	78
Till, sandy, pebbly, bluish-gray	113	191
Till, silty, sandy, pebbly, greenish-tan, compact	36	227
Till, sandy, pebbly, bluish-gray	36	263
Till, sandy, pebbly, yellow-tan, soft	25	288
Till, sandy, pebbly, gray-brown	30	318
Sand; fine, medium, coarse; fine gravel	2	320
Clay, light grayish-brown, smooth; contains some sand	13	333
Clay, light pinkish-tan, smooth; contains some brown and gray shale	94	427
Shale, brown, green, gray; contains some sandy, pebbly brown clay	35	462
Sandstone, fine-grained, gray, quartzitic; interbedded with smooth blue-gray, blue-green, dark-green, and gray-brown shale	188	650
Shale, green-gray, gray-blue, gray-brown; contains some white to buff fine sandy, chalky strata and some thin sandstone lenses	30	680
Sandstone, fine-grained, buff-gray with interbedded gray-brown and gray shale	22	702
Shale, gray-green and dark-gray, smooth, soft; contains sandstone lenses	45	747

101.41.15 cbb1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)
Soil, black, clayey	1	1
Till, clayey, sandy, pebbly, yellow-brown	25	26
Till, silty, pebbly, dark grayish-brown	11	37
Till, silty, sandy, pebbly, bouldery, gray	200	237
Till, silty, sandy, pebbly, light-gray and dark-gray	30	267
Silt, gray; very fine to medium sand	5	272
Till, silty, sandy, pebbly, yellow-brown and gray; more silty and sandy at 328–338 feet	66	338
Sand, fine; till, bouldery, yellow-brown and gray	5	343
Clay, smooth, brown (soil); silt; yellow-brown, light-gray, and gray till	7	350
Till, silty, sandy, pebbly, bouldery, yellow-brown, light-gray, gray	73	423

TABLE 6.—*Selected test hole and well logs*—Continued

101.41.22aaa1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)
Till, silty, sandy, pebbly, brown	17	17
Till, silty, sandy, pebbly, gray-brown	7	24
Sand, medium, to medium gravel, brown	7	31
Till, silty, pebbly, gray	4	35
Sand, coarse to fine, gray; fine to medium gravel	4	39
Till, silty, sandy, pebbly, yellow-brown	13	52
Till, silty, pebbly, gray	218	270
Sand; gravel	2	272
Soil, dark-brown, compact	2	274
Till, silty, sandy, pebbly, light-gray	14	288
Till, silty, sandy, pebbly, dark-gray	126	414

101.41.22bac1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)
Soil, silty, black	1. 5	1. 5
Soil, silty, yellow-brown	1. 5	3
Till, clayey, silty, yellow-brown; few pebbles	14	17
Till, clayey, silty, gray-brown; few pebbles	13	30
Till, silty, sandy, pebbly, gray	177	207
Sand; gravel	2	209
Till, silty, sandy, pebbly, gray	23	232
Rocks; gray till; some gravel	6	238
Soil, brown	3	241
Till, silty, sandy, pebbly, gray; some yellow-brown till	35	276
Silt; fine sand	3	279
Till, silty, sandy, pebbly, gray; some yellow-brown till	58	337
Till, silty, sandy, pebbly, light-gray, gray, yellow-brown, very compact	20	357
Boulders; silty, sandy, pebbly gray and yellow-brown till	15	372
Till, silty, sandy, pebbly, gray and yellow-brown	26	398

101.41.22bbb1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)
Till, silty, pebbly, yellow-brown	16	16
Clay, gray-brown; smooth	2	18
Silt; tan-gray sand	3	21
Till, silty, sandy, yellow-brown	5	26
Till, clayey, silty, sandy, gray-brown; few pebbles	23	49
Till, silty, sandy, pebbly, gray	197	246
Sand, angular to subrounded; gravel; boulders; gray and yellow-brown till	20	266
Till, silty, sandy, gray	40	306
Till, silty, yellow-brown	1	307
Till, silty, sandy, pebbly, gray	10	317
Till, silty, sandy, greenish yellow-brown	8	325
Till, silty, sandy, gray	7	332
Till, silty, grayish to light yellow-brown	36	368
Till, silty, gray-brown and yellow-brown	61	429

TABLE 6.—*Selected test hole and well logs*—Continued

102.40.7bcb1

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, silty, black, humic; contains chalk nodules in leached zone	4.5	4.5	Till, silty, sandy, pebbly, gray	60	139
Till, silty, pebbly, yellow-brown and gray	5.5	10	Sand, fine, medium, coarse, clayey; fine, medium gravel; contains buff till	5	144
Till, silty, sandy, pebbly, bouldery, gray	67	77	Till, silty, sandy, gravelly, yellow-brown	6	150
Sand, medium to coarse; fine gravel	2	79	Sand, clayey; gravel	2	152
			Till, silty, sandy, pebbly, gray	8	160

102.40.7caa1

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, silty, clayey, black, humic	2	2	Till, silty, sandy, gravelly, yellow-brown	18	154
Till, silty, sandy, pebbly, yellow-brown	9	11	Sand; gravel; yellow-brown sandy clay	2	156
Till, silty, sandy, pebbly, gray	101	112	Till, silty, sandy, gravelly, yellow-brown; contains boulders	5	161
Sand, fine, medium, coarse; fine, medium, coarse gravel; contains sandy gray clay and cobbles	7	119	Till, silty, sandy, gravelly, gray	2	163
Till, silty, sandy, gravelly, gray	17	136			

102.40.7cba2

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, silty, black, humic	3	3	Gravel, fine to coarse, subangular to rounded; contains fine, medium, coarse sand	14	126
Till, silty, sandy, pebbly, yellow-brown	6	9	Till, silty, sandy, pebbly, gray	13	139
Till, silty, sandy, pebbly, gray, compact	15	24	Till, silty, sandy, pebbly, yellow-brown	24	163
Till, silty, sandy, pebbly, yellow-brown	2	26			
Till, silty, sandy, pebbly, gray	86	112			

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TABLE 6.—*Selected test hole and well logs*—Continued

102.40.7ccc1

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, black, humic	0.5	0.5	Till, silty, sandy, pebbly, gray	64	120
Till, silty, sandy, pebbly, yellow-brown; contains some gray till	9.5	10	Sand, fine, medium, coarse; fine, medium, coarse, angular to rounded gravel; contains boulder layers	8	128
Till, silty, sandy, pebbly, gray	44	54	Till, silty, sandy, pebbly, gray, compact	7	135
Silt, clayey	2	56			

102.40.13aaa1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, black, humic	2	2	Till, silty, sandy, light-gray	42	277
Clay, light-brown and gray	2.5	4.5	Clay, silty, chocolate-brown	2	279
Sand, fine, to fine gravel; limonite stained; contains some silty, sandy yellow-brown till	4.5	9	Till, silty, sandy, olive-yellow-brown and gray	19	298
Till, silty, sandy, pebbly, gray; contains some soft silty layers, some boulders	150	159	Clay, silty, gray and brown; silty, sandy yellowish-brown to gray till	17	315
Till, silty, sandy, pebbly, light yellow-brown to light grayish-brown	11	170	Clay, pinkish-tan, gray and brown	77	393
Clay, brown	4	174	Clay, silty, gray; gray clayey siltstone; interbedded with layers of very fine quartz sand	75	468
Till, silty, pebbly, light yellow-brown	41	215			
Till, silty, sandy, pebbly, gray	20	235			

TABLE 6.—*Selected test hole and well logs*—Continued

102.40.24abc1

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, sandy, gravelly, dark-brown	2	2	Till, silty, sandy, pebbly, yellow-brown and gray; contains pinkish-tan clay and gray clay	27	360
Sand, fine, medium, yellow-brown; contains some gravel and clay	3	5	Clay, pinkish-tan and gray	78	438
Till, sandy, gravelly, yellow-brown	5	10	Shale, blue-gray, gray-black, and greenish-gray; interbedded with thin sand layers; some gray siltstone	115	553
Till, sandy, gravelly, brownish-gray	25	35	Shale, gray, compact; some yellow-brown clay	7	560
Till, sandy, pebbly dark brownish-gray	136	171	Shale, blue-gray, blue-green, gray-black and brown; contains white, gray, and yellow fine-grained sandstone	81	641
Gravel, medium to coarse, angular to rounded; contains fine to coarse sand	3	174	Sandstone, fine-grained, gray; interbedded with gray shale and siltstone; contains white kaolinitic(?) masses	61	702
Till, sandy, pebbly, dark-gray	24	198	Shale, gray; yellow-brown sandy clay; contains some weathered granite (kaolin)	15	717
Silt; sand	4	202	Granite, pink, very hard	6	723
Till, sandy, pebbly, dark-gray	4	206			
Silt; sand	3	209			
Till, sandy, pebbly, dark-gray	20	229			
Till, sandy, pebbly, yellow-brown	9	238			
Till, sandy, pebbly, dark bluish-gray, compact	10	248			
Till, silty, sandy, pebbly, yellow-brown to dark brownish-gray to gray	85	333			

102.41.12dab1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, sandy, black	2	2	Till, clayey, silty, sandy, pebbly, olive-yellow-brown and gray	11	149
Soil, yellow-brown	1	3	Till; sand; gravel; boulders	4	153
Clay, gray and yellow-brown, smooth	3	6	Till, silty, sandy, pebbly, gray	12	165
Till, silty, sandy, pebbly, yellow-brown	6	12			
Till, silty, pebbly, gray-brown	4	16			
Till, silty, sandy, pebbly, gray, compact	122	138			

TABLE 6.—*Selected test hole and well logs*—Continued

102.41.18dcc1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, silty, black	1	1	Till, sandy, pebbly, olive-yellow-brown to tan-buff, compact	56	315
Clay, dark-brown	1	2	Clay (soil), silty, black-brown, compact	3	318
Sand, fine, medium, coarse, orange; fine, medium, coarse gravel	2	4	Till, sandy, pebbly, light-gray, compact	7	325
Till, silty, yellow-brown; few pebbles	13	17	Till, sandy, pebbly, bouldery, olive-yellow-brown and gray; contains some sandy and gravelly zones	118	443
Till, silty, dark grayish-brown	12	29			
Till, silty, sandy, pebbly, gray	192	221			
Sand; till, yellow-brown	1	222			
Till, silty, sandy, pebbly, bouldery, gray	37	259			

102.41.21 ada1

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, black	2	2	Till, silty, sandy, gravelly, dark-gray	56	300
Till, clayey, silty, sandy, gravelly, yellow-brown	14	16	Sand; gravel	3	303
Till, silty, sandy, gravelly, dark-gray	113	129	Till, silty, sandy, gravelly, dark-gray	3	306
Clay; sand; gravel; contains boulders	14	143	Till, silty, sandy, gravelly, tan	69	375
Till, silty, sandy, gravelly, dark-gray	94	237	Till, tan; contains thin sand and gravel lenses	19	394
Sand, clayey; gravel	7	244			

102.41.22aad1

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, black	2	2	Boulder, limestone	3	149
Clay (till), yellow-brown	12	14	Clay (till), blue-gray	129	278
Clay (till), blue	76	90	Clay (till), olive-yellow	79	357
Sand; white and blue; gravel	6	96	Clay, dark; compact	3	360
Clay (till), sandy, blue	36	132	Clay (till), yellow, gray, blue, gritty, compact	4	364
Sand, white and blue; gravel	14	146			

TABLE 6.—*Selected test hole and well logs*—Continued

102.41.22acc1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, clayey, silty, black	4	4	Sand, fine, medium, coarse; fine, medium, coarse gravel; contains cobbles and boulders	10	82
Clay, silty, yellow-brown	2	6	Till, silty, sandy, pebbly, gray	15	97
Till, silty, sandy, pebbly, yellow-brown	4	10			
Till, silty, sandy, pebbly, gray	62	72			

102.41.22acc2

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, clayey, silty, black	4	4	Till, silty, sandy, pebbly, gray	68	78
Clay, silty, yellow-brown	2	6	Gravel, cobbles, boulders; some clay	9	87
Till, silty, sandy, pebbly, yellow-brown	4	10	Till, silty, sandy, pebbly, gray	10	97

102.41.22cad1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, clayey, silty, black	4	4	Till, silty, sandy, pebbly, gray	44	172
Clay, silty, sandy, brown to gray	3	7	Clay, silty, dark-brown, compact	3	175
Sand, fine, medium, coarse; fine, medium, coarse gravel	7	14	Till, very sandy, gray	78	253
Till, clayey, sandy, silty, gray	84	98	Till, sandy, yellow-brown; some light-gray	47	300
Sand, fine, medium, coarse; fine, medium, coarse gravel	14	112	Clay, dark-brown, compact	3	303
Till, very sandy, gravelly, gray	16	128	Till, sandy, yellow-brown	83	386
			Till, sandy, olive-gray, gray, and yellow-brown	13	399

102.41.27ada1

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, black	2	2	Till, silty, sandy, gravelly, dark-gray; contains thin sand and gravel lenses	66	158
Till, clayey, silty, sandy, gravelly, yellow-brown	18	20	Gravel, fine to coarse; contains coarse to fine sand and cobbles	8	166
Till, silty, sandy, dark-gray	67	87	Till, silty, sandy, gravelly, dark-gray	32	198
Sand, clayey; clayey gravel	5	92			

TABLE 6.—*Selected test hole and well logs*—Continued

102.43.19dda2

[Well]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, sandy, black, humic	2	2	Shale, silty, light olive-gray, smooth, noncalcareous; contains some pyrite and cream-colored silt masses	15	300
Sand, fine, medium, coarse; fine, medium, coarse gravel; some boulders	16	18	Shale, gray, smooth, calcareous	40	340
Till, sandy, pebbly, yellow-brown	2	20	Shale, black and gray, compact; contains calcite, pyrite, and quartz grains	12	352
Till, sandy, pebbly, gray, compact	35	55	Shale, light-gray, bluish-gray, gray, smooth, slightly calcareous, fossiliferous	38	390
Till, yellow-brown	40	95	Shale, gray, compact, slightly calcareous; contains few quartz grains, pyrite, some kaolinitic masses	7	397
Till, brown; contains streaks of gray till	8	103	Sandstone, medium, very fine to coarse; angular to well-rounded grains; contains Cretaceous fossils	1	398
Till, gray	22	125	Shale, gray, smooth, noncalcareous, lignitic	4	402
Till, yellow-brown	10	135			
Till, gray	45	180			
Till, yellow-brown	45	225			
Till, yellow-brown and gray	8	233			
Sand, very fine, fine	2	235			
Till, sandy, pebbly, gray	10	245			
Shale, gray to light-gray, smooth, noncalcareous, compact; contains light-buff, slightly calcareous siltstone	40	285			

103.41.4dbb1

[Test hole]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, clayey, sandy, brown-black	2	2	Till, sandy, gravelly, olive-brown	12	141
Till, silty, sandy, pebbly, blue-gray	105	107	Till, sandy, pebbly, dark-gray	35	176
Sand; gravel	2	109	Till, gray; sand; gravel	12	188
Till, silty, sandy, pebbly, blue-gray	13	122	Till, sandy, pebbly, dark-gray	8	196
Sand, fine, medium, coarse; fine, medium gravel	7	129	Till, silty, sandy, pebbly, olive-yellow-brown	17	213

TABLE 6.—*Selected test hole and well logs*—Continued

104.39.32dac1

[Geological Survey test hole]

Material	Thickness (feet)	Depth (feet)
Soil, silty, black to brown	.5	.5
Clay, tan, smooth; contains few pebbles	3.5	4
Sand, coarse to fine; fine to coarse gravel	5	9
Till, clayey, silty, sandy, light-gray; contains thin sand and gravel seams	42	51
Till, silty, sandy, pebbly, light-tan, compact	47	98
Till, silty, sandy, pebbly, gray	8	106
Gravel, fine to coarse, angular to subrounded	2	108
Till, very gravelly, gray and yellow-brown	3	111
Till, silty, pebbly, gray	23	134
Silt; fine sand; contains some pebbles	9	143
Clay, brown	2	145
Till, silty, sandy, pebbly, gray	6	151
Till, silty, sandy, olive-yellow-brown	5	156
Till, gravelly, yellow-brown and gray; silt; contains some medium gravel	4	160
Till, very pebbly, yellow-brown	29	189
Silt; medium to fine sand	3	192
Clay, silty, pinkish-tan; contains some yellow-brown and gray till (contaminated sample?) and traces of white clay	119	311
Clay, silty, gray; contains some tan clay	21	332
Clay, silty, pinkish-tan; contains some yellow-brown and gray till	38	370
Clay, gray; silt; fine sand; layered; some pyrite grains in sand	43	413

LITERATURE CITED

Baldwin, Brewster, 1949, A preliminary report on the Sioux quartzite: South Dakota Geol. Survey Rept. Inv. 63, 34 p.

Beyer, S. W., 1896, The Sioux quartzite and certain associated rocks: Iowa Geol. Survey, v. 6, p. 69–112.

Doll, H. G., 1948, The S. P. log: Theoretical analysis and principles of interpretation: Am. Inst. Mining Metall. Eng. Tech. Pub. 2463, 40 p.

Fenneman, N. M., 1938, Physiography of eastern United States: New York, McGraw-Hill Book Co., p. 559–605.

Flint, R. F., 1957, Glacial and Pleistocene geology: New York, John Wiley & Sons, 553 p., 5 pl.

Grout, F. F., Gruner, J. W., Schwartz, G. M., and Theil, G. A., 1951, Precambrian stratigraphy of Minnesota: Geol. Soc. America Bull., v. 62, no. 9, p. 1017–1078.

Guyod, Hubert, 1957, Electrical detective: Water Well Jour., v. 9, no. 3, p. 13, 32, 35–36.

Hall, C. W., Meinzer, O. E., and Fuller, M. L., 1911, Geology and underground waters of southern Minnesota: U.S. Geol. Survey Water-Supply Paper 256, 406 p.

Irving, R. D., 1885, Preliminary paper on an investigation of the Archean formations of the northwestern States: U.S. Geol. Survey 5th Ann. Rept., p. 181–242.

Lemke, R. W., 1960, Geology of the Souris River area, North Dakota: U.S. Geol. Survey Prof. Paper 325, 138 p., 16 pl.

Leverett, Frank, 1932, Quaternary geology of Minnesota and parts of adjacent States: U.S. Geol. Survey Prof. Paper 161, 149 p., 5 pl.

Leverett, Frank, and Sardeson, F. W., 1932, Map of the southern part of Minnesota showing surficial deposits, pl. 2 *in* Leverett, Frank, Quaternary geology of Minnesota and parts of adjacent States: U.S. Geol. Survey Prof. Paper 161.

Lohr, E. W., and Love, S. K., 1954, The industrial utility of public water supplies in the United States, 1952, pt. 2, States west of the Mississippi River: U.S. Geol. Survey Water-Supply Paper 1300, 456 p.

Lund, E. H., 1956, Igneous and metamorphic rocks of the Minnesota River valley: Geol. Soc. America Bull., v. 67, p. 1475–1490.

Meinzer, O. E., 1923, Outline of ground-water hydrology with definitions: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

Norvitch, R. F., 1960, Ground water in alluvial channel deposits Nobles County, Minnesota: Minnesota Div. of Waters Bull. 14, 23 p.

Schneider, Robert, 1958, Correlation of ground-water levels and air temperatures in the winter and spring in Minnesota: Minnesota Div. of Waters Tech. Paper 1, 17 p.

Stiff, H. A., Jr., 1951, The interpretation of chemical water analyses by means of patterns: Petroleum Tech. Jour., Tech. Note 84, sec. 1, p. 15–16.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., p. 519–524.

——1938, The significance and nature of the cone of depression in ground-water bodies: Econ. Geology, v. 33, no. 8, p. 889–902.

Theis, C. V. and others, 1954, Estimating transmissibility from specific capacity: U.S. Geol. Survey open-file report.

Thiel, G. A., 1944, The geology and underground waters of southern Minnesota: Minnesota Geol. Survey Bull. 31, 506 p.

U.S. Dept. of Commerce, Bureau of the Census, 1956, United States census of agriculture, 1954: U.S. Dept. of Commerce, v. 1, pt. 8.

U.S. Department of Health, Education, and Welfare, 1962 Public Health Service drinking water standards: Public Health Service Pub. 956, p. 7.

Upham, Warren, 1884, The geology of Cottonwood and Jackson Counties; the geology of Murray and Nobles Counties: The geological and natural history survey of Minnesota: Final Rept., Univ. of Minnesota, 1872–1882, v. 1, p. 491–532.

Wilder, F. A., 1899, Geology of Lyon and Sioux Counties: Iowa Geol. Survey Ann. Rept., 1899, v. 10, p. 81–155.

Winchell, N. H., 1873, The geological and natural history survey of Minnesota: Second Ann. Rept., Univ. of Minnesota, 219 p.

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