# WATER RESOURCES OF BROOKINGS AND KINGSBURY COUNTIES, SOUTH DAKOTA

By Louis J. Hamilton

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U.S. GEOLOGICAL SURVEY

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DEPARTMENT OF THE INTERIOR

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## CONVERSION FACTORS

For those readers interested in converting inch-pound units to metric (International System) units, the following factors are used:

| Multiply inch-pound unit | By | To obtain metric unit |
|---|---|---|
| acre-foot (acre-ft) | 1,233 | cubic meter |
| acre-foot (acre-ft) | 0.001233 | cubic hectometer |
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year |
| cubic foot per second ($ft^3/s$) | 0.028317 | cubic meter per second |
| cubic foot per second per square mile [$(ft^3/s)/mi^2$] | 0.01093 | cubic meter per second per square kilometer |
| foot (ft) | 0.3048 | meter |
| foot per year (ft/yr) | 0.3048 | meter per year |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer |
| foot per day (ft/d) | 0.3048 | meter per day |
| gallon per minute (gal/min) | 0.06308 | liter per second |
| inch | 25.4 | millimeter |
| inch per year (in/yr) | 25.4 | millimeter per year |
| mile (mi) | 1.609 | kilometer |
| pound per square inch ($lb/in^2$) | 6.895 | kilopascal |
| square foot per day ($ft^2/d$) | 0.09290 | square meter per day |
| square mile ($mi^2$) | 2.590 | square kilometer |

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

Brookings and Kingsbury Counties occupy an area of 1,667 square miles, mostly within the Coteau des Prairies, a plateau in eastern South Dakota. The area is mostly undulating to hummocky, glaciated plains that have thousands of small lakes and marshes. Broad, flat valleys that contain glacial outwash are incised 50 to 100 feet into the plains by the southward-flowing Big Sioux River in Brookings County. In western Kingsbury County, southward-flowing tributaries to the James River contain little outwash sand and gravel. The water resources of the area are relatively undeveloped except for large withdrawals for irrigation from shallow glacial aquifers. The aquifers can supply additional water to large-capacity wells. Total water use in 1985 was estimated to be about 16,000 acre-feet. Of this quantity, 10 percent was from surface water and 90 percent from ground water.

The largest and most reliable stream in the study area is the Big Sioux River, which drains about 2,400 square miles of the Coteau within and north of Brookings County. Average annual flow of the Big Sioux River at the streamflow gaging station near Brookings was 117,000 acre-feet during 1954-83 but has ranged from 270,000 acre-feet (in water year 1978) to 18,000 acre-feet (in water year 1981). The estimated gain in flow of the river from ground-water discharge from 700 square miles within and upstream of the study area averages about 42,000 acre-feet annually. In spite of this discharge, there are numerous periods of extremely low flow because of drought, evapotranspiration, and pumpage. The area has more than 2,000 small, shallow lakes, ponds, and marshes. Only 3 lakes in Brookings County and 6 lakes in Kingsbury County are larger than 1,000 acres. All the lakes contain fresh to slightly saline water.

Six major glacial aquifers of outwash sand and gravel store 8 million acre-feet of fresh to slightly saline, very hard water beneath about four-fifths of the study area, at depths ranging from land surface to greater than 700 feet. The Big Sioux aquifer underlies 540 square miles, at depths within a few tens of feet of land surface but locally at depths of more than 200 feet. The Vermillion East Fork aquifer is in 94 square miles of Kingsbury County at depths from land surface to as much as 120 feet. These two aquifers store 2.3 million acre-feet of water. Four buried, till-covered glacial aquifers store 5.7 million acre-feet of slightly saline, very hard water beneath about 1,200 square miles in the study area. Glacial aquifers may yield as much as 1,800 gallons per minute to a well, but pumping lifts may be as large as 500 feet for the deepest aquifer.

Water in the Big Sioux and Vermillion East Fork aquifers is suitable for irrigation. Water in buried glacial aquifers is considered to be marginal to unsuitable for irrigation because of large concentrations of dissolved solids and sodium. Effects of withdrawals on drawdown of water levels of glacial aquifers are limited because of small pumpage and large recharge. Temporary water-level drawdowns of a few feet at most wells are measured at distances of 1 mile from large-capacity wells.

Three bedrock aquifers store 67 million acre-feet of slightly saline, relatively soft water beneath three-fourths of the study area. Depths to the tops of the aquifers range from 230 feet in southwestern Kingsbury County to 1,300 feet in eastern Brookings County. Large withdrawals through flowing wells have lowered water levels of the Dakota aquifer about 200 feet during the past century and wells no longer flow. Maximum yields of wells are estimated to be about 100 gallons per minute. Water from bedrock aquifers is unsuitable for irrigation use because of large concentrations of sodium.

## INTRODUCTION

Brookings and Kingsbury Counties contain 1,667 square miles of undulating to hummocky, glaciated plains and thousands of small, shallow lakes, ponds, and marshes on the Coteau des Prairies physiographic division, an extensive plateau in eastern South Dakota (fig. 1). Broad, flat valleys containing glacial outwash are incised 50 to 100 ft into the plains by southward-flowing streams. About three-fourths of the area is cropland, the remainder being mostly pasture and rangeland (U.S. Department of Agriculture, 1970). Most of the crops are used for feeding livestock. Water covers nearly 4 percent of the area in wet years.

Agriculture, directly or indirectly, supports most of the population of nearly 31,000 people. The population relies entirely on ground water for municipal and rural domestic supplies. The population in towns and cities comprises about 70 percent of the total. The largest city, Brookings, has a population of about 15,000 people and is the home of South Dakota State University. The University conducts many agricultural research projects on research farms within a few miles of Brookings. Studies are conducted to determine the optimal concentrations of agricultural chemicals that can be applied to land and crops without contaminating the environment.

This study is another of a series of evaluations of the water resources of counties in eastern South Dakota (fig. 1). The study was conducted by the U.S. Geological Survey in cooperation with the South Dakota Geological Survey, Brookings and Kingsbury Counties, and the East Dakota Water Development District. The geology and mineral resources of the area were studied concurrently by the South Dakota Geological Survey. The author extends his appreciation for cooperation to local residents, municipal water superintendents, engineers for rural water systems, well drillers, and pump-repair contractors for information on well construction, well yields, and ground-water levels.

### Purpose and Scope

The purpose of this study was to provide reliable basic data and analyses needed for water-resources evaluation and for the efficient use of these resources for agriculture, rural water systems, municipalities, and industry. The purpose of this report is to describe (1) the extent and availability of water in streams, lakes, and glacial and bedrock aquifers, (2) the hydrologic system as it influences availability of water, (3) the effects of increased withdrawals on water availability, and (4) the quality of the water. The study emphasized glacial sand and gravel aquifers because little was known of their extent and water-yielding potential.

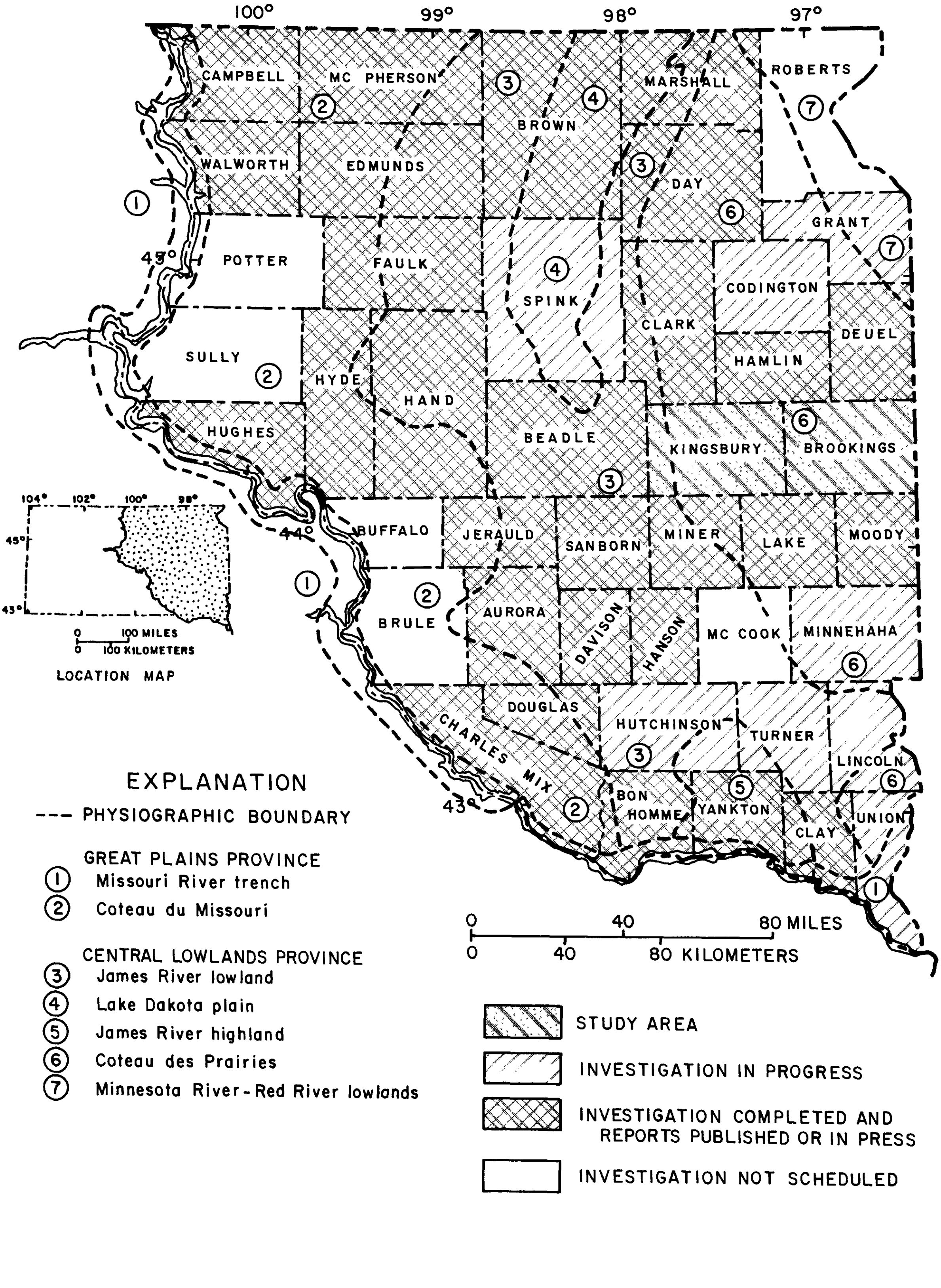



Figure 1.--Index map of eastern South Dakota showing study area, status of county investigations, and major physiographic divisions.

## Need for Future Study

Although this was a comprehensive study, a more detailed hydrologic study may be needed locally where development of large supplies of water is planned. In particular, the heterogeneous nature of glacial-outwash aquifers requires that additional holes be drilled and pumped in order to assure that the aquifer has a sufficient thickness and permeability for the required yield of water. Additional observation wells also would be necessary for accurately determining the direction and rate of ground-water movement. Chemical analysis of water from observation wells can be used to determine the quality of the water and delineate possible areas of contamination.

## Method of Investigation

Existing streamflow data were obtained from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) as computer-printed tables and statistical analyses. Additional data sources are listed in the Previous Investigations section of this report. Delineation of different oxidized till layers and soil zones in glacial deposits was useful in estimating the relative ages and connection of glacial till sheets and outwash units. Geohydrologic data from about 600 test holes and 1,400 wells were analyzed to determine the extent, thickness, yield, and water quality of aquifers. Electric logs were run on the 250 test holes that were drilled into bedrock. Water levels were measured quarterly in a network of 50 observation wells in aquifers below a depth of 100 ft. Additional water-level data are available from 80 observation wells in shallow aquifers. Most of the wells were drilled by the South Dakota Geological Survey. Water levels in shallow wells were measured four to six times each year by the South Dakota Department of Water and Natural Resources. The Department also measured water levels at 14 lake gages semiannually to determine increases in storage and flooding during 1983-87, a period of greater than normal precipitation and runoff.

Samples of water were collected from about 600 wells for field tests of specific conductance, hardness, and concentrations of bicarbonate and chloride. About 20 water samples were collected from representative wells for laboratory chemical analyses for the major constituents and selected trace elements generally detected in ground water. Wells, test holes, lake gages, and water sampling sites are numbered according to the Federal land-survey system of eastern South Dakota (fig. 2).

## Previous Investigations

Information on the regional geology and extent of aquifers was obtained from reports by Barari (1968, 1971a, 1971b), Barari and Slugg (1976), Flint (1955), Hansen (1986), Howells and Stephens (1969), Koch (1980), Koch and McGarvie (1988), Kume (1985), Lee (1958a, 1958b, 1958c), McGarvie (1983), Rothrock (1943), Tomhave (1987, 1988), and Beissel and Gilbertson (1987). A soils map for Brookings County (Westin and others, 1955) was useful for delineating shallow parts of the Big Sioux aquifer.

Information on water quality was obtained from reports by Bardwell (1984), Leibbrand (1985), Nelson and others (1984), Petri and Larson (1967), South Dakota Water Resources Institute (1986), and State Lakes Preservation Committee (1977). Streamflow data were obtained from several compilations (U.S. Geological Survey, 1964, 1969, 1973, and 1972-87). Precipitation data were obtained from annual climatic summaries for South Dakota that were prepared by the National Climatic Data Center, Asheville, North Carolina.

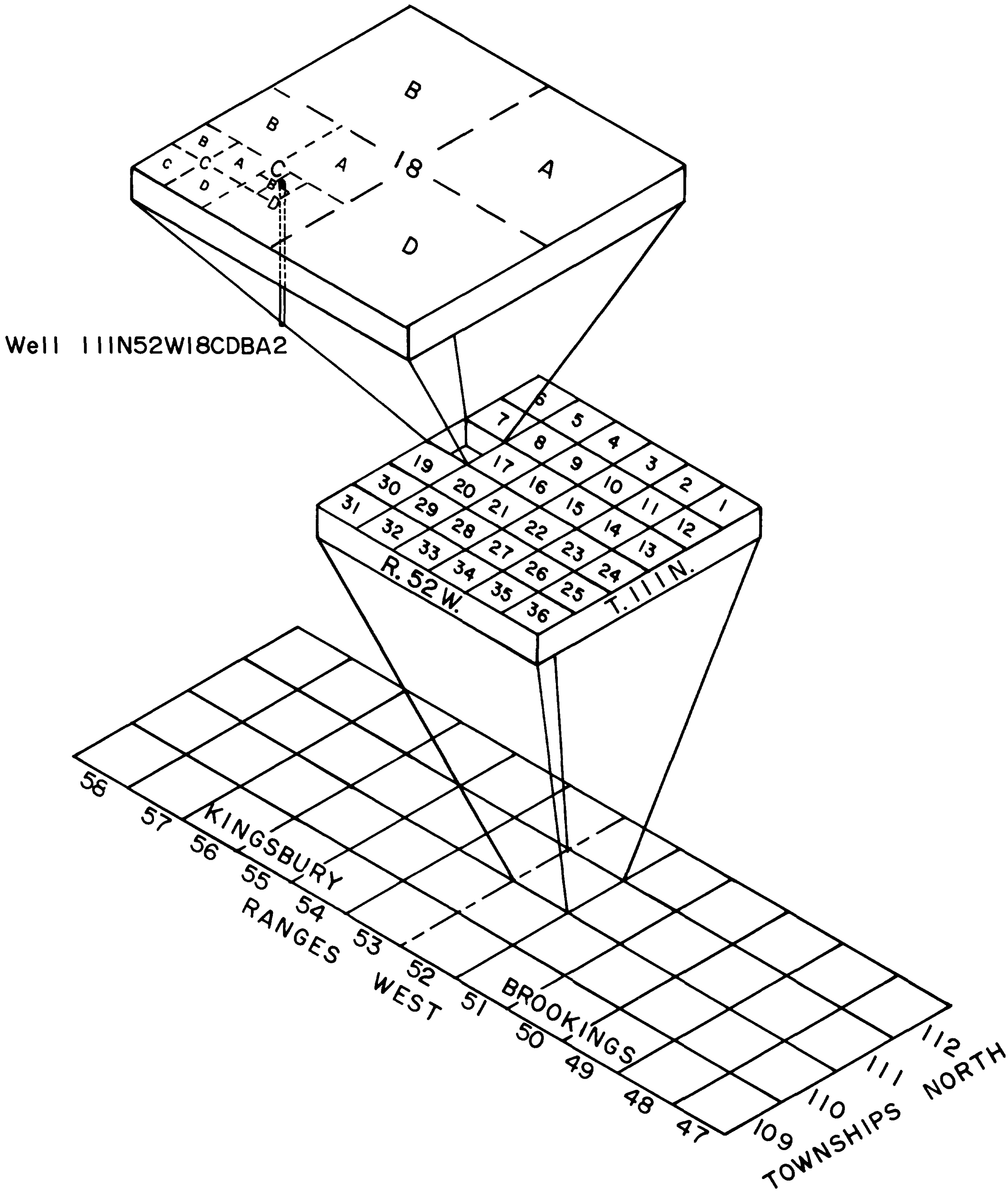



Figure 2.--Site-numbering diagram. The well number consists of township followed by "N," range followed by "W," and section number, followed by a maximum of four uppercase letters that indicate, respectively, the 160-, 40-, 10-, and 2½-acre tract in which the well is located. These letters are assigned in a counterclockwise direction beginning with "A" in the northeast quarter. A serial number following the last letter is used to distinguish between wells in the same tract. Thus, well 111N52W18CDBA2 is the second well recorded in the NE¼ of the NW¼ of the SE¼ of the SW¼ of section 18 in township 111 north and range 52 west of the 5th meridian and baseline system.

## Hydrology

All water in the study area is derived from precipitation, which supplies water for evapotranspiration, ground-water recharge, and runoff. Precipitation in the 1,667-$mi^2$ study area averages nearly 2 million acre-ft (22.5 inches) annually. Surplus precipitation, generally from snowmelt and rainfall in the spring, recharges ground water and supplies runoff to streams and lakes. Water flowing into the area through the Big Sioux River and several small streams averages about 63,000 acre-ft annually. Three-fourths of the precipitation falls during the growing season and is consumed mostly by evapotranspiration. Evapotranspiration, estimated as the difference between precipitation and runoff, averages about 1.9 million acre-ft (21.4 inches) annually. Runoff, including both ground water and surface runoff, averages about 53,000 acre-ft (0.6 inch) annually. Over many years, recharge is assumed to balance discharge of ground water and is not discussed separately in the generalized hydrologic balance between inflow and outflow. Yearly outflow through the Big Sioux River and small streams is estimated to average about 120,000 acre-ft.

## Geology of the Hydrologic System

The melting of thick, stagnant ice sheets during the Pleistocene Epoch in eastern South Dakota left an undulating to hummocky landscape. In the study area, there are many closed depressions ranging from 0.1 to 25 $mi^2$ that store much water and reduce the amount of runoff in wet years. However, the amount of ground water stored in water-yielding rock units is vastly larger than storage of surface water in the study area.

Ground water is stored in a thousand-foot-thick sequence of rock units that range in age from Pleistocene to Precambrian (table 1). The most permeable rock unit is unconsolidated sand and gravel that was deposited as outwash from continental glaciers that advanced into the area several times during the Pleistocene Epoch (Beissel and Gilbertson, 1987). Several extensive, separate sheets of outwash were deposited across many hundreds of square miles. The outwash was deposited by meltwater streams at the ice front and was then extended further into the study area as the ice advanced.

The glacial aquifers described in this report are mostly glacial outwash but locally may contain some alluvium and lake deposits. The outwash is mostly sand and gravel that is stratified and moderately to well-sorted. The sand and gravel is very permeable because it is composed of much coarse sand and fine gravel that is loosely packed, uncemented, and angular, which leaves large pore spaces between the rock fragments. There is little silt and clay that would tend to clog the pores.

Glacial till overlies all but the shallowest glacial aquifers. As each ice sheet stagnated and melted, it deposited thick layers of till over the outwash. Till is an unsorted, unstratified mixture of clay, silt, sand, gravel, and boulders. In the study area, till contains a large percentage of clay derived from soft shale fragments that were ground up by the ice. Generally, the clay causes the till to have a small permeability, yields little water to wells, and slows recharge of precipitation to aquifers. However, some of the till is sandy and moderately permeable. In addition, within the till, steeply sloping sand and gravel beds can provide hydraulic connection with buried aquifers and the land surface.

Table 1.--Principal rock units and their water-yielding characteristics

| System | Series | Geologic unit | Thickness (feet) | Water-bearing unit | Description |
|---|---|---|---|---|---|
| Quaternary | Holocene and Pleistocene | Alluvium, glacial till, and outwash | 15-800 | Outwash deposits of sand and gravel | Clay, silty; poorly permable. Contains sand and gravel; sand and gravel may occur in layers up to 300 feet thick. Very permeable. |
| Cretaceous | Upper Cretaceous | Pierre Shale | 0-143 | | Shale; contains bentonite and marl. Poorly permeable. |
| | | Niobrara Formation | 0-155 | Fractures and joints in chalk | Calcareous, brittle shale; contains thin layers of chalk; moderately to poorly permeable. |
| | | Codell Sandstone Member | 0-170 | Sandstone layers | Sandstone, very fine to medium-grained; siltstone, and shale. Moderately permeable. |
| | | Carlile Shale | 0-176 | Sand lenses | Shale, locally sandy. Poorly permeable. |
| | | Greenhorn Limestone | 0-38 | Joints and fractures in limestone | Limestone and calcareous shale. Poorly permeable. |
| | | Graneros Shale | 0-260 | Sand layers | Shale, sandy, silty. Poorly permeable. |
| | | Dakota Sandstone | 0-500 | Sandstone and siltstone | Sandstone; very fine to coarse-grained, silty, interbedded with siltstone and shale. Moderately permeable. |
| Pre-Cretaceous | | Quartzite wash | 0-30 | Sand | Quartzite sand, overlying the Sioux Quartzite. Moderately permeable. |
| Precambrian | | Sioux Quartzite | Unknown, probably thousands of feet | Joints and fractures in quartzite | Quartzite, well cemented, massive, fractured and jointed. Poorly permeable to impermeable. |
| | | Igneous and metamorphic rocks | Unknown, probably many tens of thousands of feet | Joints and fractures in upper few tens of feet | Granites, andesites, rhyolites, schists. Impermeable. |

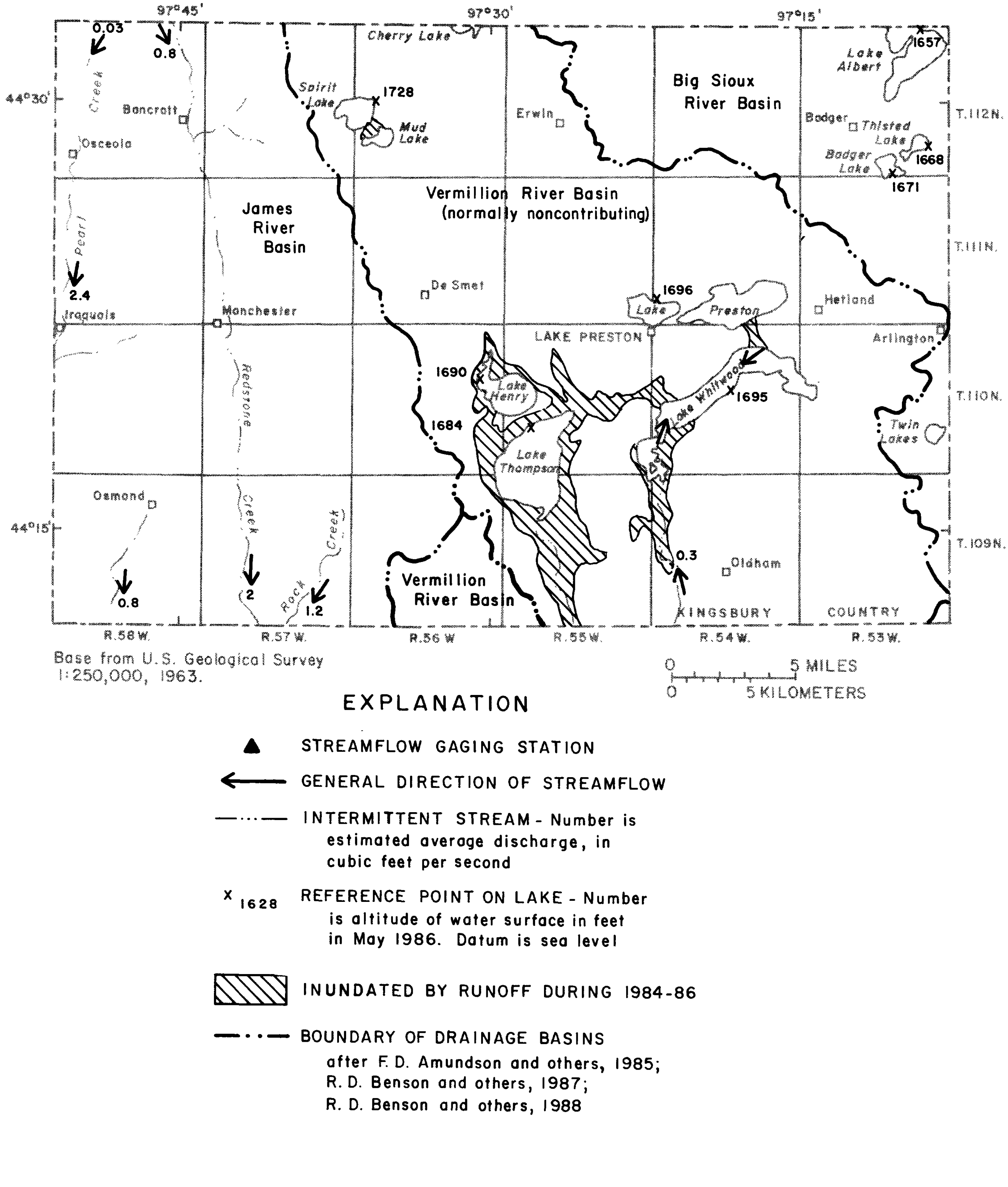



Figure 3.--Lakes, streams, and estimated streamflow.

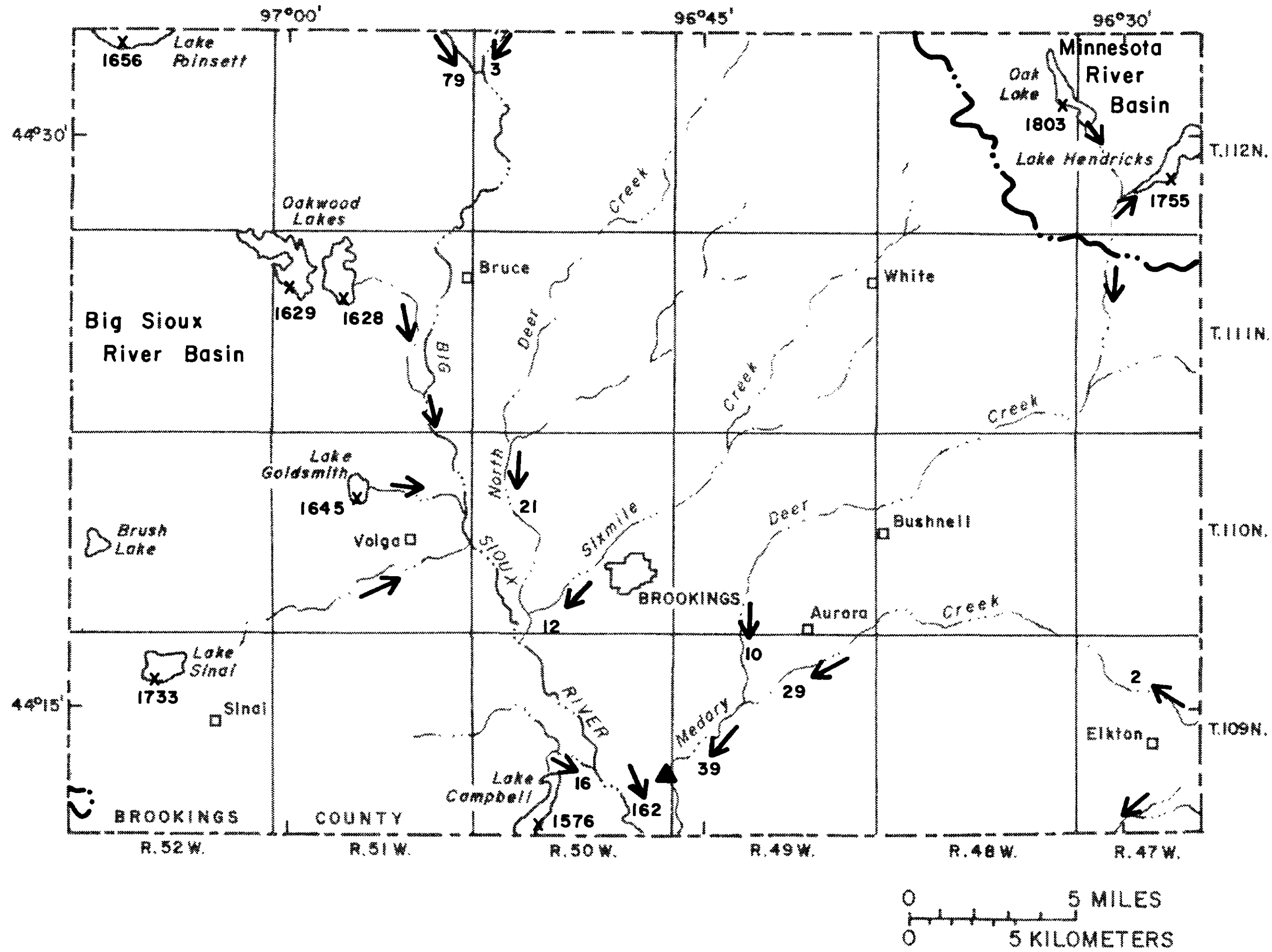



Figure 3.--Lakes, streams, and estimated streamflow.--Continued

Bedrock formations in the Cretaceous System that provide many domestic and municipal water supplies are in descending order, the Niobrara Formation, the Codell Sandstone Member of the Carlile Shale, and the Dakota Sandstone (table 1). They lie at depths that range from a few hundred feet in the James River lowland on the west to about 1,300 ft on the Coteau des Prairies in central Kingsbury County.

The Cretaceous rocks are underlaid by Precambrian Sioux Quartzite and other igneous and metamorphic rocks that probably are impermeable except for a few fractures in the upper few tens of feet. Generally, the fracture permeability is small and Precambrian-age rocks cannot supply more than a few gallons per minute to a well.

## SURFACE WATER

Surface water covers about 4 percent of the study area and includes the Big Sioux River and several of its intermittent tributaries from the east. West of the river are 20 shallow lakes, several small streams, and thousands of small ponds and marshes. The Big Sioux River and its tributaries are incised in glacial aquifers that discharge ground water to the streams. In western Kingsbury County, streams are not incised into aquifers and streams do not flow during dry periods.

### Streamflow

The average flow of small streams in the study area can be estimated from a runoff map for the United States (Gebert and others, 1987). Average annual streamflow for ungaged streams was estimated by multiplying a map runoff value of 0.6 in/yr, or 0.04 $(ft^3/s)/mi^2$, by the drainage area. Average annual streamflow is estimated to range from less than 0.1 $ft^3/s$ for drainage areas of only 1 or 2 $mi^2$ to 162 $ft^3/s$ for the Big Sioux River at the streamflow gaging station 9.5 mi southeast of Brookings (fig. 3). The small streams west of the Big Sioux River rarely have any flow, except during spring in years when precipitation during winter and spring is above average. Drainage areas for ungaged streams were derived from published data on drainage areas (Amundson and others, 1985; Benson and others, 1987, 1988) and by estimates of drainage areas by the author.

The Vermillion River noncontributing drainage area of about 400 $mi^2$ in central and southeastern Kingsbury County is mostly hummocky, poorly drained glaciated terrain where local runoff seldom overflows southward into the Vermillion River basin (fig. 3). In western Kingsbury County the average southward inflow to the study area in two small streams (Pearl and Redstone Creeks) is estimated to total about 0.83 $ft^3/s$ (600 acre-ft/yr). The average outflow from Kingsbury County in the James River basin is estimated to total 4 $ft^3/s$ (nearly 3,000 acre-ft/yr).

The Big Sioux River, a tributary of the Missouri River, flows southward along the eastern part of the Coteau and drains a contributing area of 2,419 $mi^2$ (Amundson and others, 1985) upstream of a streamflow gaging station southeast of Brookings (fig. 3). Its average inflow to Brookings County is about 79 $ft^3/s$ (57,000 acre-ft/yr, Kume, 1985, fig. 3). Gaged outflow of the Big Sioux River near Brookings for the period 1954-83 averaged 162 $ft^3/s$ (117,400 acre-ft/yr, U.S. Geological Survey, 1984). Therefore, the average streamflow gain in Brookings County is about 83 $ft^3/s$ (60,000 acre-ft/yr). Nearly 90 percent of the gain is from four major tributaries from the east. The river has large fluctuations in annual flow because there is little regulated storage in the drainage basin. The average annual flow of the river near Brookings decreased in 3 years from 373 $ft^3/s$ (270,000 acre-ft/yr) in water year 1978 to a near-record low of 24.3 $ft^3/s$ (17,600 acre-ft/yr) in water year 1981 because of a drought, increased irrigation pumpage, and decreased ground-water discharge. Ground-water discharge contributes much of the flow of the river during average years and nearly all of the flow during drought. During 1970-76, the annual discharge of ground water from the Big Sioux aquifer to the Big Sioux River and its tributaries in Brookings County, and in an area extending 14 mi north of the county, was estimated to average 58 $ft^3/s$ (42,000 acre-ft, Koch, 1980, p. 16). The discharge area included a 530-$mi^2$ area in Brookings County and a 170-$mi^2$ area, to the north, in Hamlin and Deuel Counties.

In spite of large ground-water discharge, the Big Sioux River has numerous periods of extreme low flow, both in winter and in summer. In summer, ground-water discharge to the river is reduced by evapotranspiration and pumpage for irrigation. In winter, tributary streams are frozen and ground-water recharge and discharge has greatly decreased compared to the rates of the previous spring. Figure 4 shows a low-flow frequency analysis for the Big Sioux River at the streamflow gaging station southeast of Brookings based on data collected from 1954 through 1983. A low-flow frequency analysis provides a statistical estimate, based on past experience, of how often the flow of a stream will recede below certain amounts. For example, figure 4 shows that a discharge that is less than or equal to 1 $ft^2/s$ for a 14-day period has an average recurrence interval of about 5 years (or a 20-percent chance of occurring each year). Similarly for a 120-day period, a flow less than or equal to 3.3 $ft^3/s$ also has a recurrence interval of about 5 years. Even after the wet spring of 1978, evapotranspiration and pumpage in summer reduced the flow of the river by 50 percent (from 71.4 to 35.4 $ft^3/s$ at 111N51W13A) during a 3-month period (Koch, 1980, fig. 6). Much of the decrease in flow was in tributary streams.

High flows on the Big Sioux River occur frequently and can cause extensive flooding of lowlands when they do occur over a period of several months. For example, a discharge equal to or exceeding about 2,000 $ft^3/s$ for a period of 60 days has an average recurrence interval of about 20 years for the Big Sioux River at the gaging station near Brookings (fig. 5). The river for this discharge would be at least 2.5 ft above the bankfull stage at the gaging station during the 60-day period and would cause extensive flooding and possible damage to cropland, roads, and buildings. Maps of flood-prone areas along the Big Sioux River are available at a scale of about 2.5 inches to the mile and can be obtained from the U.S. Geological Survey, Huron, S. Dak. The maps show areas subject to flooding up to a gage height that on the long-term average is reached only once in every 100 years, and has one chance in 100 of occurring in any year.

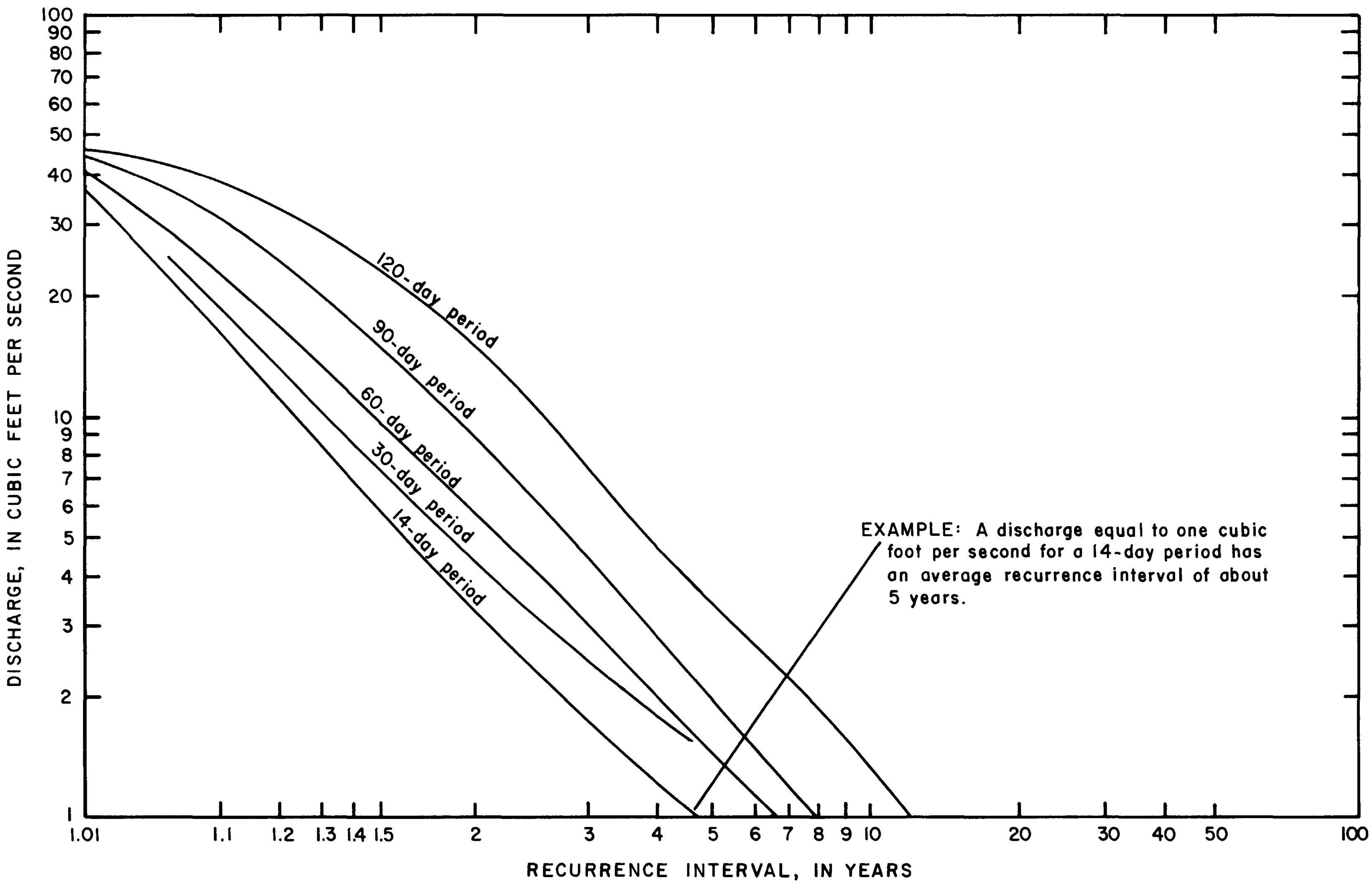



Figure 4.--Low-flow frequency curves for discharge at the Big Sioux River near Brookings (1954-83).

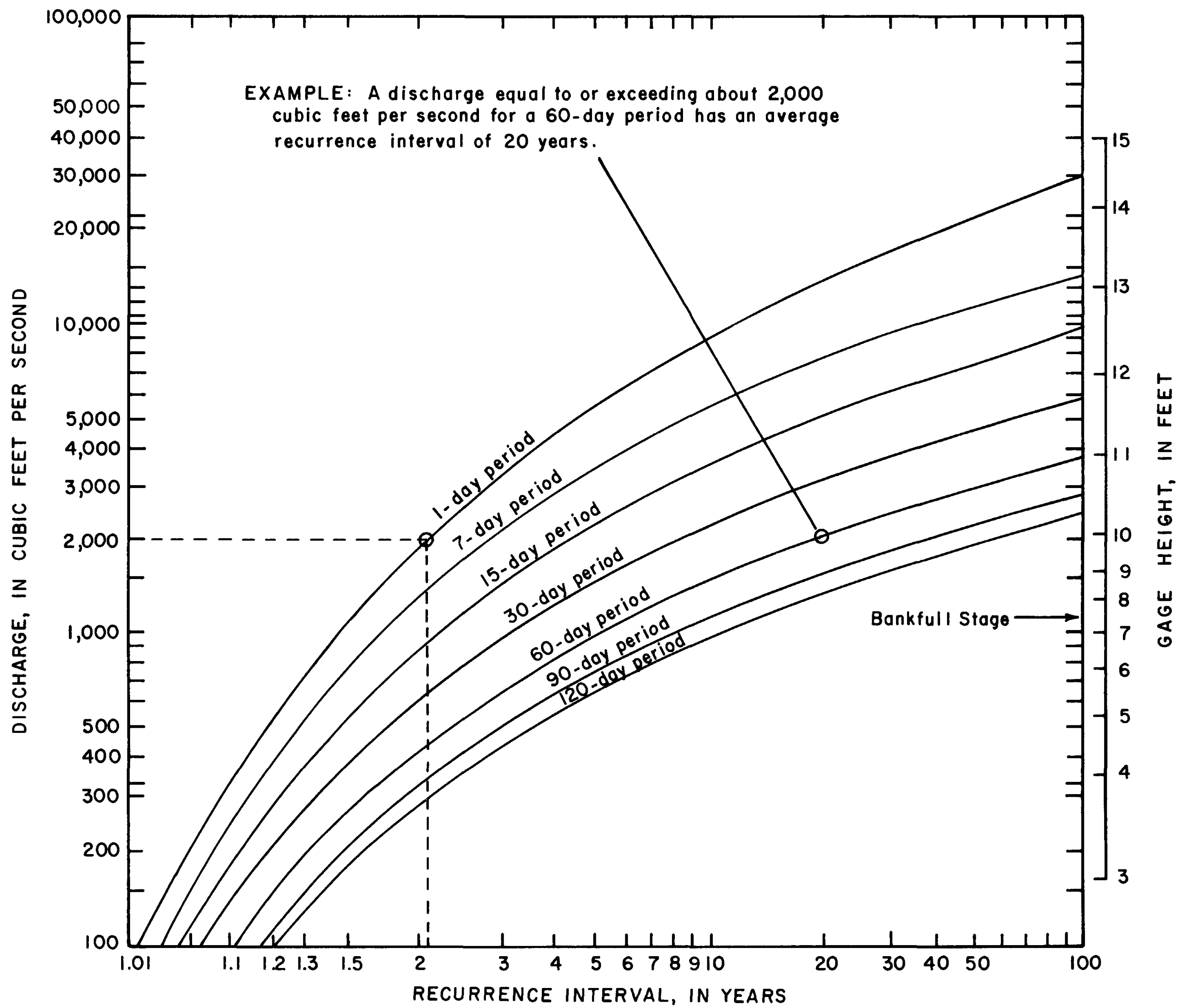



Figure 5.--High-flow frequency curves for discharge at the Big Sioux River near Brookings (1954-83).

## Lakes, Ponds, and Marshes

There are more than 2,000 small lakes, ponds, and marshes in Brookings and Kingsbury Counties, most of which are shallow and tend to become dry during prolonged drought. Three lakes in Brookings County and six lakes in Kingsbury County are larger than 1,000 acres. Most of the permanent lakes--Campbell, Goldsmith, Hendricks, and Oakwood in Brookings County; and Henry, Spirit, and Thompson in Kingsbury County (fig. 3)--are in depressions in permeable glacial outwash deposits. These lakes have moderate ground-water recharge that prevents their becoming completely dry. The larger lakes generally have average depths of only between 2 and 10 ft and are classified by the South Dakota Department of Game, Fish, and Parks as ephemeral, warm water lakes that are marginal for propagation of fish. Most of the lakes are classified as ephemeral and subject to winter kill on an average of about once every 5 years (table 2). Some spring-fed ponds are used for culture of bait fish. Most of the lakes, except for Campbell, Oakwood Lakes, Poinsett, Albert, and Whitewood, have contributing drainage areas of less than 100 $mi^2$, and tend to have limited recharge from surface runoff (State Lakes Preservation Committee, 1977). Altitudes of lake levels (fig. 3) have been surveyed several times annually, beginning in 1983, by the Water Rights Division of the South Dakota Department of Water and Natural Resources (Tom Brandner, personal commun., 1986). Many lakes had large rises of level during 1984 because there was large runoff from precipitation, particularly snowmelt. Several lakes increased in depth by more than 5 ft in 1984. Late in 1984, greater than average precipitation and runoff caused Lakes Whitewood and Henry in Kingsbury County to begin overflowing into Lake Thompson (Hansen and Miller, in press). Continued overflow during 1985 and 1986 caused the level of Lake Thompson to rise nearly 20 ft, making Lake Thompson the largest natural lake in South Dakota, with a surface area of about 25 $mi^2$ (16,000 acres) at an altitude of about 1,690 ft. Lake Poinsett, the second largest lake, had a surface area of 12 $mi^2$. In October 1986, Lake Thompson began overflowing for the first time in more than 100 years into the East Fork of the Vermillion River in T. 108 N., R. 55 W. south of the study area.

## Water Quality

Surface water in streams, lakes, ponds, and marshes in the study area generally contains less than 1,000 mg/L (milligrams per liter) of dissolved solids and should be acceptable for many uses. The major dissolved constituents are calcium, magnesium, bicarbonate, and sulfate. Hardness of water in streams generally ranges between 200 and 400 mg/L.

The quality of water in lakes, ponds, and marshes varies with runoff conditions and local differences in hydraulic connection with aquifers. In spring and early summer, and also during wet years, the quality of water in lakes, ponds, and marshes is similar to that of water in streams. During drought periods lasting several years, concentrations of dissolved solids slowly increase, because of evapotranspiration, to greater than 2,000 mg/L and hardness increases to greater than 400 mg/L. After several dry years, a dissolved-solids concentration of 2,560 mg/L and a hardness of 840 mg/L occurred in a sample from Lake Henry on Aug. 4, 1976 (State Lakes Preservation Committee, 1977, p. 217). Lake Henry has relatively large concentrations of dissolved solids because it seldom overflows to flush out mineral constituents. Spirit Lake also rarely overflows, but in August of 1976 the lake had a dissolved-solids concentration of only 1,350 mg/L (State Lakes Preservation Committee, 1977, p. 218). In Spirit Lake, there appears to be other factors reducing the concentration of dissolved solids, including occasional dilution by floodflow "flushing" solids into adjacent lakes and aquifers.

Table 2.--Summary of lake data[1]

| Lake name | Location (Township, Range, Section) | Depth (feet) Maximum | Depth (feet) Average | Depth increase during 1984 (feet) | Surface area (acres) | Contributing watershed area (square miles) | Storage capacity[2] (acre-feet) | Aquifer connection[3] | Classification for beneficial use[4] | Dissolved solids (milligrams per liter) |
|---|---|---|---|---|---|---|---|---|---|---|
| Brookings County | | | | | | | | | | |
| Brush | 110N52W18,19 | -- | 2 | 2.0 | 403 | 7 | 806 | M | WF | 1,195 |
| Campbell | 109N50W28,32,33 | 7 | 4 | 1.6 | 813 | 150 | 3,252 | M | WWM | 900 |
| Goldsmith | 110N51W9 | 12 | 6 | .3 | 301 | 23 | 1,806 | M | WWM | 900 |
| Hendricks | 112N47W15,21, 22,28,29 | 10 | 5 | -- | 1,632 | 49 | 8,160 | M | WWM | 770 |
| Oak | 112N48W12; 47W18 | 6 | 4 | 1.3 | 390 | 7 | 1,560 | L | WWM | 700 |
| Oakwood | 111N51W6,7,8,9 | 9 | 5 | .8 | 2,192 | 132 | 10,960 | M | WWM | 1,000 |
| Poinsett | 113N52W29 | 18 | 10 | 4.0 | 7,866 | [5]1,066 | 78,660 | E | WWSP | 925 |
| Sinai | 109N52W3,4,9,10 | 8 | 4 | 6.1 | 782 | 10 | 3,128 | M | WWM | 600 |
| Kingsbury County | | | | | | | | | | |
| Albert | 112N53W1,2,3,11, 12,15 | 10 | 4 | 3.7 | 3,610 | 318 | 14,440 | L | WWM | 1,500 |
| Badger | 112N53W34 | 8 | 6 | 1.0 | 506 | 23 | 3,036 | L | WWM | 629 |
| Henry | 110N55W18,19; 56W13,24 | 9 | 4 | 6.5 | 1,805 | 63 | 7,220 | M | WWM | 1,000 |
| Mud | 112N56W29 | -- | 2 | -- | 461 | 2 | 922 | L | WF | -- |
| Plum | 112N56W12 | 8 | 3 | -- | 282 | 5 | 846 | L | WWM | -- |
| Preston | 111N54W25-28, 31-35 | -- | 2 | 2.0 | 5,216 | 63 | 10,432 | O | WF | -- |
| Spirit | 112N56W19; 57W24 | 10 | 5 | 5.7 | 1,043 | 24 | 5,215 | M | WWM | 1,354 |
| Spring | 109N53W20 | -- | 2 | -- | 634 | 3 | 1,268 | O | WF | -- |
| Thisted | 112N53W26 | 8 | 4 | 3.4 | 256 | 12 | 1,024 | L | WWM | 900 |
| Thompson | 110N55W21, 28-33 109N55W (west half) | -- | 2 | 2.4 | 8,870 | 18 | 17,740 | M | WF | -- |
| Twin | 110N53W26 | -- | 2 | -- | 346 | 9 | 692 | L | WF | 1,796 |
| Whitewood | 110N54W10-13,15, 16,19,20 | -- | 2 | 5.7 | 4,966 | 108 | 9,932 | O | WF | -- |

[1] Modified from State Lakes Preservation Committee, 1977, pl. 2.2, and from files of the South Dakota Department of Game, Fish, and Parks.
[2] Calculated as product of average depth and surface area.
[3] O, primarily surficial recharge; L, limited ground-water recharge; M, moderate ground-water recharge; E, extensive ground-water recharge.
[4] The following classifications for beneficial use are from South Dakota Water Quality Standards effective Feb. 19, 1981: WF, wildlife propagation, other than fish, and stock-watering waters; WWM, warm-water marginal fish-life propagation waters, winterkill approximately every 5 years; WWSP, warm-water semi-permanent fish-life propagation waters, winterkill approximately every 10 years.
[5] Includes 793 square miles of the drainage basin upstream of a diversion ditch from the Big Sioux River to Dry Lake and Lake Poinsett in Hamlin County.

## GROUND WATER

### Glacial Aquifers

Glacial aquifers of outwash sand and gravel occur in most of the study area and can supply water to large-capacity wells. Aquifers were mapped by correlating the tops of sand and gravel beds whose altitudes generally differed by less than 50 ft in adjacent test holes. Approximately 250 test holes were drilled into bedrock at 1- to 3-mi intervals to determine the extent and thickness of glacial aquifers (fig. 6). Figure 6 includes a few sites where less than 6 ft of sand and gravel were penetrated. Additional test holes (not shown in fig. 6) were drilled with a power auger to depths of generally less than 50 ft to determine the extent and thickness of shallow sand and gravel suitable for road aggregate. The location of these holes are shown in separate publications (Tomhave, 1987, 1988). Fifty observation wells (fig. 6) were installed in areas where it was anticipated that water levels might be affected by pumpage.

Six major glacial aquifers are delineated in Brookings and Kingsbury Counties (table 3). A major glacial aquifer is defined, for the purposes of this report, as an aquifer that can be mapped and has a thickness and permeability that is sufficient to supply a sustained yield of water to large-capacity wells. (A large-capacity well is defined by South Dakota law as a well having a sustained yield of at least 18 gal/min.) In approximate order of increasing depth, the aquifers are the Big Sioux, Vermillion East Fork, Ramona, Rutland, Howard, and Altamont. The aquifers store a total of 8 million acre-ft of fresh to slightly saline, very hard water beneath an area of 1,400 $mi^2$, or about four-fifths of the study area. Data in the table are based on test holes and wells drilled through 1987. Subsequent drilling may appreciably change the values.

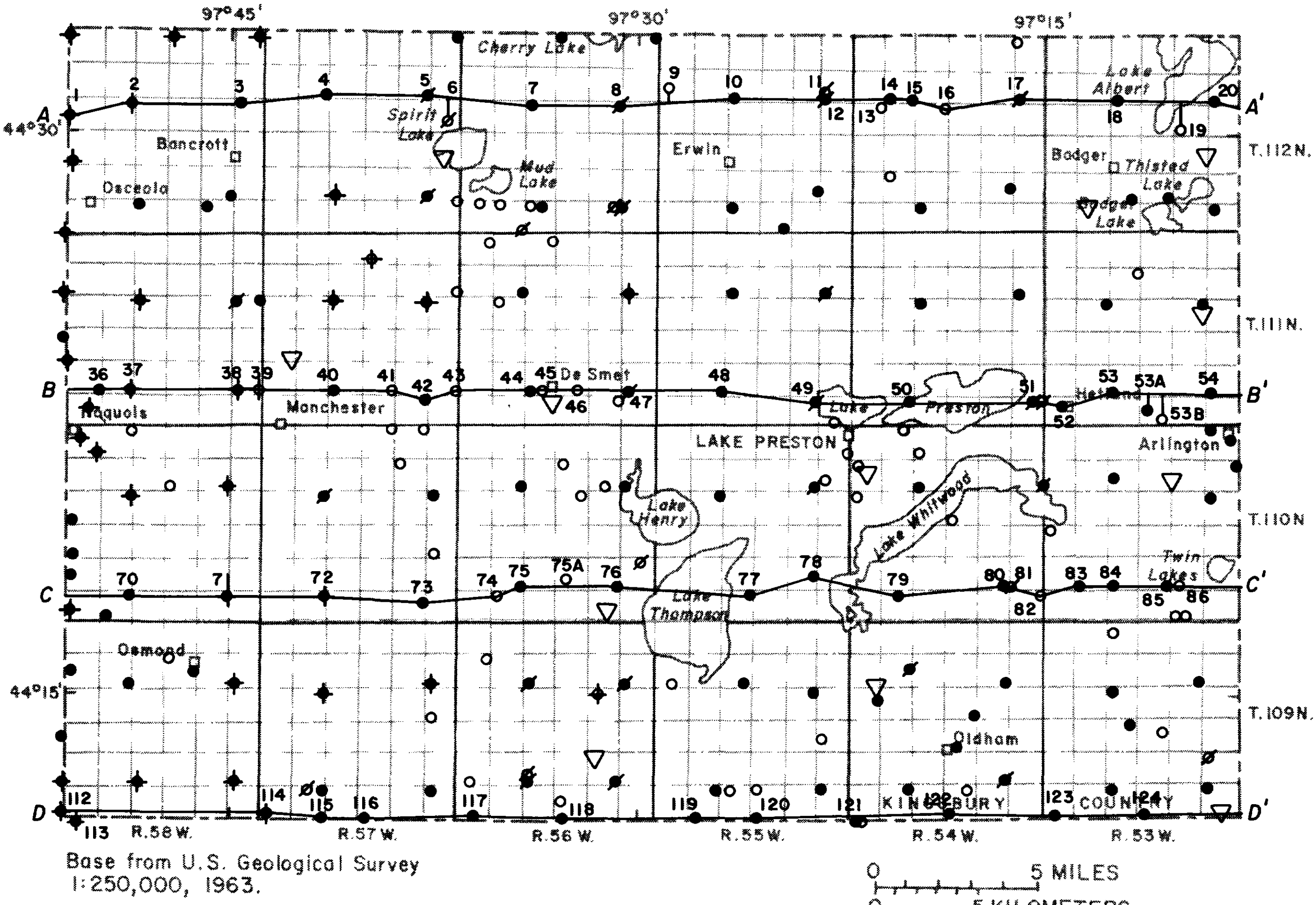
Four east-west hydrologic sections indicated that most major aquifers extend for many miles but have irregularities in their thickness and altitude (fig. 7). For example, an aquifer can be absent within a few miles or less from where its thickness is nearly 50 ft in Section B-B′ (test holes 59 and 60) and in Section C-C′ (test holes 80, 81, and 82). Where test holes are not located on the line of the section, the control for the location of aquifers on the section is obtained from aquifer maps (figs. 9, 14, 16, and 18) that shows the extent, depth to the top of the aquifer, and contours of the aquifer thickness.

The altitude of an aquifer can change by more than 50 ft between test holes that are 3 mi apart. The depth to an aquifer can change even more than 50 ft because of irregularities in the altitude of the land surface. For example, the depth to the top of the Big Sioux aquifer is only a few feet at test hole 91 but about 120 ft 1.3 mi to the west (test hole 89, C-C′). Two hydrologic sections that trend northwest and northeast in Brookings County slice through greater thicknesses and show reaches where the Big Sioux and Rutland aquifers are connected (fig. 8).

Table 3.--Summary of the hydrologic characteristics of the major aquifers

| Aquifer name | Areal extent (square miles) | Maximum thickness (feet) | Average thickness (feet) | Range in depth below land surface to top of aquifer (feet) | Range of water level (feet below or (+) above land surface) | Estimated amount of water in storage (million acre-feet) | Range of reported and estimated well yields (gallons per minute) | Suitable for irrigation[1] |
|---|---|---|---|---|---|---|---|---|
| GLACIAL AQUIFERS | | | | | | | | |
| Big Sioux | 540 | 93 | 30 | 0-212 | 0-120 | 2.0 | 2-1,300 | Yes. |
| Vermillion | 94 | 70 | 25 | 0-120 | 0-74 | .3 | 2-1,000 | Yes. |
| East Fork Ramona | 410 | 52 | 20 | 21-282 | 10-144 | 1.0 | 2-500 | Marginal to unsuitable. |
| Rutland | 240 | 50 | 15 | 37-324 | +2-212 | .4 | 2-1,800 | Yes. |
| Howard | 835 | 135 | 25 | 140-438 | 5-200 | 3.0 | 2-1,000 | Marginal to unsuitable. |
| Altamont | 380 | 305 | 25 | 345-700 | 40-420 | 1.3 | 2-1,000 | No. |
| Subtotal | | | | | | 8.0 | | |
| BEDROCK AQUIFERS | | | | | | | | |
| Niobrara | 1,400 | 155 | 100 | 230-758 | -- | 18.0 | 2-5 | No. |
| Codell | 1,450 | 170 | 80 | 320-900 | 100-340 | 15.0 | 2-100 | No. |
| Dakota | 1,100 | 500 | 200 | 770-1,300 | 10-700 | 34.0 | 2-100 | No. |
| Subtotal | | | | | | 67.0 | | |
| TOTAL | | | | | | 75.0 | | |

[1]Based on irrigation-water classification diagram (fig. 14).




## EXPLANATION

- 18 ● TEST HOLE OR WELL DRILLED INTO BEDROCK - Number is hole number shown in figures 7 and 8
- 19 ○ SHALLOW TEST HOLE OR WELL NOT DRILLED INTO BEDROCK - Number is hole number
- OBSERVATION WELLS
- TEST HOLES OR WELLS PENETRATING LESS THAN 6 FEET OF SAND OR GRAVEL
- ▽ GROUND-WATER QUALITY SAMPLING SITE--Complete chemical analysis by the U.S. Geological Survey
- A—A'—A" LINE OF HYDROLOGIC SECTION - Shown in figures 7 and 8

Figure 6.--Locations of hydrologic sections, test holes, and wells for which geologic, electric, or drillers' logs are available (excluding test holes in the Big Sioux aquifer).

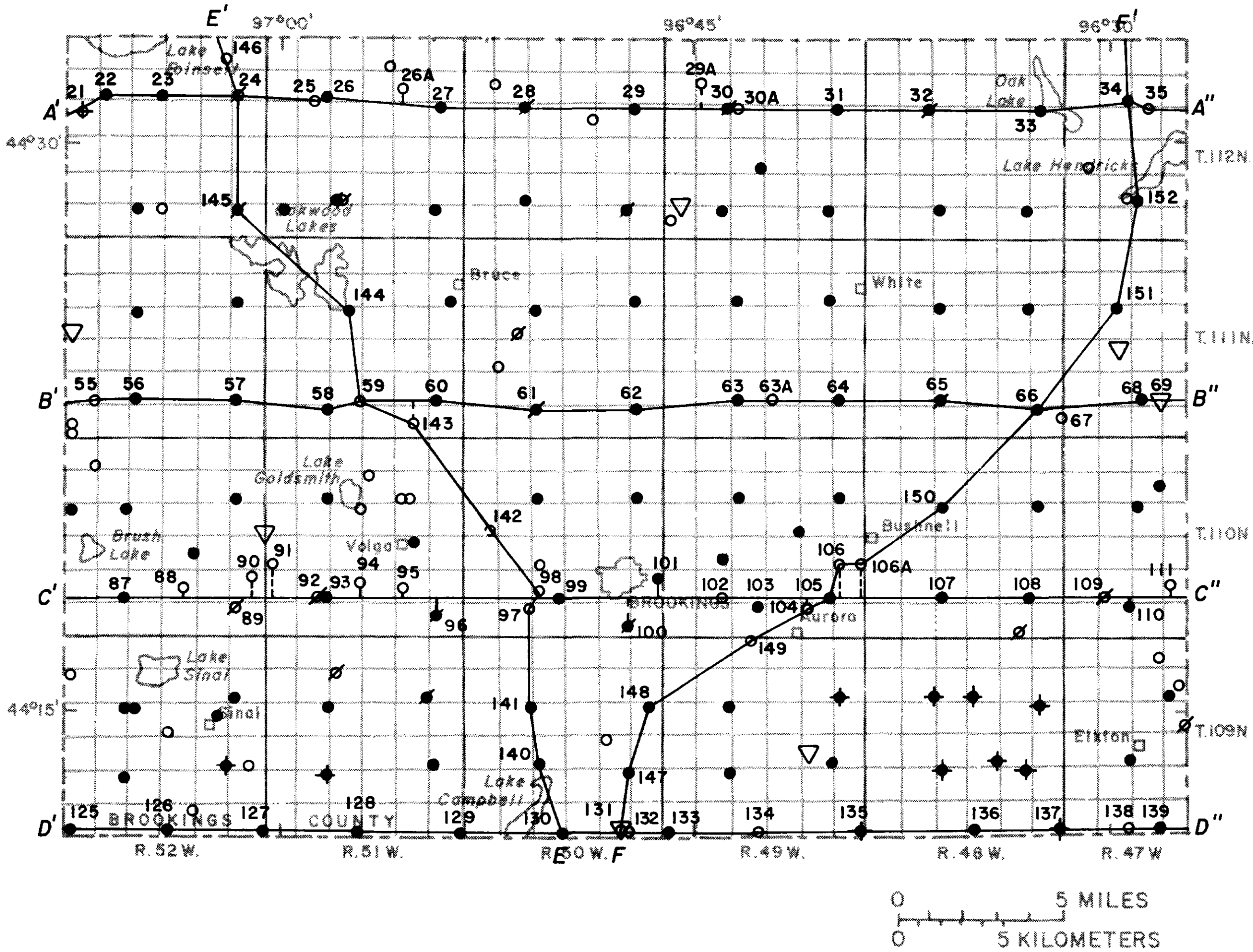



Figure 6.--Locations of hydrologic sections, test holes, and wells for which geologic, electric, or drillers' logs are available (excluding test holes in the Big Sioux aquifer).--Continued

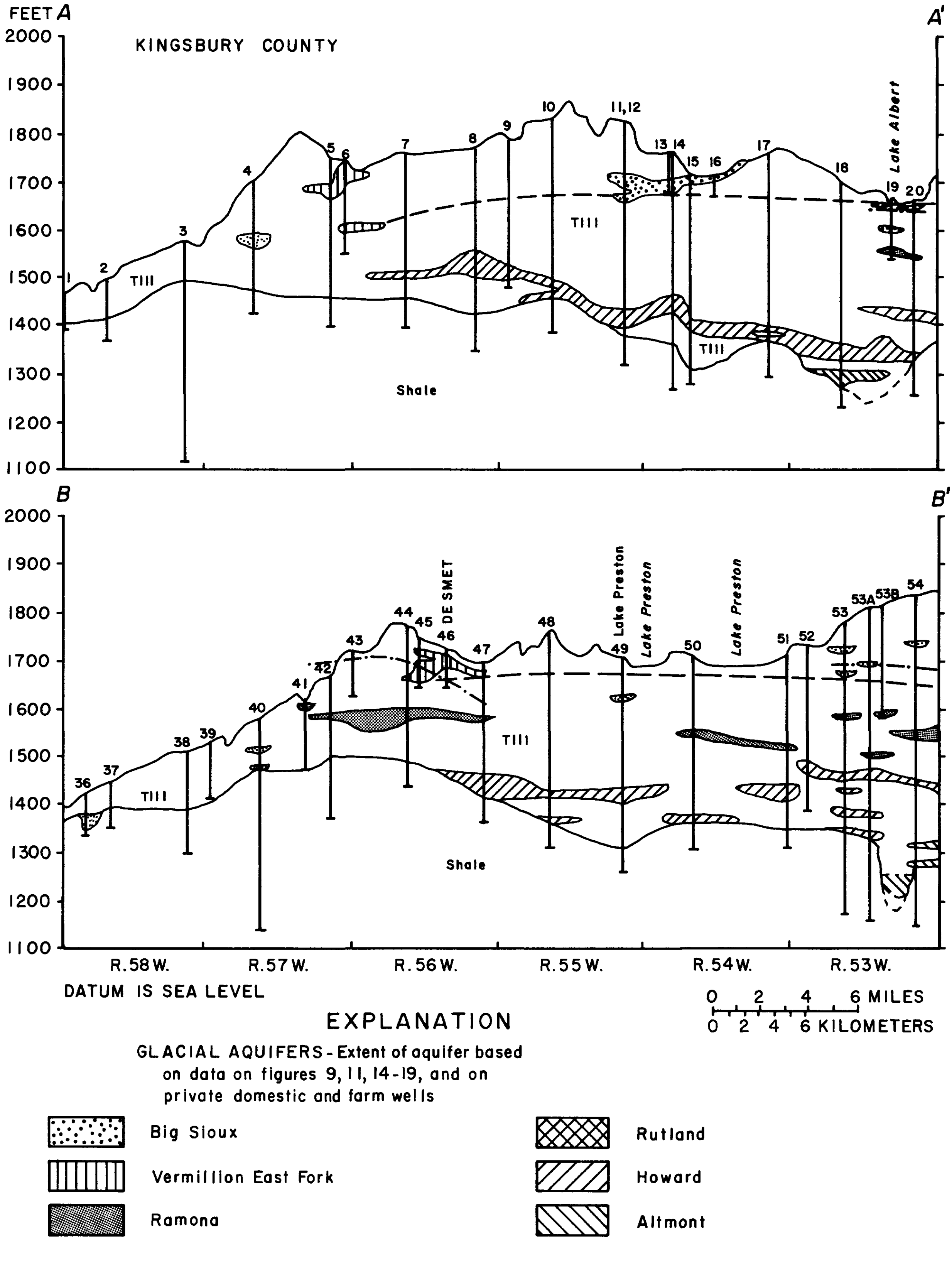



Figure 7.--Aquifers and potentiometric surfaces in glacial deposits. (Location of sections shown in fig. 6.)

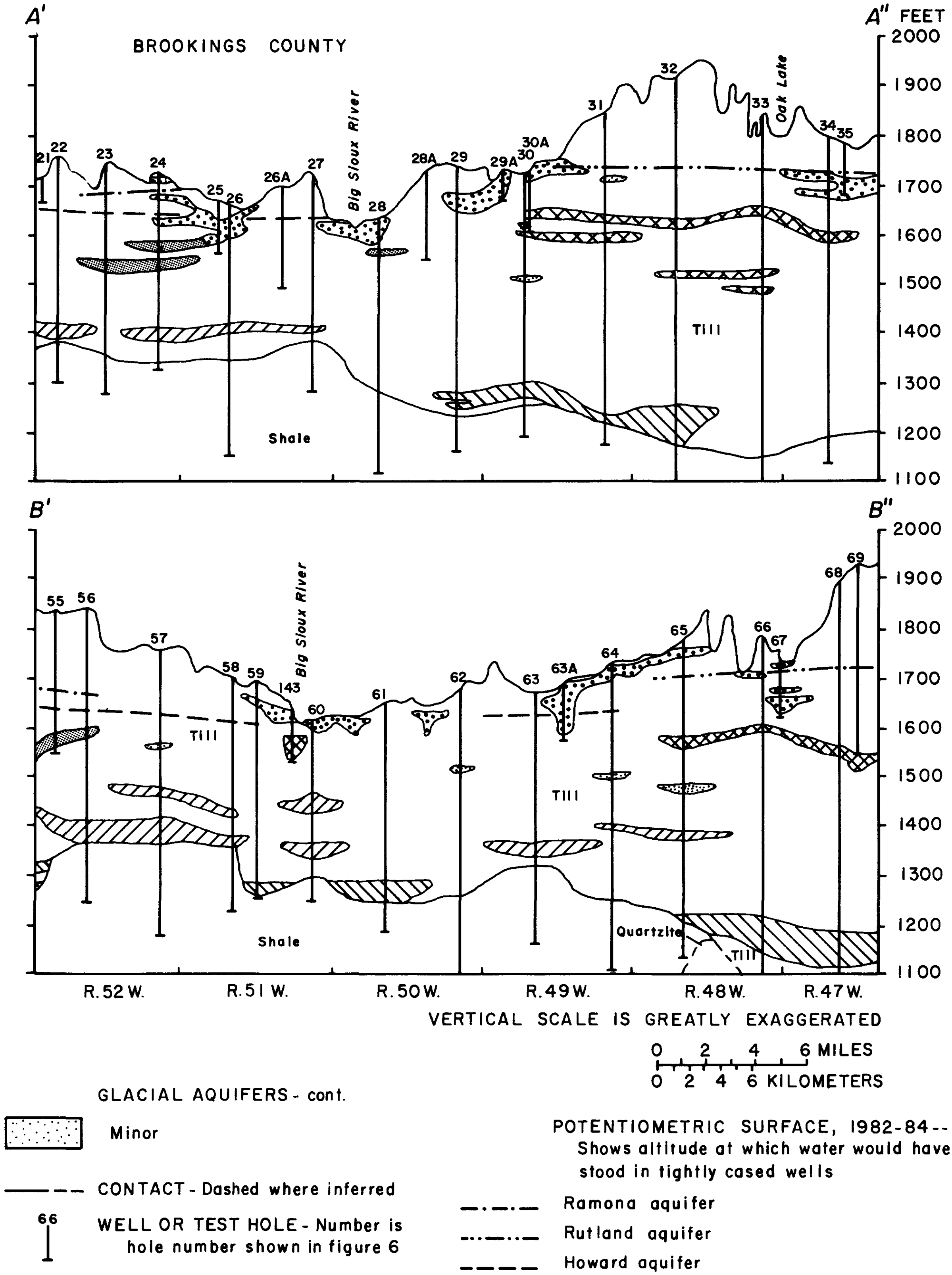



Figure 7.--Aquifers and potentiometric surfaces in glacial deposits.--Continued

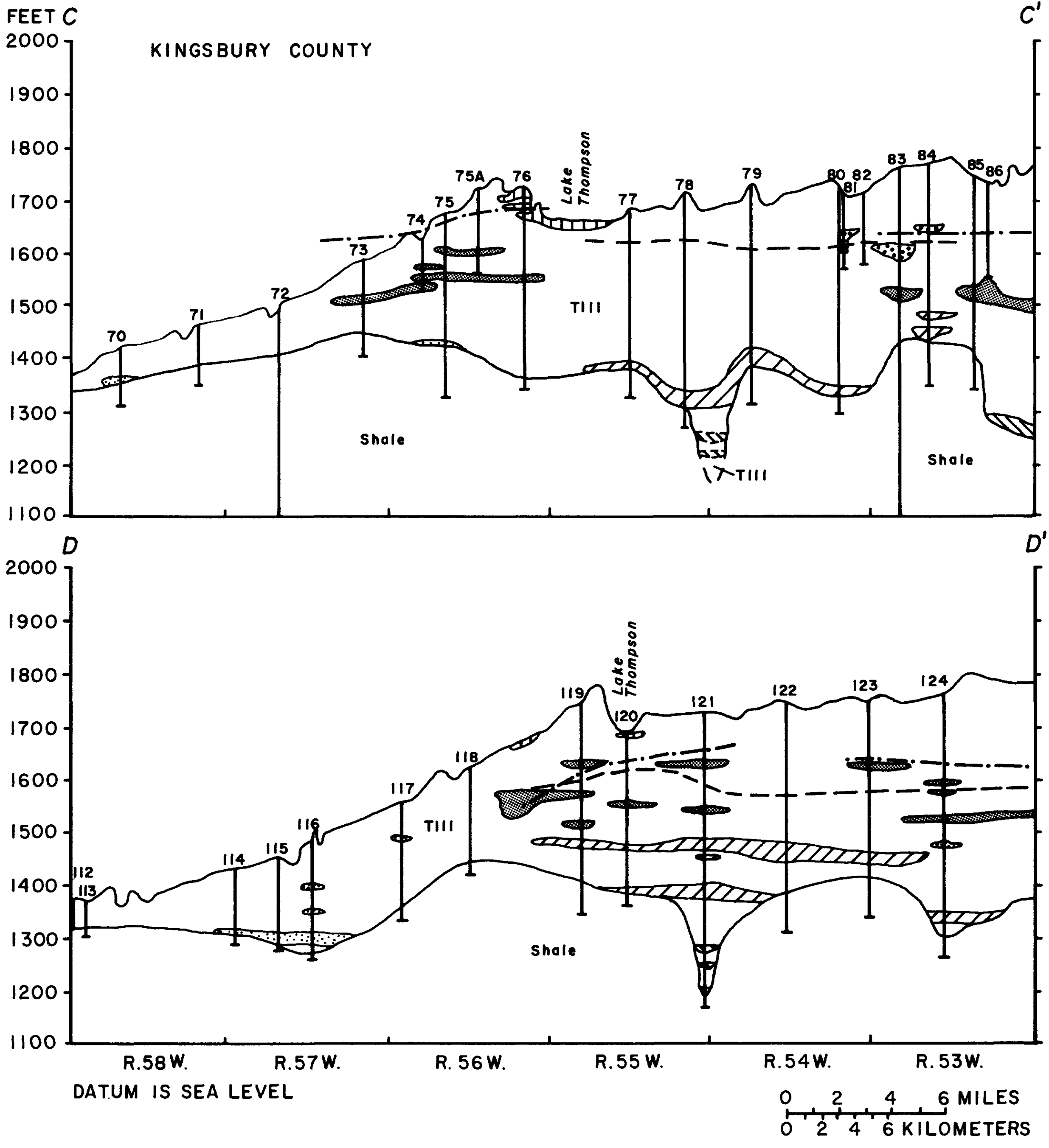



Figure 7.--Aquifers and potentiometric surfaces in glacial deposits.--Continued

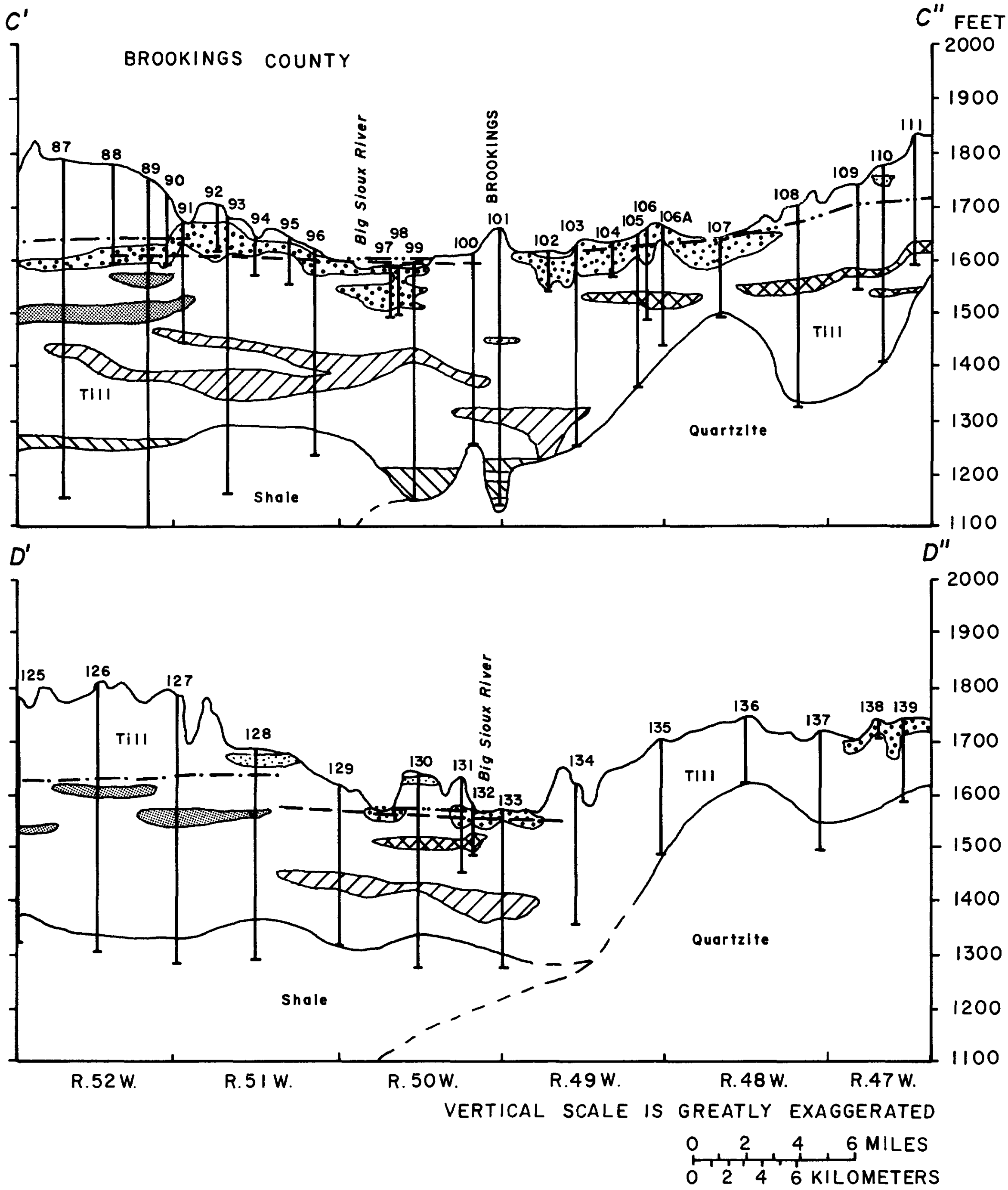



Figure 7.--Aquifers and potentiometric surfaces in glacial deposits.--Continued

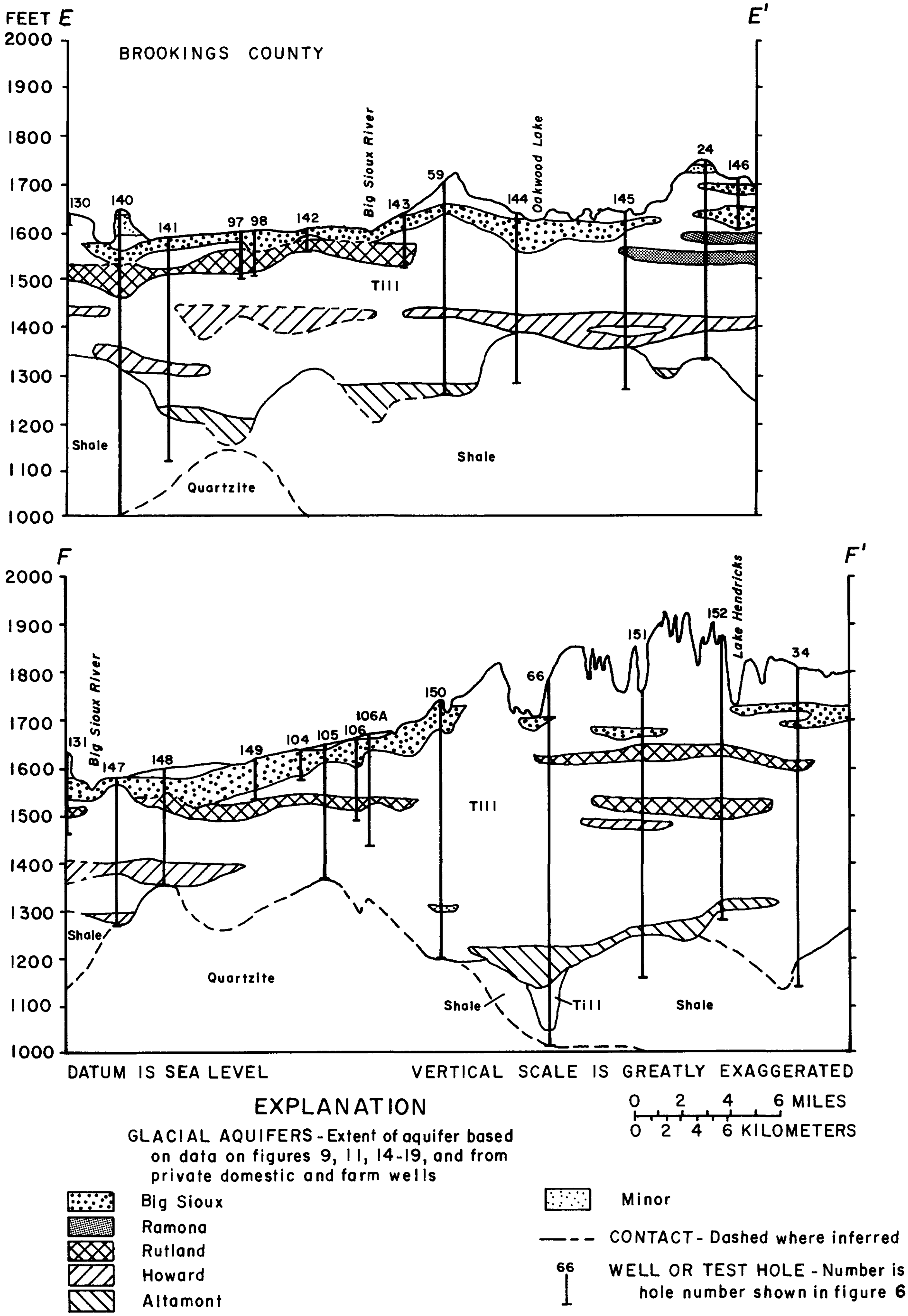



Figure 8.--Aquifers in glacial deposits.
(Location of sections shown in fig. 6.)

## Big Sioux Aquifer

Extent, depth, and thickness

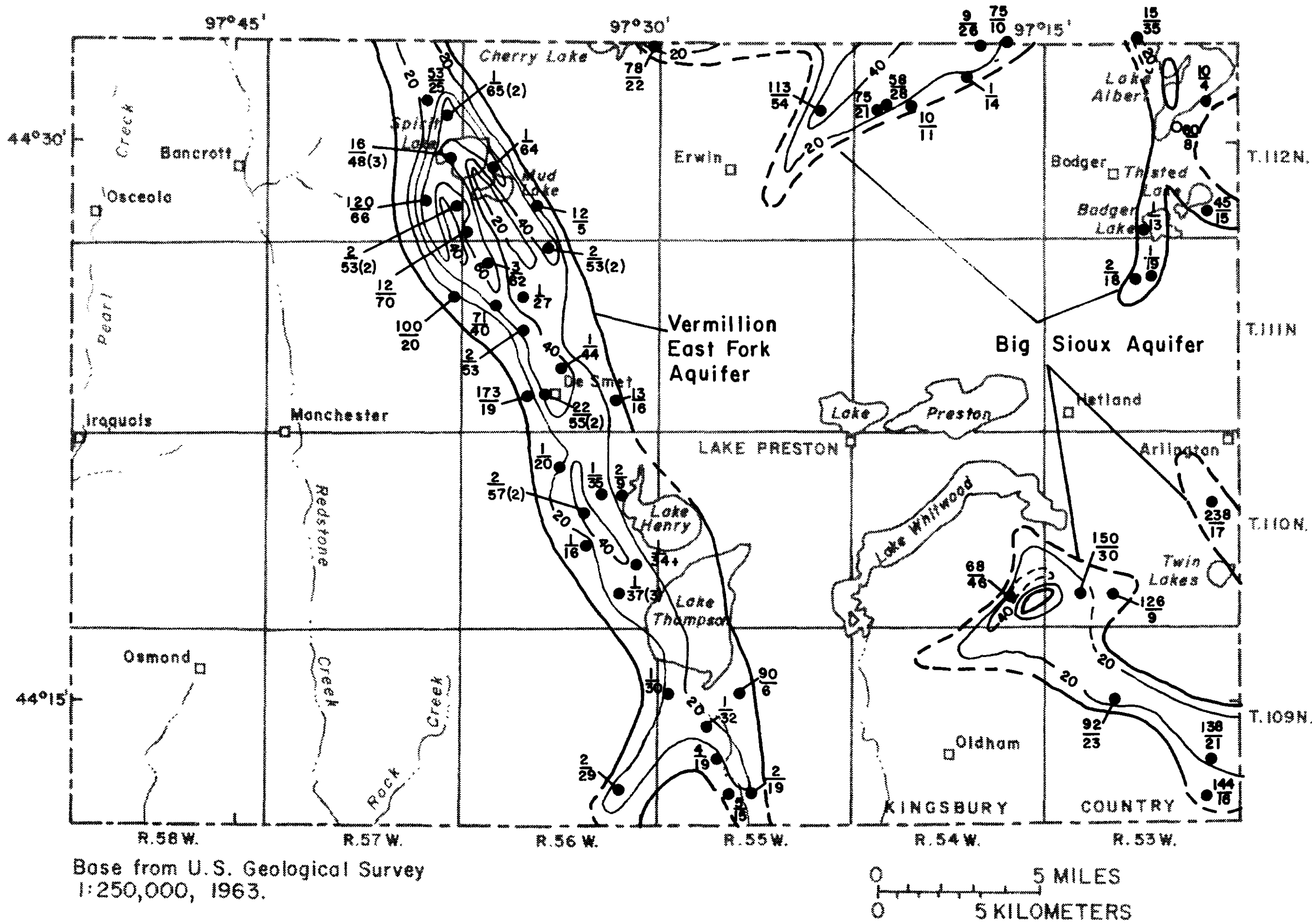
The Big Sioux aquifer stores 2 million acre-ft of water beneath 540 $mi^2$ or about one-third of the study area (fig. 9). The top of the aquifer generally slopes southward and extends east, west, north, and south from Brookings County. The aquifer extends through 70 $mi^2$ of eastern Kingsbury County. The aquifer is unconfined near the Big Sioux River and along major tributary valleys. Elsewhere it is confined beneath till but the artesian pressure is not large enough for wells to flow in the study area.

Depths to the top of the Big Sioux aquifer (table 1) range from 0 to 212 ft because the Big Sioux aquifer is at the land surface along much of the Big Sioux River valley but has been covered by large thicknesses of till in northeastern and southwestern Brookings County and in Kingsbury County. Depths to the aquifer can differ by as much as 70 ft within a distance of a few miles in the headwaters area of meltwater streams, where small, lenticular outwash deposits occur at different altitudes (fig. 7, Section C-C', test holes 81 to 84). The depth can also differ greatly in a few miles where the altitude of the land surface changes greatly (test holes 89 to 93). Most of the irregular shape of aquifer profiles is due to deposition of outwash over an irregular bedrock or till surface but some of the irregularity is due to erosion of the outwash before its burial by later till deposits.

The thickness of the aquifer averages 30 ft but exceeds 40 ft in many areas of Brookings County (fig. 9). The largest thickness tends to be where narrow meltwater streams were confined between hills. These streams scoured their channels deeply into underlying till before depositing outwash. The aquifer generally is a single unit but can be a composite of as many as three beds near the headwater areas of meltwater streams (test hole 67, B-B', fig. 7, and 111N48W36AA, fig. 9).

Composition and well yields

The Big Sioux aquifer is composed of well-sorted, very permeable glacial outwash sand and gravel, mostly medium to very coarse sand and very fine to medium gravel. Sieve tests of test-hole cuttings indicate that none of the samples contained more than 50 percent of fine and medium sand (including coarse silt) as illustrated on a triangular diagram (fig. 10). The hydraulic conductivity of most of the aquifer materials likely exceeds the range of 70 to 140 ft/d that is representative of fine sand (Koch, 1980, table 2). Hydraulic conductivity is defined as the rate of flow of water through a porous material of unit cross-sectional area under a unit hydraulic gradient and usually is expressed as feet per day. The average hydraulic conductivity of sand and gravel of the Big Sioux aquifer, calculated from four aquifer tests of large-capacity wells, ranges from 500 to 1,500 ft/d (Koch, 1980, table 1). Transmissivity, the product of hydraulic conductivity and aquifer thickness, ranges from 20,000 to 42,000 $ft^2/d$. On the basis of these tests, the maximum well yield is estimated to be 1,300 gal/min (table 3). A yield of more than 500 gal/min usually is obtained where the thickness of clean sand and gravel is at least 20 ft. Pumping lifts for large capacity wells probably range from 30 ft where the aquifer lies within 10 ft of land surface to 250 ft where the aquifer is deeply buried in northeastern Brookings County.




## EXPLANATION

● 70/34+ WELL OR TEST HOLE - Upper number is depth, in feet, to top of sand and gravel including the unsaturated zone. Lower number is thickness, in feet, of sand and gravel, including the unsaturated zone. A plus (+) indicates greater than shown. Number in parenthesis is number of aquifer units penetrated, where greater than one

—— 40 — — LINE OF EQUAL THICKNESS OF SAND AND GRAVEL - Dashed where inferred. Interval 20 feet

——· · ·—— INTERMITTENT STREAM

———— — — AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and private domestic and farm wells

Figure 9.--Extent, depth, and thickness of the Big Sioux and Vermillion East Fork aquifers.

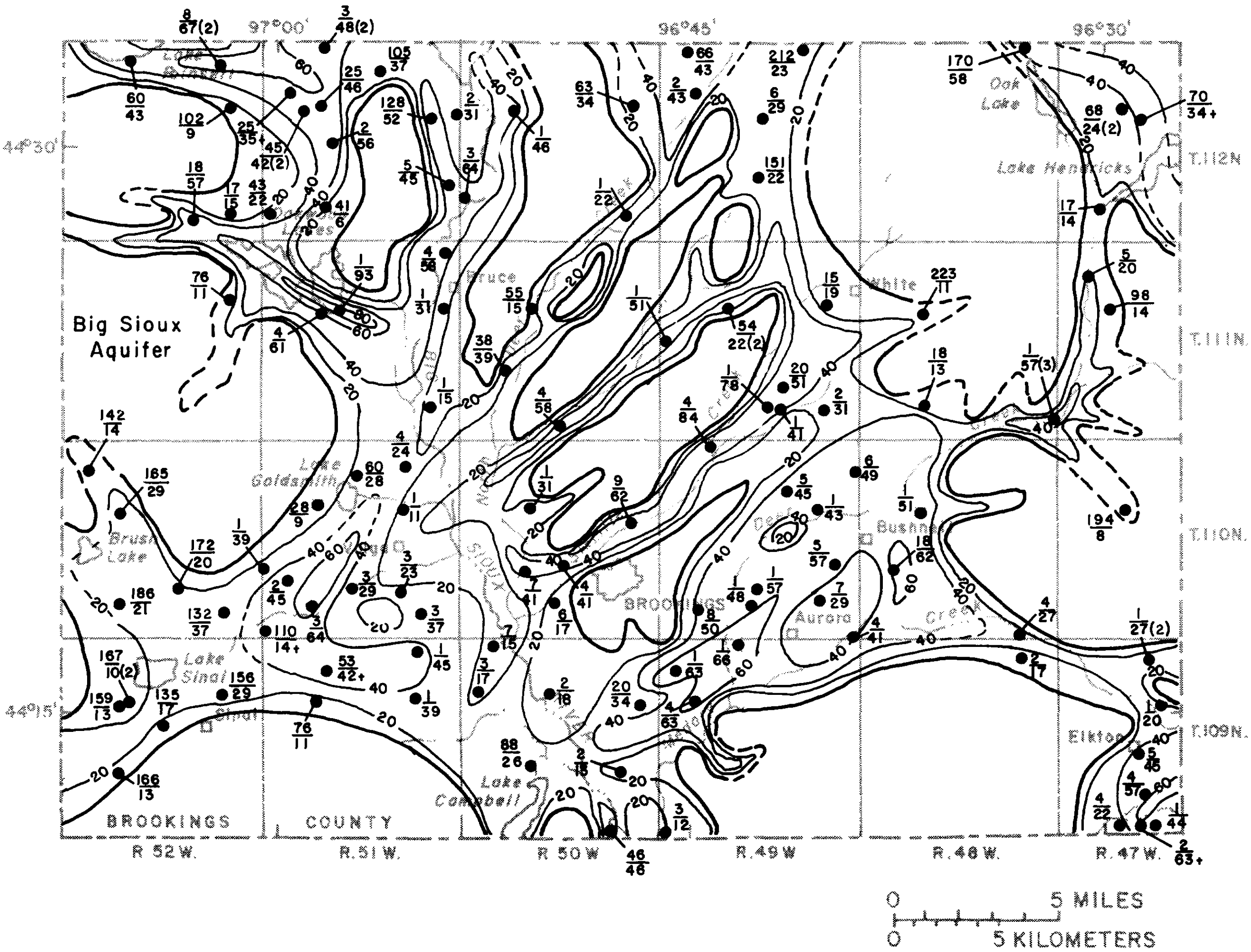



Figure 9.--Extent, depth, and thickness of the Big Sioux and Vermillion East Fork aquifers.--Continued

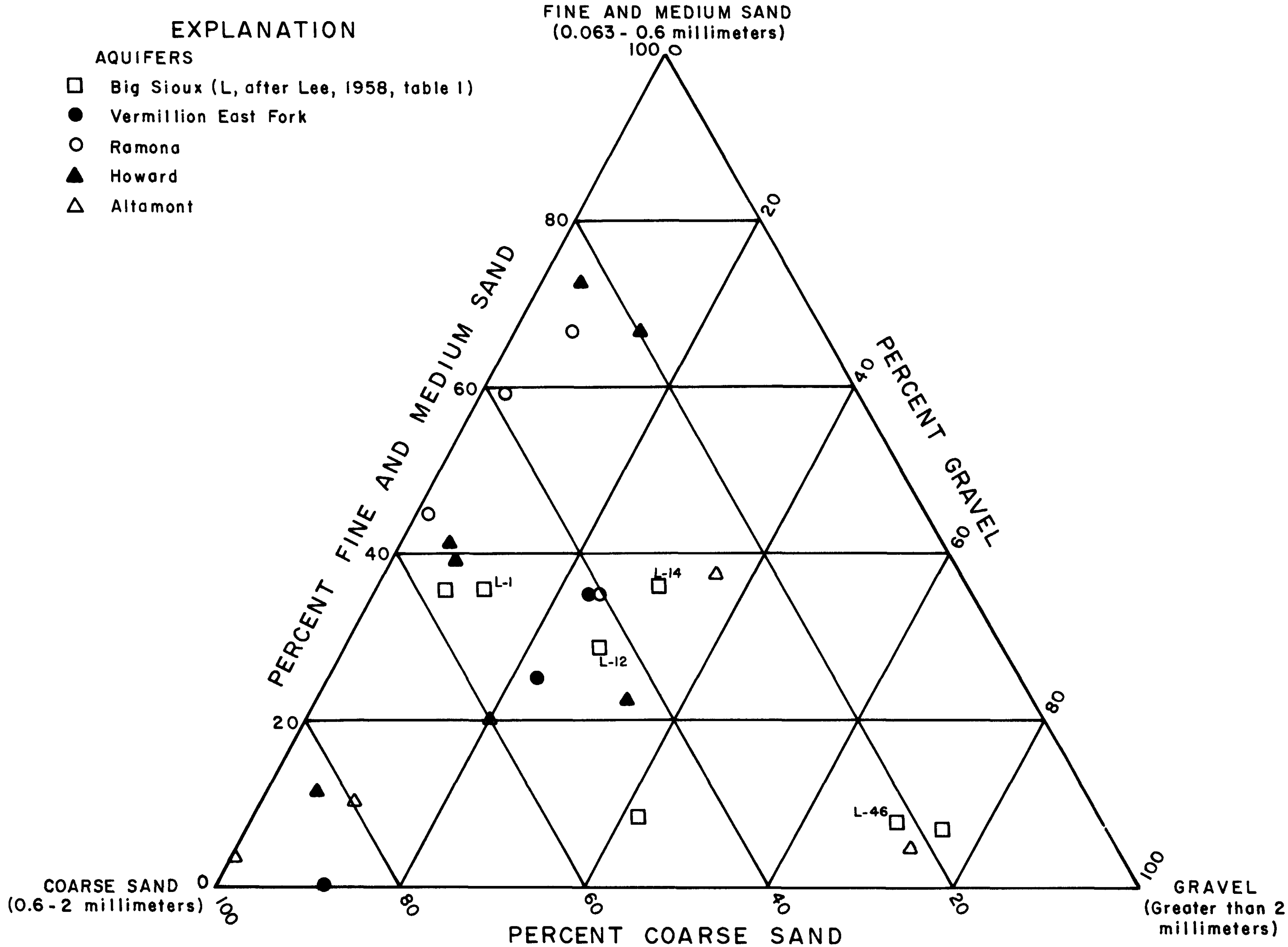



Figure 10.--Size composition of aquifer sand and gravel, in percent.

Water movement

The Big Sioux aquifer is recharged by infiltration of precipitation and by slow seepage through till, lake deposits, and underlying aquifers. Water in the aquifer generally moves in the direction of the slope of the land surface toward areas of discharge into lakes and the Big Sioux River. The average annual gain in flow of the river from ground-water discharge in an area of 700 $mi^2$ was estimated from a computer-simulated hydrologic budget to be 42,600 acre-ft during the period 1970-76, which included a severe drought (Koch, 1980, p. 25). The budget area includes Brookings County and parts of Hamlin and Deuel Counties to the north.

The direction of ground-water movement is perpendicular to the contours on the potentiometric surface or water table (fig. 11). In much of central Brookings County east of the Big Sioux River, the hydraulic gradient of the Big Sioux aquifer is southwestward at about 15 to 25 ft/mi toward the Big Sioux River. The gradient decreases to less than 10 ft/mi in the northwestern part of the county and also near the city of Brookings, due in part to a large increase in the thickness and transmissivity of the aquifer. A small eastward gradient in southwestern Brookings County and southeastern Kingsbury County probably is due to small recharge to the aquifer, which lies beneath thick glacial till. In northeastern Kingsbury County, outflow through the aquifer is northward.

The potentiometric contour map shown in figure 11 represents a period of above-normal recharge resulting in the water levels in the Big Sioux aquifer being from 5 to 10 ft above normal. As a result, the water-level contours are shifted 1 to 2 mi closer to the recharge areas causing the hydraulic gradients to be steeper. Consequently, the flow estimates in the vicinity of the recharge area are probably larger than for periods of normal recharge.

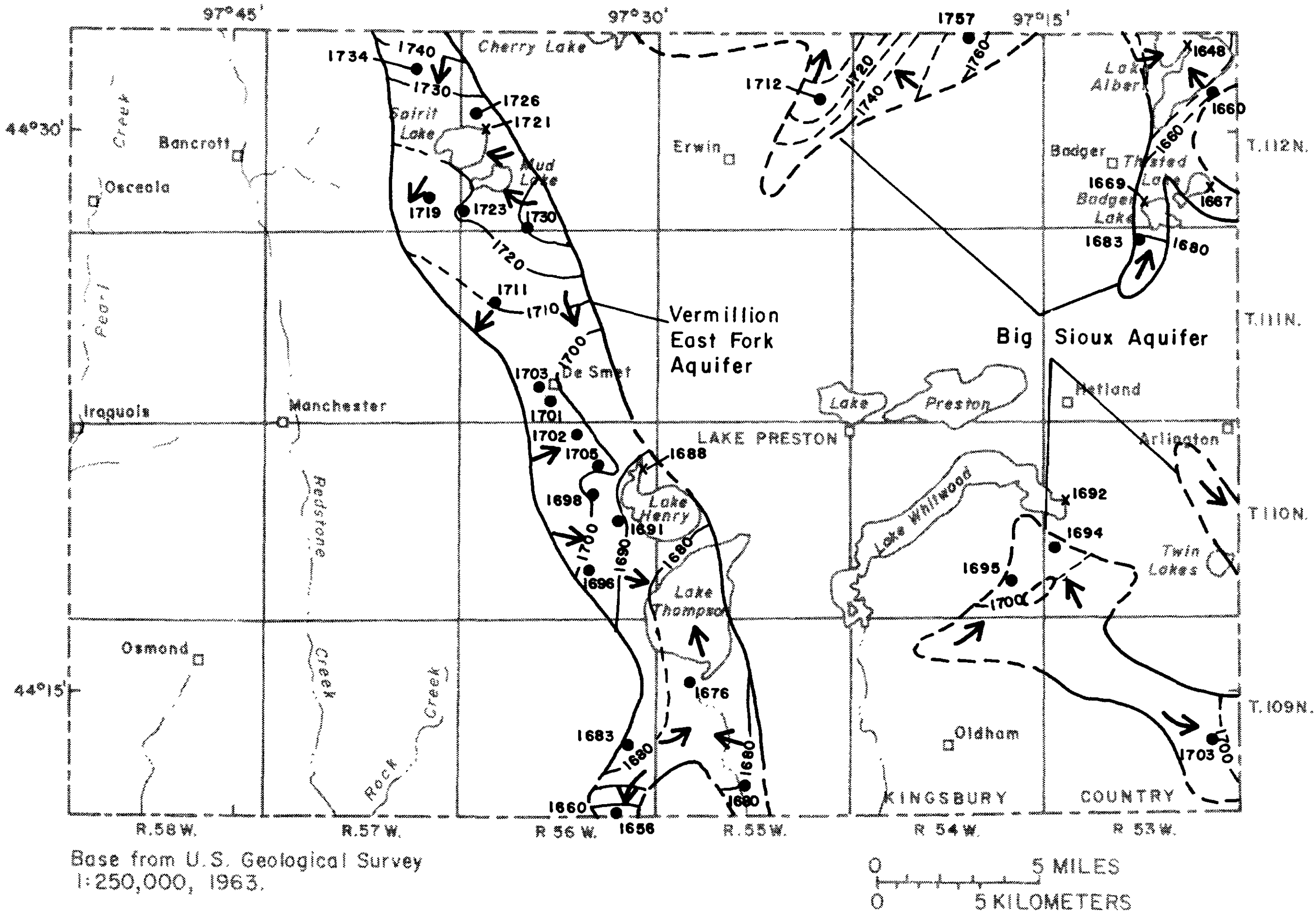
Flow through the aquifer can be estimated by the equation

$$Q = 8.38 \times 10^{-3}\ T\ I\ L$$

where Q = discharge (cubic feet per day);
T = transmissivity (feet squared per day);
I = hydraulic gradient (feet per mile);
L = width perpendicular to the direction of flow (miles); and
$8.38 \times 10^{-3}$ = factor to convert cubic feet per day to acre-feet per year.

Transmissivity was estimated from descriptive and electric logs of test holes by multiplying the thickness of the aquifer by the assumed average hydraulic conductivity. Estimates of hydraulic conductivity throughout this report are made conservatively small to adjust for the fact that drillers do not always record the presence of silty, fine sand in coarser-grained deposits and because of the lenticularity of coarse sand and gravel beds.

The following representative calculation is for flow westward in 1982-84 from Minnesota into the study area through the Big Sioux aquifer in T. 109 N., R. 47 W. The effective hydraulic conductivity of the aquifer in that area is estimated from drillers' logs to be controlled by significant amounts of fine to medium sand, which has an estimated hydraulic conductivity of 200 ft/d (Koch, 1980, table 2). Multiplying this by the thickness of the aquifer, which averages about 30 ft (fig. 9), the transmissivity is estimated to be 6,000 $ft^2/d$. The average hydraulic gradient across the northern part of the state line in T. 109 N. is 10 ft/mi (fig. 11) and the effective aquifer width (adjusted for the angle of flow) is about 3 mi. The product of these last three figures multiplied by $8.38 \times 10^{-3}$ provides an estimate of




## EXPLANATION

—1660-- POTENTIOMETRIC CONTOUR - Dashed where inferred. Shows altitude of the potentiometric surface, 1982-84. Contour interval 10 feet. Datum is sea level

● 1607 WELL OR TEST HOLE - Number is altitude of water level, in feet above sea level

x 1575 SURFACE WATER CONTROL POINT - Number is altitude of water surface, in feet above sea level

←—— GENERAL DIRECTION OF GROUND-WATER MOVEMENT

—··· — INTERMITTENT STREAM

——-- AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and private domestic and farm wells

Figure 11.--Potentiometric contours of the Big Sioux and Vermillion East Fork aquifers, 1982-84.

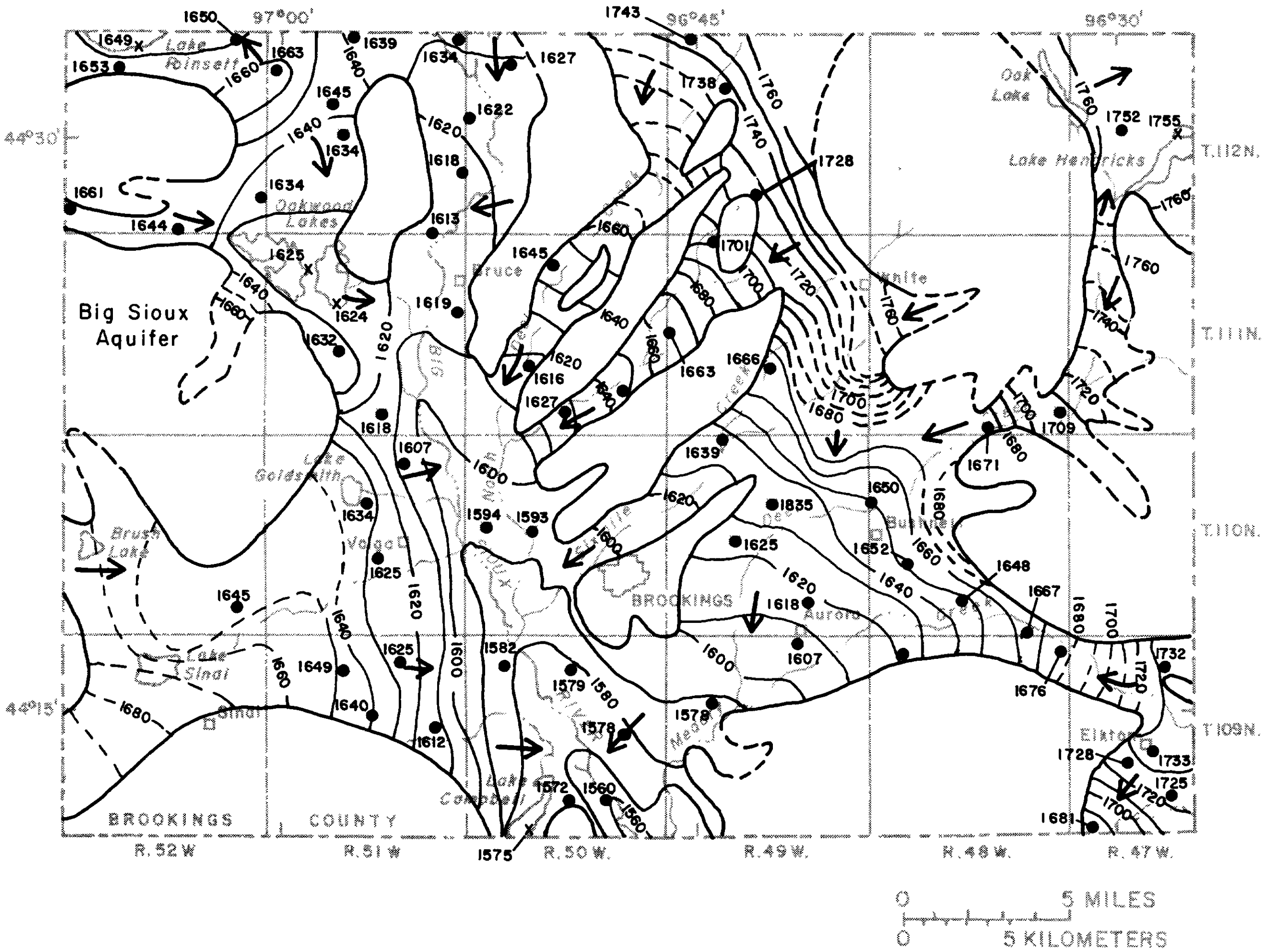



Figure 11.--Potentiometric contours of the Big Sioux and Vermillion East Fork aquifers, 1982-84.--Continued

subsurface inflow from Minnesota of 1,500 acre-ft/yr. Subsurface outflow southward through the Big Sioux aquifer through T. 109 N., R. 50 W. is relatively small, about 100 acre-ft/yr, because most discharge is to the Big Sioux River. In contrast, southward flow in T. 109 N., R. 47 W. is at least 1,000 acre-ft/yr because flow is not into the creek.

Water levels and effects of withdrawals

Water-level fluctuations in wells are caused by seasonal changes in recharge and discharge. Infiltration of precipitation is the primary source of recharge. Discharge is by evapotranspiration, discharge to streams and lakes, and withdrawals from wells. Water levels for wells in the Big Sioux aquifer generally rise in the spring because of recharge from snowmelt and rainfall (fig. 12). Evapotranspiration and pumpage from large-capacity wells cause water-level declines during much of the remainder of the year. Long-term changes in the annual maximum or minimum water level consisted of a gradual decline of 1 to 2 ft over a period of several years due to drought. The drought periods (fig. 12) include several periods of above-normal precipitation that reversed the downward trend of cumulative departure curves but had little influence on ground-water levels. The decline generally is followed by a recovery of water levels caused by recharge from above-normal precipitation and reduced pumpage. Water-level rises during 1982-85 in the two wells in the Big Sioux aquifer coincide with a sharp increase in the cumulative departure from normal precipitation (fig. 12).

Effects of withdrawals from wells that tap the Big Sioux aquifer generally are small because of extensive recharge and unconfined conditions. Drawdown of water levels is temporary and a few feet at most at distances of about a mile from large-capacity wells. However, a digital computer model of a reach of the aquifer extending through Brookings County to 12 mi north of the county indicated that water levels would undergo a large decline at 4 sites and streamflow would decrease by 3,600 acre-ft as a result of maximum pumping. For example, water levels were simulated to decline as much as 6 ft after 4 months of intensive pumping at the 1976 rate with no recharge (Koch, 1980, fig. 12). This decline would be about one-fifth of the saturated thickness of the aquifer and could increase pumping costs 5 to 10 percent or more. Pumping was simulated at nearly 44,000 acre-ft of water during a 4-month period of no recharge, similar to the severe-drought year of 1976 (Koch, 1980, p. 44). This indicates that if many more large-capacity wells are developed in the aquifer, they may cause excessive drawdown in many areas unless there is recharge sufficient to replenish the aquifer. Drawdown near a pumping well can be approximated from a table of theoretical drawdown for unconfined conditions (table 4).

In general, the drawdown after a year of continuous pumping at the rate of 1,000 gal/min theoretically is only 1 ft at a distance of 5,000 ft for the aquifer conditions shown. Either doubling the pumping rate or halving the transmissivity of the aquifer would each have the effect of doubling drawdown values. Drawdown at a given distance for confined conditions is two to ten times larger than drawdown for unconfined conditions (table 5). For example, drawdown at a distance of 1,000 ft from a well pumping 1,000 gal/min for 100 days would be 3 ft for unconfined conditions (table 4) but would be at least 12 ft for a confined aquifer of the same transmissivity (table 5). In many situations drawdown is much larger than shown because there is a nearby zone of smaller transmissivity or a poorly permeable boundary of till or shale.

Table 4.--Theoretical drawdown[1] for unconfined conditions

[Theoretical drawdown, in feet, at various distances from a well pumping continuously at 1,000 gallons per minute from a glacial aquifer under unconfined conditions and no recharge. The aquifer is assumed to be infinite in areal extent[2]. Transmissivity = 13,000 square feet per day; specific yield = 0.2]

| Time since pumping started | Distance from pumping well, in feet | | | | | |
|---|---|---|---|---|---|---|
| | 100 | 300 | 500 | 700 | 1,000 | 5,000 |
| 1 day | 3 | 1 | 0 | 0 | 0 | 0 |
| 10 days | 6 | 3 | 2 | 2 | 1 | 0 |
| 100 days | 8 | 6 | 5 | 4 | 3 | 0 |
| 1 year | 10 | 7 | 6 | 5 | 5 | 1 |

[1]Theoretical drawdown is calculated from curves showing nondimensional response to pumping a fully penetrating well in an unconfined aquifer. Observation wells are open at the middle of the aquifer (Lohman, 1972, pl. 6).
[2]Since the glacial aquifers in Brookings and Kingsbury Counties are limited in areal extent, the actual drawdown may be much greater than shown because of nearby poorly permeable boundaries.

Table 5.--Theoretical drawdown for confined conditions

[Theoretical drawdown, in feet, at various distances from a well pumping continuously at 1,000 gallons per minute from a glacial aquifer under confined conditions and no recharge[1]. The aquifer is assumed to be infinite in areal extent[2]. Transmissivity = 13,000 square feet per day; storage coefficient = 0.0001]

| Time since pumping started | Distance from pumping well, in feet | | | | | |
|---|---|---|---|---|---|---|
| | 100 | 300 | 500 | 700 | 1,000 | 5,000 |
| 1 day | 12 | 9 | 8 | 7 | 6 | 3 |
| 10 days | 14 | 12 | 11 | 10 | 9 | 6 |
| 100 days | 17 | 15 | 13 | 13 | 12 | 8 |
| 1 year | 19 | 16 | 15 | 14 | 14 | 10 |

[1]The effects of pumping a well in a confined aquifer will nearly always be much larger than shown here, since the effects of nearby boundaries will be much greater. Method for calculating theoretical drawdown is from the Theiss type curve (Lohman, 1972, pl. 6).
[2]Since the glacial aquifers in Brookings and Kingsbury Counties are limited in areal extent, the actual drawdown may be much greater than shown because of nearby poorly permeable boundaries.

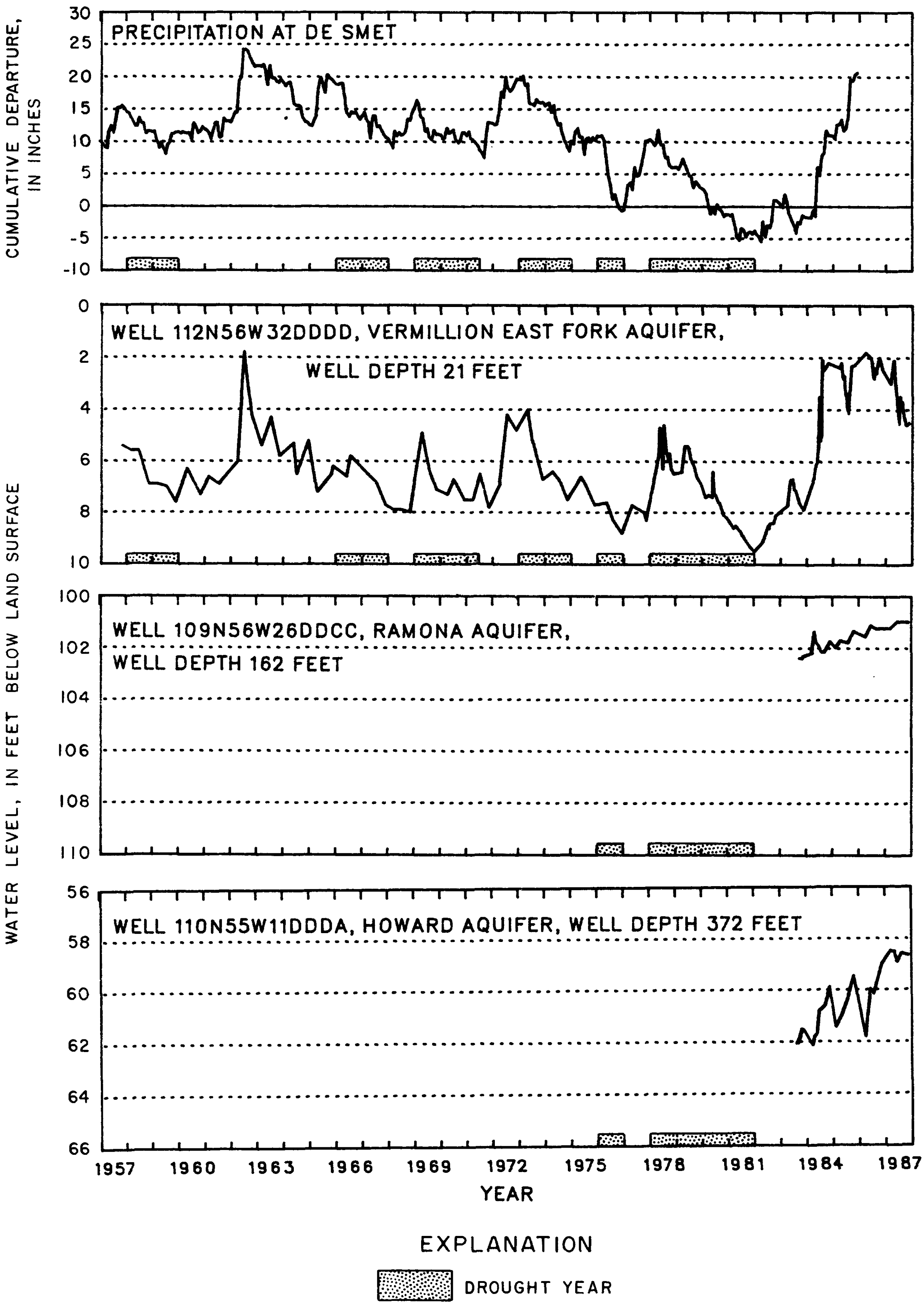



Figure 12.--Water-level changes in glacial aquifers and cumulative departure of precipitation from normal (1951-80) at De Smet and Brookings.

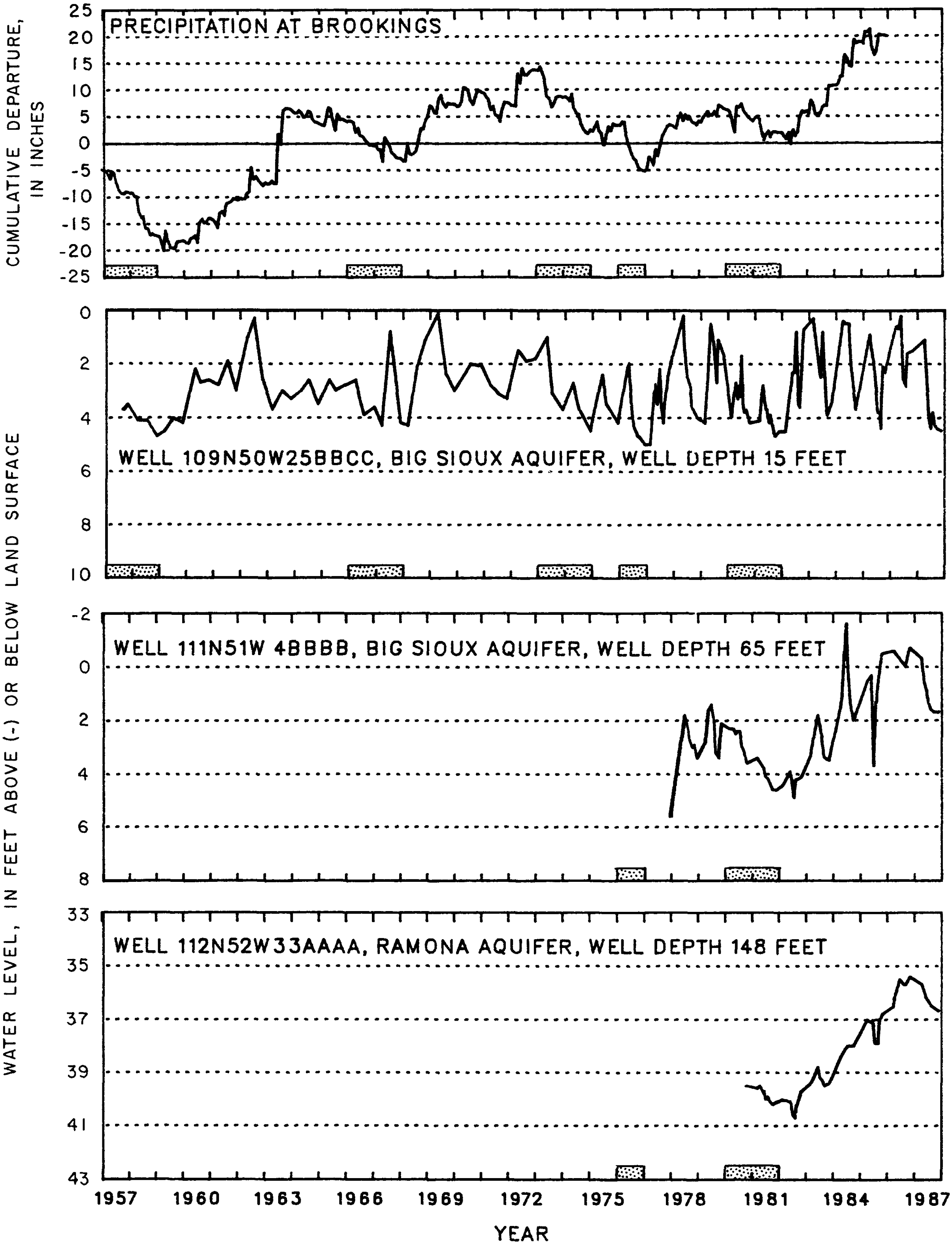



Figure 12.--Water-level changes in glacial aquifers and cumulative departure of precipitation from normal (1951-80) at De Smet and Brookings.--Continued

### Water quality

Water from the Big Sioux aquifer is fresh to slightly saline. Slightly saline water as generally defined has concentrations of dissolved solids in the range of 1,000 to 3,000 mg/L. Dissolved-solids concentrations of water in the Big Sioux aquifer in the study area range from 200 to 2,500 mg/L and average about 700 mg/L. The water generally is a calcium bicarbonate type. Hardness of the water ranges from 160 to 1,640 mg/L and averages about 480 mg/L. Statistical summaries of major chemical constituents in water from the aquifer indicate that there are large differences in the quality of the water in the aquifer (Bardwell, 1984, fig. 6).

The suitability of water for use in irrigation is determined from its specific conductance and from its concentration of dissolved sodium and sodium-adsorption ratio (table 6). Much of the water from the Big Sioux aquifer in the study area meets South Dakota standards for irrigation when applied with regard to soil classes (fig. 13 and South Dakota Division of Conservation, no date). For example, water from one well completed in the Big Sioux aquifer (sample 7, fig. 13) can be applied to clayey loams where the depth to less permeable clay is only 20 to 60 inches (soil class D3) because its specific conductance adjusted for calcium, sulfate, and rainfall plots below the D3 line on figure 13. This plotting position was obtained by subtracting 800 from the specific conductance of 2,200 microsiemens per centimeter at 25 °C (table 6). The subtraction is an adjustment for calcium and sulfate concentrations and also for rainfall, as explained in figure 13. If the same water were applied to a less permeable soil like a silty or sandy clay that is underlaid by less permeable clay (soil class E3), there is a strong possibility that there would be little or no drainage and there would be an increased hazard of a large salinity buildup that would harm crops. This hazard is indicated by the plot of sample No. 7 above the E3 line.

Water from the Big Sioux aquifer generally does not have a large concentration of sodium or a large sodium-adsorption ratio (SAR). Only water with an adjusted SAR above six would be restricted in its use for irrigation. This restriction is indicated by an analysis plotting in the middle column in figure 13. The significance of other chemical and physical properties of water is discussed in table 7.

## Vermillion East Fork Aquifer

The Vermillion East Fork aquifer generally is unconfined and stores 0.3 million acre-ft of water in 94 $mi^2$ of central Kingsbury County along a northwest-trending, 2- to 4-mi-wide band (fig. 9). Depths to the top of the aquifer range from land surface to as much as 120 ft. The thickness of the aquifer averages 25 ft but locally exceeds 40 ft between De Smet and Spirit Lake. At Spirit Lake, the aquifer is 48 to 64 ft thick, extends to a depth of 90 ft, and is composed of up to 3 units separated by till (fig. 7). The aquifer is less than 40 ft thick in most of southern Kingsbury County.

The Vermillion East Fork aquifer is composed of glacial outwash, medium to very coarse sand and fine gravel. The average hydraulic conductivity of the aquifer is estimated from examination of drill cuttings to range from 200 to 600 ft/d. The maximum yield of wells is estimated to be 1,000 gal/min (table 3). Pumping lifts for large capacity wells should range from 20 to 100 ft, being greatest beneath hills along the west side of the aquifer.

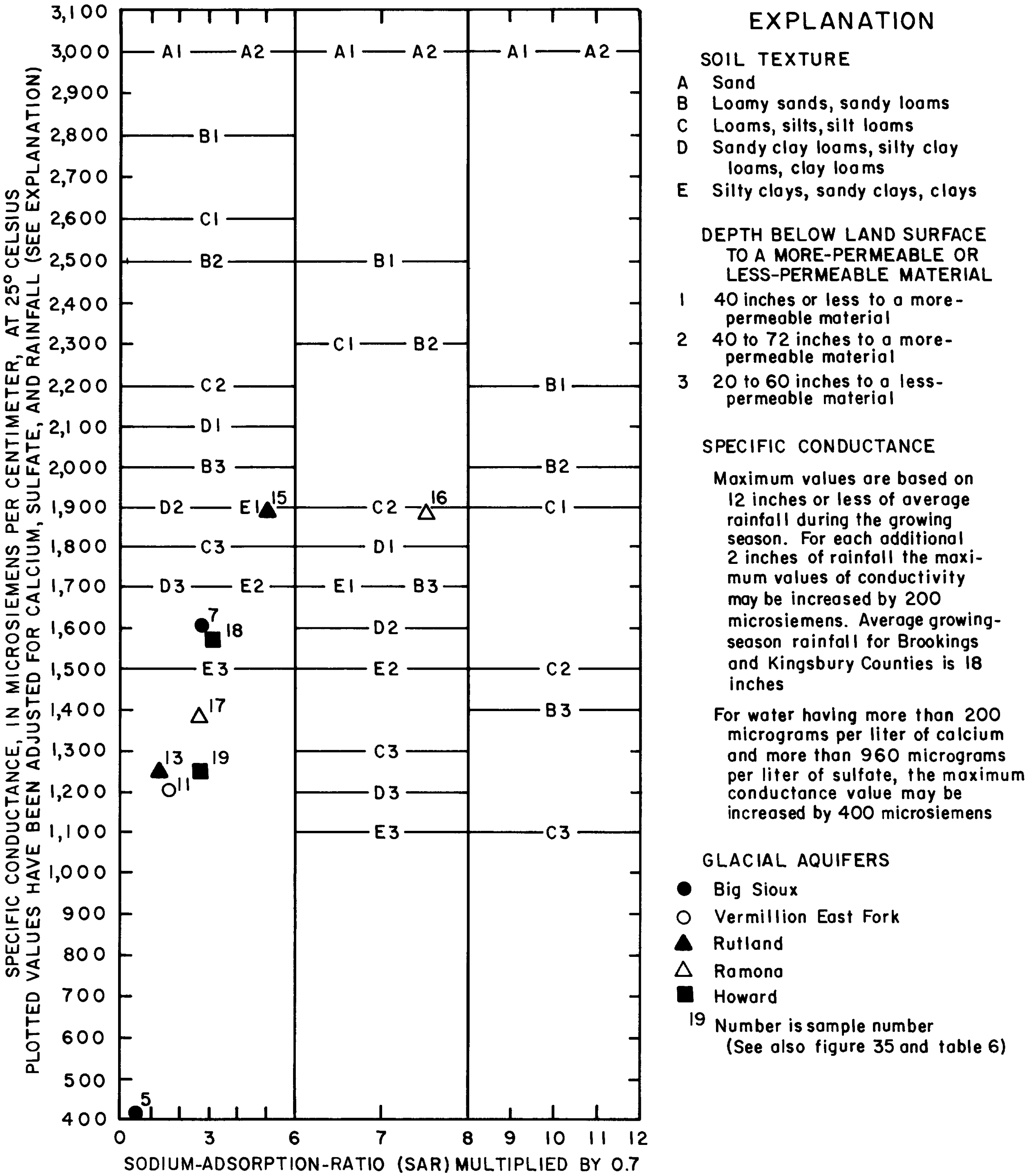



Figure 13.--Irrigation-water classification diagram, based on South Dakota standards (revised Jan. 7, 1982) for maximum allowable specific conductance and adjusted sodium-adsorption-ratio values for which an irrigation permit can be issued for applying water under various soil texture conditions. Water can be applied under all soil conditions at or above the plotted point but not below it provided other conditions are met (South Dakota Division of Conservation, no date). Modified from Koch, 1984.

Table 6.--Selected chemical analyses of ground water

[Analyses by U.S. Geological Survey Laboratory unless otherwise noted. Limits, where given, are primary (mandatory) and secondary (recommended) limits for concentrations of substances in drinking water as set forth by the U.S. Environmental Protection Agency (1986a, b). Reported in milligrams per liter (mg/L) except as indicated. One milligram per liter is approximately equal to one part per million. One microgram per liter (µg/L) is equal to one part per billion. < signifies less than]

| Sample number | Well depth (feet) | Location | Date | Silica | Iron (µg/L) | Manganese (µg/L) | Calcium | Magne-sium | Sodium | Potas-sium | Bicar-bonate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Recommended limit (* indicates mandatory limit, from table 7) | | | | -- | 300 | 50 | -- | -- | -- | -- | -- |
| | | | | GLACIAL AQUIFERS | | | | | | | |
| | | | | Big Sioux aquifer | | | | | | | |
| 1 | 65 | Brookings, Well #1 | 5-27-82 | -- | 2,370 | 640 | 130 | 42 | 16 | 3.1 | 320 |
| 2 | 56 | Aurora | 1-13-83 | -- | <20 | <20 | 83 | 34 | 16 | 2.0 | 310 |
| 3 | 36 | Bruce | 8-24-83 | -- | 20 | 350 | 100 | 37 | 20 | 2.5 | 400 |
| 4 | 30,55 | R.W.S.[1]-Bruce | 1-23-85 | -- | <20 | 880 | 81 | 36 | 11 | 2.3 | 290 |
| 5 | 24 | Elkton-North | 11- 3-82 | -- | 40 | 40 | 130 | 48 | 18 | 3.3 | 350 |
| 6 | 45 | Volga | 5-24-83 | -- | 190 | 490 | 82 | 29 | 11 | 4.7 | 260 |
| 7 | 150 | 112N49W30CDDC | 7-17-85 | 27 | 40 | 160 | 110 | 160 | 83 | 16 | 600 |
| | | | | Vermillion East Fork aquifer | | | | | | | |
| 8 | 54 | De Smet | 12-12-83 | -- | 750 | 500 | 100 | 32 | 13 | 5.0 | 320 |
| 9 | 45 | R.W.S.[1]-De Smet | 12- 1-83 | -- | 760 | 540 | 92 | 29 | 18 | 5.1 | 310 |
| 10 | 30 | 110N56W35DBCC | 7-16-85 | 23 | 54 | 1,100 | 110 | 60 | 46 | 10 | 390 |
| 11 | 78 | 111N56W33ABBD | 7-16-85 | 28 | 470 | 750 | 230 | 80 | 50 | 8.5 | 520 |
| 12 | 90 | 112N57W24DCCA | 8-17-85 | 25 | 130 | 2,100 | 230 | 60 | 110 | 16 | 230 |
| | | | | Rutland aquifer | | | | | | | |
| 13 | 75 | 109N50W35DDCC | 8-31-82 | 28 | 50 | 5,000 | 310 | 68 | 40 | 6.5 | 420 |
| 14 | 120 | 110N49W36CDBD | 7-17-85 | 29 | 370 | 1,100 | 250 | [4]60 | 80 | 6.1 | 540 |
| 15 | 382 | 111N47W28DDD | 7-18-85 | 12 | 12,000 | 310 | 280 | 150 | 200 | 12 | 310 |
| | | | | Ramona aquifer | | | | | | | |
| 16 | 135 | 109N56W26BBBB | 7-16-85 | 29 | 40 | 880 | 310 | 79 | 310 | 21 | 260 |
| 17 | 150 | 112N53W23ADDD | 7-17-85 | 28 | 260 | 3,900 | 370 | 87 | 120 | 13 | 190 |
| | | | | Howard aquifer | | | | | | | |
| 18 | 400 | 109N53W36CDDD | 7-16-85 | 16 | 5,800 | 7,000 | 410 | 95 | 110 | 13 | 300 |
| 19 | 316 | 110N54W 7BCBA | 7-17-85 | 30 | 1,000 | 1,900 | 230 | 65 | 94 | 12 | 360 |
| | | | | Altamont aquifer | | | | | | | |
| 20 | 617 | 110N53W 1ACDD | 8- 2-82 | -- | 1,150 | 150 | 97 | 33 | 550 | 16 | 450 |
| 21 | 586 | 111N52W18CCCB | 7-15-85 | 29 | 1,200 | 120 | 110 | 39 | 490 | 19 | 430 |
| | | | | BEDROCK AQUIFERS | | | | | | | |
| | | | | Codell aquifer | | | | | | | |
| 22 | 718 | 109N52W14CADB | 1-23-80 | -- | 1,200 | 60 | 48 | 18 | 560 | 14 | 495 |
| 23 | 780 | 110N52W13DDDA | 7-15-85 | 8.1 | 40 | 30 | 50 | 17 | 530 | 11 | 390 |
| 24 | 550 | 111N57W19DDDD | 8-17-85 | 9.7 | 160 | 40 | 14 | 5.1 | 650 | 6.1 | 405 |
| | | | | Dakota aquifer | | | | | | | |
| 25 | 1,020 | 109N54W22CCAC | 12- 6-79 | -- | 530 | <20 | 9.8 | 4.1 | 830 | 7.2 | 550 |
| 26 | 950 | 109N57W28AABA | 6- 2-69 | 9.4 | 460 | 20 | 7.5 | 3.3 | 770 | 5.8 | 360 |
| 27 | 1,240 | 110N53W10DAAA | 7-17-85 | 2.2 | 50 | 10 | .4 | .3 | 740 | 6.1 | 725 |
| 28 | 1,157 | 110N55W 1ACDA | 5-24-83 | -- | 180 | 80 | 8.0 | 3.2 | 760 | 6.5 | 428 |
| 29 | 855 | 110N58W 6CBBA | 5-24-83 | -- | 280 | 70 | 17 | 4.6 | 680 | 7.7 | 307 |
| 30 | 1,260 | 111N52W25DDCC | 4-27-64 | 10 | 120 | 40 | 15 | 5.0 | 1,200 | 8.0 | 585 |

[1]Rural water system (composite of 2 wells).
[2]Nitrate only.
[3]South Dakota Department of Water and Natural Resources, Office of Drinking Water.
[4]Calculated.

| Sulfate | Chloride | Fluoride | Nitrate plus nitrite (dissolved as N) | Boron (µg/L) | Dissolved solids: Residue at 180 °C | Dissolved solids: Calculated | Total hardness (Ca,Mg) | Sodium-adsorption ratio (SAR) | Specific conductance (microsiemens per centimeter at 25 °C) | pH (units) |
|---|---|---|---|---|---|---|---|---|---|---|
| 250 | 250 | *4.0 | *10 | -- | 500 | 500 | -- | -- | -- | -- |
| 260 | 1.7 | -- | [2]<0.1 | -- | 647 | -- | 500 | 0.3 | 960 | [3]7.3 |
| 94 | 9.7 | .4 | [2]6.7 | -- | 476 | -- | 350 | .4 | 710 | [3]7.5 |
| 46 | 16 | .3 | [2]9.1 | -- | 497 | -- | 410 | .4 | 780 | [3]7.2 |
| 100 | 8.4 | .3 | [2]1.4 | -- | 434 | -- | 350 | .3 | 636 | [3]7.5 |
| 99 | 38 | .8 | [2]36 | -- | 632 | -- | 520 | .3 | 1,030 | [3]7.2 |
| 110 | 12 | 1.0 | [2]<.3 | -- | 407 | -- | 320 | .3 | 645 | [3]7.3 |
| 220 | 140 | -- | 91 | -- | -- | 1,460 | 930 | 1.2 | 2,200 | 7.3 |
| 160 | 5.7 | .9 | [2].6 | -- | 537 | -- | 380 | .3 | 799 | [3]7.4 |
| 150 | 7.0 | .2 | [2].1 | -- | 499 | -- | 350 | .4 | 745 | [3]7.2 |
| 170 | 23 | -- | -- | -- | -- | 637 | 520 | 1.0 | 1,210 | 7.3 |
| 320 | 210 | -- | .4 | -- | -- | 1,190 | 900 | .8 | 1,820 | 7.0 |
| 910 | 13 | -- | .1 | -- | -- | 1,480 | 820 | 1.8 | 1,750 | 7.4 |
| 770 | 3.0 | .3 | <.1 | 500 | 1,560 | 1,430 | 1,100 | .6 | 1,850 | 7.2 |
| [4]600 | -- | .4 | .3 | 430 | -- | -- | 1,640 | .4 | 1,530 | 7.6 |
| 1,600 | 2.6 | -- | <.1 | -- | -- | 2,420 | 1,300 | 2.4 | 2,900 | 7.3 |
| 1,500 | 14 | -- | 1.3 | -- | -- | 2,400 | 1,100 | 4.1 | 2,880 | 7.4 |
| 1,300 | 10 | -- | <.1 | -- | -- | 2,030 | 1,300 | 1.5 | 2,380 | 7.3 |
| 1,500 | 22 | .2 | <.1 | 980 | -- | 2,330 | 1,400 | 1.3 | 2,590 | 7.1 |
| 770 | 25 | -- | .6 | -- | -- | 1,410 | 840 | 1.5 | 1,840 | 7.2 |
| 870 | 200 | 2.3 | [2].8 | -- | 1,990 | -- | 380 | 12 | 3,050 | [3]7.6 |
| 1,000 | 160 | -- | .4 | -- | -- | 2,060 | 440 | 10 | 3,050 | 7.6 |
| 825 | 110 | 1.6 | [2]<.1 | -- | 1,890 | -- | 195 | 18 | 2,800 | [3]7.8 |
| 650 | 260 | -- | 1.5 | -- | -- | 1,730 | 190 | 17 | 2,890 | 7.8 |
| 930 | 230 | -- | 2.3 | -- | -- | 2,050 | 56 | 38 | 3,200 | 8.4 |
| 960 | 240 | 8.5 | [2]1.4 | -- | -- | -- | 40 | 56 | 3,300 | [3]8.3 |
| 1,000 | 240 | 3.5 | 2.9 | 3,400 | 2,320 | 2,250 | 30 | 59 | 3,380 | 8.1 |
| 800 | 210 | -- | .1 | -- | -- | 2,120 | 2 | 215 | 3,380 | 7.4 |
| 1,000 | 227 | 5.7 | [2].2 | -- | 2,230 | -- | 33 | 58 | 3,430 | [3]8.1 |
| 1,030 | 170 | 2.1 | [2].2 | -- | 2,050 | -- | 60 | 38 | 2,910 | [3]8.2 |
| 1,100 | 610 | 8.1 | [2]9.2 | 7,300 | 3,280 | 3,260 | 58 | 67 | 4,980 | 7.9 |

The Vermillion East Fork aquifer is recharged directly by precipitation and leakage from adjacent and underlying till (fig. 7). Potentiometric contours show that regional flow in the aquifer generally was southward and local flow was toward lakes in 1982-84 (fig. 11). The potentiometric contour map shown in figure 11 represents a period of above-normal recharge resulting in the water levels in the Vermillion East Fork aquifer being from 5 to 10 ft above normal. As a result, the water-level contours are shifted 1 to 2 mi closer to the recharge areas causing the hydraulic gradients to be steeper. Consequently, the flow estimates in the vicinity of the recharge area are probably larger than for periods of normal recharge. Flow calculations use methods described previously for the Big Sioux aquifer. Inflow of water in the aquifer from north of Kingsbury County was about 1,000 acre-ft/yr. Outflow southward from the county was estimated to be 300 acre-ft/yr. Flow toward Lakes Henry and Thompson in the south totaled about 3,500 acre-ft/yr, while flow to Spirit Lake in the north totaled about 3,300 acre-ft/yr. Westward outflow from Spirit Lake as ground water, estimated at 1,600 acre-ft/yr, probably is consumed entirely by evapotranspiration in T. 111 and 112 N., R. 57 W. because streams flowing westward off the Coteau west of Spirit Lake were observed to have no flow in 1986. Discharge from Lakes Henry and Thompson also is mainly by evapotranspiration except during wet periods like 1985-87 when most lakes in the study area overflowed. During 1985-86, the water level in Lake Thompson rose by nearly 20 ft due to large surface- and ground-water runoff after large increases in precipitation.

Water-level fluctuations in wells are caused by seasonal changes in recharge and discharge. For example, water levels rose sharply 1 to 3 ft almost every year in the spring during 1957-84 in a 21-ft-deep well in the Vermillion East Fork aquifer because most of the aquifer is shallow and readily recharged by snowmelt and rainfall (fig. 12). The water level declined 1 to 3 ft in most years during summer and fall because of increased evapotranspiration and drainage to streams and lakes. Similar declines in some other wells are due to pumpage of nearby large-capacity wells in summer.

Long-term effects of withdrawals through wells are limited because of extensive recharge and unconfined conditions (table 4). Drawdown of water levels is temporary and only a few feet at distances of about a mile from large-capacity wells. More large-capacity wells can be developed in most of the aquifer, provided they are not installed so close to existing wells as to cause excessive drawdown of water levels.

Annual high or low water levels fluctuated but showed a gradual long-term decline of 4 ft during 1963-81, a period during which cumulative departure from normal precipitation at De Smet decreased by about 30 inches (fig. 12). During 1982-85, precipitation increased dramatically, departing 24 inches from normal. This caused a water-level rise of about 9 ft in the observation well.

Water from the Vermillion East Fork aquifer is fresh to slightly saline and a calcium bicarbonate type. Concentrations of dissolved solids average 800 mg/L and range from about 500 to 2,700 mg/L. Hardness of the water averages 460 mg/L and ranges from 100 to 1,700 mg/L. Selected chemical analyses are listed in table 6. Generally, the water is suitable for use in irrigation, as shown in figure 13.

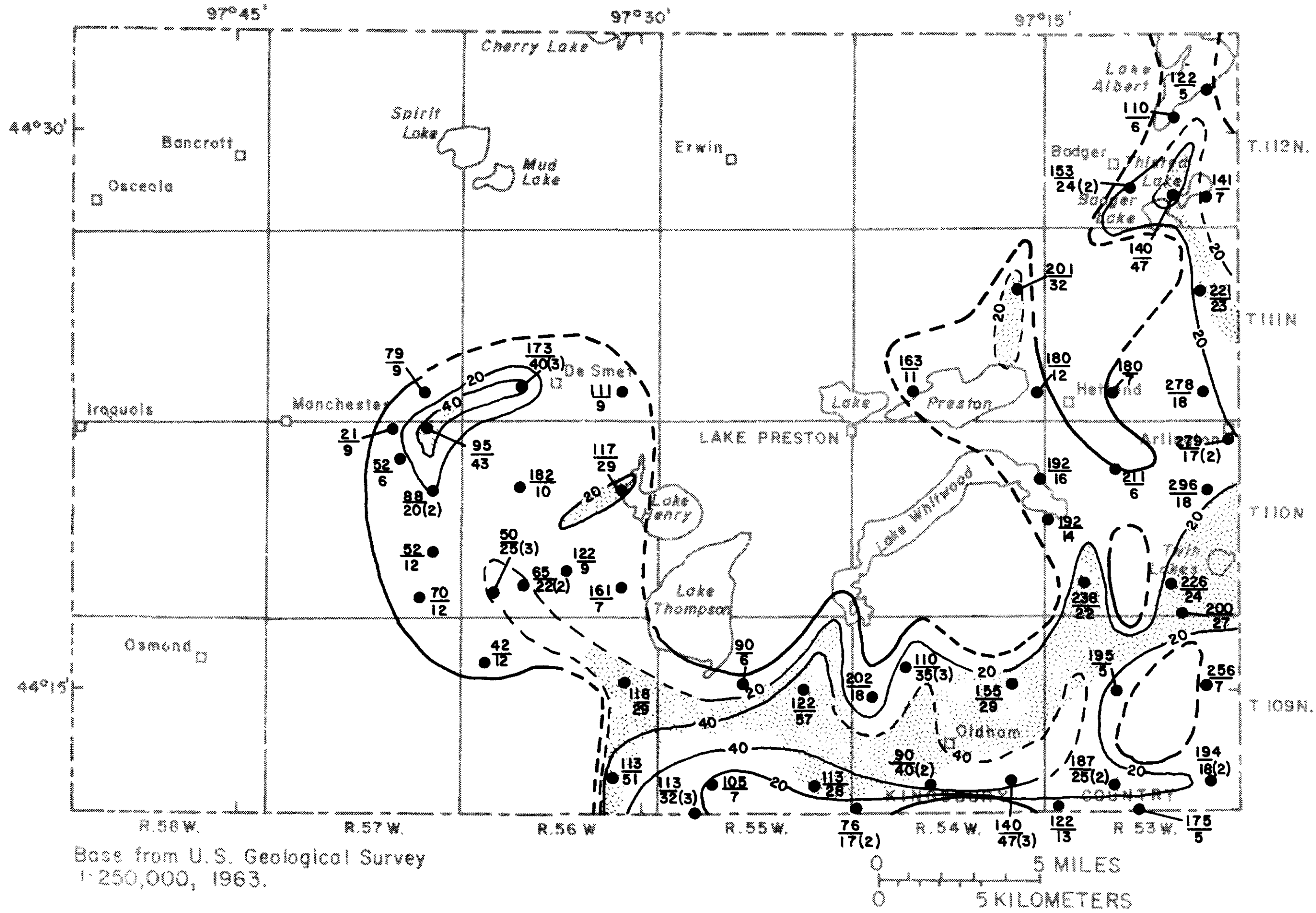
## Ramona Aquifer

The Ramona aquifer underlies 410 $mi^2$ in western Brookings County and eastern Kingsbury County (fig. 14). The aquifer is confined under artesian conditions by till but wells do not flow. The aquifer extends north and south from the study area as thin sand beds which are not mapped as part of the Ramona aquifer (Kume, 1985; Hansen, 1986). Observed depths from land surface to the top of the aquifer range from 21 ft east of Manchester to 282 ft southeast of Arlington. The aquifer thickness averages 20 ft but exceeds 40 ft locally in southern and northeastern Kingsbury County. The Ramona is a poor aquifer in many areas of southern Kingsbury County because it is composed only of thin beds of sand and gravel that are separated by as much as 50 ft of till. Even though the till is sandy and probably provides some hydraulic connection between sand beds, there is a small probability of obtaining large-capacity wells. Yield of a well pumping from several separated thin sand beds is not as large as for a well pumping from one unit of the same total thickness because thin beds tend to be lenticular. The aquifer map shows areas with a large probability of an aquifer unit at least 20 ft thick. Such a thick aquifer could supply wells of larger capacity than could several thin-bedded units, but pumping tests are required in order to estimate the sustained yield of a well.

The Ramona aquifer is composed of glacial outwash, very fine to coarse sand, and fine gravel that is moderately permeable. The average hydraulic conductivity of the aquifer is estimated to range from 100 to 400 ft/d. The hydraulic conductivity generally should be lower than for the other glacial aquifers because the Ramona is composed of as much as 67 percent of fine and medium sand (fig. 10). The maximum yield of wells probably is about 500 gal/min. Pumping lifts for large-capacity wells may range from 30 ft in western Kingsbury County to as much as 300 ft beneath southwestern Brookings County.

The Ramona aquifer probably is recharged by slow downward leakage of precipitation through till and lake deposits and locally by infiltration through thick sand deposits that penetrate through till layers. A more detailed study will be required to delineate where this recharge occurs. The potentiometric contour map shown in figure 15 represents a period of above-normal recharge resulting in the water levels in the Ramona aquifer also being above normal. These water-level rises in the Ramona aquifer are not as high as in the shallower aquifers due to the thickness of the overlying till and lake deposits which reduce the recharge rates. Potentiometric contours for the Ramona aquifer show that ground-water movement in northwestern Brookings County is toward the southwest in T. 112 N., R. 52 W. and toward the northeast in T. 111 N., R. 52 W. (fig. 15). Downgradient along the southern end of T. 112 N., R. 52 W., the flow direction changes to the southeast, toward the Big Sioux aquifer in the Oakwood Lakes area. In this area, the Big Sioux aquifer is more than 40 ft thick, and its base is near to the level of the Ramona aquifer (fig. 8, E-E′, well 145). Therefore, the two aquifers may be hydraulically connected through till and lake deposits because their water levels are similar. In northeastern Kingsbury County near Lake Albert, there may be recharge of the Ramona by upward leakage where the potentiometric surface for the Ramona is lower than that for the Howard aquifer (fig. 7, A-A′, wells 19, 20). Recharge is greatly retarded by the 100 ft of till between the aquifers.

Flow southward from southern Brookings County and southeastern Kingsbury County is estimated to be 500 acre-ft/yr, using methods previously described in the section for the Big Sioux aquifer. The hydraulic gradient is as steep as 40 ft/mi in south-central Kingsbury County and probably due to poor hydraulic connection between adjacent aquifer units rather than to large local recharge and large subsurface outflow. Discharge can occur by flow into adjacent minor aquifers or by upward leakage into till and then by evapotranspiration. Detailed hydrogeologic studies will be required in order to determine areas and quantities of recharge and discharge.




## EXPLANATION

AREA OF LARGE PROBABILITY OF FINDING AN AQUIFER UNIT AT LEAST 20 FEET THICK

—40— LINE OF EQUAL THICKNESS OF SATURATED SAND AND GRAVEL - Dashed where inferred. Interval 20 feet

● 95/43 WELL OR TEST HOLE - Upper number is depth, in feet, to top of saturated sand and gravel. Lower number is thickness, in feet, of sand and gravel. Number in parenthesis is number of aquifer units penetrated where greater than one

—— – – AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and private domestic and farm wells

Figure 14.--Extent, depth, and thickness of the Ramona and Rutland aquifers.

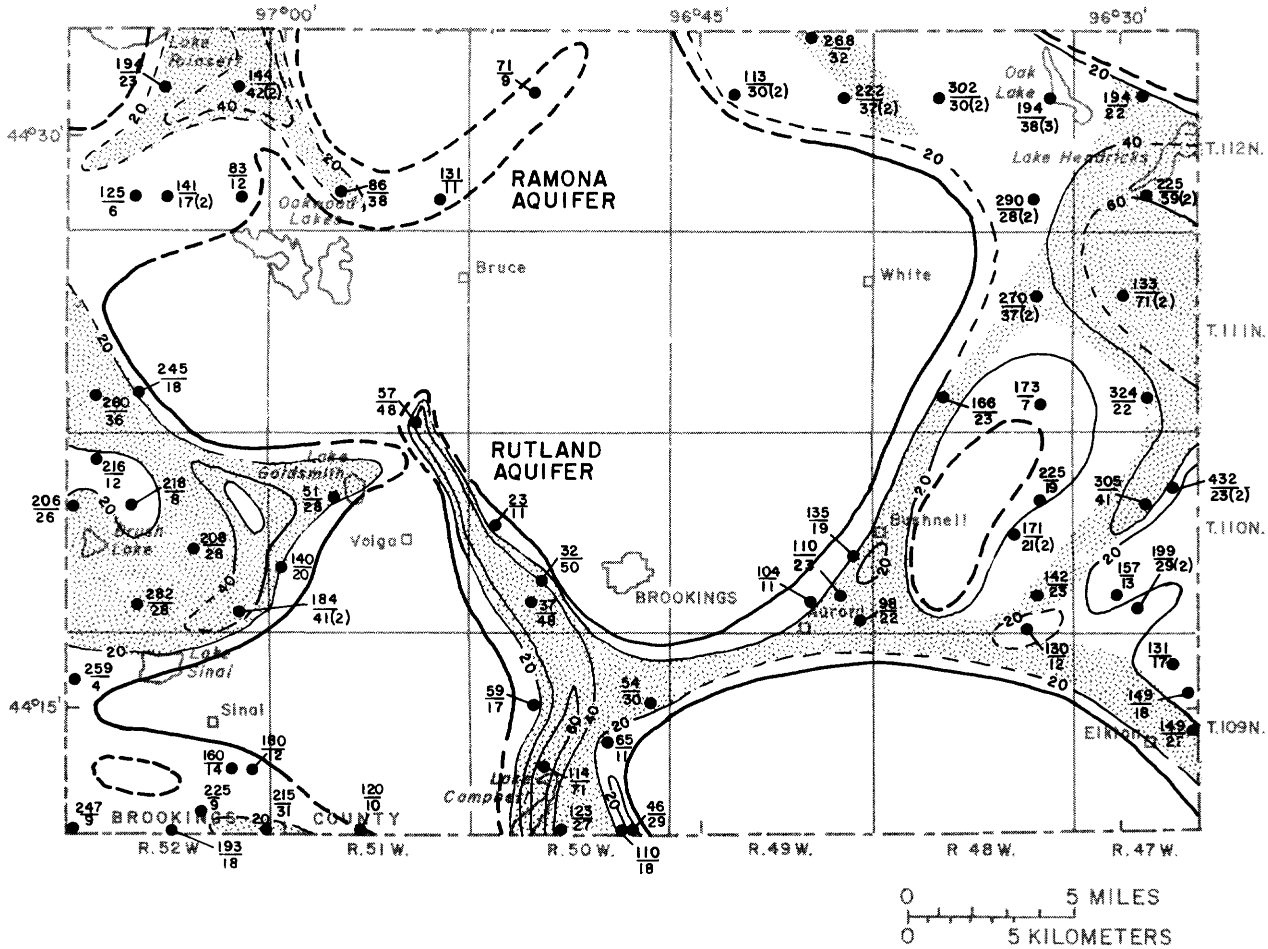
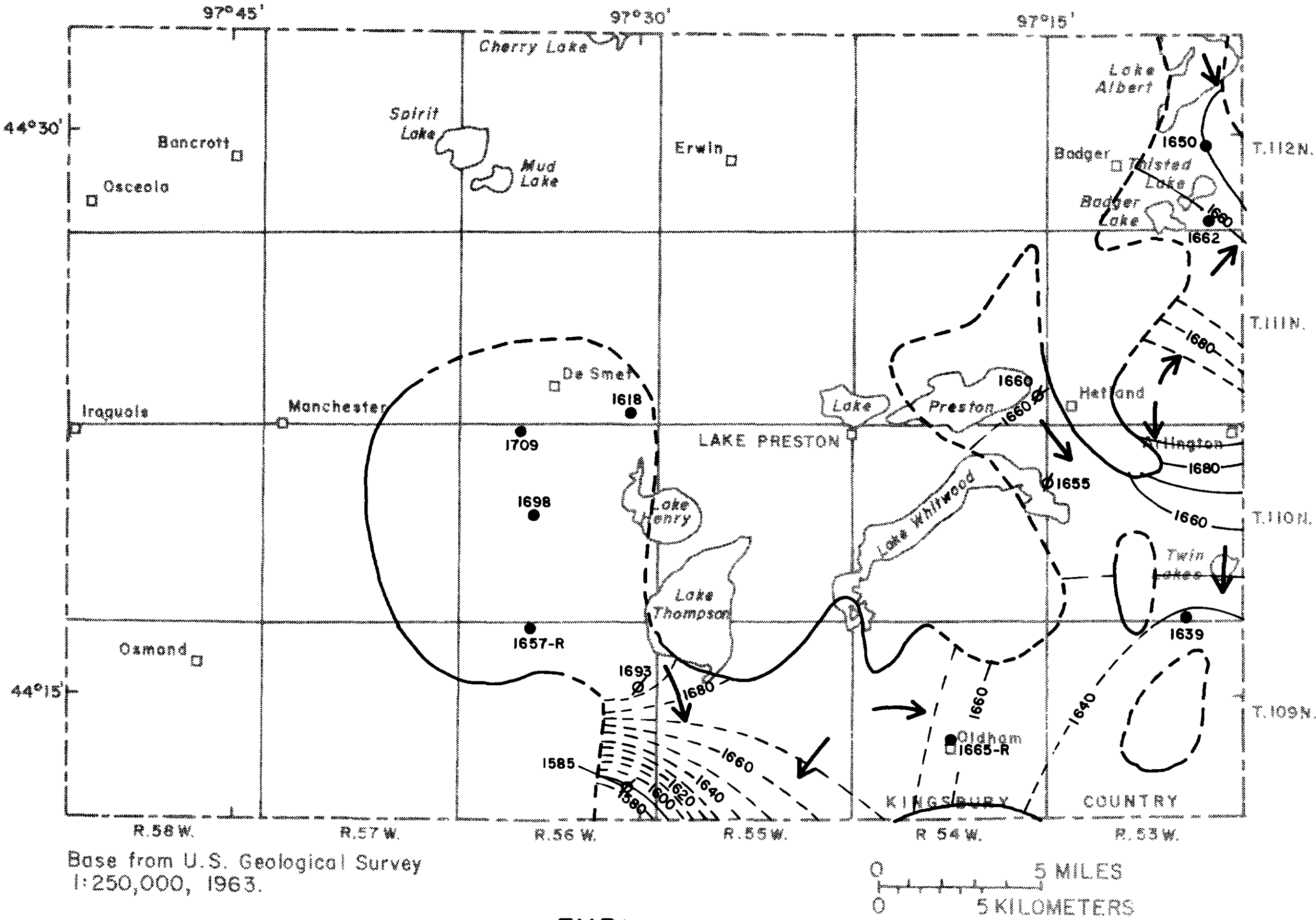



Figure 14.--Extent, depth, and thickness of the Ramona and Rutland aquifers.--Continued




## EXPLANATION

—1660 – – POTENTIOMETRIC CONTOUR - Dashed where inferred. Shows altitude at which water would have stood in tightly cased, nonpumping wells in 1982-85. Contour interval 10 feet. Datum is sea level

● 1731-R WELL - Number is altitude of water level, in feet above sea level. An "R" indicates a reported water level

ø OBSERVATION WELL - Quarterly measurements

⟵ GENERAL DIRECTION OF GROUND-WATER MOVEMENT

—— – – – AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and private domestic and farm wells

Figure 15.--Potentiometric contours of the Ramona and Rutland aquifers, 1982-85.

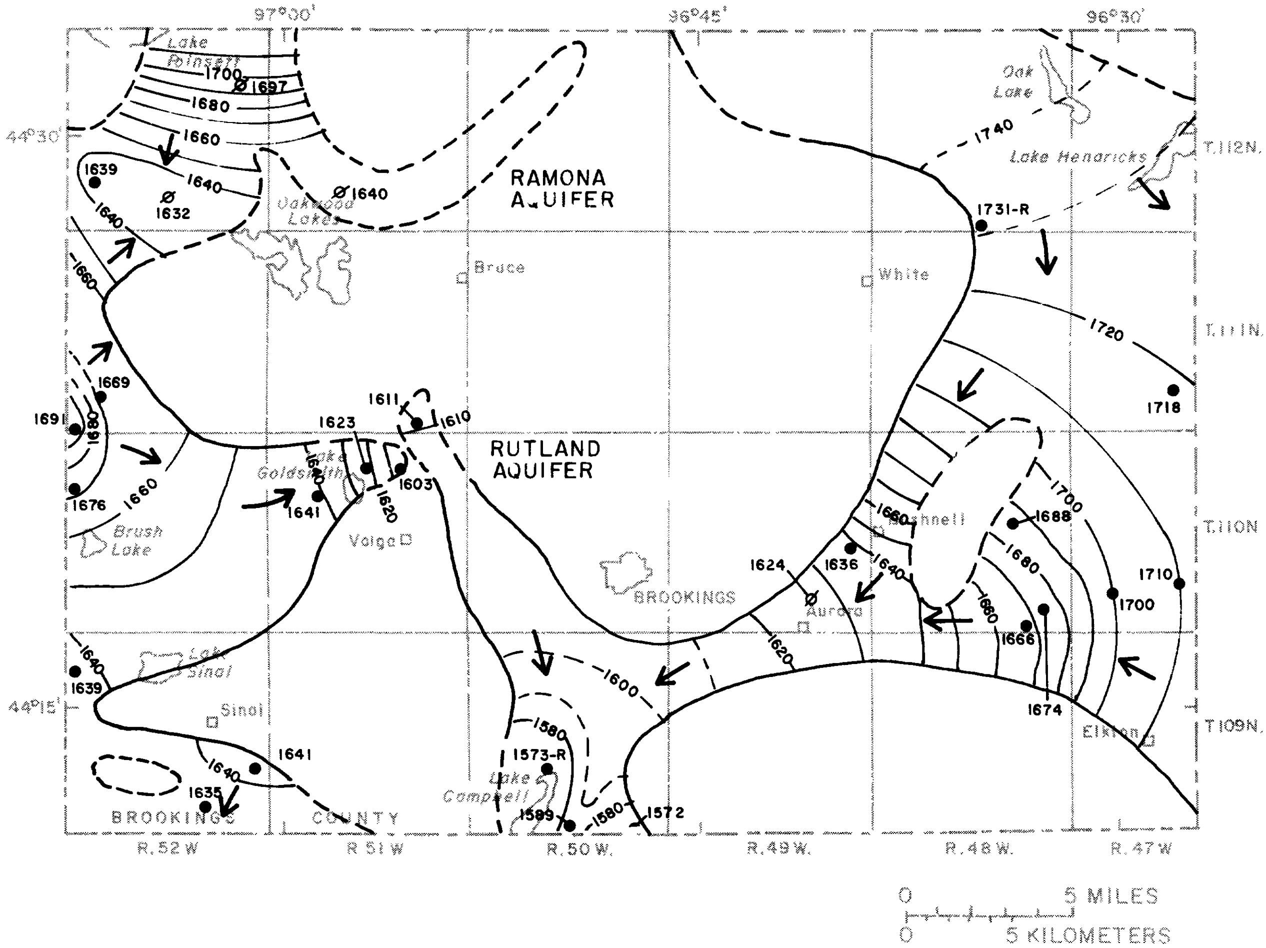



Figure 15.--Potentiometric contours of the Ramona and Rutland aquifers, 1982-85.--Continued

Water-level fluctuations are not as large for the Ramona aquifer as for shallower aquifers because there is less pumpage from the Ramona, and the confining till layers retard evapotranspiration and recharge. Locally, there are small effects from pumping. The hydrograph for an observation well in northwestern Brookings County shows water-level declines of about one foot during the summers of 1982, 1983, and 1985 due to pumping of an irrigation well a mile east (fig. 12). Intermittent pumping of a domestic well in southern Kingsbury County produced summer declines of 0.3 ft in an observation well 0.1 mi to the north (fig. 12). Long-term water-level rises are 2.8 ft and 1.0 ft respectively in the two observation wells during the 1982-86 period of above-normal precipitation. These rises tend to be less than for shallower aquifers because the confining till layers tend to retard recharge to the aquifer.

Water from the Ramona aquifer is slightly saline and a calcium sulfate type. Concentrations of dissolved solids average 1,800 mg/L and range from 1,400 to 2,600 mg/L. Hardness of the water averages 790 mg/L and ranges from 600 to 1,800 mg/L. Representative chemical analyses are listed in table 6. The water is marginal to unsuitable for use in irrigation, depending on soil texture and permeability (fig. 13).

## Rutland Aquifer

The Rutland aquifer underlies an area of 240 $mi^2$ in central and eastern Brookings County (fig. 14). The aquifer is confined by till and depths to the top of the aquifer range from 23 ft, 3 mi west of Brookings, to 432 ft eastward near the State line at 110N47W9DAAA. The thickness of the aquifer averages about 15 ft but exceeds 40 ft west of the city of Brookings (fig. 14).

The Rutland aquifer is composed of glacial outwash, mostly fine to very coarse sand, and very fine to medium gravel. The southern part of the aquifer tends to be coarser grained than the northern part. The average hydraulic conductivity of the aquifer is estimated from examination of drill cuttings to range from 300 to 1,000 ft/d. The maximum yield of wells is reported to be as large as 1,800 gal/min (table 3). Pumping lifts of large-capacity wells should range from about 100 ft near the city of Brookings to as much as 400 ft along ridges in northeastern Brookings County.

The Rutland aquifer may be recharged by slow leakage of precipitation through hundreds of feet of till and through sand and gravel aquifers that are thick enough to penetrate through the till. However, additional studies would be necessary to delineate areas and quantities of recharge. Flow in the Rutland aquifer in eastern Brookings County generally is southwestward into T. 109 N., R. 50 W. (fig. 15), where the Rutland appears to be discharging into the Big Sioux aquifer. The potentiometric surface of the Rutland aquifer is above that for the Big Sioux in the township (fig. 11). Discharge into the Big Sioux aquifer probably is through till where it is only a few feet thick and also where there is direct contact of the two aquifers (fig. 7, wells 97-98, C-C′, 131-133, D-D′, fig. 8). Subsurface outflow through the Rutland aquifer, south, into Moody County is estimated to be about 6,000 acre-ft/yr, using methods described previously for the Big Sioux aquifer.

Water-level fluctuations in the Rutland aquifer are larger than those for wells in the Ramona aquifer because the Rutland is tapped by large-capacity wells. In T. 109 N., R. 50 W., the Rutland also is affected by pumpage in the overlying Big Sioux aquifer. Short-term water-level declines in the Rutland aquifer are as much as 2 to 5 ft in T. 109 N., R. 50 W., because of pumping from the overlying Big Sioux aquifer. Fourteen miles east of Brookings the water level declined 60 ft in a 160-ft-deep observation well at 110N47W29CCCC, about one-half mile from two irrigation wells in the Rutland aquifer. This drawdown greatly exceeds the theoretical drawdown for confined conditions, indicating that the Rutland aquifer is thinner, has a much lower transmissivity, or is much less extensive than the theoretical aquifer assumed for table 5.

Water from the aquifer is fresh to slightly saline and a calcium-magnesium bicarbonate-sulfate type or a calcium sulfate type. Concentrations of dissolved solids in water in the Rutland aquifer average 1,400 mg/L and range from 400 to 2,420 mg/L. Hardness of the water averages 1,300 mg/L and ranges from 300 to 1,640 mg/L. Representative chemical analyses are listed in table 6. The water is suitable to marginal for use in irrigation, depending on soil texture and drainage (fig. 13).

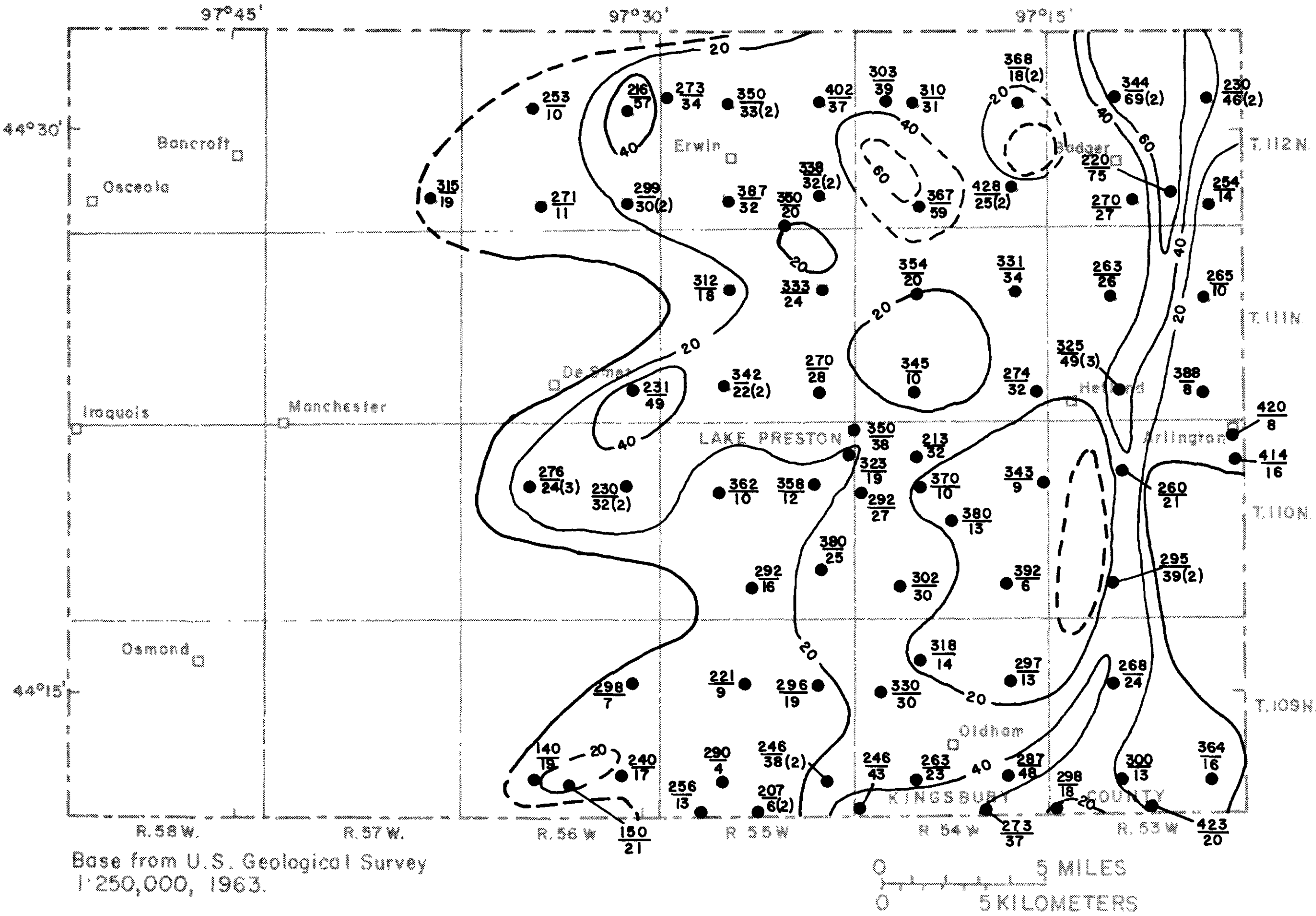
## Howard Aquifer

The Howard aquifer lies confined beneath hundreds of feet of till in an area of 835 $mi^2$ in eastern Kingsbury County and western Brookings County (fig. 16). Observed depths from land surface to the top of the aquifer range from 140 ft in south-central Kingsbury County to as much as 438 ft, 2 mi east of Arlington, and generally are greater than 200 ft (table 3). The thickness of the aquifer averages 25 ft but locally exceeds 100 ft. In western Brookings County, much of the aquifer is composed of two or more units that are separated by as much as 100 ft of poorly permeable till. Locally, the till is sandy and probably provides hydraulic connection between the sand units. The configuration of these units are shown in hydrologic sections (fig. 7).

The Howard aquifer is composed of glacial outwash, mostly very fine to very coarse sand, and some very fine to fine gravel. The average hydraulic conductivity of the aquifer is estimated from examination of drill cuttings to range from 200 to 600 ft/d. The maximum yield of wells is estimated to be as large as 1,000 gal/min locally (table 3). However, in many areas the maximum yield would be much less than 1,000 gal/min because of the large percentages of silt and fine and medium sand in the aquifer (fig. 10). Pumping lifts of large-capacity wells may range from 70 ft in south-central Brookings County to 250 ft in northern Kingsbury County.

The Howard aquifer may be recharged by slow leakage of precipitation through hundreds of feet of clayey till that locally includes silty or sandy lake deposits. An analysis of hydrographs of observation wells indicates that leakage may be as little as 0.01 in/yr. Locally greater recharge may occur through thick sand deposits that completely penetrate the overlying till, however, the 3-mi spacing of test holes was inadequate for detecting recharge areas. Detailed studies will be required to determine how and where recharge occurs. Potentiometric contours indicate that the direction of water movement in the Howard aquifer is southward and out of the study area (fig. 17).

Water levels in observation wells in the Howard aquifer have seasonal and long-term fluctuations but changes are not as large as for shallow aquifers because recharge and pumpage is smaller. Although recharge by leakage to buried aquifers is continuous, the spring recharge peak for shallow aquifers generally is not reflected in deeply buried aquifers for several years because of poor hydraulic connection through till.




## EXPLANATION

AREA OF LARGE PROBABILITY OF FINDING AN AQUIFER UNIT THICKNESS EXCEEDING 60 FEET

—40 -- LINE OF EQUAL THICKNESS OF SATURATED SAND AND GRAVEL - Dashed where inferred. Interval 20 feet

● 273/34 WELL OR TEST HOLE - Upper number is depth, in feet, to top of saturated sand and gravel. Lower number is thickness, in feet, of sand and gravel. Number in parenthesis is number of aquifer units penetrated where greater than one

——-- AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and private domestic and farm wells

Figure 16.--Extent, depth, and thickness of the Howard aquifer.

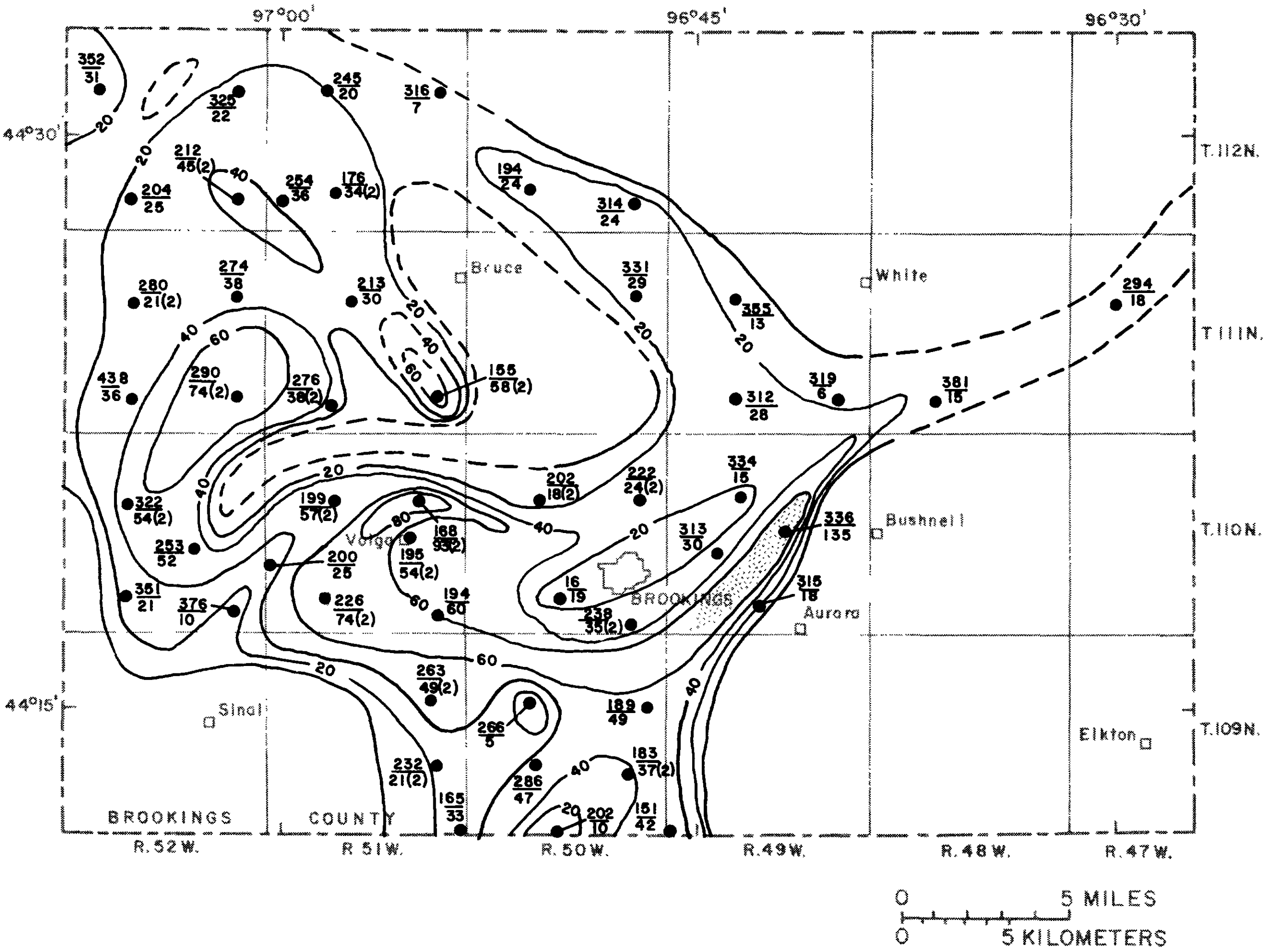
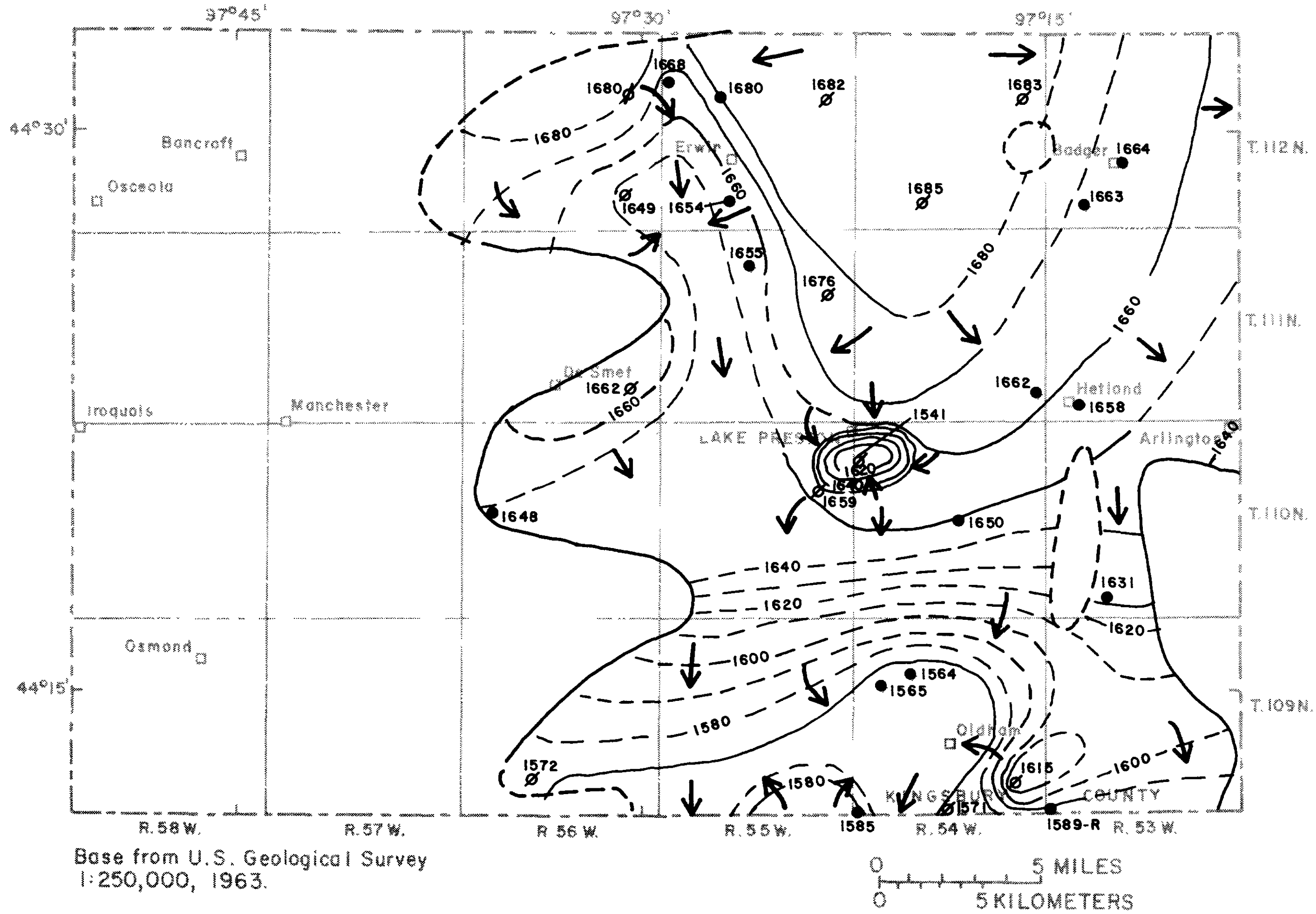



Figure 16.--Extent, depth, and thickness of the Howard aquifer.--Continued




Base from U.S. Geological Survey
1:250,000, 1963.

## EXPLANATION

——1660 — — POTENTIOMETRIC CONTOUR - Dashed where inferred. Shows altitude at which water would have stood in tightly cased, nonpumping wells in 1982-85. Contour interval 10 feet. Datum is sea level

● 1631-R WELL - Number is altitude of water level, in feet above sea level. An "R" indicates a reported water level

ø OBSERVATION WELL - Quarterly measurements

←—— GENERAL DIRECTION OF GROUND-WATER MOVEMENT

——— — — AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and private domestic and farm wells

Figure 17.--Potentiometric contours of the Howard aquifer, 1982-85.

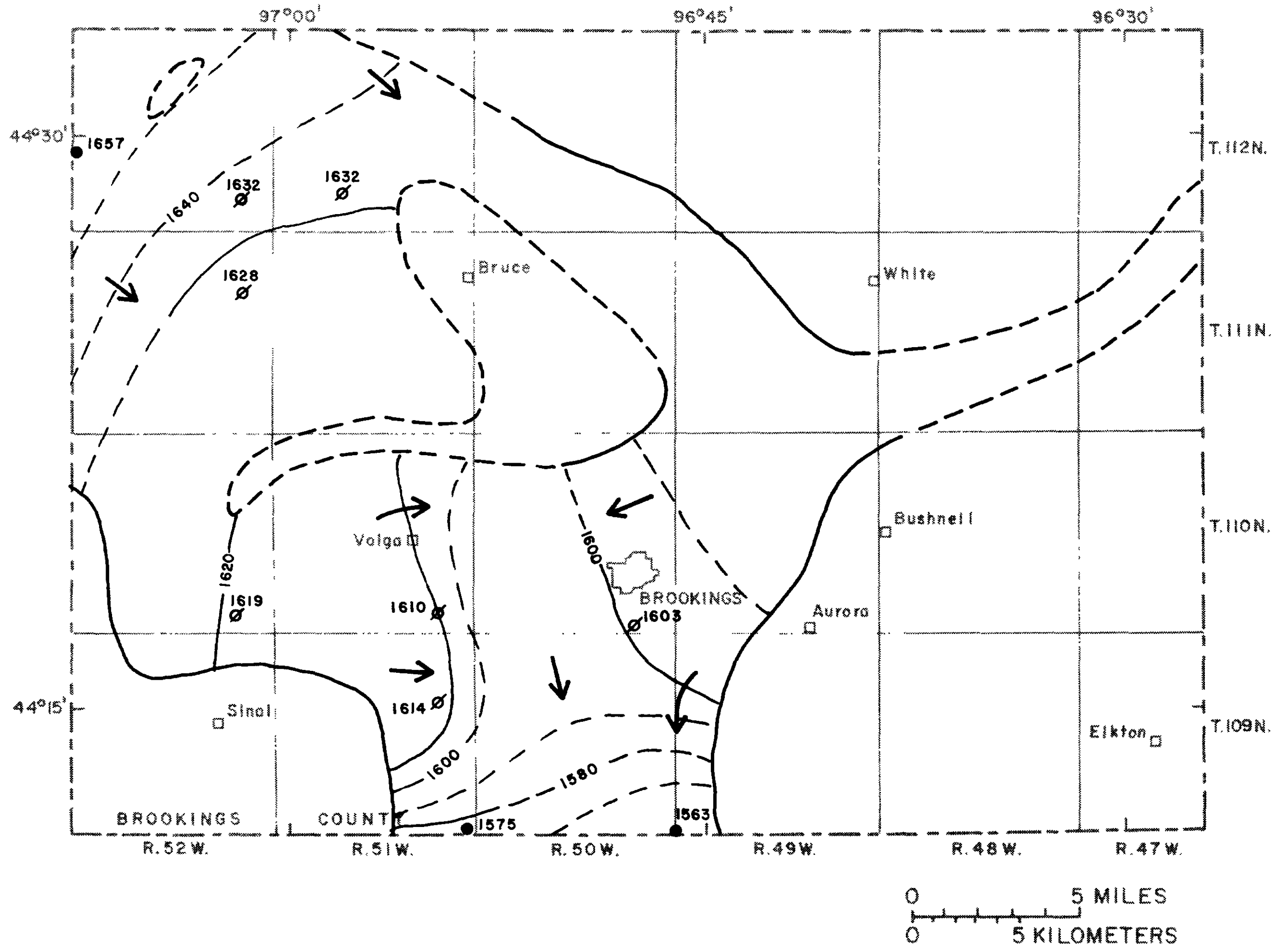



Figure 17.--Potentiometric contours of the Howard aquifer, 1982-85.--Continued

Seasonal water-level declines of 2 to 3 ft in a 372-ft-deep observation well in the Howard aquifer occurred each winter during 1983-86, probably due to increased pumpage from nearby domestic and livestock wells and the Lake Preston municipal well about 1 mile distant (fig. 12). The seasonal decline during winter is unusual because water levels generally decline during summer because of increased pumping for irrigation and livestock needs. During 1983-86, however, there was less summer pumpage because of greater than normal rainfall. These declines were superimposed on a long-term rise of 2.5 ft in annual peaks due to increased recharge during 1983-86.

Water from the Howard aquifer generally is slightly saline and a calcium sulfate type. Concentrations of dissolved solids average 2,200 mg/L and range from 1,410 to 3,400 mg/L. Hardness of the water averages 800 mg/L and ranges from 350 to 1,800 mg/L. Representative chemical analyses are listed in table 6. The water is marginal to unsuitable for irrigation, depending on soil texture and drainage (fig. 13). The concentration of boron in the water also may make the water unsuitable for irrigating certain sensitive crops (see table 7).

### Altamont Aquifer

The Altamont aquifer lies confined under hundreds of feet of till in an area of 380 $mi^2$ that is mostly in Brookings County (fig. 18). The aquifer extends west into Kingsbury County along channels that are 1 to 4 mi wide. The aquifer is believed to extend along erosional channels in bedrock. Observed depths to the top of the aquifer range from 345 ft 4 mi southwest of the city of Brookings, to greater than 700 ft at 111N47W28CCCC. The aquifer averages 25 ft in thickness and locally is as much as 305 ft thick (110N49W20DBBB). The aquifer generally occurs in a single layer (figs. 7 and 8).

The Altamont aquifer is composed of glacial outwash, mostly very fine to very coarse sand, and very fine to fine gravel. In Kingsbury County, much of the aquifer is composed of very fine to medium sand that has a small hydraulic conductivity. Coarse, well-sorted sand and gravel at the city of Arlington has a large conductivity. The hydraulic conductivity of the aquifer is estimated from examination of drilling samples to range from 100 to 600 ft/d. The maximum yield of wells is estimated to be as large as 1,000 gal/min (table 3). Pumping lifts of large-capacity wells may range from about 100 ft close to the city of Brookings to 500 ft in northeastern Brookings County.

A small amount of recharge of the Altamont aquifer may occur by slow leakage of precipitation through several hundreds of feet of till and overlying aquifers. Locally there may be greater recharge through thick sand deposits that completely penetrate the overlying till. However, just as with the Howard aquifer, no areas have been found in test drilling where the till is completely replaced by sandy deposits. Even where the Altamont aquifer is 305 ft thick (110N49W20DBBB), there is 34 ft of clayey till between the Altamont and the overlying Howard aquifer. Detailed studies will be required to determine how and where recharge occurs.

Potentiometric contours for the Altamont aquifer indicate that water moves through the aquifer eastward from Kingsbury County and beneath the city of Brookings in one channel, and southeastward and then eastward from northeastern Brookings County in another channel (fig. 19). There probably is appreciable subsurface outflow into Minnesota. Additional test drilling and well data will be needed to estimate the amount of flow through the aquifer.

Water levels in observation wells in the Altamont aquifer generally do not have fluctuations because recharge is small and there is little pumpage. An exception is the municipal well at Arlington which pumps intermittently about 100 gal/min from the Altamont. A pumping test of the well indicates that fluctuations in the water level are a few feet at a distance of several hundred feet from the pumping well. Water-level rises from increased precipitation and recharge during 1983-86 amounted to less than one foot for three observation wells in central and eastern Brookings County.

Water from the Altamont aquifer probably is slightly saline and a sodium sulfate type in much of the study area. There were only a few wells available for sampling for chemical analysis. Concentrations of dissolved solids in water from two wells 3 mi apart were 1,990 and 2,060 mg/L. Hardness of the two water samples was 380 and 400 mg/L (table 6). The water probably is unsuitable for irrigation of many types of soils because of its relatively large concentrations of sodium.

## Bedrock Aquifers

Three bedrock aquifers store 67 million acre-ft of slightly saline, relatively soft water beneath about three-fourths of the study area. In order of increasing depth, the aquifers are the Niobrara Formation, the Codell Sandstone Member of the Carlile Shale, and the Dakota Sandstone (table 1).

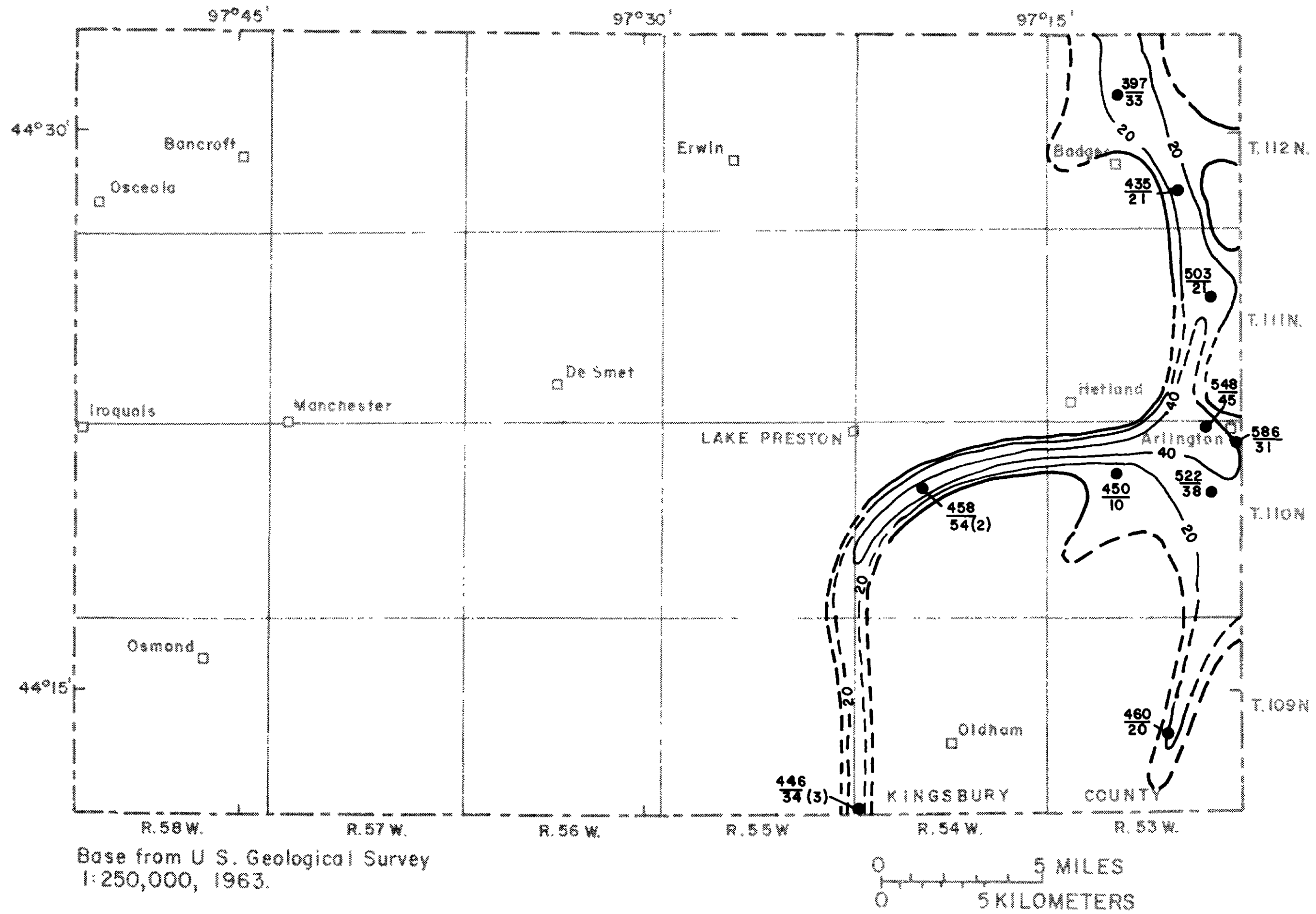
### Niobrara Aquifer

The Niobrara aquifer, as much as 155 ft of calcareous shale containing thin layers of chalk, extends throughout most of the study area. The aquifer underlies as much as 140 ft of Pierre Shale and overlies the Carlile Shale (table 1). Depths to the top of the aquifer in Brookings County range from 403 ft in the south-central to 744 ft in the northeast part of the county (fig. 20). In Kingsbury County, depths range from 226 ft in the southwest to 758 ft north-central. The top of the aquifer slopes generally northwestward at 3 ft/mi. The Niobrara and underlying aquifers are missing in southeastern Brookings County where the Sioux Quartzite extends upward above the top of the Niobrara.

The Niobrara aquifer generally is confined by shale or till but wells do not flow. The few wells that penetrate the aquifer are reported to have water levels within 100 ft of land surface. Well yield is estimated to range from 2 to no more than 5 gal/min because the chalky shale is moderately to poorly permeable. No information is available on the quality of water from the aquifer because the aquifer is relatively unused.

### Codell Aquifer

The Codell aquifer, as much as 170 ft of very fine to medium-grained, silty sandstone, siltstone, and shale, underlies all of the area except southeastern Brookings County (fig. 21). The thickness of the aquifer exceeds 100 ft in southwestern Brookings County and around the towns of Lake Preston and Iroquois in Kingsbury County. Depths to the top of the aquifer range from 568 to 785 ft below land surface in Brookings County and in Kingsbury County from about 320 ft in the southwest to more than 950 ft below land surface in the north-central part. The top of the aquifer slopes to the northwest at about 5 ft/mi in Brookings County and 15 ft/mi in eastern Kingsbury County. In western Kingsbury County, the top of the aquifer slopes northeastward at about 7 ft/mi, producing a northward-sloping trough. The trough may have formed by subaerial erosion before deposition of overlying shales.




## EXPLANATION

AREA OF LARGE PROBABILITY OF FINDING AN AQUIFER UNIT THICKNESS EXCEEDING 60 FEET

—40— LINE OF EQUAL THICKNESS OF SATURATED SAND AND GRAVEL - Dashed where inferred. Interval 20 feet

● 140/19+ WELL OR TEST HOLE - Upper number is depth, in feet, to top of saturated sand and gravel. Lower number is thickness, in feet, of sand and gravel. Number in parenthesis is number of aquifer units penetrated where greater than one. A plus (+) indicates greater than shown

AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and private domestic and farm wells

Figure 18.--Extent, depth, and thickness of the Altamont aquifer.

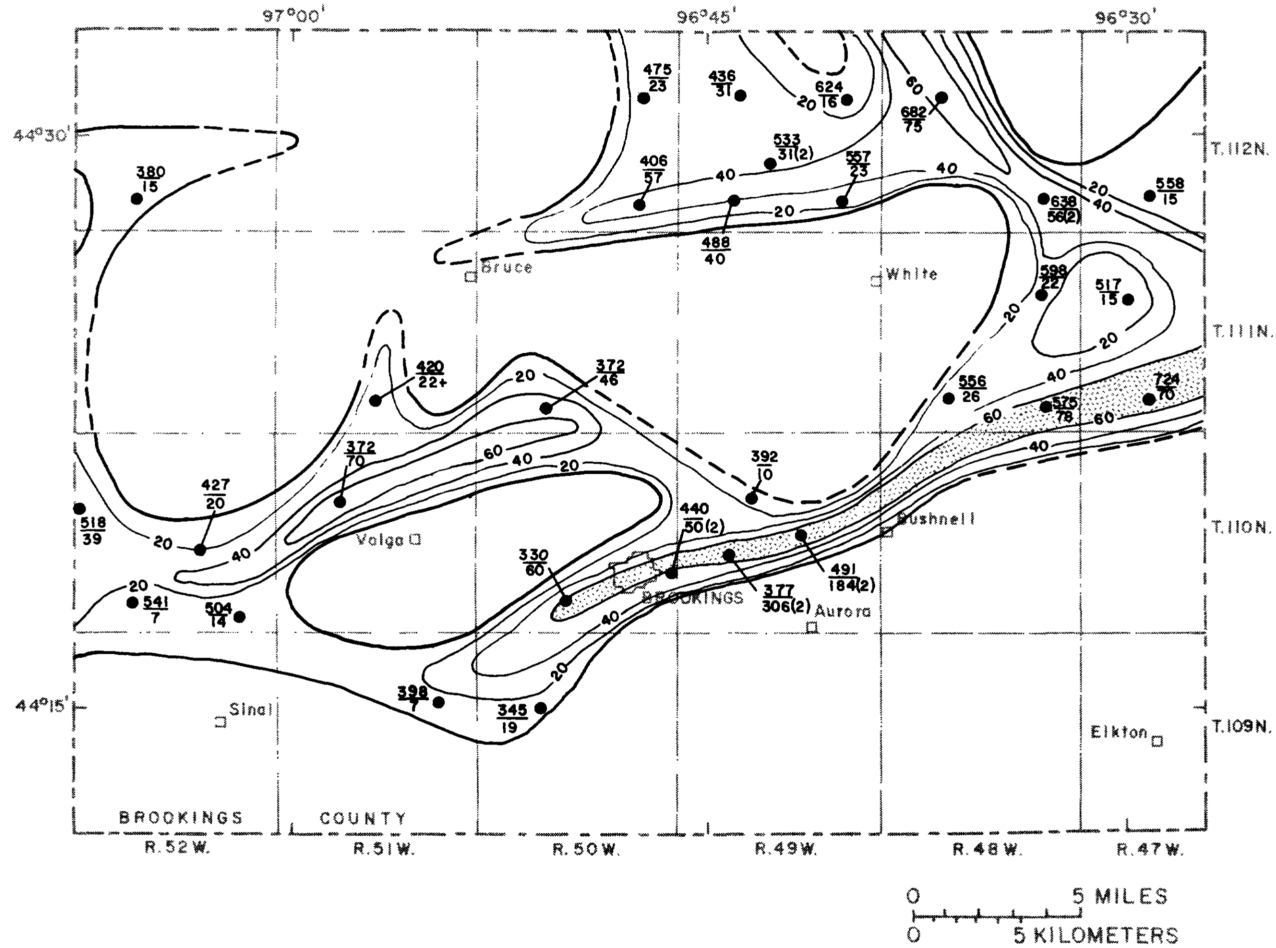



Figure 18.--Extent, depth, and thickness of the Altamont aquifer.--Continued

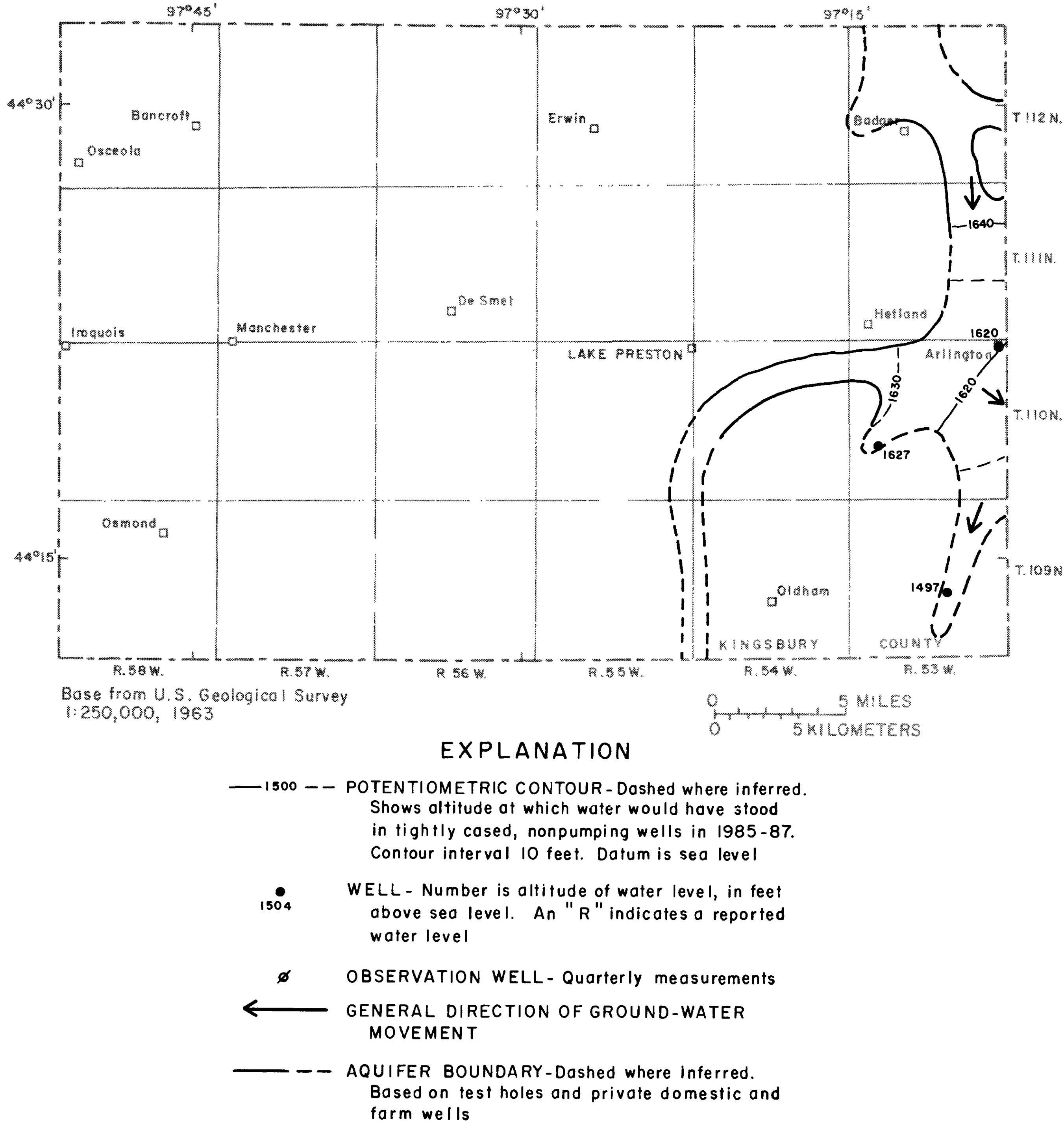



Figure 19.--Potentiometric contours of the Altamont aquifer, 1985-87.

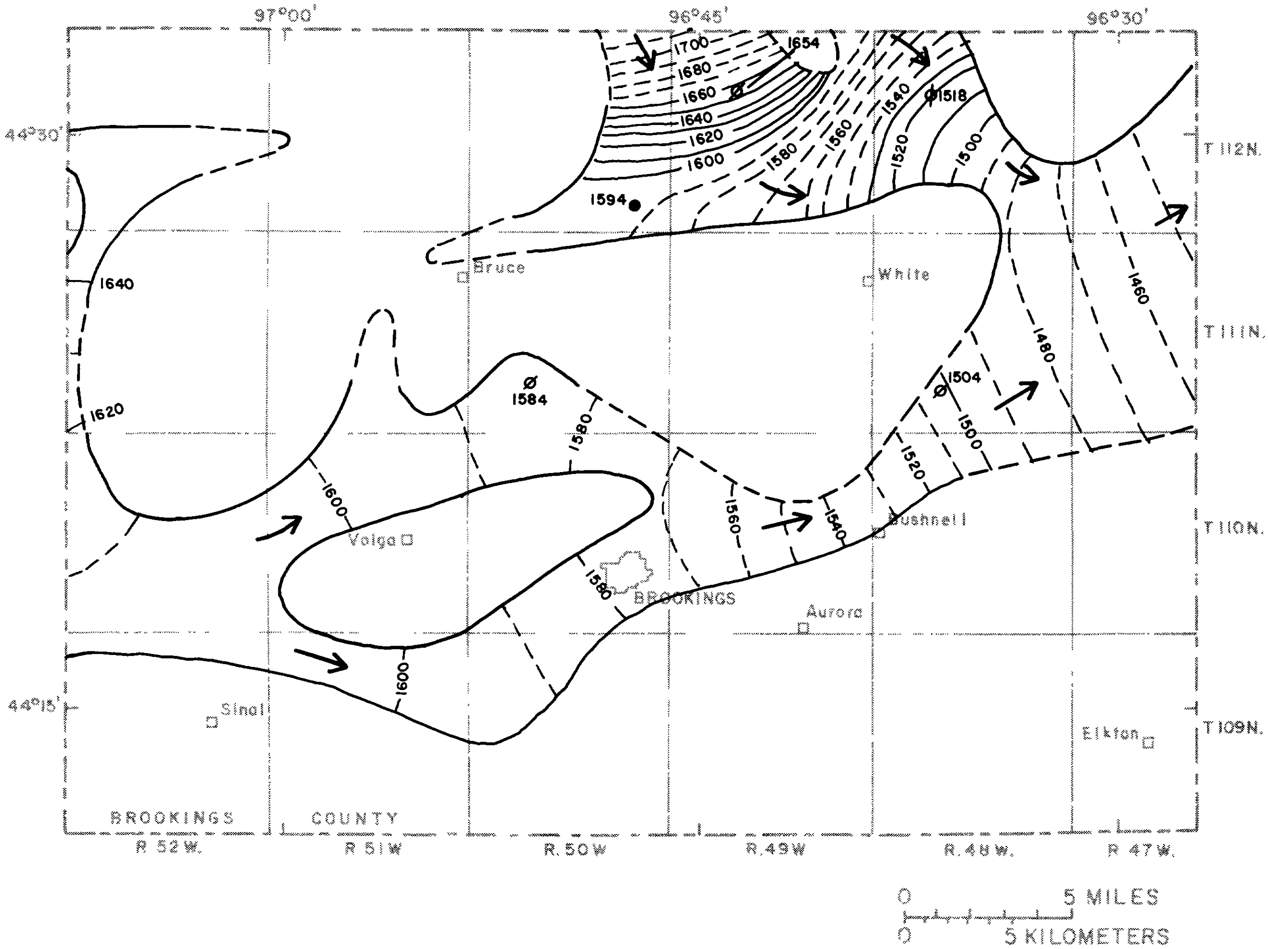
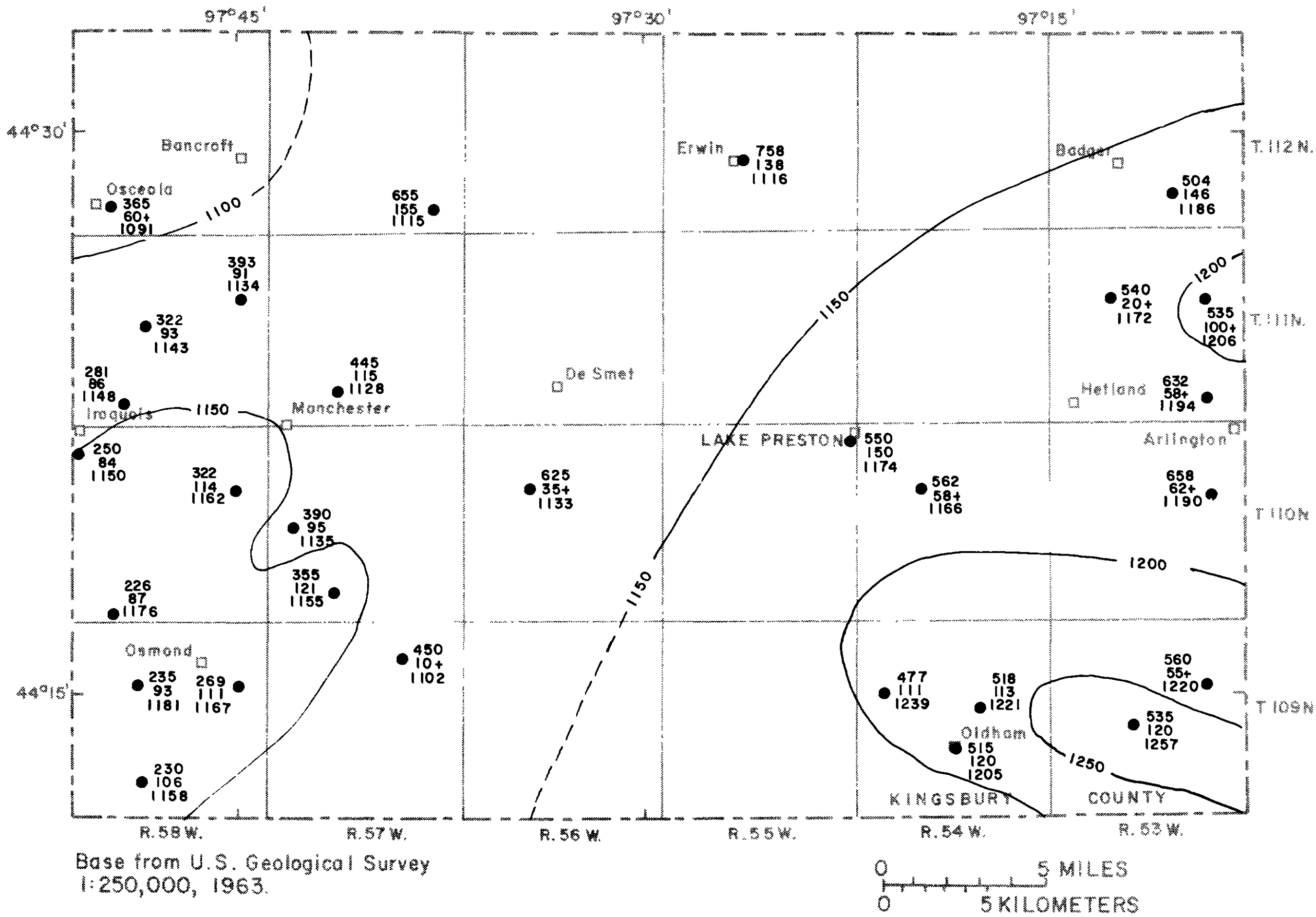



Figure 19.--Potentiometric contours of the Altamont aquifer, 1985-87.--Continued




## EXPLANATION

—— 1200 — — STRUCTURE CONTOUR - Dashed where inferred. Shows altitude of the top of the aquifer. Contour interval 50 feet. Datum is sea level

● 460 / 40+ / 1232 WELL OR TEST HOLE - Upper number is depth, in feet, to top of aquifer. Middle number is aquifer thickness, in feet. A plus (+) indicates a thickness greater than shown. Lower number is altitude of top of aquifer, in feet above sea level

———— — — AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and reported depths of private domestic farm wells

Figure 20.--Depth, thickness, and structure contours of the Niobrara aquifer.

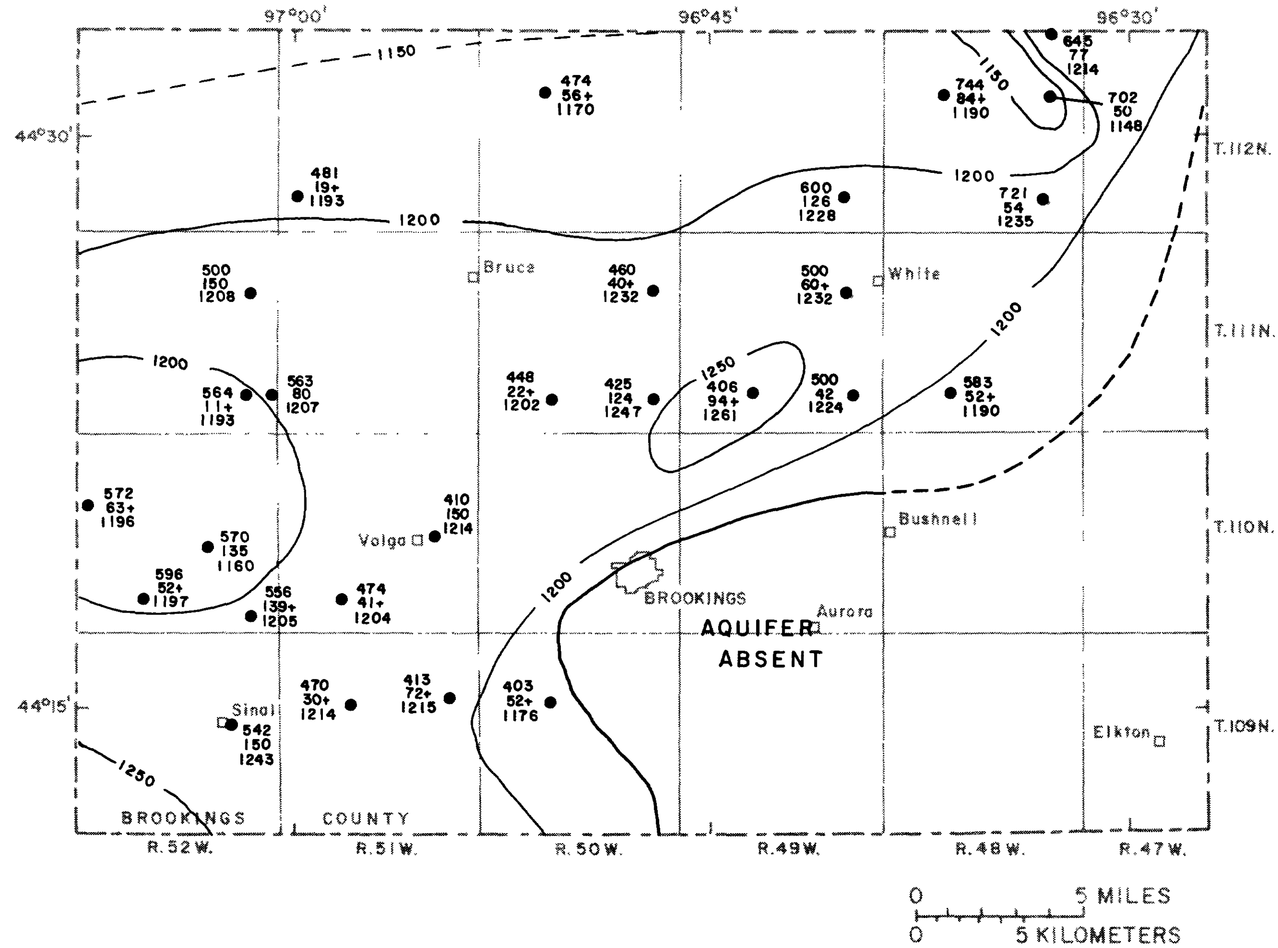
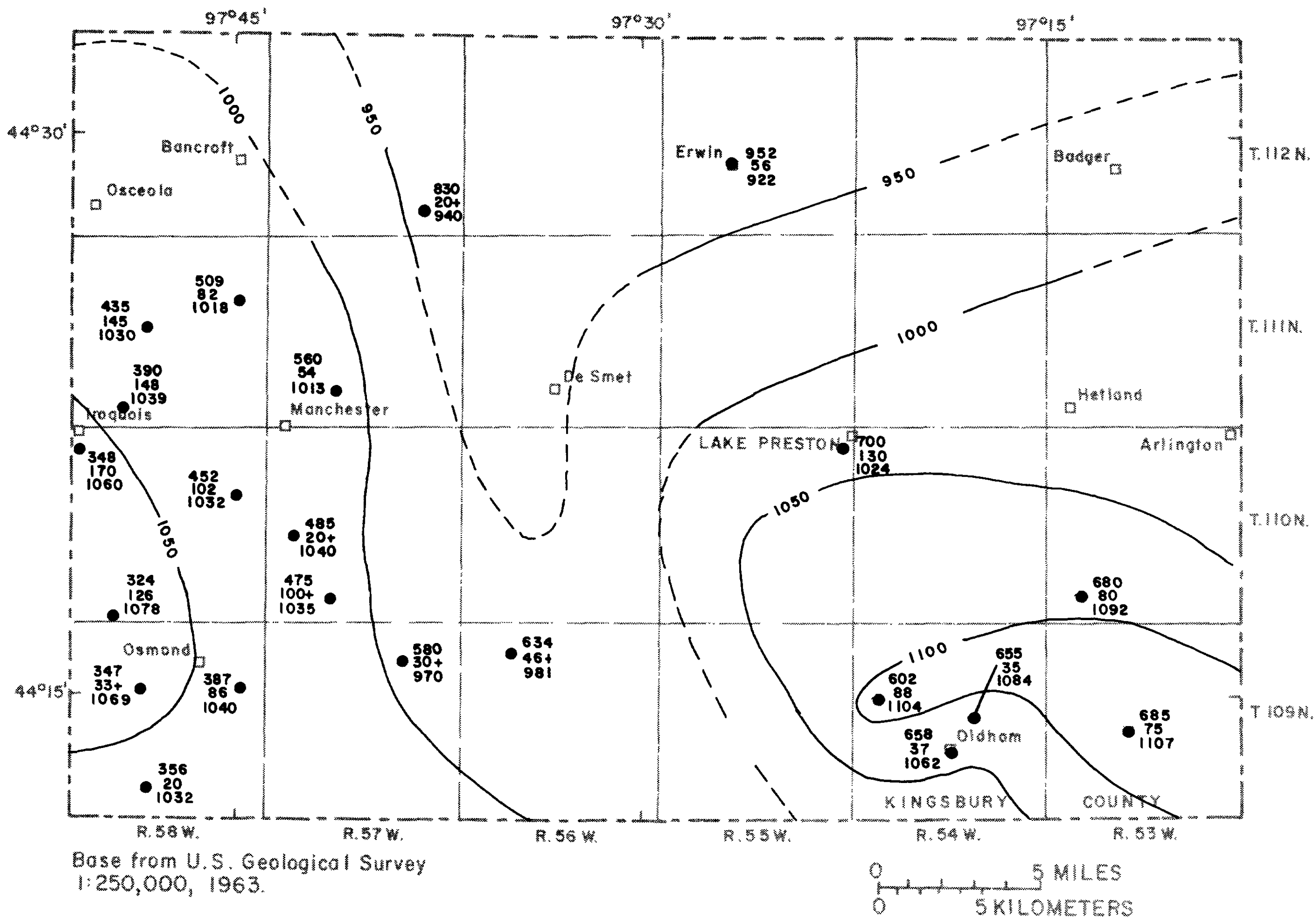



Figure 20.--Depth, thickness, and structure contours of the Niobrara aquifer.--Continued




## EXPLANATION

—— 1000 — — STRUCTURE CONTOUR - Dashed where inferred. Shows altitude of the top of the aquifer. Contour interval 50 feet. Datum is sea level

● 692 / 22+ / 1093 WELL OR TEST HOLE - Upper number is depth, in feet, to top of aquifer. Middle number is aquifer thickness, in feet. A plus (+) indicates a thickness greater than shown. Lower number is altitude of top of aquifer, in feet above sea level

———— — — AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and reported depths of private domestic farm wells

Figure 21.--Depth, thickness, and structure contours of the Codell aquifer.

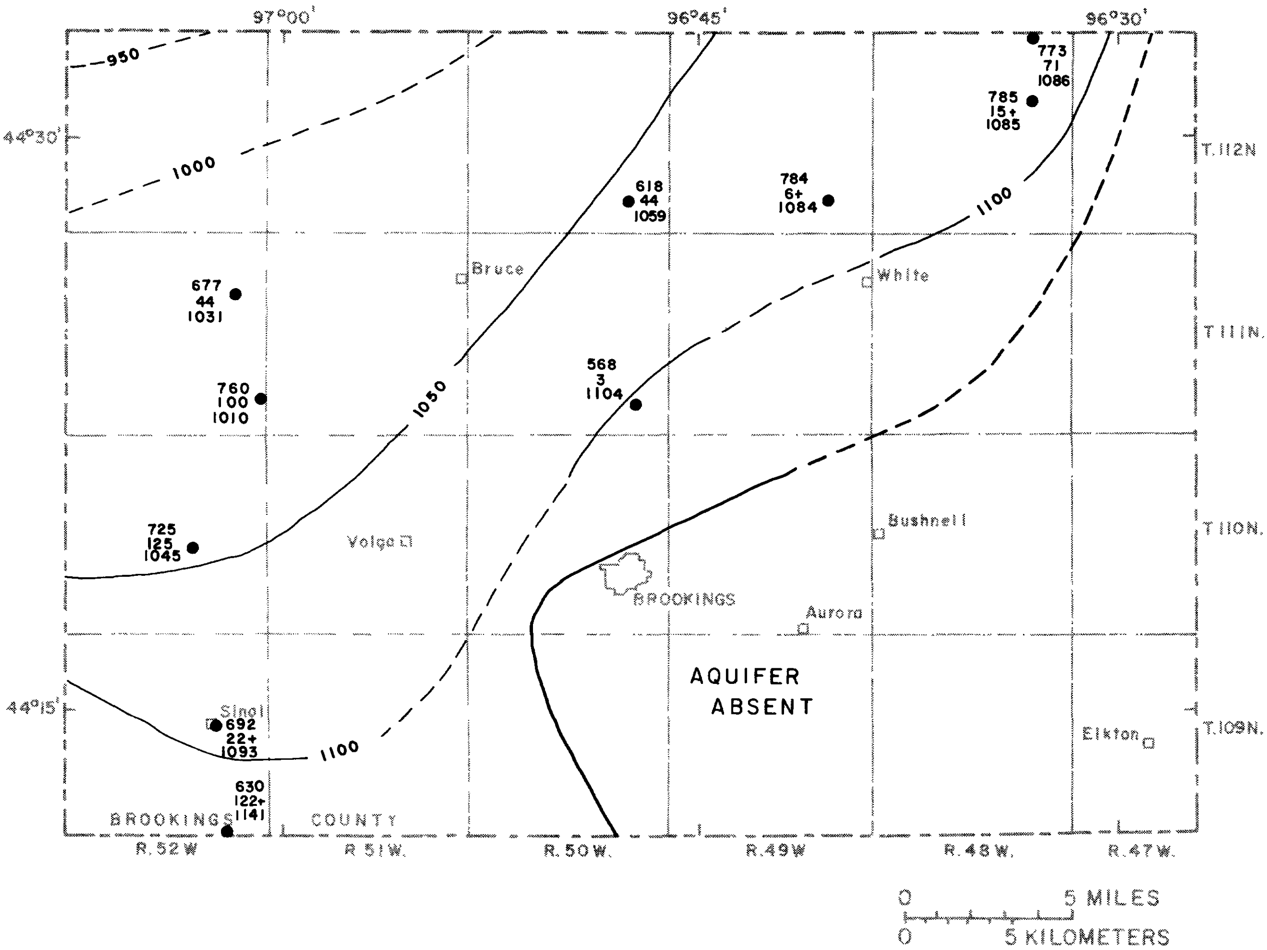



Figure 21.--Depth, thickness, and structure contours of the Codell aquifer.--Continued

The potentiometric surface for the Codell aquifer is not shown because most water-level information is reported only from the southern part of the study area. However, the potentiometric surface probably slopes westward in Kingsbury County at about 7 ft/mi. The altitude of the potentiometric surface ranges from about 1,500 ft near Oldham to 1,420 ft north of Iroquois. Water movement probably is toward the James River basin, where the potentiometric surface has been lowered by heavy withdrawals from both the Codell and Dakota aquifers.

Yield of wells in the Codell aquifer is reported to range from 2 to 20 gal/min but larger yields up to 100 gal/min could be obtained. Wells generally are not completed in the Codell in the northern part of the study area, probably because the aquifer is too fine-grained and silty to allow development of sand-free water and because glacial aquifers are available at shallower depths.

Water from the Codell aquifer is slightly saline and a sodium sulfate type. Concentrations of dissolved solids average 1,800 mg/L and range from 1,730 to 2,050 mg/L (table 6). Hardness of the water averages 120 mg/L and ranges from 17 to 240 mg/L. The water is unsuitable for use in irrigation because of its large concentration of sodium, 530 to 650 mg/L.

## Dakota Aquifer

The Dakota aquifer is composed of as much as 500 ft of very fine to coarse-grained, silty sandstone, siltstone, and shale. The thickness of the aquifer averages 200 ft and ranges from 37 ft in northeastern Brookings County to more than 425 ft at De Smet (fig. 22). Some layers of the aquifer are cemented, like quartzite. In Brookings County, the Dakota aquifer is limited to the extreme western and northern parts where it is penetrated at depths of about 1,000 ft below land surface. In Kingsbury County, the aquifer is penetrated at depths ranging from 772 ft in the southwest to 1,297 ft in the north-central at the town of Erwin. The aquifer is absent in southern and eastern Brookings County where Precambrian quartzite or granite extends upward to within a few hundred feet of land surface along a buried ridge (fig. 7, C-C′, D-D′).

The top of the Dakota aquifer appears to slope westward, at about 7 ft/mi in Brookings County and at about 3 ft/mi in eastern Kingsbury County. In southwestern Kingsbury County, the aquifer appears to slope eastward at about 6 ft/mi.

The potentiometric surface for the Dakota aquifer in Brookings County is estimated to slope northeastward at about 10 ft/mi (fig. 23). Flow probably is toward ground-water discharge areas along rivers in southwestern Minnesota, 20 mi east of the South Dakota State line in T. 112 N. (Novitski and others, 1969). Water-level data in Kingsbury County indicate that movement of water in the Dakota aquifer generally is southwestward at a gradient of about 4 ft/mi. The water moves toward areas of large discharge through flowing wells in the James River valley. A local, 6- to 10-mi-wide depression in the potentiometric surface, centered approximately in T. 110 N., R. 55 W., is produced by withdrawals from the Dakota aquifer through two municipal wells at Lake Preston.

Total pumpage from the Dakota aquifer in the study area is estimated to be 410 acre-ft/yr. Outflow to the southwest was estimated at about 460 acre-ft/yr and outflow to the northeast was estimated at 180 acre-ft/yr, using methods described previously for the Big Sioux aquifer.

Wells in the Dakota aquifer are reported to have yields of 2 to 40 gal/min but larger yields of as much as 100 gal/min can be obtained. Large withdrawals of water, first through flowing wells and later by pumped wells in western Kingsbury County, have lowered the potentiometric surface of the Dakota aquifer about 200 ft since 1890 when the first flowing well was drilled in the city of Iroquois (fig. 24). The initial flow of the Iroquois well, reportedly about 1,000 gal/min in 1890, produced a rapid decrease in both artesian pressure and flow at the well (Darton, 1909, p. 113). Four years later the flow of the well was reported to be 213 gal/min and the artesian pressure was measured by the State Agricultural Experiment Station at 85 $lb/in^2$ (Shepard, 1895, p. 30). By 1915 the well had very little flow and artesian pressure was only about 7 $lb/in^2$, equivalent to a water level of 16 ft above land surface (South Dakota State Engineer, 1916, p. 236). Since then, pumping has gradually lowered the water to a depth of about 23 ft below land surface at Iroquois. Water levels at Lake Preston have decreased at a similar rate to a depth of about 285 ft below land surface (fig. 24). After the period 1910-20 when artesian flow ended for much of the study area, the rate of decline in head decreased greatly to the present rate of about 0.2 ft/yr.

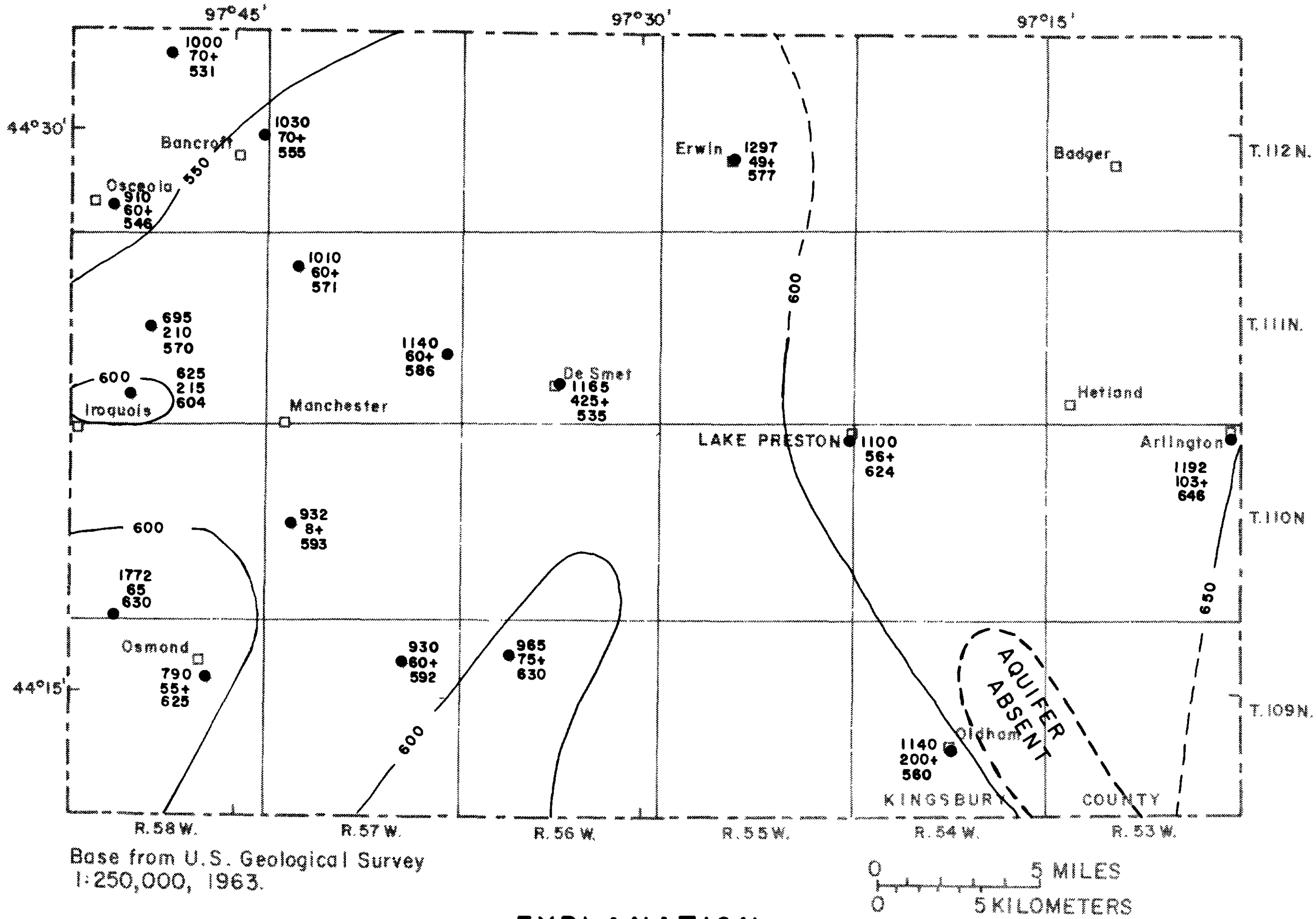
Water from the Dakota aquifer is slightly saline and a sodium sulfate type. Concentrations of dissolved solids average 2,300 mg/L and range from 2,050 to 3,280 mg/L (table 6). Hardness of the water averages 35 mg/L and ranges from 2 to 60 mg/L. The water is unsuitable for use in irrigation because of its large concentration of sodium, 680 to 1,200 mg/L.

## Water Quality

Ground water from shallow wells in glacial aquifers such as the Big Sioux and Vermillion East Fork is generally fresh. Water from wells deeper than about 70 ft is slightly saline; concentrations of dissolved solids locally exceed 1,000 mg/L (table 6). As fresh water seeps downward through soil, till, and aquifers, it leaches fine-grained gypsum and carbonate minerals which are soluble and contribute to the hardness of the water. The hardness of much of the water from the Rutland, Ramona, and Howard aquifers exceeds 1,000 mg/L (table 6).

Major chemical constituents in water from glacial aquifers are calcium, magnesium, sodium, bicarbonate, and sulfate ions. Concentrations of sulfate are largest, ranging from 600 to 1,600 mg/L in water from buried aquifers.

Water from bedrock aquifers of sandstone is slightly saline and a sodium sulfate type. Concentrations of dissolved solids range from 1,730 to 3,280 mg/L and hardness ranges from 2 to 195 mg/L.




## EXPLANATION

—— 600 – – STRUCTURE CONTOUR - Dashed where inferred. Shows altitude of the top of the aquifer. Contour interval 50 feet. Datum is sea level

● 1100 / 56+ / 624 WELL OR TEST HOLE - Upper number is depth, in feet, to top of aquifer. Middle number is aquifer thickness, in feet. A plus (+) indicates a thickness greater than shown. Lower number is altitude of top of aquifer, in feet above sea level

—— – – AQUIFER BOUNDARY - Dashed where inferred. Based on test holes and reported depths of private domestic farm wells

Figure 22.--Depth, thickness, and structure contours of the Dakota aquifer.

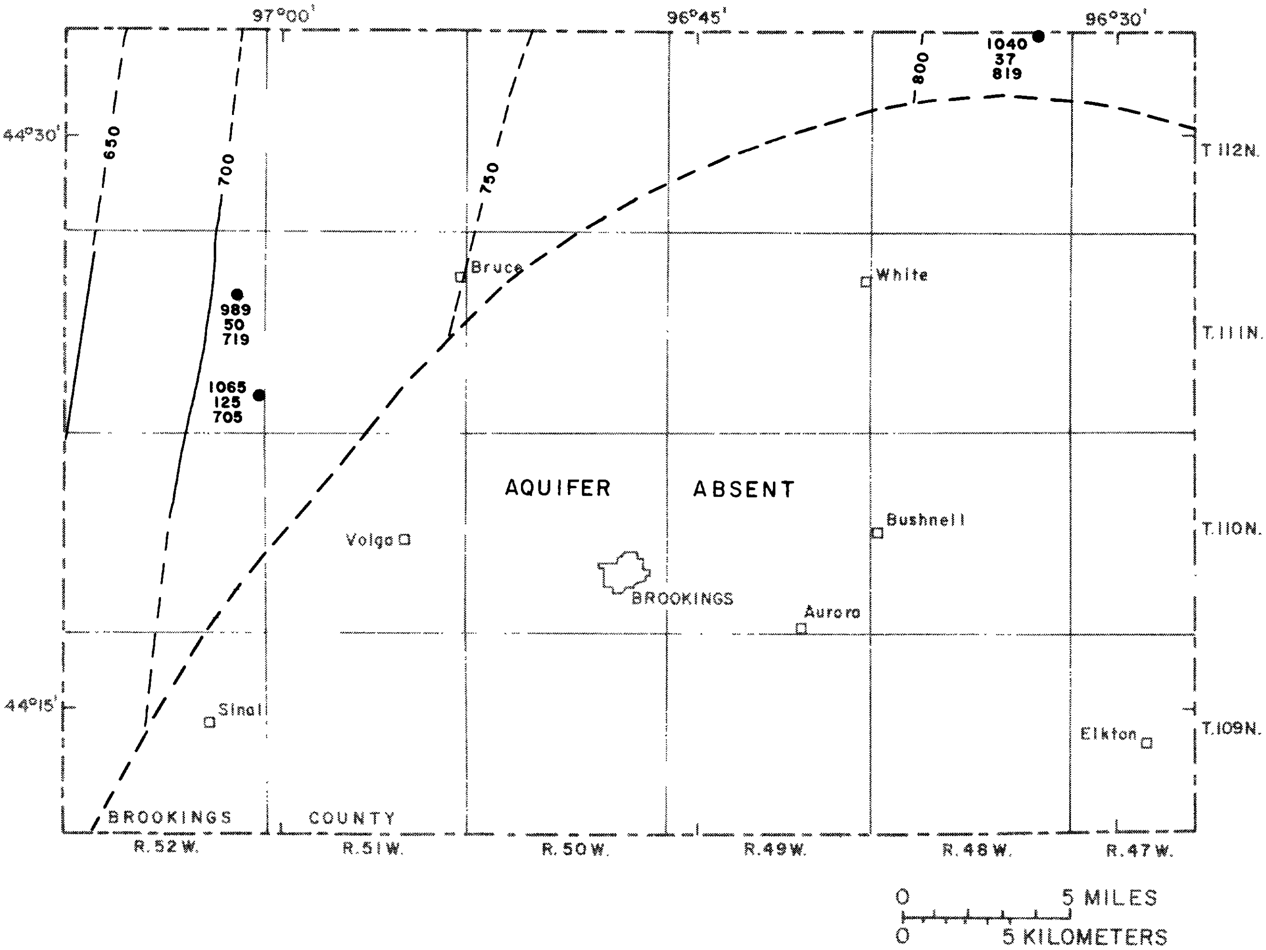
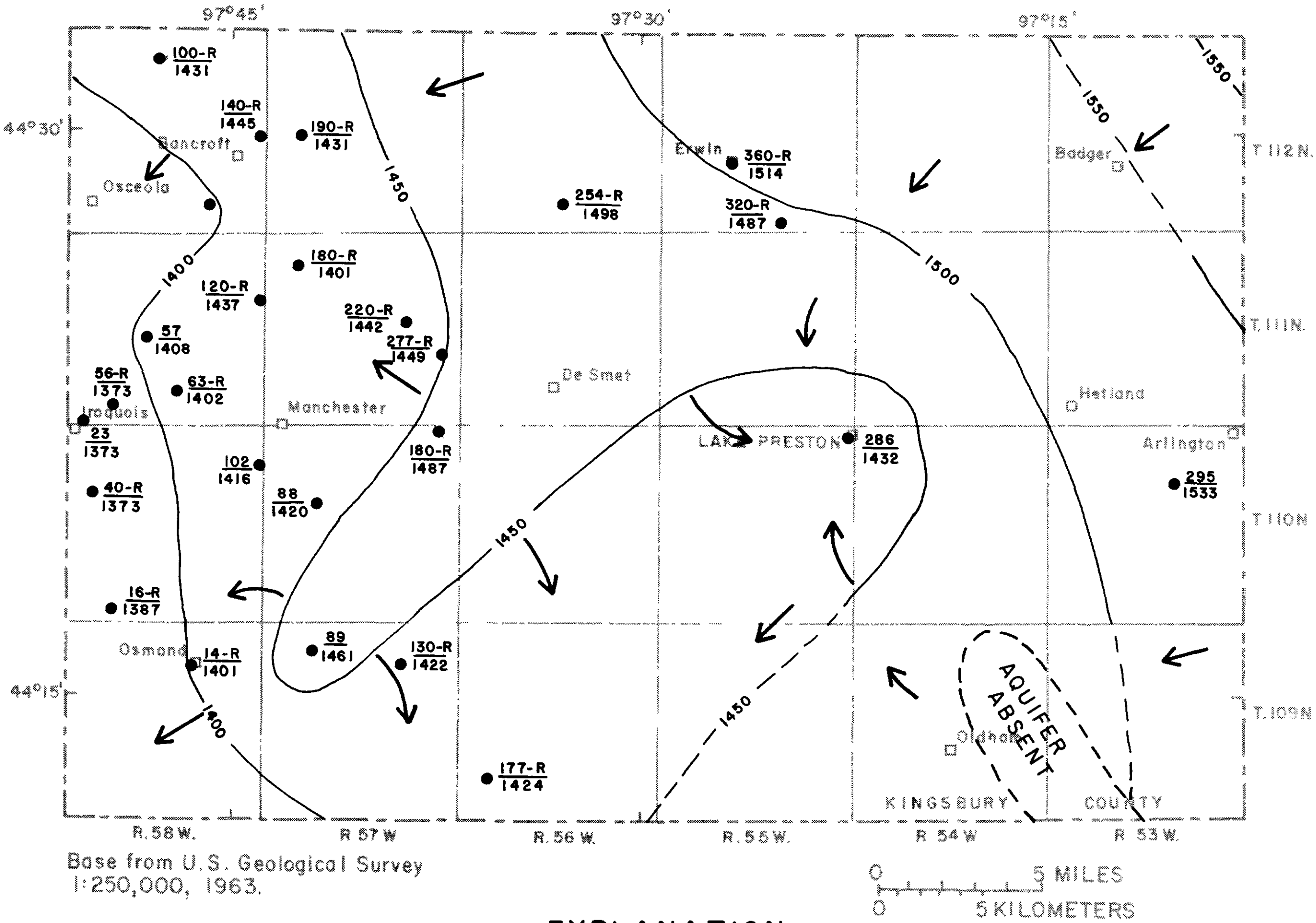



Figure 22.--Depth, thickness, and structure contours of the Dakota aquifer.--Continued




## EXPLANATION

—1450— — POTENTIOMETRIC CONTOUR-Dashed where inferred. Shows altitude at which water would have stood in tightly cased, nondischarging wells in 1974-85. Contour interval 50 feet. Datum is sea level

● 360-R/1514 WELL - Upper number is depth to water, in feet, below land surface. An "R" indicates a reported level. Lower number is altitude of water level, in feet above sea level

← GENERAL DIRECTION OF GROUND-WATER MOVEMENT

——— — — AQUIFER BOUNDARY-Dashed where inferred. Based on test holes and private domestic and farm wells

Figure 23.--Potentiometric contours of the Dakota aquifer.

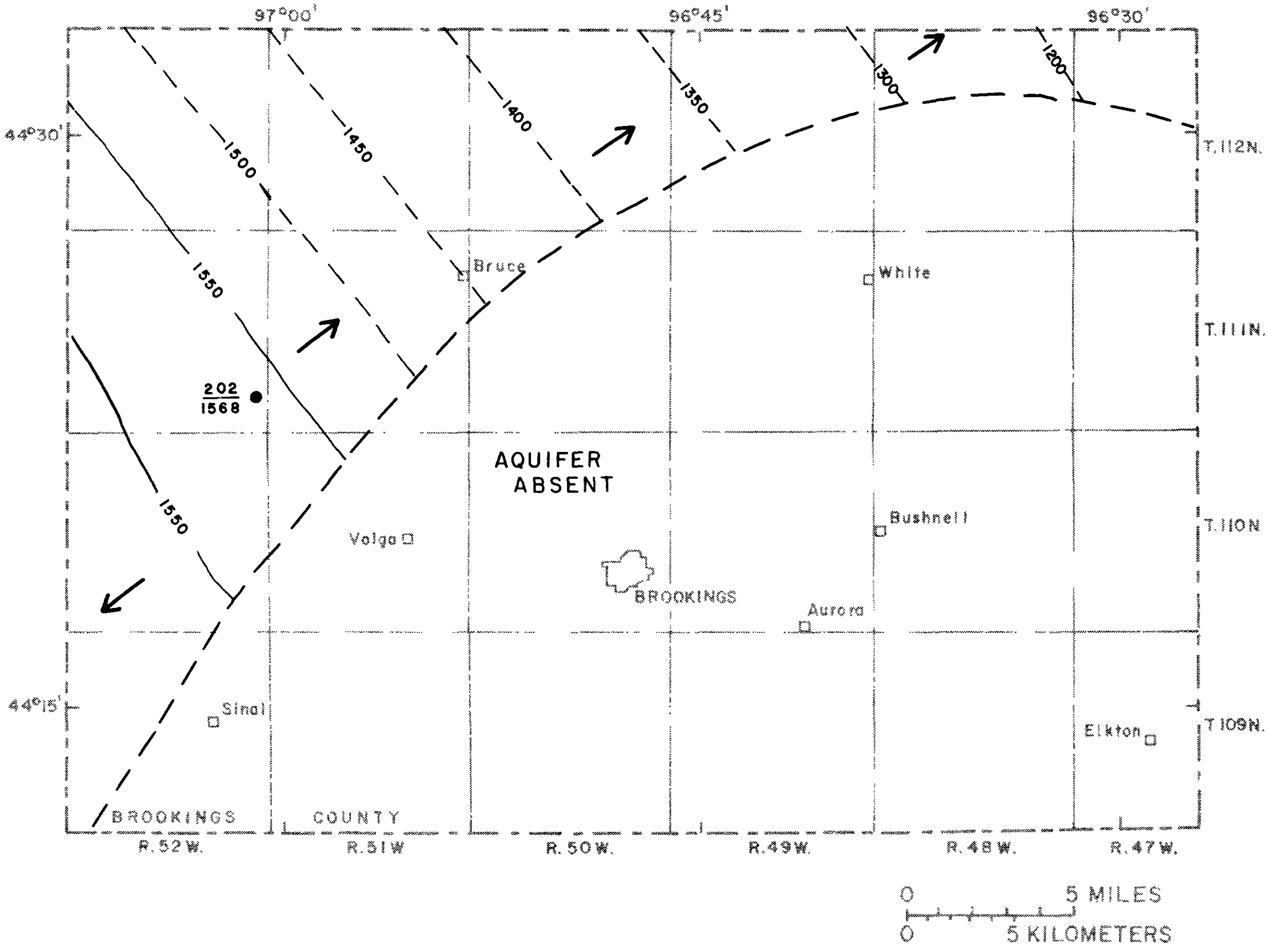



Figure 23.--Potentiometric contours of the Dakota aquifer.--Continued

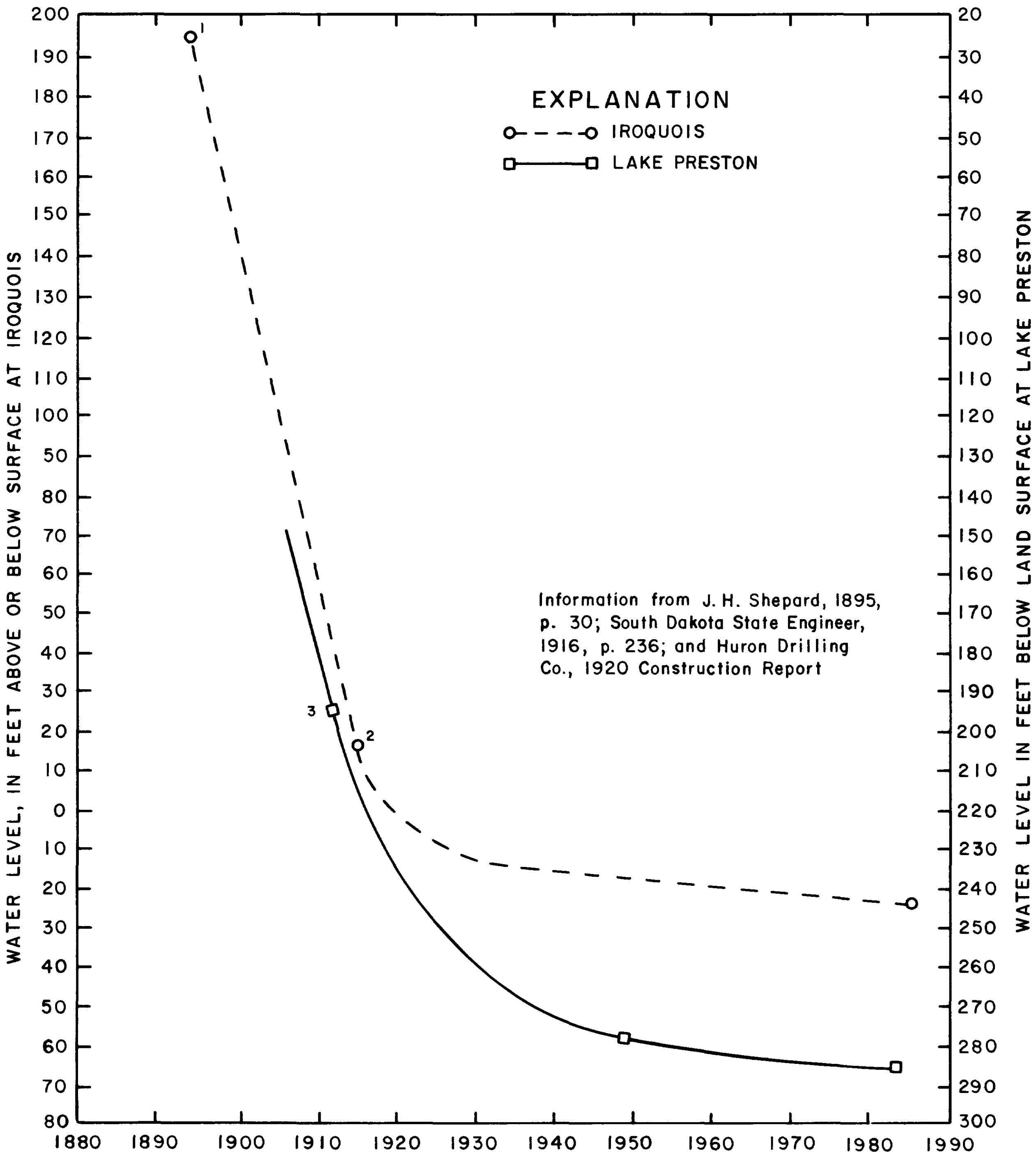



Figure 24.--Water-level declines in the Dakota aquifer at Iroquois and Lake Preston.

## Composition of Ground Water

The chemical composition of water in glacial aquifers differs markedly from that of water in bedrock aquifers (fig. 25). The predominant constituents in water from bedrock aquifers are sodium (more than 70 percent of cations, in milliequivalents per liter, in the left triangle) and sulfate (45 to 65 percent of anions in the right triangle). When these percentages are combined with their corresponding 15 to 25 percent chloride percentages, the composition plots in the far right-hand corner of the diamond-shaped diagram for total composition. The composition for water from most glacial aquifers plots near the upper left edge of the total composition, diamond-shaped diagram. Water from shallow glacial aquifers generally has large percentages of calcium and bicarbonate ions. Bicarbonate in water in the study area generally is derived from organic processes in the soil zone and leaching of limestone fragments in till. Sulfate is the dominant anion in water from deep glacial aquifers. Sulfate in the study area generally is derived from leaching of gypsum fragments in till. The large percentage of sodium water from the deepest glacial aquifer, the Altamont, is similar to the percentage for sodium water from bedrock aquifers. This is because the Altamont aquifer contains shale fragments eroded from bedrock. Cation exchange on shale fragments consists of adsorption of calcium and magnesium ions and release of sodium ions into Altamont water.

## Suitability of Ground Water for Various Uses

Although much of the ground water in the study area is slightly saline, the water is suitable for many uses. For some domestic and industrial uses, the water would need treatment to remove excessive concentrations of dissolved iron and manganese and to reduce the hardness. In many samples, the concentration of iron exceeded the recommended limit of the U.S. Environmental Protection Agency (1986b) of 300 $\mu$g/L (micrograms per liter) and the concentration of manganese exceeded the recommended limit of 50 $\mu$g/L (table 7). The limits are recommended to avoid problems of staining of plumbing fixtures, utensils, and fabrics, and taste.

Some of the water from glacial aquifers in the study area meets South Dakota standards for irrigation use when applied with regard to soil classes (fig. 13). The interpretation of figure 13 has been discussed previously under the section on water quality of the Big Sioux aquifer. Much of the water from the Big Sioux and Vermillion East Fork aquifers can be applied to all soil classes, but some water from the Ramona aquifer (fig. 13, sample 16) should only be applied to loams that have permeable underlying material. Water from the Altamont aquifer and bedrock aquifers generally should not be used for irrigation because of their extremely large sodium concentrations and resultant large sodium-adsorption ratios (table 6). In addition, large concentrations of boron in water from bedrock aquifers would be harmful to many types of plants (table 7).

Nitrate (as N) concentrations larger than 1 or 2 mg/L in the study area may indicate pollution by feedlot runoff, sewage, or fertilizers. The average concentration of nitrate-nitrogen calculated as nitrogen for wells in the Big Sioux basin is 0.35 mg/L for 95 samples from observation wells and 3.9 mg/L for 27 samples from domestic wells (Leibbrand, 1985, p. 11-12). The nitrate concentration may be larger for domestic wells than for observation wells because domestic wells generally are closer to sources of pollution. The nitrate-nitrogen mean of 3.9 mg/L for domestic wells is exceeded in 3 of the 8 samples of water from public water-supply systems in the Big Sioux and Vermillion East Fork aquifers in the study area (table 6, samples 1-6, 8, and 9). Only one of the 8 samples exceeded the mandatory limit of 10 mg/L $NO_3$ (as N) established by the U.S. Environmental Protection Agency (1986a).

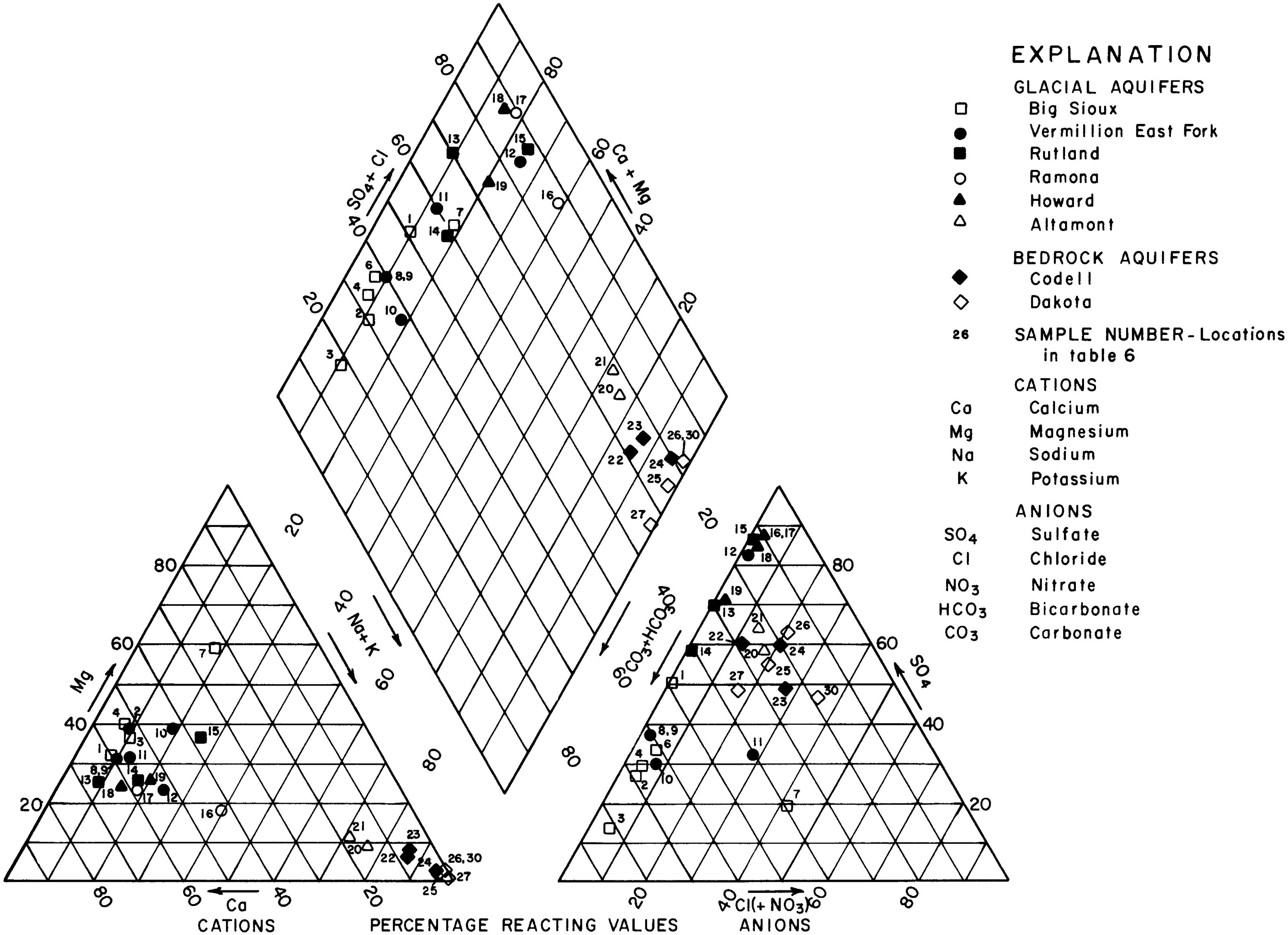



Figure 25.--Predominant chemical constituents of ground water.

Table 7.--Significance of chemical and physical properties of water

[Modified from Howells, 1979. Limits, where given, are primary (mandatory) and secondary (recommended) limits for concentrations of substances in drinking water as set forth by the U.S. Environmental Protection Agency (1986a, b). The unit milligrams per liter (mg/L) is approximately equivalent to parts per million. The unit micrograms per liter (µg/L) is approximately equivalent to parts per billion. The unit milliequivalents per liter (meq/L) is obtained by dividing the concentration, in milligrams per liter, by the combining weight of the ionic species]

| Constituent or property | Limit | Significance |
|---|---|---|
| Temperature | | Affects the usefulness of water for many purposes. Generally, users prefer water of uniformly low temperature. Temperature of ground water tends to increase with increasing depth to the aquifer. |
| Silica (as $SiO_2$) | | Forms hard scale in pipes and boilers and may form deposits on blades of steam turbines. Inhibits deterioration of zeolite-type water softeners. |
| Iron | 300 µg/L (recommended) | Forms rust-colored sediment; stains laundry, utensils, and fixtures reddish brown. Objectionable for food and beverage processing. Can promote growth of certain kinds of bacteria that clog well openings. |
| Manganese | 50 µg/L (recommended) | Causes gray or black stains on porcelain, enamel, and fabrics. Can promote growth of certain kinds of bacteria. |
| Calcium plus magnesium | | Cause most of the hardness and scale-forming properties of water (see hardness). |
| Sodium plus potassium | | Large concentrations may limit use of water for irrigation and industrial use and, in combination with chloride, give water a salty taste. Abnormally large concentrations may indicate natural brines, industrial brines, or sewage. |
| Bicarbonate | | In combination with calcium and magnesium forms carbonate hardness. |
| Sulfate | 250 mg/L (recommended) | Sulfates of calcium and magnesium form hard scale. Large concentrations of sulfate have a laxative effective on some people and, in combination with other ions, give water a bitter taste. |
| Chloride | 250 mg/L (recommended) | Large concentrations increase the corrosiveness of water and, in combination with sodium, give water a salty taste. |
| Fluoride | 4.0 mg/L (mandatory) 2.0 mg/L (recommended) | Reduces incidence of tooth decay when optimum fluoride concentration is present in water consumed by children during the period of tooth calcification. Some children exposed to concentrations greater than 2.0 mg/L may develop dental fluorosis. Exposure for many years through drinking water with concentrations greater than 4.0 mg/L may result in some cases of crippling skeletal fluorosis, a serious bone disorder. |
| Nitrate (as N) | 10 mg/L (mandatory) | Concentrations greater than local average may indicate pollution by feedlot runoff, sewage, or fertilizers. Concentrations greater than 10 mg/L as nitrogen may be injurious when used in feeding infants. |
| Boron | | Essential to plant growth, but may be toxic to crops when present in excessive concentrations in irrigation water. Sensitive plants show damage when irrigation water contains more than 670 µg/L and even tolerant plants may be damaged when boron exceeds 2,000 µg/L. The recommended limit is 750 µg/L for long-term irrigation on sensitive crops (U.S. Environmental Protection Agency, 1976). |
| Dissolved solids | 500 mg/L (recommended) | The total of all dissolved mineral constituents, usually expressed in milligrams per liter. The concentration of dissolved solids may affect the taste of water. Water that contains more than 1,000 mg/L is unsuitable for many industrial uses. Some dissolved mineral matter is desirable, otherwise the water would have no taste. |

Table 7.--Significance of chemical and physical properties of water--Continued

| Constituent or property | Limit | Significance |
|---|---|---|
| Hardness (as $CaCO_3$) | | Related to the soap-consuming characteristic of water, results in formation of scum when soap is added. May cause deposition of scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate in water is called carbonate hardness; hardness in excess of this concentration is called noncarbonate hardness. Water that has a hardness less than 61 mg/L is considered soft; 61-120 mg/L moderately hard, 121-180 mg/L hard; and more than 180 mg/L very hard. |
| Percent sodium | | Ratio of sodium to total cations in milliequivalents per liter expressed as a percentage. Important in irrigation waters; the greater the percent sodium, the less suitable the water for irrigation. |
| Sodium-adsorption ratio (SAR) | | A ratio used to express the relative activity of sodium ions in exchange reactions with soil. Important in irrigation water; the greater the SAR, the less suitable the water for irrigation. |
| Specific conductance | | A measure of the ability of water to conduct an electrical current; varies with temperature. Values are reported in microsiemens per centimeter at 25 °Celsius. Magnitude depends on concentration, kind, and degree of ionization of dissolved constituents; can be used to determine the approximate concentration of dissolved solids. |
| pH | 6.5-8.5 units (recommended) | A measure of the hydrogren ion concentration; pH of 7.0 indicates a neutral solution, pH values smaller than 7.0 indicate acidity, pH values larger than 7.0 indicate alkalinity. Water generally becomes more corrosive with decreasing pH; however, excessively alkaline water also may be corrosive. |
| Aluminum | | No known necessary role in human or animal diet. Nontoxic in the concentrations normally found in natural water supplies. Concentrations greater than 1,000 μg/L may decrease yields of some crops. Long-term exposure to concentrations of more than 100 μg/L can be lethal to some types of fish. |
| Arsenic | 50 μg/L (mandatory) | No known necessary role in human or animal diet, but is toxic. A cumulative poison that is slowly excreted. Can cause nasal ulcers; skin cancer; damage to the kidneys, liver, and intestinal walls; and death. |
| Barium | 1,000 μg/L (mandatory) | Toxic; used in rat poison. In moderate to large concentrations can cause death; smaller concentrations cause damage to the heart, blood vessels, and nerves. |
| Bromide | | Not known to be essential in human or animal diet. Is nontoxic in small concentrations; less than 1,000 μg/L has no detectable affect even on fish. |
| Cadmium | 10 μg/L (mandatory) | A cumulative poison of very toxic potential. Not known to be either biologically essential or beneficial. Believed to promote renal arterial hypertension. In animal experiments, concentrations of of 100 to 10,000 μg/L for 1 year caused liver and kidney damage; greater concentrations cause anemia, retarded growth, and death. |
| Chromium in hexavalent form | 50 μg/L (mandatory) | No known necessary role in human or animal diet. In the hexavalent form is toxic, leading to intestinal damage and to nephritis. |
| Copper | 1,000 μg/L (recommended) | Essential to metabolism; copper deficiency in infants and young animals results in nutritional anemia. Large concentrations of copper are toxic and may cause liver damage. |
| Iodide | | Essential and beneficial element in metabolism; deficiency can cause goiter. |

Table 7.--Significance of chemical and physical properties of water--Continued

| Constituent or property | Limit | Significance |
|---|---|---|
| Lead | 50 μg/L (mandatory) | A cumulative poison, toxic in small concentrations. Can cause lethargy, loss of appetite, constipation, anemia, abdominal pain, gradual paralysis in the muscles, and death. |
| Lithium | | Reported as probably beneficial in small concentrations (250 to 1,250 μg/L). Reportedly may help strenghen the cell wall and improve resistence to genetic damage and to disease. Lithium salts are used to treat certain types of psychosis. |
| Mercury | 2 μg/L (mandatory) | No known essential or beneficial role in human or animal nutrition. Liquid metallic mercury and elemental mercury dissolved in water are comparatively nontoxic, but some mercury compounds, such as mercuric chloride and alkyl mercury, are very toxic. Elemental mercury is readily alkylated, particularly to methyl mercury, and concentrated by biological activity; fish and shellfish can contain more than 3,000 times the concentration of mercury as the water in which they live. Toxic affects of mercury compounds include chromosomal abnormalities, congenital mental retardation, progressive weakening of the muscles, loss of vision, impairment of cerebral functions, paralysis, and death. |
| Molybdenum | | In minute concentrations, appears to be an essential nutrient for both plants and animals, but in large concentrations may be toxic. |
| Nickel | | Very toxic to some plants and animals. Toxicity for humans is believed to be very minimal. |
| Phosphate | | Essential to plant growth. Concentrations greater than local average may indicate pollution by fertilizer seepage or sewage. |
| Selenium | 10 μg/L (mandatory) | Essential to human and animal nutrition in minute concentrations, but even a moderate excess may be harmful or potentially toxic if ingested for a long time. Selenium poisoning in livestock can cause loss of hair; loss of weight; abnormal hoof growth; hoof loss; liver, kidney, and heart damage; poor health and decreased disease resistance; and death. In humans, selenium can interfere with the normal function of the pancreas and other organs and cause changes in the insulin requirements of people with diabetes mellitus. Selenium is known to be a hazard to humans and livestock in parts of South Dakota. |
| Silver | 50 μg/L (mandatory) | Causes permanent bluish darkening of the eyes and skin (argyria). Where found in water is almost always from pollution or by intentional addition. Silver salts are used in some countries to sterilize water supplies. Toxic in large concentrations. |
| Strontium | | Importance in human and animal nutrition is not known, but believed to be essential. Toxicity believed very minimal--no more than that of calcium. |
| Vanadium | | Not known to be essential to human or animal nutrition, but believed to be beneficial in trace concentrations. May be an essential trace element for all green plants. Large concentrations may be toxic. |
| Zinc | 5,000 μg/L (recommended) | Essential and beneficial in metabolism; its deficiency in young children or animals will retard growth and may decrease general body resistance to disease. Seems to have no ill effects even in fairly large concentrations (20,000 to 40,000 μg/L), but can impart a metallic taste or milky appearance to water. Zinc in water commonly is derived from galvanized coatings of piping; unfortunately, common contaminants of zinc used in galvanizing are cadmium and lead. |

Table 8.--Selected trace elements in ground water

[Analyses by U.S. South Dakota Department of Water and Natural Resources, Office of Drinking Water, unless otherwise noted. Reported in micrograms per liter (μg/L). One microgram per liter is approximately equal to one part per billion. < signifies less than, -- signifies not determined]

| Sample number | Well depth (feet) | Location | Date | Aluminum | Arsenic | Barium | Beryllium | Cadmium | Chromium |
|---|---|---|---|---|---|---|---|---|---|
| Recommended limit (* indicates mandatory limit, from table 7) | | | | -- | *50 | *1,000 | -- | *10 | *50 |
| | | | | GLACIAL AQUIFERS | | | | | |
| | | | | Big Sioux aquifer | | | | | |
| 1 | 65 | Brookings | [1]11- 8-83 | -- | 2 | <50 | -- | <1 | 4 |
| 2 | 56 | Aurora | 4-23-84 | -- | 1 | 120 | -- | <1 | <1 |
| 3 | 36 | Bruce | 3-21-83 | -- | <1 | 90 | -- | <1 | 2 |
| 4 | 42 | Elkton | 4-28-83 | -- | <1 | 140 | -- | <1 | 2 |
| 5 | 28,45 | Volga | 9- 8-82 | -- | 1 | 32 | -- | <1 | <1 |
| | | | | Vermillion East Fork aquifer | | | | | |
| 6 | 42 | De Smet | 5- 6-82 | -- | 5 | 80 | -- | <1 | 5 |
| 7 | 45 | R.W.S.[3]- De Smet | 11- 3-81 | -- | 2 | 66 | -- | <1 | 1 |
| | | | | Rutland aquifer | | | | | |
| 8 | 75 | 109N50W35DDCC | [4]8-31-82 | <50 | -- | 30 | <1 | <1 | <50 |
| | | | | Howard aquifer | | | | | |
| 9 | 350 | Hetland | 9-23-81 | -- | 2 | 43 | -- | 1 | <1 |
| 10 | 325 | Lake Preston | 11- 8-80 | -- | -- | -- | -- | -- | -- |
| | | | | Altamont aquifer | | | | | |
| 11 | 618 | Arlington | 8-14-81 | -- | 2 | 18 | -- | <1 | 2 |
| | | | | BEDROCK AQUIFERS | | | | | |
| | | | | Codell aquifer | | | | | |
| 12 | 720 | Sinai | [1]2- 9-83 | -- | 5 | <50 | -- | <1 | <1 |
| | | | | Dakota aquifer | | | | | |
| 13 | 1,020 | Oldham | [1]10-21-81 | -- | 7 | <5 | -- | <1 | 2 |
| 14 | 1,178 | Lake Preston | [1]4-22-81 | -- | 3 | <5 | -- | <1 | <1 |
| 15 | 1,008 | Iroquois | [1]2-16-83 | -- | 6 | <50 | -- | <1 | 1 |

[1]Composite sample of several wells.
[2]From sample collected on another date.
[3]Rural water system.
[4]U.S. Geological Survey.

| Cobalt | Copper | Lead | Lithium | Mercury | Molybdenum | Nickel | Selenium | Silver | Strontium | Vanadium | Zinc |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -- | 1,000 | *50 | -- | *2 | -- | -- | *10 | *50 | -- | -- | 5,000 |
| -- | [2]14 | 3 | -- | <.2 | -- | -- | <1 | <1 | -- | -- | 11 |
| -- | -- | 2 | -- | <.2 | -- | -- | 6 | <1 | -- | -- | -- |
| -- | -- | 8 | -- | <.2 | -- | -- | <1 | <1 | -- | -- | -- |
| -- | -- | 1 | -- | <.2 | -- | -- | 4 | <1 | -- | -- | -- |
| -- | -- | <1 | -- | <.2 | -- | -- | <1 | <1 | -- | -- | -- |
| -- | -- | 2 | -- | <.2 | -- | -- | 7 | <1 | -- | -- | -- |
| -- | -- | <1 | -- | <.2 | -- | -- | <1 | <1 | -- | -- | -- |
| <5 | <10 | <30 | 100 | -- | <10 | <50 | -- | -- | 1,000 | <10 | 30 |
| -- | -- | 1 | -- | <.2 | -- | -- | <1 | <1 | -- | -- | -- |
| -- | 70 | -- | -- | -- | -- | -- | -- | -- | -- | -- | 23 |
| -- | -- | <1 | -- | <.2 | -- | -- | 1 | 4 | -- | -- | -- |
| -- | [2]7 | 3 | -- | <.2 | -- | -- | 5 | <1 | -- | -- | 65 |
| -- | [2]12 | 14 | -- | <.2 | -- | -- | 9 | <1 | -- | -- | 22 |
| -- | -- | 39 | -- | <.2 | -- | -- | 4 | <1 | -- | -- | -- |
| -- | -- | 3 | -- | <.2 | -- | -- | 7 | <1 | -- | -- | -- |

This sample was from a 24-ft well at the city of Elkton. Wells less than 30 ft deep frequently are very susceptible to pollution from barnyards, feedlots, and septic tanks if the depth to the well openings is not sufficient to permit some adsorption and filtration of pollutants by soil and vegetation.

Nitrate-nitrogen concentration as large as 91 mg/L was reported from a 150-ft-deep rural domestic well (sample 7, table 6). This well is located in an area where the Big Sioux aquifer is within a few feet of land surface. Large nitrate concentrations also can occur in water from deep wells in buried aquifers that are covered by relatively impermeable glacial till. In both cases, the most likely path for pollution of deep wells is through a poorly constructed or deteriorated well, or through a nearby abandoned well. It is important that wells be located away from sources of contamination and properly constructed to reduce the opportunities for contamination. Nelson and others (1984) describe methods of locating and constructing wells to prevent contamination.

Water-quality monitoring in the Oakwood Lakes and Lake Poinsett areas during 1984-86 shows that the largest concentrations of nitrate occur at shallow depths (South Dakota Water Resources Institute, 1986). This study also shows that there is little contamination of ground water in the two areas by agricultural pesticides or herbicides.

Fluoride concentrations in water from the Dakota aquifer frequently exceed the recommended limit of 2.0 mg/L or the mandatory limit of 4.0 mg/L (tables 6 and 7). Excessive amounts of fluoride may cause mottling of teeth or possibly skeletal fluorosis (table 7). Concentrations of 10 trace elements in samples from 15 public water supplies in the study area do not exceed recommended limits (table 8).

## Water Use

Withdrawals of surface water during 1985 were estimated to total 1,340 acre-ft. Most of this was from watering of livestock at lakes and ponds. Withdrawals of water from glacial and bedrock aquifers in the study area were estimated at 14,690 acre-ft in 1985 (table 9). About 97 percent of withdrawals are from glacial aquifers and 54 percent of withdrawals are from the Big Sioux aquifer, for use in irrigation. There are about 200 irrigation wells in Brookings County and 30 irrigation wells in Kingsbury County. Withdrawals for irrigation totaled 9,280 acre-ft or 63 percent of all withdrawals in 1985. The second largest use of water is by municipalities, which withdrew 2,650 acre-ft, or 18 percent of the total.

Data on irrigation withdrawals were obtained from reports of the South Dakota Department of Water and Natural Resources. Other data were reported by municipalities and rural water systems or were estimated from population figures and average per capita use (R. D. Benson, U.S. Geological Survey, personal commun., 1986).

Table 9.--Estimated withdrawal of ground water in 1985

| Source | Total | | Municipal | | Rural-domestic | | Livestock | | Irrigation | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Acre-feet | Percent | Acre-feet | Percent | Acre-feet | Percent | Acre-feet | Percent | Acre-feet | Percent |
| GLACIAL AQUIFERS | | | | | | | | | | |
| Big Sioux | 11,290 | 76.9 | 2,280 | 15.5 | [1]280 | 1.9 | 830 | 5.6 | 7,900 | 53.8 |
| Vermillion East Fork | 1,820 | 12.4 | 130 | .9 | [1]320 | 2.2 | 110 | .7 | 1,260 | 8.6 |
| Ramona | 100 | .7 | 0 | 0 | [2]0 | 0 | 100 | .7 | 0 | 0· |
| Rutland | 140 | 1.0 | 0 | 0 | [2]0 | 0 | 20 | .1 | 120 | .8 |
| Howard | 280 | 1.9 | 10 | .1 | [2]0 | 0 | 270 | 1.8 | 0 | 0 |
| Altamont | 100 | .7 | 80 | .5 | [2]0 | 0 | 20 | .1 | 0 | 0 |
| Minor aquifers | 450 | 3.1 | 0 | 0 | [2]0 | 0 | 450 | 3.1 | 0 | 0 |
| Subtotal[3] | 14,180 | 96.5 | 2,500 | 17.0 | 600 | 4.1 | 1,800 | 12.2 | 9,280 | 63.2 |
| BEDROCK AQUIFERS | | | | | | | | | | |
| Niobrara | 10 | .1 | 0 | 0 | [2]0 | 0 | 10 | .1 | 0 | 0 |
| Codell | 90 | .6 | 10 | .1 | [2]0 | 0 | 80 | .5 | 0 | 0 |
| Dakota | 410 | 2.8 | 140 | 1.0 | [2]0 | 0 | 270 | 1.8 | 0 | 0 |
| Subtotal[3] | 510 | 3.5 | 150 | 1.0 | 0 | 0 | 360 | 2.4 | 0 | 0 |
| Total, all aquifers[3] | 14,690 | 100.0 | 2,650 | 18.0 | 600 | 4.1 | 2,160 | 14.7 | 9,280 | 63.2 |

[1]Ninety-nine percent supplied by rural water systems.
[2]Less than 1 acre-foot.
[3]Total percentage may not equal sum of components because of rounding.

## SUMMARY

Brookings and Kingsbury Counties, an area of 1,667 $mi^2$ in eastern South Dakota, have widely distributed and relatively undeveloped surface-water and ground-water resources. The aquifers can supply additional water to large-capacity wells.

The largest and most reliable source of surface water in the study area is the Big Sioux River, which drains about 2,400 $mi^2$ at the gaging station near Brookings. The average annual inflow to Brookings County is 57,000 acre-ft and the outflow (near Brookings) is 117,000 acre-ft, for a net streamflow gain of about 60,000 acre-ft. Four major tributaries from the east in Brookings County account for nearly 90 percent of the gain. Flow of the river fluctuates greatly and the annual outflow decreased from 270,000 acre-ft in water year 1978 to 17,600 acre-ft in 1981 because of drought and pumpage. The river has numerous periods of extremely low flow. A 14-day discharge of less than 1 $ft^3/s$ has an average recurrence interval of about 5 years. Two small, ephemeral, south-flowing streams in the James River basin in western Kingsbury County are estimated to have a combined average annual inflow estimated at 600 acre-ft and an annual combined outflow of nearly 3,000 acre-ft.

There are more than 2,000 lakes, ponds, and marshes in the study area. Three lakes in Brookings County and six lakes in Kingsbury County are larger than 1,000 acres but have average depths of only 2 to 10 ft. During 1984, greater than average precipitation and runoff caused lakes in Kingsbury County to overflow into Lake Thompson. The level of Lake Thompson rose about 20 ft in 2 years, spread over 25 $mi^2$, and became the largest natural lake in South Dakota. Most of the lakes are classified as ephemeral warm-water lakes marginal for propagation of fish and subject to winterkill on an average of once in approximately every 5 years.

Surface water in the study area generally is fresh, having concentrations of dissolved solids less than 1,000 mg/L. The hardness of surface water generally ranges from 200 to 400 mg/L. During drought periods lasting several years, concentrations of dissolved solids gradually increase in some lakes to more than 2,000 mg/L.

Ground water can support more intensive water development in Brookings and Kingsbury Counties. Six major glacial aquifers composed of outwash sand and gravel store 8 million acre-ft of water beneath four-fifths of the study area at depths ranging from land surface to 700 ft. Withdrawal of ground water for all uses totaled 14,700 acre-ft in 1985. The Big Sioux and Vermillion East Fork aquifers are the major sources of shallow, fresh ground water. The Big Sioux aquifer stores 2 million acre-ft of water beneath 540 $mi^2$ of Brookings and Kingsbury Counties and the Vermillion East Fork aquifer stores 0.3 million acre-ft of water beneath 94 $mi^2$ of Kingsbury County. Reported yields to wells are as much as 1,300 gal/min in the Big Sioux aquifer and 1,000 gal/min in the Vermillion East Fork aquifer. Four other major glacial aquifers, the Ramona, Rutland, Howard, and Altamont, store about 5.7 million acre-ft of water beneath 1,200 $mi^2$ and are covered by 20 ft to as much as 700 ft of clayey till. The aquifers potentially may yield as much as 1,800 gal/min to a well but pumping lifts may reach 500 ft for the deepest (Altamont) aquifer. Effects of withdrawals on current (1980's) water levels are small because of small pumpage and extensive recharge. Temporary water-level drawdowns of a few feet at most are observed at distances of 1 mi from large-capacity wells in glacial aquifers.

Three bedrock aquifers supply relatively small amounts of slightly saline, relatively soft water to municipal and private wells. The Niobrara, Codell, and Dakota aquifers, in order of increasing depth, store a combined 67 million acre-ft of water beneath about three-fourths of the study area. The Codell and Dakota aquifers, mostly fine- to medium-grained sandstone, lie at depths ranging from about 320 to 1,300 ft below land surface. The sandstone in the Codell and Dakota aquifers is estimated to yield as much as 100 gal/min to wells. Since 1890, withdrawals through flowing and pumping wells have caused the potentiometric surface for the Dakota aquifer to decline about 200 ft to a level where wells no longer flow. Pumping wells cause water levels to continue a slow decline at a rate of about 0.2 ft/yr. Ground-water withdrawals comprised 90 percent of the total water use of 16,000 acre-ft in 1985.

Ground water from shallow wells in glacial aquifers in the study area generally is fresh and a calcium bicarbonate type. Water from wells deeper than about 70 ft is slightly saline; concentrations of dissolved solids at many places exceed 1,000 mg/L. The hardness of water in buried glacial aquifers can exceed 1,000 mg/L. Water from bedrock aquifers also is slightly saline and a soft, sodium sulfate type. The hardness of water from bedrock ranges from 2 to 195 mg/L. Much of the water from both glacial and bedrock aquifers would need treatment to remove hardness, iron, and manganese in order to be suitable for some domestic and industrial uses.

Most water from buried glacial aquifers in the study area is considered to be marginal to unsuitable for use in irrigation depending on soil texture, because of large concentrations of dissolved solids. All water from bedrock aquifers is unsuitable for use in irrigation because of large concentrations of sodium. Fluoride concentrations in water from bedrock frequently exceed recommended limits and can cause mottling of teeth and possibly skeletal fluorosis.

Nitrate concentrations in water from wells in shallow glacial aquifers locally can exceed recommended limits where the well is close to sources of pollution like barnyards and septic tanks. Deep wells also can become polluted through a poorly constructed or deteriorated well or a nearby abandoned well.

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