WATER RESOURCES OF HUGHES COUNTY, SOUTH DAKOTA

By Louis J. Hamilton

U.S. GEOLOGICAL SURVEY

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UNITED STATES DEPARTMENT OF THE INTERIOR

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

Multiply inch-pound unit	By	To obtain SI unit
acre	0.4047	hectare
acre-foot (acre-ft)	1,234	cubic meter
acre-foot (acre-ft)	0.001234	cubic hectometer
acre-foot per square mile (acre-ft/mi^2)	476.1	cubic meter per square kilometer
acre-foot per year (acre-ft/yr)	1,234	cubic meter per year
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
square foot per day (ft^2/d)	0.0929	square meter per day
cubic foot per minute (ft^3/min)	0.02832	cubic meter per minute
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	25.40	millimeter
inch per year (in/yr)	25.40	millimeter per year
micromho per centimeter at 25° Celsius (μmho/cm at 25°C)	1.000	microsiemen per centimeter at 25° Celsius
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
pound per square inch (lb/in^2)	6.895	kilopascal

Temperature can be converted to degrees Fahrenheit ($^\circ$F) or degrees Celsius ($^\circ$C) by the following equations:

$$^\circ F = 9/5\ (^\circ C) + 32$$
$$^\circ C = 5/9\ (^\circ F - 32)$$

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 mean sea level. NGVD of 1929 is referred to as sea level in this report.

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ABSTRACT

Fresh surface water and fresh to slightly saline ground water are available in large quantities in Hughes County in central South Dakota. The county comprises 784 square miles of gently undulating, glaciated, till-mantled plains that are deeply incised by the outwash- and alluvium-filled valleys of the Missouri River and its tributaries. The most prominent feature is the Missouri River trench, incised 300 feet into the Great Plains. Oahe Dam on the Missouri River at the northwest end of the county impounds a 240-mile-long reservoir, Lake Oahe. A second reservoir, Lake Sharpe, borders the county downstream from Oahe Dam. The normal maximum storage of the two reservoirs totals about 24 million acre-feet of water. Storage is sustained by river flow that averages nearly 18 million acre-feet per year (25,000 cubic feet per second). Streams tributary to the Missouri River in the county are small and ephemeral; the combined average flow of the seven largest streams is estimated at only about 11,000 acre-feet per year (15 cubic feet per second). The flow of the largest tributary, Medicine Knoll Creek, exceeds 1 cubic foot per second only 15 percent of the time.

Four major glacial aquifers consisting of outwash sand and gravel that underlie one-third of Hughes County store about 1 million acre-feet of water. These aquifers can yield as much as 1,000 gallons per minute to wells at depths of from 30 to 300 feet. Well yields could exceed 300 gallons per minute where the thickness of water-yielding sand and gravel exceeds 30 feet. Depths to water in wells completed in glacial aquifers range from 4 to 250 feet below land surface. Most recharge to the aquifers is from infiltration of precipitation, and recharge is estimated to exceed 2,400 acre-feet per year.

Three major bedrock aquifers, in order of increasing age, are the Dakota, Inyan Kara-Sundance, and Minnelusa-Madison aquifers. They are composed of sandstone and shale or limestone and dolomite. The aquifers store about 83 million acre-feet of water beneath the county and can yield as much as 1,600 gallons per minute to flowing wells 800 to 2,600 feet deep. Shut-in pressures in flowing wells increase with well depth to more than 400 pounds per square inch. Past withdrawals of as much as 2 million cubic feet per day through flowing wells have caused the potentiometric surface of the Dakota aquifer to decline as much as 400 feet in the area of the city of Pierre. Recently, however, a rapid decline in hydraulic head has been prevented by greatly restricting the flow from a high-pressure well. In some upland areas, water levels in wells completed in the Dakota may be more than 200 feet below land surface. Recharge of the deepest bedrock aquifer, the Minnelusa-Madison, is from precipitation and streamflow across its outcrop in the Black Hills of western South Dakota. Natural leakage from the Minnelusa-Madison aquifer, estimated at 180,000 acre-feet per year in the county, recharges the overlying bedrock aquifers.

Most of the water from glacial aquifers is slightly saline. Concentrations of dissolved solids in water from glacial aquifers average about 1,800 milligrams per liter but may be more than 5,000 milligrams per liter in some places. The average hardness of the water is about 900 milligrams per liter, but locally can exceed 3,000 milligrams per liter.

Water from the bedrock aquifers also is slightly saline, concentrations of dissolved solids average about 2,000 milligrams per liter, but locally are nearly 3,500 milligrams per liter. The average hardness of water from the Dakota aquifer is only 200 milligrams per liter, but the average hardness of water from underlying aquifers is about 1,400 milligrams per liter. Bedrock aquifers are an enormous geothermal resource; the maximum temperature increasing with depth from 22 to 49° Celsius. Water from both glacial and bedrock aquifers commonly contains excessive concentrations of iron and manganese. Some ground water is unsuitable for use in irrigation because the sodium-adsorption ratio is larger than 4.

INTRODUCTION

The purpose of this report is to provide hydrogeologic information about the quantity and quality of water supplies that are available for future water development and planning. In October 1979, the South Dakota Geological Survey and the U.S. Geological Survey began a 4-year study of the geology and water resources of Hughes County, an area of 784 mi^2 in central South Dakota. The study was financed cooperatively with State, county, and Oahe Conservancy Sub-District funds matched by Federal funds. The location of the study area and the status of the program of cooperative geologic and hydrologic studies in eastern South Dakota are shown in figure 1.

The study area consists of gently undulating, till-mantled prairies of the Coteau du Missouri division of the Great Plains physiographic province and the deeply incised valleys of the Missouri River and its tributaries. The most prominent physical feature is the Missouri River trench, incised 300 ft into the Great Plains. Oahe Dam on the Missouri River on the northwestern edge of the study area (about 6 mi northwest of Pierre) impounds a 240-mi-long reservoir, Lake Oahe.

The city of Pierre, the Hughes County seat and capital of South Dakota, is on the east bank of the Missouri River and had a population in 1980 of about 12,000 persons. The remaining county population of 2,200 persons lives mostly in the rural areas. The population of the two other towns in the county are Blunt, 420 persons, and Harrold, 200 persons.

Purpose and Scope

The purpose of this study was: (1) To determine the availability of surface and ground water, (2) to describe how the hydrologic system effects water availability, (3) to describe the water quality, and (4) to estimate the effects of development of water supplies on the availability of surface and ground water. This report is a general appraisal of the water resources; any large-scale water development needs to be preceded by detailed hydrologic studies.

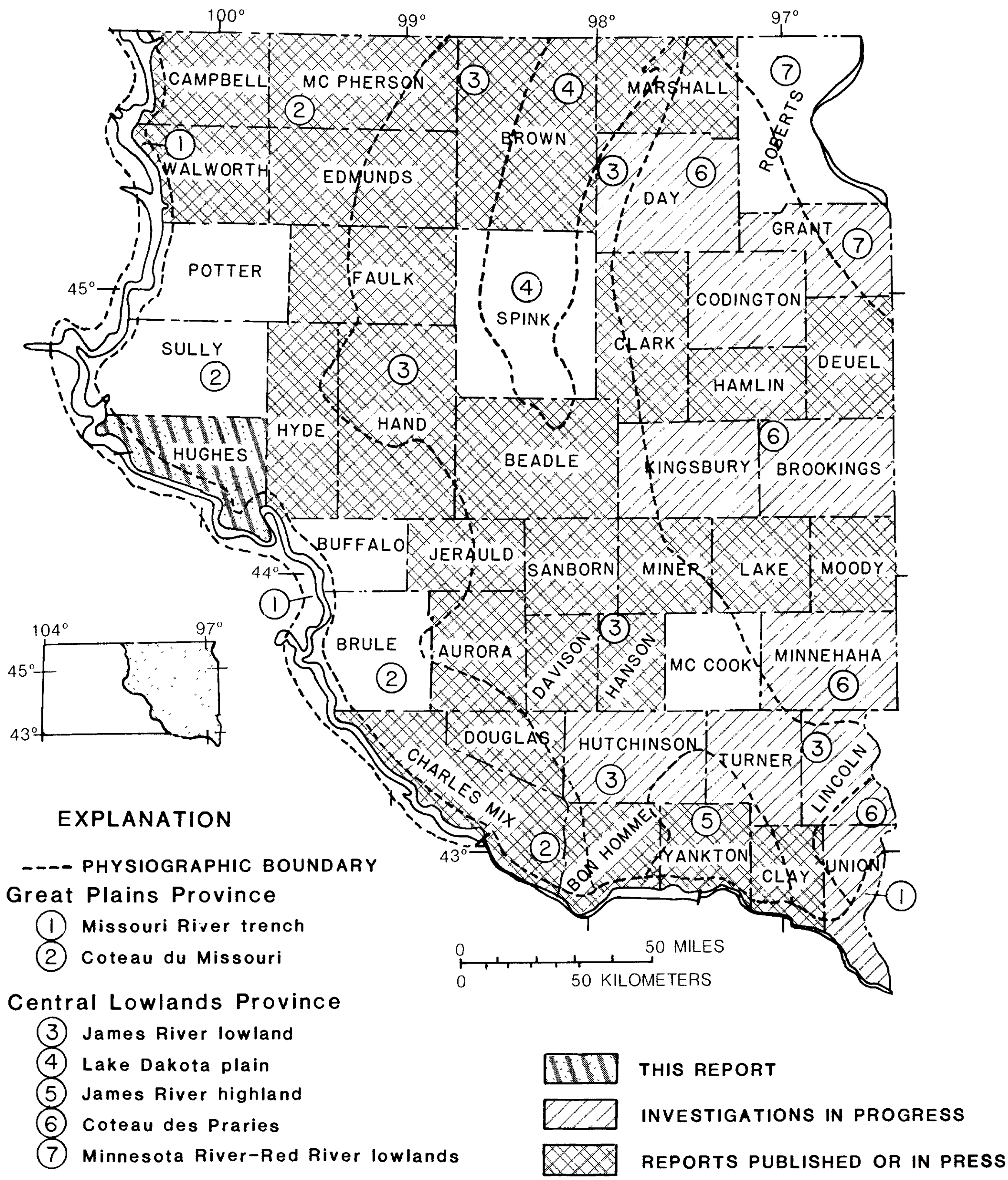

Figure 1.--Index map of eastern South Dakota showing area of this study, status of county investigations, and major physiographic division.

Existing data on streamflow and bedrock aquifers were assembled and interpreted. Field studies concentrated mostly on glacial aquifers because little was known of their extent, thickness, depth, storage, recharge, discharge, water levels, well yields, and water quality. Glacial aquifers yield water that has a smaller concentration of dissolved solids than water from bedrock aquifers in many parts of South Dakota.

Method of Investigation

Streamflow data, reservoir levels, and water-quality data were compiled from several publications (U.S. Geological Survey, 1964, 1969, 1972-83, and 1973). Records of water-level fluctuations in observation wells were available from the Water Rights Division of the South Dakota Department of Water and Natural Resources.

Data from about 300 test holes and another 300 wells were studied to determine the extent, thickness, water yields, and water quality of aquifers. Most of the test holes were drilled by the South Dakota Geological Survey during 1980-82. Logs of test holes are available from the South Dakota Geological Survey in Vermillion or the U.S. Geological Survey in Huron. Three aquifer tests of the Gray Goose glacial aquifer were made to determine aquifer characteristics and to estimate the response of the aquifer to pumping stress.

Water samples for chemical analysis have been collected from the Missouri River and from the Missouri River reservoirs for many years. Since 1971, samples of water have been collected from the Missouri River at Pierre every month for complete chemical analysis. Water samples from 200 wells were tested at the sampling site to determine general chemical properties and 35 additional samples of ground water were collected for complete chemical analysis.

Wells, test holes, and sampling sites are numbered according to the Federal land survey of eastern South Dakota (fig. 2).

Previous Investigations

Information about the regional geology is found in reports by Rothrock (1943) and by Flint (1955). A study of the geology of the Pierre area described the Pierre Shale and overlying glacial deposits and related their structure and drainage to engineering problems such as road failures (Crandell, 1958). A report on his geologic studies of Hughes County is being prepared by George Duchossois of the South Dakota Geological Survey. Soils maps (Smalley, 1975) and a study of sand and gravel deposits being prepared by Dennis Tomhave of the South Dakota Geological Survey were useful in estimating the extent of permeable soil and in mapping near-surface aquifers. The logs of numerous test holes along the route of the proposed Pierre canal of the Oahe Irrigation Project were supplied by the U.S. Bureau of Reclamation. The results of special studies to locate additional water supplies have been published for the city of Pierre (Brinkley, 1971) and the town of Harrold (Helgerson, 1975). A geohydrologic study describes the geology and availability and quality of water in the Crow Creek and Lower Brule Indian Reservations (Howells, 1974). The Crow Creek Reservation extends into four townships in southeastern Hughes County (fig. 3). A short information circular summarizes the extent, depth, and water quality of major aquifers in Hughes County (Hamilton, 1986).

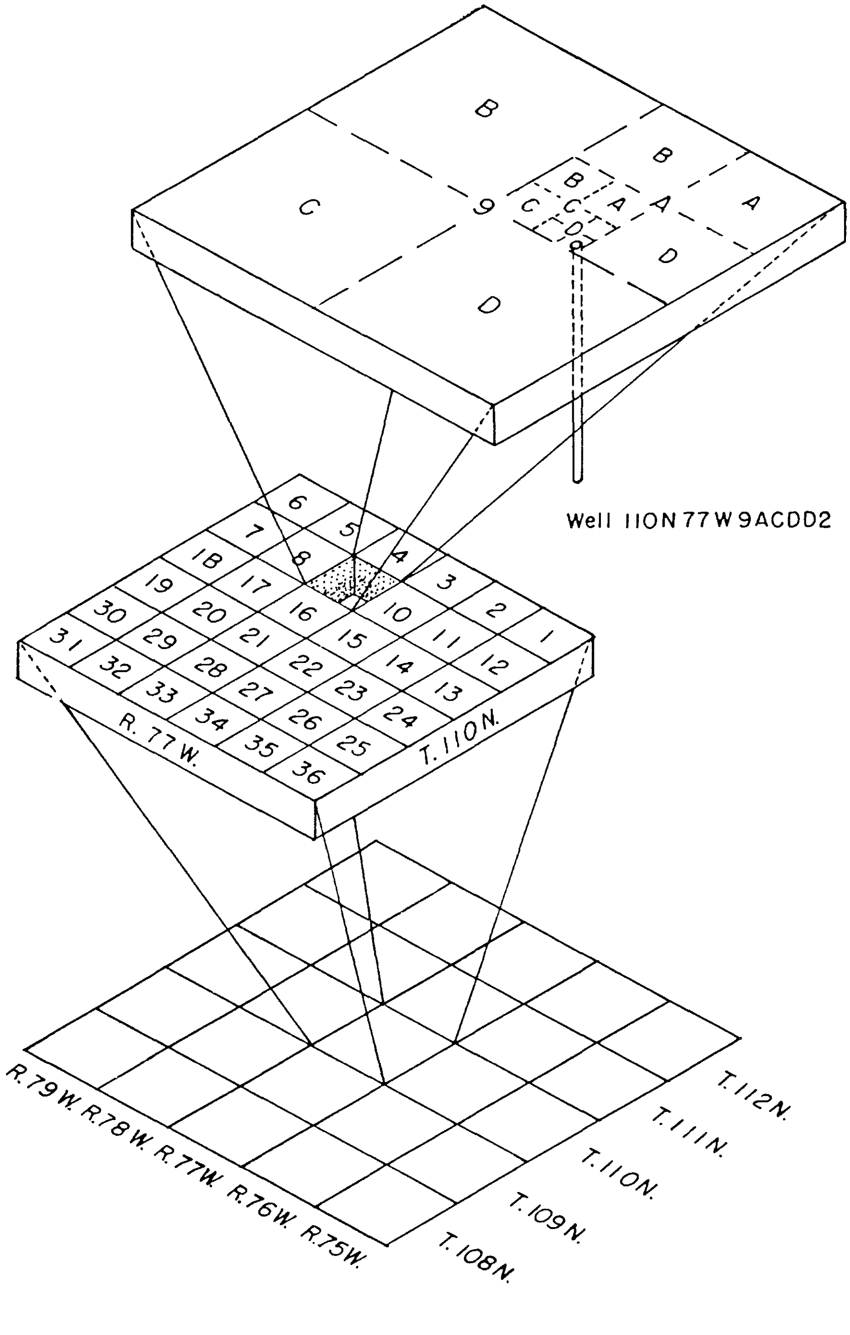

Figure 2.--Site-numbering diagram. The site number consists of township followed by "N," range followed by "W," and section number, followed by a maximum of four uppercase letters that indicate, respectively, the 160-, 40-, 10-, and 2½-acre tract in which the well is located. These letters are assigned 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 110N77W9ACDD2 is the second well recorded in the SE¼ of the SE¼ of the SW¼ of the NE¼ of section 9 in township 110 north and range 77 west of the 5th meridian and baseline system.

The Water Environment

Climate and Hydrology

All water in Hughes County is derived from precipitation. Inflow of the Missouri River and bedrock aquifers is derived from precipitation outside the study area. Recharge of ground water occurs when rain or melting snow infiltrates to the water table. Normal annual precipitation is 18 in. but is 3 in. or more less than normal an average of 1 year out of 5. Fortunately, three-fourths of the annual precipitation usually occurs during the growing season. Nevertheless, supplemental irrigation often is needed during the hot, windy summers for successful agriculture. Maximum daily air temperatures can exceed 100°F for as long as 2 weeks. Consequently, strong, hot, dry winds rapidly desiccate crops that are not irrigated.

The average annual quantity of water entering the county totals 18.7 million acre-ft. About 18 million acre-ft is from streamflow, mostly in the Missouri River, and the remainder is precipitation. Water leaving the county consists of about 18 million acre-ft flowing down the Missouri River and about 0.7 million acre-ft as evapotranspiration. Pumpage from reservoirs and wells is included with evapotranspiration because most of the pumpage is for consumptive uses. Recharge of the bedrock aquifer system by precipitation occurs in the Black Hills of South Dakota, 150 mi west of the study area, but it is a separate hydraulic system that has not been included in the above figures.

Hydrogeology

The availability of ground water depends on the recharge, storage, thickness, and water yield of aquifers. Recharge of aquifers is small compared to either the flow of the river or the evapotranspiration loss but is important for stabilizing ground-water storage and water levels.

Recharge to glacial aquifers is mostly by infiltration of precipitation. Recharge to glacial aquifers is decreased and evapotranspiration is increased because infiltration is slowed by relatively impermeable glacial till. The till, which is mostly silty clay, mantles upland areas to depths that exceed 200 ft. Some water may be transmitted rapidly, however, along joints and fractures in the till. Recharge is small and runoff large on steeply sloping valley walls consisting of till and shale that erode into "badlands" along the Missouri River and its tributaries.

Recharge to bedrock aquifers is by leakage from underlying aquifers that are under higher artesian pressure. Leakage is slowed by thick beds of relatively impermeable shale but some water may be transmitted along joints and fractures in the shale. Leakage is larger in the southeastern part of the county where many of the shale beds are missing.

The storage and water yield of aquifers usually is determined by aquifer tests. The important hydraulic characteristics that can be estimated from aquifer tests are the coefficient of storage, the transmissivity, and the hydraulic conductivity. The water stored in an aquifer is equal to the volume of its saturated pore spaces or other openings. The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head.

The size and interconnection of pores determines the capacity of an aquifer to transmit water. Transmissivity is the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Hydraulic conductivity is the rate of flow of water transmitted through a porous medium of unit cross-sectional area under a unit hydraulic gradient.

Many wells that are completed in glacial aquifers have large yields because of the large hydraulic conductivity of the sand and gravel. These aquifers tend to have little of the silt and clay that clog pores and decrease hydraulic conductivity. This is due to the fact that much of the sand and gravel that was deposited as glacial outwash was washed clean of fine material when a thick continental ice sheet melted during late Pleistocene time and carved channels 300 ft deep and as much as several miles wide in shale bedrock. Sand and gravel outwash was deposited in the channels as the volume and velocity of the meltwater decreased. Outwash of the Gray Goose aquifer was deposited in an early erosional channel. Later, the sand and gravel deposits were buried by about 200 ft of till when the ice front readvanced. When the ice sheet melted the last time, sand and gravel was again deposited at shallow depths in the valleys of the Missouri River and its tributaries. These later deposits compose the Missouri, Highmore-Blunt, and Chapelle Creek aquifers.

Large well yields of as much as 1,600 gal/min are obtained from three hydraulically connected artesian bedrock aquifers (Dakota, Inyan Kara-Sundance, and Minnelusa-Madison, table 1). The 3 units range in thickness from 50 to 880 ft. They underlie all or part of the county at depths of from 800 to 2,600 ft below land surface. The Minnelusa-Madison, the deepest bedrock aquifer, is recharged by precipitation in the Black Hills of western South Dakota where it is exposed at the land surface. The other bedrock aquifers are recharged in the study area by upward leakage from the Minnelusa-Madison aquifer. Bedrock aquifers, confined by nearly impermeable shale, contain water under artesian pressures that can exceed 400 lb/in^2 at land surface in the deepest wells. Below the base of these aquifers are other sedimentary rocks of Cambrian to Devonian age, which may be aquifers; underlying these rocks are nearly impermeable quartzite or granite of Precambrian age. No wells are known to have completely penetrated or to have obtained water or other fluids from the granite. The granite may extend for miles down into the crust of the Earth.

Water Use

About 30,000 acre-ft of surface and ground water were withdrawn for municipal, rural-domestic, livestock, and irrigation use during 1981. The author estimates that withdrawals of both surface and ground water will at least double within 30 years. Most of this increase will be for irrigation and for geothermal energy.

Withdrawal of surface water during 1981 was about 17,000 acre-ft and almost all of this water was pumped from the Missouri River for irrigation. This is less than 0.1 percent of the average flow of the Missouri River.

Withdrawal of ground water during 1981 was about 13,000 acre-ft. Nearly 14 percent of this quantity (1,730 acre-ft) was from glacial aquifers for irrigation (table 2). Municipal withdrawals, which comprised 23 percent of the ground-water withdrawals (2,880 acre-ft), were mainly by the city of Pierre which withdrew 2,400 acre-ft of water from eight wells completed in the Missouri glacial aquifer. The remaining 65 percent of ground-water withdrawal (8,150 acre-ft) was from bedrock

Table 1.--Bedrock units and their water-yielding characteristics and water quality

[Modified from Howells, 1974, 1979]

System	Formation or deposit	Thickness (feet)	Description	Water yielding characteristics and water quality[1/]
Cretaceous	Pierre Shale	80-700	Gray, brown, and black, tough, gummy to friable shale, non-calcareous to mostly calcareous; contains widely persistent zones of limestone, bentonite, and iron-manganese concretions.	Relatively impermeable.
	Niobrara Formation	40-110	Tanish to bluish-gray and light to dark-gray mostly calcareous shale; contains abundant microfossils.	Relatively impermeable.
	Carlile Shale	300-500	Light-blue or light-gray to black shale, generally non-calcareous; contains one or more sandstone or sandy intervals (probably equivalent to the Codell Sandstone Member found elsewhere) in the top one-half.	Relatively impermeable. Sandstone may yield small quantities of moderately saline water.
	Greenhorn Limestone	50-110	Buff to bluish, white, or gray, very calcareous shale; commonly marly and fossiliferous. May be interbedded with thin limestone layers.	Relatively impermeable. Can yield small quantities of moderately saline water in some areas.
	Graneros Shale	220-320	Medium to dark-gray non-calcareous shale. Calcareous concretions and pyrite and marcasite crystals common. Locally the formation may contain thin lenses and beds of sandstone and may be sandy or silty at the base.	Relatively impermeable. Sandstone yields slightly to moderately saline, muddy water to flowing and pumped wells.
	Dakota Formation	240-430	White, tan, or light-gray sandstone, very fine to medium-grained, loose to tightly cemented; interbedded with dark-colored shale.	A major aquifer. Yields from 2 to 1,600 gallons per minute of slightly saline water to pumped or flowing wells. Hardness of the water ranges from 50 to 580 mg/L (milligrams per liter).
	Skull Creek Shale	30-200	Dark bluish-gray shale.	Relatively impermeable.
	Inyan Kara Group	30-70	White to light-gray or tan sandstone, fine to medium-grained; contains beds of gray to black and reddish to buff shale and siltstone.	A major aquifer. Can yield 20 to 1,000 gallons per minute of slightly saline water to pumped or flowing wells. Hardness of the water ranges from 633 to 1,540 mg/L.
Jurassic	Sundance Formation	20-110	White, buff, dark-pink, or red sandstone, medium to fine-grained; may be glauconitic in some areas; contains layers of red to brown, green, and gray shale.	

Permian and Pennsylvanian	Minnelusa Formation	70-480	White to yellow, buff, or red sandstone interbedded with anyhydrite, brick-red to orange, green, or black shale, and white to brown to gray limestone and dolomite.	A major aquifer. Can yield 50 to 1,000 gallons per minute of slightly saline water to pumped or flowing wells. Hardness of the water ranges from 1,060 to 1,600 mg/L.
Mississippian	Madison Group	0-400	White to tan, brown, and gray limestone and dolomite.	
Devonian	Undifferentiated	0-170	Gray to tan dolomite and sandstone; interbedded with red, greenish-gray, or black shale.	Unknown. Dolomite and sandstone probably are part of the overlying major aquifer.
Ordovician	Red River Formation	0-150	Gray to light brown dolomite.	Unknown. Dolomite probably is part of the overlying major aquifer.
Cambrian	Deadwood Formation	0-150	White to buff to brownish-red sandstone, siltstone, dolomite, and limestone. May include Lower Ordovician rocks.	Unknown. Sandstone may be an aquifer.
Cambrian (?) and Precambrian (?)	Transgressive facies termed "basal wash"	0-50	White and buff to pink to light reddish-purple sandstone, generally coarse-grained but ranges from fine-grained to gravelly. Reflects the lithology of underlying or nearby Precambrian rocks. This is a coarse clastic facies that overlies the Precambrian surface throughout much of South Dakota.	Unknown. May be an aquifer.
Precambrian	Sioux Quartzite	Unknown	Pale maroon, pink; red or purple, hard, dense, quartzite. Locally white, locally friable.	Relatively impermeable.
	Igneous and metamorphic rocks	Unknown	Various colored granite, gneiss, schist, and other igneous and metamorphic rocks.	Relatively impermeable.

1/ Terms used for relative salinity have the following ranges of values for dissolved solids, in milligrams per liter: Fresh, less than 1,000; slightly saline, 1,000 to 3,000; moderately saline, 3,000 to 10,000; very saline, 10,000 to 35,000; briny, more than 35,000.

Table 2.--Estimated withdrawal of ground water during 1981

Source	Total		Municipal		Rural-Domestic		Livestock		Irrigation	
	Acre-feet	Percent	Acre-feet	Percent	Acre-feet	Percent	Acre-feet	Percent	Acre-feet	Percent
GLACIAL AQUIFERS										
Gray Goose	1,410	11	0	0	5	1/0.0	35	0.3	1,370	10.8
Missouri	2,450	19	2,400	19	35	1/.3	15	.1	0	.0
Highmore-Blunt	520	4	160	1	10	1/.0	30	.2	320	2.5
Minor aquifers	150	1	0	0	10	1/.0	100	.8	40	.3
Subtotal	4,530	35	2,560	20	60	.5	180	1.4	1,730	13.6
BEDROCK AQUIFERS										
Dakota	3,900	31	0	0	20	1/.1	3,880	30.6	0	.0
Inyan Kara-Sundance	1,210	10	0	0	2	1/.0	1,208	9.5	0	.0
Minnelusa-Madison	3,040	24	2/320	3	2	1/.0	2,718	21.4	0	.0
Subtotal	3/8,150	65	320	3	24	.2	7,806	61.6	0	.0
Total, all aquifers	12,680	100	2,880	23	84	.7	7,986	63.0	1,730	13.6

1/ Less than 0.1 percent.
2/ Geothermal well at Pierre (St. Mary's Hospital).
3/ More than 90 percent is unused flow.

aquifers. The first geothermal well, at St. Mary's Hospital in Pierre, withdrew an average of 200 gal/min (320 acre-ft/yr) of water during 1979-81. The water with a temperature of 41.7°C was withdrawn from the Madison Group for heating the hospital. However, more than 90 percent of the water withdrawn from bedrock aquifers is unused discharge through flowing wells.

SURFACE WATER

Streamflow

The Missouri River and its two reservoirs, both in volume and in potential for development, vastly overwhelm all other sources of surface water in the study area. The Missouri River is the southwestern boundary of Hughes County (fig. 3). The river has an average flow of nearly 18 million acre-ft/yr (25,000 ft^3/s) that is regulated by many upstream dams for flood control. It provides water for navigation, power generation, and irrigation. The flow of the Missiouri River at Pierre is controlled by releases of water from Lake Oahe for power generation. During 1966-81, after Lake Oahe had filled, the average annual discharge ranged from 21,000 ft^3/s in 1973 to 36,700 ft^3/s in 1975.

The eight named ephemeral streams that are tributary to the Missouri River in Hughes County (fig. 3) are estimated to have a combined average flow of 15 ft^3/s (nearly 11,000 acre-ft/yr). Runoff in all of the streams in the county is important to the economy because the runoff fills livestock ponds.

Tributary streams have ephemeral flow because precipitation is small and erratic, evapotranspiration consumes almost all of the precipitation in summer, runoff is rapid, and there is small discharge of ground water. Although Medicine Knoll Creek near Blunt (113N75W31B) has an average flow of 4.8 ft^3/s, there is a 50 percent probability that the flow for an entire year will never exceed 2.5 ft^3/s. A daily discharge of 1 ft^3/s was equaled or exceeded only about 15 percent of the time during 1951-80 (fig. 4). Likewise, a discharge of 0.1 ft^3/s was equaled or exceeded only about 30 percent of the time even though the drainage area upstream from the gaging station is 317 mi^2. The steep slope of the flow-duration curve shown in figure 4 probably is typical of streams in the county. Freezing of streams also contributes to the length of periods when there is little or no streamflow.

Lakes and Ponds

Lake Oahe, on the Missouri River along the northwestern side of the county, has a normal maximum storage of about 22 million acre-ft of water. The lake extends northward for 240 river miles from Oahe Dam into North Dakota and has an average surface area of 340,000 acres. Evaporation from Lake Oahe averages about 1.0 million acre-ft/yr. Lake Sharpe on the Missouri River downstream from Pierre has a normal maximum storage of about 2 million acre-ft. The lake extends south and east for 80 river miles from Pierre to Big Bend Dam and has a surface area of 50,000 acres. Evaporation from Lake Sharpe probably averages about 20,000 acre-ft annually. Seven other lakes and about 300 stock ponds in the county have an aggregate surface area of about 3,000 acres and evaporation losses total about 9,000 acre-ft/yr. Evaporation losses amount to more than one-half of the average storage capacity of the small lakes and ponds.

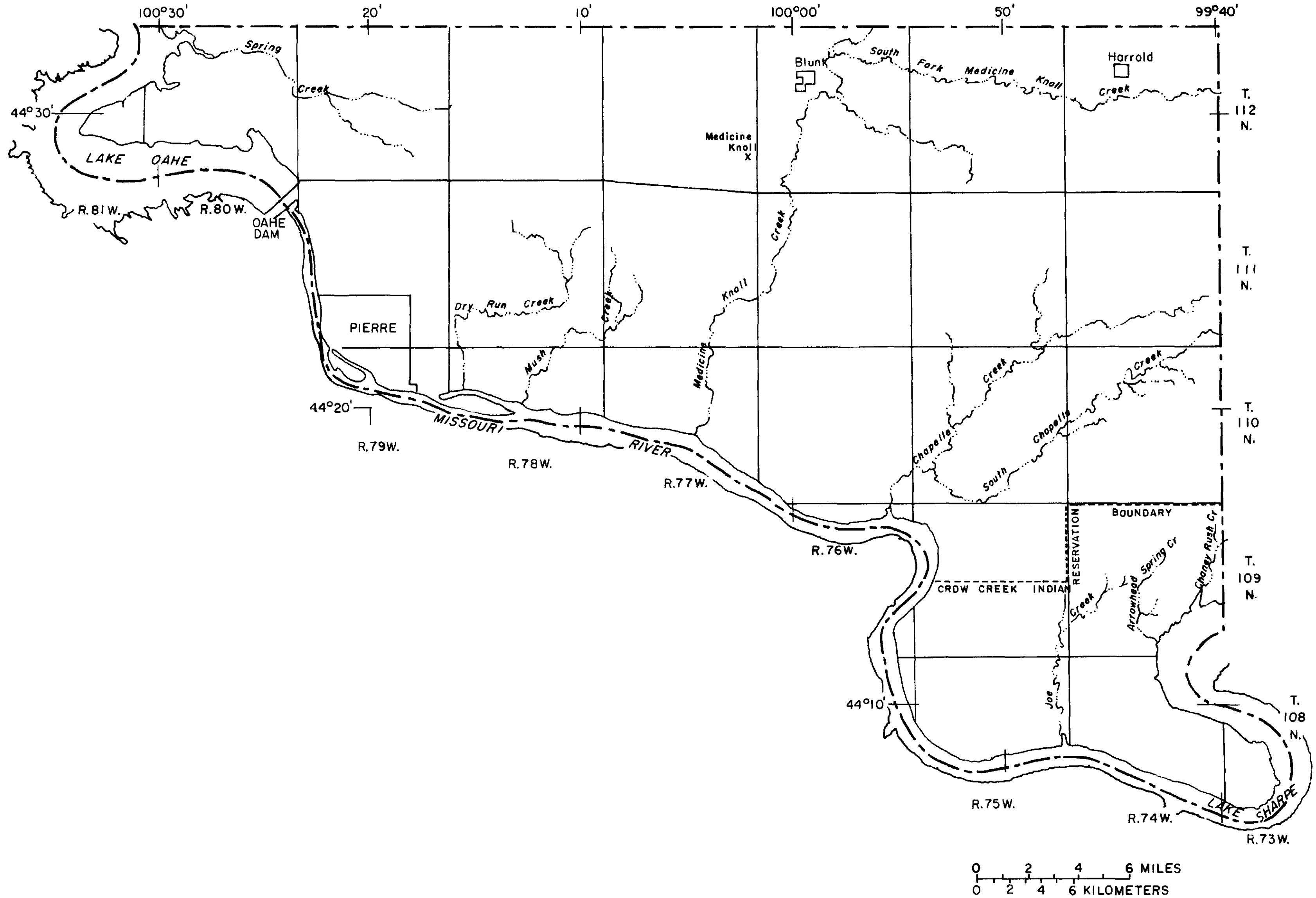

Figure 3.--Streams and lakes in or near Hughes County.

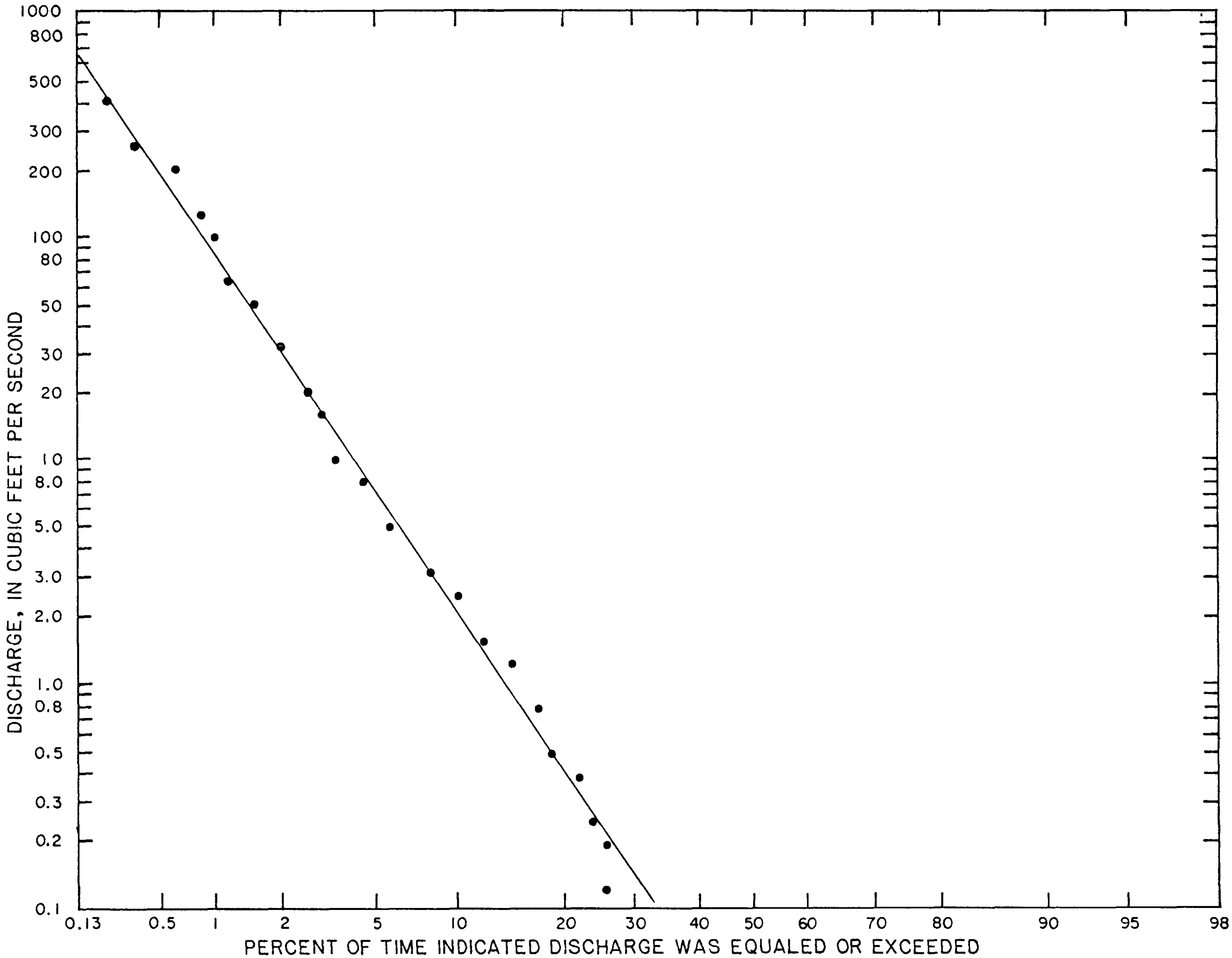

Figure 4.--Flow duration curve for Medicine Knoll Creek near Blunt, S. Dak., 1951-80.

Effects of the development of surface water in Hughes County are widespread and include the filling of Lake Oahe and Lake Sharpe behind dams on the Missouri River. These two reservoirs flooded 30,000 acres of the most productive farm and ranch land in the county and increased the quantity of water lost to evapotranspiration by an estimated 650,000 acre-ft/yr. Compensating for this loss are the stabilization of the flow and quality of water in the Missouri River, the availability of new sources of water for development, huge electric power generation capacity, and water for fish, wildlife habitat, and recreation. Unfortunately, the filling of these reservoirs by sediment from erosion at a more rapid rate than anticipated gradually is decreasing their storage capacity and usefulness. Sedimentation eventually may harm the fishing and recreation potential of the lakes.

GROUND WATER

Glacial Aquifers

Four major glacial aquifers, composed mostly of outwash sand and gravel, underlie 240 mi^2 (nearly 30 percent) of the county and store nearly 1 million acre-ft of water (table 3). Although this storage is only about 1 percent of the storage in major bedrock aquifers, it can readily be withdrawn through large-capacity wells that yield as much as 1,000 gal/min. Recharge is mostly from infiltration of precipitation and probably exceeds 2,400 acre-ft/yr. During 1981, pumpage was estimated to total 4,380 acre-ft or about 0.4 percent of storage. Aquifer water levels decline temporarily in summer as a result of pumpage.

Gray Goose Aquifer

The Gray Goose aquifer is mostly a buried deposit of outwash sand and gravel that partly fills a broad, irregular river channel that was carved into shale bedrock. The aquifer extends for 30 mi from the northwestern corner to the central part of the county (fig. 5). The channel generally is 2 to 5 mi wide along its western extent but is inferred to narrow to about 1 mi and extend eastward through the center of T. 111 N., R. 76 W. The sand and gravel in the channel possibly once extended farther southeast but was later removed by glacial erosion. The total area of the aquifer in the county is about 110 mi^2.

The depth below land surface of the top of the Gray Goose aquifer ranges from a few feet in T. 112 N., R. 80 W. (well 1, fig. 6), to 230 ft in T. 112 N., R. 78 W. (well 26, fig. 6). The aquifer mainly consists of a single layer that occurs between the altitudes of 1,560 and 1,650 ft in test holes 1-4 at the west end of the county (A-A', fig. 6) and between 1,500 and 1,600 ft in test holes in T. 112 N., R. 78 and 79 W. (B-B', fig. 6). A lower unit occurs below an altitude of 1,500 ft within a narrow channel incised in bedrock near Medicine Knoll Creek (wells 48 and 51, C-C', fig. 6). The lower unit also has been penetrated by test holes at 111N77W14AAAA and 111N76W22DDDD.

The aquifer is unconfined, the depth to water in wells ranging from 15 ft at 112N80W9AADC to 250 ft in T. 112 N., R. 78 W.

The total thickness of sand and gravel in the area of the Gray Goose aquifer, including the unsaturated zone and overlying unnamed aquifers (B-B', fig. 6) averages 40 ft but it exceeds 60 ft along a meandering band of irregular width (fig. 7). The band extends eastward from Lake Oahe to the southern end of T. 111 N., R. 77 W. and has a total area of about 45 mi^2.

Table 3 begins on next page

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

Major aquifer	Areal extent[1/] (square miles)	Maximum thickness (feet)	Average thickness (feet)	Estimated average hydraulic conductivity (feet per day)	Range of depth below land surface (feet)	Range of water level above (+) or below land surface (feet)
			GLACIAL AQUIFERS			
Gray Goose	110	93	40	400	0 to 230	15 to 250
Missouri	70	111	30	500	0 to 200	4 to 100
Highmore-Blunt	40	45	20	200	8 to 40	8 to 30
Chapelle Creek	20	32	5	400	0 to 100	4 to 60
			BEDROCK AQUIFERS			
Dakota	784	430	300	8	800 to 1,800	+230 to 230
Inyan Kara-Sundance	784	180	130	--	1,200 to 2,000	+470 to +200
Minnelusa-Madison	784	[4/]880	400	--	1,800 to 2,600	+1,120 to +310

1/ Extent in Hughes County. All aquifers listed extend beyond the county.

2/ Not entirely recoverable by pumping wells. Based on average thickness (feet) times areal extent (acres) times an estimated porosity of 20 percent.

3/ Estimated on discharge calculations for 1981 assuming no change in storage. Estimates are omitted for aquifers having little information on thickness, transmissivity, and water levels. Bedrock aquifers are recharged at outcrops in the Black Hills west of the study area, and also by upward leakage.

4/ Maximum thickness is about 1,200 feet in the northwest part of the county for the aquifer and underlying rocks that probably also contain aquifers and are hydraulically connected with the aquifer.

Estimated volume of water in storage[2/] (acre-feet)	Average annual recharge[3/]			Range of reported well yields (gallons per minute)	Suitable for irrigation
	(acre-feet)	(acre-feet per square mile)	(inches)		
560,000	1,500	14	0.3	10 to 800	Yes, locally no.
270,000	--	--	--	10 to 1,000	Yes.
100,000	900	20	.4	10 to 500	Yes.
10,000	--	--	--	2 to 100	Yes.
30 million	2,400	3	.1	2 to 1,600	No.
13 million	180,000	235	4.4	20 to 60	May be marginal.
40 million	180,000	235	4.4	50 to 500	May be marginal.

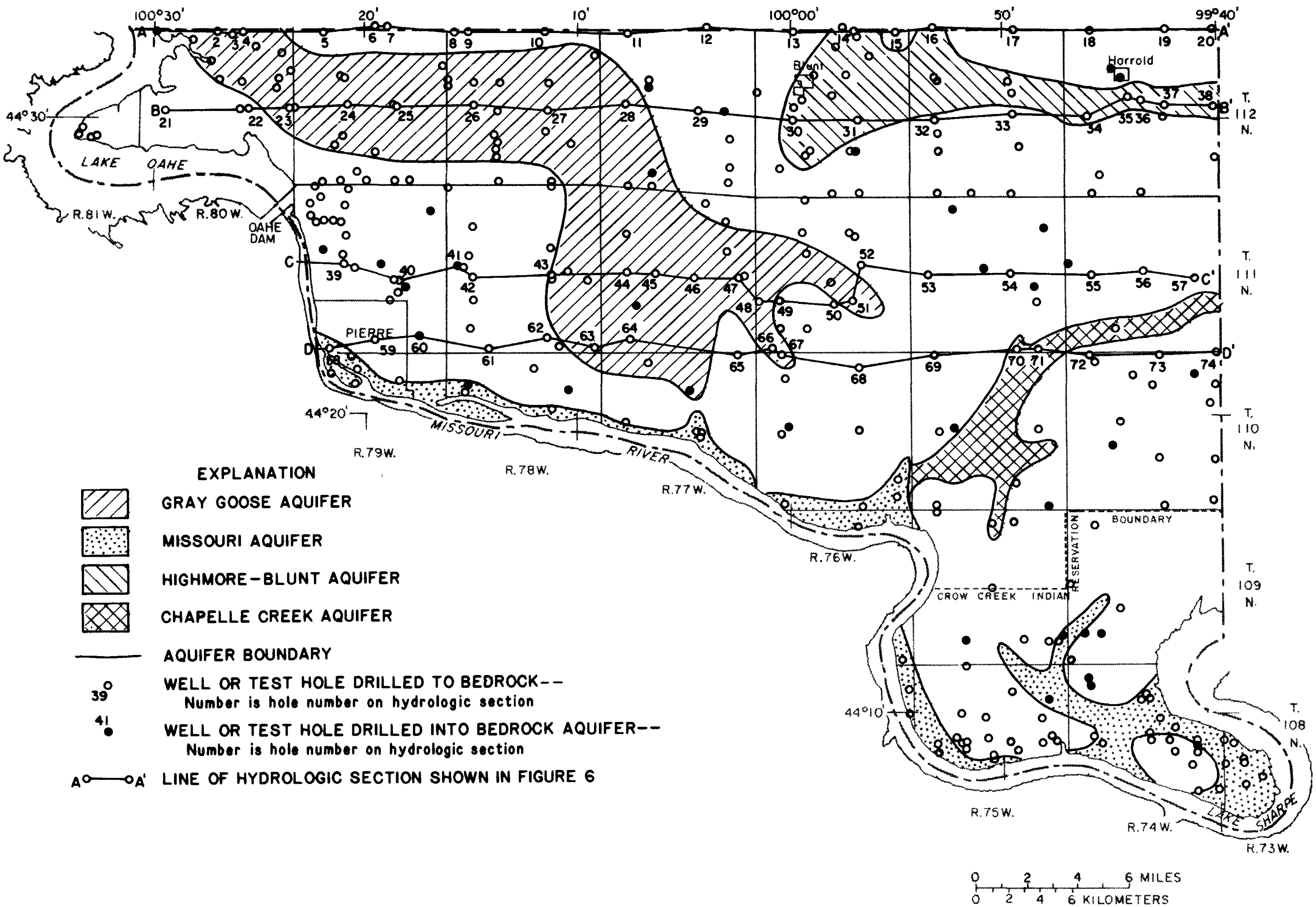

Figure 5.--Major glacial aquifers and locations of hydrologic sections, test holes, and wells for which geologic or drillers' logs are available.

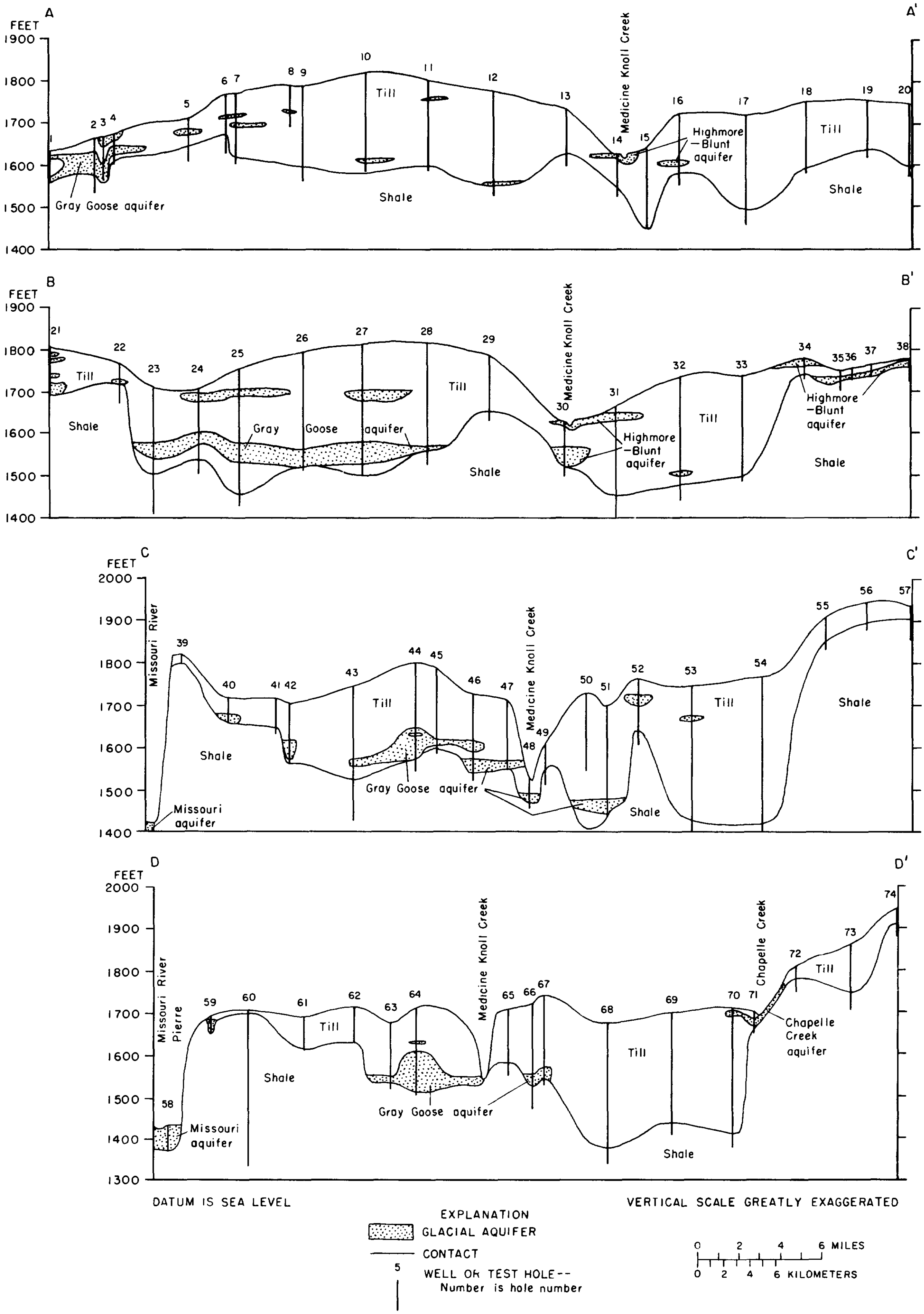

Figure 6.--Hydrologic sections showing glacial aquifers.

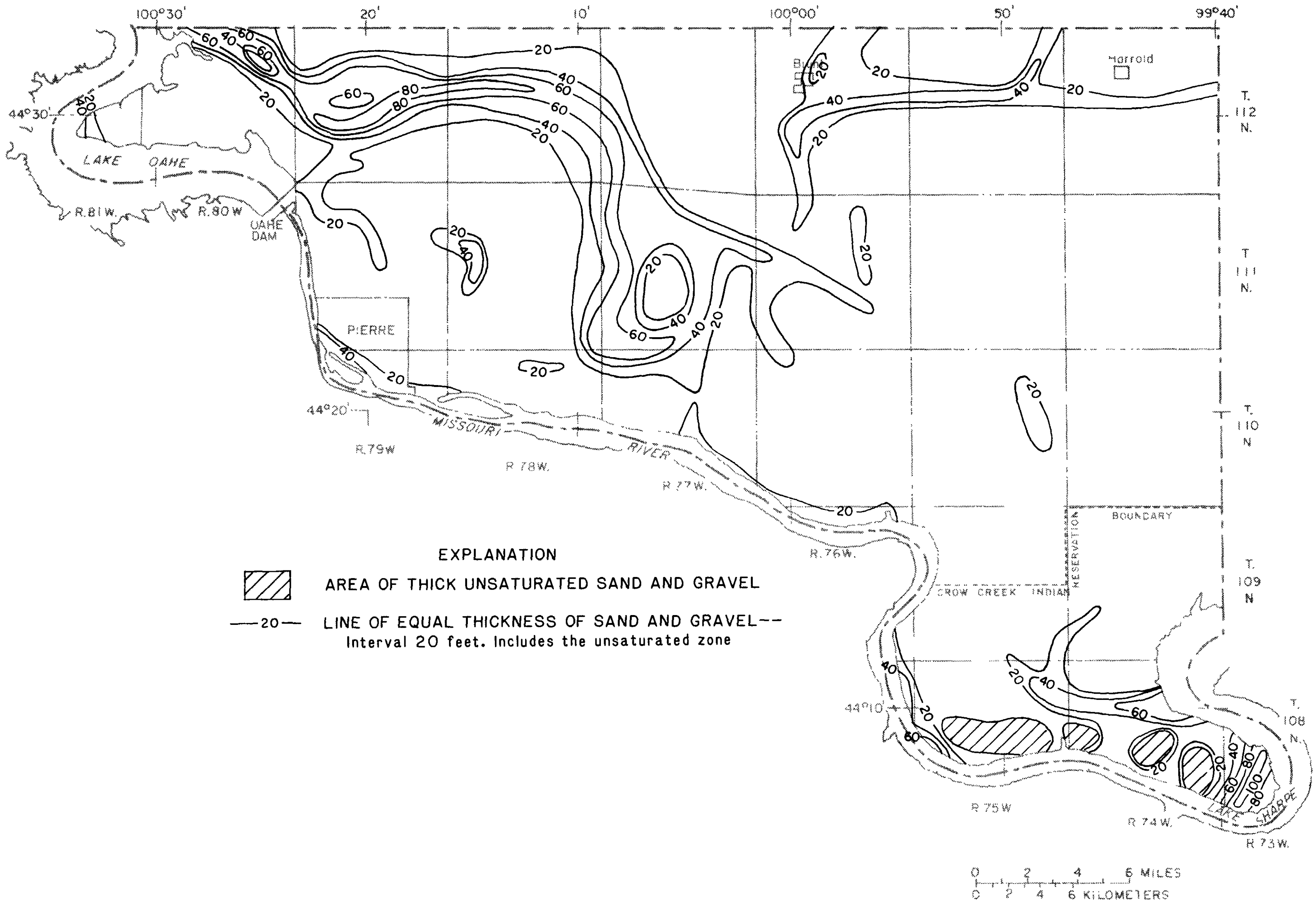

Figure 7.--Thickness of sand and gravel in glacial deposits.

The saturated thickness of the Gray Goose aquifer changes greatly within short distances in the western part of the county, particularly in T. 112 N., R. 80 W. (fig. 8). Sand and gravel of unnamed aquifers to the south in T. 111 N., R. 78 and 79 W. is not hydraulically connected to the Gray Goose aquifer.

The Gray Goose aquifer is composed mostly of medium to very coarse sand and fine gravel that is very permeable. The sand and gravel probably has an average hydraulic conductivity of about 400 ft/d, based on three aquifer tests in T. 112 N., R. 80 W. The transmissivity, the product of hydraulic conductivity and aquifer thickness, probably averages 16,000 ft^2/d. In areas where the aquifer saturated thickness is at least 30 ft, the yield from large-capacity wells could range from 500 to 800 gal/min. Where the aquifer contains fine silty sand, or is less than 30 ft thick, the yield of large-capacity wells may be much less than 500 gal/min. The depth of large-capacity wells can range from 80 ft to as much as 300 ft in T. 112 N., R. 77 and 78 W.

Water movement in the Gray Goose aquifer generally is about 100 ft/yr for the typical slope of the potentiometric surface of 1 to 2 ft/mi. Water moves perpendicular to the contours on the potentiometric surface, from the northwest to discharge areas in the south-central part of the county (fig. 9).

Recharge of the Gray Goose aquifer is by infiltration of precipitation and flow from Lake Oahe when the level of the lake is above the potentiometric surface for the aquifer. Recharge of the aquifer, estimated from the gain in flow between Lake Oahe and discharge areas, is estimated to total 1,200 acre-feet/yr (0.2 in/yr) (table 3).

Water moves from Lake Oahe into the aquifer when the level of the lake is above the potentiometric surface of the aquifer (fig. 10). Much of the inflow from the lake is bank storage that discharges back into the lake when the level of the lake declines. However, water does move southeast beyond the zone of bank storage when the level of the lake stays above an altitude of 1,605 ft for more than 2 months. Bank storage began in 1964 when the level of Lake Oahe rose to an altitude of 1,580 ft or more above sea level. By 1968, the level of the lake and the potentiometric surface of the aquifer had risen to 1,605 ft above sea level while bank storage increased to an estimated 12,000 acre-ft (fig. 11). The estimate is calculated from the product of the rise in water level (25 ft), the area affected (1,600 acres), and the porosity of the aquifer (0.3). During 1976-82, bank storage varied between 11,400 and 12,400 acre-ft. The estimates were made by applying an equation to an aquifer 2.5 mi long and 1 mi wide extending into a reservoir with which it has free hydraulic connection on both sides (Simons and Rorabaugh, 1971, p. 38, eq. 5b).

Recharge to the Gray Goose aquifer within 3 mi of Lake Oahe is estimated from flow calculations to average 336 acre-ft/yr. This is equivalent to an average annual recharge intensity of 84 acre-ft/mi^2. The estimate is based on the product of transmissivity (40,000 ft^2/d), hydraulic gradient (1 ft/mi), and length of the most permeable part of the aquifer perpendicular to the direction of flow (1 mi). Flow is northwest into the lake. Flow eastward through the aquifer in R. 78 W. is about 420 acre-ft/yr. The flow estimate is the product of an average transmissivity of 9,800 ft^2/d, an average hydraulic gradient of 1.7 ft/mi, and an aquifer length of 3 mi perpendicular to the direction of flow. The annual recharge intensity of 11 acre-ft/mi^2 for an area of 38 mi^2 is used for estimating recharge to the aquifer east of R. 78 W. The eastward gain in flow totals 1,164 acre-ft/yr. Most of the flow probably discharges by evapotranspiration in the valley of Medicine Knoll Creek (fig. 3). Recharge estimated for the 2 flow directions thus totals 1,500 acre-ft/yr, equivalent to an average annual recharge intensity of 14 acre-ft/mi^2 (table 3).

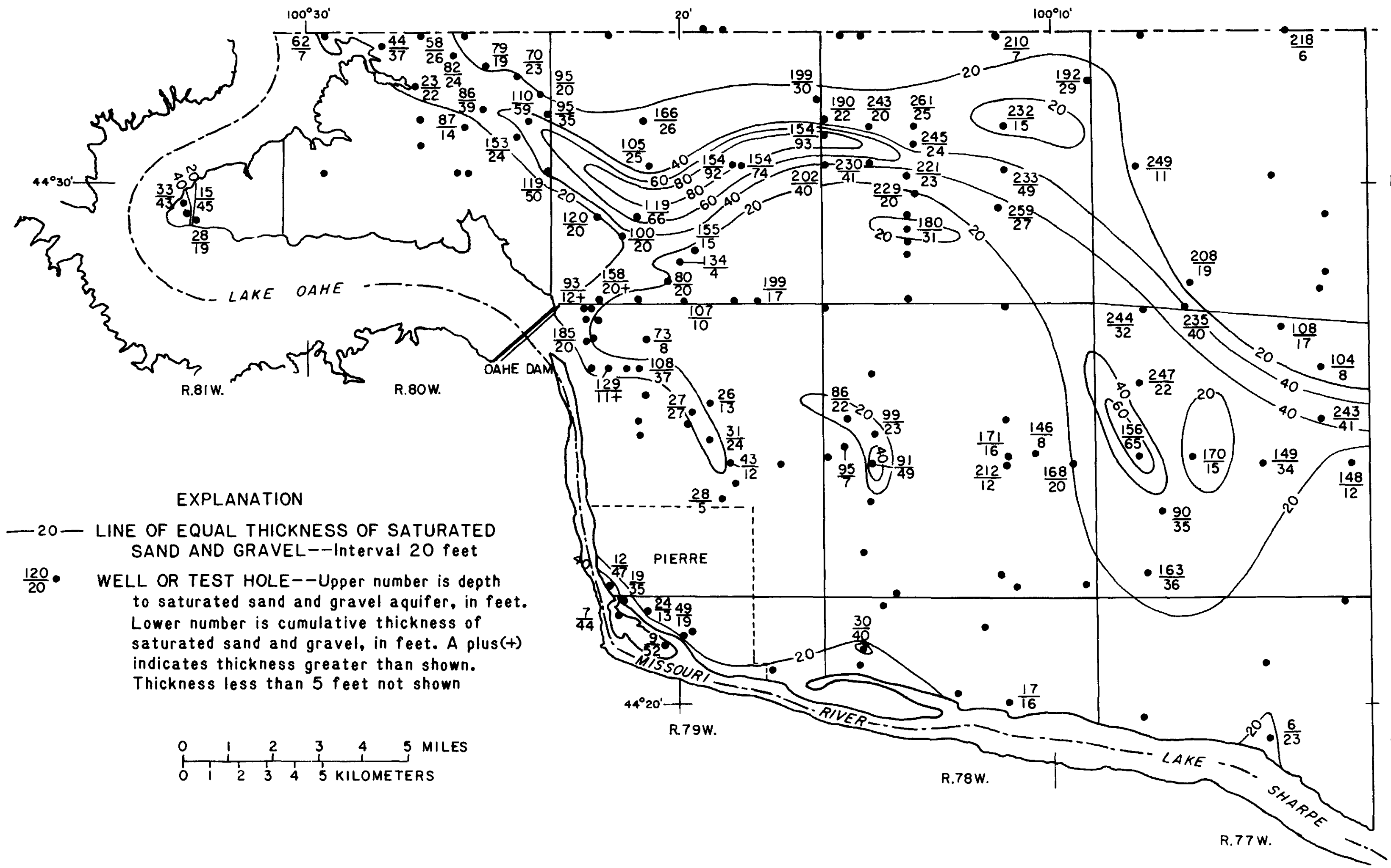

Figure 8.--Depth to and thickness of saturated sand and gravel in western Hughes County.

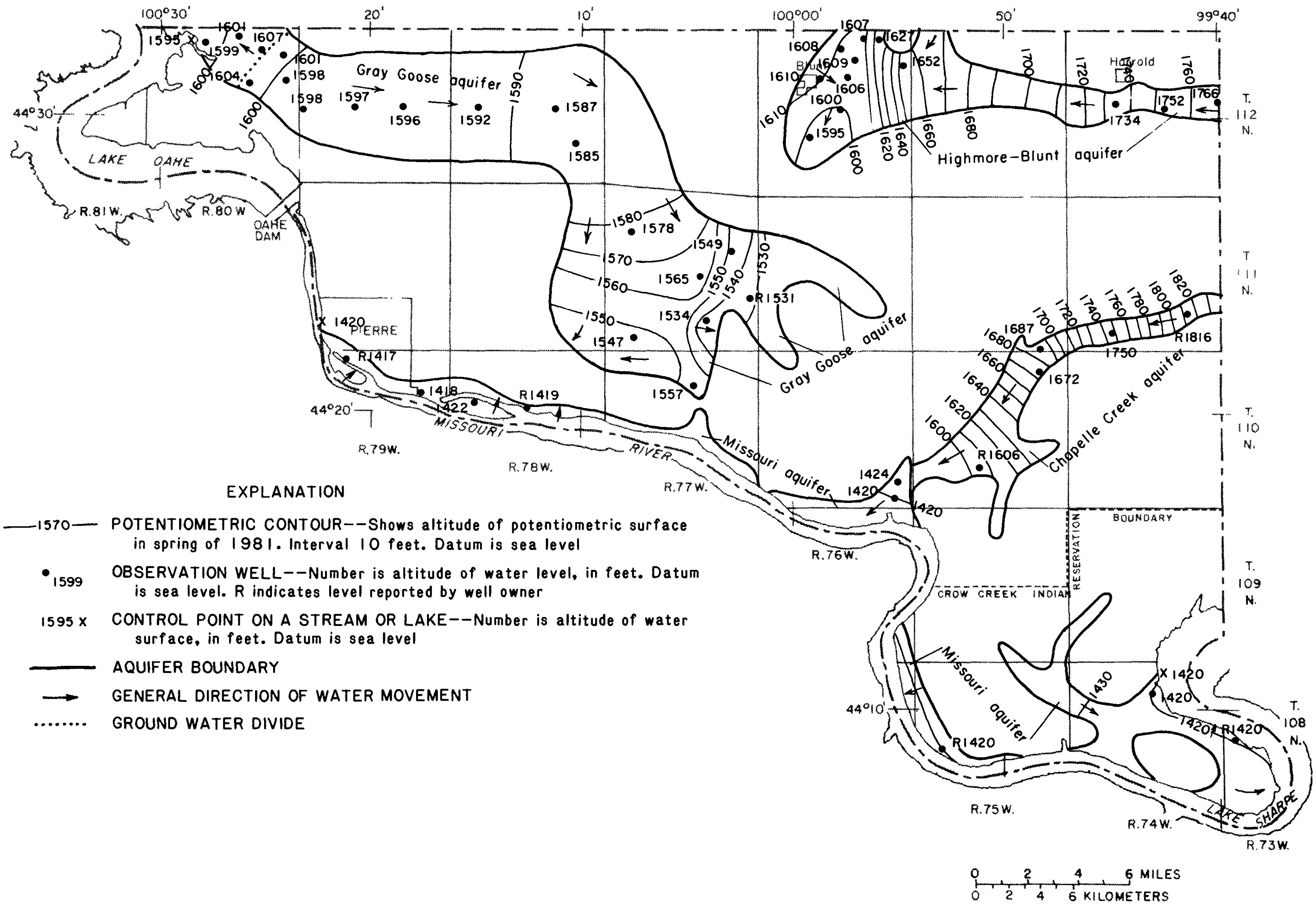

Figure 9.--Potentiometric contours of major glacial aquifers.

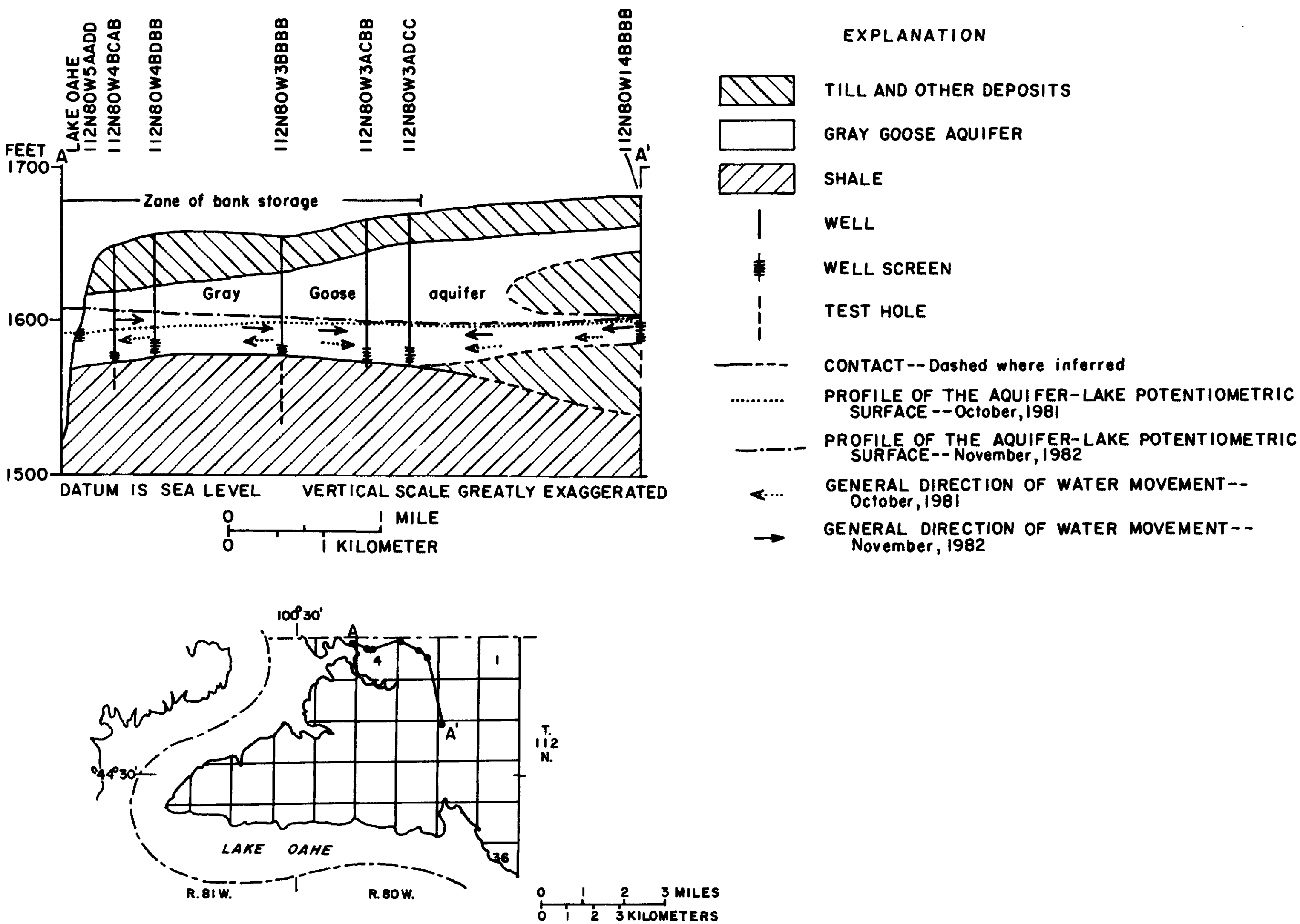

Figure 10.--Water movement in the Gray Goose aquifer near Lake Oahe.

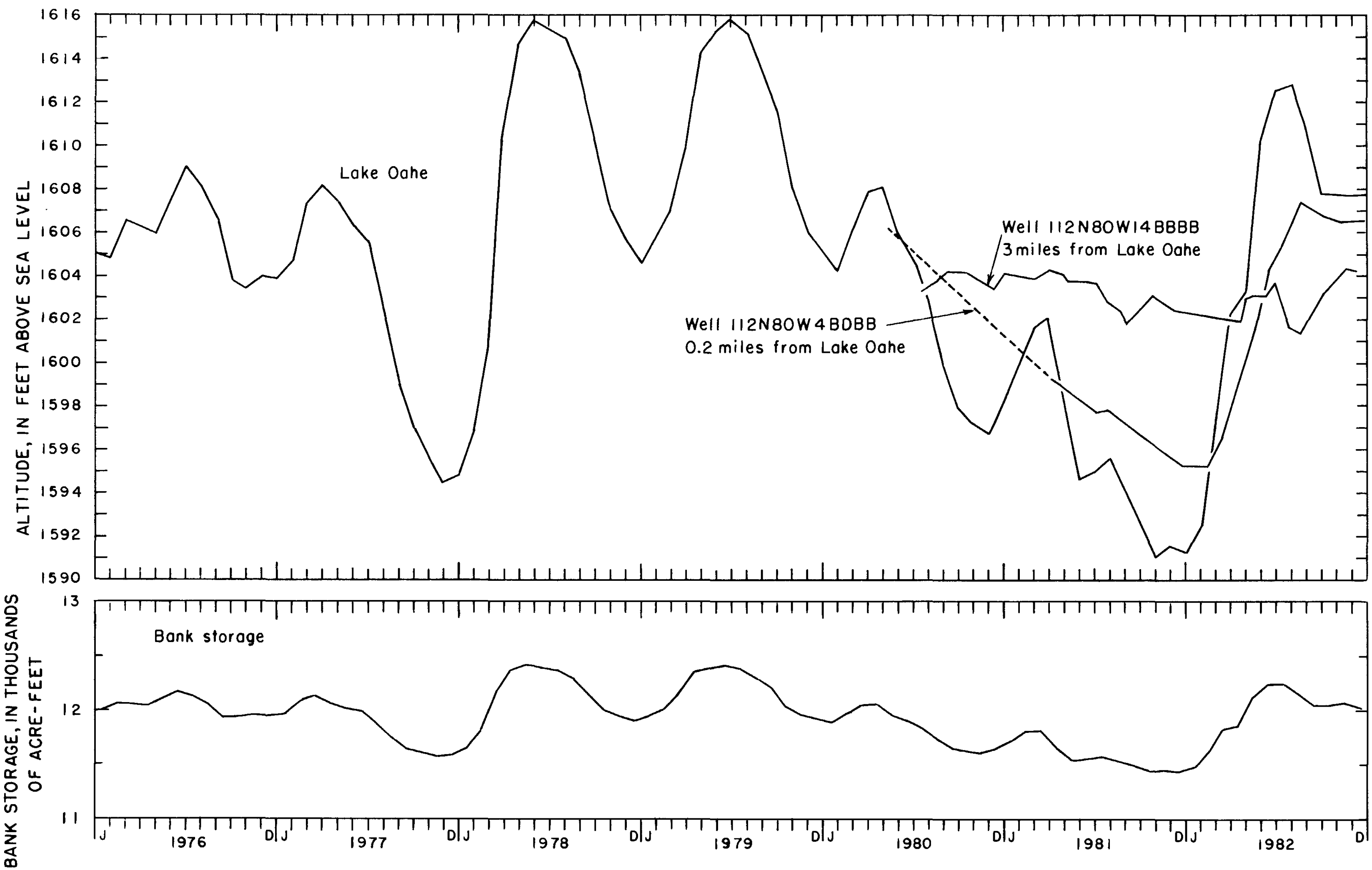

Figure 11.--Water-level and bank-storage changes for the Gray Goose aquifer and Lake Oahe, 1976-82.

Water-level changes in wells in the Gray Goose aquifer are caused both by seasonal and by long-term changes in recharge and discharge. Water levels generally rose 0.5 to 1 ft in wells 3, 4, and 5 during winter and spring of 1981 and 1982 owing to increased recharge from snowmelt and rainfall (fig. 12). These small changes in water level correlate with the small change in the cumulative departure from average precipitation during 1980 and 1981. Water levels declined in summer because of decreased recharge, increased evapotranspiration, and increased pumpage. Recharge induced from Lake Oahe probably has decreased the water-level declines in wells 3 and 4. During the summer, the water level in well 4 declined nearly 2 ft in 1981 and 3 ft in 1982 because of pumping of nearby irrigation wells. Comparing the decline in water level in well 4 with that in wells 3 and 5, which were less affected by pumpage, indicates that about one-half of the summer decline for well 4 was due to less recharge during this period and not by increased pumpage.

The period of record of hydrographs for wells completed in the Gray Goose aquifer is too short to show long-term trends. Nevertheless, a continuing increase in the number of irrigation wells could produce a gradual, long-term decline in water levels. In contrast, an increase in the rate of recharge could decrease the decline in water levels. It appears that the Gray Goose aquifer potentially can supply many additional wells because of its large recharge and saturated thickness and because existing pumpage temporarily lowers water levels only a few feet at observation wells located within 1 mi of large-capacity wells. Intensive pumping over large areas eventually could lower water levels enough to increase the rate of recharge from Lake Oahe and also decrease the rate of natural discharge by evapotranspiration.

Missouri Aquifer

The Missouri aquifer is a 2- to 3-mile-wide river-channel deposit of alluvium and outwash sand and gravel that underlies 70 mi^2 to depths from land surface to as much as 200 ft at 108N74W17CCBC (table 3). Most of the aquifer is in the flood plain of the Missouri River and is hydraulically connected to the river (fig. 5). An inferred branch of the aquifer, a possible abandoned river channel buried by 100 ft of till, trends northwest through 108N75W12BDDD. Most of the aquifer is under water-table conditions and the upper 10 to 20 ft of the sand and gravel may not be saturated in some areas. The depth to water in wells ranges from 4 to 30 ft except in the deeply buried part of the aquifer where the depth to water may be as much as 100 ft.

The average saturated thickness of the Missouri aquifer is about 30 ft but locally the thickness (saturated and unsaturated) can exceed 100 ft. Large areas of thick unsaturated sand and gravel occur beneath 15 mi^2 in T. 108 N., R. 74 and 75 W. (fig. 7). In these townships, recharge drains rapidly from the permeable sand and gravel into the river.

The Missouri aquifer is composed mostly of medium to coarse sand and fine gravel that has an average hydraulic conductivity of about 500 ft/d. The transmissivity of the aquifer is estimated to average 15,000 ft^2/d. Where the saturated part of the aquifer is at least 30 ft thick, yields from large-capacity wells may range from 300 to 1,000 gal/min. The depth of large-capacity wells may range from 30 ft, near the river, to as much as 160 ft in T. 108 N., R. 75 W.

Water movement in the Missouri aquifer generally is at a rate of 6 ft/yr for the average slope of the potentiometric surface of 0.2 ft/mi. Water moves toward the Missouri River from recharge areas along the flood plain and adjacent terraces.

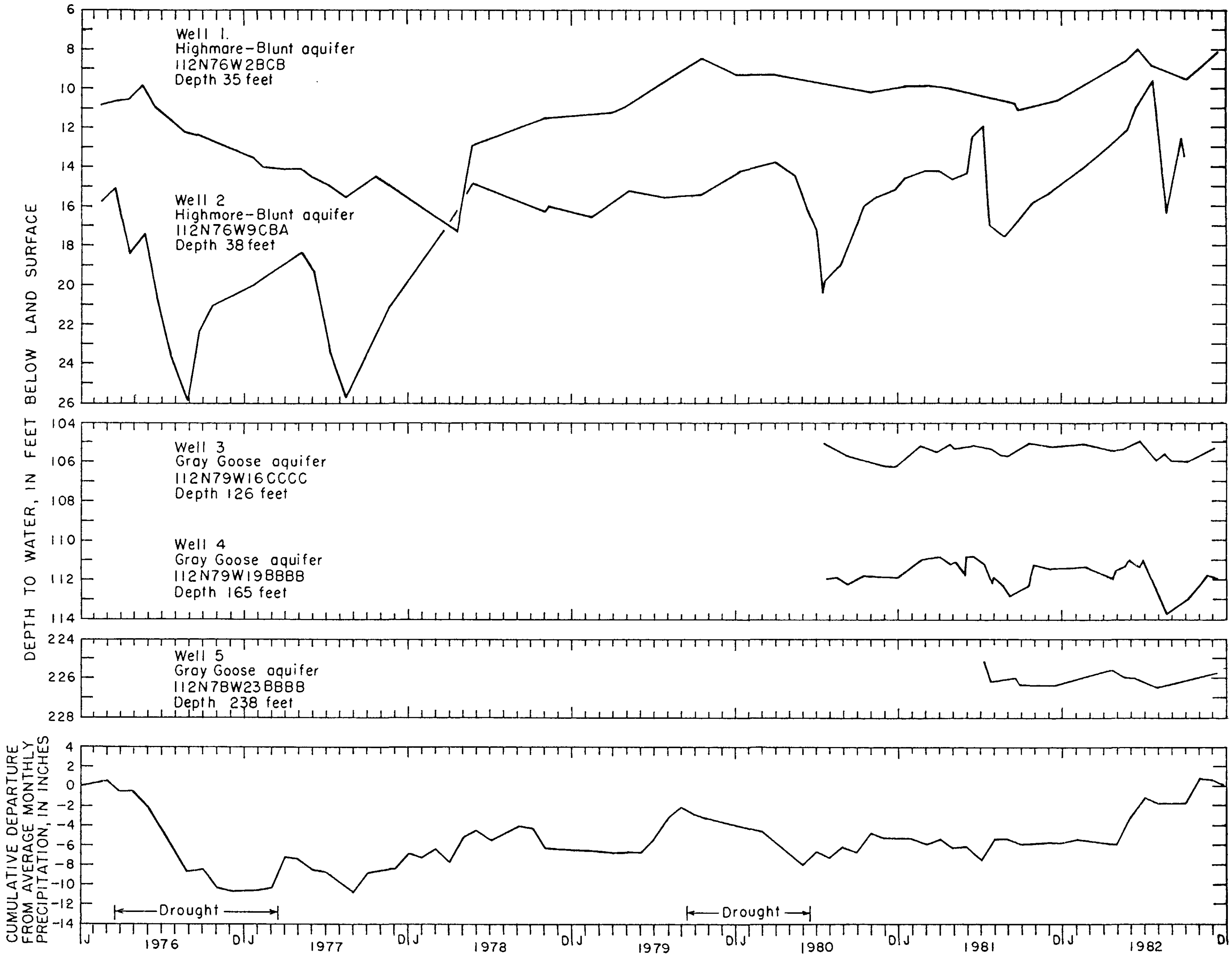

Figure 12.--Water-level changes in wells completed in glacial aquifers and cumulative departure from average monthly precipitation at Blunt, 1976-82. (Base period for average precipitation, 1976-82.)

Lateral recharge induced from the river to the Pierre municipal wells probably averages about 2,200 acre-ft/yr. Average recharge was not estimated because there is little data on water-level fluctuations. The Missouri aquifer can supply many more wells because of the potential for recharge being induced from the river.

Highmore-Blunt Aquifer

The Highmore-Blunt aquifer, in northeastern Hughes County, is composed mostly of sand and gravel deposited as glacial outwash and alluvium. The aquifer underlies 40 mi^2 of the valley of Medicine Knoll Creek in T. 112 N., R. 74, 75, and 76 W. at depths of as much as 40 ft. The width of the aquifer increases from less than 1 mi in T. 112 N., R. 74 W. to 4 mi in T. 112 N., R. 76 W. The aquifer extends into Sully County on the north and Hyde County on the east (fig. 5). In Hyde County, the Highmore-Blunt aquifer was named the Highmore aquifer (Koch, 1980, fig. 17).

The aquifer is mostly unconfined and the upper 10 to 20 ft of the sand and gravel is unsaturated. The depth to water ranges from 8 to 30 ft. The aquifer is composed of fine to coarse sand and fine gravel with a maximum thickness of 45 ft, an average thickness of 20 ft, and an average hydraulic conductivity of about 200 ft/d. The transmissivity of the aquifer is estimated to average 4,000 ft^2/d. Where the saturated thickness exceeds 20 ft, large-capacity wells could yield from 20 to 500 gal/min.

Flow calculations for spring 1981 indicate that recharge to the aquifer averaged about 900 acre-ft/yr (0.4 in./yr). Water movement in the Highmore-Blunt aquifer in the eastern part of T. 112 N., R. 76 W. is at a rate of 200 ft/yr due to the 30-ft/mi slope of the potentiometric surface. Water moves westward from recharge areas in T. 112 N., R. 74, 75, and 76 W. and southwestward from areas north of the study area. The water discharges mostly by evapotranspiration along the valley of Medicine Knoll Creek in the western part of R. 76 W.

Water levels in two wells completed in the Highmore-Blunt aquifer had seasonal and long-term changes during 1976-82 (fig. 12). The water level in well 2 gradually rose 3 to 10 ft during the fall, winter, and spring because of decreased pumpage and increased recharge from precipitation. The water level in the well declined 6 to 8 ft during late spring and summer in most years due to pumpage from a nearby municipal well. The decline was much greater than the 1- or 2-ft decline measured in well 1 because the aquifer is confined at well 2 and unconfined at well 1. Drawdown of water level due to pumping is several times larger for confined than for unconfined aquifers because of the smaller storage coefficient of confined aquifers.

The hydrographs for both wells show long-term trends. The annual lowest or highest water level generally rose during 1977-82 because of increased precipitation and recharge after the severe drought of 1976. At Blunt during 1976, the cumulative departure from the 7-year mean monthly precipitation was nearly 11 inches less than average, but precipitation generally increased during the 6 subsequent years (fig. 12).

Chapelle Creek Aquifer

The Chapelle Creek aquifer is mostly a shallow, thin layer of glacial outwash sand and gravel and alluvium that underlies 20 mi^2 of Chapelle Creek and the outwash-mantled uplands that extend for 3 mi southeast of the creek in T. 110 N., R. 75 W. The aquifer on the uplands is 100 to 150 ft above the valley bottom and is mostly unsaturated during dry years. The aquifer has the potential, locally, for yielding more than 100 gal/min to large-capacity wells. A deeper unit of the aquifer lies at a depth of 100 to 122 ft at 109N75W3CBBB, but little is known of the extent or yield of this unit.

The greatest thickness of the aquifer and largest well yields occur near Chapelle Creek. A large-capacity well in the aquifer at 110N75W2ACDB is reported to be 25 ft deep, penetrate 17 ft of gravel, and yield at least 100 gal/min. Depths to water in wells along the creek range from 4 to 20 ft below land surface.

Minor Glacial Aquifers

A few minor glacial aquifers are present in the study area. For example, about 3 mi northeast of Pierre, a local aquifer at a depth of 91 ft is reported to be more than 40 ft thick at 111N78W20BBBA (fig. 8). Along some narrow creek valleys (fig. 3), thin deposits of sand and gravel occur at shallow depths. Well yields of at least 10 gal/min can be obtained locally from minor aquifers.

Effects of Aquifer Development

The effects of development of a large-capacity well on water levels can be estimated from aquifer transmissivity and a table showing theoretical water-level drawdown at several distances from a pumping well completed in an unconfined aquifer (table 4). For example, where the transmissivity of the Gray Goose aquifer is estimated to be 13,400 ft^2/d, the drawdown of the water level 500 ft from a well pumping 1,000 gal/min for 100 days would be 5 ft. If the transmissivity is about one-half of the estimated value or 7,000 ft^2/d, drawdown would be double the values shown in the table. Also, if the aquifer is not extensive and there is a nearby boundary of relatively impermeable till, the drawdown would be larger than indicated. Thus, the long-term yield of a well could be much less than 1,000 gal/min. Estimates of transmissivity can be made from an examination of aquifer materials from test holes and from aquifer tests. Aquifer tests include controlled pumping of a test well for several days and frequent measuring of water levels in several widely spaced observation wells; from the data so collected, transmissivity and storage coefficient of the aquifer can be calculated for the area at and near the pumped well.

Aquifer tests of 5 days duration were conducted in 1981 for three separate wells that were pumping about 800 gal/min from the Gray Goose aquifer. Data from these tests in T. 112 N., R. 80 W. show that there is a large change in the hydraulic properties of the aquifer within a distance of 1 mi or less. Estimates of the transmissivity of the aquifer range from 7,000 ft^2/d to 58,000 ft^2/d. Estimates of the average hydraulic conductivity range from 400 ft/d to 1,800 ft/d. Estimates of the storage coefficient range from 0.00001 (confined conditions) to 0.4 (specific yield for unconfined conditions). The wide range in these hydraulic properties suggest that the table of theoretical drawdowns (table 4) cannot be used to predict drawdowns everywhere in an aquifer.

Another possible effect of development of an aquifer is a gradual change in the quality of water due to induced recharge of water of different quality by intensive pumping. Pumping induces recharge by lowering water levels below the water level in adjacent formations and surface-water bodies. There is insufficient data to determine whether or not there has been a gradual change in the quality of water yielded by wells in extensively pumped areas.

Table 4.--Theoretical drawdowns for an unconfined aquifer

[Theoretical drawdown, in feet, at various distances from a well pumping continuously at 1,000 gallons per minute from an unconfined glacial aquifer.1/ The aquifer is assumed to be infinite in areal extent.2/]

(Transmissivity = 13,400 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/ Drawdown for confined aquifers may be much larger than for unconfined aquifers because of a much smaller coefficient of storage and because the effects of nearby relatively impermeable boundaries are greater under confined conditions.

2/ Drawdown may be much greater than shown because of nearby relatively impermeable boundaries.

Bedrock Aquifers

Three major bedrock aquifers, composed mostly of sandstone, siltstone, and shale, or limestone and dolomite, underlie the county and extend throughout much of South Dakota and into adjacent States. In Hughes County, these aquifers store about 80 million acre-ft of water, and can supply wells that yield as much as 1,600 gal/min (table 3). The uppermost bedrock aquifer is in the Dakota Formation. The lower two bedrock aquifers are in the Inyan Kara Group and Sundance Formation and the Minnelusa Formation and Madison Group. The Inyan Kara-Sundance aquifer is separated from the Dakota by as much as 200 ft of the Skull Creek Shale (table 1). The maximum thicknesses of the aquifers are 430 ft for the Dakota, 180 ft for the Inyan Kara-Sundance, and 880 ft for the Minnelusa-Madison. Below the base of the Madison Group is as much as 320 ft of rocks ranging in age from Devonian to Precambrian. These rocks probably contain aquifers that are hydraulically connected to the Madison Group. Below the lowest aquifer, the "basal wash," is basement rock, consisting of relatively impermeable quartzite or igneous and metamorphic rock of Precambrian age.

Dakota Aquifer

The Dakota aquifer, the uppermost bedrock aquifer in the county, is composed of as much as 430 ft of very fine to medium-grained sandstone interbedded with shale. The aquifer is overlain by about 1,000 ft of relatively impermeable shale. The Dakota is separated from underlying aquifers by 30 to 200 ft of shale. The Dakota slopes generally north and northwest at 5 to 10 ft/mi from an altitude of 634 ft above sea level in T. 109 N., R. 76 W. to an altitude of 295 ft in T. 112 N., R. 80 W. (fig. 13). Aquifer thickness averages 300 ft and ranges from 240 to 430 ft.

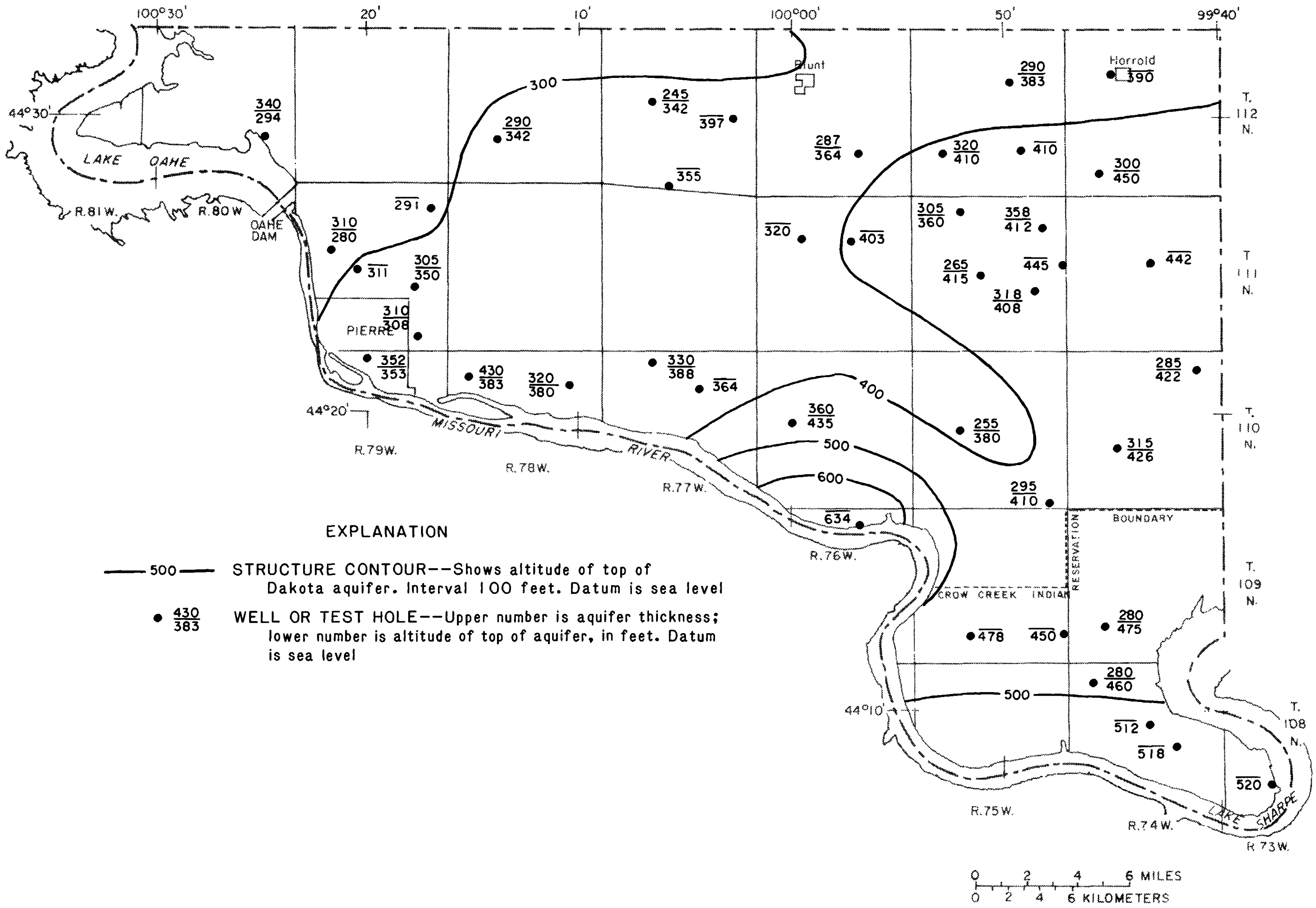

Figure 13.--Thickness and structure contours of the Dakota aquifer.

The aquifer generally yields 2 to 500 gal/min of water to pumping or flowing wells completed at depths of from 800 to 1,800 ft. A few wells have larger flows. For example, the old, 1,350-ft well at the State capitol in Pierre is reported to flow about 1,600 gal/min. The unusually large yield of this old well appears to be caused by the well intersecting a deep fracture that provides hydraulic connection to underlying, high-pressure aquifers. A well drilled in 1944 about 500 ft north of the first well was reported to yield only 200 gal/min.

Although no wells in the Dakota aquifer have been tested in the study area, hydraulic properties of the aquifer can be estimated based on the effects of development that are described below for the city of Pierre. A transmissivity of 2,700 ft^2/d is estimated from discharge and artesian-head drawdowns occurring during 1880-1915, using the standard method of analysis for extensive artesian aquifers (Theis, 1935). The estimated discharge of 9,000 gal/min within an area of about 2 mi^2 and the estimated drawdown of 400 ft was analyzed as if it occurred at a single well. The analysis indicated that the average hydraulic conductivity for the 350-ft thickness of the aquifer was about 8 ft/d, a value that is typical of very fine to medium-grained sand.

The altitude of the potentiometric surface of the Dakota aquifer during 1971-81 ranged from 1,641 ft in the southeast to 1,744 ft above sea level in the northern part of the county (fig. 14). The surface is about 200 ft below the potentiometric surface shown by Darton (1909) because of withdrawals through flowing wells (Schoon, 1971, fig. 15). The potentiometric surface generally is irregular, and hummocky, the result of local differences in the rate of withdrawal and of differences in artesian head between the upper and lower parts of the aquifer. Locally, the aquifer may be slightly repressurized by leakage from wells that are completed in deeper, higher-pressure aquifers. A northwest-trending trough in the potentiometric surface follows the general trend of the Missouri River trench and has been caused by the discharge of many flowing wells in the valley.

Recharge of the Dakota aquifer principally is by upward leakage from deeper aquifers (Swenson, 1968, p. 174; Schoon, 1971, p. 18; Howells, 1974). Discharge principally is through about 60 pumped and flowing wells. Recharge by upward leakage through the relatively impermeable Skull Creek Shale can be estimated as the product of the vertical hydraulic conductivity of the shale of 1.3×10^{-6} ft/d (Bredehoeft and others, 1983, p. 20) and the 400-ft difference in hydraulic head between the Dakota and the underlying Inyan Kara-Sundance aquifer, divided by the estimated 40-ft average thickness of the shale. The leakage estimate is 1.3×10^{-5} ft/d, or 2,400 acre-ft/yr for the county area of 784 mi^2. A small quantity of water also recharges the Dakota by leakage through drill holes that penetrate deeper aquifers. Discharge through wells is estimated to be 3,900 acre-ft/yr (table 2). The difference between recharge and discharge, 1,500 acre-ft/yr, is obtained from a decrease of storage (50 acre-ft/yr) and an inflow from the north that is greater than the outflow to the south and east.

The effect of development of the Dakota aquifer on its artesian head has been very large. From 1880 to 1900, during the early development of the Dakota, the artesian pressure was reported to be 165 lbs/in^2 for a 1,192-ft-deep well at Pierre and 27 lb/in^2 for a 1,453-ft-deep well at Harrold. Thus, the initial potentiometric surface at Pierre was at an altitude of at least 1,820 ft and at Harrold was at least 1,862 ft above sea level (Darton, 1896, p. 630). As wells were drilled deeper into the Dakota, higher pressures were reported. A 1,256-ft-deep well at Pierre was reported to have a

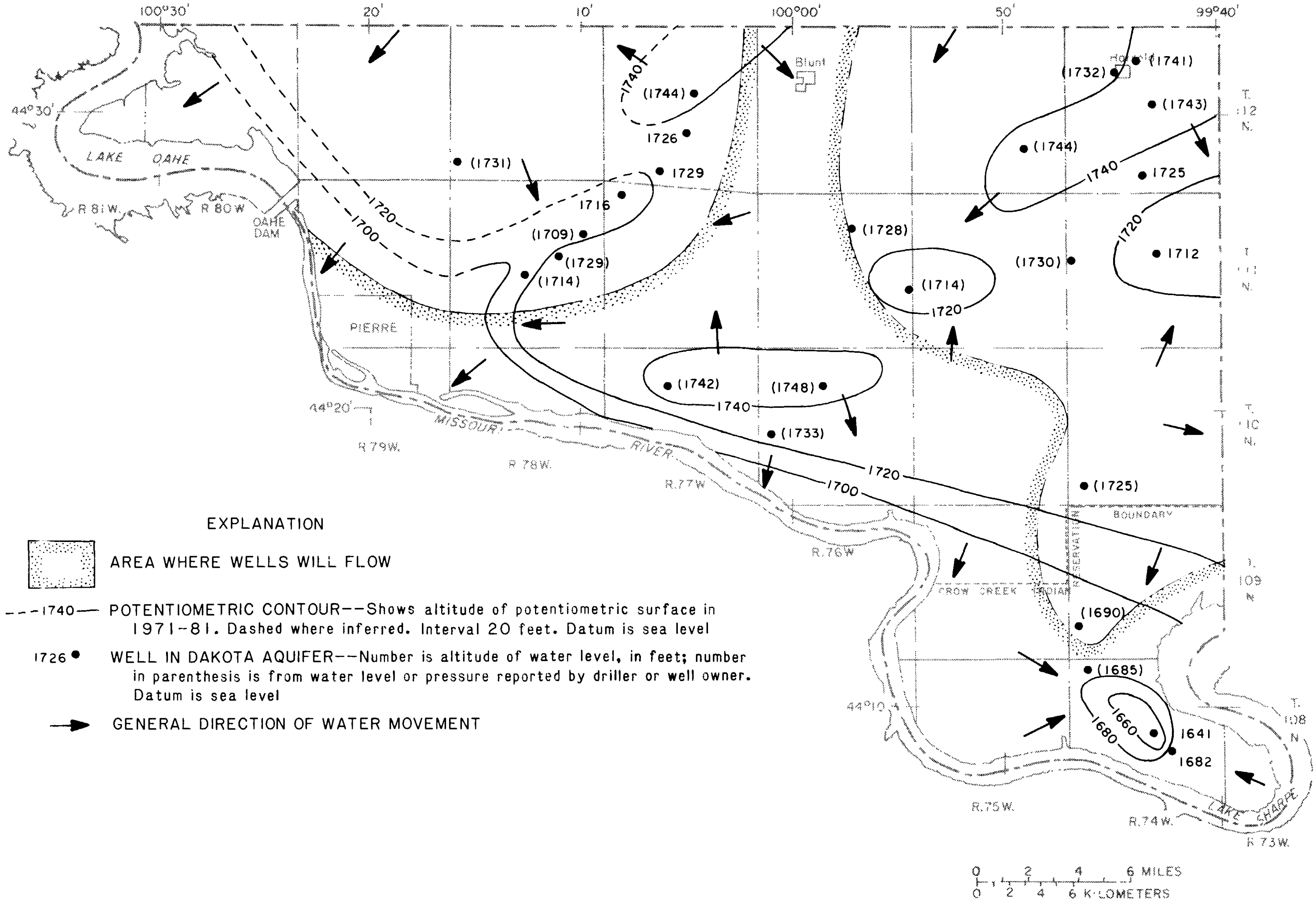

Figure 14.--Potentiometric contours of the Dakota aquifer.

pressure of 210 lb/in^2 and to yield a large flow of water that contained gas (Darton, 1909, p. 108). The potentiometric surface for the lower part of the Dakota aquifer was about 100 ft above that for the upper part, or 1,900 to 2,000 ft above sea level.

In 1910, a 1,350-ft-deep well completed near the State capitol in Pierre was reported to have a pressure of 165 lb/in^2, a water flow of 2,200 gal/min, and a flow of methane gas of 59 ft^3/min (South Dakota State Engineer, 1916, p. 227). Because of the very large flow of water, the pressure in the well at the capitol decreased rapidly. By 1915, the pressure at the capitol well had decreased to 30 lb/in^2 and the gas flow had decreased to 11 ft^3/min. The flow of water also had decreased greatly. There were at least 25 wells in the county that were completed in the Dakota aquifer by 1912. These wells had a combined flow of more than 10,000 gal/min (South Dakota State Engineer, 1912, p. 123) and at least 90 percent of this flow probably was in or near Pierre. Thus, between 1880 and 1915, the altitude of the potentiometric surface for the lower part of the Dakota aquifer at Pierre had declined approximately 400 ft to an altitude of about 1,530 ft.

Since 1915, artesian pressure probably has partially recovered, at least near Pierre, because many of the old flowing wells have collapsed. However, the depression of the potentiometric surface has expanded across the county, lowering that surface an average of 200 ft between 1880 and 1980. During 1970-80, the rate of decline was about 1 ft/yr. If this rate of decline continues, it may no longer be possible to obtain flowing wells in the Dakota aquifer in all upland areas of the county by 2100.

Another possible effect of development of the Dakota aquifer is a gradual change in the quality of its water as the artesian pressure is decreased by large withdrawals through wells. The pressure decrease can induce recharge of extremely hard water from the underlying, high-pressure Inyan Kara-Sundance aquifer. Existing data is inadequate to detect any change in quality of water from the Dakota.

Inyan Kara-Sundance Aquifer

The Inyan Kara-Sundance aquifer is composed of as much as 180 ft of fine- to medium-grained sandstone, siltstone, and shale (table 1). The thickness of the aquifer averages 130 ft but locally is only 80 ft. The two formations that comprise the aquifer have hydraulic connection across beds of sandy shale and siltstone that locally are as much as 50 ft thick. The aquifer also is in contact with the underlying Minnelusa-Madison aquifer in the southern part of the county where both aquifers yield water of similar chemical composition. The top of the Inyan Kara-Sundance aquifer slopes northwest at about 6 ft/mi (fig. 15). The altitude of the top of the aquifer decreases from about 150 ft above sea level in the southeast to more than 200 ft below sea level in the northwest part of the county.

The Inyan Kara-Sundance aquifer yields 20 to 60 gal/min of water to flowing wells at depths of from 1,200 to 2,000 ft below land surface. Shut-in pressures for wells range from 86 to 200 lb/in^2 at land surface.

The altitude of the potentiometric surface of the Inyan Kara-Sundance aquifer is estimated to range from about 2,100 ft in the southeast to more than 2,500 ft locally near Pierre in T. 111 N., R. 79 W. (fig. 16). The potentiometric surface slopes generally southward at 10 to 20 ft/mi, although there are several irregularities in the surface. Mounds in the surface may be caused by locally large leakage from the underlying, higher-pressure Minnelusa-Madison aquifer, apparently due to the absence of relatively impermeable shale beds between the aquifers.

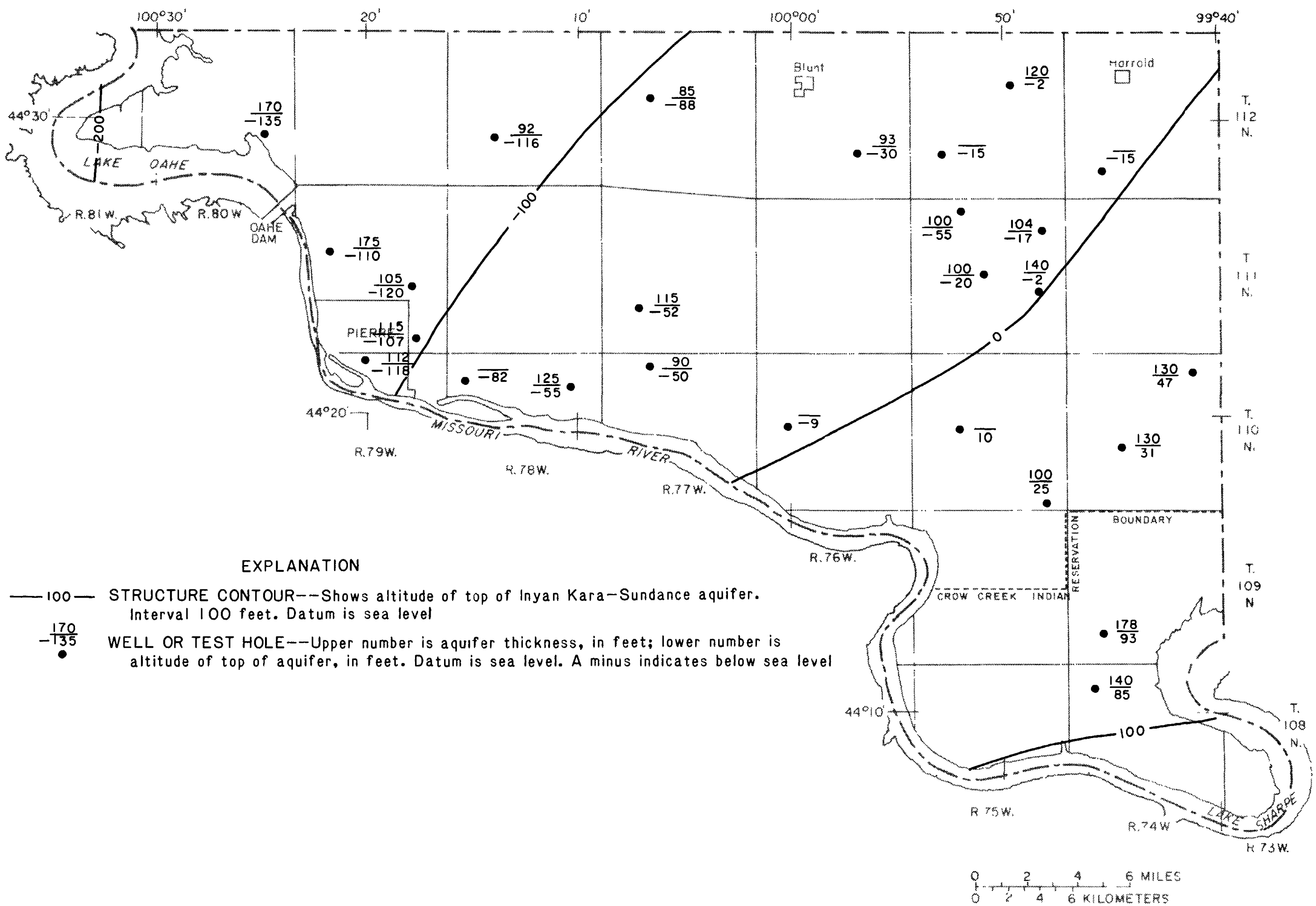

Figure 15.--Thickness and structure contours of the Inyan Kara-Sundance aquifer.

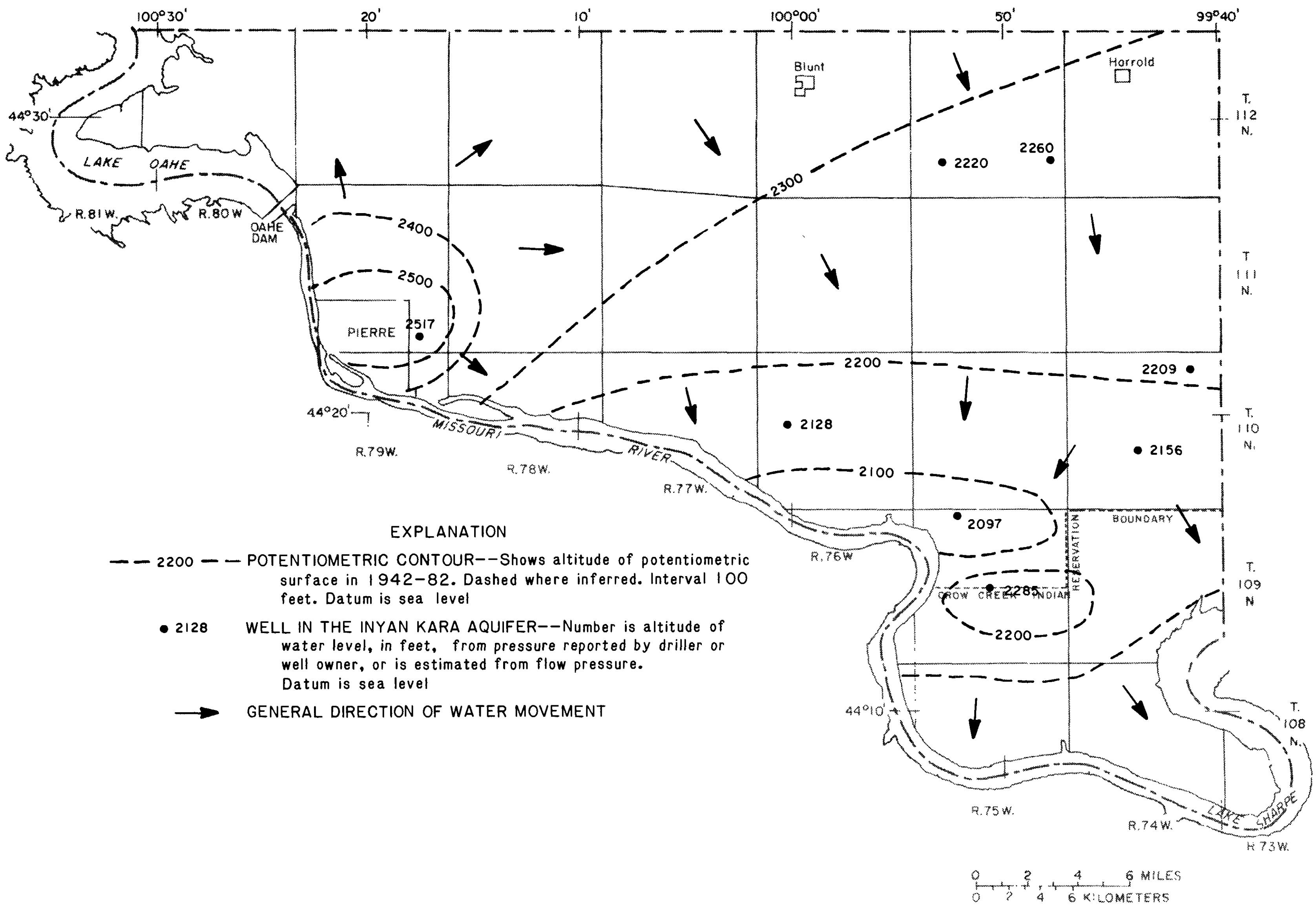

Figure 16.--Potentiometric contours of the Inyan Kara-Sundance aquifer.

Recharge of the Inyan Kara-Sundance is mostly by natural upward leakage. Leakage through the relatively impermeable shale in the Minnelusa Formation is calculated as the product of the estimated vertical hydraulic conductivity of the shale (1×10^{-4} ft/d, Bredehoeft and others, 1983, p. 20) and the estimated average difference in hydraulic head between the Inyan Kara-Sundance and Minnelusa-Madison aquifers (200 ft), divided by the estimated 20-ft average thickness of the shale. The leakage estimate is 1×10^{-3} ft/d, or 180,000 acre-ft/yr for the county. Discharge through 15 wells in the Inyan Kara-Sundance is estimated to total only 1,210 acre-ft/yr. The large estimated excess of recharge compared to discharge indicates that there must be a large outflow to the south and southeast.

Effect of development of the Inyan Kara-Sundance aquifer is large because of the large leakage upward due to development of the Dakota aquifer. The potentiometric surface of the Inyan Kara-Sundance probably has declined 150 to 300 ft since the development of these bedrock aquifers began in the 1880's.

Minnelusa-Madison Aquifer

The Minnelusa-Madison aquifer is composed of an average of 400 ft of sandstone, limestone, and dolomite. The aquifer thickness ranges from 70 ft in the southeast to 880 ft in the northwest. In the northern part of the county, the aquifer probably is hydraulically connected with as much as 320 ft of dolomite and sandstone of older rock units that occur between the Madison Group and the relatively impermeable quartzite or granite basement rock that is the base of the hydrologic system (table 1). The aquifer slopes generally north and northwest at 5 to 10 ft/mi (fig. 17). The altitude of the top of the aquifer decreases from about 50 ft above sea level in the southeast to more than 300 ft below sea level in the northwest part of the county.

The aquifer yields 50 to 500 gal/min of water to high-pressure wells at depths of from 1,800 to 2,600 ft below land surface. Shut-in pressures range from 134 to 485 lb/in^2 at land surface. The maximum pressure was measured in a 2,176-ft-deep well at Pierre in 1979. Pressures north and east of Pierre probably will be less because the land surface is higher and because of friction losses of hydraulic head as the water flows eastward in the aquifer. The altitude of the potentiometric surface is estimated to range from about 2,400 ft in the southeast part of the county to more than 2,500 ft above sea level locally in the west (fig. 18). The potentiometric surface is inferred to have a general eastward slope of about 5 ft/mi. Some of the estimates of the altitude probably are low because the wells are open to and lose pressure to the overlying Inyan Kara-Sundance aquifer.

Recharge of the Minnelusa-Madison aquifer is from precipitation and from streamflow where the aquifer crops out in the Black Hills of western South Dakota (Swenson, 1968, p. 174; Schoon, 1971, p. 24). Discharge is through flowing wells and by leakage upward into the Inyan Kara-Sundance aquifer. Discharge by 23 wells in the study area is estimated to total 3,040 acre-ft/yr.

Effects of increased withdrawal from the aquifer probably will be similar to those discussed for the Dakota aquifer. The shut-in pressure for a geothermal well completed in the Minnelusa-Madison aquifer in Pierre decreased from 485 to 420 lb/in^2 from 1979 to 1981; accompanied by a hydraulic-head decline of 150 ft. During 1981-82, however, no decrease in pressure in the well was observed. This was probably because the flow of the well was greatly restricted by a control valve when the water was not being used for heating St. Mary's Hospital.

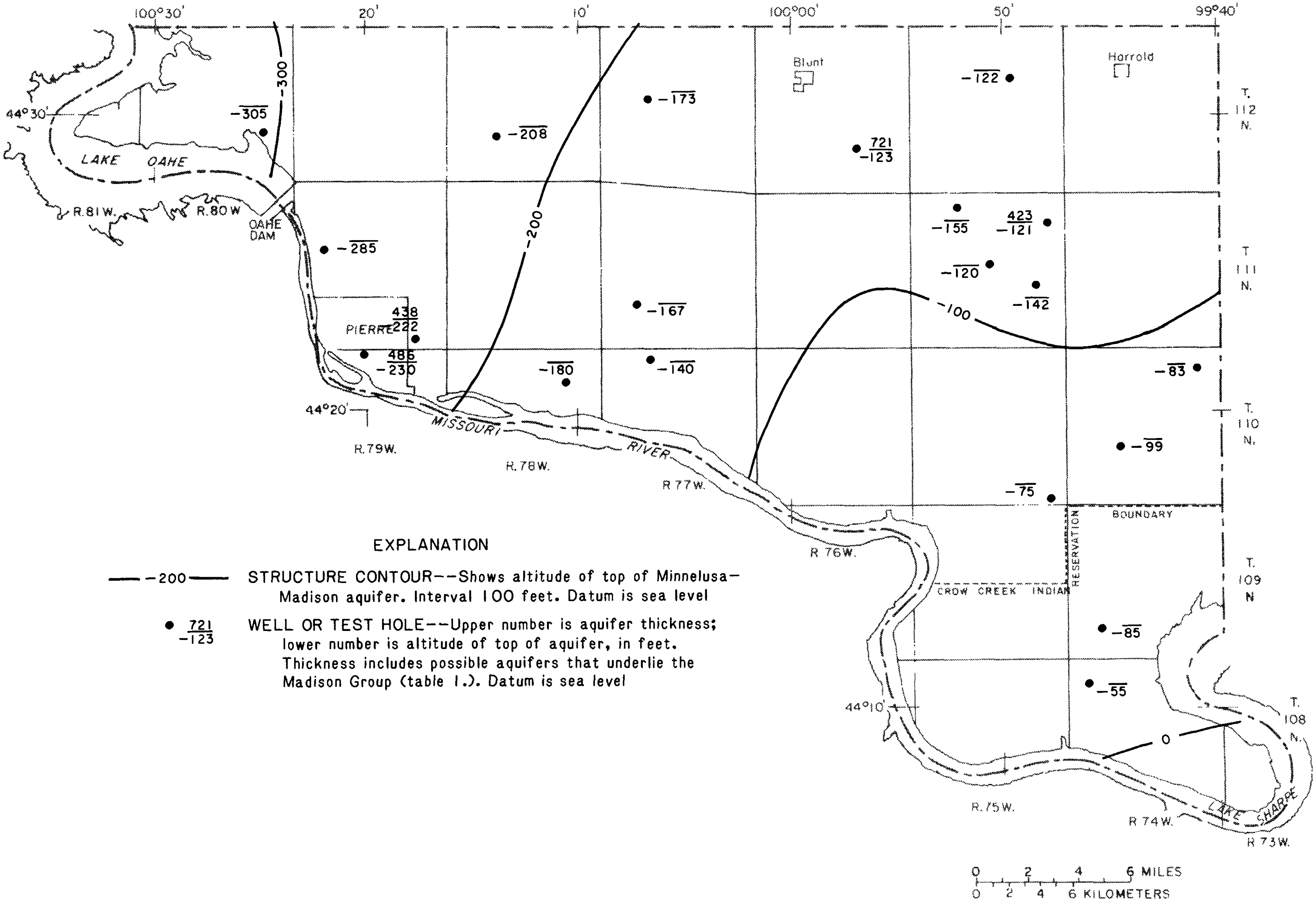

Figure 17.--Thickness and structure contours of the Minnelusa-Madison aquifer.

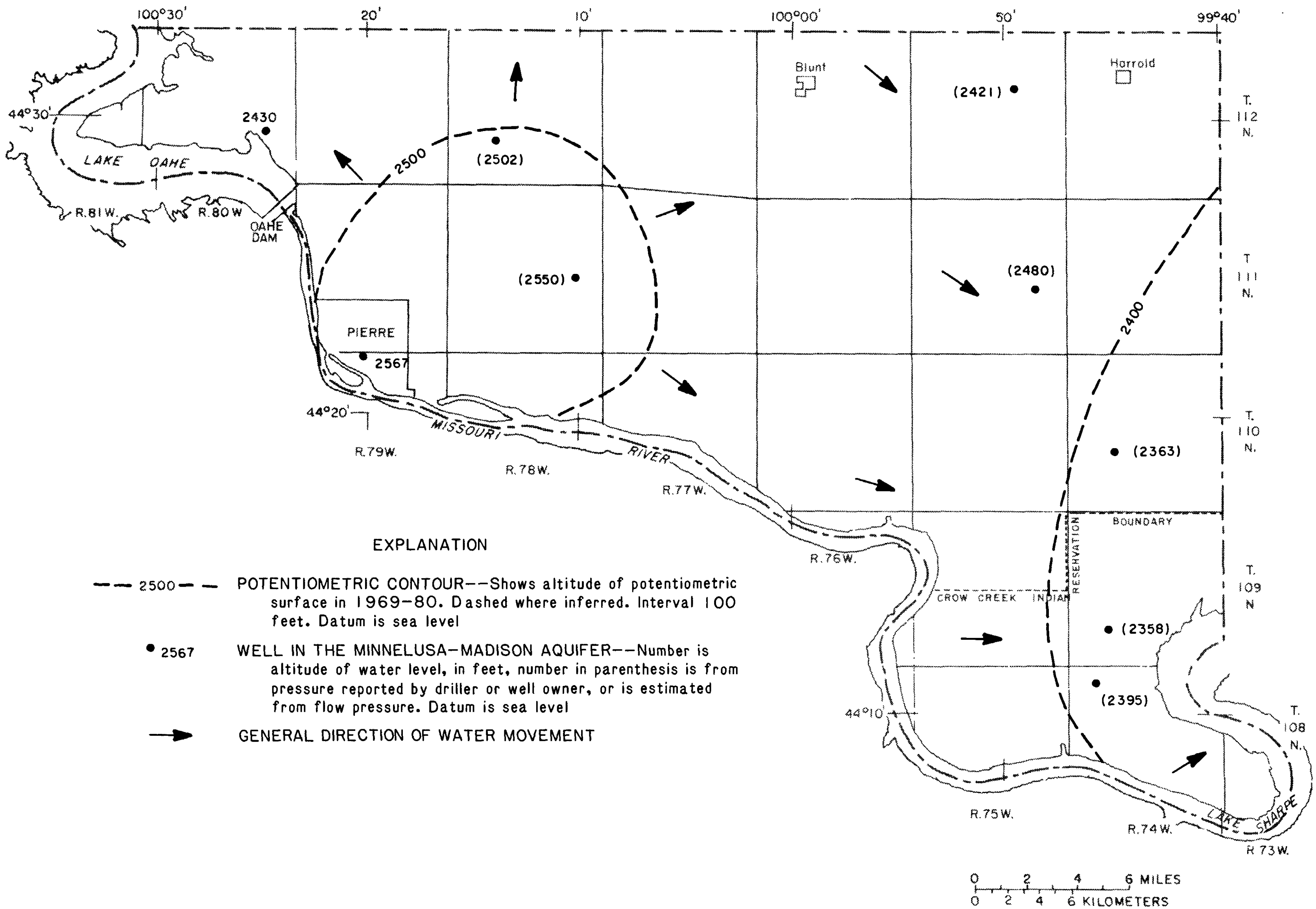

Figure 18.--Potentiometric contours of the Minnelusa-Madison aquifer.

WATER QUALITY

Surface water in the Missouri River has concentrations of dissolved solids of less than 1,000 mg/L (milligrams per liter). Such water is classified as fresh. Most of the ground water is classified as slightly saline (1,000 to 3,000 mg/L dissolved solids). Calcium, magnesium, sodium, bicarbonate, and sulfate compose more than 90 percent by weight of the dissolved minerals in the Missouri River and ground water (table 5). Most of the ground water has a hardness of more than 180 mg/L and is classified as very hard.

Water from the Gray Goose aquifer generally is slightly saline, whereas that from the Missouri and Highmore-Blunt aquifers is fresh to slightly saline. Water from glacial aquifers has concentrations of dissolved solids that average about 1,800 mg/L but range from less than 500 to more than 5,200 mg/L. Water hardness averages 900 mg/L but ranges from 110 mg/L to at least 3,600 mg/L. Most of the glacial aquifers have one or more areas where the hardness of the water exceeds 1,000 mg/L.

The quality of water can change greatly in a short distance within a glacial aquifer. Most of this change in quality probably is due to areal differences in the rate of recharge. For example, aquifers that are within a few tens of feet of the surface and that are recharged through sand and permeable soil tend to yield water with less-than-average concentrations of dissolved solids (table 5, samples 9, 14, 15, 18, 19, and 20), whereas water that recharges aquifers below depths of 50 ft tends to dissolve much calcium and sulfate from gypsum fragments and increase in dissolved solids and hardness as it slowly infiltrates downward through relatively impermeable till. Between 2 adjacent wells 160 and 212 ft deep, the concentration of dissolved solids increased with depth from about 1,200 to 3,300 mg/L, and the hardness increased from 460 to 2,100 mg/L within a depth interval of 52 ft (table 5, sample 7).

There are some exceptions to the above generalizations. Some shallow wells yield very mineralized water due to concentration by evapotranspiration from a shallow water table (table 9, samples 16, 21, and 24). Many wells completed in aquifers underlying thick till deposits yield water having less-than-average hardness and dissolved-solids concentrations (table 5, samples 6, 8, 12, and 13). This may be due to recharge rates increasing because of fractures in the overlying till. This would decrease the contact time for solution of minerals. In contrast, some wells yield mineralized water that has a small concentration of hardness (table 5, samples 22 and 23). The small hardness indicates that the aquifer either is being recharged by soft water from adjacent shale bedrock or recharge water is being softened by base exchange with clay or shale fragments in the aquifer.

Water from bedrock aquifers is slightly saline and has concentrations of dissolved solids that average about 2,000 mg/L but range from 1,500 to 3,490 mg/L. Average hardness of the water is only about 200 mg/L for the Dakota aquifer, but is about 1,400 mg/L for the underlying aquifers. The extremely large concentrations of hardness in water from the Inyan Kara-Sundance and Minnelusa-Madison aquifers is caused by large concentrations of dissolved calcium, magnesium, and sulfate. These constituents were leached from carbonate and sulfate minerals during the long time that the water flowed through the limestone aquifers from recharge areas in the Black Hills (Busby and others, 1983, p. 16). The relatively small concentrations of hardness in water from the Dakota may be due to base-exchange softening of recharge water as it seeps upward from high-pressure aquifers through 30 to 200 ft of shale.

Table 5 begins on next page

Table 5.--Selected chemical analyses of water

[Analyses by South Dakota Geological Survey Laboratory unless otherwise noted. Reported in milligrams per liter (mg/L) except as indicated. One milligram per liter is approximately equal to 1 part per million. One microgram per liter (ug/L) is approximately equal to 1 part per billion]

Sample number	Location	Date	Well depth (feet)	Use of water	Temperature (°C)	Silica (SiO_2)	Iron (Fe) (µg/L)	Manganese (Mn) (µg/L)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)
				SURFACE WATER									
				Missouri River									
1	Lake Oahe, near dam	2-12-79	--	1/ 2/	--	--	80	6	--	26	77	5.5	220
2	Lake Oahe, near dam	8-14-79	--	1/ 2/	--	--	240	70	--	56	70	5.0	200
3	River, at Pierre	1-18-82	--	3/	1.0	4.7	<10	2	61	26	82	4.5	210
4	River, at Pierre	7-26-82	--	3/	17.5	4.2	< 3	7	61	23	73	4.7	210
				GLACIAL AQUIFERS									
				Gray Goose aquifer									
5	111N77W24DCDA	9-18-81	80	Domestic	--	--	100	990	110	24	460	13	600
6	112N78W26ADAD	8-25-81	280	Stock	--	--	700	1,300	110	29	380	16	650
7	112N79W14CCDB	8-25-81	212	Domestic	11.0	--	20	290	600	150	150	16	420
8	112N79W21BBCB	10-20-81	136	Domestic	--	--	640	1,100	160	52	250	21	900
9	112N80W 1CCDD	8-20-81	97	Irrigation	11.5	--	1,100	870	120	34	83	9.5	490
10	112N80W 3ACBB	8-26-81	115	Irrigation	11.0	--	780	1,800	310	64	6.0	8.4	330
11	112N80W 4BDBC	8-26-81	84	Irrigation	11.0	--	10	460	790	25	120	14	360
12	112N80W13BBDD	8-21-81	180	Irrigation	13.0	--	970	1,900	170	48	170	19	620
13	112N80W13DDAD	10- 7-81	146	Domestic	12.0	--	940	1,100	120	24	60	10	440
				Missouri aquifer									
14	5N31E34ABBA	10- 2-81	59	Municipal	11.0	--	140	2,300	79	24	87	4.4	240
15	110N79W 5ABCC	10- 2-81	60	Municipal 3/	11.9	24	120	--	73	29	160	5.8	280
16	110N78W16AACB	9-18-81	50	Domestic	13.3	--	5,400	1,600	290	78	480	12	550
17	108N74W10BCCD	6- 9-70	91	Domestic 3/	12.0	31	3,000	1,300	220	59	160	25	800
				Highmore-Blunt aquifer									
18	112N74W16BADA	9-18-81	45	Municipal	--	--	5,200	1,200	100	31	69	8.5	440
19	112N76W 3DABA	8-21-81	40	Irrigation	9.0	--	90	2,300	200	74	190	11	630
20	112N76W 9BCCD	8-20-81	72	Municipal	11.0	--	100	1,900	190	65	87	8.2	280
				Chapelle Creek aquifer									
21	110N75W 2ACCA	8-24-81	22	Domestic	11.9	--	700	250	240	110	210	11	420
				Minor aquifers									
22	111N78W18DCCC	9- 2-81	93	Domestic	13.0	--	40	200	66	13	650	10	630
23	111N79W11ADDA	9- 2-81	148	Domestic	13.0	--	100	220	33	7.0	390	7.7	630
24	112N81W22DACC	10- 2-81	66	Unused	--	--	≤10	30	640	490	270	13	290

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate plus nitrite (dissolved as N)	Orthophosphorus (dissolved as P)	Boron (B) (μg/L)	Dissolved solids: Residue at 180°C	Dissolved solids: Calculated	Hardness: Calcium, Magnesium	Hardness: Noncarbonate	Percent sodium	Sodium-adsorption ratio (SAR)	Residual sodium carbonate (RSC)	Specific conductance (microsiemens per centimeter at 25° Celsius)	pH (units)
--	230	13	0.6	--	0.01	190	--	--	260	--	--	--	--	--	--
--	210	10	--	--	.03	200	--	--	240	--	--	--	--	--	--
--	250	10	.5	0.15	--	--	530	541	260	89	40	2.3	--	800	8.5
--	230	10	.5	<.1	--	--	530	512	250	71	39	2.1	--	790	7.9
--	650	160	.4	.2	--	1,200	1,800	--	360	--	73	11	5.2	2,650	7.3
--	540	42	.3	.1	--	1,100	1,060	--	380	--	67	8.4	6.0	2,050	7.5
--	1,700	210	.2	44	--	330	3,300	--	2,100	--	13	1.4	.0	3,800	7.1
--	370	55	.2	6.4	--	680	1,360	--	620	--	46	4.4	4.8	2,150	6.7
--	140	22	.4	.1	--	150	750	--	430	--	29	1.7	.0	1,100	7.4
--	750	30	.4	.4	--	180	1,460	--	1,000	--	1.2	.1	.0	1,750	6.8
--	1,900	20	.2	75	--	--	3,870	--	2,100	--	11	1.1	.0	3,950	6.7
--	380	22	.3	.1	--	560	1,260	--	620	--	36	3.0	.0	1,700	7.0
--	96	6.0	.4	.1	--	360	542	538	390	--	25	1.3	.0	860	6.9
--	250	12	.4	<.1	--	190	565	--	300	--	39	2.2	.0	850	7.3
--	300	89	.5	.1	--	200	--	821	300	72	53	4.4	.0	1,290	7.3
--	1,400	36	.6	.1	--	370	2,600	--	1,000	--	50	6.5	.0	3,200	7.4
--	490	9.5	.0	.1	--	710	1,460	1,390	790	140	29	2.4	.0	1,890	7.8
--	160	13	.1	.1	--	170	540	--	380	--	28	1.5	.0	950	7.2
--	690	38	.1	.6	--	210	1,570	--	800	--	34	2.9	.0	2,050	7.7
--	260	280	.2	.1	--	210	1,300	--	740	--	20	1.4	.0	1,800	7.4
--	1,000	31	.4	.1	--	250	1,940	--	1,030	--	31	2.9	.0	2,380	7.1
--	880	190	.2	.2	--	1,200	2,020	--	220	--	86	19	12	3,200	8.1
--	36	260	.4	.1	--	1,800	1,040	--	110	--	88	16	16	1,840	8.0
--	3,100	97	.3	62	--	200	5,240	--	3,600	--	14	2.0	.0	5,200	7.2

Sample number	Location	Date	Well depth (feet)	Use of water	Temperature (°C)	Silica (SiO_2)	Iron (Fe) (µg/L)	Manganese (Mn) (µg/L)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)
					BEDROCK AQUIFERS								
					Dakota aquifer								
25	108N74W15CBDC	5-27-69	1,210	Stock 3/	22.2	12	200	80	65	17	450	16	220
26	108N75W14CCBB	5-27-69	1,180	Stock 3/	--	12	340	10	66	18	390	15	230
27	109N74W12DDBA	6- 9-70	1,100	Stock 3/	23.0	10	470	10	33	9.0	490	15	230
28	110N76W19BCBA	9-13-62	1,450	Stock 3/	34.4	17	650	10	54	19	780	20	460
29	110N79W 4BABD	8-25-82	1,350	Unused	34.0	--	190	10	31	14	1,300	20	690
30	111N76W10ACCA	8-25-82	1,525	Stock	--	--	50	30	18	12	810	15	460
31	111N78W14BCBA	6-21-63	1,538	Domestic 3/	29.4	21	2,800	120	110	43	590	23	410
32	112N74W 4DC	7- 2-80	1,460	Stock 3/	23.7	9.4	70	20	12	4.9	610	12	560
33	112N74W 8AADA	8-24-82	1,620	Domestic	--	--	400	50	72	25	1,000	19	620
					Inyan Kara-Sundance aquifer								
34	108N75W 2CCBB	8- 3-78	1,700	Stock 3/	27.3	13	2,600	70	410	90	83	20	170
35	110N75W17DCDD	9-15-81	1,600	Stock	--	--	1,900	220	430	90	100	20	160
36	111N79W23BACD	9- 1-81	2,040	Domestic	41.0	--	1,500	320	370	90	140	23	150
					Minnelusa-Madison aquifer								
37	110N74W 1CBCC	8-24-82	2,050	Stock	28.5	--	1,600	110	390	100	60	18	180
38	111N75W 5ACD	8- 2-78	2,065	Stock 3/	22.6	13	1,300	100	380	120	66	19	170
39	111N78W 2ADCD	8-31-81	2,120	Stock	41.0	--	50	10	480	94	65	20	160
40	112N75W10DAAA	7- 2-80	1,875	Stock 3/	29.6	13	1,300	60	430	95	50	17	180
41	112N77W17AADD	9- 1-81	2,020	Stock	41.0	--	510	60	480	98	66	20	160
42	112N80W23DDCA	8-25-82	2,205	Domestic	44.5	--	570	100	360	84	120	25	170
43	110N79W 4AAC	7-25-79	2,176	Heating 3/	41.7	24	180	40	420	100	56	21	190

1/ U.S. Army Corps of Engineers analysis.
2/ Total recoverable (dissolved and suspended).
3/ U.S. Geological Survey analysis.
< Signifies less than the number to the right.
≤ Signifies less than or equal to the number.

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate plus nitrite (dissolved as N)	Orthophosphorus (dissolved as P)	Boron (B) (µg/L)	Dissolved solids: Residue at 180°C	Dissolved solids: Calculated	Hardness: Calcium, Magnesium	Hardness: Noncarbonate	Percent sodium	Sodium-adsorption ratio (SAR)	Residual sodium carbonate (RSC)	Specific conductance (microsiemens per centimeter at 25° Celsius)	pH (units)
0.0	910	110	2.5	0.1	--	2,000	1,780	1,690	230	50	80	13	0.0	2,500	7.6
.0	700	140	2.2	.0	--	1,200	1,500	1,470	240	50	76	11	.0	2,200	8.0
.0	900	93	2.2	.1	--	1,900	1,680	1,670	120	0	89	20	1.4	2,420	7.7
.0	.3	1,100	1.3	.4	--	3,700	2,260	2,240	210	0	88	23	3.3	4,090	7.5
--	5.0	1,800	1.1	<.1	--	2,300	3,490	--	140	--	95	50	17	6,300	7.3
--	8.0	1,100	1.6	<.1	--	2,100	2,150	--	93	--	94	37	11	4,100	8.1
.0	290	830	2.5	.0	--	2,600	2,130	2,120	460	120	72	12	.0	3,610	7.2
--	250	510	4.5	.0	<0.1	7,300	1,720	1,700	50	0	95	38	16	3,020	8.0
--	300	1,200	1.8	<.1	--	2,400	3,120	--	280	--	88	27	8.9	4,200	7.9
.0	1,200	110	3.2	--	.0	220	2,230	2,030	1,400	1,300	11	1.0	.0	2,350	7.0
--	1,100	170	2.8	.3	--	220	2,170	--	1,400	--	13	1.2	.0	2,400	7.1
--	1,300	88	2.7	<.1	--	150	2,050	--	1,300	--	19	1.7	.0	2,530	6.8
--	1,200	73	3.3	<.1	--	230	2,110	--	1,400	--	9	.7	.0	2,430	7.7
.0	1,300	80	3.2	--	.0	190	2,220	2,080	1,500	1,300	9	.8	.0	2,350	6.9
--	1,300	88	3.3	<.1	--	130	2,110	--	1,600	--	8	.7	.0	2,360	7.1
--	1,300	64	3.2	.0	<.1	170	2,180	2,060	1,500	1,300	7	.6	.0	2,400	7.2
--	1,400	90	3.2	<.1	--	150	2,100	--	1,600	--	8	.7	.0	2,450	7.0
--	1,200	84	3.2	<.1	--	260	2,040	--	1,200	--	17	1.5	.0	2,400	6.7
--	1,300	100	1.6	--	.0	180	2,240	2,130	1,500	1,300	8	.6	.0	2,420	6.9

The significance of the various chemical constituents in water is related to their concentrations and also to the use made of the water (table 6). Surface water in the Missouri River is of suitable quality for most uses but requires treatment before consumption by humans because of its susceptibility to pollution. Although most of the ground water is slightly saline, it also is suitable for many uses. Water from glacial aquifers and the Inyan Kara-Sundance and Minnelusa-Madison bedrock aquifers may need treatment to decrease the extremely large concentrations of hardness in the water.

Most ground water contains concentrations of dissolved iron in excess of 0.3 mg/L and concentrations of dissolved manganese in excess of 0.05 mg/L. This can cause staining of laundry, utensils, and plumbing fixtures and can accelerate the growth of certain kinds of bacteria. This growth in turn may cause deposition of iron and manganese minerals that can block the flow of water through well screens and in plumbing systems.

Water from some of the aquifers contains large concentrations of sulfate that may form scale deposits in plumbing, may have a laxative effect on some people, or may give the water a bitter taste. Water from the Dakota aquifer may have a salty taste because of large chloride and sodium concentrations. Water from bedrock aquifers characteristically has fluoride concentrations in excess of 1.5 mg/L.

Three chemical analyses of water from glacial aquifers showed concentrations of nitrate plus nitrite as nitrogen that exceeded 10 mg/L and might indicate pollution. This large concentration of nitrate in water from glacial aquifers beneath till may be caused by pollutants that contaminated the well during its construction or later entered the well from the land surface through openings in or along the casing. Large nitrate concentrations also may be a natural result of rapid infiltration locally through open fractures or joints in the till. Wells could be vulnerable to pollution from barnyards, feedlots, and septic tanks if the depth to the well screen is not sufficient to permit adsorption and filtration of pollutants from water recharging the aquifer.

The concentrations of other minor or trace elements were less than the mandatory limits except for chromium and selenium in 2 water samples. The chromium and selenium detected in water from two wells completed in glacial aquifers (table 7, samples 7 and 11) was associated with abnormally large concentrations of nitrate (table 5) and may indicate contamination of the wells from the land surface. There is no evidence, however, as to what levels of chromium can be tolerated by man for a lifetime without adverse affects on health (U.S. Environmental Protection Agency, 1977, p. 63).

The suitability of water for irrigation is determined primarily from its specific conductance and its concentration of dissolved sodium and sodium-adsorption ratio (SAR) (table 6). Much of the water from glacial aquifers in the study area meets South Dakota standards for irrigation when applied with regard to soil classes (fig. 19 and South Dakota Division of Conservation, no date). For example, water from one well completed in the Highmore-Blunt aquifer (sample 19) can be applied to soil class D1 because these are sandy or silty clay loams and clay loams that have more permeable materials at a depth of 40 inches or less. The permeable material allows salt to be leached from the root zone. Thus, this water also can be applied to soil that is more sandy and permeable than class D1. In contrast, water from one well completed in the Gray Goose aquifer (sample 8) has a relatively large adjusted SAR and can be applied to soil class B1 or A, loamy sands, sandy loams and sand. If such water were applied to

Table 6.--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 (1976, 1977). 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 (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 (Fe)	0.3 mg/L (recommended)	Forms rust-colored sediment; stains laundry, utensils, and fixtures reddish brown. Objectionable for food and beverage processing.
Manganese (Mn)	0.05 mg/L (recommended)	Causes gray or black stains on porcelain, enamel, and fabrics. Can promote growth of certain kinds of bacteria.
Calcium (Ca) and magnesium (Mg)		Cause most of the hardness and scale-forming properties of water (see hardness).
Sodium (Na) and potassium (K)		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 (HCO_3)		In combination with calcium and magnesium forms carbonate hardness.
Sulfate (SO_4)	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 (Cl)	250 mg/L (recommended)	Large concentrations increase the corrosiveness of water and, in combination with sodium, give water a salty taste.
Fluoride (F)	1.5 mg/L (mandatory)	Reduces incidence of tooth decay when optimum fluoride concentration is present in water consumed by children during the period of tooth calcification. Limit varies inversely with average annual maximum air temperature. Excessive concentrations of fluoride may cause mottling of teeth.
Nitrate (NO_3) (as N)	45 mg/L 10 mg/L (mandatory)	Concentrations greater than local average may indicate pollution by feed-lot runoff, sewage, or fertilizers. Concentrations greater than 45 mg/L may be injurious when used in feeding infants.
Boron (B)		Essential to plant growth, but may be toxic to crops when present in excessive concentrations in irrigation water. Sensitive plants may show damage when irrigation water contains more than 0.67 mg/L and even tolerant plants may be damaged when boron exceeds 2.0 mg/L.

Table 6.--Significance of chemical and physical properties of water--Continued

Constituent or property	Limit	Significance
Dissolved solids	500 mg/L (recommended)	The total of all dissolved mineral constituents, usually expressed in milligrams per liter or in parts per million of weight. 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 a flat taste.
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 (Na)		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.
Residual sodium carbonate (RSC)		The quantity expressed in milliequivalents per liter of carbonate and bicarbonate a water would contain after the removal of an equivalent quantity of calcium and magnesium. RSC is a measure of the "black alkali" hazard of water. Water having an RSC greater than 2.5 meq/L is not considered suitable for irrigation; an RSC of 1.25 to 2.5 meq/L is considered marginal; and an RSC of less than 1.25 meq/L is considered "probably safe" for irrigation.
Specific conductance		A measure of the ability of a unit cube of water to conduct an electrical current; varies with temperature, therefore reported at 25° Celsius. Values are reported in microsiemens per centimeter. 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 hydrogen 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 (Al)		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.

Table 6.--Significance of chemical and physical properties of water--Continued

Constituent or property	Limit	Significance
Arsenic (As)	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 (Ba)	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 (Br)		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 (Cd)	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 100 to 10,000 µg/L for 1 year caused liver and kidney damage; greater concentrations cause anemia, retarded growth, and death.
Chromium (Cr) 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 (Cu)	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 (I)		Essential and beneficial element in metabolism; deficiency can cause goiter.
Lead (Pb)	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 (Li)		Reported as probably beneficial in small concentrations (250 to 1,250 µg/L). Reportedly may help strengthen the cell wall and improve resistence to genetic damage and to disease. Lithium salts are used to treat certain types of psychosis.
Mercury (Hg)	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.

Table 6.--Significance of chemical and physical properties of water--Continued

Constituent or property	Limit	Significance
Molybdenum (Mo)		In minute concentrations, appears to be an essential nutrient for both plants and animals, but in large concentrations may be toxic.
Nickel (Ni)		Very toxic to some plants and animals. Toxicity for humans is believed to be very minimal.
Phosphate (PO_4)		Essential to plant growth. Concentrations greater than local average may indicate pollution by fertilizer seepage or sewage. Concentrations greater than 200 mg/L may have a laxative effect.
Selenium (Se)	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 effect changes in the insulin requirements of people with diabetes mellitus. Selenium is known to be a hazard in parts of South Dakota.
Silver (Ag)	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 (Sr)		Importance in human and animal nutrition is not know, but believed to be essential. Toxicity believed very minimal--no more than calcium.
Vanadium (V)		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 (Zn)	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 7 begins on next page

Table 7.--Trace elements in water

[Analyses by South Dakota Geological Survey Laboratory unless otherwise noted. Reported in micrograms per liter (µg/L). One microgram per liter is approximately equal to 1 part per billion]

Sample number (same as table 5)	Aluminum (Al)	Arsenic (As)	Barium (Ba)	Beryllium (Be)	Bromide (Br)	Cadmium (Cd)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)
				SURFACE WATER					
				Missouri River					
1	40	--	40	0	--	1.0	0	4	9
2	210	2	80	0	--	1.0	0	3	3
3	--	2	--	--	--	<1.0	<10	<3	3
4	--	2	--	--	--	<1.0	<10	<1	9
				GLACIAL AQUIFERS					
				Gray Goose aquifer					
5	--	--	--	--	--	--	--	--	--
6	--	3	--	--	--	<.5	<20	--	<20
7	--	2	--	--	--	<.5	140	--	--
8	--	1	--	--	--	<.5	<20	--	<20
9	--	--	--	--	--	--	--	--	--
10	--	3	--	--	--	<.5	<20	--	<20
11	--	0	--	--	--	<.5	140	--	20
12	--	--	--	--	--	--	--	--	--
13	--	--	--	--	--	--	--	--	--
				Missouri aquifer					
14	--	2	--	--	--	<.5	20	--	<20
15	20	--	--	--	500	--	0	--	--
16	--	10	--	--	--	.6	40	--	20
17	--	10	--	--	--	--	--	--	--
				Highmore-Blunt aquifer					
18	--	5	--	--	--	<.5	20	--	<20
19	--	0	--	--	--	.8	<20	--	<20
20	--	0	--	--	--	1.0	<20	--	<20
				Chapelle Creek aquifer					
21	--	--	--	--	--	--	--	--	--
				Minor aquifers					
22	--	--	--	--	--	--	--	--	--
23	--	--	--	--	--	--	--	--	--
24	--	--	--	--	--	--	--	--	--

Iodide (I)	Lead (Pb)	Lithium (Li)	Mercury (Hg)	Molybdenum (Mo)	Nickel (N)	Selenium (Se)	Silver (Ag)	Strontium (Sr)	Vanadium (V)	Zinc (Zn)
—	10	50	0.2	—	10	0	—	—	0.0	40
—	10	40	—	0	10	1	0	—	.0	20
—	3	—	.1	—	—	1	—	—	—	7
—	<1	—	<.1	—	—	1	—	—	—	12
—	—	250	—	—	—	—	2	—	—	—
—	<2	220	—	—	<20	<.2	2	—	—	10
—	<3	220	.0	—	<20	160	11	—	—	30
—	<2	190	.0	—	<20	<.2	4	—	—	400
—	—	60	—	—	—	—	—	—	—	—
—	<2	60	.0	—	<20	1	4	—	—	10
—	<2	170	.0	—	<20	34	12	—	—	30
—	—	140	—	—	—	—	—	—	—	—
—	—	70	—	—	—	—	—	—	—	—
—	<2	60	.0	—	<20	<.2	<2	—	—	5
10	—	—	.0	—	—	—	.0	—	—	5
—	<2	430	.0	—	<20	<.2	6	—	—	30
—	—	—	—	—	—	6	—	—	—	—
—	2	40	.0	—	<20	.6	3	—	—	10
—	<2	60	.0	—	<20	.9	4	—	—	70
—	3	80	.0	—	<20	<.2	4	—	—	60
—	—	17	—	—	—	—	—	—	—	—
—	—	290	—	—	—	—	—	—	—	—
—	—	190	—	—	—	—	—	—	—	—
—	—	200	—	—	—	—	—	—	—	—

Table 7.--Trace elements in water--Continued

Sample number (same as table 5)	Aluminum (Al)	Arsenic (As)	Barium (Ba)	Beryllium (Be)	Bromide (Br)	Cadmium (Cd)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)
				BEDROCK AQUIFERS					
				Dakota aquifer					
25	--	--	--	--	--	--	--	--	--
26	--	--	--	--	--	0	0	0	0
27	--	--	--	--	--	--	--	--	--
28	--	--	--	--	--	--	--	--	--
29	--	<0.2	--	--	--	<.5	<20	--	<20
30	--	--	--	--	--	--	--	--	--
31	--	--	--	--	--	--	--	--	--
32	0	1	0	--	4,200	0	0	--	3
33	--	--	--	--	--	--	--	--	--
				Inyan Kara-Sundance aquifer					
34	0	2	200	--	400	0	10	--	0
35	--	--	--	--	--	--	--	--	--
36	--	1	--	--	--	.6	60	--	≤20
				Minnelusa-Madison aquifer					
37	--	1	--	--	--	.7	60	--	20
38	0	1	100	--	300	0	10	--	0
39	--	<.2	--	--	--	2.0	80	--	<20
40	10	1	800	--	100	0	10	--	2
41	--	--	--	--	--	--	--	--	--
42	--	2	--	--	--	<.5	50	--	--
43	0	1	0	--	400	0	0	--	0

< Signifies less than the number to the right.
≤ Signifies less than or equal to the number.

Iodide (I)	Lead (Pb)	Lithium (Li)	Mercury (Hg)	Molyb-denum (Mo)	Nickel (N)	Selenium (Se)	Silver (Ag)	Strontium (Sr)	Vanadium (V)	Zinc (Zn)
--	--	--	--	--	--	--	--	--	--	--
--	0	100	--	--	0	0	--	--	--	0
--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--
--	<2	350	0.0	--	<20	<.2	5	--	--	<5
--	--	170	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--
1,100	0	130	--	0	--	0	--	440	1.0	500
--	--	220	--	--	--	--	--	--	--	--
10	0	100	1.0	0	--	0	--	9,300	.0	20
--	--	150	--	--	--	--	--	--	--	--
--	<2	190	.0	--	<20	<.2	6	--	--	<5
--	<2	90	.0	--	<20	<.2	7	--	--	30
10	0	110	1.0	0	--	0	--	9,400	.0	10
--	<5	110	.0	--	<20	<.2	7	--	--	8
10	0	80	.0	0	--	1	--	1,000	.0	190
--	--	100	--	--	--	--	--	--	--	--
--	<2	150	.0	--	<20	<.2	6	--	--	20
10	0	100	.0	0	--	0	--	10,000	1.0	10

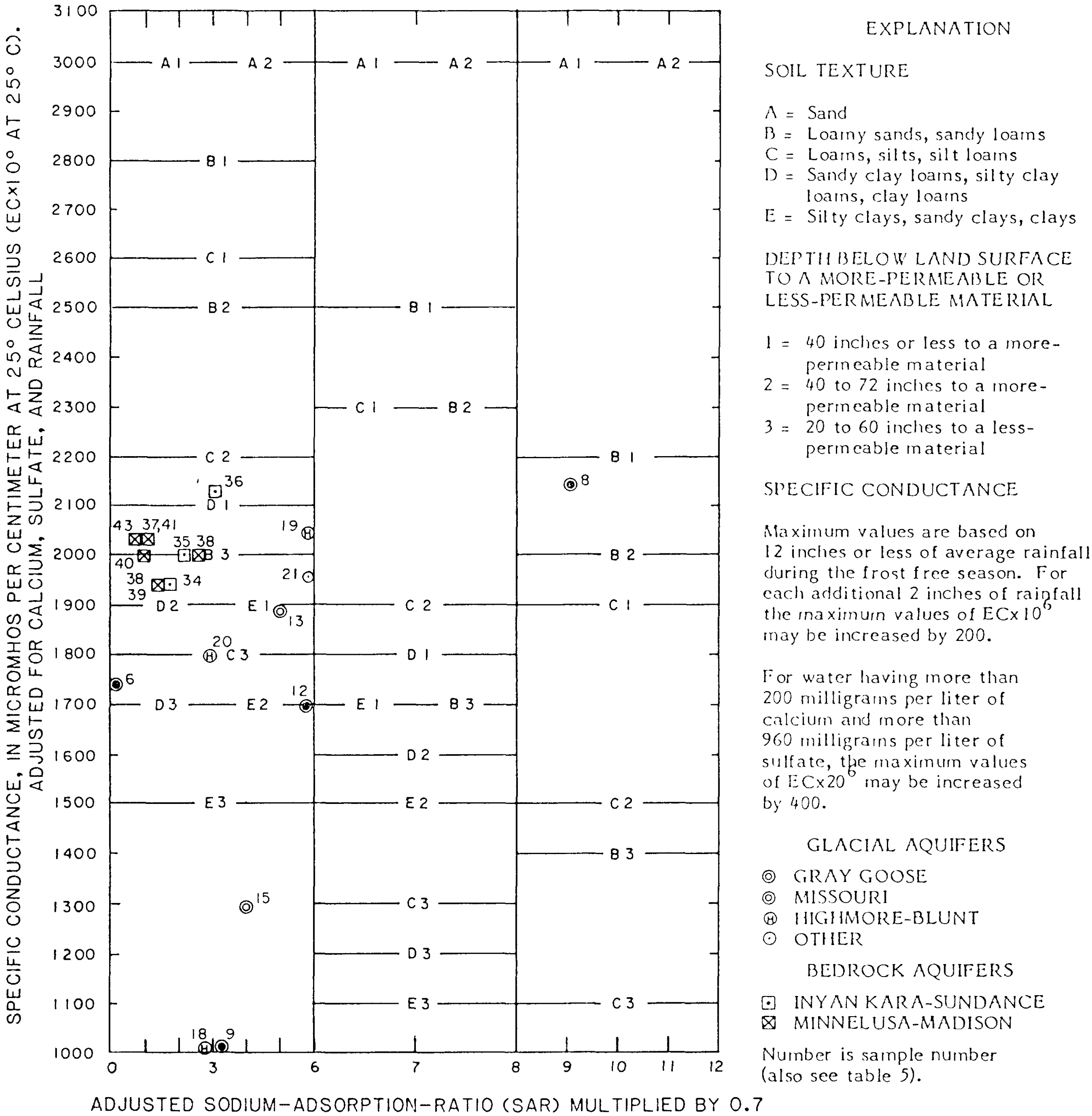

Figure 19.--Irrigation-water classification diagram, based on South Dakota standards (revised January 7, 1982) for maximum allowable specific conductance and adjusted sodium-adsorption-ratio values for which an irrigation permit can be used for applying water under various soil texture conditions. Water 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.

clayey, less-permeable soil, the sodium could damage the soil structure, making the soil much less permeable. Water that has an unadjusted SAR larger than 4 (table 5) generally is unsuitable for irrigation. Thus, some water from glacial aquifers and all water from the Dakota aquifer would be considered unsuitable for irrigation of most soils.

Most water from the Inyan Kara-Sundance and Minnelusa-Madison aquifers can be applied to soil class DI and more permeable soil that is above DI in figure 19, provided other conditions as defined by the South Dakota Division of Conservation (no date) are met.

The bedrock aquifers are an enormous geothermal resource. The maximum temperature of water from the aquifers increases with depth from 22° to 49° C.

SUMMARY AND CONCLUSIONS

Fresh surface water and fresh to slightly saline ground water are available in large quantities for future development in Hughes County. The Missouri River, the southern and western boundary of the county, has an average flow of nearly 18 million acre-feet per year (25,000 cubic feet per second). Storage in two reservoirs on the river averages about 24 million acre-feet. The flow of water in tributaries to the Missouri River is generally very small. Seven ephemeral tributary streams have a combined average flow of only about 11,000 acre-feet per year (15 cubic feet per second). The flow of the largest tributary stream, Medicine Knoll Creek, exceeded 1 cubic foot per second near Blunt only about 15 percent of the time.

Withdrawal of water from the Missouri Ri er for use in the county during 1981 is estimated to have been about 17,000 acre-feet, or about 0.1 percent of the flow of the river.

Four major glacial aquifers consisting of outwash sand and gravel underlie about one-third of the county and store about 1 million acre-feet of water. These aquifers can yield as much as 1,000 gallons per minute to wells from depths of 30 to 300 feet. Where the thickness of saturated sand and gravel is more than 30 feet, the yield of large-capacity wells could exceed 300 gallons per minute. Recharge to these aquifers, mostly from precipitation, is estimated to exceed 2,400 acre-feet per year. Pumpage during 1981 is estimated to have been 4,380 acre-feet, or about 0.4 percent of storage.

Depths to water in wells completed in glacial aquifers range from 8 to 250 feet. The water levels in one observation well temporarily declined 3 feet and in another well declined 8 feet during 1976-82 due to pumpage of nearby large-capacity wells.

Three major bedrock aquifers (the Dakota, Inyan Kara-Sundance, and Minnelusa-Madison) are composed of sandstone and shale or limestone and dolomite and store about 83 million acre-feet of water beneath the county. The aquifers extend throughout much of South Dakota and into adjacent States. These aquifers can yield as much as 1,600 gallons per minute to flowing wells from depths of 800 to 2,600 feet. Generally, the largest yields are from high-pressure wells in the deepest aquifer. Shut-in pressures increase with well depth to more than 400 pounds per square inch at land surface. Wells completed in the Dakota aquifer do not flow in some upland areas because water levels for the Dakota locally may be more than 200 feet below land surface.

Recharge of the deepest bedrock aquifer (Minnelusa-Madison aquifer) is from precipitation and streamflow across its outcrop in the Black Hills of western South Dakota. The overlying bedrock aquifers are recharged by upward leakage from the Minnelusa-Madison aquifer, estimated to be 180,000 acre-feet per year.

Withdrawal of water from bedrock aquifers is estimated to have been 8,150 acre-feet during 1981, less than 0.01 percent of storage.

Artesian head in the Dakota aquifer was reported to have declined as much as 400 feet after 1880. By 1915, withdrawals from the Dakota aquifer were reported to have exceeded 2 million cubic feet per day (10,000 gallons per minute). Effects on artesian head of an increase in withdrawals from the deeper bedrock aquifers probably will be similar to the effects on the Dakota aquifer. However, a rapid decline in hydraulic head has been prevented by greatly restricting the flow of an artesian well in the Minnelusa-Madison aquifer at Pierre.

Most of the water from glacial aquifers is slightly saline and very hard but is suitable for many uses. Concentrations of dissolved solids average about 1,800 milligrams per liter but range from 538 to 5,240 milligrams per liter. The hardness of water from glacial aquifers averages 900 milligrams per liter but ranges from 110 to at least 3,600 milligrams per liter.

Concentrations of dissolved solids in the slightly saline water from bedrock aquifers average about 2,000 milligrams per liter and range from 1,500 to 3,490 milligrams per liter. Only the water from the Dakota aquifer has relatively small concentrations of hardness. Water from the Dakota has an average hardness concentration of about 200 milligrams per liter. Water from the deeper bedrock aquifers has an average hardness concentration of about 1,400 milligrams per liter. Water from both glacial and bedrock aquifers in Hughes County generally contains excessive concentrations of iron and manganese. Water from the Dakota aquifer and some water from glacial aquifers is unsuitable for use in irrigation because the sodium-adsorption ratio is larger than 4.

Bedrock aquifers are an important potential source of geothermal energy for local use. The maximum temperature of water from the aquifers increases with depth from 22° to 49° C.

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