WATER RESOURCES OF AURORA AND JERAULD COUNTIES, SOUTH DAKOTA

By Louis J. Hamilton

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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 mile (ft/mi)	0.1894	meter per kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile (ft^2/s)/mi^3	0.01093	cubic meter per second per square kilometer
square foot per day (ft^2/d)	0.0929	square meter per day
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meter
gallon per minute (gal/min)	0.06308	liter per second
inch	25.40	millimeter
micromho per centimeter at 25° Celsius (umho/cm at 25°C)	1.000	microsiemens per centimeter at 25° Celsius
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

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

Large amounts of fresh to slightly saline ground water underlie Aurora and Jerauld Counties, 1,236 square miles of glaciated, till-covered hills and plains in southeastern South Dakota. More than 1 million acre-feet of water is located beneath 340 square miles in five major glacial aquifers, composed mostly of outwash sand and gravel. About 58 million acre-feet of water is stored in three major bedrock aquifers that extend through most of the area. The three bedrock aquifers in downward sequence are marl and chalk of the Niobrara aquifer and sandstone of the Codell and Dakota aquifers.

Wells that yield as much as 1,000 gallons per minute can be developed in several aquifers. Recharge of aquifers by infiltration of precipitation averages about 31,000 acre-feet annually. Withdrawals of ground water in 1979 were estimated to total about 5,400 acre-feet, 17 percent of the recharge. About 40 percent of withdrawals were for irrigation.

The effects of increases in water withdrawals generally have been small for glacial aquifers, but large for some bedrock aquifers. Observation wells located less than a mile from irrigation wells pumping 300 to 1,000 gallons per minute from glacial aquifers generally had water-level declines of 0.6 to 4 feet during 1978-81. In contrast, water levels in the Niobrara aquifer temporarily declined as much as 40 feet near a well that pumped 1,500 gallons per minute. The large decline was due to the small artesian storage. Artesian pressure of the Dakota aquifer declined about 200 feet between 1909 and 1979 because of large withdrawals through flowing wells.

The availability of surface water is limited because streams are ephemeral and have large flows only during abnormally wet periods or intense thunderstorms. Most of the lakes are small, semipermanent, and shallow.

Most surface water in the study area is fresh, by definition containing less than 1,000 milligrams per liter of dissolved solids. Most of the ground water is hard to very hard and fresh to slightly saline, concentrations of dissolved solids ranging from 320 to 2,650 milligrams per liter. Water from the Niobrara and Codell aquifers generally is unsuitable for use in irrigation because the sodium-adsorption ratio is larger than 4 and boron concentrations exceed 2,000 micrograms per liter.

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, particularly irrigation, and to supply information that is useful in planning for development. In July 1976, the South Dakota Geological Survey and the U.S. Geological Survey began a 4-year cooperative study of the geology and water resources of Aurora and Jerauld Counties, an area of 1,236 mi^2 in southeast South Dakota (fig. 1). Western Jerauld and southern Aurora Counties are in a hilly area, the Coteau du Missouri. One-half of the study area is in the James basin, which is about 500 ft lower in altitude than the Coteau. Agriculture is the principal occupation of the sparse population of about 6,500 persons.

Purpose and Scope

The purpose of the study was to provide the reliable basic data and analyses needed to evaluate and make efficient use of the water resources of Aurora and Jerauld Counties. The report describes (1) the availability of surface and ground water, (2) the effects of possible increases in withdrawals on the availability of surface and ground water, and (3) the quality of the water. Emphasis was on studying glacial aquifers, mostly outwash sand and gravel, because little was known of their extent and water-yielding potential. Although this is a comprehensive report, more detailed hydrologic study may be needed where development of large supplies of water is planned.

A separate report describing the geology of the study area is being prepared by L. S. Hedges of the South Dakota Geological Survey.

Method of Investigation

Geohydrologic data from about 300 test holes and 700 wells were analyzed to determine the extent, thickness, water yields, and water quality of aquifers. Four pumping tests of wells were performed in order to determine local aquifer characteristics. Water levels were measured 4 to 10 times annually in 50 wells and at 8 lake gages to determine changes in storage. About 50 water samples were obtained from wells for detailed chemical analyses.

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

Useful information on well construction and yields was supplied by local residents, well drillers, and municipal water superintendents. Information on a possible ground-water supply for the city of Wessington Springs is available in a separate report (Steece and Schurr, 1966).

Information on the regional geology was obtained from reports by Rothrock (1943) and Flint (1955). A soil map (Klingelhoets and others, 1951), geologic maps (Hoff, 1960; Steece, 1967a, 1967b), and maps of sand and gravel deposits (Blaze, 1980a, 1980b) were useful in estimating the extent of near-surface aquifers. A short information circular (Hamilton, 1980) summarizes the extent, depth, and water quality of major aquifers.

Streamflow data were obtained from several compilations (U.S. Geological Survey, 1964, 1969, 1972-75, 1973, and 1976-81).

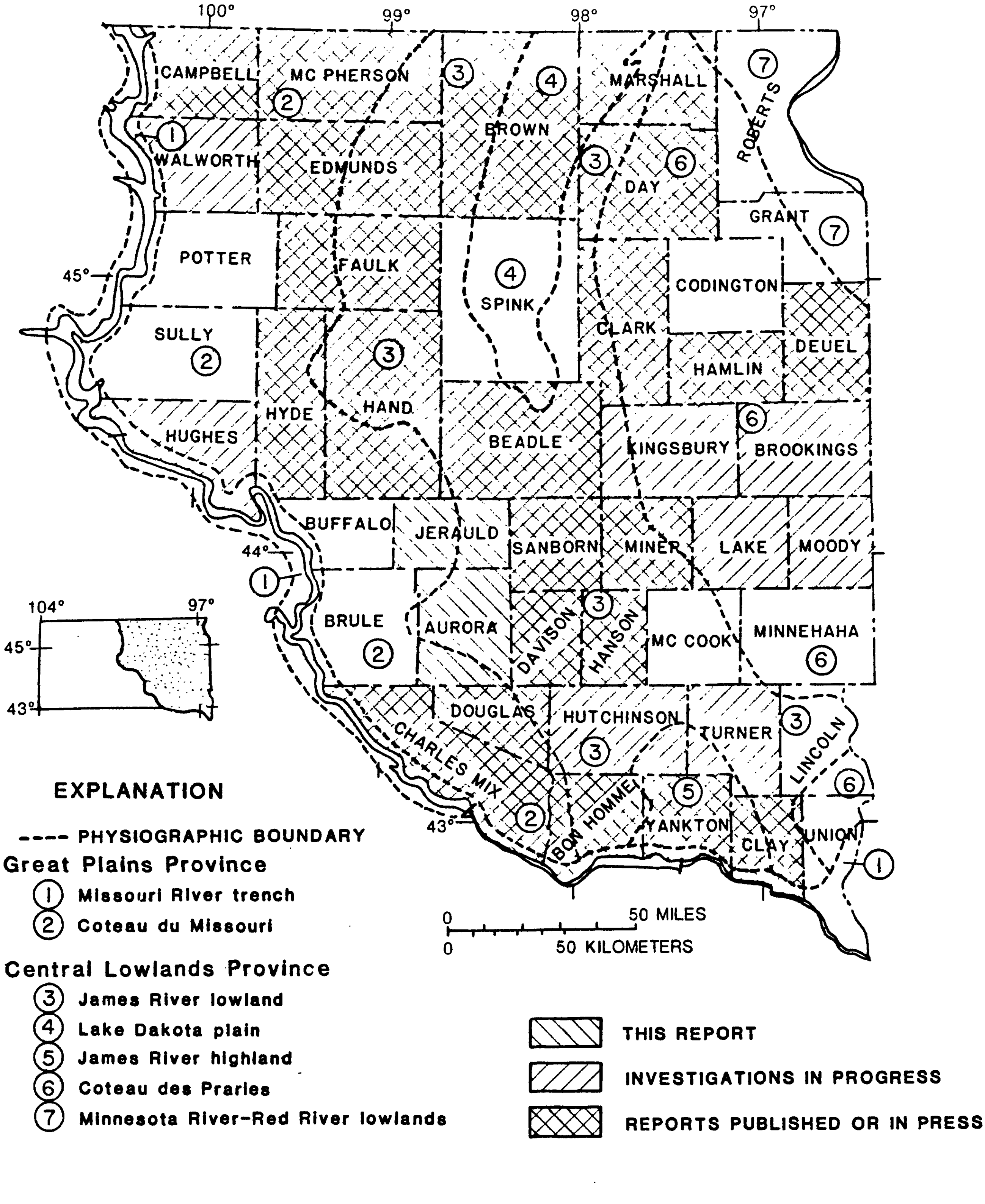


Figure 1.--Index map of eastern South Dakota showing area of study, status of county investigations, and major physiographic divisions.

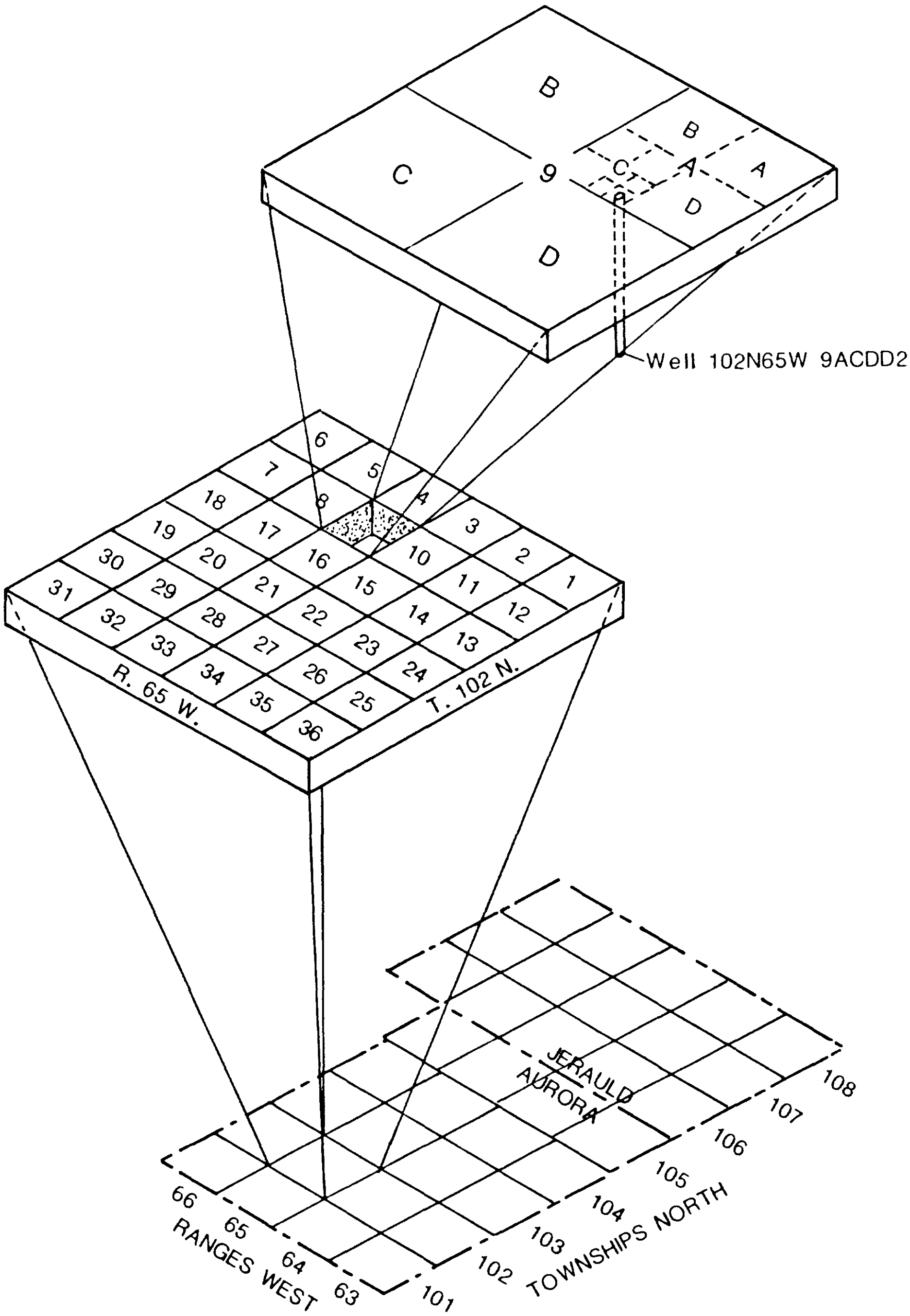


Figure 2.--Site-numbering diagram. The well number consists of township followed by "N," range followed by "W," and section number, followed by a maximum of four uppercase letters that indicate, respectively, the 160-, 40-, 10-, and 2½-acre tract in which the well is located. These letters are assigned in a counterclockwise direction beginning with "A" in the northeast quarter. A serial number following the last letter is used to distinguish between wells in the same tract. Thus, well 102N65W9ACDD2 is the second well recorded in the SE¼ of the SE¼ of the SW¼ of the NE¼ of section 9 in township 102 north and range 65 west of the 5th meridian and baseline system.

The Water Environment

Climate, Hydrology, and Geology

Average annual precipitation is about 21 inches and is 3 inches or more below normal three of every 10 years. On the average, three-fourths of the annual precipitation occurs during the growing season. However, supplemental irrigation is often needed to maintain crop yields and stabilize the year-to-year variations in crop production. Land is mostly in range and field crops used for livestock consumption. Water demands are greatest in summer for irrigation, but demands for ground water also are great in winter when ponds and streams are ice-covered and 200,000 livestock must be watered from wells.

Although the general availability of water depends on precipitation, the geology and soil types in the area have an influence on runoff to streams and recharge of ground water. Runoff from the study area is larger than from adjacent areas because of rapid runoff from extensive areas of poorly permeable clayey soil on glacial till. There is also rapid runoff from steeply sloping hills of the Coteau du Missouri. Slopes of streams range from 5 ft/mi in the James basin part of the study area to 200 ft/mi in gullies on the coteau.

Recharge of ground water is greatest in areas of sandy, gravelly soil on the alluvium adjacent to streams. Elsewhere, poorly permeable clayey till slows recharge. Most of the recharge in areas of till probably is restricted to seepage along joints or fractures and through animal burrows in the till. Joints and fractures tend to expand during drought as the soil shrinks and this facilitates subsequent recharge.

The availability of ground water depends on the recharge, storage, thickness, and water-yielding characteristics of rock units (table 1). In the study area, most wells yielding 25 to 1,000 gal/min penetrate saturated outwash sand and gravel deposits of glacial aquifers that locally are as much as 100 ft thick. Yields of as much as 1,500 gal/min are also obtained from several consolidated rock units of Cretaceous age. The bedrock aquifers in downward order of increasing age are marl and chalk in the Niobrara Formation, the Codell Sandstone Member of the Carlile Shale, and sandstone in the Dakota Formation. These rock units are interbedded with relatively impermeable shale that restricts movement of water between units and to overlying Quaternary deposits.

Water Budget and Water Use

A description of the surface water and ground water is aided by an analysis of the water budget (table 2). The budget is the balance between the amounts of water entering and leaving the hydrologic systems in the study area. The dominant budget items are precipitation, which averages 21.0 inches, and evapotranspiration, estimated to average 19.8 inches annually. Evapotranspiration is calculated as the long-term difference between precipitation plus inflow and pumpage plus outflow, assuming the net change of ground-water and surface-water storage during a period of several years is negligible. Evapotranspiration includes evaporation from soil and water surfaces and transpiration by vegetation.

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

Age		Unit	Lithology	Maximum thickness (feet)	Water-yielding characteristics
QUATERNARY	PLEISTOCENE	Alluvium	Sand, silt, clay, and fine gravel; stratified.	20	Permeable. Yields small amounts of water to wells.
		Lake sediments	Clay, silt, and fine sand; stratified.	86	Permeable. Wells may yield 1 to 5 gallons per minute.
		Outwash	Sand and gravel, well-sorted and stratified.	100	Very permeable. Forms major glacial aquifers. Wells may yield 25 to 1,000 gallons per minute.
		Till	Clay mixed with variable proportions of silt, sand, and gravel. Locally may contain sand lenses.	400	Slightly permeable. Acts as a confining layer over deeper outwash deposits. Locally wells may yield 1 to 5 gallons per minute.
CRETACEOUS		Pierre Shale	Shale, some thin chalk beds in lower part.	800	Relatively impermeable. Usually a barrier to the movement of water. Locally wells may yield 1 to 5 gallons per minute from fractured chalk.
		Niobrara Formation	Marl and chalk, shaly.	190	Slightly to very permeable. In some areas may yield 25 to 1,500 gallons per minute to wells.
		Codell Sandstone Member	Sandstone, fine- to medium-grained, siltstone, and shale.	136	Permeable. Wells may yield as much as 100 gallons per minute.
		Carlile Shale	Shale, locally may contain some sand lenses.	335	Relatively impermeable. Usually a barrier to the movement of water. Not known to yield water to wells.
		Greenhorn Limestone	Limestone, interbedded with limey shale.	35	Low permeability. In some areas may yield small amounts of water to wells.
		Graneros Shale	Shale interbedded with silt and very fine sand.	260	Relatively impermeable. Usually a barrier to the movement of water. Locally, sand lenses may yield water at sufficient pressure to flow at land surface.
		Dakota Formation	Sandstone, fine to very fine-grained, contains shale.	440	Permeable. Wells yield water under sufficient pressure to flow at land surface in eastern and southwestern parts of study area. Wells may yield as much as 500 gallons per minute.
PRECAMBRIAN		Sioux Quartzite	Quartzite.	Unknown, but probably many hundreds of feet	Nearly impermeable. Not considered to be an aquifer. Locally might be possible to obtain water from fractures.
		Precambrian rocks undifferentiated	Igneous and metamorphic rock. Mostly granite.	Unknown, but probably many tens of thousands of feet	Nearly impermeable. Not considered to be an aquifer. Locally might be possible to obtain water from fractures.

Table 2.--Average annual water budget

	Acre-feet	(inches)
Water in:		
Precipitation	1,384,000	(21.0)
Ground-water inflow 1/	30,000	(.5)
Total	1,414,000	(21.5)
Water out:		
Evapotranspiration 2/	1,328,000	(20.2)
Pumpage 3/	5,400	(.1)
Ground-water outflow 1/	44,600	(.7)
Surface-water outflow	36,000	(.5)
Total	1,414,000	(21.5)

1/ Based on ground water entering or leaving the county through aquifers and till.
2/ Calculated as the difference between other budget items.
3/ Includes flowing wells.

Withdrawals of ground water from all aquifers were estimated to total 5,400 acre-ft (1.8 billion gal) in 1979 (table 3). This amounted to 17 percent of recharge (table 6) and 7 percent of outflow of ground and surface water. About 40 percent of withdrawal was for irrigation. Nearly one-half of the total was withdrawal from glacial aquifers, mainly for irrigation. Withdrawals from the Dakota aquifer, mainly for livestock, were about one-third of the total. Nearly one-half of the Dakota withdrawals was reported to be unused discharge of flowing wells.

SURFACE WATER

Streamflow

The streams in the study area are ephemeral, generally flowing only during late winter and spring of wet years as a result of snowmelt and later in spring and summer as a result of intense thunderstorms. Most of the creeks do not flow during a severe, prolonged drought. Streamflow from the area is estimated to average about 50 ft^3/s (36,000 acre-ft/yr), based on the average runoff of about 0.04 $(ft^3/s)/mi^2$ for the gaging station on Firesteel Creek near Mount Vernon, which is 4 mi east of the Aurora-Davison County line. The average annual discharge at the Firesteel Creek gaging station for 1955-80 was 21 ft^3/s or 28 acre-ft/mi^2 (table 4). Firesteel Creek, a tributary of the James River, drains about 45 percent of the study area (fig. 3). The rest of the study area is drained by Crow, Smith, and Platte Creeks which are tributaries of the Missouri River and Sand Creek which is a tributary of the James River.

Table 3.--Estimated withdrawal of ground water in 1979

Source	Total		Municipal		Rural-domestic		Livestock		Irrigation	
	acre-feet	percent	acre-feet	percent	acre-feet	percent	acre-feet	percent	acre-feet	percent
GLACIAL AQUIFERS										
Crow Creek aquifer	1,300	24.1	0	0	5	0.1	25	0.5	1,270	23.5
Crow Lake aquifer	140	2.6	0	0	5	.1	25	.5	110	2.0
Warren aquifer	830	15.3	0	0	2	.0	18	.3	810	15.0
White Lake aquifer	6	.1	0	0	1	.0	5	.1	0	0
Corsica aquifer	15	.3	0	0	2	.0	13	.2	0	0
Minor glacial aquifers	390	7.2	220	4.1	20	.4	150	2.8	0	0
Subtotal	2,681	49.6	220	4.1	35	.6	236	4.4	2,190	40.6
BEDROCK AQUIFERS										
Pierre Shale	49	.9	0	0	5	.1	44	.8	0	0
Niobrara aquifer	330	6.1	30	.5	20	.4	170	3.1	1/ 110	2.0
Codell aquifer	370	6.8	220	4.1	20	.4	130	2.4	0	0
Dakota aquifer	2/ 1,970	36.5	60	1.1	140	2.6	1,770	32.8	0	0
Subtotal	2,719	50.4	310	5.7	185	3.5	2,114	39.1	110	2.0
Total	5,400	100.0	530	9.8	220	4.1	2,350	43.5	2,300	42.6

1/ Withdrawal discontinued in 1981.
2/ Nearly one-half of the withdrawal is unused flow from flowing wells.

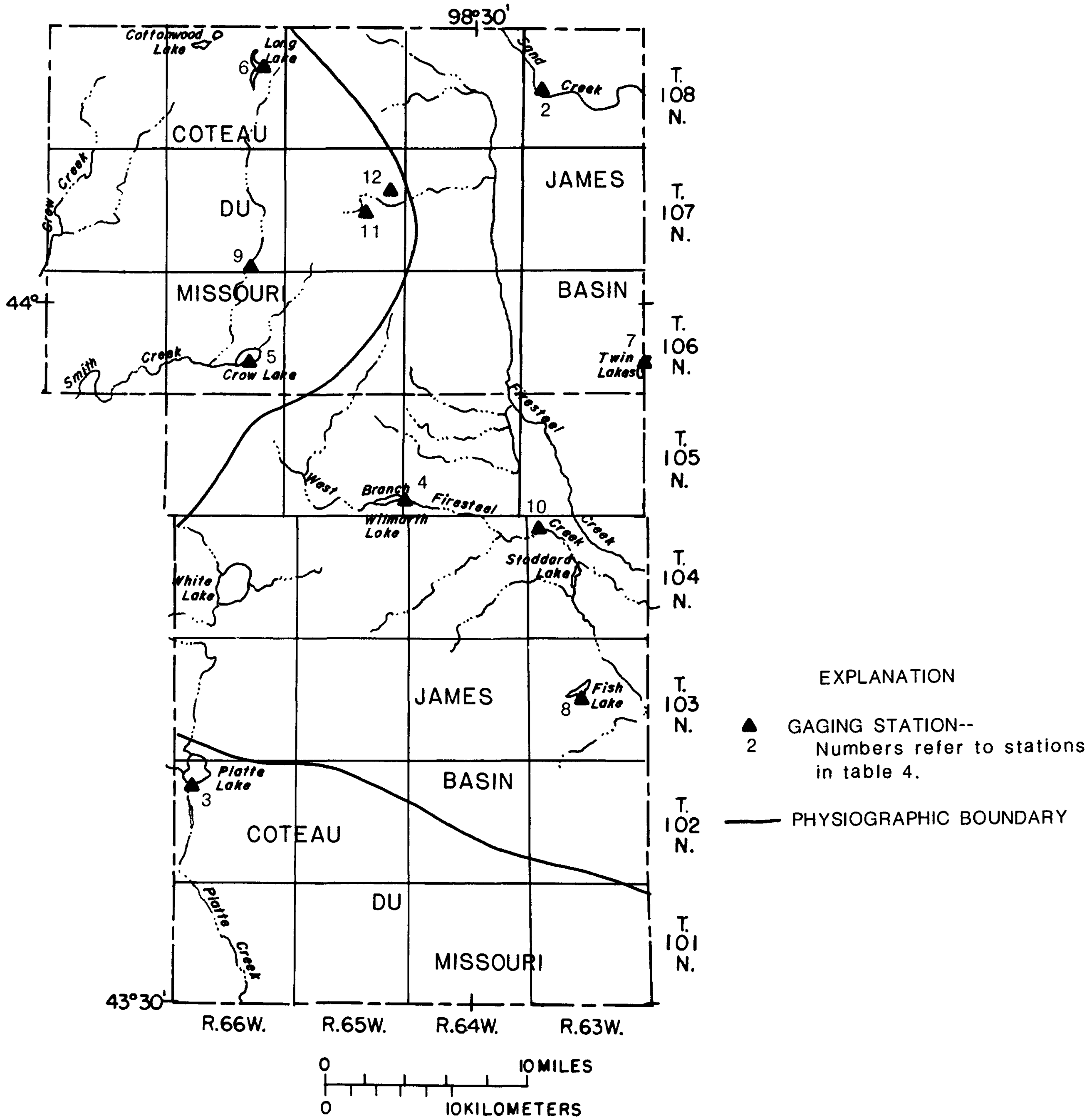


Figure 3.--Locations of gages on streams and lakes during 1977-80.

Table 4.--Estimated average annual flows at gaging stations

No.[1/]	Gaging station name	Estimated drainage area (square miles)	Drainage-basin runoff: Acre-feet per square mile	Drainage-basin runoff: Measured (cubic feet per second)	Drainage-basin runoff: Estimated[2/] (cubic feet per second)
1	Firesteel Creek near Mount Vernon (not on fig. 3).	540	28	[3/] 21	14
2	Sand Creek near Alpena	240	27	[4/] 8.9	5.0
3	Platte Lake	60	43	[5/] 3.5	3.6
4	Wilmarth Lake	32	17	[5/] .8	.8
5	Crow Lake	26	66	[5/] 2.4	1.6
6	Long Lake	9.0	63	[5/] .8	.5
7	Twin Lakes	8.0	57	[5/] .6	.3
8	Fish Lake	6.0	48	[5/] .4	.2
9	Smith Creek tributary	5.9	—	—	.3
10	Estepond	2.7	22	[5/] .1	.1
11	Deans Lake	1.5	65	[5/] .1	.1
12	Firesteel Creek tributary	.2	—	—	.01

1/ Number refers to gaging station located in figure 3.
2/ Estimated using the method described by Larimer (1970).
3/ Based on 25 years of data.
4/ Based on 30 years of data.
5/ Based on changes of storage in lakes during early 1978.

The duration of streamflow in the study area is short because of scanty precipitation, rapid runoff, large evapotranspiration in summer, and little base-flow discharge from ground water. For example, a daily discharge of 10 ft^3/s was equaled or exceeded less than 10 percent of the time at the Sand Creek gaging station during 1951-80 and at the Firesteel Creek gaging station during 1956-80 (fig. 4). Likewise, a discharge of 0.1 ft^3/s was equaled or exceeded less than 50 percent of the time. The steep slopes of the flow-duration curves are typical of ephemeral runoff from basins having little discharge of ground water to streams.

A hydrograph for Sand Creek is included in figure 5 to show that changes in precipitation affect creek levels and also that peaks and troughs in the hydrograph nearly coincide with those of lakes because both are affected by changes in runoff and evapotranspiration. The water level at the Sand Creek gaging station, located 4 mi southwest of the city of Alpena, rose almost every year during February and March because of both increasing runoff of snowmelt and backwater effects from ice. The hydrograph peaks were sharper than those for lakes but the peak for the creek in 1978 nearly coincided in time with similar peaks in the lake hydrographs. The creek generally ceased flowing in early summer when the gage height decreased to 7.4 ft (fig. 5). However, in the drought year of 1976 the creek ceased flowing in early spring.

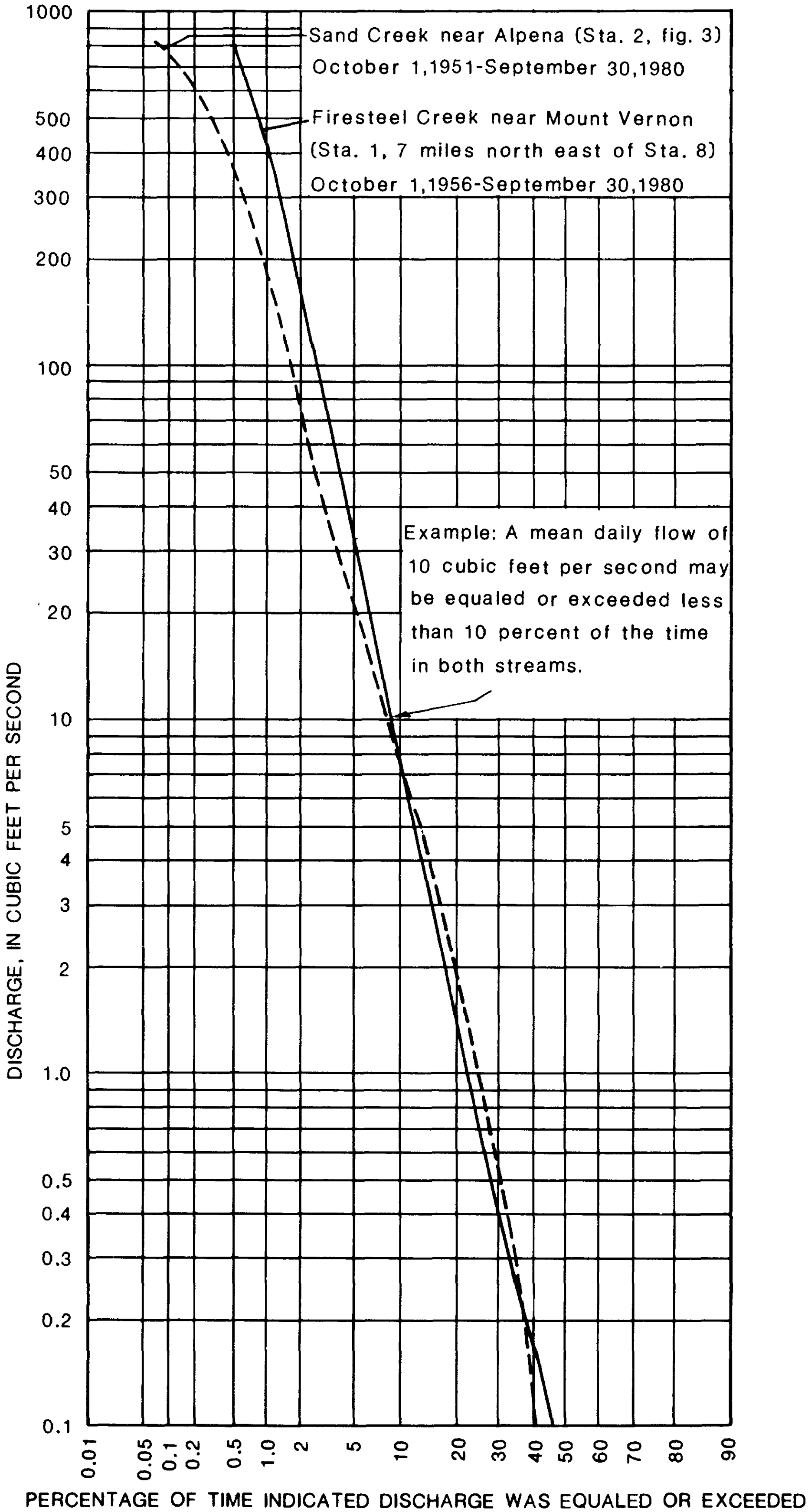


Figure 4.--Steep flow-duration curves for two streams show that stream runoff periods are short.

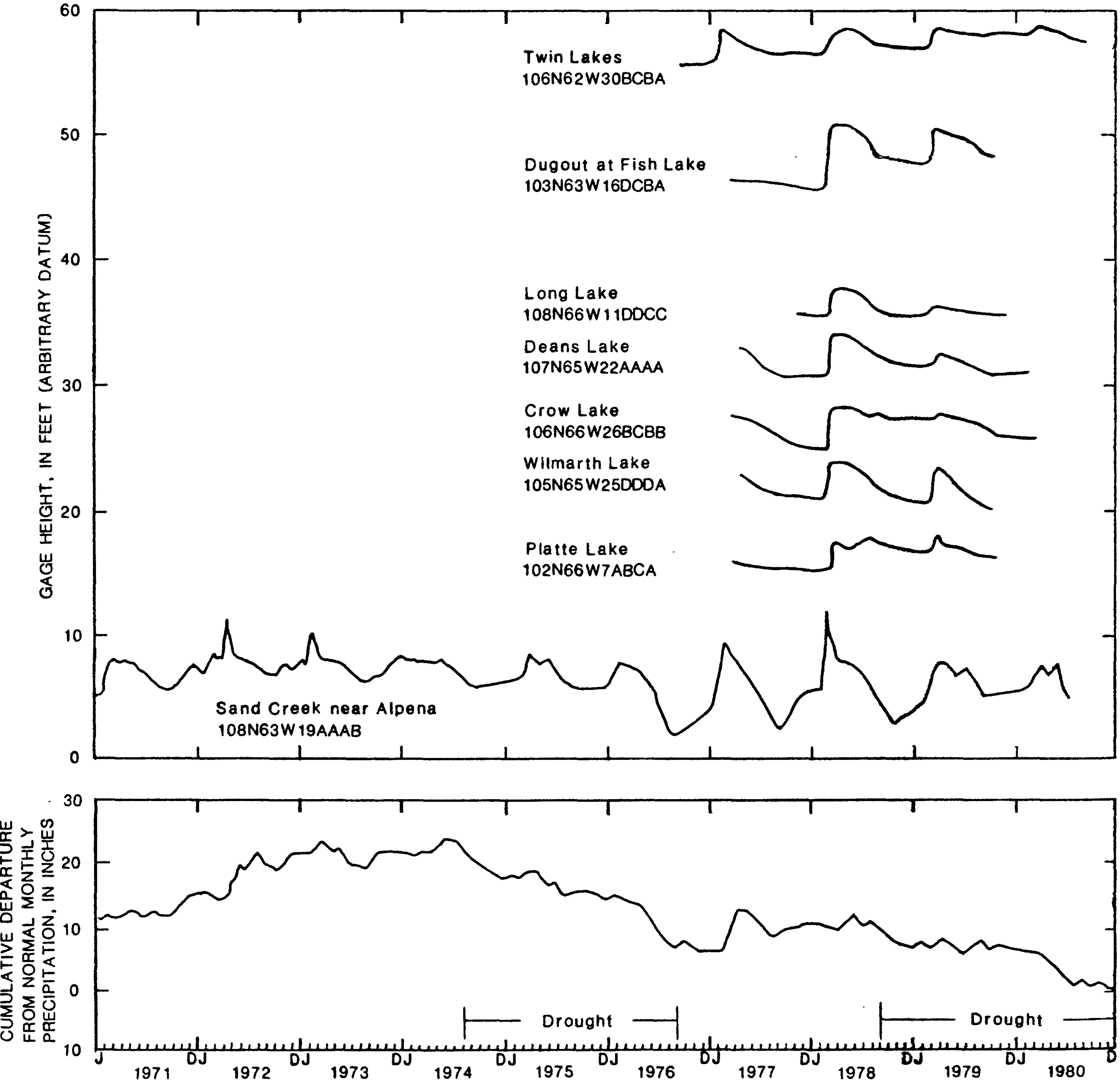


Figure 5.--Water-level changes in lakes and Sand Creek and cumulative departure from normal monthly precipitation at Wessington Springs, 1971-80. (Base period for normal precipitation is 1951-80.)

Subsequently the water level in the pool at the gaging station declined 5.5 ft to a gage height of about 2 ft and the pool was completely dry by late summer for the first time in the memory of local people. This sharp decline in water level was caused by increasing evapotranspiration and possibly also by pumping of a new irrigation well 0.7 mi southeast of the gage.

Lakes

Most lakes in the study area are small, semipermanent, and shallow. Many lakes became dry sometime during 1974-80 because of two droughts (fig. 5). The general downward trend in the curve for cumulative departure from normal monthly precipitation indicates that drought was severe during 1974-76 and also from the summer of 1978 through 1980. The levels of most lakes rose in spring when snowmelt and precipitation produced both runoff and recharge of ground water. Seasonal declines during summer were caused by increasing evapotranspiration and decreasing inflow.

Increased recharge of ground water contributed to the rise in level of lakes in 1978. Twin Lakes also received discharge from flowing wells. At Fish Lake, the sharp rise in the water level in the dugout in March 1978 represented a rise of the water table beneath the lake bed. Ground water began seeping into Fish Lake when the water table reached a gage height of about 49 ft (arbitrary datum).

Streamflow into lakes is estimated from the change in gage heights observed at staff gages in the lakes (table 4). Storage changes in lakes are computed as the change of gage height times the lake surface area measured on a topographic map. Changes in area with changes in gage height are ignored. Flow into lakes was estimated from the changes of storage in lakes in early 1978. This period was assumed to have near-average runoff because precipitation was near normal. Annual streamflow is estimated to be as much as 66 acre-ft/mi^2 into Crow Lake (station 5, table 4). The lake has a hilly basin which is drained by the East Fork of Smith Creek. Gullies leading to the creek have slopes of nearly 200 ft/mi. Steep slopes there and elsewhere in the Coteau tend to promote greater runoff than in the James basin. However, inflow to Long Lake and Twin Lakes (stations 6 and 7), which are surrounded by gently sloping terrain, was estimated to be 63 and 57 acre-ft/mi^2 respectively. This large inflow may be due to ground-water seepage from extensive areas of shallow, permeable sand and gravel deposits in both basins (Blaze, 1980a). These runoff estimates are larger than the estimates using the method described by Larimer (1970) (table 4). This may be due to a larger than average discharge of ground water to streams in 1978.

Even though most lakes in the study area are shallow they are a valuable resource for wildlife habitat and esthetic values. Several of the lakes are deep enough during many years to provide water for recreation and fish propagation (table 5). Twin Lakes and Wilmarth Lake, a manmade reservoir, have maximum depths of more than 10 ft and are considered to be permanent fish-propagation waters because they have a winter fish kill only 1 year of 10 on the average. Crow Lake and Fish Lake have maximum depths of less than 10 ft and winter kill occurs on an average of 1 of every 5 years; therefore, the lakes are considered to be marginal waters for fish propagation.

Table 5.--Summary of lake data

Lake name	Location	Depth 1/ (feet) Maximum	Depth 1/ (feet) Average	Surface area 1/ (acres)	Storage capacity (acre-feet)	Classification for beneficial use 2/
Cottonwood	108N66W4	--	--	320	--	9
Crow	106N66W23, 26	9	5	540	2,700	6, 7, 8
Fish	103N63W16	5	3	175	525	6, 7, 8
Long	108N66W11, 14	6	3	400	1,200	9
Platte	102N66W5, 6	4	2	1,800	3,600	9
Twin	106N63W25, 36	12.5	6	262	1,572	4, 7, 8
White	104N66W15, 16, 21, 22	10	6	2,300	13,800	9
Wilmarth	105N65W35, 36	26	11	100	1,100	4, 7, 8

1/ Oral communication from South Dakota Department of Game, Fish, and Parks.
2/ The following classifications for beneficial use are from South Dakota Water Quality Standards effective Feb. 19, 1981: 1, 2, 3, and 5 are not applicable to this area; 4, warm water permanent fish life propagation waters; 6, warm water marginal fish life propagation waters; 7, immersion recreation waters; 8, limited contact recreation waters; and 9, wildlife propagation and stock watering waters.

GROUND WATER

Five major glacial aquifers and three major bedrock aquifers store nearly 60 million acre-ft of water in Aurora and Jerauld Counties (table 6). This volume is equivalent to a lake 75 ft deep extending across the entire area. Although glacial aquifers contain 1.15 million acre-ft, about 2 percent of the ground water, they receive 65 percent of the annual recharge of 31,000 acre-ft. In many areas, large-capacity wells yielding as much as 1,000 gal/min can be developed.

Glacial Aquifers

Major glacial aquifers, mostly outwash sand and gravel, store 1.15 million acre-ft of water beneath 340 mi^2, about 25 percent of the study area. Storage is estimated to range from 460,000 acre-ft in the 120-mi^2 area of the Corsica aquifer to 80,000 acre-ft in the 40-mi^2 area of the White Lake aquifer (table 6).

Most of the major aquifers occur in areas where the cumulative thickness of saturated sand and gravel exceeds 25 ft (fig. 6). Although the average thickness of most of the aquifers is about 30 ft, the thickness can change greatly within a distance of a mile. Areas where the thickness exceeds 50 ft generally coincide with valleys that were eroded into bedrock by glacial meltwater.

There also is a large range in aquifer depths and water levels because of the large range in altitude of the land surface and because some aquifers are deposited within deep bedrock valleys. The Crow Creek, Crow Lake, and Warren aquifers can occur at shallow depths in creek valleys. The Crow Creek, Crow Lake, and Corsica aquifers can lie at great depths within buried valleys in bedrock (fig. 7).

Although the aquifers are mostly artesian, except for the Crow Creek aquifer, there is only one area where flowing wells can be obtained (sections 17 and 20, T. 105 N., R. 65 W.).

Crow Creek Aquifer

The Crow Creek aquifer, composed of permeable, well-sorted, medium to very coarse sand and gravel, underlies 70 mi^2 of western Jerauld County at depths from 19 to as much as 165 ft below land surface (fig. 8). The deepest unit reaches a depth of about 300 ft within a bedrock valley (fig. 7, C-C'). The aquifer thickness ranges from 5 to 98 ft and exceeds 30 ft beneath about 22 mi^2. The maximum thickness, a composite of several layers, occurs within a bedrock valley at 106N67W11BBCC. Three miles to the west at 106N67W7DAAA, aquifer sand and gravel is interbedded with thick layers of fine, silty sand that provides hydraulic connection between aquifer units.

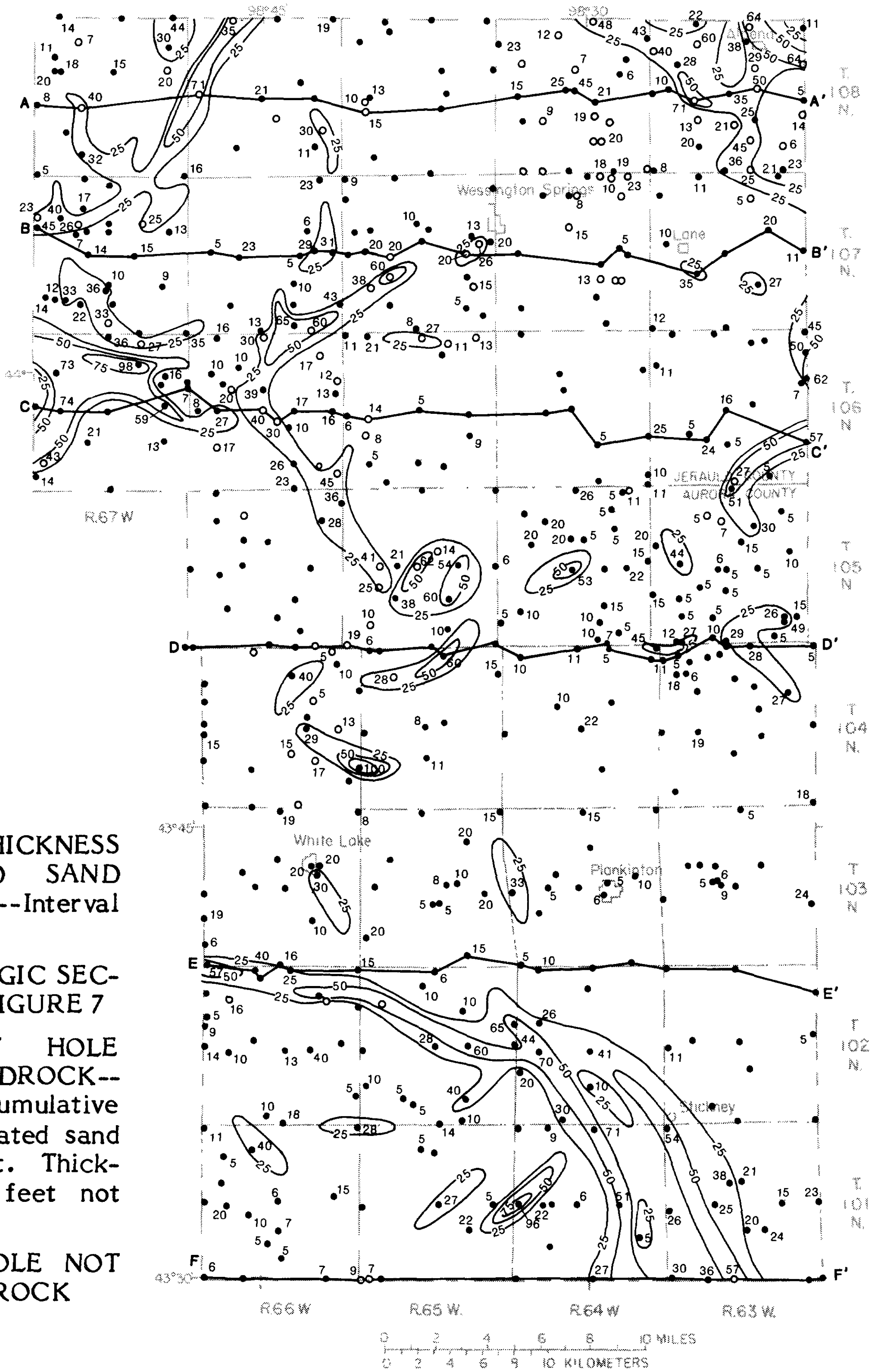
The transmissivity of the aquifer is estimated to exceed 13,000 ft^2/d in a large part of T. 106 N., R. 67 W. (fig. 9), where the potential yield of wells can be as large as 1,000 gal/min. Transmissivity at each well or test hole was calculated by multiplying the thickness of each aquifer layer by the estimated hydraulic conductivity. Typical estimates of conductivity ranged from 50 ft/d for fine sand to 500 ft/d for clean, coarse sand and gravel. The maximum value for hydraulic conductivity was estimated from the specific capacity of two irrigation wells in T. 107 N., R. 67 W.

Recharge to the Crow Creek aquifer, estimated to average 9,100 acre-ft (2.4 inches) annually, is mostly by direct infiltration of precipitation through overlying deposits of sandy alluvium, outwash, and till. Some water also seeps laterally from

Table 6.--Selected physical and hydrological characteristics of major aquifers

Aquifer name	Range in depth to top (feet)	Areal extent (square miles)	Average thickness (feet)	Range in water level below land surface (feet), a + indicates above land surface	Water storage[1/] (acre-feet)	Average annual recharge[2/] Acre-feet	Acre-feet per square mile	Inches	Estimated maximum well yield (gallons per minute)
GLACIAL AQUIFERS									
Crow Creek[3/]	19-165	70	30	+2-105	270,000	9,100	130	2.4	1,000
Crow Lake	16-180	50	30	7-60	190,000	3,800	76	1.4	1,000
Warren[3/]	4-82	60	30	5-55	150,000	2,200	37	.7	1,000
White Lake	6-124	40	15	5-50	80,000	1,800	45	.8	unknown
Corsica[3/]	78-420	120	30	50-210	460,000	3,400	28	.5	1,000
BEDROCK AQUIFERS									
Niobrara[3/]	77-770	1,220	80	+10-250	12,000,000	9,000	7	.1	1,500
Codell[3/]	60-470	900	50	30-240	6,000,000	1,700	2	.04	100
Dakota[3/]	400-1,300	1,230	250	+84-430	40,000,000	--	--	--	500
TOTAL					59,150,000	31,000			

1/ Based on average thickness (feet) times areal extent (acres) times an estimated porosity of 20 percent.
2/ Estimated from discharge calculations assuming no change in storage. The values are small because they ignore discharge by evapotranspiration. The Dakota aquifer is recharged west of the study area.
3/ Extend beyond the study area.



EXPLANATION

—25— LINE OF EQUAL THICKNESS OF SATURATED SAND AND GRAVEL--Interval 25 feet.

A—A' LINE OF HYDROLOGIC SECTION SHOWN IN FIGURE 7

•33 WELL OR TEST HOLE DRILLED INTO BEDROCK--Numbers are cumulative thickness of saturated sand and gravel, in feet. Thickness less than 5 feet not shown.

o8 WELL OR TEST HOLE NOT DRILLED TO BEDROCK

Figure 6.--Thickness of saturated sand and gravel and locations of hydrologic sections, test holes, and wells for which geologic or drillers' logs are available.

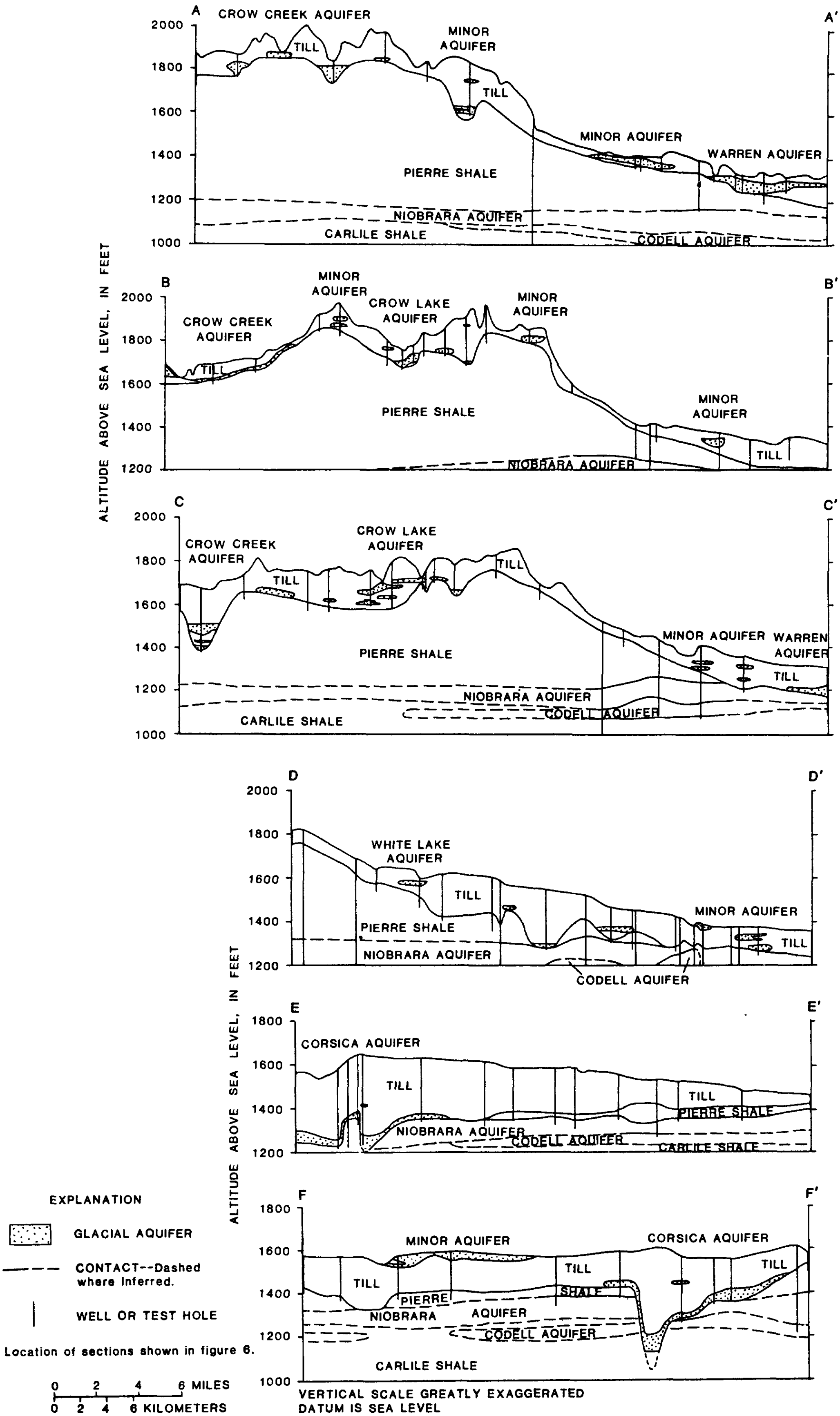
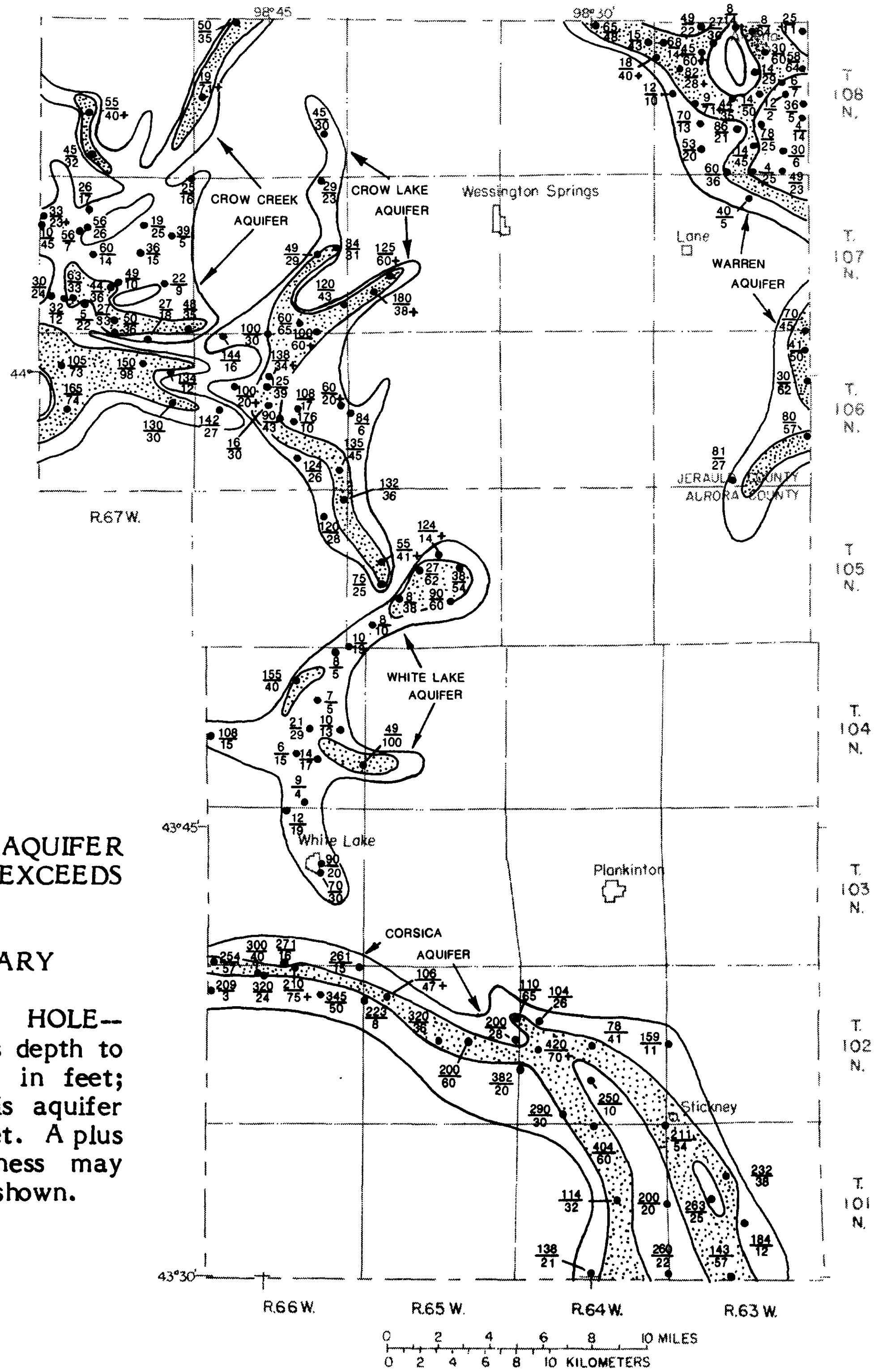


Figure 7.--Hydrologic sections showing glacial and bedrock aquifers.



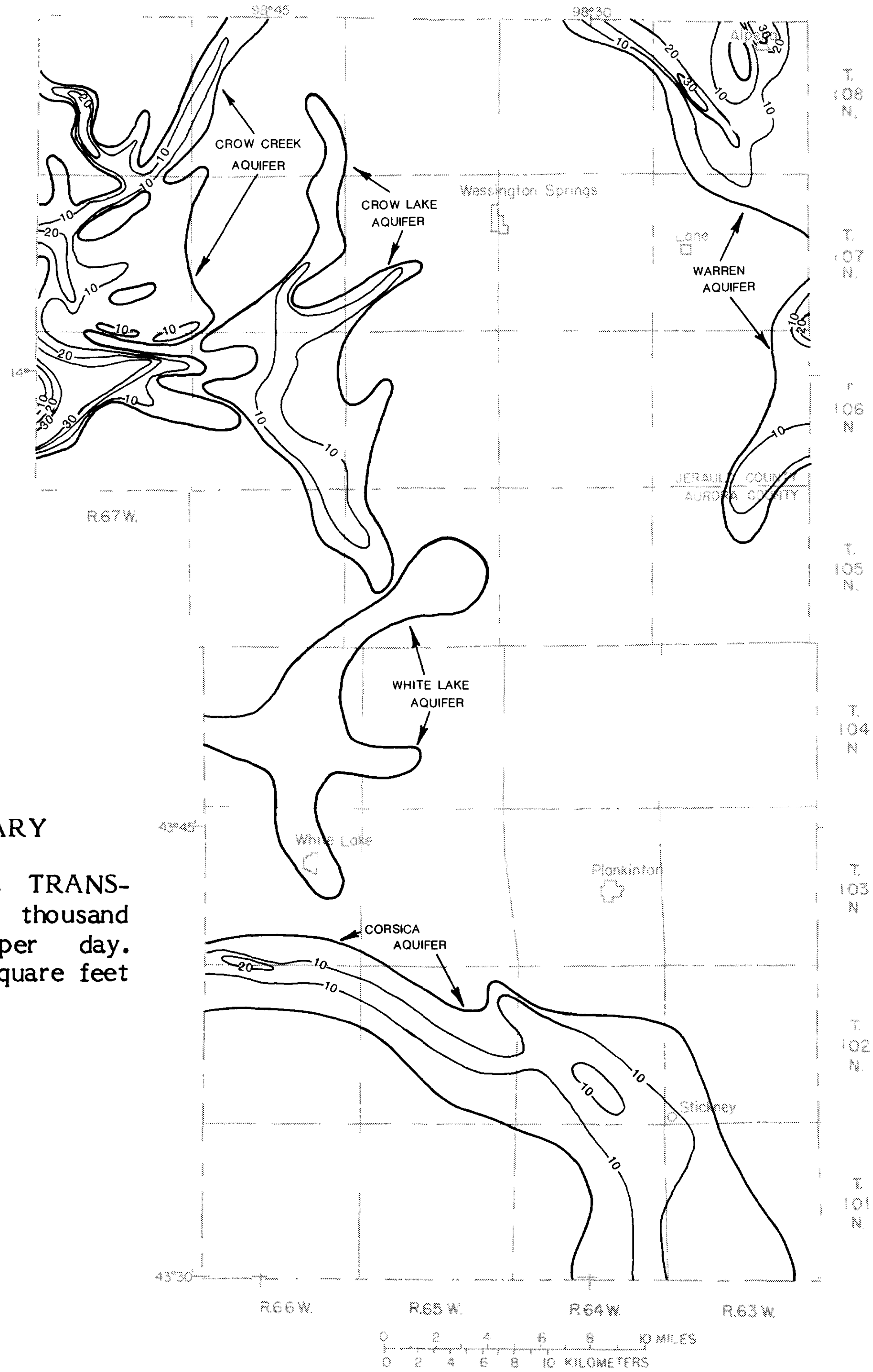
EXPLANATION

AREA WHERE AQUIFER THICKNESS EXCEEDS 30 FEET

AQUIFER BOUNDARY

45 / 32+ WELL OR TEST HOLE--Upper number is depth to top of aquifer, in feet; lower number is aquifer thickness, in feet. A plus indicates thickness may be greater than shown.

Figure 8.--Extent, depth, and thickness of major glacial aquifers.



EXPLANATION

——— AQUIFER BOUNDARY

—10— LINE OF EQUAL TRANSMISSIVITY--In thousand square feet per day. Interval 10,000 square feet per day.

Figure 9.--Estimated transmissivity of major glacial aquifers.

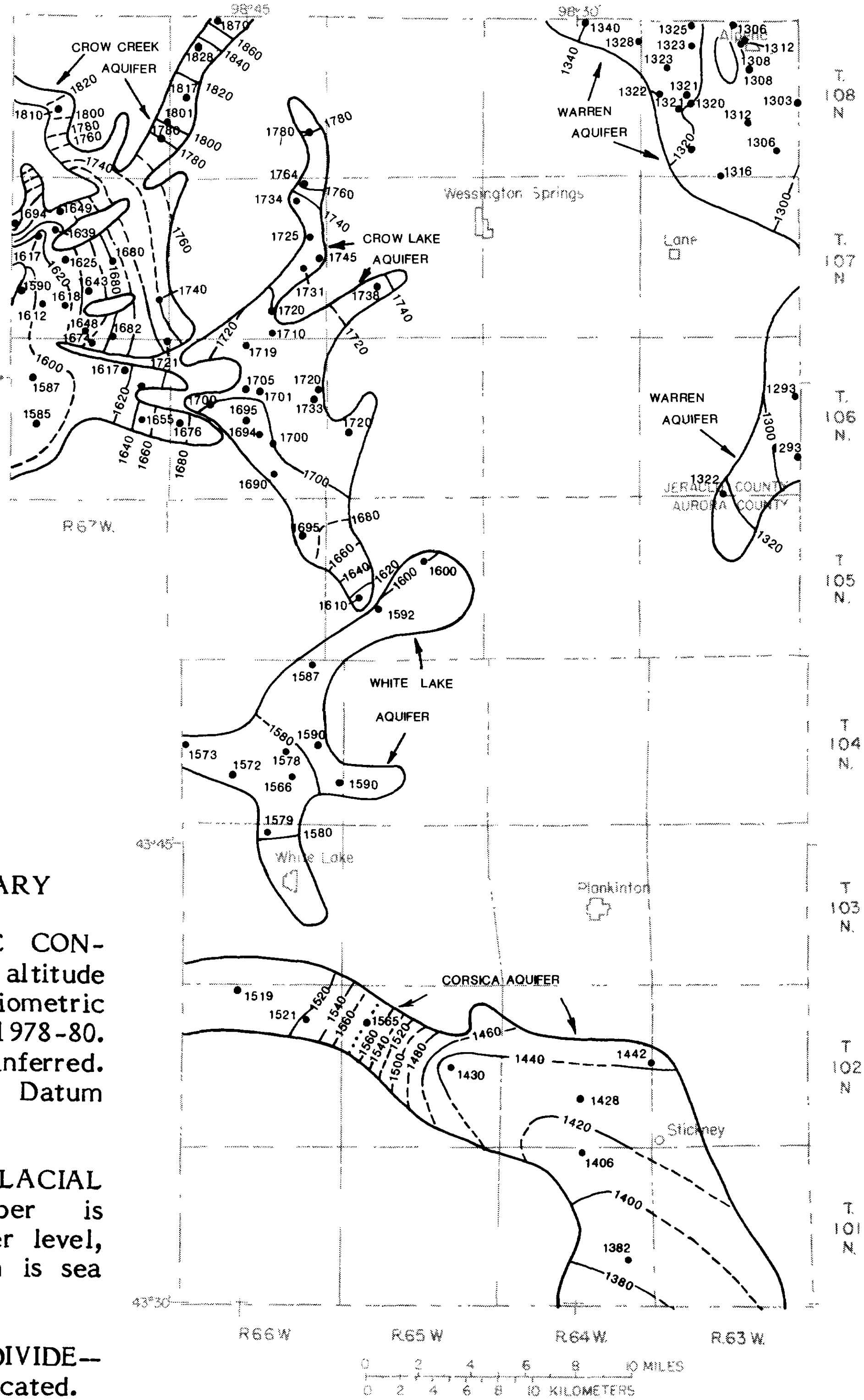
adjacent till. The rate of recharge is relatively high for the study area because the sandy deposits overlying the aquifer are very permeable. Recharge is estimated as equal to the sum of pumpage and ground-water outflow along the western side of the aquifer, where the average hydraulic gradient is southwest at about 10 ft/mi (fig. 10). The outflow of 7,800 acre-ft/yr is the product of the gradient, average transmissivity (15,000 ft^2/d), and aquifer length perpendicular to the direction of flow (6 mi). Discharge is by pumpage, evapotranspiration, and flow from springs and seeps into Crow Creek.

Storage changes in an aquifer, indicated by both seasonal and long-term changes in water levels, are the result of changes in recharge and discharge (fig. 11). Changes in water levels in wells in the Crow Creek were similar to the changes in the other major glacial aquifers in the study area. In winter and spring during 1977-81, the water level rose 1.0 to 2.5 ft in well A and about 0.5 ft in well B (fig. 11) because of decreased pumpage and increased recharge from spring snowmelt and rainfall. During summer, water levels declined 0.6 to 4.0 ft because of decreased recharge, increased evapotranspiration, and increased pumpage for irrigation. Both wells are located less than 1 mi from large-capacity irrigation wells. The larger fluctuation of water level in the shallower of the two wells (well A) probably was the result of larger recharge, larger pumpage, and shorter distance to poorly permeable boundaries.

Long-term changes in water levels were evident as a decline in the annual highest or lowest water level. The 5-year decline totaled 3.5 to 4.0 ft as a result of decreased recharge and increased pumpage during drought periods. A large decrease in recharge was indicated by the monthly cumulative departure from normal precipitation at Wessington Springs, which decreased by 11 inches during 1977-80 (fig. 5). The water levels should rise during a series of wet years, when recharge increases and pumpage decreases.

The pumping capacity of a well and the hydrologic characteristics of the aquifer at a well can be determined by an aquifer test. One characteristic, the transmissivity, measures the rate at which water is transmitted through a unit width (one foot) of an aquifer under a unit hydraulic gradient (one foot per foot). In general, the larger the transmissivity the smaller the drawdown at any given rate of pumping. Another characteristic, the specific yield or storage coefficient, is the volume of water (cubic foot) an aquifer releases from or takes into storage per unit surface area (square foot) per unit change in potentiometric head (one foot). Water-table aquifers have a specific yield of about 0.2 and artesian aquifers have a storage coefficient of about 0.0001 in many tests.

Effects of increased withdrawals from the Crow Creek aquifer were observed to consist of a few feet of drawdown of water levels near pumping wells of large capacity. The approximate amount of drawdown can be inferred from a table of theoretical drawdowns for water-table conditions (table 7). Drawdown at a given distance from a pumping well in a water-table aquifer is only 10 to 50 percent of the drawdown in an artesian aquifer (table 8). For example, drawdown at a distance of 1,000 ft from a well pumping 1,000 gal/min for 100 days could be only 3 ft for a water-table aquifer but 12 ft for an artesian aquifer of the same transmissivity. Actual drawdown could be much larger than shown if there is a zone of smaller transmissivity or a poorly permeable boundary of till or shale near the well. In addition, boundary effects are much larger for artesian conditions than for water-table conditions because the pressure drop expands outward from an artesian well very rapidly. This rapid expansion of the area of influence is due to the very small storage coefficient of artesian aquifers.



EXPLANATION

——— AQUIFER BOUNDARY

—1460--- POTENTIOMETRIC CONTOUR--Shows altitude of the potentiometric surface in 1978-80. Dashed where inferred. Interval 20 feet. Datum is sea level.

•1430 WELL IN A GLACIAL AQUIFER--Number is altitude of water level, in feet. Datum is sea level.

...... GROUND-WATER DIVIDE--Approximately located.

Figure 10.--Potentiometric contours of major glacial aquifers.

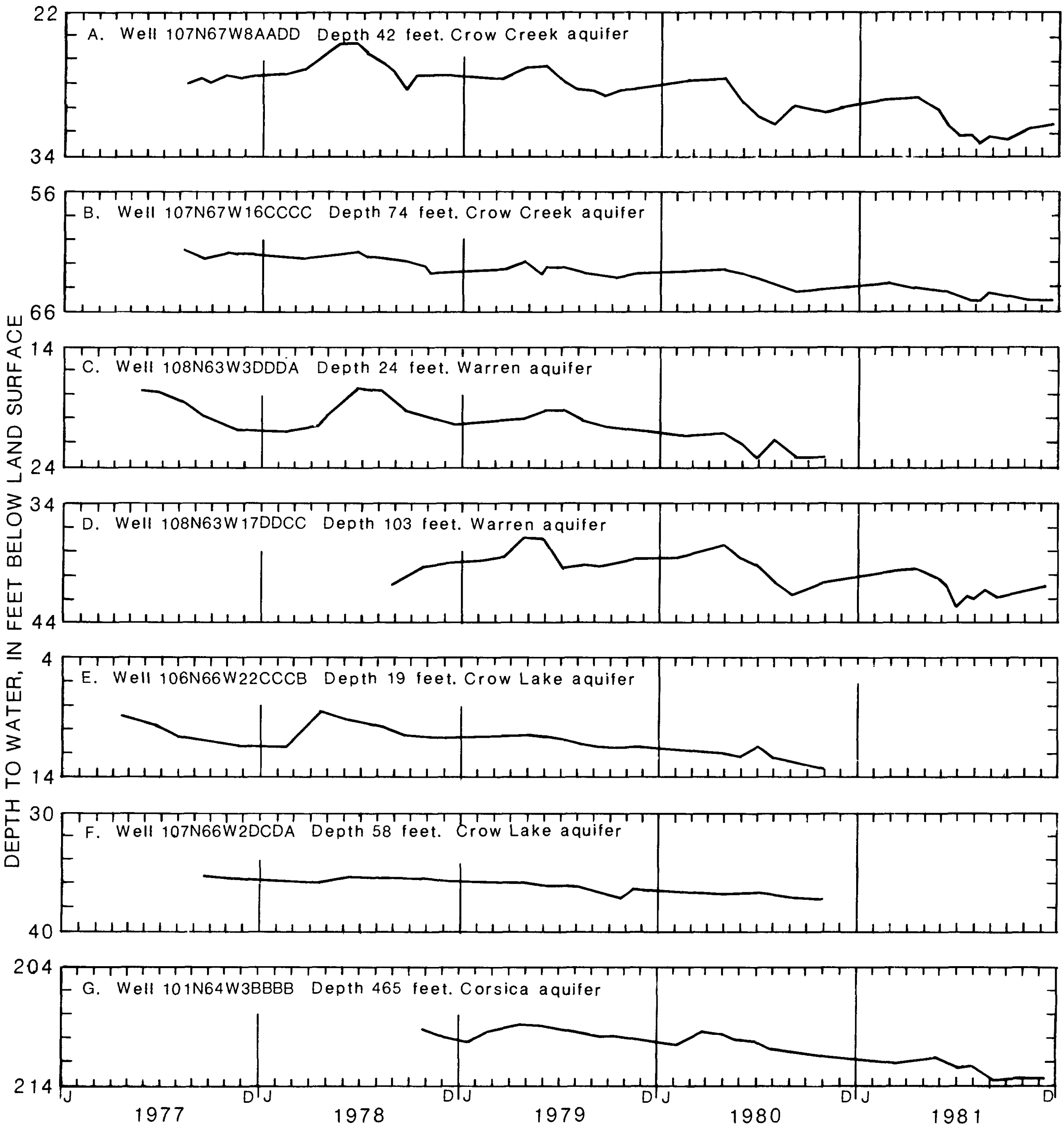


Figure 11.--Water-level changes in wells in glacial aquifers during 1977-81.

Table 7.--Theoretical drawdowns for water-table conditions

Theoretical drawdown, in feet, at various distances from a well pumping continuously at 1,000 gallons per minute from a glacial aquifer under water-table conditions. The aquifer is assumed to be infinite in areal extent.1/ Transmissivity = 13,000 square feet per day; specific yield = 0.2

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

1/ Since the glacial aquifers in Aurora and Jerauld Counties are limited in areal extent, the actual drawdown may be much greater than shown because of nearby poorly permeable boundaries.

Table 8.--Theoretical drawdowns for artesian conditions

Theoretical drawdown, in feet, at various distances from a well pumping continuously at 1,000 gallons per minute from a glacial aquifer under artesian conditions.1/ The aquifer is assumed to be infinite in areal extent.2/ Transmissivity = 13,000 square feet per day; storage coefficient = 0.0001

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

1/ The effects of pumping a well in a confined aquifer will nearly always be much larger than shown here, since the effects of nearby boundaries will be much greater.

2/ Since the glacial aquifers in Aurora and Jerauld Counties are limited in areal extent, the actual drawdown may be much greater than shown because of nearly poorly permeable boundaries.

As additional wells are completed in an aquifer, drawdown increases due to interference from adjacent wells. The interference is additive and increases as well spacing decreases. Thus, if four other wells at a distance of 1,000 ft from a center well have each pumped 1,000 gal/min continuously for 100 days from the water-table aquifer of table 7, then the 3-ft interference for each of the 4 wells add up to an interference drawdown of 12 ft at the center well. In this situation, if the thickness of the aquifer is only a few tens of feet, there would be large, temporary dewatering of the upper part of the aquifer and a consequent decrease in the efficiency and yield of the center well.

In addition to increased drawdowns due to well interference, it is likely that adjacent marshes and streams which are hydraulically connected to the aquifer would dry up during prolonged periods of pumping from the Crow Creek aquifer.

Crow Lake Aquifer

The Crow Lake aquifer, composed of permeable, well-sorted, medium to very coarse sand and gravel, underlies 50 mi^2 at depths of 16 to as much as 180 ft (fig. 8). The aquifer thickness ranges from 6 to more than 60 ft and exceeds 30 ft beneath about 16 mi^2, where the transmissivity is estimated to exceed 13,000 ft^2/d (fig. 9). The potential yield of wells can be as large as 1,000 gal/min in areas of large transmissivity.

Recharge of the Crow Lake aquifer, estimated to average 3,800 acre-ft (1.4 inches) annually (table 6), is by infiltration of precipitation through overlying till or alluvium. Some recharge also is from adjacent till. Recharge is estimated as equal to the sum of pumpage and ground-water outflow at the southern downgradient end of the aquifer. The outflow of 3,700 acre-ft/yr is the product of the gradient (20 ft/mi southeast; fig. 10), average transmissivity (11,000 ft^2/d), and aquifer length perpendicular to the direction of flow (2 mi). Discharge is to the White Lake aquifer, pumpage, and evapotranspiration.

Storage changes in the Crow Lake aquifer were similar to those described for the Crow Creek aquifer. In spring during 1977-80, water levels rose 0.5 to 2.5 ft from decreased pumpage and increased recharge (fig. 11, wells E, F). The levels declined 0.3 to 2.0 ft during summer because of decreased recharge and increased evapotranspiration and pumpage.

Effects of withdrawals of water, totaling 140 acre-ft in 1979, generally were very small, except for a large drawdown near one of the two irrigation wells developed in the aquifer. Temporary drawdown at an observation well located 20 ft from irrigation well 108N66W25BCBD was about 25 ft after 12 hours pumping at a reported rate of about 600 gal/min. The drawdown is larger than for several other aquifers because the transmissivity is relatively small, the aquifer is artesian, and there is a nearby poorly permeable boundary. In areas of higher transmissivity, drawdowns that can be expected are shown in table 7 or table 8. Future large and extensive withdrawals from the aquifer could cause interference between wells, similar to that predicted for the Crow Creek aquifer.

Warren Aquifer

The Warren aquifer, composed of permeable, fine to very coarse sand and gravel, underlies about 60 mi^2 at depths of 4 to as much as 82 ft (fig. 8). The aquifer thickness ranges from 2 to 80 ft and exceeds 30 ft beneath 20 mi^2, where the transmissivity is estimated to exceed 13,000 ft^2/d (fig. 9). The potential yield of wells can be as large as 1,000 gal/min.

Recharge to the Warren aquifer, estimated to average 2,200 acre-ft (1.0 inch) annually, is by infiltration of precipitation through overlying till and some lateral seepage from adjacent till. Recharge is estimated equal to the sum of pumpage and ground-water outflow at the eastern downgradient side of the aquifer. The outflow of 1,400 acre-ft/yr is the product of the gradient (7 ft/mi eastward, fig. 10), average transmissivity (3,000 ft^2/d), and aquifer length perpendicular to the direction of flow (9 mi). Discharge is by pumpage, evapotranspiration, and seepage into Sand Creek. The aquifer contacts and discharges into the Niobrara bedrock aquifer in T. 106 N., R. 63 W. (fig. 7, C-C').

Storage changes in the Warren aquifer were similar to those described for the Crow Creek aquifer. In winter and spring during 1977-81, water levels rose 0.2 to 3.5 ft as a result of decreased pumpage and increased recharge (fig. 11, wells C, D). The levels declined during summer because of decreased recharge and increased pumpage. Pumpage of irrigation well 108N63W20ABCC at a rate of 900 gal/min during summer caused a 2.5- to 4-ft decline in the water level in well D, located about 2,000 ft from the pumped well. These declines were approximately one-half to one-third of the expected theoretical drawdown for an artesian aquifer because the transmissivity is two to three times higher than that assumed for table 8. A 3-day pumping test of the well indicates the transmissivity exceeds 27,000 ft^2/d within the test area.

Effects of future large and extensive withdrawals from the aquifer would be interference between wells, similar to that predicted for the Crow Creek aquifer. In addition, adjacent marshes and streams that are hydrologically connected to the Warren aquifer probably would dry up during prolonged pumping.

White Lake Aquifer

The White Lake aquifer, composed of moderately permeable, fine to coarse, clayey sand and gravel, underlies about 40 mi^2 at depths from 6 to as much as 124 ft (fig. 8). The aquifer thickness ranges from 4 to 100 ft and exceeds 30 ft beneath 7 mi^2. The transmissivity of much of the aquifer probably is less than 7,000 ft^2/d because of its small thickness and moderate permeability. The potential yield of wells is unknown.

Recharge of the White Lake aquifer, estimated to average 1,800 acre-ft (0.8 inch) annually, is by infiltration of precipitation and lateral seepage from till. Discharge is mostly by evapotranspiration.

Corsica Aquifer

The Corsica aquifer, composed of permeable, very fine to very coarse sand and fine gravel, underlies 120 mi^2 at depths from 78 to as much as 420 ft (fig. 8). In T. 102 N., R. 64 W. and 65 W., the aquifer is composed of 2 or 3 layers separated by as much as 100 ft of poorly permeable, clayey till. The cumulative thickness of the aquifer ranges from 3 to more than 70 ft and exceeds 30 ft beneath 30 mi^2. Where the transmissivity exceeds 13,000 ft^2/d (fig. 9), the potential yield of wells open to all layers of the aquifer can be as large as 1,000 gal/min.

Recharge of the Corsica aquifer, estimated to average about 3,400 acre-ft (0.5 inch) annually, is by infiltration of precipitation from overlying till. Some recharge is from adjacent till and bedrock aquifers. Recharge is estimated equal to the sum of pumpage and ground-water outflow at the southeastern downgradient side of the aquifer (fig. 10). The outflow of 3,370 acre-ft/yr is the product of the gradient (8 ft/mi southward), average transmissivity (6,000 ft^2/d), and aquifer length perpendicular to the direction of flow (8 mi). Discharge from the aquifer in the study area is by small pumpage and recharge into the Niobrara and Codell aquifers.

Storage changes in the Corsica aquifer were similar to those described for the other aquifers. Changes were indicated by a water-level rise of as much as 1 ft during 1979-81 from increased recharge in spring. A subsequent decline of as much as 2 ft occurred during summer and fall because of decreased recharge and increased pumpage (fig. 11, well G).

Effects of future large and extensive withdrawals from the aquifer could be interference between wells larger than that predicted for the Crow Creek and Warren aquifers because the Corsica aquifer is confined under artesian conditions.

Minor Glacial Aquifers

Sand and gravel aquifers that lie beyond the boundaries of major aquifers are found in many townships (fig. 6). In several of the townships the cumulative thickness of sand and gravel beds locally can exceed 25 ft. However, wells that are screened opposite several thin beds probably yield less water than a well screened in the same thickness in a single layer. This is because a thin aquifer layer can become unsaturated more readily than a thick layer that discharges into a pumping well. Pumpage of large-capacity wells in minor aquifers could cause rapid dewatering of the aquifer and reduction of yields because many of these aquifers are not extensive and receive less recharge than major aquifers.

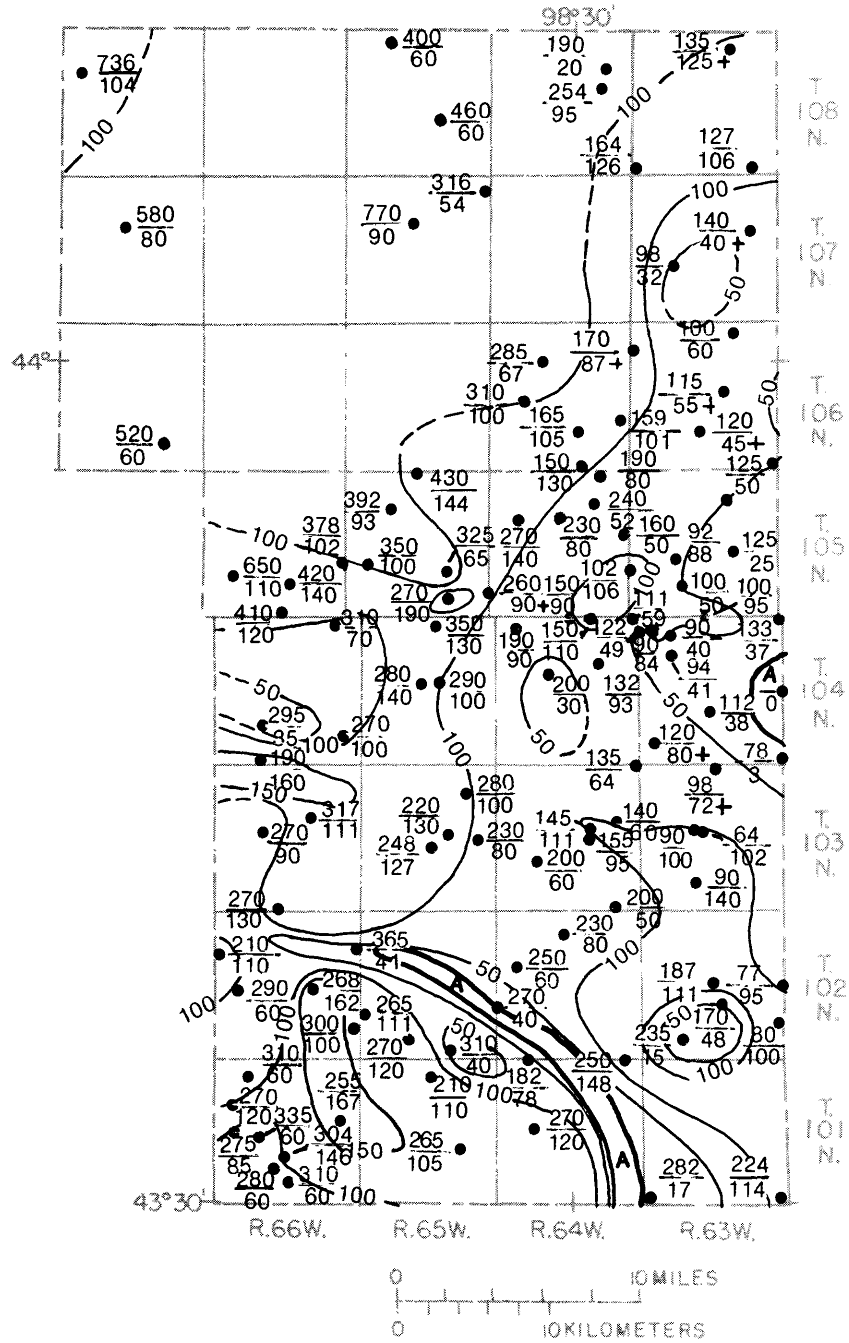
Bedrock Aquifers

Three major bedrock aquifers composed of chalk, marl, siltstone, and shaly sandstone underlie much of the study area and each stores from 6 to 40 million acre-ft of water (table 6). Recharge to the Niobrara and Codell aquifers is by infiltration of precipitation through glacial deposits. The Dakota aquifer is not recharged in the study area. Discharge is through pumped and flowing wells. Municipal wells are the only large-capacity wells in these aquifers because the water generally is of unsuitable quality for use in irrigation. The uppermost bedrock formation, the Pierre Shale (table 1), yields small amounts of water to domestic and stock wells and is not a major aquifer.

Niobrara Aquifer

The Niobrara aquifer, called "chalk" or "chalkstone" by drillers, underlies most of the study area. It is composed of as much as 190 ft of gray, firm to soft, thin-bedded chalk and calcareous claystone (marl) that is interbedded with very soft, dark-gray, calcareous shale. In much of the area the aquifer underlies the Pierre Shale (fig. 7 and table 1). In areas where the chalk is thick, fractured, and weathered, the aquifer probably can supply large-capacity wells. The aquifer probably is a poorly permeable, calcareous shale in northwestern Aurora and western Jerauld Counties.

The thickness of the aquifer varies greatly but tends to be greatest in southern Aurora County (fig. 12). Depths to the top of the aquifer range from 77 ft in the eastern part to 770 ft in the western part of the study area. The transmissivity is estimated to range from 50,000 ft^2/d to about 1 ft^2/d, but probably averages about 4,000 ft^2/d in much of the area. A screened irrigation well in the aquifer had a yield of



EXPLANATION

A — AQUIFER ABSENT

——100-- LINE OF EQUAL THICKNESS OF AQUIFER--Dashed where approximately located. Interval 50 feet.

• 248/127 WELL OR TEST HOLE--Upper number is depth to top of aquifer, in feet; lower number is aquifer thickness, in feet. A plus signifies thickness may be greater than shown.

Figure 12.--Extent, depth, and thickness of the Niobrara aquifer.

1,500 gal/min in sec. 6, T. 104 N., R. 63 W. Yields of other wells are reported to range from 2 to 40 gal/min. The average yield probably could be increased if screens instead of slotted casings were installed in more wells.

Although the Niobrara aquifer is artesian it is recharged from overlying deposits and recharges the underlying Codell aquifer in much of the study area. In an area where the Niobrara has sufficiently high artesian head to supply flowing wells (sec. 20, T. 104 N., R. 63 W.), it also recharges overlying deposits and nearby glacial aquifers. In southern Aurora County the Niobrara also recharges a glacial aquifer along a deep erosional channel that was cut through the Niobrara aquifer (fig. 13). The depth to water in wells ranges from 20 ft or less in the eastern part of the area to 150 ft in central Aurora and to 250 ft in southwestern Aurora County.

Eastward outflow of 5,600 acre-ft/yr of water is estimated as the product of the eastward slope of the potentiometric surface (5 ft/mi), the average transmissivity of the aquifer (4,000 ft^2/d), and the aquifer length perpendicular to the direction of flow (33 mi). Outflow south is estimated to be 3,400 acre-ft/yr. The total outflow of 9,000 acre-ft/yr should be balanced by an equal amount of recharge. Pumpage, losses by evapotranspiration, and changes in storage are a negligible part of the budget (table 6).

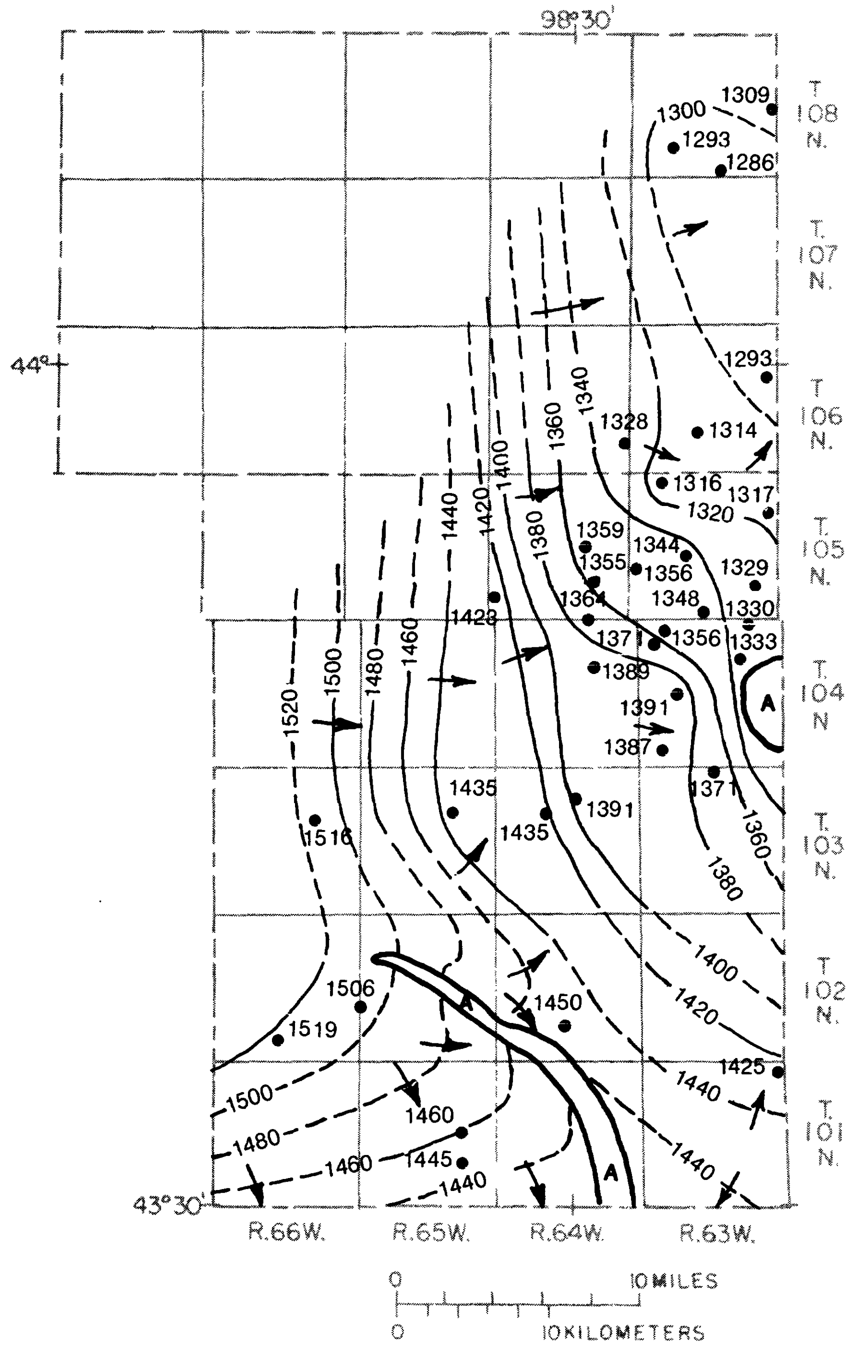
Recharge in most of the study area is slow because the aquifer is overlain by poorly permeable shale or clayey till. Recharge is probably greatest in T. 104 and 105 N., R. 63 W., where the aquifer is overlain by sandy, permeable till. The absence of a recharge mound on the potentiometric surface there is due to the relatively large transmissivity of the aquifer.

The potentiometric map also is useful in locating areas where it may be possible to obtain large-capacity wells. A large spacing between contours indicates that the gradient is lower because the transmissivity is larger there than in adjacent areas, assuming the rate of recharge is uniform. Additional test drilling and aquifer tests are customary where development of large-capacity wells is planned.

Changes in storage in the Niobrara aquifer are negligible because almost all wells pump only a few gallons per minute. Only one well was known to affect storage. An irrigation well at 104N63W6ADBB, pumping intermittently for a month during 1979 at a metered rate of 1,500 gal/min, caused the water level to temporarily decline as much as 40 ft in an observation well one-half mile west of the pumping well (fig. 14, hydrograph A). When pumping stopped, recovery of the water level was 75 percent after 2 months and nearly 100 percent after 8 months. Three miles from the irrigation well (fig. 14, hydrograph C) the drawdown was about 3 ft. Drawdown could be detected over an area of 40 mi^2 but the temporary decrease in storage was only 26 acre-ft because of the small artesian coefficient of storage.

Codell Aquifer

The Codell aquifer, called "sandrock" by drillers, underlies much of the study area. The Codell underlies the Niobrara aquifer and is within the Carlile Shale. Locally, the Codell is separated from the Niobrara by more than 100 ft of shale. The aquifer is composed of up to 136 ft of gray, brown, reddish-brown, green, or black cemented, fine- to medium-grained sandstone, siltstone, and much soft, fine to medium sand and silty shale. The thickness of the aquifer exceeds 50 ft in most of the eastern one-half of the study area (fig. 15). The aquifer thins westward and is absent along



EXPLANATION

[A] AQUIFER ABSENT

——1300—— POTENTIOMETRIC CONTOUR--Shows altitude of the potentiometric surface in 1977-79. Dashed where approximately located. Interval 20 feet. Datum is sea level.

• 1387 WELL IN THE NIOBRARA AQUIFER--Number is altitude of the water level, in feet. Datum is sea level.

→ GENERAL DIRECTION OF GROUND-WATER MOVEMENT

Figure 13.--Potentiometric contours of the Niobrara aquifer.

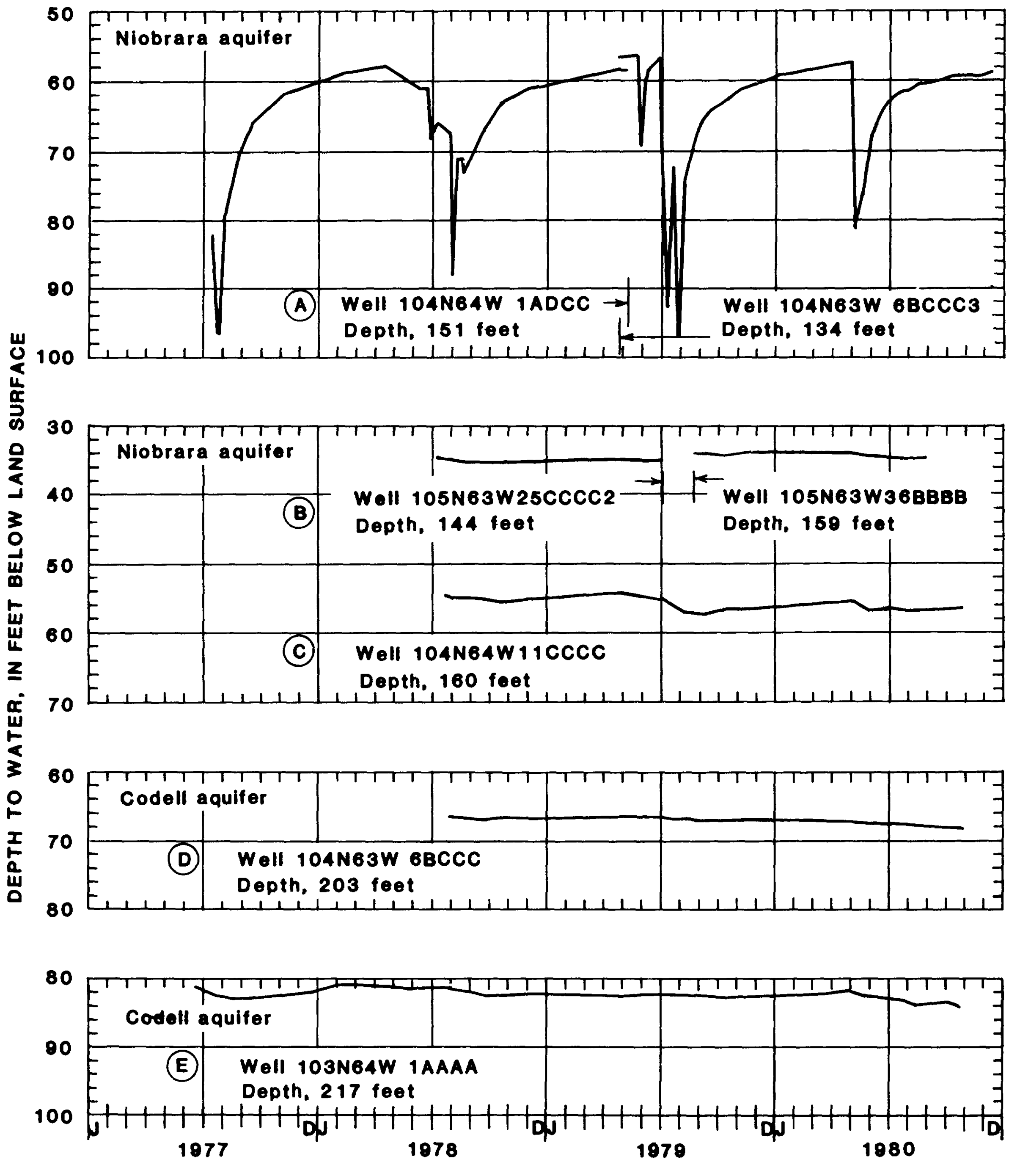
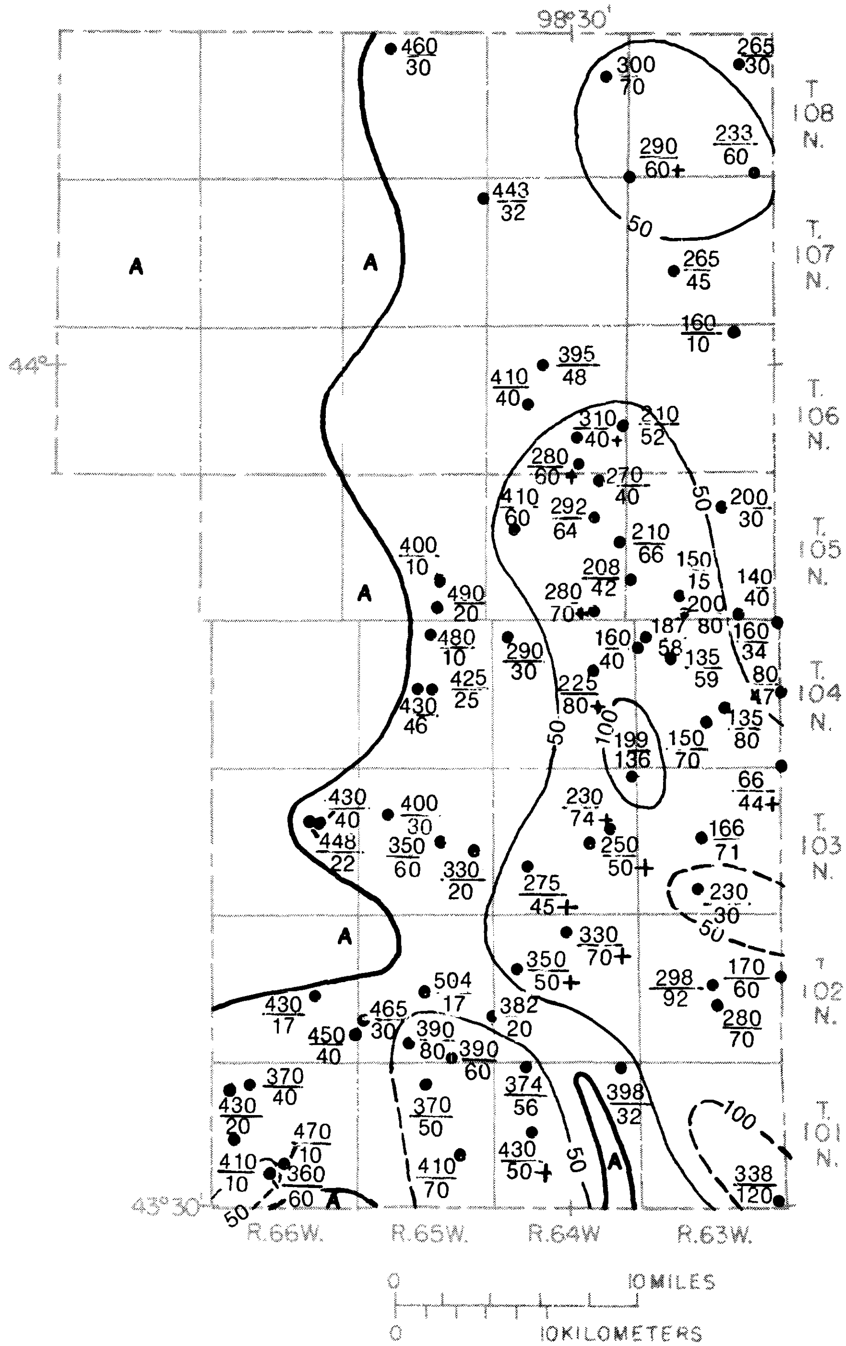


Figure 14.--Water-level changes in wells in the Niobrara and Codell aquifers during 1977-80.



EXPLANATION

A	AQUIFER ABSENT
—— 50 - -	LINE OF EQUAL THICKNESS OF AQUIFER--Dashed where approximately located. Interval 50 feet.
• 430/50+	WELL OR TEST HOLE--Upper number is depth to top of aquifer, in feet; lower number is aquifer thickness, in feet. A plus signifies thickness may be greater than shown.

Figure 15.--Extent, depth, and thickness of the Codell aquifer.

most of the western side of the area. The depth to the top of the aquifer ranges from less than 200 ft in the east to more than 400 ft near the western edge of the aquifer. Based on aquifer thickness and the results of one aquifer test, the transmissivity of the aquifer is estimated to range from 100 to 1,000 ft^2/d and average 700 ft^2/d.

Most wells in the aquifer are located in the southern and eastern part of the area. Well yields range from 2 to 100 gal/min.

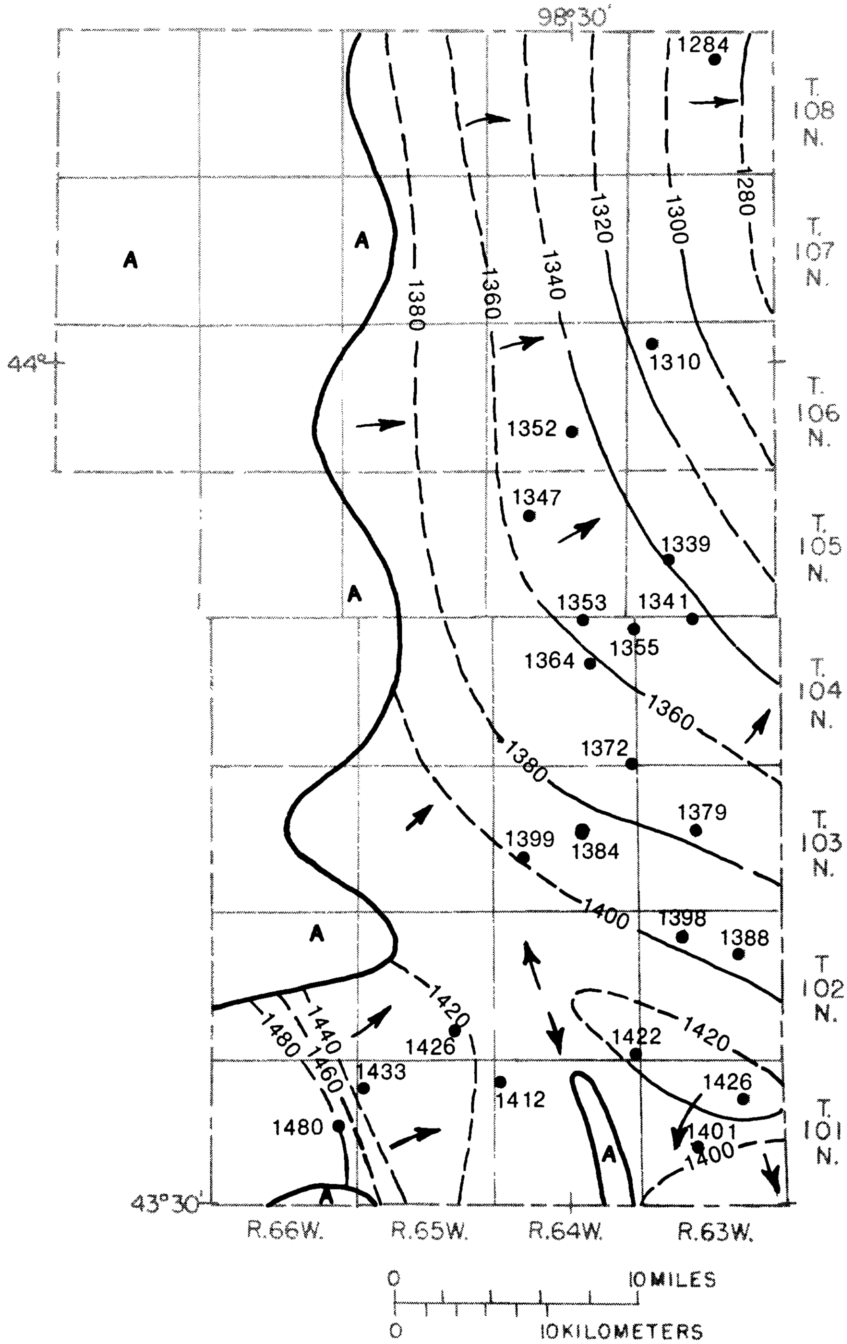
The Codell is an artesian aquifer but wells in the aquifer do not flow. The depth to water in wells ranges from 30 ft in northeastern Jerauld County to 240 ft in southeastern Aurora County. Water flows generally northeastward, in the direction of the maximum slope of the potentiometric surface (fig. 16). Outflow is estimated at 1,700 acre-ft/yr from the product of the average slope of the potentiometric surface (6 ft/mi), the average transmissivity (700 ft^2/d), and the aquifer length measured along the contours (50 mi). Outflow is balanced by an equal amount of recharge because changes in storage and pumpage are a small part of the budget. Recharge is from infiltration of precipitation through glacial deposits and the Niobrara aquifer. The head on the Niobrara ranges from a few feet above that for the Codell in eastern Jerauld County to many tens of feet above the Codell in western Aurora County. Recharge to the Codell is much less than that to the Niobrara because the Codell generally is overlain by poorly permeable shale.

Changes in storage in the Codell are negligible because most wells pump only a few gallons per minute. The water-level trend of an observation well in the Codell (fig. 14, hydrograph D) showed no effects from the pumping of a nearby irrigation well in the Niobrara aquifer. This probably is because the aquifers are separated by poorly permeable marl. The seasonal 2-ft decline in water level during late spring and summer of 1977 and 1980 in a second observation well may be due to increased pumping of municipal and institutional wells in the Codell at Plankinton, 3½ mi to the southwest (fig. 14, hydrograph E).

The only development of the Codell aquifer probably will be additional small-capacity stock and domestic wells and a few municipal and industrial wells of moderate capacity. Hence, excessive lowering of water levels probably will not occur. However, there may be local interference between pumping wells if several wells, each pumping 100 gal/min, are located in the same section.

Dakota Aquifer

The Dakota aquifer, called "artesian sandrock" or "hard water sand" by drillers, underlies the study area. It lies on top of nearly impermeable Sioux Quartzite and beneath 300 to 400 ft of poorly permeable Carlile Shale and Graneros Shale (table 1). The Dakota is composed of interbedded tan, gray, and white siltstone, sandstone, and shale. The consolidation of beds ranges from hard, dense, and cemented to soft, loose, and susceptible to caving into well openings. The thickness of the Dakota aquifer increases from about 50 ft over the buried ridge of Sioux Quartzite in southern Aurora County to about 500 ft in northern Jerauld County (fig. 17). The aquifer is thin or may be missing in the northwest corner of T. 104 N., R. 63 W., where a buried quartzite hill penetrates upward through the Dakota. Such hills probably exist elsewhere in the study area.



EXPLANATION

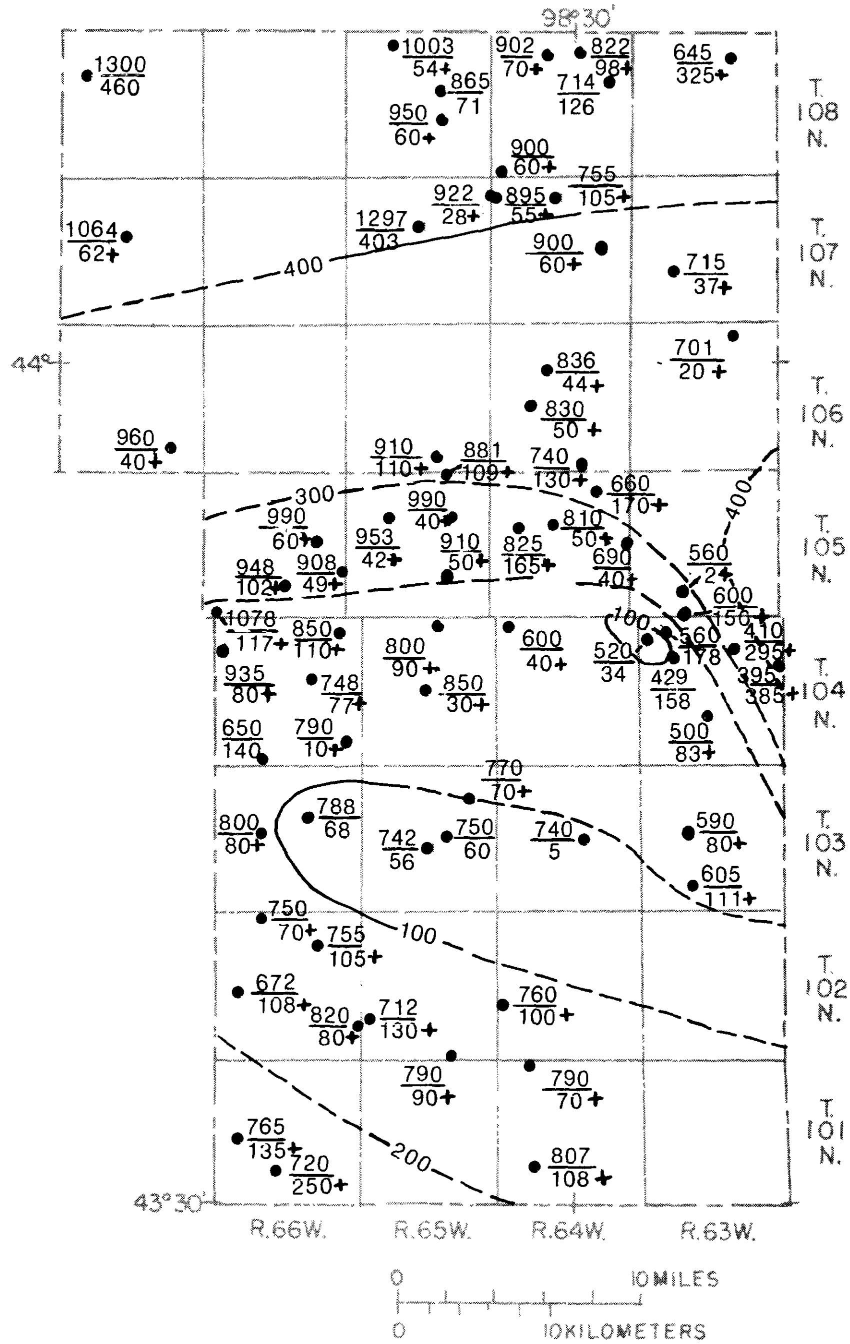
A AQUIFER ABSENT

—1400-- POTENTIOMETRIC CONTOUR--Shows altitude of the potentiometric surface in 1977-79. Dashed where approximately located. Interval 20 feet. Datum is sea level.

• 1384 WELL IN THE CODELL AQUIFER--Number is altitude of water level, in feet. Datum is sea level.

→ GENERAL DIRECTION OF GROUND-WATER MOVEMENT

Figure 16.--Potentiometric contours of the Codell aquifer.



EXPLANATION

—— 400 - - - LINE OF EQUAL THICKNESS OF AQUIFER--Dashed where approximately located. Interval 100 feet.

850• / 110+ WELL OR TEST HOLE--Upper number is depth to top of aquifer, in feet; lower number is aquifer thickness, in feet. A plus signifies thickness may be greater than shown.

Figure 17.--Extent, depth, and thickness of the Dakota aquifer.

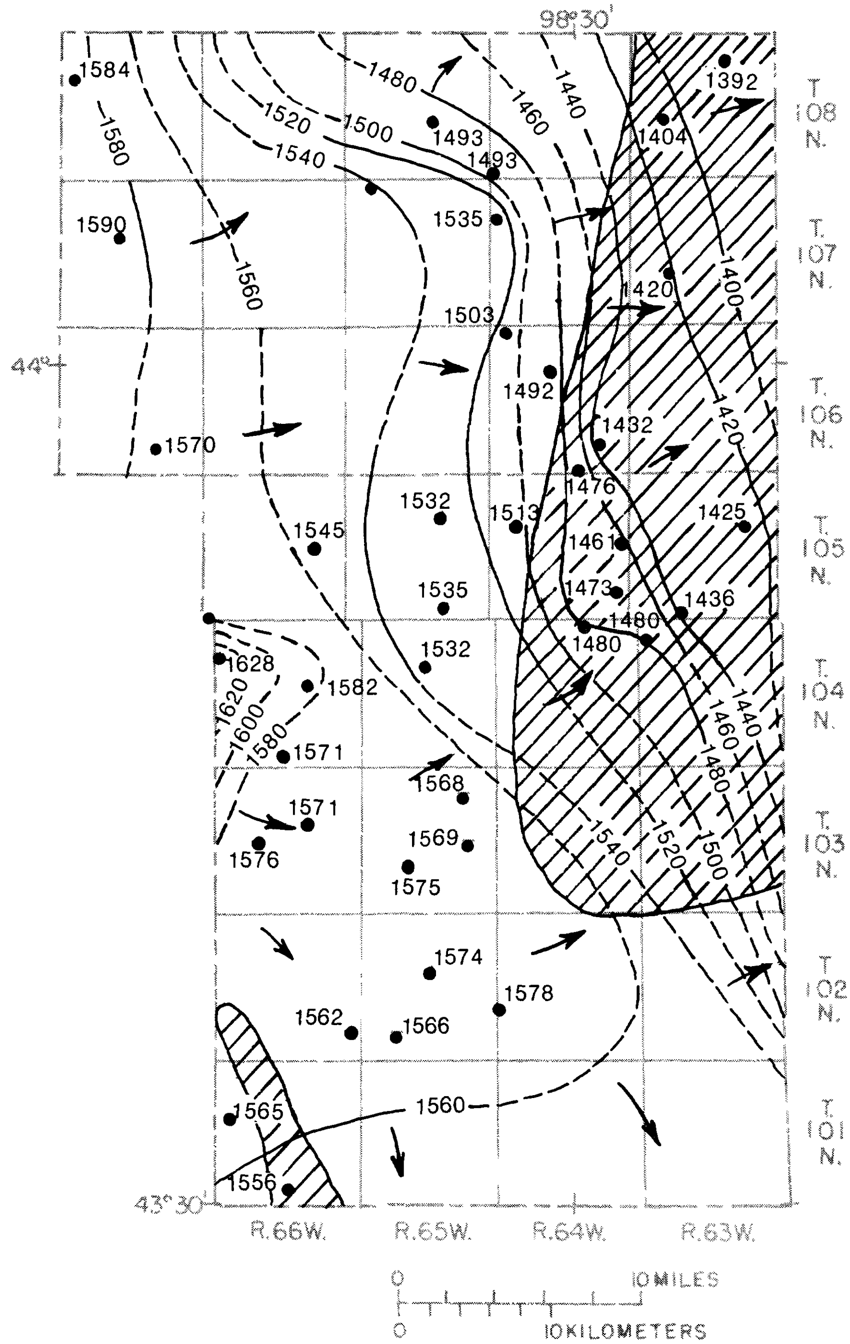
The depth to the top of the aquifer ranges from about 400 ft in northeastern Aurora County to 800 ft in the western and southern parts of the county to 1,300 ft in northwestern Jerauld County. The transmissivity of the Dakota is estimated to range from 300 to 13,000 ft^2/d and probably averages 4,000 ft^2/d. These estimates are based on aquifer thickness and the results of one aquifer test.

Many wells in the Dakota aquifer flow in the James River basin areas in eastern Jerauld County and in northeastern and southwestern Aurora County (fig. 18). Flowing wells are reported to yield from 5 to 150 gal/min. Pumped wells probably could yield as much as 500 gal/min. Depths to water in wells range from above land surface in southwestern Aurora County to a reported 430 ft below land surface in northwestern Jerauld County.

Ground water flows generally northeastward in the direction of the maximum slope of the potentiometric surface (fig. 18). Northeastward flow is estimated at nearly 15,700 acre-ft/yr from the product of the average slope of the potentiometric surface (10 ft/mi), the average transmissivity (4,000 ft^2/d), and the aquifer length measured along the contours (45 mi). A similar computation indicates a southward outflow in T. 101 N. of 2,200 acre-ft/yr. Discharge through wells is estimated to be nearly 2,200 acre-ft/yr. Subsurface outflow and well discharge of 20,000 acre-ft/yr is balanced by subsurface inflow from west of the study area and a decrease in storage. Recharge to the Dakota aquifer in eastern South Dakota, as first proposed by Dyer and Goehring (1965), is probably derived from water that enters the Madison (Pahasapa) Limestone in the Black Hills of western South Dakota. The recharge water flows eastward to the central part of South Dakota, where the limestone aquifer pinches out. The water then probably moves upward to recharge the Dakota (Swenson, 1968, p. 174).

The long-term decrease in water storage in the Dakota aquifer in Jerauld and Aurora Counties was estimated by comparing the potentiometric surface of the aquifer in 1909 (Schoon, 1971, fig. 15) with the most recent potentiometric surface (fig. 18). The decline in artesian head averages about 200 ft. The equivalent decrease in storage, using 0.0001 as the coefficient of storage, is estimated to be nearly 13 acre-ft/mi^2. This totals nearly 10,000 acre-ft for the study area.

Since the first half of the 20th century many low-pressure wells in the Dakota have stopped flowing. Some well owners have taken care to restrict the flow of their wells. Although this has resulted in a decrease in the rate of decline in artesian head, the decline during the period 1960-79 ranged from 12 to 27 ft in wells tapping the aquifer in Aurora County (fig. 19), and in Jerauld County (fig. 20). The greatest decrease in storage was 1.7 acre-ft/mi^2 near well 105N64W13DDA (fig. 19, well A). This well showed the greatest annual rate of head decline, about 2 ft/yr, during 1972-79. This was due to 10 new flowing wells, having an estimated combined discharge of about 250 gal/min, being completed in the aquifer within a 10-mi radius of the well. If this discharge is increased so the artesian head decreases at the same rate, well 105N64W13DDA may cease flowing about the year 2000. Many wells will cease flowing in other parts of the area if similar increases in discharge occur. If, however, the rate of withdrawal is stabilized at 1,970 acre-ft/yr (table 3), wells may flow in the area for an additional 100 years.



EXPLANATION

AREA OF FLOWING WELLS

— 1500 — — POTENTIOMETRIC CONTOUR--Shows altitude of the potentiometric surface in 1976-78. Dashed where approximately located. Interval 20 feet. Datum is sea level.

1568 WELL IN THE DAKOTA AQUIFER--Number is altitude of water level, in feet. Datum is sea level.

→ GENERAL DIRECTION OF GROUND-WATER MOVEMENT

Figure 18.--Potentiometric contours of the Dakota aquifer.

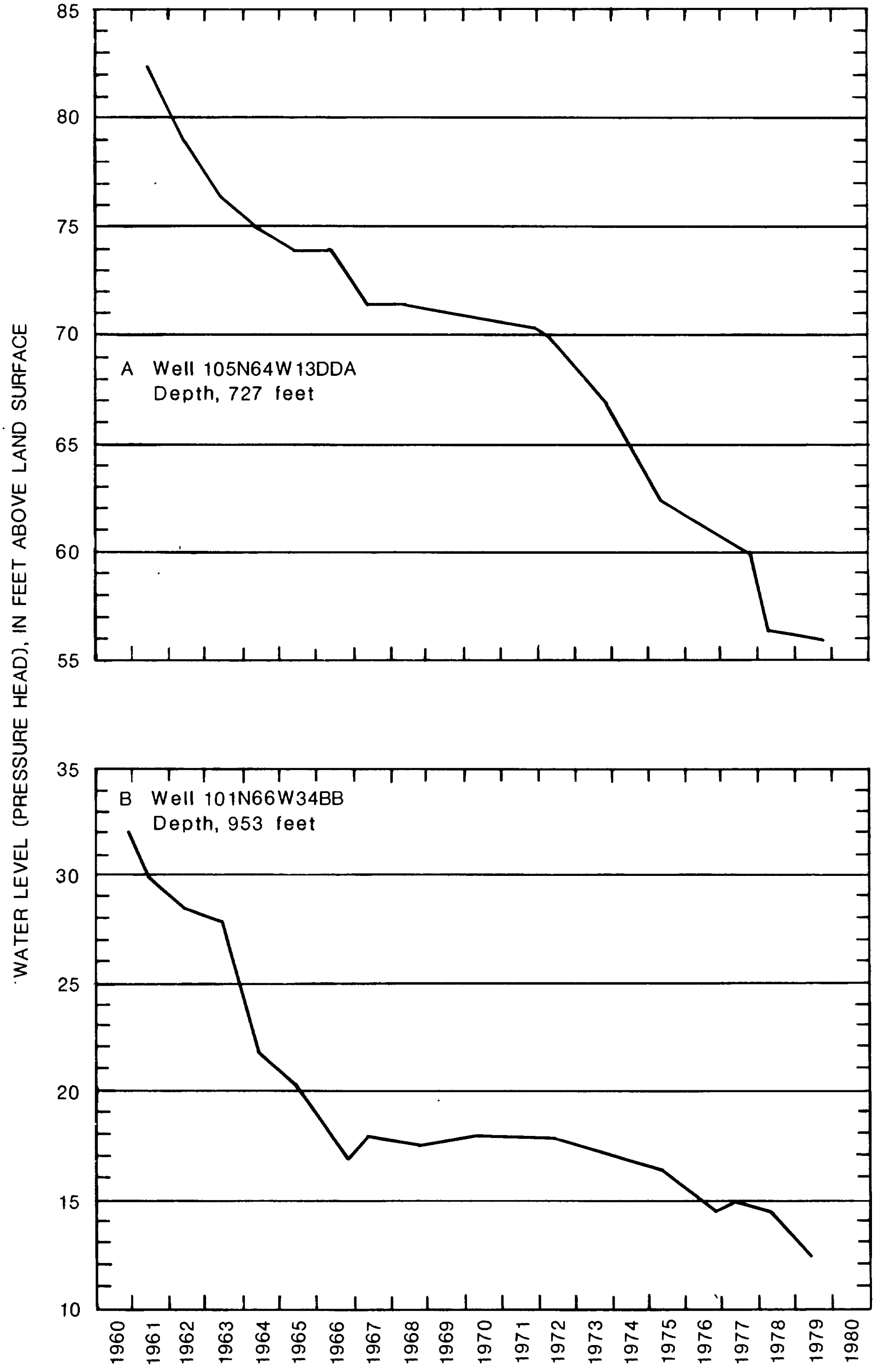


Figure 19.--Water-level changes in wells in the Dakota aquifer in Aurora County during 1960-80.

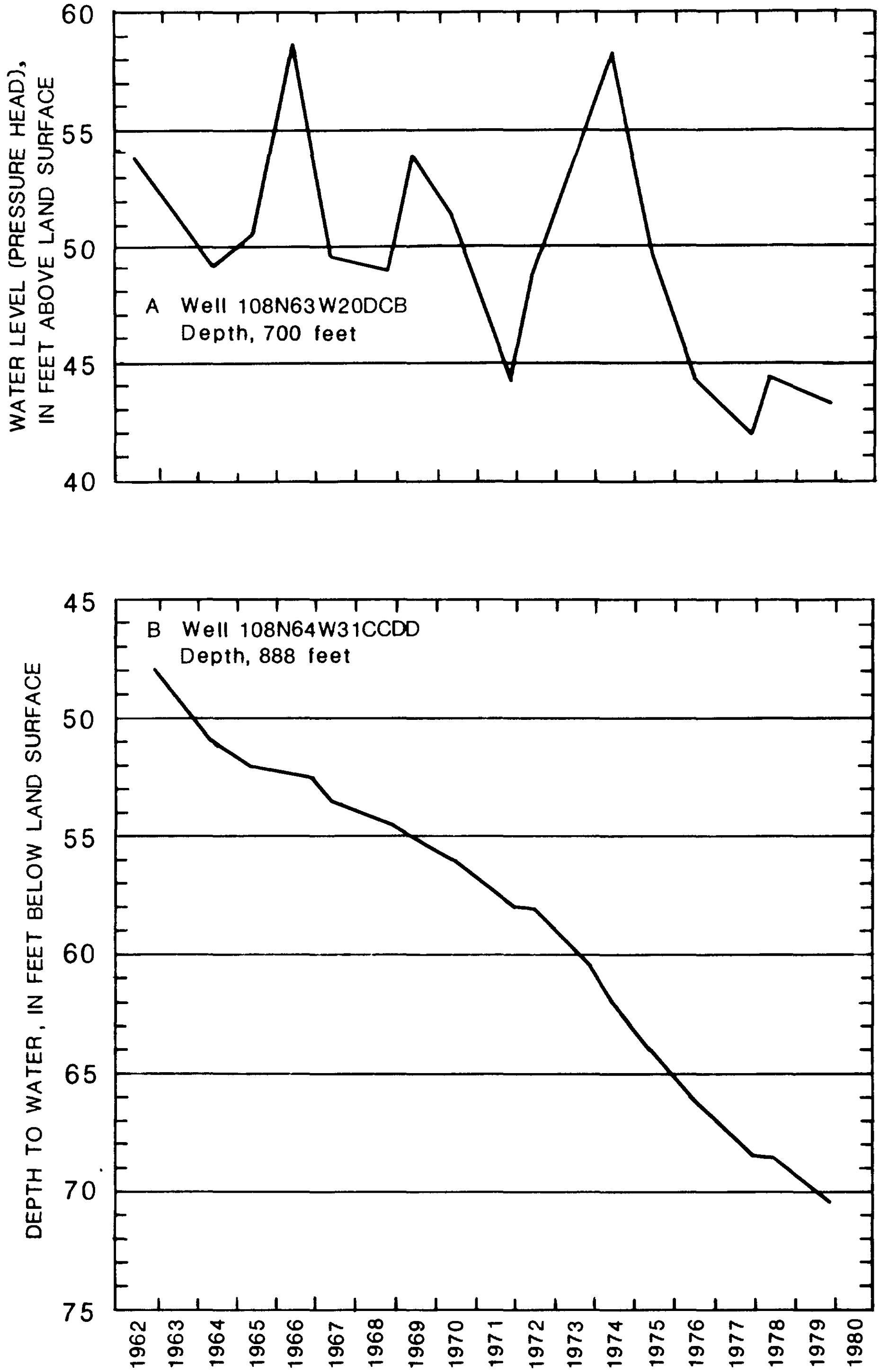


Figure 20.--Water-level changes in wells in the Dakota aquifer in Jerauld County during 1962-80.

WATER QUALITY

The importance of the various chemical constituents in water is related to their concentration and also the use made of the water. Surface water in the study area generally contains less than 1,000 mg/L (milligrams per liter) dissolved solids, but the ground water generally has more than 1,000 mg/L and is classified as slightly saline (table 9). Concentrations of dissolved solids in water from glacial aquifers range from 320 to 2,650 mg/L. Water from bedrock aquifers has concentrations of dissolved solids ranging from 1,540 to 2,220 mg/L. Calcium, magnesium, sodium, bicarbonate, and sulfate compose more than 90 percent by weight of the constituents in water in the study area.

Suitability of the Water for Various Uses

Although most of the ground water in the study area is slightly saline, it is suitable for many uses. Some of the water needs treatment to reduce excessive amounts of turbidity, iron, manganese, or hardness. In some aquifers, concentrations of dissolved iron exceed the recommended limit of 0.3 mg/L and concentrations of dissolved manganese exceed the recommended limit of 0.05 mg/L (table 10). Much of the ground water is very hard, having a hardness of more than 180 mg/L. Water from the Dakota aquifer contains fluoride in concentrations that exceed the recommended limit and may cause mottling of children's teeth. Only three of the selected samples contained concentrations of nitrate that could indicate pollution. However, wells less than 30 ft deep could be vulnerable to pollution from barnyards, feedlots, and septic tanks if the depth to the well screen is not sufficient to permit adequate adsorption and filtration of pollutants from water.

The concentrations of other minor or trace elements are all less than the recommended limit except for excessive barium in one sample (table 11, sample 33). A large barium concentration is not representative of ground water in the study area.

The suitability of water for irrigation use depends primarily on its specific conductance and on its concentrations of dissolved sodium. Much of the water from streams, lakes, glacial aquifers, and the Dakota aquifer in the study area meet South Dakota standards for use in irrigation when applied with regard to soil classes (fig. 21). This is because the specific conductance of the water is less than 1,000 umhos/cm after reducing it for calcium, sulfate, and rainfall, as described below. In contrast, a sample of water from the Corsica aquifer has a specific conductance of 3,300 umhos/cm (table 9, sample 24). This is above all soil classes in the diagram, but the classes can be raised (or the conductance values reduced) as noted in the explanation of the diagram (fig. 21). The conductance can be reduced by 400 umhos/cm because rainfall averages nearly 16 inches during the frost-free season. The conductance can be reduced another 400 umhos/cm because the sample contained more than 200 mg/L of calcium and 960 mg/L of sulfate. Thus, the total displacement would be 800 umhos/cm downward, the sample plotting at a conductance level of only 2,500 umhos/cm. Samples from other aquifers were adjusted in the same way. Even with the adjustment for specific conductance, the sample of water from the Corsica aquifer would only be suitable for applying to sand (soil classes A1 and A2) because the adjusted sodium-adsorption ratio multiplied by 0.7 is 10.5 (fig. 21).

Most water from the Niobrara and Codell aquifers has an adjusted sodium-adsorption ratio, multiplied by 0.7, of much more than 12 and cannot be plotted in the diagram. Such water could, if used for irrigation, create a high sodium (alkali) hazard,

Table 9.—Selected chemical analyses of water. Analyses by U.S. Geological Survey Laboratory unless otherwise noted

Sample number	Location	Date	Silica (SiO_2)	Iron (Fe) (µg/L)	Manganese (Mn) (µg/L)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_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	Total hardness (Ca, Mg)	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos per centimeter at 25°C)	pH (units)
	Reported in milligrams per liter (mg/L) except as indicated. One milligram per liter is approximately equal to one part per million. One microgram per liter (µg/L) is approximately equal to one part per billion.																					
	STREAMS AND LAKES																					
	Crow Lake																					
1	102N66W 7BCBC3/	4-14-77	—	200	< 50	120	250	150	—	84	1,150	28	—	0.23	—	—	1,660	—	1,330	0.8	2,000	9.8
2	102N66W 7BCBC1/	6- 8-78	—	—	—	—	—	—	—	225	—	10	—	—	—	—	—	270	235	—	540	—
	Twin Lakes																					
3	106N62W30 2/	5-31-79	—	—	—	—	—	—	—	50	3,280	309	—	<.1	4/0.04	—	5,590	—	2,490	5.6	5,100	9.1
	Firesteel Creek																					
4	104N62W26CCCC	4-14-77	19	—	—	93	30	100	14	200	330	72	0.2	.04	4/.33	410	—	757	360	2.3	1,170	8.2
5	104N62W26CCCC	3-20-80	2.2	60	130	52	23	180	10	244	350	61	.3	.13	—	—	—	801	220	5.2	1,180	8.6
	Wilmarth Lake																					
6	105N65W25 2/	5-31-79	—	—	—	—	—	—	—	234	147	14	—	<.1	4/.12	—	450	—	—	—	625	8.3
	Platte Lake																					
7	102N66W 7ABB3/	4-14-77	—	200	< 50	25	25	30	—	146	50	13	—	<.1	—	—	230	—	165	1.0	425	8.2
8	102N66W 7ABB1/	6-13-78	—	—	—	—	—	—	—	160	—	17	—	—	—	—	—	180	115	—	340	—
	Deans Lake																					
9	107N65W22AAAA3/	5-12-77	—	100	100	45	45	15	—	230	70	2.5	—	<.1	—	—	290	—	297	.4	580	8.4
10	107N65W22AAAA1/	6- 8-78	—	—	—	—	—	—	—	225	—	6.0	—	—	—	—	—	300	300	—	610	—
	Long Lake																					
11	108N66W 2DDDC3/	5-12-77	—	100	200	35	32	15	—	210	< 25	2.5	—	<.1	—	—	220	—	218	.4	480	7.3
	Long Lake																					
12	108N66W11DDCC1/	6- 8-78	—	—	—	—	—	—	—	205	—	10	—	—	—	—	—	220	185	—	440	—
	Fish Lake																					
13	103N63W16DCBA1/	6-13-78	—	—	—	—	—	—	—	290	—	10	—	—	—	—	—	250	220	—	500	—
	White Lake																					
14	104N66W28BBBA1/	6-13-78	—	—	—	—	—	—	—	310	—	10	—	—	—	—	—	230	200	—	470	—

Table 9.--Selected chemical analyses of water. Analyses by U.S. Geological Survey Laboratory unless otherwise noted--Continued

Reported in milligrams per liter (mg/L) except as indicated. One milligram per liter is approximately equal to one part per million. One microgram per liter (μg/L) is approximately equal to one part per billion.

Sample number	Location	Date	Silica (SiO_2)	Iron (Fe) (μg/L)	Manganese (Mn) (μg/L)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_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	Total hardness (Ca, Mg)	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos per centimeter at 25°C)	pH (units)
	GLACIAL AQUIFERS																					
	Crow Creek aquifer																					
15	108N67W20ADDD	8-30-79	34	150	400	270	66	47	18	560	620	9.0	0.4	0.22	0.03	210	--	1,340	950	0.7	1,750	6.8
16	107N67W17DDBD	8- 8-78	23	80	650	140	42	47	9.4	420	260	15	.3	.06	--	180	--	745	520	.9	1,120	7.7
17	107N67W33DADB	8- 8-78	26	70	1,400	130	36	50	10	420	220	15	.2	.02	--	200	--	696	470	1.0	1,000	7.3
18	106N67W11BBAA	9- 4-79	30	680	1,200	91	22	190	16	410	390	17	.4	.00	.03	730	--	961	320	4.6	1,900	7.2
19	107N65W29BCBA	8-27-79	33	4,200	1,000	170	43	53	16	550	290	4.1	.2	.01	.01	360	--	886	600	.9	1,600	6.7
20	107N66W34DADA	9- 4-79	29	390	1,400	92	25	63	11	310	230	6.2	.3	.01	.03	310	--	436	240	1.8	1,180	7.2
21	106N66W22BDDA	9- 4-79	27	490	1,800	200	55	150	13	410	720	13	.2	.01	.01	630	--	1,380	730	2.4	1,800	7.1
	Warren aquifer																					
22	108N63W20ABCC	6-14-79	29	2,600	430	160	55	230	14	600	550	19	.2	.01	.03	550	1,360	1,360	630	4.0	2,100	6.9
23	108N63W35BBAC	8- 8-78	27	30	410	100	33	70	9.4	420	160	23	.2	.09	--	200	--	631	390	1.6	880	8.0
	Corsica aquifer																					
24	101N64W 4DACA	8-29-79	28	1,200	2,800	240	58	450	31	110	1,700	78	.4	.00	.00	2,600	--	2,650	840	6.8	3,300	7.2
	Minor aquifer																					
--	107N65W13ADBD	6-19-79	32	150	2,400	190	46	79	14	480	420	10	.3	.00	.00	470	860	1,030	670	1.3	1,490	7.0
	BEDROCK AQUIFERS																					
	Niobrara aquifer																					
25	107N63W20DDBD	8-28-79	21	240	80	40	15	530	14	790	500	86	.7	.00	.00	2,600	--	1,600	160	18	2,270	7.6
26	104N63W 2AADD	7-26-78	20	190	20	41	14	460	15	560	630	80	.8	.00	.00	3,500	--	1,540	160	16	2,450	7.8
27	103N66W14BCDB	8-31-77	13	240	60	21	7.0	770	12	680	220	660	1.9	.02	--	5,200	--	2,050	81	37	--	7.8
28	103N65W11CDAC	8-30-79	11	90	20	21	7.6	750	11	620	590	380	1.8	.01	.04	5,100	--	1,780	84	36	3,300	7.7
29	103N64W17DDCD	7-31-79	18	440	80	71	85	570	19	480	980	73	.8	.59	.00	3,900	--	2,060	530	11	3,000	7.5
	Codell aquifer																					
30	104N64W 3AAAA	7-26-78	7.6	80	20	11	4.0	700	9.7	670	480	360	1.3	.00	.00	4,900	--	1,910	44	46	3,150	8.3
31	103N64W15DDCC	9- 1-77	9.2	80	20	27	9.8	570	13	550	810	60	1.4	.00	.05	4,600	1,750	1,780	110	24	2,480	7.9
32	102N63W31CBCA	8-31-77	8.7	930	40	120	37	360	27	390	910	16	.8	.00	--	3,300	--	1,680	450	7.4	2,200	7.9

Table 9.--Selected chemical analyses of water. Analyses by U.S. Geological Survey Laboratory unless otherwise noted--Continued

Reported in milligrams per liter (mg/L) except as indicated. One milligram per liter is approximately equal to one part per million. One microgram per liter (µg/L) is approximately equal to one part per billion.

Sample number	Location	Date	Silica (SiO_2)	Iron (Fe) (µg/L)	Manganese (Mn) (µg/L)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_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	Total hardness (Ca, Mg)	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos per centimeter at 25°C)	pH (units)
	BEDROCK AQUIFERS (Cont.)																					
	Dakota aquifer																					
33	103N66W15AAAA	8-31-77	10	3,800	160	290	76	200	27	170	1,200	86	2.1	0.00	0.00	500	2,090	1,990	1,000	2.7	2,420	7.5
34	105N63W33CDBB	9- 1-77	10	2,000	140	340	83	130	26	170	1,200	76	2.4	.00	.00	350	--	1,950	1,200	1.6	2,380	7.5
35	108N67W 7DDDB	6-20-79	10	4,700	200	360	85	110	21	162	1,300	60	2.9	.00	.03	280	--	2,030	1,300	1.4	2,650	7.2
36	107N65W 5BBBA	7-25-79	11	5,100	130	340	89	130	21	194	1,300	59	2.3	--	--	420	2,140	2,060	1,200	1.6	2,440	7.4
37	108N63W11BBCD	8-22-79	9.2	1,100	90	210	59	360	21	160	1,200	92	2.1	.01	.00	850	--	2,040	770	5.7	2,700	7.7
—	101N66W34BB	8-30-79	8.3	3,300	170	370	100	110	21	160	1,300	130	2.8	.06	.01	230	2,220	2,130	1,300	1.3	2,750	6.7

1/ Field analysis.
2/ South Dakota Department of Environmental Protection.
3/ South Dakota State Chemist, Vermillion, S. Dak.
4/ Phosphorous (total as P).

Table 10.—Significance of chemical and physical properties of water

[Modified from Howells (1979). Limits, where given, are those set forth by the U.S. Environmental Protection Agency (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 mg/L, by the combining weight of the ionic species.]

Constituent or property	Recommended limit (mg/L)	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	Forms rust-colored sediment; stains laundry, utensils, and fixtures reddish brown. Objectionable for food and beverage processing.
Manganese (Mn)	.05	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 amounts may limit use of water for irrigation and industrial use and, in combination with chloride, give water a salty taste. Abnormally high 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	Sulfates of calcium and magnesium form hard scale. Large amounts of sulfate have a laxative effect on some people and, in combination with other ions, give water a bitter taste.
Chloride (Cl)	250	Large amounts increase the corrosiveness of water and, in combination with sodium, give water a salty taste.
Fluoride (F)	1.5	Reduces incidence of tooth decay when optimum fluoride content is present in water consumed by children during the period of tooth calcification. Excessive amounts of fluoride may cause mottling of teeth.
Nitrate (NO_3)	45*	Concentrations higher than local average may indicate pollution by feed-lot runoff, sewage, or fertilizers. Concentrations higher than 45 mg/L may be injurious when used in feeding infants.
(as N)	10*	
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.
Dissolved solids		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 power 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 amount is called non-carbonate 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 equivalents per million (epm) expressed as a percentage. Important in irrigation waters; the higher the percent sodium, the less suitable the water for irrigation.

Table 10.—Significance of chemical and physical properties of water--Continued

Constituent or property	Recommended limit (mg/L)	Significance
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 higher the SAR, the less suitable the water for irrigation.
Residual sodium carbonate (RSC)		The amount, expressed in epm, of carbonate and bicarbonate a water would contain after the removal of an equivalent amount 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°C (77°F). Values are reported in micromhos 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	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.

Constituent or property	Recommended limit (µg/L)	Significance
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 reduce yields of some crops. Long-term exposure to concentrations of more than 100 µg/L can be lethal to some types of fish.
Arsenic (As)	10 50*	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*	Toxic; used in rat poison. In moderate to high concentrations can cause death; smaller amounts cause damage to the heart, blood vessels, and nerves.
Bromide (Br)		Not known to be essential in human or animal diet. Is nontoxic in low concentrations; less than 1,000 µg/L has no detectable affect even on fish.
Cadmium (Cd)	10*	A cumulative poison of high 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; higher concentrations cause anemia, retarded growth, and death.
Chromium (Cr)	50* (hexavalent)	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	Essential to metabolism; copper deficiency in infants and young animals results in nutritional anemia. Large doses of copper are toxic and may cause liver damage. Some people can detect the taste of as little as 1 to 5 mg/L of copper.
Iodide (I)		Essential and beneficial element in metabolism; deficiency can cause goiter.
Lead (Pb)	50*	A cumulative poison, toxic in small quantities. Can cause lethargy, loss of appetite, constipation, anemia, abdominal pain, gradual paralysis in the muscles, and death.

Table 10.—Significance of chemical and physical properties of water--Continued

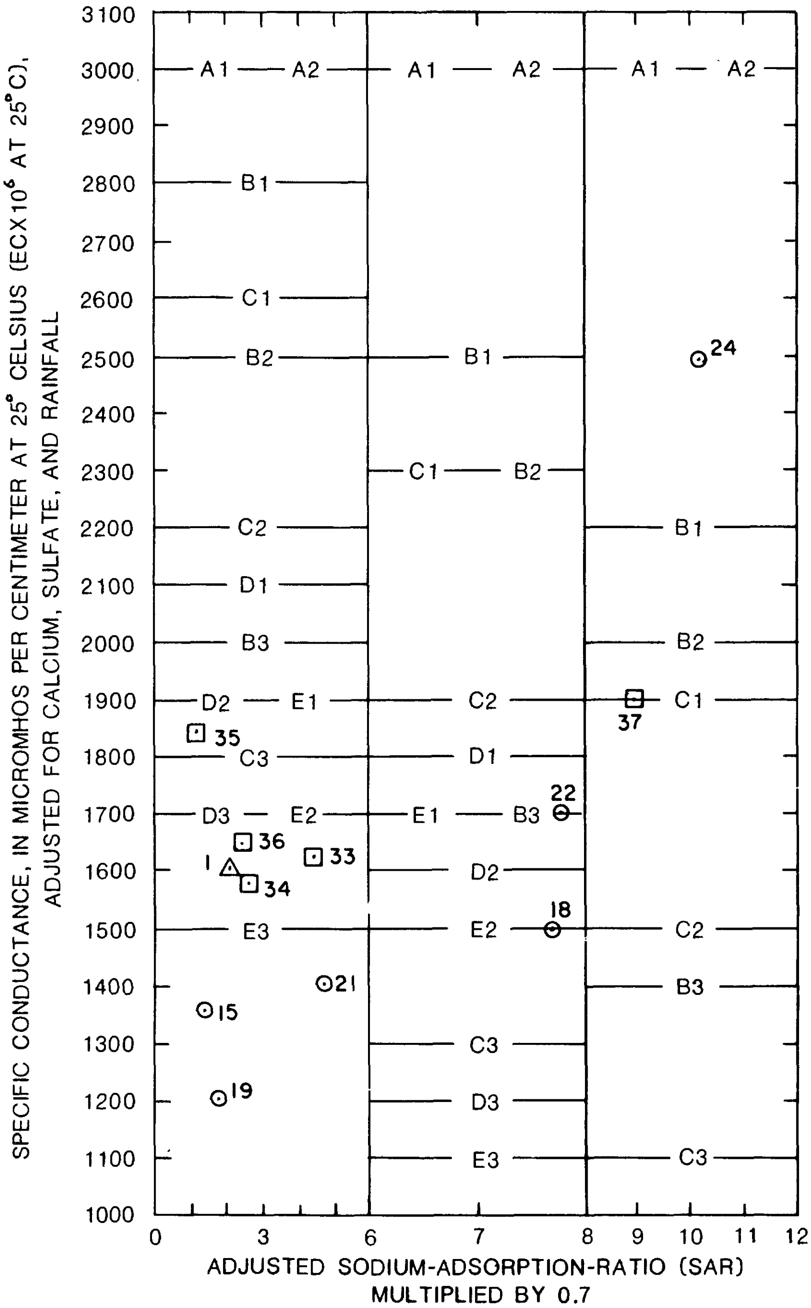
Constituent or property	Recommended limit (µg/L)	Significance
Lithium (Li)		Reported as probably beneficial in small concentrations (250 to 1,250 µg/L). Reportedly may help strengthen the cell wall and improve resistence to genetic damage and to disease. Lithium salts are used to treat certain types of psychosis.
Mercury (Hg)	2*	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 highly toxic. Elemental mercury is readily alkylated, particularly to methyl mercury, and concentrated by biological activity; fish and shellfish can contain more than 3,000 times the concentration of mercury as the water in which they live. Toxic affects of mercury compounds include chromosomal abnormalities, congenital mental retardation, progressive weakening of the muscles, loss of vision, impairment of cerebral functions, paralysis, and death.
Molybdenum (Mo)		In minute amounts, appears to be an essential nutrient for both plants and animals, but in large amounts may be toxic.
Nickel (Ni)		Highly toxic to some plants and animals. Toxicity for humans is believed to be very low.
Phosphate (PO_4)		Essential to plant growth. Concentrations higher than local average may indicate pollution by fertilizer seepage or sewage. Concentrations greater than 200 mg/L may cause diarrhea.
Selenium (Se)	10*	Essential to human and animal nutrition in minute amounts, but even a moderate excess may be harmful or potentially toxic if ingested over long periods of 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 lowered 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*	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 dosages.
Strontium (Sr)		Importance in human and animal nutrition is not known, but believed to be essential. Toxicity believed very low--no more than calcium.
Vanadium (V)		Not known to be essential to human or animal nutrition, but believed to be beneficial in trace amounts. May be an essential trace element for all green plants. Large amounts may be toxic.
Zinc (Zn)	5,000	Essential and beneficial in metabolism; its deficiency in young children or animals will retard growth and may reduce general body resistance to disease. Seems to have no ill effects even in fairly large amounts (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.

*Mandatory limit.

Table 11.--Trace elements in water. Analyses by U.S. Geological Survey Laboratory

Reported in micrograms per liter (µg/L) except as indicated. One microgram per liter is approximately equal to one part per billion. One milligram per liter (mg/L) is approximately equal to one part per million.

Sample number	Location	Date	Aluminum (Al)	Arsenic (As)	Barium (Ba)	Beryllium (Be)	Bromide (Br)	Cadmium (Cd)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Cyanide (CN) (mg/L)	Iodide (I)	Lead (Pb)	Lithium (Li)	Mercury (Hg)	Molybdenum (Mo)	Nickel (Ni)	Selenium (Se)	Silver (Ag)	Strontium (Sr)	Vanadium (V)	Zinc (Z)
	GLACIAL AQUIFERS																						
	Crow Lake aquifer																						
19	107N65W29BCBA	8-27-79	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
20	107N66W34DADA	9- 4-79	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
21	106N66W22BDDA	9- 4-79	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Warren aquifer																						
22	108N63W20ABCC	6-14-79	0	9	0	--	100	1	0	0	0	--	10	0	160	0.0	0	2	0	0	1,300	1.0	20
23	108N63W35BBAC	8- 8-78	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Corsica aquifer																						
24	101N64W 4DACA	8-29-79	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Minor aquifer																						
--	107N65W13ADBD	6-19-79	0	1	0	--	100	1	0	2	0	--	30	0	120	1.0	4	4	0	0	1,200	.0	20
	BEDROCK AQUIFERS																						
	Niobrara aquifer																						
25	107N63W20DDBD	8-28-79	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
26	104N63W 2AADD	7-26-78	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
27	103N66W14BCDB	8-31-77	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
28	103N65W11CDAC	8-30-79	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
29	103N64W17DDCD	7-31-79	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Codell aquifer																						
30	104N64W 3AAAA	7-26-78	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
31	103N64W15DDCC	9- 1-77	10	0	200	--	500	1	20	0	1	--	70	17	260	.0	0	3	0	0	700	.0	0
32	102N63W31CBCA	8-31-77	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Dakota aquifer																						
33	103N66W15AAAA	8-31-77	10	0	1,200	--	400	0	0	0	0	--	10	7	180	.0	2	3	0	0	8,300	1.4	10
34	105N63W33CDBB	9- 1-77	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
35	108N67W 7DDDB	6-20-79	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
36	107N65W 5BBBA	7-25-79	0	0	0	--	200	0	10	--	0	--	10	0	160	.3	0	--	0	--	8,500	3.0	40
37	108N63W11BBCD	8-22-79	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
--	101N66W34BB	8-30-79	0	1	0	--	600	0	10	0	0	--	10	0	140	.3	2	2	0	0	8,700	3.0	10



EXPLANATION

SOIL TEXTURE

A = Sand
B = Loamy sands, sandy loams
C = Loams, silts, silt loams
D = Sandy clay loams, silty clay loams, clay loams
E = Silty clays, sandy clays, clays

DEPTH BELOW LAND SURFACE TO A MORE-PERMEABLE OR LESS-PERMEABLE MATERIAL

1 = 40 inches or less to a more-permeable material
2 = 40 to 72 inches to a more-permeable material
3 = 20 to 60 inches to a less-permeable material

SPECIFIC CONDUCTANCE

Maximum values are based on 12 inches or less of average rainfall during the frost-free season. For each additional 2 inches of rainfall, the maximum values of $ECx10^6$ may be increased by 200.

For water having more than 200 milligrams per liter of calcium and more than 960 milligrams per liter of sulfate, the maximum values of $ECx10^6$ may be increased by 400.

△ STREAM OR LAKE
⊙ GLACIAL AQUIFER
⊡ DAKOTA AQUIFER

Number is sample number (also see fig. 22 and table 9).

Figure 21.--Classification diagram of the South Dakota State standards for irrigation water. (Based on standards (revised January 7, 1982) for maximum allowable specific conductance and adjusted sodium-adsorption-ratio values for which an irrigation permit can be issued for applying water under various soil texture conditions. Water can be applied under all soil conditions at or above the plotted point but not below it provided other conditions as defined by the State Conservation Commission are met). Modified from Koch, 1983.

damage soil structure, and eventually produce a hardpan. In addition, large concentrations of boron in the water in excess of 2,000 ug/L (micrograms per liter) may be harmful to crops.

Water from the Dakota aquifer has an adjusted sodium-adsorption-ratio of less than 6 and a specific conductance (adjusted) of about 1,600 umhos/cm. This indicates the water can be applied to all soil above class E3, provided other conditions as defined by the South Dakota State Conservation Commission are met. Water that has a sodium-adsorption-ratio (unadjusted, table 9) larger than 4 probably would not be used for irrigation.

Variability of Water Quality

The chemical composition of water from lakes and streams changed greatly with changes in runoff during 1977-79 (fig. 22), whereas the composition of water from aquifers changed very little. The greatest changes in composition, shown by arrows, were in Crow Lake and Firesteel Creek (samples 1, 2, 4, and 5, fig. 22). Water in Crow Lake changed from a calcium-magnesium sulfate type in 1977 to a calcium-magnesium bicarbonate type in 1978 as runoff during spring diluted concentrations of dissolved solids (table 9, samples 1 and 2). Photosynthesis by plankton and algae in late spring caused an increase in bicarbonate. The composition change in Firesteel Creek from 1979 to 1980 was due to decreased runoff. In 1980, the small flow probably was mostly sodium-enriched water from flowing wells and livestock wastes. The calcium-magnesium bicarbonate water in other lakes was the result of photosynthesis and the discharge of calcium- and magnesium-enriched shallow ground water. Twin Lakes has high dissolved-solids concentrations of a calcium-magnesium sulfate type as a result of discharge into the lake of about 100 gal/min from flowing wells.

Differences in the chemical composition of water from glacial aquifers are caused by local differences in geology and recharge. The water is a mixed calcium-magnesium bicarbonate-sulfate type (fig. 22). The bicarbonate is derived from organic processes in the soil zone and the sulfate is derived from leaching of gypsum in till. Slightly higher percentages of sodium indicate base-exchange softening of water by clay or zeolite minerals that were reworked into the aquifers from erosion of bedrock. In deep aquifers, high dissolved-solids concentrations can indicate much solution of minerals by recharge water moving through till (table 9, sample 24).

Water from the Niobrara and Codell aquifers is a sodium sulfate-bicarbonate type (fig. 22). Water in the Codell in southeastern Aurora County (fig. 22, samples 19, 32) is relatively high in calcium, magnesium, and sulfate, indicating recharge by water from till or the Corsica aquifer. The Codell and Corsica aquifers are in contact in southeastern Aurora County (section F-F', fig. 7).

Water from the Dakota aquifer is a calcium-magnesium sulfate type (fig. 22). The long time that the water has been in transit from the Black Hills has allowed it to dissolve much sulfate mineral from limestone aquifers that underlie and recharge the Dakota west of the study area.

Hardness and Other Water-Quality Problems

The hardness of water from wells in glacial aquifers ranges from 240 to 1,800 mg/L (fig. 23). Extremely high hardness is caused by recharge water dissolving gypsum and carbonate particles as it moves through clayey till or sand. The hardness of

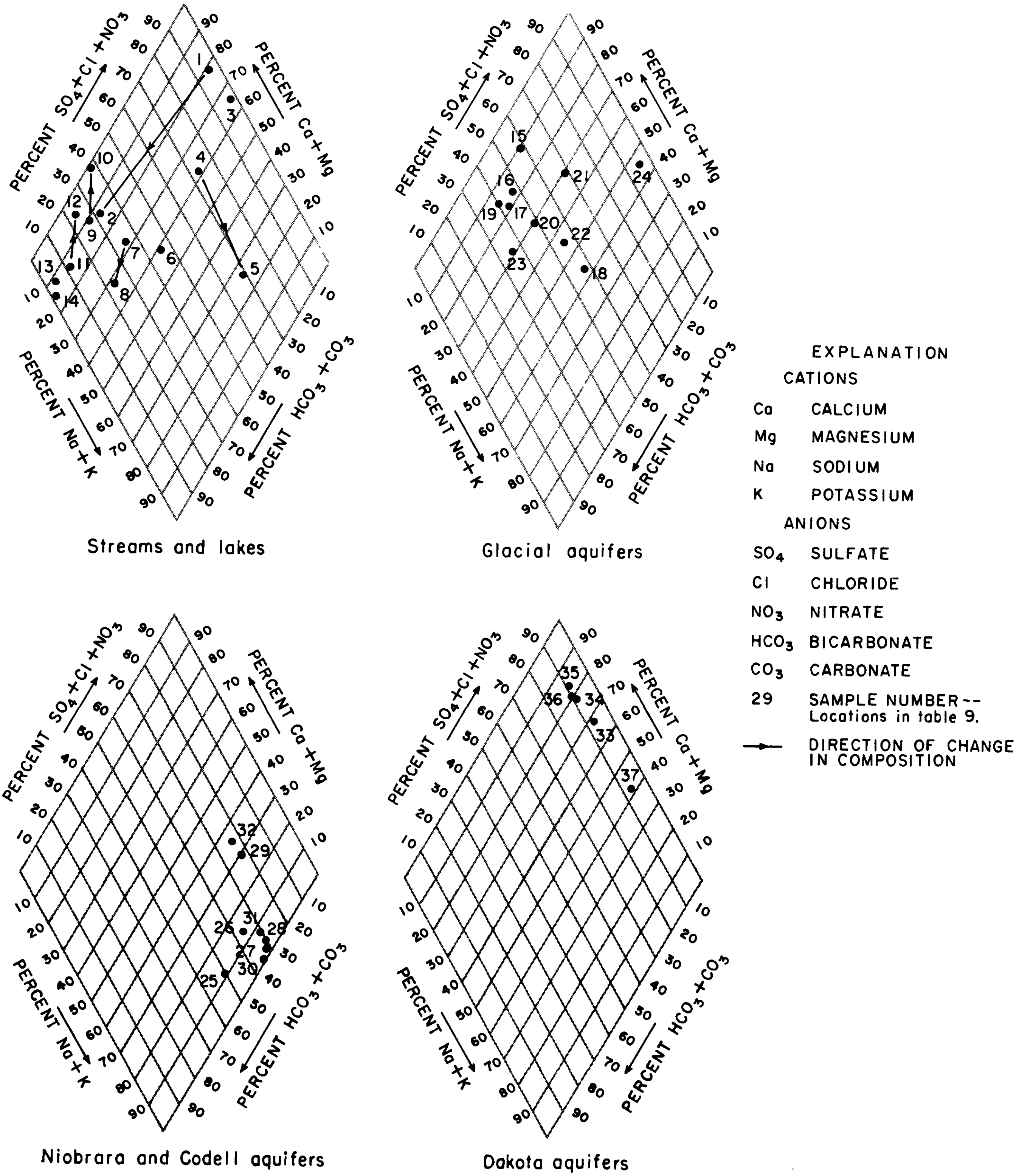
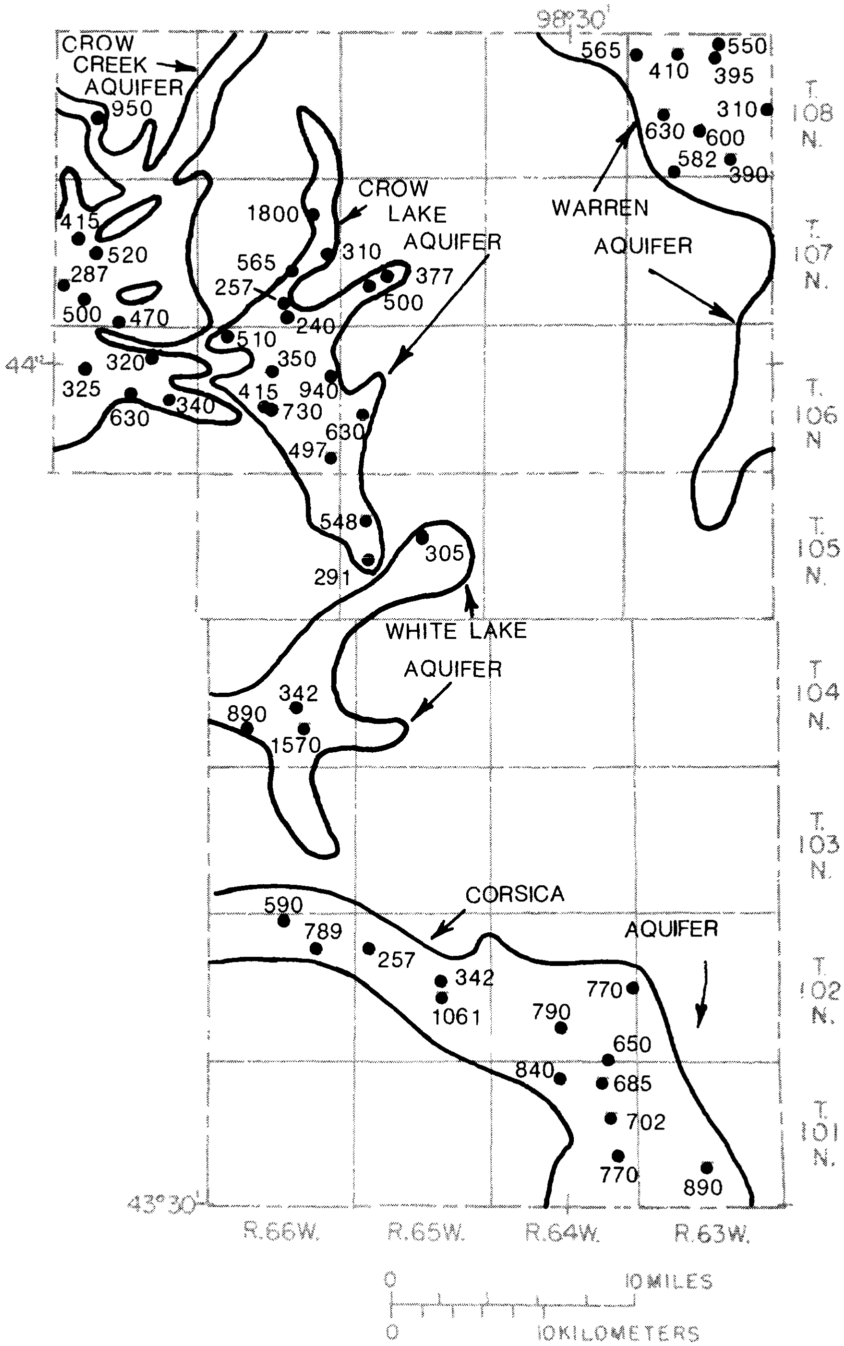


Figure 22.--Percentage composition of water from streams, lakes, and aquifers.



EXPLANATION

AQUIFER BOUNDARY

305 WELL IN A GLACIAL AQUIFER--Number is hardness of water, in milligrams per liter.

Figure 23.--Hardness of water from glacial aquifers.

water from the relatively shallow aquifers in Jerauld County generally does not exceed 600 mg/L because they are recharged through permeable layers of sandy soil and alluvium. In contrast, the hardness of water from the deeply buried Corsica aquifer, in southern Aurora County, generally exceeds 600 mg/L because recharge must infiltrate slowly through as much as 400 ft of clayey till to reach the aquifer. The low hardness for two wells in T. 102 N., R. 65 W. probably is caused by recharge of the Corsica aquifer by softer water from the Niobrara aquifer.

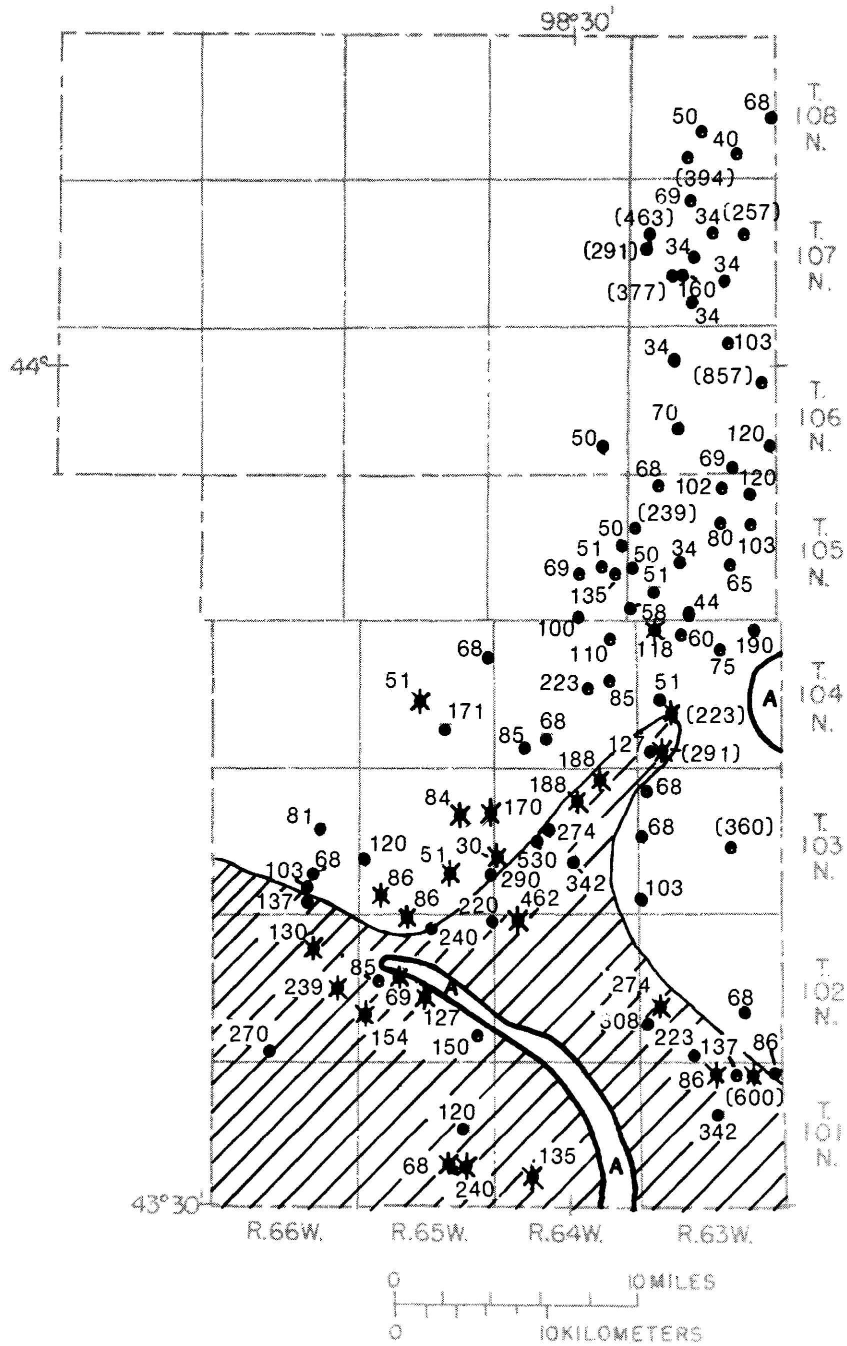
The hardness of water from the Niobrara aquifer ranges from 34 to 857 mg/L (fig. 24). The hardness exceeds 120 mg/L in much of southern Aurora County, where the aquifer is overlain by soluble, calcareous shale that slows recharge and increases the hardness of the water. In some areas hardness probably varies greatly due to flow between the Niobrara and Corsica aquifers. Higher hardness also may be due to seepage of water from shale or overlying glacial deposits through perforated or corroded openings in well casings.

Some of the water from the Niobrara in Aurora County has a strong odor of hydrogen sulfide gas (sewer gas) or a dark gray color or both. The color is from dissolved organic matter from overlying shale. The sulfate-rich recharge water probably is reduced by organic matter or by anaerobic bacteria to produce the gas. The gas is not harmful in trace amounts and can be removed by chlorination or aeration. Likewise, the color is natural, not an indicator of pollution, and can be reduced by filtering or by allowing the organic matter to settle in a cistern or other reservoir.

The hardness of water from wells in the Codell aquifer ranges from 17 to 496 mg/L but is less than 120 mg/L in most areas (fig. 25). Although hard water from glacial deposits recharges the Codell through the Niobrara, as discussed previously, the water probably is softened by base exchange on clay minerals within the Codell. Hardness in excess of 120 mg/L can be caused by very hard water seeping into a Codell well from the Niobrara aquifer through slotted or corroded well casing. The area of very hard water in the Codell in southeastern Aurora County may be due to recharge of very hard water from the Corsica aquifer.

The hardness of water from wells in the Dakota aquifer ranges from 460 to 1,440 mg/L but mostly exceeds 1,000 mg/L (fig. 26). The water is much harder than water from other bedrock aquifers because the Dakota aquifer is recharged by very hard water that leaks upward from deeper aquifers to the west. The hardness generally is less than 1,000 mg/L in eastern Jerauld County, an area where the aquifer discharges through many flowing wells. The hardness probably is reduced by base exchange as the water moves upward across shale beds toward flowing wells. Locally, soft water that is salty can enter wells in the Dakota from the Graneros Shale (table 1) if the casing becomes corroded.

Other than the hardness of the water, the most prominent problem with the Dakota aquifer is that it can yield fine, silty sand that plugs pumping equipment. This problem is reported to be common in the vicinity of the city of White Lake, T. 103 N., R. 66 W. The problem may be reduced by use of screened and sand-packed wells.



EXPLANATION

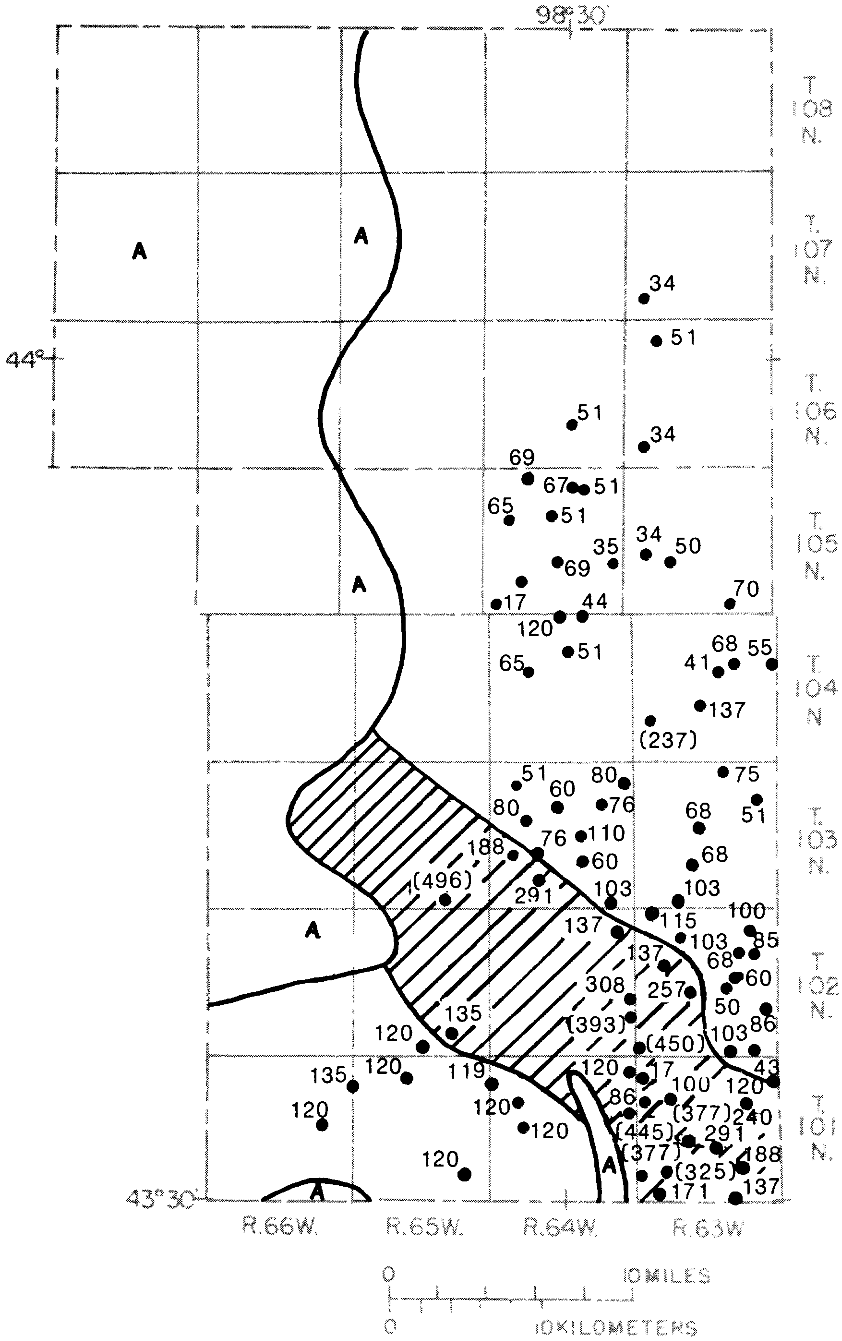
AREA WHERE HARDNESS OF WATER EXCEEDS 120 MILLIGRAMS PER LITER FOR MANY WELLS IN THE NIOBRARA AQUIFER

A — AQUIFER ABSENT

69 ● WELL IN THE NIOBRARA AQUIFER--Number is hardness of water, in milligrams per liter. A number in parenthesis indicates water that may be seeping into the well from overlying glacial deposits.

✱ WELL YIELDING WATER HAVING GAS ODOR OR DARK GRAY COLOR OR BOTH

Figure 24.--Hardness of water from the Niobrara aquifer.



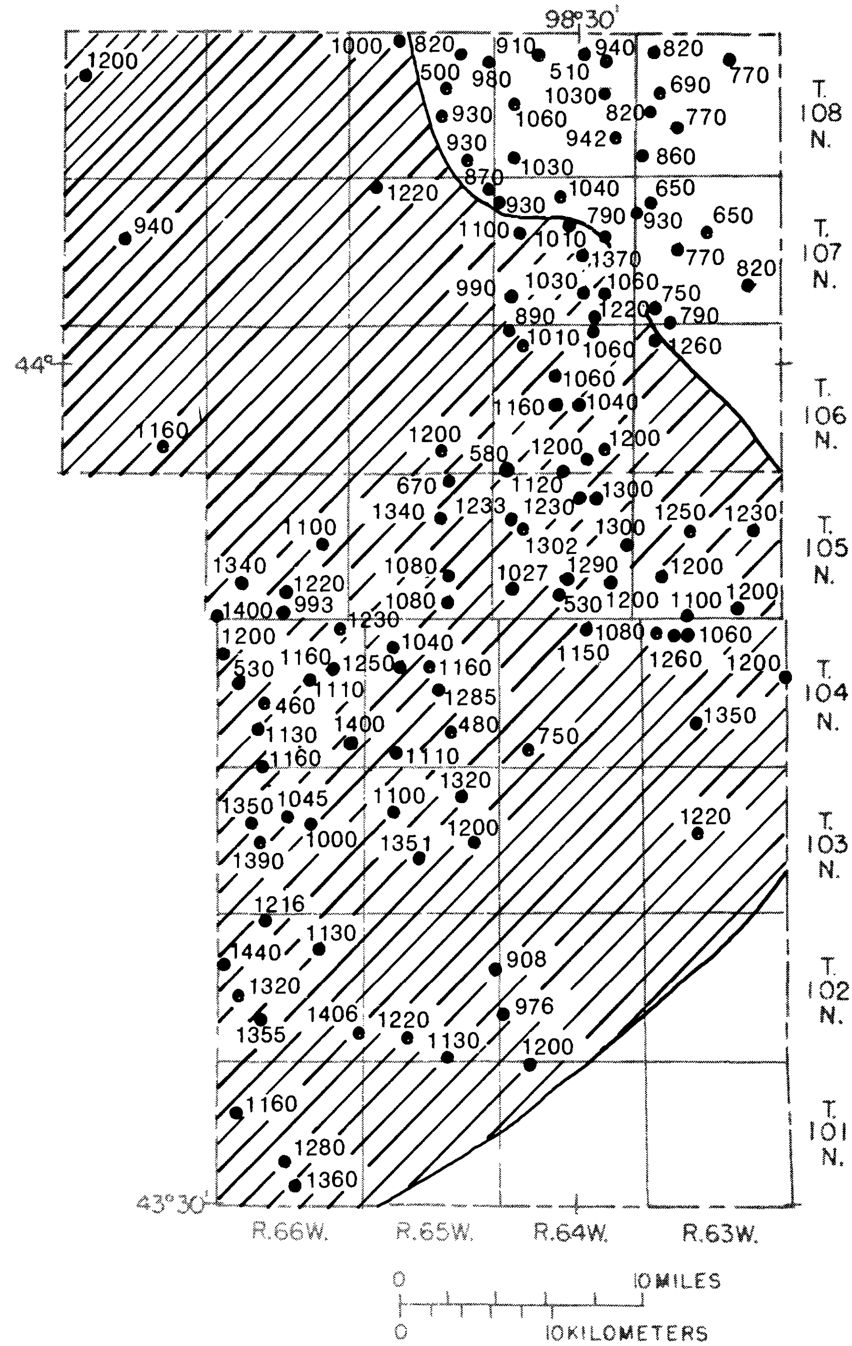
EXPLANATION

AREA WHERE HARDNESS OF WATER EXCEEDS 120 MILLIGRAMS PER LITER FOR MANY WELLS IN THE CODELL AQUIFER

A AQUIFER ABSENT

• 51 WELL IN THE CODELL AQUIFER--Number is hardness of water, in milligrams per liter. A number in parenthesis indicates water that may be seeping into the well from the Niobrara aquifer or glacial deposits.

Figure 25.--Hardness of water from the Codell aquifer.



EXPLANATION

AREA WHERE HARDNESS OF WATER EXCEEDS 1,000 MILLIGRAMS PER LITER FOR MANY WELLS IN THE DAKOTA AQUIFER

•750 WELL IN THE DAKOTA AQUIFER--Number is hardness of water, in milligrams per liter.

Figure 26.--Hardness of water from the Dakota aquifer.

SUMMARY AND CONCLUSIONS

Aurora and Jerauld Counties have generally small surface-water resources. Average streamflow is estimated to total 50 cubic feet per second (36,000 acre-feet per year) but it is distributed among six streams. The largest stream, Firesteel Creek, has a measurable flow less than 50 percent of the time. The dozen or so scattered lakes are small, semipermanent, and shallow. Most of the surface water is fresh, containing less than 1,000 milligrams per liter dissolved solids.

Productive glacial aquifers, mostly outwash sand and gravel, store more than 1 million acre-feet of water beneath 25 percent of the 1,236-square-mile study area. Wells yielding as much as 1,000 gallons per minute can be developed in major glacial aquifers where their thickness exceeds 30 feet and where their transmissivities exceed 13,000 square feet per day. Increased withdrawals from glacial aquifers had only small effects on water levels during the study. Observation wells located less than a mile from large-capacity wells had temporary water-level declines of only 0.6 to 4 feet.

Most water in glacial aquifers is very hard, the hardness ranging from 240 to 1,800 milligrams per liter. Most of the water is slightly saline, having dissolved solids totaling more than 1,000 milligrams per liter. Concentrations of dissolved solids range from 320 to 2,650 milligrams per liter.

Productive bedrock aquifers, shaly marl and chalk of the Niobrara aquifer and fine, silty sandstone of the Codell and Dakota aquifers, store 58 million acre-feet of water in the study area. Wells yielding as much as 150 gallons per minute by flowing and 500 gallons per minute by pumping can be developed in the Dakota aquifer. The maximum yield of wells in the other bedrock aquifers generally ranges from 10 to 100 gallons per minute but locally can be as much as 1,500 gallons per minute from the Niobrara aquifer. Increased withdrawals from some bedrock aquifers have caused large declines in water levels because of the small artesian storage coefficient. Artesian pressure in the Dakota aquifer declined about 200 feet during 70 years and continued to decline at the rate of 2 feet per year in one area of large withdrawals during 1972-79. If increases in withdrawals continue, many wells in the Dakota may cease flowing by the year 2000. In the Niobrara aquifer, water levels temporarily declined as much as 40 feet one-half mile from a well pumping 1,500 gallons per minute.

The hardness of water from the Niobrara and Codell aquifers ranges from 17 milligrams per liter to 857 milligrams per liter. The hardness of water from the Dakota aquifer ranges from 460 to 1,440 milligrams per liter. Bedrock-aquifer water is slightly saline, total dissolved solids ranging from 1,540 to 2,220 milligrams per liter. Most water from the Niobrara and Codell aquifers has a sodium-adsorption ratio larger than 4 which indicates a high sodium (alkali) hazard and possible damage to soil structure if used for irrigation.

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