AVAILABILITY AND CHEMICAL QUALITY OF WATER FROM SURFICIAL AQUIFERS IN SOUTHWEST MINNESOTA

By D. G. Adolphson

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 83-4030

Prepared in cooperation with the

SOUTHWEST REGIONAL DEVELOPMENT COMMISSION and the

MINNESOTA DEPARTMENT OF NATURAL RESOURCES

St. Paul, Minnesota
1983

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additonal information
write to:

District Chief
U.S. Geological Survey
702 Post Office Building
St. Paul, Minnesota 55101
Telephone: (612) 725-7841

Copies of this report can be
purchased from:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425, Federal Center
Denver, Colorado 80225
Telephone: (303) 234-5888

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS—Continued

TABLES

CONVERSION FACTORS

Multiply inch-pound units	By	To obtain SI (metric) units
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
acre	0.4047	hectare
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
foot squared per day (ft^2/d)	0.0920	meter squared per day (m^2/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
cubic foot per second (ft^3/s)	0.2832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.6309	liter per second (L/s)

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."

AVAILABILITY AND CHEMICAL QUALITY OF WATER FROM SURFICIAL AQUIFERS IN SOUTHWEST MINNESOTA

By D. G. Adolphson

ABSTRACT

The principal surficial aquifers in southwest Minnesota are composed of outwash and alluvial material in river valleys. The largest and most productive of these aquifers occupy the valleys of the Cottonwood, Des Moines, Redwood, and Rock Rivers and of tributaries to the Big Sioux River. Minor aquifers in the valleys of the tributaries to the major streams yield small water supplies that are adequate for farm use.

The surficial aquifers range in width from 0.5 to 2 miles, in thickness from 0 to 110 feet, and in saturated thickness from 0 to 80 feet. Grain size varies both laterally and vertically. A veneer of fine-grained sediment, as thick as 15 feet, has been deposited over the outwash by post-glacial streams.

Availability of water in the surficial aquifers varies greatly within short distances. Probable maximum well yield is as much as 1,000 gallons per minute; however, yields generally range from 10 to 100 gallons per minute.

The concentration of dissolved solids in water from the surficial aquifers ranges from 313 to 958 milligrams per liter. Analyses of 25 samples show that the water locally contains concentrations of iron, sulfate, and nitrate that are above the limits recommended by the Minnesota Department of Health for drinking water. Based on these standards, the water is generally of acceptable chemical quality for most uses, although it is hard.

INTRODUCTION

Background

The lack of rainfall and an increased demand for ground water in southwestern Minnesota during the mid-1970's have increased the need for information on the availability and quality of water supplies. Twelve municipalities that obtain water from wells in surficial aquifers had shortages during the drought of 1976-77 (J. G. Fax, Minnesota Department of Natural Resources, oral commun., 1979). Also during this period, the acreage irrigated by sprinklers increased from 852 to 8,681 (University of Minnesota, 1978).

The U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources and eight of the nine counties that are associated with the Southwestern Minnesota Regional Development Commission, made a study during 1977-80 to assess the availability of water from surficial outwash deposits in those counties. Information from that study will aid in management of the resource.

Purpose and Scope

The objectives of the study were to (1) determine the areal extent, thickness, and water-yielding capability of aquifers in the surficial deposits, (2) estimate the amount of water in storage in the aquifers, (3) determine the chemical quality of water in the aquifers, and (4) establish observation wells to monitor the effects of ground-water development on water levels and storage in the aquifers.

Surficial aquifers are defined for this study as those aquifers in glacial deposits and alluvium that occur at land surface. These aquifers can be located by their topographic expression.

Location, Extent, and Climate

The study area consists of 4,870 mi^2 in southwestern Minnesota. It includes parts of seven watersheds, as defined by the Minnesota Department of Conservation, Division of Waters (1959), and eight counties, Cottonwood, Jackson, Lincoln, Murray, Nobles, Pipestone, Redwood, and Rock (fig. 1). The area lies between lat. 43°30' and 44°42' N., and long. 94°51' and 96°27' W.

Southwestern Minnesota has a continental-type climate characterized by cold, snowy winters and hot summer days with cool nights. Mean annual precipitation ranges from 24 in. in the northwestern part of the area to 28 in. in the extreme southeastern part (Kuehnast, 1972). Approximately two-thirds of the annual precipitation occurs as rain during the growing season from April through September. During the study, 1976 was a year of below normal precipitation, 1977 and 1978 were years of normal precipitation, and 1979 was a year of above-normal precipitation.

Methods

Nearly 500 test holes were drilled with a power auger in 1978 and 1979 to determine the thickness and extent of the surficial aquifers, depth to water, grain size of the material penetrated, and to estimate the water-yielding characteristics of the material. Aquifer properties (transmissivity, storage coefficient, and hydraulic conductivity) were determined from data generated from nine aquifer tests (Fax, 1980). The present augering was in addition to the test holes augered by Norvitch (1960), Schiner and Schneider, (1964), and Helgeson, (1967).

Other work included completing 24 auger holes as observation wells for monitoring the seasonal fluctuations in water levels and collecting water samples for chemical analysis from 15 of the observation wells. Ten analyses from previous studies are also included in the analysis of water quality. Streamflow was measured at sites on the Redwood and Cottonwood Rivers in October 1978 to determine ground-water discharge to the streams and to determine rates of inflow and outflow. Previous low-flow measurements were also used to determine the best locations for potential sources of ground water.

Previous Investigations

Reports are available that contain information on the geology or water resources. The geohydrologic maps are based on the geologic maps of Leverett (1932), Leverett and Sardeson (1932), and Matsch (1972). Reports by Hall, Meinzer, and Fuller (1911), Norvitch (1960), Schneider and Rodis (1961), Rodis (1963), Norvitch (1964), Thompson (1965), Helgesen (1967), Ellis and Adolphson (1969), and Ellis, Adolphson, and West (1969) describe the geology and water resources of the project area or adjoining areas.

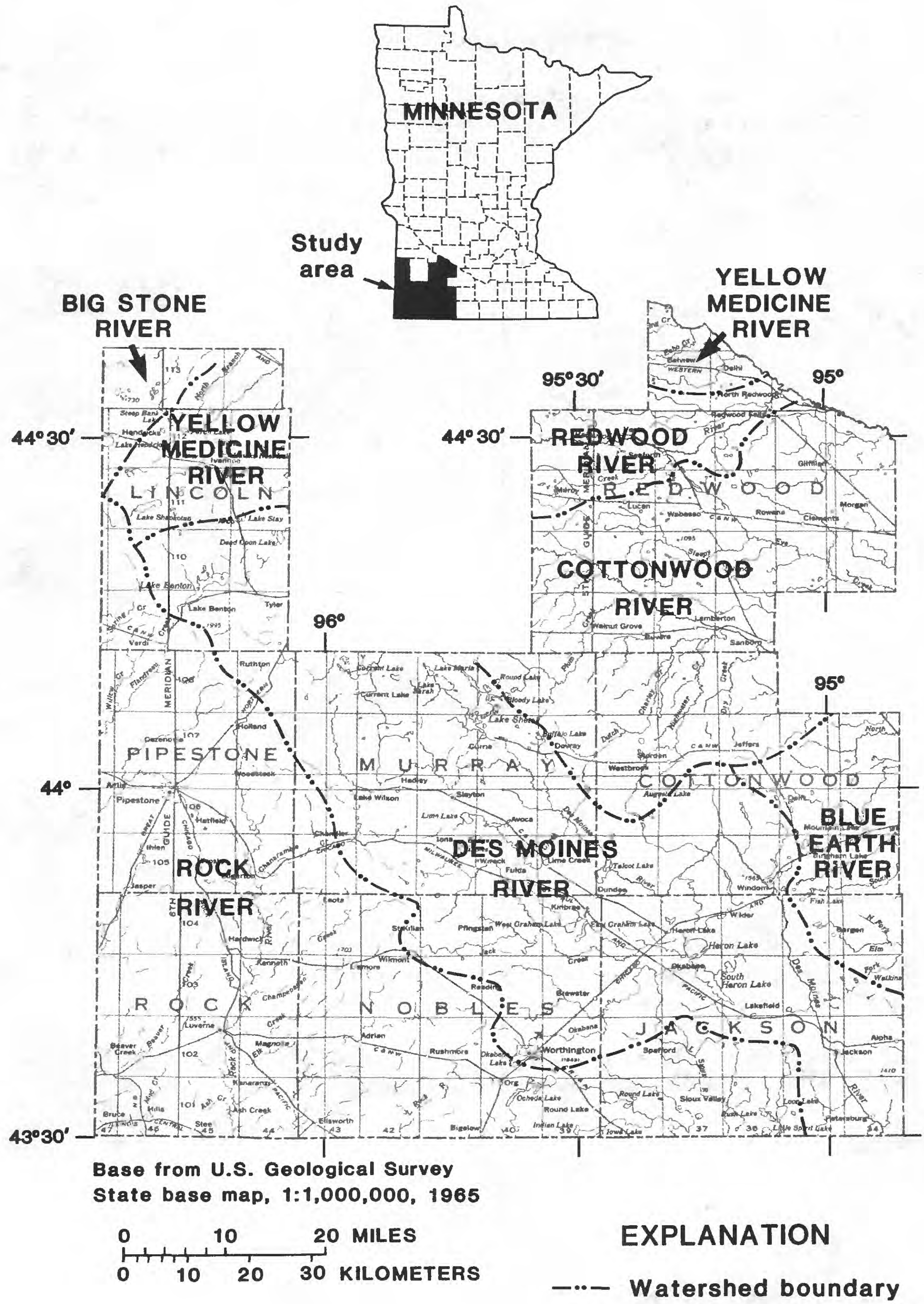


Figure 1.--Location of study area and watersheds

The following U.S. Geological Survey hydrologic atlases provide a hydrologic framework of watersheds: Lac Qui Parle River (Cotter and Bidwell, 1968), Yellow Medicine River (Novitzki and others, 1969), Redwood River (Van Voost and others, 1970), Cottonwood River (Broussard and others, 1973), Blue Earth River (Anderson and others, 1974), Rock River (Anderson and others, 1976a), and Des Moines River (Anderson and others, 1976b).

Well and Test-Hole Numbering System

The method of numbering wells and test holes is based on the U.S. Bureau of Land Management's system of subdivision of public lands. The area is in the fifth principal meridian and base-line system. The first segment of a well or test-hole number indicates the township north of the baseline; the second, the range west of the principal meridian; and the third, the section in which the well is situated. The uppercase letters A, B, C, and D, following the section number indicate the location of the well in the section. The first letter denotes the 160-acre tract, the second denotes the 40-acre tract, and the third denotes the 10-acre tract. The letters are assigned in a counterclockwise direction beginning with the northeast quarter. Consecutive numbers beginning with 1 are added as suffixes to distinguish wells within a given 10-acre tract. Figure 2 illustrates the method of numbering. Thus, the number 112N37W12DDB1 identifies the first test hole or well in the NW¼SE¼SE¼ sec. 12, T. 112 N., R. 37 W.

Glossary

Acre-foot - the quantity of water required to cover 1 acre to a depth of 1 ft; equal to 43,560 ft^3 or 325,851 gal.

Alluvium - sand, gravel, and other material that has been transported and deposited by streams.

Aquifer - a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Aquifer test - a means for determining the water-bearing properties of an aquifer. One test is to pump a well at a constant rate while measuring the decline and recovery of the water level in the pumped well and in observation wells.

Base flow - sustained or fair-weather runoff. In most streams, base flow is composed largely of ground-water discharge to the stream.

Confining bed - a body of material with low permeability adjacent to one or more aquifers.

Drawdown - the vertical distance between the nonpumping water level and the level caused by pumping.

Drift - all deposits resulting from glacial activity.

Evapotranspiration - the process by which water is withdrawn from a land area by evaporation from water surfaces and moist soil and by transpiration by plants.

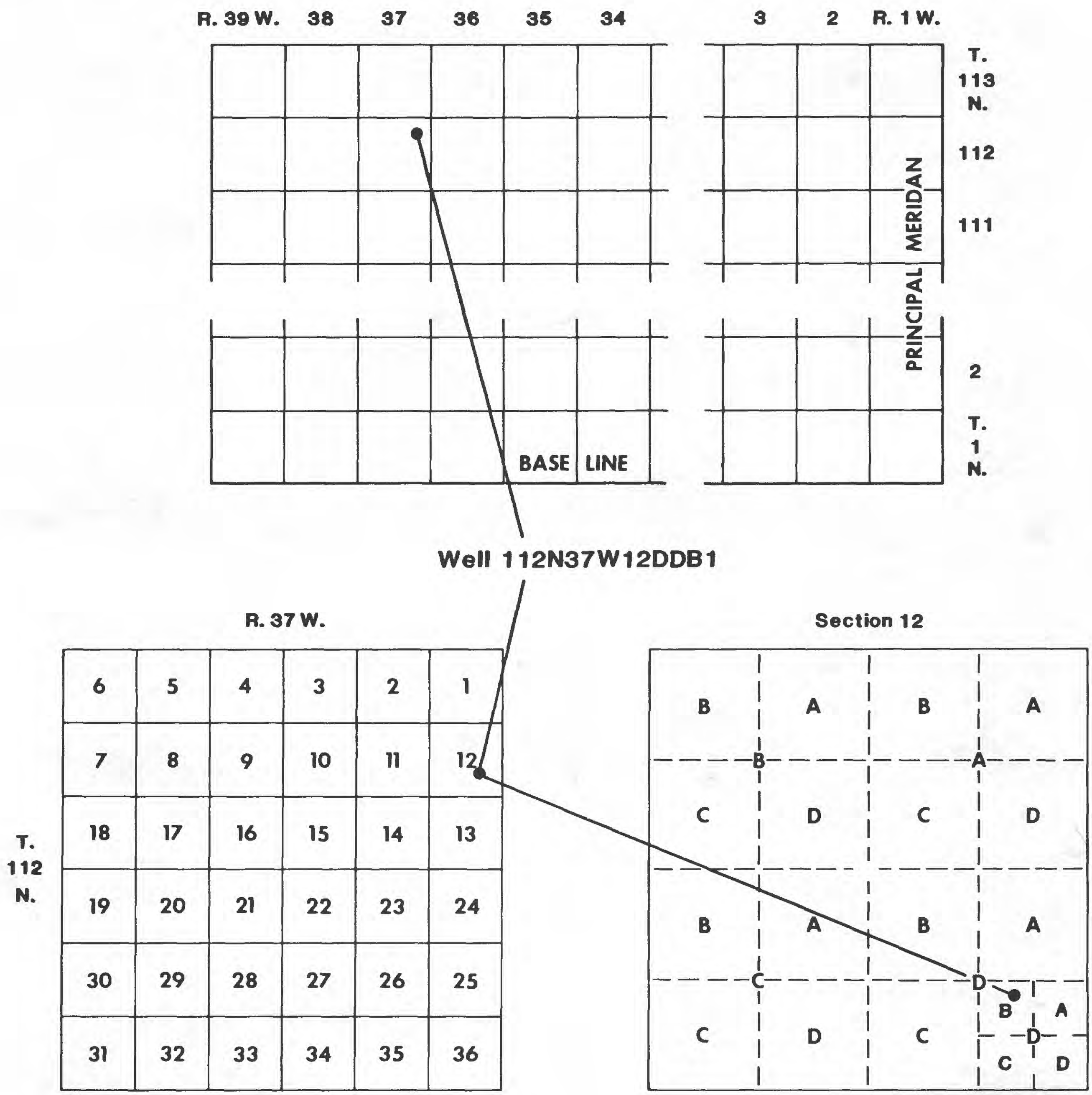


Figure 2.--Well and test-hole numbering system

Hydraulic conductivity - the rate of flow of water transmitted through a porous medium of unit cross-sectional area under a unit hydraulic gradient at the prevailing kinematic viscosity; measured at right angles to the direction of flow.

Milligrams per liter - a unit for expressing the concentration by weight of a chemical constituent per liter of solution.

Milliequivalants per liter - concentration (in milligrams per liter) divided by the formula weight of the chemical constituent and multiplied by its charge.

Moraine - drift, deposited chiefly by direct glacial action; commonly has constructional topography independent of control by the surface on which it lies.

Outwash - sorted stratified drift deposited beyond the ice front by melt-water streams.

Potential evapotranspiration - water loss that will occur if there is never a deficiency of water in the soil for use by vegetation.

Recharge - the processes by which water is added to an aquifer.

Runoff - that part of the precipitation that appears in streams. It is the same as streamflow unaffected by artificial diversions, storage, or other works of man in or on the stream channels or on the drainage area.

Specific capacity - the rate of discharge of water from a well divided by the drawdown of water level within the well. It varies slowly with duration of discharge, which should be stated when known. If the specific capacity is constant except for time variation, it is roughly proportional to the transmissivity of the aquifer.

Storage coefficient - the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, it is virtually equal to the specific yield.

Surficial deposits - unconsolidated residual, alluvial, or glacial deposits lying on the bedrock.

Till - unsorted, unstratified drift deposited directly by the ice.

Transmissivity - the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unconfined conditions - conditions under which the water in an aquifer is not confined by overlying, relatively impermeable strata. Under these conditions, water can be obtained from storage in the aquifer by gravity drainage, that is, by lowering the water level, as in a pumped well.

Water table - the surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells that penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists.

Physiography and Surficial Geology

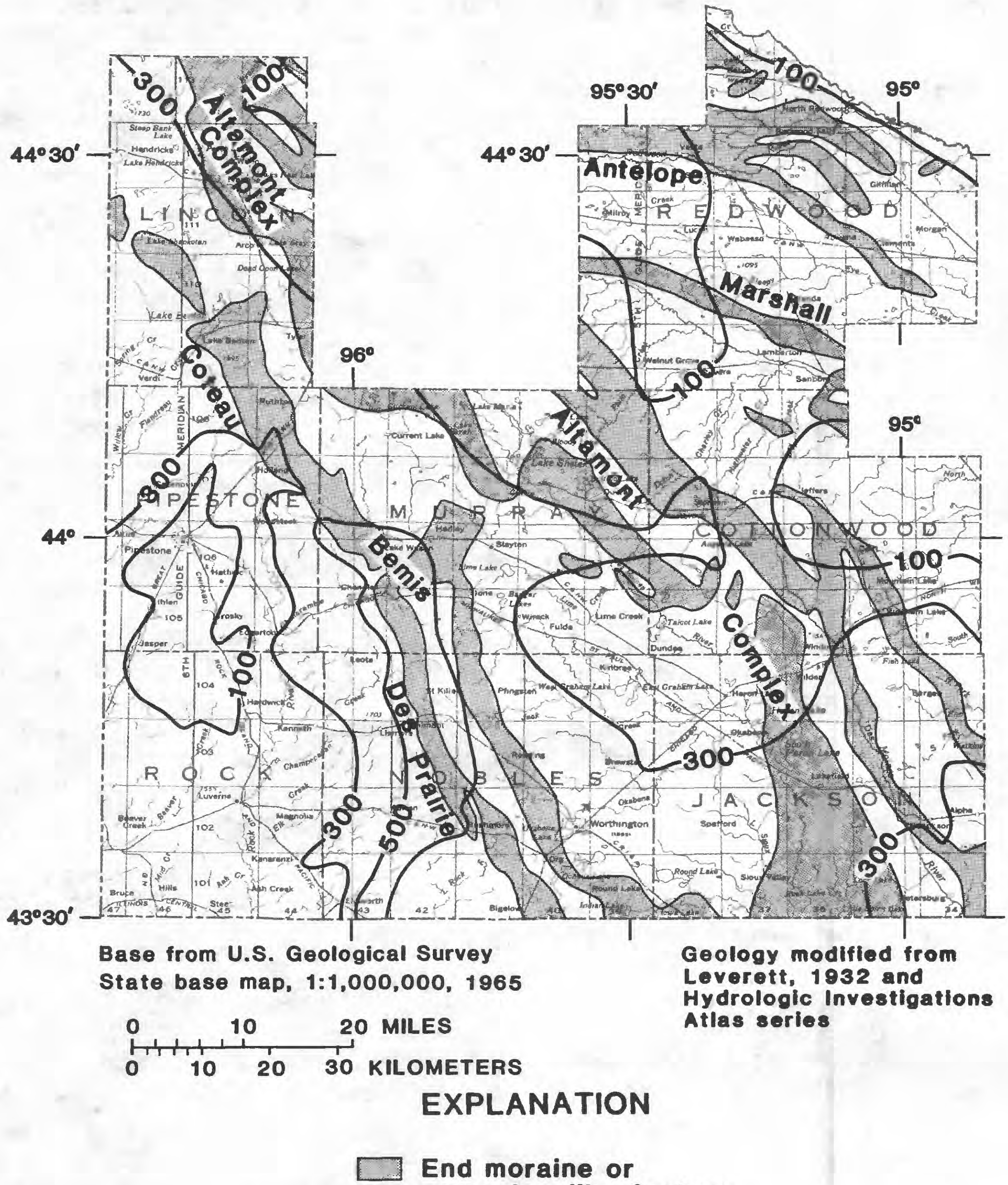
The topography of most of southwestern Minnesota is slightly rolling to flat. Altitudes gently descend from west to east. Marshes and lakes are numerous. The Coteau des Prairie, or Highland Divide of the Prairie, is the most conspicuous surface feature (fig. 3). This highland extends southeastward from the South Dakota border across Lincoln, Murray, and Nobles Counties, and into Iowa. It forms the divide between the Missouri and Mississippi Rivers. Headwaters of the Redwood, Cottonwood, and Des Moines Rivers are on the northern slope of the highland. The Redwood and Cottonwood Rivers flow northeastward into the Mississippi River by way of the Minnesota River. Rock River, Pipestone, and Flandreau Creeks head on the southern slope of the highland. These streams and the Des Moines River, flow south or southwest into the Missouri River.

The physiography is dominated by glacial features that were formed during the pre-Wisconsin and Wisconsin Glaciation of the Pleistocene Epoch (Matsch, 1972). End moraines, which were formed during the recession of the last glacier, are the most prominent features. They form a series of morainic belts that mark some of the river-basin boundaries. The belts generally trend north-south or northwest-southeast.

The Bemis moraine (fig. 3) is the northeastern boundary of the Coteau des Prairie and is the outer terminal moraine of the last ice advance in southwestern Minnesota (Leverett, 1932). The moraine is well drained and is marked by numerous gullies. After the ice front withdrew, an end moraine of rugged relief and poor drainage was produced on the northeastern flank of the Coteau. Leverett (1932) called this feature the Altamont-Cary moraine; however, Matsch (1972) has designated this dead-ice moraine the Altamont moraine complex. Other features to the northeast, which resulted during the advance and retreat of the glacier, were previously mapped as end moraines (Leverett, 1932). However, these have been re-interpreted by Matsch (1972) to be a "large crevasse filling" (Antelope moraine) and a "trend of higher relief resulting from erosion along a meltwater channel system" (Marshall moraine). The Bemis and Altamont moraines merge gradually to the northeast with intervening ground moraines. The morainal topography is typically irregular, with numerous knolls, hummocks, and closed depressions that contain many marshes and lakes.

Well-sorted surficial outwash, crevasse fillings, and terrace gravel were also deposited during the last advance and retreat of the Des Moines lobe. The outwash was deposited in a network of long and narrow melt-water channels that commonly occupy the present stream courses. These major outwash deposits constitute the surficial aquifers investigated during this project.

Drift overlies sedimentary rocks of Cretaceous age and igneous and metamorphic rocks of Precambrian age. It ranges in thickness from less than 1 ft locally in Redwood, Rock, Cottonwood, and Pipestone Counties to about 600 ft in a buried bedrock valley in western Nobles County and in places underlying the Coteau (Anderson and others, 1976a).



Base from U.S. Geological Survey
State base map, 1:1,000,000, 1965

Geology modified from
Leverett, 1932 and
Hydrologic Investigations
Atlas series

0 10 20 MILES

0 10 20 30 KILOMETERS

EXPLANATION

End moraine or moraine–like feature

—100— LINE OF EQUAL THICKNESS OF DRIFT — Interval 100 feet and 200 feet

Figure 3.--Generalized thickness of drift and predominant glacial features

AVAILABILITY OF GROUND-WATER SUPPLIES

Six major surficial aquifers are associated with stream valleys in southwest Minnesota. For convenience of discussion and identification and for future reference, the aquifers are named after nearby prominent geographic features. They are identified on figure 4 as the Redwood, Cottonwood, Des Moines, Nobles, Rock, and Big Sioux. All extend beyond the study area.

The grain size of the surficial outwash deposits is extremely variable; it changes both laterally and vertically in short distances. Flooding and lateral changes in position of stream channels have given the melt-water channels their flat-surface expression. Post-glacial streams have deposited a veneer of fine-grained sediments (flood-plain alluvium) as thick as 20 ft over much of the outwash. Because the flood-plain alluvium commonly overlies and forms a single aquifer with the thicker and more extensive outwash deposits, the alluvium is considered to be a part of the surficial aquifers.

The surficial aquifers contain sufficient saturated material at many places to yield large quantities of water to wells. In general, the yield at a given location depends on the areal extent and thickness of saturated sand and gravel and on the amount of drawdown in the pumping well. Yields decrease toward the aquifer boundaries because of the thinning of the sand and gravel units and the decrease in saturated thickness. The estimated potential yields to properly constructed wells in the aquifers are as much as 1,000 gal/min. The large yields (more than 200 gal/min) are generally obtained where the surficial deposits consist of 20 ft or more of saturated sand and gravel.

Water in the surficial deposits is generally under unconfined conditions and is hydraulically connected to streams. When thin layers of silt and clay overlie the deposits, the water occurs under confined conditions.

Water is discharged from aquifers by wells and springs, seepage to surface-water bodies, ground-water outflow, transpiration by plants, and evaporation from the soil where the water level is at or near the land surface. During periods of base flow, ground-water discharge constitutes most of the surface-water flow. Most recharge to the surficial aquifers is by infiltration of precipitation, seepage from streams, and ground-water inflow from adjacent areas.

The water table fluctuates in response to changes in storage within an aquifer in much the same manner as the water level in a surface reservoir varies with storage. When recharge exceeds discharge, ground-water storage is increased, and water levels rise. Conversely, when discharge exceeds recharge, ground-water storage decreases, and water levels decline. The water table, however, does not rise or decline uniformly. Changes of water level in one well do not necessarily reflect changes throughout an aquifer. Periodic water-level measurements in a network of observation wells are necessary to estimate the quantity of ground water in storage at any given time.

As part of this investigation, water levels were measured monthly in 24 observation wells (fig. 5). Hydrographs of representative observation wells for each aquifer are shown on plates 1 through 8. Ground-water levels are generally lowest during the winter, when the ground is frozen and the aquifer cannot receive any significant recharge. In late March and early April, when the ground thaws, the water level rises as a result of recharge from snowmelt. During the rest of April and May, water levels continue to rise in response to early spring rains. In June, the water levels generally decline slightly,

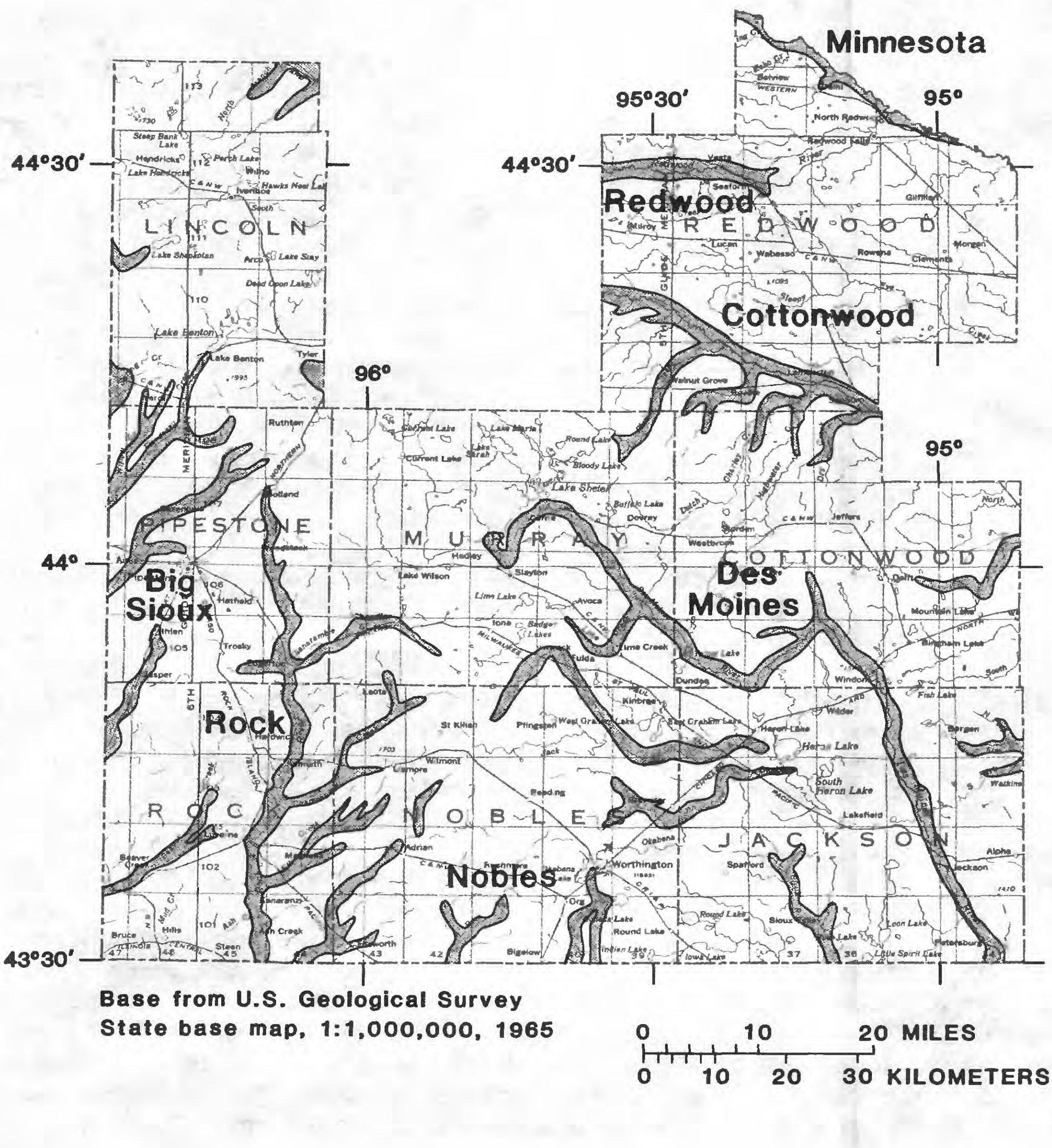


Figure 4.--Location and name of surficial aquifers

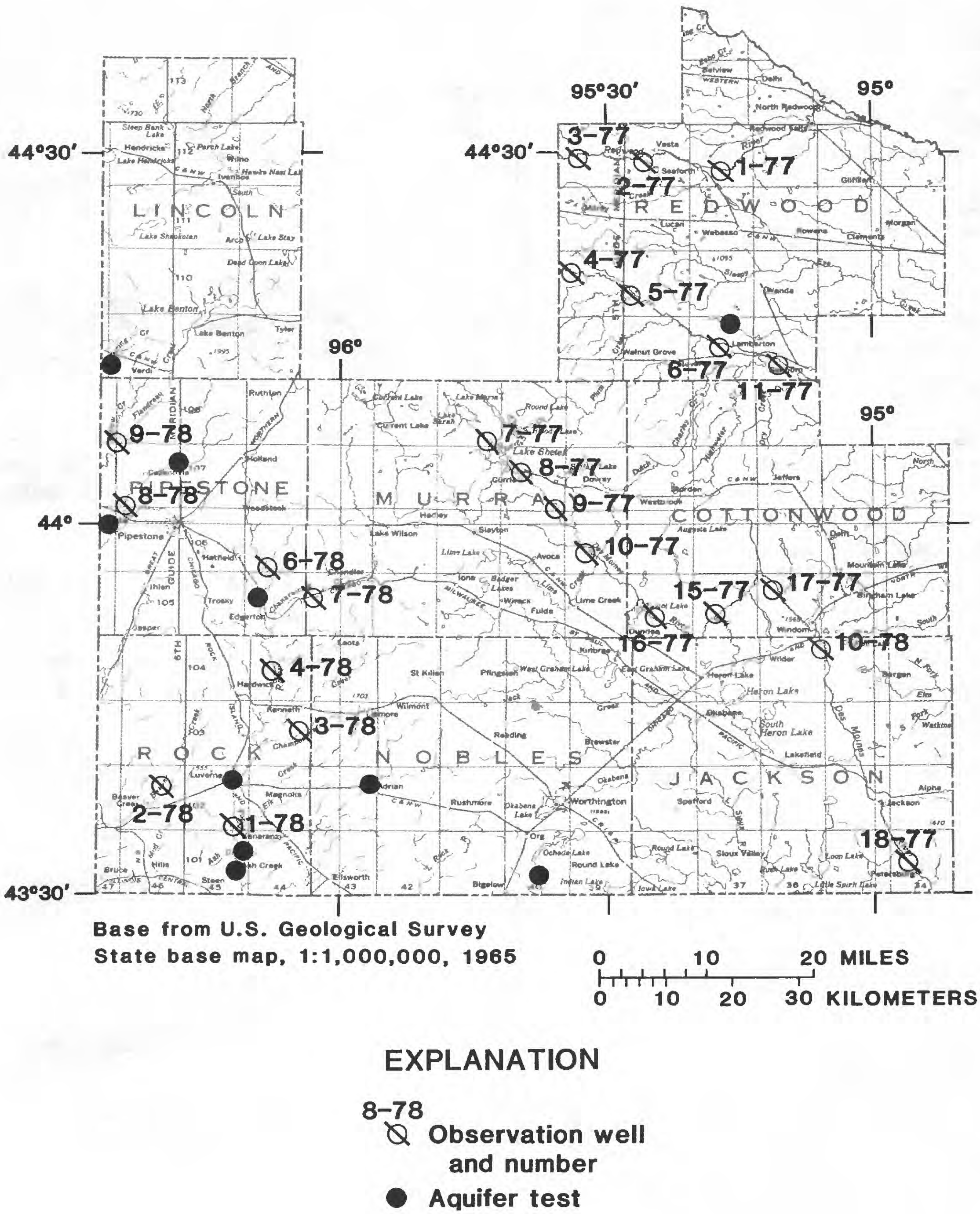


Figure 5.--Location of observation wells and aquifer tests

although the largest percentage of annual precipitation occurs in June. The decline in water levels that starts in June and continues into September is probably due to large water losses by evapotranspiration and irrigation pumpage. After the first killing frost, generally during early October, ground-water levels commonly rise slightly until the ground freezes.

The primary hydraulic characteristics of an aquifer are its hydraulic conductivity, saturated thickness, and storage coefficient. Hydraulic conductivity and saturated thickness are commonly combined as transmissivity (hydraulic conductivity times saturated thickness), and storage coefficient is virtually equal to specific yield in unconfined (water-table) aquifers. These parameters can be used to determine the rate and the magnitude of water-table declines resulting from withdrawal of water from an aquifer.

Hydraulic characteristics of the surficial aquifers were determined from data collected during nine aquifer tests (fig. 5). Values of aquifer characteristics determined by the aquifer tests are representative only in the immediate area of the test location. Guided by aquifer test results, however, values were estimated at other locations based on examination of samples collected during test drilling and published data for similar materials. Specific yield of 0.12 was considered to be representative. The relation of particle-size classification to hydraulic conductivity is virtually that used by Larson (1976). This relationship was used to estimate the hydraulic conductivity at the test-hole sites. Lower conductivity values in each range were assigned to relatively poorly sorted material, and higher values were assigned to well-sorted material. Transmissivity was then determined by multiplying the estimated hydraulic conductivity by the saturated thickness.

Calculations of a theoretical optimum yield of a properly constructed well were made to evaluate the surficial aquifer. The following assumptions were made in the calculations:

1. The aquifer is homogeneous and of infinite areal extent.

2. The well is screened over the entire saturated thickness of the aquifer, is 100 percent efficient, and is of large diameter (24 in.).

3. The well is pumped continuously for 30 days.

4. Drawdown, the decrease in water level in the well caused by pumping, is two-thirds of the original saturated thickness. Theoretically, this corresponds to 90 percent of the maximum yield for unconfined aquifers and is generally accepted as the optimum design specification (Edward E. Johnson, Inc., 1966, p. 107-108).

Based on these assumptions, the nonequilibrium equations of Theis (1935), with a drawdown correction for unconfined aquifers (Jacob, 1944), can be used to compute well discharge. Although some assumptions may never be fully satisfied, the method produces a quantitative measure of the aquifer's water-yielding potential. Water-yielding potential of the surficial aquifer, as shown on plates 1-8 and tables 3-10, closely follows the distribution of saturated thickness. Areal variation of hydraulic conductivity is not as significant as variation of saturated thickness. Well yields in this report are classified as follows: small, less than 50 gal/min; moderate, 50 to 200 gal/min; large, more than 200 gal/min.

QUALITY OF GROUND WATER

The degree to which the shallow ground-water resources of southwestern Minnesota may be further developed depends not only on the quantity of water available but also on the chemical quality of the water. The chemical quality depends mostly on the constituents dissolved from the minerals and organic compounds with which the water has been in contact. Some of the chemical constituents, physical properties, and charcteristics most significant in determining the suitability of water for domestic, livestock, and irrigation use are iron, sulfate, nitrite or nitrate, fluoride, dissolved solids, hardness, temperature, taste, color, odor, specific conductance, sodium-adsorption-ratio (SAR), and percent sodium.

The National Academy of Science and National Academy of Engineering (1973) standards for some of the chemical constituents commonly present in drinking water are shown in table 1.

Table 1.—Standards for some of the chemical constituents

Constituent	Concentration, in mg/L Recommended maximum	Recommended rejection
Chloride	250	none
Fluoride	1.0*	1.6
Iron and manganese	0.3	none
Nitrite-nitrogen	10.0	none
Sulfate	250	none
Dissolved solids	500	2,000

*Based on annual average of maximum daily air temperatures of 23.7°C.

The heterogeneity of the drift is reflected by a wide range of mineral constituents in the ground water. In general, the water contains large quantities of calcium, magnesium, sulfate, and bicarbonate.

Water samples collected from 15 observation wells distributed throughout the area (table 2) were analyzed. Results of three chemical analyses of ground water in Nobles County (Norvitch, 1964) and four analyses for Cottonwood, Jackson, Lincoln, and Murray Counties (Broussard and others, 1973; Anderson and others, 1976a; DeWild and others, 1979) are also included in table 2. These data indicate that, in general, the ground water is suitable for domestic uses, although it is very hard. Locally, sulfate concentrations exceeded the National Academy of Science and National Academy of Engineering (1973) recommended limits in samples collected from the Des Moines, Cottonwood, and Kanaranzie aquifers, in Murray, Redwood, and Nobles Counties, respectively. Recommended concentrations of nitrate as nitrogen were exceeded in samples from the Chanarambie, Rock, Flandreau, and Beaver aquifers in Pipestone and Rock Counties.

Table 2.—Chemical analyses of ground

[Analyses in milligrams per

Well location	Well depth (ft)	Aquifer	Date of collection	Total iron (Fe) and manganese (Mn) (ug/L)	Dissolved boron (B) (ug/L)	Dissolved calcium (Ca)	Dissolved magnesium (Mg)	Dissolved sodium (Na)
Cottonwood County								
105N36W25AAB	100	Des Moines	7- -70	—	—	92	19	6
105N37W29AAA	7	do.	9-26-78	990	70	140	45	11
105N38W20BAA	15	do.	9-26-78	3120	20	49	41	4.7
105N38W25ABD	31	do.	9-29-72	3800	—	140	33	6.8
Murray County								
105N43W01	30	Chanarambie	9-08-69	—	—	470	—	29
105N43W18BCC	—	do.	9-06-79	10,500	20	110	30	5.4
105N44W17ABB	60	Rock	6-14-78	—	—	83	33	7.6
106N39W21dad	7	Des Moines	9-27-78	8800	100	130	51	7.9
106N40W12ABB	15	do.	9-27-78	4320	70	180	66	15
107N40W21AAB	15	do.	9-06-79	6120	50	150	46	15
Pipestone County								
106N44W33CCD	14	Rock	9-27-78	6080	20	68	48	4.9
107N47W12CDC	14	Flandreau	9-06-79	2100	50	130	39	11
Redwood County								
109N36W21DCC	15	Cottonwood	9-26-78	9500	210	120	46	21
109N37W09CCC	19	do.	9-05-79	22,950	50	120	37	7.3
110N39W17AAA	15	do.	9-28-78	6800	200	170	72	21
112N39W22BBB	10	Redwood	9-27-78	2620	110	90	40	34
Rock County								
102N45W35DDC	14	Rock	9-27-78	3510	50	150	44	11
102N46W14AAA	14	Beaver	9-06-78	17,090	6	72	90	3.2
104N44W21CDC	14	Rock	9-06-78	6770	2	78	25	4.3
Nobles County								
101N43W20DBD1	19	Norwegian	6-23-59	—	—	82	31	11
102N40W27CCD4	30	Nobles	6-10-58	—	—	118	37	13
103N42W07AAB1	26	Kanaranzie	6-22-59	—	—	145	50	16
Jackson County								
102N35W24BDB2	42	Des Moines	3-01-70	—	—	140	44	32
Lincoln County								
109N47W25DDD	53	Elk	9-12-78	0.27	—	94	30	11
109N47W36ADD	57	do.	11-09-78	0.04	—	75	26	4.4

water from surficial deposits

liter, except as noted]

Dissolved potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Dissolved sulfate (SO_4)	Dissolved chloride (Cl)	Dissolved fluoride (F)	Nitrite plus nitrate (as N)	Dissolved solids res. evap. 180°C	Hardness, as $CaCO_3$ Calcium, magnesium	Hardness, as $CaCO_3$ Noncarbonate	pH
5.0	230	—	110	8.5	0.2	—	400	310	120	7.2
5.6	400	0	200	7.2	.2	2.7	666	330	210	7.2
1.6	230	0	65	9.0	.1	.9	417	190	100	7.3
1.2	290	—	250	1.6	.7	—	600	250	—	7.3
—	—	—	220	41	.2	14	830	630	250	7.0
2.3	—	—	90	8.3	.3	10	502	270	130	7.3
1.9	330	—	70	6.8	.2	.2	414	270	—	7.5
2.2	470	0	100	7.2	.3	0	558	390	150	7.4
1.9	320	0	260	42	.6	2.4	763	260	400	7.2
4.2	—	—	240	34	.2	0	795	250	310	7.2
.9	330	0	61	50	.2	17	694	270	97	7.2
.9	—	—	180	12	.4	16	655	250	240	7.4
2.2	310	0	260	9.7	.3	4.3	665	250	230	7.0
.6	—	—	52	15	.5	.18	419	390	62	7.3
1.3	380	0	420	22	.4	.12	958	310	410	7.3
5.2	260	0	200	17	.4	1.5	557	210	180	7.3
1.6	460	0	170	14	.2	2.8	658	380	180	7.2
0.2	160	0	32	7.5	.4	15	313	240	82	7.2
1.3	—	—	37	4.1	.3	13	357	230	68	7.3
1.6	333	—	60	5.8	.1	8.6	425	332	59	7.5
1.0	328	—	184	8.0	.3	.7	552	178	6	7.2
3.4	344	—	307	6.5	.0	.6	870	568	286	8.0
—	427	—	180	41	.4	4.4	655	530	180	7.3
2.3	394	—	46	1.2	.3	.6	428	323	—	7.5
1.7	289	—	37	3.9	.2	3.0	350	237	—	7.6

Hardness is a property of water generally related to its suds-inhibiting power. Hardness as $CaCO_3$ ranged from 178 mg/L in a sample from the Nobles aquifer to 630 mg/L in a sample from the Chanarambie aquifer. The U.S. Geological Survey generally accepts a classification of hardness according to the following table:

Grains per gallon (approximate)	Milligrams per liter	Classification
0- 3.5	0- 60	Soft
3.6- 7.0	61-120	Moderately hard
7.1-10.5	121-180	Hard
More than 10.5	More than 180	Very hard

Dissolved solids in water, a general measure of water quality, ranged from 313 to 958 mg/L. Most water containing less than 500 mg/L dissolved solids is considered to be satisfactory for most uses (National Academy of Science and National Academy of Engineering, 1973). Water having less than 2,000 mg/L of dissolved solids is generally satisfactory for irrigation, although boron, salinity, and sodium (alkalinity) problems may result. However, the amount of potential damage to crops from these problems depends on other factors also, such as porosity of the soil, drainage, irrigation practices, and crop management (U.S. Salinity Laboratory Staff, 1954).

The U.S. Salinity Laboratory Staff, (1954) has developed a sodium-adsorption-ratio (SAR) method that is commonly used in evaluating water for irrigation. SAR is related to the adsorption of sodium from water by soil to which the water is added. The sodium hazard of water from the surficial aquifer samples ranged from 0.1 to 0.8, which is considered to be low. The water can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium.

PRESENTATION OF DATA BY COUNTIES

Geohydrologic data on the surficial aquifers in each county are presented in the following text, plates, and tables. Data on the plates consist of (1) delineation of the areal extent of the surficial deposits, (2) graphical representations of water quality, (3) locations of test holes and observation wells, (4) water-level hydrographs, (5) hydrogeologic sections, (6) areas of 20 ft or more of saturation, and (7) locations of aquifer-test sites. The tables contain summaries of data from auger holes and aquifer tests.

Cottonwood County

The Des Moines River drains the southwest part of Cottonwood County (pl. 1). The Little Cottonwood River, and Pell, Dutch Charlie, Highwater, Dry, and Mound Creeks drain northward into the Cottonwood River, and the Watonwan River and its tributaries drain eastward into the Minnesota River. Outwash and alluvium in the valley of the Des Moines River form the principal aquifer in the county (table 3). Minor aquifers occur in the other river valleys. Irrigation in the county increased from 180 acres in 1970 to 2,888 acres in 1977. About half the acreage is irrigated by wells that tap surficial deposits.

Table 3.—Summary of test-hole data for surficial deposits in Cottonwood County, Minnesota

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Des Moines valley										
West area	20	8	18	29	17	Reddish-brown medium sand to fine gravel with interbedded lenses of silt and clay.	17	10	13,000	Small to moderate
East area	34	11	17	72	54	Fine sand to coarse gravel with numerous interbedded lenses of silt and clay.	7	20	11,000	Moderate to large
Watonwan River	18	8	6	20	13	Very fine sand to coarse silty gravel containing some silt.	3	7	1,600	Small to moderate
Highwater Creek	13	5	4	16	10	Medium sand to fine gravel with lenses of sandy silt.	3	5	1,200	Do.

Des Moines River valley aquifer

The Des Moines River valley ranges from about 0.5- to 2-mi wide and is 24 mi long in Cottonwood County. The area northwest of Windom, where the river makes an abrupt turn to the southeast, is called "Great Bend." In general, deposits in the aquifer are composed of fine sand, silty sand, and sandy gravel interbedded with lenses of silty clay. Test drilling of 35 holes indicates that the aquifer material is coarsest in the "Great Bend". The water-table gradient is about 2 ft/mi in the main valley and as much as 10 ft/mi in the tributaries. Test drilling of 17 holes indicates that the outwash is as thick as 72 ft in the main valley but only 20 ft thick in the tributaries. Irrigation wells penetrated outwash as thick as 85 ft in the aquifer north of the Great Bend. The outwash consists mainly of coarse sand interbedded with clay and gravel. The cross-sectional shape of the valley shows that the thickest part of the aquifer is on the east side of the channel, although thickness varies considerably within short distances. The valley is 2-mi wide at Windom, but decreases to less than 1-mi wide to the north. Water levels in wells were lowest during the winter and highest during May. Fluctuations were about 4 ft in 1978 and 6 ft in 1979. The Great Bend area is the major source of water to wells in the county and is the most promising area for development. Irrigation wells have yields as high as 1,000 gal/min (table 3). The saturated thickness of the aquifer is 20 ft or more (pl. 1). About 11,000 acre-ft of water is stored in the aquifer (table 3). The water is generally a mixed calcium sulfate bicarbonate type of relatively good chemical quality. The average dissolved-solids concentration among four samples is 545 mg/L.

Jackson County

Although the Des Moines River is the main stream in Jackson County, drainage to the river is poor (pl. 2). Drainage in the central part of the county is toward Heron, South Heron, Loon, and Little Spirit Lakes. Irrigated acreage decreased from 52 acres in 1970 to 35 acres in 1977, and the potential for irrigation from wells in surficial aquifers other than in the Des Moines River valley aquifer is small (table 4).

Des Moines River valley aquifer

The Des Moines River valley aquifer ranges from 0.25- to 0.5-mi wide. Throughout most of the county, the valley is incised from 100- to 150-ft deep. Drilling of 18 test holes indicates that the aquifer is as thick as 51 ft in the northern part of the valley and 40-ft thick in the southern part. In the middle part of the county, however, the aquifer is less than 20-ft thick. In general, the aquifer is composed of fine to coarse sand, clayey sand, and silty fine to medium gravel. Test drilling determined that the material is coarsest in the northern and southern parts of the river valley. Data from an observation well near the Cottonwood County line indicate that the water level declined 5 ft during 1978 but rose 7 ft during spring 1979. Periodic measurement in an observation well in the southern part of the county indicated that the water level, which is 11 ft below land surface, did not change significantly during the 2-year period of record. The area that has the greatest potential for development, shown on plate 2 as an area of 20 ft or more of saturated sand and gravel, is near the Cottonwood County line. Results of test drilling indicate that the outwash is as thick as 51 ft. Saturated thickness was 45 ft during the summer of 1979, which indicates that large well yields are probably obtainable. Potential yields in other areas are small. Water from the aquifer is fairly low in dissolved solids, which ranges from 350 mg/L in the northern part of the aquifer to 650 mg/L in the southern part (Anderson and others, 1976b). The water is a mixed calcium sulfate bicarbonate type.

Table 4.—Summary of test-hole data for surficial deposits in Jackson County, Minnesota

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Des Moines valley	24	6	18	51	37	Silt and sand in middle part of county. As much as 30 ft of gravel is present in north part and 25 ft in the south part.	20	12	18,000	Moderate to large
Okabena to Creek	18	8	4	21	11	Silty, fine to coarse sand.		2	5	800Small moderate
Jack Creek	15	6	1	15	9	Gray sandy silt.	3	9	2,100	Do.
Little Sioux River	16	4	6	28	18	Greenish-gray sand and gravel.	3	6	1,400	Do.
North Fork Elm Creek	18	6	3	20	14	Gravelly silt. Auger hole 104N34W36DDD penetrated 14 ft of gravel.	2	12	1,800	Do.
South Fork Elm Creek	16	5	4	19	12	Fine to coarse gravel. Gray sandy silt in lower part.	1	8	600	Do.

Lincoln County

Most of Lincoln County is on the Coteau above the surrounding prairie. Although there are several stream channels in the Coteau, evidently formed during the last glaciation, no major surficial outwash was deposited. However, several aquifers contain sufficient saturated deposits to be considered for development. These aquifers, shown on plate 3 where the saturated thickness is greater than 20 ft, are in the Flandreau Creek channel, Elkton outwash plain, and Porter area. Test-hole data on the aquifers are given in table 5.

Flandreau Creek-Lake Benton channel aquifer

The Flandreau Creek-Lake Benton channel extends from Lake Benton southward to the Pipestone County line. Flandreau Creek begins about 1 mi south of Lake Benton. North of this point, the drainage is toward Lake Benton. The channel is 0.5-mi wide or less in Lincoln County, but increases to more than 0.5-mi wide south of the Pipestone County line. Most of the deposits in the channel near Lake Benton consist of clay and sandy silt, but the sand and gravel content increases southward. A series of test holes across the channel at the Pipestone County line indicate that the outwash is thick. Moderate yields should be obtainable in this area.

Elkton aquifer

The Elkton outwash plain, which is associated with narrow bands of outwash in Spring and Medary Creeks, has an area of 6 mi^2 in the southwest corner of Lincoln County. Although the seven test holes drilled penetrated as much as 66 ft of sand and gravel in the southern part of the outwash plain, much of the material in the northern part consists of clay and sandy silt. Potential yields to wells are large in the southern part, but are small in the northern part. In August and September 1978, test wells were drilled west of Verdi for the Lincoln-Pipestone Counties Rural Water District (DeWild and others, 1979). The wells ranged in depth from 53 to 67 ft. Static water level ranged from 25 to 30 ft. Aquifer tests were made on five production wells during October and November 1978. The wells were pumped from 12 to 146 hours at 75 to 600 gal/min. Aquifer transmissivities ranged from 13,000 to 16,000 ft^2/d and storage coefficients from 0.01 to 0.014 (Fax, 1980). Specific capacity of the test wells ranged from 12 to 35 (gal/min)/ft. Water is of good chemical quality, and water type is a mixed calcium sulfate bicarbonate. Dissolved solids in water from two of the test wells were 350 and 428 mg/L (DeWild and others, 1979).

Porter aquifer

The Porter aquifer, in the northeast corner of Lincoln County, includes the outwash in the valleys of the Yellow Medicine River and its tributary, the North Fork. Most of the material consists of thin deposits of silt and fine to medium sand. However, more than 30 ft of fine to coarse gravel was penetrated in test hole 113N44W11DCC. Moderate yields can be expected locally.

Murray County

The Des Moines River valley is underlain by outwash that forms the largest surficial aquifer in the county (pl. 4). Aquifers in the valleys of Beaver, Chanarambie, Line, Plum, and Willow Creeks yield only small quantities of water to wells, none for irrigation. The summary of test-hole data for surficial deposits in Murray County is shown in table 6.

Table 5.—Summary of test-hole data for surficial deposits in Lincoln County, Minnesota

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Flandreau Creek-Lake Benton channel	32	3	5	35	33	Mostly fine sand and clayey silt. Twenty feet of fine to coarse gravel in auger holes at the Pipestone County border.	3	30	6,900	Moderate to large
Elkton outwash plain	32	25	7	66	42	Fine sand, clay, and silt at surface. As much as 30 ft of gravel below a clay layer in southern part of area.	6	25	11,500	Do.
Lake Shaokatan channel	15	6	4	20	16	Brown sandy silt in eastern part of channel; sand and gravel content increases westward.	2	9	1,400	Small to moderate
Porter outwash-Yellow Medicine River	23	6	10	36	27	Till and fine sand; however, more than 30 ft of sand and gravel in test holes 113N44W12CCC and 113N44W11DCC.	8	15	9,200	Moderate to large
Tyler outwash plain	22	6	2	25	22	Silty brown clay in the northern part and fine to coarse sand and gravel in the southern part.	3	10	2,300	Small to moderate

Table 6.—Summary of test-hole data for surficial deposits in Murray County, Minnesota

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Des Moines valley	17	6	41	40	33	Fine sand to coarse gravel with dark gray silty clay and interbedded silt lenses.	20	10	15,400	Moderate to large
Lime Creek	20	7	8	25	27	Fine to coarse silty sand with silty clay lenses.	8	11	6,800	Do.
Willow Creek	21	8	4	36	21	Fine sand to coarse gravel with lenses of sandy silt.	2	11	1,700	Do.
Beaver Creek	15	6	7	24	8	Fine sand to fine gravel with blue and bluish-gray silt and lenses of clay.	3	2	500	Small to moderate
Chanarambie Creek	20	7	11	30	22	Fine sand to coarse gravel with dark gray till at base.	8	13	8,000	Moderate to large
Lake Wilson area	19	5	4	35	28	Fine sand to coarse gravel with dark gray till at base.	4	12	3,700	Do.

Des Moines River valley aquifer

The Des Moines River valley is about 0.5-mi wide near Lake Shetek and increases to 2-mi wide at the Cottonwood County border. The deposits in the valley consist of fine sand to coarse gravel interbedded with dark-gray silty clay and lenses of silt. Analyses of 41 test holes indicate that the deposits range in thickness from 6 to 40 ft and average 17 ft. The maximum saturated thickness was 33 ft in test hole 107N40W35BAB. Hydrographs of four observation wells show that the water level rose from 4 to 6 ft in spring 1979, and that the water levels in summer 1979 were 2 to 3 ft above levels in summer 1978. Above-normal precipitation during winter and spring 1979 caused the water levels to rise to all-time highs. Generally, high water levels occur in March and April and low water levels in September. Yields of wells in the aquifer vary greatly. Small yields may be expected from wells in most of the aquifer, but moderate yields may be expected locally where the saturated thickness of the sand and gravel is greater than 20 ft. The most favorable area is shown on plate 4 to extend from Currie southeast for 7 mi. A sample from observation well 107N40W21AAB (August 1977) at the south edge of Currie show that the dissolved-solids concentration was 795 mg/L, and that the water can be classified as a magnesium sulfate type (table 2). Analyses from observation wells 5, 8, and 13 mi below Currie show that the dissolved-solids concentration decreased to 763, 558, and 417 mg/L, respectively.

Nobles County

The physiography of Nobles County is dominated by the Coteau des Prairie, which trends south and southeast from the Murray County border to Iowa. Associated with the Coteau are surficial-outwash deposits that occur as long, narrow bodies following stream courses (pl. 5). The drainageways that head on the east side of the Coteau are relatively narrow and contain fine-grained material. During the Pleistocene age, flow in these streams, which drained the back slopes of the moraines, may have been too small to carry large amounts of gravel (Norvitch, 1960). Drainageways that formed on the front slopes of the Coteau contain gravel deposits.

Large water supplies may be obtained from aquifers in the Kanaranzi Creek valley and the Worthington channels. The surficial aquifers are used by Worthington, Bigelow, Lismore, and Adrian. Irrigation from surficial aquifers was about 500 acres in 1977. The summary of test-hole data for surficial deposits in Nobles County is shown in table 7.

Kanaranzi Creek valley aquifer

Kanaranzi Creek has the largest drainage system in Nobles County. The width of the valley varies from less than 0.5 mi to more than 1 mi near the Rock County border. Logs of 21 test holes show that the thickness of the sand and gravel averages 24 ft from the Rock County border to 4 mi north of Adrian. East of Adrian the deposits become clayey. The saturated thickness is generally 12 ft. Yields to wells will probably be small where the aquifer is narrow; however, large yields should be obtainable where the deposits are greater than 25-ft thick and 1-mi wide. Pumping rates of the Adrian and Lismore wells are 115 and 50 gal/min, respectively. Water from the aquifer is very hard and high in sulfate concentration.

The Norwegian Creek valley ranges from about 0.25-mi wide in the headwaters to about 1-mi wide at the Rock County border. Results of 4 test holes drilled in 1959 show that the outwash ranges from 21- to 60-ft thick and averages 37 ft (Norvitch, 1960).

Table 7.—Summary of test-hole data for surficial deposits in Nobles County, Minnesota

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Elk Creek, east	18	13	4	20	15	Sandy silt, underlain by dark gray clay.	2	8	1,200	Small to moderate
Elk Creek, west	16	4	2	17	11	Silt underlain by brownish-gray clay.	2	10	1,500	Moderate to large
Worthington channels	20	7	11	61	59	Alluvium consisting of fine sand to coarse gravel. Underlain by clay.	8	13	8,000	Do.
Bigelow Lake plain	18	8	3	20	12	Brown-gray sandy silt, underlain by dark clay.	3	9	2,100	Small to moderate
Jack Creek	24	9	9	46	41	Sandy silt, underlain by gravel and dark gray clay.	3	10	2,300	Do.
Champepadan Creek	18	3	7	22	19	Sandy silt, underlain by silty gravel and dark gray clay.	6	15	7,000	Moderate to large

Table 7.—Summary of test-hole data for surficial deposits in Nobles County, Minnesota—Continued

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Kanaranzi Creek	23	6	21	35	26	Alluvium consisting of brownish clayey sand and gravel in upstream section; downstream section consists of more rounded sand and gravel with many limestone fragments.	15	17	19,600	Moderate to large
Norwegian Creek	34	10	4	60	52	Mostly fine gray sand and some gravel.	8	10	5,000	Do.
Little Rock River, West Branch	14	8	15	25	15	Alluvium consisting of clay, overall brownish color.	8	10	5,000	Do.

Three locations, shown on plate 5, where saturated thickness is greater than 20 ft, have a potential for the development of large supplies. The most promising area extends from the Rock County border to Adrian.

Worthington channels

The Worthington channels consist of two outwash valleys that extend south from Okabena Lake to Ocheda Lake. Below Ocheda Lake, the Ocheyeda River flows in the west channel to Lake Bella near the Iowa border. The east channel joins the west channel 1 mi north of the border. The valley floors are less than 0.5-mi wide and are less than 20 ft below the prairie. Three test holes drilled in the channel deposits south of the west arm of Ocheda Lake in 1959 (Norvitch, 1960) and eight holes drilled in the same general area in 1978, show that the maximum thickness of the deposits was 61 ft; the average thickness was 20 ft. The deposits consist of sandy silt underlain by gravel. Static water levels average 7 ft, and the saturated thickness averages 13 ft. Yields to wells will vary considerably within short distances because of abrupt changes in lithology and thickness. The city of Worthington had 10 wells pumping from the channel deposits in 1978. The 5 wells located 1 mi south of town yield 35 gal/min each, whereas, the 5 wells 6 mi south of town yield 400 to 500 gal/min each. Saturated thicknesses ranged from 40 to 50 ft in the southernmost wells. The only potential for further development is south of Lake Ocheda. Test hole 101N40W27BAB penetrated 56 ft of fine to coarse gravel. Analyses of water from well 102N40W27CCD4 (table 2) indicate that the dissolved-solids concentration is 552 mg/L. The water is hard and is a calcium sulfate bicarbonate type. Concentrations of sulfate and calcium are 184 and 118 mg/L, respectively.

Pipestone County

The Coteau des Prairie crosses the northeastern corner of Pipestone County and gives rise to the Redwood River, Rock River, Flandreau Creek, and Pipestone Creek (pl. 6). Water use for irrigation is restricted to the Pipestone Creek aquifer. Irrigation by sprinklers has increased from 120 acres in 1970 to 1,421 acres in 1977. The village of Edgerton wells tap the Rock River valley aquifer. Table 8 contains the summary of test-hole data for surficial deposits in Pipestone County.

Rock River valley aquifer

The Rock River heads on the southwestern flank of the Coteau and flows southward through a 1-mi wide valley near the eastern edge of the county. Results of 20 auger holes indicate that deposits in the Rock River valley aquifer consist of thin lenses of sand and gravel interbedded with clay. The deposits ranged from 4 to 37 ft in thickness and averaged 19 ft. Thicker and coarser material occurs locally. A hydrograph of well 106N44W33CCD (June 1978, pl. 6) shows that the water level was 6 ft below land surface during 1978 but recovered 4 ft during spring 1979. Throughout the rest of the year the water level gradually declined except in July when heavy rains fell. Fluctuations of water levels in observation well 105N43W18BCC (July 1978) at the Murray County line in the Chanarambie Creek valley were similar to those in the Rock River valley aquifer. Analyses of material penetrated in test holes and results of an aquifer test indicate that potential well yields are small. A well tapping coarse gravel deposits 30-ft thick in the headwaters of East Branch Rock River is reported to yield 600 gal/min. However, yields of 100 gal/min can be expected from much of the aquifer because of the limited drawdown. A test well 2 mi north of Edgerton was pumped for 24 hours at 68 gal/min (DeWild and others, 1979). The well taps 57 ft of deposits. Transmissivity was 4,000 ft^2/d. Logs

Table 8.—Summary of test-hole data for surficial deposits in Pipestone County, Minnesota

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Rock valley										
Rock, and East Branch Rock Rivers, Chanarambie, and Poplar Creeks	19	8	30	37	22	Outwash consisting of thin lenses of sand and gravel interbedded with clay. Thicker, coarser, and better-sorted material occurs locally.	18	10	18,000	Moderate to large
Big Sioux tributaries										
Flandreau Creek and tributaries	20	8	11	28	22	Fine to coarse sand and gravel, silty; contains lenses of silty clay and gravelly clay. Locally consists of clean sand and gravel.	7	12	6,500	Do.
Pipestone and North Branch Creeks	26	8	24	60	39	Fine to coarse sand and gravel with silt and clay.	12	17	15,700	Moderate to large
Split Rock Creek	9	8	2	12	3	Little or no water available to wells.	1	2	150	Small to moderate

of test holes indicate that the deposits are clayey. Chemical analyses of water from observation well 106N44W33CCD (June 1978) and test hole 105N44W17ABB indicate that dissolved-solids concentrations were 694 mg/L and 414 mg/L, respectively (table 2). The water is very hard and is of the calcium bicarbonate type. The National Academy of Science and National Academy of Engineering (1973) recommended limit of nitrite-nitrate concentration was exceeded in well 106N44W33CCD (June 1978).

Big Sioux tributary aquifers

Flandreau, Pipestone, and Split Rock Creeks drain the western half of Pipestone County. All flow southwestward to the Big Sioux River in South Dakota. Deposits in the Split Rock Creek valley do not have sufficient saturated thickness to yield water to wells.

The Flandreau Creek valley is a well-developed channel that is 0.5-mi wide. The valley floor is 50 ft below the prairie. Deposits consisting of silty sand and gravel with lenses of clay range in thickness from 16 to 28 ft and average 20 ft. The water level in observation well 107N47W12CDC (September 1978) rose 4 ft in spring 1978 and 3 ft in spring 1979 but declined 1.5 ft during summer 1978 and 1979. Potential well yields from the deposits are small. Large yields may be available locally where deposits are coarser and thicker; such as the area near the Lincoln County line (pl. 6). The concentration of dissolved solids was 655 mg/L (table 2) from observation well 107N47W12CDC (September 1978). The water, which is of the calcium sulfate type, exceeds the National Academy of Science and National Academy of Engineering (1973) recommended limit for nitrite-nitrate concentrations.

Pipestone Creek heads on the western slope of the Coteau. The Creek valley is partly filled with water-laid sand and gravel. Data from 24 test holes indicate that the outwash ranges in thickness from 15 to 60 ft and averages 26 ft. Thick deposits of sand and gravel in the drainage system form broad terraces near the confluence of tributaries. Two holes penetrated 40 and 60 ft of sand and gravel near the confluence of the North Branch and Pipestone Creeks. Saturated thicknesses were 19 and 39 ft, respectively. Water-level fluctuations in observation well 107N47W12CDC (September 1978) indicate that the annual change is about 4 ft. Water levels rose sharply in spring, were highest in May, and then decreased gradually the rest of the year except as affected by precipitation. Five irrigation wells produce water from the Pipestone Creek valley aquifer and terrace deposits, which are hydraulically connected. Yields range from 400 to 725 gal/min and depths range from 41 to 62 ft. Aquifer tests were made on two irrigation wells (Fax, 1980). The well in the upper reach is 56 ft deep and was pumped at 725 gal/min. Drawdown was 27 ft after 72 hours. The average transmissivity was 15,600 ft^2/d and the storage coefficient was 0.02. The other test was made on well 106N46W08DAB near the South Dakota border. The well is 61-ft deep and was pumped at 550 gal/min. Transmissivity was 16,000 ft^2/d.

Redwood County

Drift forms a gently undulating plain over the bedrock in Redwood County. The plain is interrupted in part by the Cottonwood River valley and by the large Minnesota River valley and its tributary, the Redwood River valley. The most productive surficial aquifers are in the valleys of the Redwood and Cottonwood Rivers (pl. 7). Irrigation from wells has increased from 340 acres in 1970 to 1,095 acres in 1977. However, only 2 of the 12 wells are completed in the surficial aquifers. Test-hole data are given in table 9.

Table 9.—Summary of test-hole data for surficial deposits in Redwood County, Minnesota

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Cottonwood River	30	6	31	60	55	Fine sand to coarse gravel. Thick lenses of clay in western part and sand and gravel in valley center.	17	20	26,100	Moderate to large
Pell Creek	18	12	1	18	6	Fine sand to coarse gravel with lenses of silt and clay.	—	—	—	—
Dutch Charlie and High-water Creeks	22	8	3	18	10	Sandy silt with thin layer of fine to coarse gravel.	3	5	1,200	Small to moderate
Minnesota River	18	8	12	37	25	Mostly silt and clay with thin lenses of sand.	10	10	7,700	Small to moderate
Redwood River and its tributaries	21	9	50	61	52	Fine sand to coarse gravel with lenses of fine gray sand. Locally interbedded with blue clay.	12	25	23,000	Moderate to large

Redwood River valley aquifer

The Redwood River flows northeastward across Redwood County and occupies a broad, shallow valley, which ranges in width from 0.5 to 1 mi. The Redwood valley is parallel to the Antelope Moraine (Leverett, 1932) and is associated with a melt-water channel incised in the underlying shale of Cretaceous age to a depth of about 60 ft (Schneider and Rodis, 1961). In places, the outwash in the valley is underlain directly by granite (Helgeson, 1967). The melt-water channel was filled with till, glacio-lake deposits, and thick deposits of highly permeable water-bearing sand and gravel. Results of 50 test holes show that the sand and gravel range in thickness from 10 to 60 ft and average 25 ft. Water levels fluctuated only 3 ft during the 2 years of record in observation wells 112N37W21CCB and 112N39W22BBB (pl. 7) Cause of the small fluctuation was probably due to limited water use of the aquifer and high specific yield of the deposits. Water levels in observation well 112N38W21BBC fluctuated 4 ft, probably because the well is developed in less permeable material. Water levels show a seasonal fluctuation closely related to rainfall. Large well yield can be expected from most of the aquifer. The area where the saturated thickness is 20 ft or greater, as shown on plate 7, extends from the Lyon County border to Seaforth. Aquifer tests made near Marshall, Lyon County, indicated transmissivity values of 4,000 ft^2/d (Rodis, 1963) and 5,400 ft^2/d (Thompson, 1965). Water from observation well 112N39W22BBB (March 1977) had a dissolved-solids concentration of 557 mg/L. The water is very hard and of the calcium sulfate bicarbonate type (table 2).

Cottonwood River valley aquifer

The Cottonwood River enters Redwood County from the west and flows southeasterly, leaving the county at the southeast corner. Major tributaries are Plum, Pell, Dutch Charlie, Highwater, and Dry Creeks. All tributaries are on the south side because the river is adjacent to the southern edge of Leverett's "Marshall moraine" (1932) and the land surface in the area slopes northeastward from the crest of the Coteau. The Cottonwood River valley aquifer, which underlies 17 mi^2, consists of a narrow band of sand, gravel, silt, and clay. The valley floor is about 50 ft below the level of the prairie. Data from 31 test holes indicate that the thickness of the outwash ranges from 12 to 65 ft and averages 27 ft. Drilled in the central part and northern side of the valley generally penetrated thicker and more numerous sand and gravel lenses than those drilled on the southern side. The saturated thickness of the aquifer ranged from 1 to 60 ft, but was generally less than 25 ft. Monthly measurements in four observation wells in the aquifer for 2 years indicate that the annual water level fluctuates 4 ft (pl. 7). Irrigation well 109N37W02DCC, which is 34-ft deep and penetrates 17 ft of sand in the Cottonwood aquifer, was pumped for 72 hours at 300 gal/min. Analyses of the aquifer-test data indicate that the transmissivity was 3,900 ft^2/d, storage coefficient 5.6×10^{-2}, and specific capacity 18.1 (gal/min)/ft (Fax, 1980). Potential yields to wells range from moderate to large. Small yields are available from aquifers in the tributaries. Water from observation wells 110N39W17AAA (April 1977), 109N37W09CCC (June 1977), and 109N36W21DCC (November 1977) is a calcium sulfate bicarbonate type that ranges in dissolved-solids concentrations from 419 to 958 mg/L. Sulfate concentrations ranged from 310 to 380 mg/L.

Rock County

Surficial aquifers are present in the valleys of the Rock River and its tributaries (Champepadan, Elk, and Kanaranzi Creeks) and the Big Sioux tributaries (Split Rock and Beaver Creeks). The aquifer in the Rock River valley is the largest and most productive. During 1970-77, the irrigation acreage increased from 160 to 1,652. The aquifer is also tapped by wells for Luverne. The summary of test-hole data is given in table 10.

Rock River valley aquifer

The Rock River enters Rock County from Pipestone County, and flows southward through the eastern part of the county. The width of the valley increases from 0.5 to 1.5 mi, as shown on plate 8. Deposits in the valley consist of fine to coarse sand with interbedded silt and gravel. The average thickness is 22 ft in the northern part of the county and 24 ft in the southern part. Maximum thickness is 42 ft and maximum saturated thickness is 38 ft. Water levels are generally less than 8 ft below land surface. Water levels in observation wells rose more than 2 ft during the 1979 spring snowmelt in the valley north of Luverne in well 104N44W21CDC (April 1978) and more than 4 ft in the valley south of Luverne in well 102N45W35DDC (January 1978). Two areas are shown on plate 8 where saturated thickness is greater than 20 ft. One area is east of Hardwick and the other extends from Blue Mounds State Park south to 1 mi from the Iowa border. Data from test holes and aquifer tests indicated that large yields may be expected locally in these areas. Results of three aquifer tests are also shown on plate 8. Two wells were tested north of Ash Creek by Rock County Rural Water District (DeWild and others, 1979). The wells are 32-ft deep and penetrate fine sand and medium to coarse gravel. Transmissivities were 4,000 and 8,000 ft^2/d and the storage coefficient was 0.12. Results of the third aquifer test, which used a well in the surficial deposits at Luverne, determined that the transmissivity was 7,300 ft^2/d (Fax, 1980). The well was 38-ft deep and pumped at 200 gal/min. Analysis of a water sample from observation well 104N44W21CDC (April 1978), in the northern part of the aquifer, shows that the dissolved-solids concentration is 357 mg/L. Nitrite-nitrate concentration exceeded the recommended National Academy of Science and National Academy of Engineering (1973) limits. The sample from observation well 102N45W35DDC (January 1978) in the southern part of the aquifer had 658 mg/L dissolved solids and high concentration of sulfate.

Big Sioux tributary aquifers

Beaver Creek drains the west-central part of Rock County. The creek probably was the outlet for the swamp or shallow lake that covered a depression in the northwest part of the county. The valley is 0.5-mi wide in the upper reach and increases to 1-mi wide at the South Dakota border.

Outwash in Beaver Creek valley aquifer ranged from 10- to 40-ft thick, based on logs from eight test holes. The average saturated thickness was 20 ft. The outwash consists of medium to coarse sand, but some silt and very coarse sand occurs. A hydrograph of observation well 102N46W14AAA shows that the water level fluctuated 4 ft during 1978 and 5 ft during 1979. Water levels averaged 8 ft below land surface during 1978 and 6 ft below land surface during 1979. An analysis of water from observation well 102N46W14AAA (February 1978) shows that the dissolved-solids concentration is 313 mg/L. Concentrations of nitrite-nitrate was 15 mg/L (table 2).

Table 10.—Summary of test-hole data for surficial deposits in Rock County, Minnesota

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Rock valley and tributaries										
Rock River and minor tributaries from Pipestone County to Luverne	22	10	34	40	31	Well rounded sand and gravel.	18	17	23,500	Moderate to large
Rock River from Luverne to Iowa border	26	7	26	42	38	Well rounded sand and gravel.	12	17	15,500	Do.
Champepadan Creek from east county border to confluence with Rock River	25	5	7	26	23	Well rounded sand and gravel.	3	20	4,500	Do.
Kanaranzi Creek	17	5	7	23	19	Alluvium consisting of silt, fine sand, and coarse gravel.	5	15	5,600	Do.

Table 10.—Summary of test-hole data for surficial deposits in Rock County, Minnesota—Continued

Aquifer	Average thickness (ft)	Average depth to water below land surface (ft)	Number of test holes	Maximum thickness (ft)	Maximum saturated thickness (ft)	Physical characteristics	Aquifer extent (mi^2)	Average saturated thickness (ft)	Estimated amount of water in storage (acre-ft)	Potential well-yield classification
Elk Creek	—	—	—	—	—	—	5	12	4,500	Moderate to large
Big Sioux tributaries										
Split Rock Creek	18	8	5	22	12	Sandy silt, fine sand, and thin lenses of coarse sand.	3	10	2,200	Small to
Beaver Creek and Little Beaver Creek	23	10	8	40	32	Alluvium consisting of greenish-gray sand; but contains some gravel, silt, and silty sand.	8	10	5,900	Moderate to large

SUMMARY AND CONCLUSIONS

Surficial aquifers in southwest Minnesota consist of unconfined surficial outwash and alluvium in stream channels. Principal surficial aquifers are in the Cottonwood, Des Moines, Redwood, and Rock River valleys, the aquifers in Nobles County, and the Big Sioux tributary aquifers in Pipestone and Rock Counties. These aquifers are important sources of water because they contain large deposits of saturated sand and gravel, have large quantities of water in storage, and are readily recharged. Other factors that make the aquifers significant are that the (1) areal extent can be traced with relative ease, (2) water is of fairly good quality, (3) depth of wells is generally less than 100 ft, and (4) yield to individual wells is as much as 1,000 gal/min. Although high yields are obtained locally, yields are generally less than 100 gal/min.

Well yields sufficient for domestic use can generally be obtained wherever the sand-and-gravel aquifers are present. Yields sufficient for municipal, irrigation, or industrial use are possible in parts of the aquifer. Desirable locations for large yields seem to be (1) where the outwash in the valley is the widest, thickest, and most permeable, (2) near a surface-water body such as a lake or stream, (3) near the confluence of two channels, and (4) away from relatively impermeable hydrologic boundaries, such as valley walls. The following summary by counties is a brief description of where potential well yields are moderate to large (200 gal/min or greater).

Cottonwood County has some of the highest yielding wells. North of Windom, irrigation wells that yield as much as 1,000 gal/min are completed in surficial deposits of the Des Moines River valley.

Jackson County has two areas in the Des Moines aquifer that are favorable for further development. Well yields sufficient for domestic and small industrial supplies are available near the Iowa border. Moderate well yields are available in a small area near the Cottonwood County border.

In Lincoln County, potentially large well yields are available from the more permeable deposits at the county line in the Flandreau aquifer, in the southern part of the Elkton aquifer, and in the southern part of the Porter aquifer.

In Murray County, large well yields can be obtained from surficial deposits only from the Des Moines River valley aquifer near Currie.

Nobles County has four areas where aquifers will potentially yield as much as 200 gal/min. Two are from the Kanaranzi aquifer near Adrian and another is from the Kanaranzi aquifer near Ellsworth. The fourth area is the channel deposits south of Worthington.

In Pipestone County, well yields of as much as 1,000 gal/min are obtained from the Pipestone Creek aquifer. Moderate yields can potentially be obtained from the Flandreau aquifer near the Lincoln County border.

In Redwood County, moderate well yields can be expected from the Redwood and Cottonwood aquifers. Only small yields are available from aquifers in tributaries to the Cottonwood River.

In Rock County, moderate well yields are generally obtained from aquifers in the Rock River and its tributaries. However, large yields may be expected locally.

Dissolved-solids concentrations in water from surficial-outwash aquifers is generally less than 800 mg/L. The water is very hard, most ranging from 100 to 630 mg/L as $CaCO_3$. Dissolved iron and manganese concentrations are generally high. Sulfate concentrations in the Kanaranzi Creek valley aquifer and the Cottonwood River valley aquifer are high. Locally, high concentrations of nitrite-nitrate are present in the Chanarambie Creek valley aquifer in Murray County, the Rock River valley and Flandreau Creek valley aquifers in Pipestone County, and the Beaver Creek valley and Rock River valley aquifers in Rock County

REFERENCES

Anderson, H. W., Jr., Broussard, W. L., Farrell, D. H., and Felsheim, P. E., 1976a, Water resources of the Rock River watershed, southwestern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-555.

Anderson, H. W., Jr., Broussard, W. L., Farrell, D. F., and Hult, M. F., 1976b, Water resources of the Des Moines River watershed, southwestern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-553.

Anderson, H. W., Jr., Farrell, D. F., and Broussard, W. L., 1974, Water resources of the Blue Earth River watershed, south-central Minnesota: U.S. Geological Survey Hydrologic Atlas HA-525.

Broussard, W. L., Anderson, H. W., Jr., and Farrell, D. F., 1973, Water resources of the Cottonwood River watershed, southwestern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-466.

Cotter, R. D., and Bidwell, L. E., 1968, Water resources of the Lac qui Parle River watershed, southwestern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-269.

DeWild, Grant, Reckert, and Associates, Co., 1979, Report of exploratory test drilling, electrical resistivity, well construction, and test pumping, Lincoln-Pipestone rural water, Minnesota: Project no. 2688, Rock Rapids, Iowa.

Ellis, M. J., and Adolphson, D. G., 1969, Basic hydrologic data for a part of the Big Sioux drainage basin, eastern South Dakota: South Dakota Geological Survey and South Dakota Water Resources Commission, Water Resources Report 5, 124 p.

Ellis, M. J., Adolphson, D. G., and West, R. E., 1969, Hydrology of a part of the Big Sioux drainage basin, eastern South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-311.

Fax, F. G., 1980, Selected aquifer tests in Minnesota: Minnesota Department of Natural Resources Technical Paper no. 8, 130 p.

Hall, C. W., Meinzer, O. E., and Fuller, M. L., 1911, Geology and underground waters of southern Minnesota: U.S. Geological Survey Water-Supply Paper 206, 406 p.

Helgesen, J. O., 1967, Hydrogeolugy of outwash associated with the Antelope moraine, southwestern Minnesota: Master of Science thesis, Colorado State University, Fort Collins, Colorado.

Jacob, C. E., 1944, Notes on determining permeability by pumping tests under water-table conditions: U.S. Geological Survey Bulletin 41, 193 p.

Kuehnast, E. L., 1972, Climate of Minnesota: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Climatography of the United States no. 60-21, p. 1-3.

Larson, S. P., 1976, An appraisal of ground water for irrigation in the Appleton area, west-central Minnesota: U.S. Geological Survey Water-Supply Paper 2039-B, 34 p.

Leverett, Frank, 1932, Quaternary geology of Minnesota and parts of adjacent States: U.S. Geological Survey Professional Paper 161, 149 p.

Leverett, Frank, and Sardeson, F. W., 1932, Map of the southern part of Minnesota showing surficial deposits in Leverett, Frank, 1932, Quaternary geology of Minnesota and parts of adjacent States: U.S. Geological Survey Professional Paper 161, 149 p.

Matsch, C. L., 1972, Quaternary geology of southwestern Minnesota, in Sims, P. K., and Morey, G. B., eds., Geology of Minnesota—a centennial volume: Minnesota Geological Survey, University of Minnesota, p.548-560.

Minnesota Division of Waters, 1959, Hydrologic atlas of Minnesota: Minnesota Division of Waters Bulletin 10, 182 p.

National Academy of Science and National Academy of Engineering, 1973 (1974), Water quality criteria, 1972: U.S. Government Printing Office, Washington, D. C.

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

____ 1964, Geology and ground-water resources of Nobles County and part of Jackson County, Minnesota: U.S. Geological Survey Water-Supply Paper 1749, 70 p.

Novitzki, R. P., Van Voast, W. A., and Jerabek, L. A., 1969, Water resources of the Yellow Medicine River watershed, southwestern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-320.

Rodis, H. G., 1961, Availability of ground water in Lyon County, Minnesota: U.S. Geological Survey Circular 444, 7 p.

____ 1963, Geology and occurrence of ground water in Lyon County, Minnesota: U.S. Geological Survey Water-Supply Paper 1619-N, 41 p.

Schiner, G. R., and Schneider, Robert, 1964, Geology and ground-water conditions of the Redwood Falls area, Redwood County, Minnesota: U.S. Geological Survey Water-Supply Paper 1669-R, 46 p.

Schneider, Robert, and Rodis, G. H., 1961, Aquifers in melt-water channels along the southwest flank of the Des Moines Lobe, Lyon County, Minnesota: U.S. Geological Survey Water-Supply Paper 1539-F, 11 p.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transcript, v. 16, pt 2, p.519-524.

Thiel, G. A., 1944, The geology and underground water of southern Minnesota: Minnesota Geological Survey Bulletin 31, 506 p.

Thompson, G. L., 1965, Hydrology of melt-water channels in southwestern Minnesota: U.S. Geological Survey Water-Supply Paper 1809-K, 11 p.

U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvements of saline and alkaline soils: U.S. Department of Agriculture Handbook 60, 160 p.

Van Voast, W. A., Jerabek, L. A., and Novitzki, R. P., 1970, Water resources of the Redwood River watershed, southwestern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-345.

☆ U.S. Government Printing Office: 1983--666-094/251 Region No. 6