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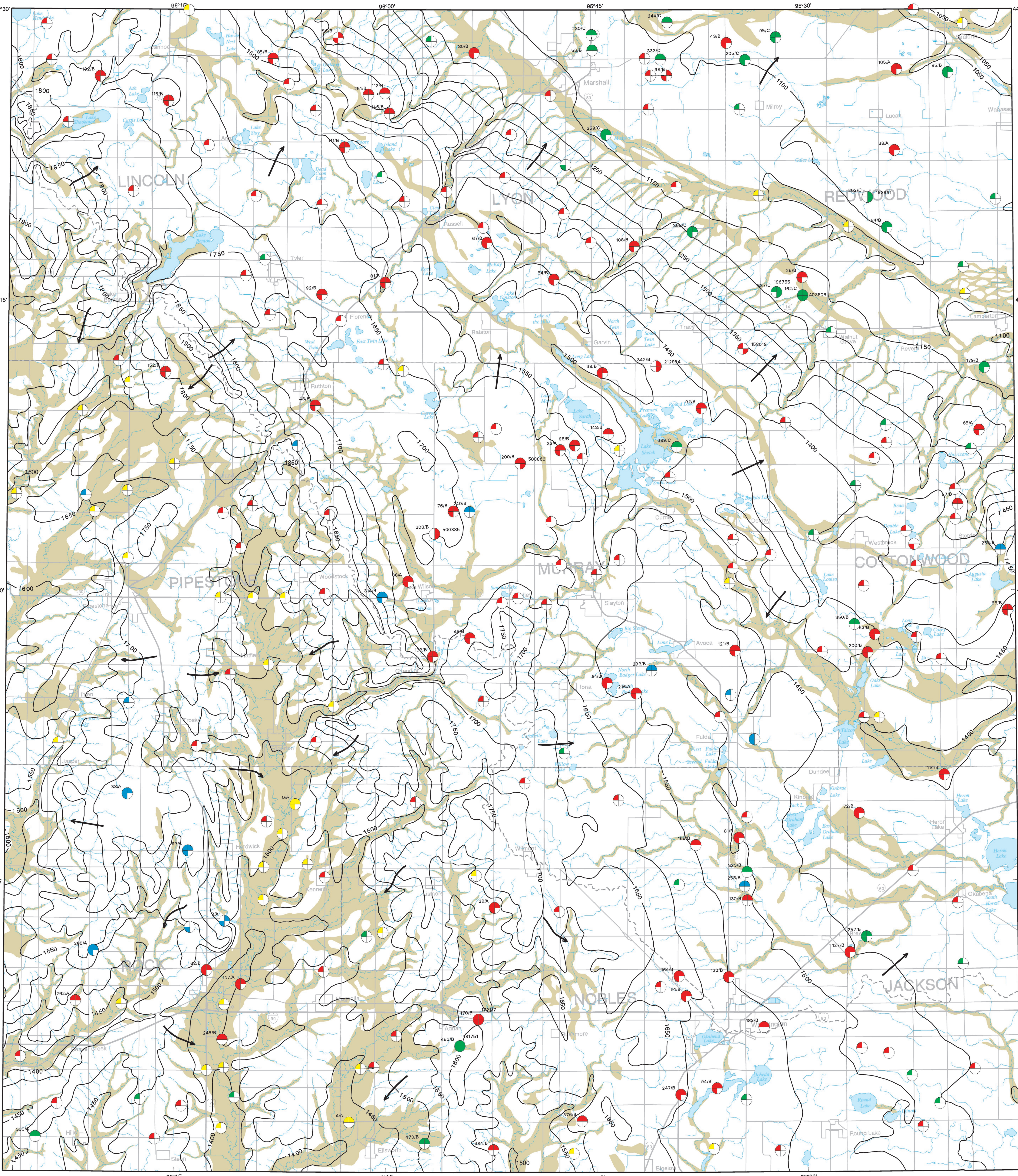


Digital roads data modified from 1990 Census TIGER/Line Files of the U.S. Bureau of the Census (source scale 1:100,000). Digital hydrology data modified from 1989 Digital Line Graph (DLG) files from the U.S. Geological Survey (source scale 1:100,000). Digital base annotation by the Minnesota Geological Survey and the Minnesota Department of Natural Resources.

Universal Transverse Mercator projection, grid zone 15, 1983 North American Datum, map angle 1.987. Vertical datum is mean sea level. Compiled 1996.

GIS and cartography by Shawn Boeser, Malathi Bhattacharjee, Michael Scharber, Minnesota Department of Natural Resources, and Norman Anderson, Land Management Information Center, Minnesota Planning Office. Desktop publishing layout by Kim Anderson, Communications.Media, Minnesota Department of Administration. Digital assembly by Nordic Press.

SCALE 1:200 000

5 0 5 10 15 MILES

5 0 5 10 15 KILOMETERS

CONTOUR INTERVAL 50 FEET
DATUM IS MEAN SEA LEVEL

Partial funding for this project approved by the Minnesota Legislature M.L. 91, Ch. 254, Art. 1, Sec. 14, Subd. 4(f) and M.L. 93, Ch. 172, Sec. 14, Subd. 11(g) as recommended by the Legislative Commission on Minnesota Resources from the Minnesota Environment and Natural Resources Trust Fund. Base funding established by the 1989 Groundwater Protection Act, M.L. 89, c. 326, art. 10, sec. 1, subd.6, item a. and b.

EXPLANATION

1000 — **Water table elevation (feet above sea level)**

General direction of ground-water movement

Regional surface-water divide

Aquifer

- Quaternary, unconfined
- Quaternary, confined
- Cretaceous
- Sioux Quartzite

Data collection symbols

- Well measured for water level
- Well sampled for general chemistry
- Well sampled for tritium
- Well Sampled for ^{14}C, ^{13}C, ^{2}H, and $^{18}0$; data are shown in Table 2.

Approximate depth to top of aquifer (feet) – not shown for wells measured only for water levels.

100/A 158019

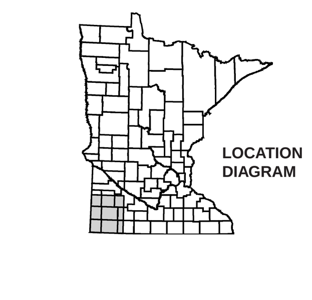
Unique number – shown only for wells sampled for isotopes listed in Table 2.

Water type

Water types

A – Calcium-magnesium-bicarbonate
B – Calcium-magnesium-sulfate
C – Sodium-sulfate

Surficial sand and gravel deposits – Map units *sb, sd, sld, so,* and *sv* as shown on Plate 1, Part A. Indicates approximate extent of surficial aquifers. Uncolored where water table occurs in materials that do not yield significant quantities of water.



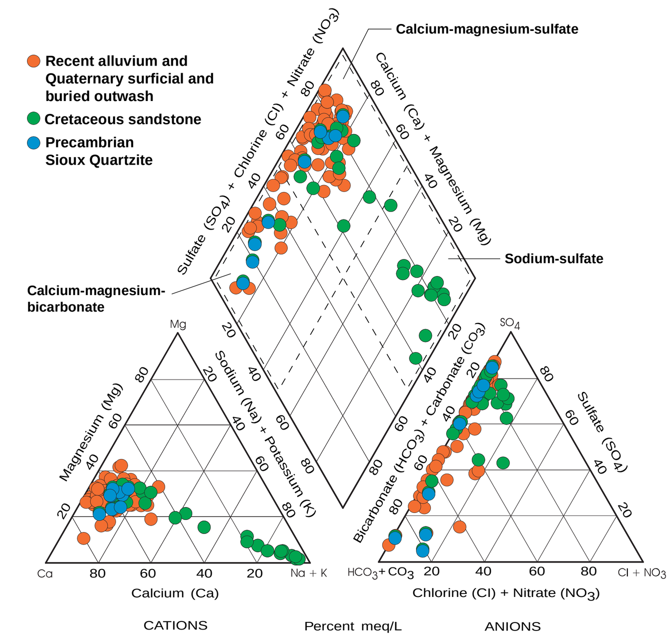


FIGURE 1. ***Piper trilinear diagram showing composition of ground-water samples by aquifer. Dashed lines outline water-type fields.***

TABLE 2. Oxygen, hydrogen, and carbon isotope data for nine wells in the Southwestern Minnesota RHA study area.
[Samples collected during 1994 and 1995 by Minnesota Department of Natural Resources staff; per mil, parts per thousand; B.P., before present; TU, tritium units; n.s., not sampled]

Unique Number	Well depth feet	$\delta^{18}O$ per mil	$\delta^{2}H$ per mil	$\delta^{13}C$ per mil	^{14}C % modern	Age* years B.P.	Tritium TU
Quaternary wells†							
158019	193	-10.42	-73.8	-15.3	0.141	13,000	n.s.
172117	180	-9.4	-63.2	-20.5	0.004	>35,000	<0.8
212954	390	-11.34	-79	-17.2	0.085	18,000	n.s.
500869	215	-9.61	-77.1	-12.9	0.300	5,000	n.s.
500885	320	-11.09	-70.6	-15.9	0.036	24,000	n.s.
Cretaceous wells							
193961	222	-11.33	-80.2	-17.9	0.012	34,000	n.s.
196755	350	-11.25	-80.8	-16.7	0.021	29,000	n.s.
403808	194	-11.61	-83.8	-17.3	0.003	>35,000	<0.8
491751	496	-10.70	-76.9	-20.1	0.843	100	<0.8

* Age interpretation by Scott C. Alexander and Dr. E. Calvin Alexander, Jr., University of Minnesota, Department of Geology and Geophysics.
† Buried aquifer wells only.

SURFICIAL HYDROGEOLOGY

By
Randy Bradt
1997

INTRODUCTION

The Southwestern Minnesota Regional Hydrogeologic Assessment study area extends north one degree of latitude and east one degree of longitude from the southwestern corner of the state. The study area covers 4,136 square miles and includes all or part of nine counties. This plate describes, on a regional scale, ground-water occurrence, movement, and chemistry, with primary focus on ground water in surficial deposits. Data collected for this study include two synoptic water-level measurements of 230 domestic and 40 observation wells, and general water chemistry analyses for 107 wells. Samples were also collected for isotope analysis including tritium for 76 wells and ^{14}C and stable isotopes of hydrogen and oxygen for nine wells.

WATER TABLE

Construction of a water-table map usually relies on water levels obtained from wells located in a water-table aquifer. However, the water table in most of the study area exists in loam to clay loam till, materials generally not considered suitable as an aquifer. Therefore, water-table wells are rarely found in these areas. However, the water table is commonly expressed at the surface in lakes, rivers, and wetlands. The water-table elevations for these features were obtained from U.S. Geological Survey (USGS) 1:24,000 topographic maps. Additional information included depth to water-table data from geophysical work by Department of Natural Resources staff in Rock and Pipestone counties. The available information suggests that the water table is everywhere within 50 feet of the land surface and approximates a subdued surface topography. Therefore, topographic contours from USGS 1:100,000 map sheets were used to guide contour placement in areas lacking water-table information. The water-table contours shown on the map provide a regional description of the water-table surface. The general direction of ground-water flow is at right angles to these lines toward lower elevations, as shown by the arrows on the map. However, the lack of control points and the scale at which the map was created preclude its use for determining depth to the water table.

Recharge to the water table occurs throughout the study area by infiltration of precipitation, surface runoff, and ground-water movement from adjacent areas. The ability of geologic materials to transmit water (hydraulic conductivity) is a major controlling factor of the recharge rate. Ground water in areas where recharge is rapid is more susceptible to contamination (see Plate 4).

The water-table map shows highest water-table elevations in the western part of the study area and along the regional surface water divide. The divide coincides with the Bemis Moraine along much of its length (see Plate 1, Part A). Regionally, ground water flows north and east of the divide toward discharge areas along the Minnesota River, and south and west of the divide toward the Missouri River. Locally, ground water discharges toward topographically low areas, wetlands, streams, and lakes.

AQUIFERS

Most wells in the study area are completed in Quaternary sand and gravel deposits. Locally important aquifers include Cretaceous sandstones and fractured Precambrian Sioux Quartzite. Precambrian rocks underlie the entire region (Figure 4, Plate 2, Part A). High-standing areas of Precambrian rocks are composed of Sioux Quartzite, which is at or near the surface in Pipestone and Rock counties. A subsurface ridge of Sioux Quartzite extends eastward from Pipestone County to northwestern Jackson County. The supply potential for the Sioux Quartzite aquifers is generally as little as a few to several tens of gallons per minute (gpm). The supply potential is quite variable depending on the hydraulic characteristics of fractures (Kanivetsky, 1978) and weathered zones in the quartzite, and the degree of hydraulic connection to the surface or to an overlying aquifer. These factors are difficult to identify or predict with existing information.

Cretaceous sediments overlie the Precambrian crystalline rocks (Setterholm, 1990) and are found in topographically low areas on the bedrock surface. These sedimentary deposits are composed primarily of interbedded shale, siltstone, and sandstone. In drill cuttings these deposits may be difficult to distinguish from glacial sediments. In the northeastern part of the study area, chiefly Lyon and Redwood counties, wells completed in Cretaceous deposits are common because the overlying Quaternary deposits are typically less than 100 feet thick and in many places lack a reliable aquifer. Woodward and Anderson (1986) described yields from wells in Cretaceous sandstones as variable, ranging from a few to several tens of gpm.

Quaternary sediments in the study area represent several glacial advances and retreats which occurred over the last 2 million years (see Plate 2, Part A). The bulk of these deposits are made up of till, which is an unsorted mixture of clay, silt, sand, and gravel. Till in the study area has a low hydraulic conductivity and is considered a confining unit. During each glacial retreat, water from the melting ice left behind sand and gravel deposits generally referred to as outwash. These deposits tend to form networks of long, narrow meltwater channels generally oriented parallel or perpendicular to northwest-southeast-trending end moraines. Subsequent glacial events buried these potential aquifers beneath confining materials, including till, lacustrine sediments, loess (wind-blown deposits), or alluvial sediments. The last glacial retreat deposited surficial sand and gravel, mapped as stream sediment on Plate 1, Part A. These deposits are in many areas unconfined and form the beds of present-day streams. The extent of the mapped stream sediment approximates the extent of the surficial aquifer. Yields for Quaternary sediments are extremely variable. Higher yields are generally associated with surficial sand and gravel deposits that can yield as much as 1,000 gpm. However, yields are generally less than 100 gpm (Adolphson, 1983; Kanivetsky, 1979).

WATER CHEMISTRY

Water samples for chemical analysis were collected from April 1994 to June 1995 from 72 wells completed in Quaternary deposits (only two samples represent unconfined sand and gravel deposits), 26 wells completed in Cretaceous sediments, and 9 wells completed in the Sioux Quartzite. The locations of the sampled wells, with the exception of 16 wells located just outside the study area, are indicated on the map. The results were used to characterize water from these aquifers, and to evaluate ground-water recharge processes. Table 1 summarizes the water chemistry by aquifer.

Ground water contains dissolved minerals derived from the geologic materials (soil, till, etc.) through which it moves. Factors affecting ground-water chemistry include residence time, length of flow path, initial water chemistry, chemical reactions, and land use.

Generally, ground water in the study area is very hard with total dissolved solids (TDS) ranging from 270 milligrams per liter (mg/L) to 2,749 mg/L, with most samples exceeding 500 mg/L, the U.S. Environmental Protection Agency's (EPA) secondary (non-enforceable) standard for public drinking water supplies. Chemical constituents commonly exceeding EPA's secondary drinking water standard include sulfate, iron, and manganese. Excessive quantities of these chemicals may give water an objectionable taste or odor, stain laundry and porcelain, or even plug well screens.

EPA's primary (enforceable) public water supply standard for nitrate, 10 mg/L, was exceeded in less than 10 percent of samples analyzed. Seven samples from wells completed in Quaternary deposits and two samples from wells completed in Sioux Quartzite exceeded the standard. No samples from wells completed in Cretaceous sediments exceeded the EPA primary standard for nitrate.

Water from Quaternary confined aquifers is usually more highly mineralized than water from unconfined aquifers, as shown by both water-chemistry data collected for this study and chemistry data from mostly surficial outwash aquifers collected by Adolphson (1983). Similar results were noted by Ruhl (1987) from a statewide study of glacial drift aquifers. The higher concentrations of chemical constituents in water from confined aquifers are due primarily to longer residence times, compared to the generally shorter residence times in surficial aquifers. The degree of mineralization of surficial aquifers most likely reflects the proportion of more mineralized recharge from till and buried sand and gravel aquifers, and less mineralized contributions from precipitation and surface runoff.

Quaternary unconfined aquifers are usually used to a greater extent than confined sand and gravel aquifers for drinking water supplies, not only for their lower degree of mineralization, but also for their greater yields and lower well construction expense. However, surficial aquifers are geographically limited, and are commonly associated with floodplains, making them inaccessible to most domestic well owners. In addition, they are more susceptible to contamination and drought conditions than confined aquifers. Confined aquifers are scattered throughout most of the study area, are better protected from contamination, and are less susceptible to drought. However, they are difficult to locate, tend to have smaller yields and higher well construction costs, and the water is likely to have a higher degree of mineralization.

The Piper trilinear diagram in Figure 1 shows the results of water chemical analyses for the three main aquifers. Plotted on the lower left and right triangles (ternary diagrams) are points representing the positively charged ions (cations), and negatively charged ions (anions) in each sample. Each vertex represents 100 percent of a particular ion or group of ions. The position of sample points on each ternary diagram reflects the relative percentages in millequivalents per liter of the major cations or anions in each sample. The cation and anion points for each sample are projected onto the center diamond. The plotted water chemistry data can be classified into three types based on major ion concentrations. The three water-types are indicated on Figure 1. The first type is calcium-magnesium-bicarbonate water, which is defined by greater than 50 percent calcium plus magnesium and greater than 50 percent bicarbonate plus carbonate ions. Many wells completed in Quaternary deposits or the Sioux Quartzite have water of this type. Also, this type tends to be relatively low in TDS. The remaining two water types are sodium-sulfate and calcium-magnesium-sulfate, which have much higher TDS values. The sodium-sulfate water type is defined by greater than 50 percent sodium plus potassium and greater than 50 percent sulfate plus chlorine and nitrate. Sodium-sulfate waters are found in some wells completed in Cretaceous deposits in parts of Lyon, Redwood, Cottonwood, and Murray counties. This water either originated as lateral flow from South Dakota or is the result of cation-exchange processes. The remaining Cretaceous and many Quaternary and Sioux Quartzite samples are calcium-magnesium-sulfate-type water. Waters of this type are defined by greater than 50 percent calcium plus magnesium and greater than 50 percent sulfate plus chlorine and nitrate ions. Many samples from wells completed in either Cretaceous or Quaternary deposits plot in the region defined as calcium-magnesium-sulfate water. The similarity in water chemistry may be due to either incorporation of Cretaceous sediments into till during ice advances or seepage of water from Cretaceous deposits into the overlying till.

Many of the wells were sampled for one or more isotopes. Isotopes are atoms of the same element that have different masses. Tritium is an isotope of hydrogen that is used for age dating ground water. Most tritium in ground water is attributable to elevated levels of tritium in precipitation caused by atmospheric testing of nuclear weapons during the 1950s and 1960s. The presence of detectable tritium in ground water indicates a component of post-1953 recharge. Tritium samples were collected from 76 wells. Tritium was detected in all samples from wells completed within 50 feet of the land surface. However, detectable tritium was found in only half of the wells completed between 50 and 100 feet below the surface. Only three wells completed at depths greater than 100 feet had detectable tritium. The depths at which tritium is found are an indicator of the ability of the less permeable material surrounding the aquifer to inhibit ground-water flow.

Elevated levels of nitrate, from sources such as septic systems and fertilizers, may also indicate recently recharged precipitation. Data from Adolphson (1983) and this study indicate elevated nitrate levels were found mostly in wells completed in Quaternary unconfined or confined aquifers within 150 feet of the land surface. These findings are consistent with the tritium results.

Tritium results show that ground water in wells completed more than 150 feet below the surface entered the ground before about 1953. Nine samples of ground water from wells completed 180 to 495 feet below the surface were collected for age date determination using the ^{14}C isotope technique. As shown in Table 2, eight of the samples had ages in the range from 5,000 to greater than 35,000 years old. Water from Cretaceous aquifers, on average, was older than water from Quaternary aquifers. The relatively young waters found in aquifers within 150 feet of the surface suggest the presence of local and intermediate flow systems that recharge and discharge over distances of a few miles or less. The much older waters found in aquifers deeper than 150 feet are interpreted to reflect regional flow systems that recharge and discharge over much longer distances.

The nine samples listed in Table 2 were also analyzed for levels of stable isotopes of hydrogen (^{2}H) and oxygen (^{18}O). The results indicate the ground water samples were mostly recharged from precipitation. Additionally, the data suggest that most of the precipitation infiltrated during a climatic period having a mean annual air temperature similar or slightly cooler than today.

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ACKNOWLEDGMENTS

I would like to express my sincere appreciation for the assistance provided by Division of Waters staff at the Minnesota Department of Natural Resources. Thanks are due to the report review committee members for their constructive comments. Special thanks are owed to all of the well owners who provided access to their wells.

TABLE 1. Characteristics of natural waters by aquifer in the Southwestern Minnesota RHA study area.
[Samples collected during 1994 and 1995 by Minnesota Department of Natural Resources staff; µS/cm, microsiemens per centimeter; TDS, total dissolved solids, bicarbonate volatilization correction method, (Hem, 1992); °C, degrees centigrade; mV, millivolts; mg/L, milligrams per liter; TU, tritium units]

Aquifer	Conductivity µS/cm	TDS mg/L	Temperature °C	pH pH units	Eh mV	Dissolved oxygen mg/L	Alkalinity as $CaCO_3$ mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Fe mg/L	SO_4 mg/L	Cl mg/L	Nitrate+ Nitrite as N mg/L	Mn mg/L	Sr mg/L	B mg/L	SiO_2 mg/L	Tritium TU
Quaternary																				
Mean	1515	1495	9.8	7.08	44	0.25	341	286	82.4	60.9	9.70	4.34	816	11.1	3.4	1.063	1.457	0.243	14.39	5.4
Median	1524	1543	9.7	7.11	49	<0.01	333	294	85.1	52.4	8.17	3.71	848	3.0	<0.01	0.796	1.490	0.257	14.28	<0.8
Minimum	426	338	8.4	5.95	-185	<0.01	227	69.7	19.3	4.78	1.78	0.01	22.1	0.51	<0.01	0.001	0.239	0.052	8.14	<0.8
Maximum	2768	2731	14.4	7.69	432	9.11	502	592	168.0	185.2	128	16.77	1700	108	56.5	3.620	3.279	0.623	26.25	35.5
Standard deviation	549	618	0.9	0.25	116	1.17	63	121	31.5	43.9	14.5	3.62	456	19.9	10.5	0.893	0.691	0.146	2.56	9.0
Number of samples	75	72	75	75	75	75	75	72	72	72	72	72	72	72	72	72	72	18	72	57
Cretaceous																				
Mean	1854	1591	11.0	7.66	-13	0.06	295	158	54.8	277.8	9.35	1.95	861	40.8	0.3	0.464	1.821	1.116	8.36	<0.8
Median	1725	1522	10.5	7.65	2	<0.01	290	128	37.3	256.9	8.59	0.96	802	12.38	0.2	0.073	1.837	0.637	4.74	<0.8
Minimum	853	571	9.4	6.98	-250	<0.01	174	7.94	3.24	30.32	3.71	0.03	171	0.72	<0.01	0.012	0.225	0.162	2.99	<0.8
Maximum	3337	2749	14.1	8.54	309	0.88	425	456	167.8	741.0	16.1	10.91	1720	143	2.4	2.870	4.280	2.755	22.05	<0.8
Standard deviation	581	584	1.3	0.51	116	0.17	69	134	47.8	206.9	3.58	2.58	406	47.1	0.6	0.815	1.127	1.106	5.75	0.0
Number of samples	27	26	27	27	27	27	27	26	26	26	26	26	26	26	26	26	26	6	26	12
Sioux Quartzite																				
Mean	1164	1135	9.6	7.09	31	2.59	283	215	65.5	51.4	5.73	2.6	591	8.79	5.9	0.546	1.053	0.220	10.79	3.2
Median	1059	1094	9.6	7.10	70	0.08	290	216	62.1	36.0	5.69	2.7	534	3.19	0.3	0.501	0.910	0.104	10.54	2.1
Minimum	505	270	8.7	6.87	-148	<0.01	163	65.3	22.1	11.20	<0.707	<0.01	20.49	0.39	<0.01	<0.003	0.229	<0.023	8.53	<0.8
Maximum	2410	2516	10.7	7.33	195	9.52	364	399	155.0	122.7	10.0	7.0	1633	35.2	29.2	1.477	2.294	0.684	13.24	13.6
Standard deviation	598	812	0.7	0.13	121	3.50	61	130	45.5	41.6	3.06	2.4	591	11.2	10.6	0.539	0.728	0.254	1.55	4.6
Number of samples	11	9	11	11	11	11	11	9	9	9	9	9	9	9	9	9	9	6	9	7

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REGIONAL HYDROGEOLOGIC ASSESSMENT
SOUTHWESTERN MINNESOTA