SURFICIAL HYDROGEOLOGY

By
Randy Bradt and James A. Berg
2000

INTRODUCTION

The Upper Minnesota River Basin Regional Hydrogeologic Assessment focuses on ground-water occurrence, movement, and chemistry on a regional scale. The study area spans a large portion of the Minnesota River headwaters. The Minnesota River bisects the study area from northwest to southeast. The aquifers within and beneath the fine-grained sediments provide most domestic water supplies. The significant fraction of readily soluble minerals in these sediments helps to explain the high dissolved mineral content in ground water for most of the aquifers in the area. Data collected from 84 wells included general water chemistry; radioactive isotopes of hydrogen and carbon; and stable isotopes of sulfur, hydrogen, and oxygen.

GROUND-WATER OCCURRENCE AND MOVEMENT

Water Table

Water infiltrating the land surface moves generally downward through unsaturated soil and geologic materials. This water eventually reaches the water table, which is the surface that separates saturated sediments from overlying unsaturated sediments. The water table is commonly referred to as an unconfined surface; this means the pressure exerted on this surface is equal to atmospheric pressure. Most wells in the region, however, are completed in buried aquifers that generally have water that is under greater than atmospheric pressure. These buried aquifers are referred to as confined aquifers.

Contour lines on the map provide a regional depiction of the water-table surface. Delineation of the water-table contours relied on information available in the County Well Index (CWI) data base maintained by the Minnesota Geological Survey, including depth to water measurements taken when wells were drilled. Since only 6 percent of the wells listed in the data base for this study area are screened in a water-table aquifer, and these few wells are geographically limited, additional information was needed to determine depth to the water table. Water-table elevations were inferred where the water table is expressed at some lakes, streams, and wetlands. The water elevations for these features were obtained from U.S. Geological Survey (USGS) 1:24,000-scale topographic maps. Depth to water table was also determined using seismic refraction, which measures differences in the physical properties of saturated and unsaturated geologic materials to locate the water-table surface. Results obtained from eight locations show areas with low-relief topography generally have a shallow (less than 20 feet below land surface) water table, while high-relief areas have deeper water tables, sometimes more than 50 feet below land surface. In most of the study area, the water table approximates a subdued surface topography. Contours of surface elevations generated from the USGS 1:24,000-scale Digital Elevation Model (DEM) were used to guide placement of the water-table contours.

Flow arrows on the water-table map illustrate the regional ground-water flow directions in the near-surface geologic sediments. The rate of ground-water flow depends on the ability of these sediments to transmit water (hydraulic conductivity) and the slope of the water-table surface (hydraulic gradient). The mapped geologic materials shown on Plate 1, Part A, can be subdivided into two general categories: the more permeable sand and gravel stream deposits (speckled pattern on the map) and less permeable loam to clay tills or lake deposits. The actual rate of ground-water flow through geologic materials in the two permeability categories is determined by the hydraulic gradient, which is reflected in the spacing of the water-table contours. More closely spaced contours indicate a steeper hydraulic gradient and faster ground-water movement.

Aquifers

Aquifers are porous and permeable geologic materials that yield sufficient quantities of water to wells for the intended use. Most wells in the study area are completed in Quaternary sand and gravel deposits. Locally important aquifers include Cretaceous sandstones and fractured Precambrian bedrock. Precambrian igneous and metamorphic rocks underlie the entire study area. Few wells are completed in Precambrian rocks because the yields are generally poor. They are used only when overlying Quaternary or Cretaceous aquifers are either absent or do not yield sufficient water for the intended use. The supply potential for Precambrian aquifers generally ranges from a few gallons per minute (gpm) to several tens of gpm. Wells are often drilled deeply into the Precambrian rocks in order to intersect as many fractures as possible and to provide storage space for water between pumping intervals. Less than 2 percent of the wells listed in CWI are completed in Precambrian rocks, and most of these wells are found along the Minnesota River in the southeastern part of the study area.

Cretaceous sediments overlie Precambrian rocks in approximately half the study area (see Figure 3 on Plate 2, Part A) and are generally found southwest of the Minnesota River. Cretaceous sediments consist of interbedded shale, siltstone, and sandstone and have thicknesses mapped by Setterholm (1990) exceeding 600 feet southwest of the City of Canby in Yellow Medicine County. Approximately 12 percent of the wells in CWI are screened in Cretaceous sandstones; these wells range in depth from less than 50 feet to more than 400 feet below land surface. Wells completed in Cretaceous aquifers are common in areas where the overlying Quaternary aquifers are absent or lack sufficient yield. Woodward and Anderson (1986) reported that yields for Cretaceous aquifers are generally from a few gpm to several tens of gpm.

During the past 800,000 years, several glacial advances have deposited a complex series of glacial sediments that are more than 600 feet thick in northern Lincoln County and eastern Swift County. In the rest of the study area, the sediments are generally less than 300 feet thick. Most of these deposits are glacial tills, which are unsorted mixtures of clay, silt, sand, and gravel. Other important sediments include lake deposits, which primarily consist of clays, silts, and a few fine sands. Some of the most extensive lake deposits are associated with glacial Lake Benson. Rittenour, Geiger, and Cotter (1998) interpreted glacial Lake Benson to have a maximum depth of 60 feet; therefore, the lake sediments are less than 60 feet thick. During each glacial retreat, meltwater streams from the glaciers deposited sands and gravels, generally referred to as outwash. Some of these deposits formed networks of long, narrow meltwater channels, while others were more widespread such as the delta deposits. Subsequent glacial events buried these potential aquifers beneath confining materials, including tills and lake sediments.

Thicknesses of the outwash deposits vary from a few feet to more than 100 feet in some locations. A median thickness of approximately 8 feet was determined using CWI well log information for both surficial and buried outwash deposits. In plan view, outwash deposits commonly occur in dendritic patterns that reflect their deposition by streams. In cross-section, outwash deposits appear as lenticular, thin, and discontinuous, but they commonly yield enough water for domestic water needs. Most of the wells listed in CWI are completed in buried outwash deposits. Buried aquifers are indicated on this map where they are at least 20 feet thick and information is sufficient to determine their areal extent. These aquifers are color-coded according to stratigraphic position to match the aquifer classifications in Figures 3, 4, and 5 on Plate 2, Part A. The last glacial retreat deposited surficial sand and gravel mapped as either stream or delta sediment on Plate 1, Part A. Approximately 25 percent of the study area is mapped as having sand and gravel at or near the land surface (speckled pattern on the map). Few wells are completed in these deposits because most of the sediments are too thin to provide a useable water supply. In addition, the sediments are commonly associated with floodplains, which have building and well construction limitations. Some of the thickest deposits, sometimes exceeding 50 feet, are located near the City of Appleton and along the Pomme de Terre River. Most of the irrigation wells in the study area are completed in deposits at these locations. Yields of wells completed in Quaternary deposits are extremely variable primarily because of variations in aquifer thickness and areal extent and hydraulic properties of aquifer materials. Quaternary aquifers will generally yield less than 100 gpm (Kanivetsky, 1978). However, numerous wells, especially near the City of Appleton, have yields from several hundred gpm to more than a thousand gpm.

Recharge and Discharge

Recharge to the water table occurs throughout the study area by infiltration of precipitation, surface runoff from areas of lower to higher infiltration, and subsurface ground-water movement from adjacent areas. Sources of recharge include some lakes and wetlands and short reaches along stream segments. Water-table elevations fluctuate in response to seasonal variations in recharge to and discharge from the ground-water system. Spring rain and snowmelt are major sources of recharge to surficial aquifers and cause water levels to rise significantly. During the summer, evapotranspiration uses most of the available precipitation and recharge to the water table is negligible. When recharge does occur in the summer, it likely coincides with significant rainfall events. Recharge can also occur in the fall, depending on rainfall, runoff, and evapotranspiration rates. Water levels decline in the winter, when precipitation is stored on the land surface as snow, and typically reach a low point before spring thaw.

Recharge amounts to the water table in surficial sand and gravel aquifers in Swift County were estimated by Delin (1986) using hydrographs from 12 observation wells. Annual average recharge estimates ranged from 1.2 inches to 15.1 inches and averaged 6.0 inches. This average is consistent with the findings by Larson (1976) that showed recharge estimates for the same region of 8.4 inches and 5.0 inches for 1972 and 1973, respectively. The recharge amounts to buried aquifers are much less. Exponential increases in ground-water age with well depth observed in this study support this conclusion. For example, if the average annual recharge amount of 6 inches were applied to buried aquifers, the residence time of water in these aquifers would be only a few decades to a few hundred years old. In fact, however, several samples from buried aquifers were age-dated to several thousands of years. Factors determining the amount of recharge to buried aquifers are the vertical hydraulic gradient, which is the head difference between the water table and the water level in the buried aquifer; the thickness of overlying geologic materials; and the geologic materials' hydraulic conductivity.

The amount of water that recharges ground water through wetlands has likely been reduced since the advent of ditching and tiling. Presettlement wet mineral soils and peatlands covered approximately 35 percent of the study area (Minnesota Department of Natural Resources, 1997). The mapped locations of these features are likely areas where wetlands existed prior to the advent of tiling and ditching. Today only 5.5 percent of the area is wetlands and lakes according to the National Wetlands Inventory. Some of the potential recharge to ground water is now redirected by agricultural tiling and ditching (Magner and Alexander, 1994). Drainage tiles intercept infiltrating water, discharging it directly to river systems via ditches.

Ground-water discharge occurs both naturally and artificially. Regionally, natural discharge occurs as ground water flows from topographically high areas toward the Minnesota River. Locally, ground water discharges toward topographically low areas, wetlands, streams, and lakes. The contribution of ground water to wetlands and streams, for example, is evident during drought when streams continue to flow and wetlands do not dry up. Artificial discharge is represented by pumping from wells, which accounts for an increasing proportion of ground-water discharge. Artificial ground-water discharge could significantly reduce the amount of water available to wetlands, streams, and other surface water bodies.

WATER CHEMISTRY

The chemical evolution of ground water begins as surface water and precipitation infiltrate below the land surface. The chemistry of the water changes as it percolates through soil and geologic material. Factors affecting ground-water chemistry include land use, initial water chemistry, length of flow path, chemical reactions, and residence time.

Water samples were collected for chemical analysis in 84 wells from autumn 1997 to autumn 1998. Seventy-eight of these samples were collected from wells completed in Quaternary deposits (only two of these samples represent water-table wells), and six samples were from wells completed in Cretaceous deposits. Sampling locations are indicated on the map, and the chemistry results are summarized in Table 1 according to aquifer type. The chemistry results were used to characterize water resources and to evaluate ground-water recharge processes.

Water Quality Indicators

As water infiltrates into the subsurface, it accumulates additional carbon dioxide (CO_2) gas from decaying organic material. Dissolution of carbonate minerals in sediments is limited by the amount of dissolved carbon dioxide, which in turn controls the amount of dissolved calcium, magnesium, and bicarbonate. Water hardness is the sum of dissolved calcium and magnesium. Ground water from most sampled wells was very hard.

Another measure of water quality is the total dissolved mineral concentration in water samples. The 84 samples collected in this study had reported values for total dissolved solids (TDS) ranging from 298 milligrams per liter (mg/L) to 2,599 mg/L. Most samples exceeded the U.S. Environmental Protection Agency's (EPA's) secondary standard for TDS of 500 mg/L. Other chemical constituents commonly exceeding EPA's secondary standards include sulfate (SO_4), iron (Fe), and manganese (Mn). Excessive quantities of these chemicals may give water an objectionable taste or odor, stain laundry and porcelain, or even plug well screens. The lowest TDS and sulfate concentrations in the sampled wells are found in the northeast, primarily eastern Swift County. This water chemistry likely represents a difference in the mineralogy of subsurface glacial sediment in that area. In the northeastern part of the study area, Des Moines lobe sediments originating from the northwest are thin and overlie glacial sediment originating from the northeast (C. Patterson, oral commun., 1999). The northeast-sourced glacial sediments are generally not as calcareous and lack gypsum. Glacial deposits of the Des Moines lobe incorporated materials that are more calcareous and are commonly associated with gypsum.

Nitrate (reported as nitrogen [NO_3-N]) at concentrations greater than 1 mg/L is an important indicator of human impacts on ground water. Principal sources include septic systems, feedlots, and agricultural chemicals. EPA's primary public water supply standard for nitrate, 10 mg/L, was exceeded in only one of the 84 sampled wells, and two other wells had elevated levels (greater than 1 mg/L). The low frequency of elevated nitrate concentrations in most of the sampled wells may have two explanations. First, nitrate is usually found in near-surface ground water, but most of the wells sampled in this study are screened below the water table in aquifers overlain by low-permeability glacial sediments. Second, biologically mediated nitrate removal (denitrification) may have occurred. The oxygen-poor (anoxic) ground water commonly found in buried aquifers and deeper parts of some water-table aquifers is a likely environment for denitrification.

Chloride (Cl) is another parameter that may indicate human impacts on ground water. Artificial sources of chloride include road salt; fertilizers; and industrial, human, and animal wastes. Several of the sampled wells in this study may have chloride from contaminant sources. Natural sources of chloride include precipitation and Cretaceous shale. Interpretations of chloride sources for individual wells are inconclusive because elevated natural sources of chloride levels were also encountered in some Cretaceous and buried glacial aquifers.

Major Ion Water Chemistry

The Piper trilinear diagram (Figure 1) shows the water chemistry results graphically. The sample points on each triangle (ternary diagram) reflect the percentages in milligram equivalents per liter (meq/L) of the major cations and anions in each sample.

The lower left ternary diagram of Figure 1 compares the major cations for calcium, magnesium and sodium, plus potassium. There is a fairly constant ratio of calcium to magnesium throughout the study area superimposed on a trend toward sodium-rich water. As waters containing calcium and magnesium pass through clays and shales, adsorbed sodium is exchanged into the water. This process is similar to how a household water softener works. Higher levels of strontium (Sr) associated with higher proportions of sodium support this ion exchange hypothesis.

The lower right ternary diagram compares the major anions, bicarbonate, sulfate, and chloride plus nitrate. Samples tend to plot along a narrow band ranging from bicarbonate-rich waters with low TDS toward sulfate-rich waters with higher TDS limited by the solubility of gypsum. Sulfate concentrations range from less than 1 mg/L to 1,630 mg/L. Common sources of sulfate are dissolution of gypsum and oxidation of sulfide minerals. Sulfate is one of the dominant components of TDS values for this study area. Based on the five sulfur isotope (delta [δ] ^{34}S) values in Table 2, most of the sulfate originates by the oxidation of sulfides ($\delta^{34}S$ = -20 to 0 per mille [parts per thousand or ‰]) and not from gypsum dissolution ($\delta^{34}S$ = +15 to +25‰) (Clark and Fritz, 1997). The central diamond-shaped field shows the overall chemical behavior of the ground water by plotting a third point representing the intersection of rays projected from the cation and anion triangles. An example is shown in the Piper diagram.

Aquifer Water Chemistry

The chemistries of water samples from Cretaceous aquifers completely overlap the range of chemistries in Quaternary aquifers (see Figure 1). This observation is not surprising since large amounts of Cretaceous materials are incorporated into the glacial drift. The wide scattering of points on the diagram illustrates the wide variation in major ion water chemistry for both Cretaceous and Quaternary aquifers. The amount of dissolved minerals in ground water in the study area apparently evolves in a fairly short period of time, a fact supported by the absence of a relationship between the total dissolved mineral content and the observed residence time (as determined by tritium). Residence time refers to the time that ground water has resided below the land surface. This means that most of the dissolved mineral content of ground water results from chemical evolution that occurs in less than 45 years.

The cation exchange with sodium observed in some samples is associated with waters having a greater than 45-year residence time. Conversely, samples younger than 45 years were not observed to have evidence of cation exchange. One possible explanation is that in sediments presently containing water with less than a 45-year residence time, any available sodium was exchanged and removed at an earlier time. It is also possible that these sediments never had sodium available for exchange.

Environmental Isotopes

Ground-water residence time. All 84 wells were sampled for tritium, an isotope of hydrogen. Tritium is a naturally occurring radioactive isotope of hydrogen with a 12.5-year half-life that is useful for estimating ground-water residence time. Before 1954, natural levels of tritium were about 3 to 5 tritium units (TU). Atmospheric testing of nuclear weapons during the 1950's and 1960's increased the tritium in precipitation more than a thousand-fold. Water that recharged before 1954 has lost most of its tritium by decay over several half-lives. The presence of more than about 8 TU in ground water indicates that recharge occurred since 1953 (modified from Alexander and Alexander, 1989).

Ground-water movement can be interpreted by relating the presence of tritium to well depth. Approximately 25 percent of the sampled wells contained detectable levels of tritium. Ground water less than 50 feet below the land surface will likely have measurable tritium, although two of the three wells sampled in this depth range did not have tritium. Less than half of the sampled wells screened at depths between 50 and 100 feet had detectable tritium. This depth range probably represents the maximum that tritium has penetrated since 1953. Only 16 percent of the sampled wells greater than 100 feet deep had tritium. This percentage likely overestimates the probability of tritium being present in wells greater than 100 feet deep. Well construction problems and geologic conditions may account for tritium being observed deeper than expected. For example, two wells completed at 150 feet and 215 feet deep had low but detectable levels of tritium. The two wells are close to each other and located southeast of the City of Appleton where some of the thickest sand and gravel aquifers in the entire study area are found. In the Appleton area (Figures 4 and 5 on Plate 2, Part A), some surficial sand and gravel deposits may be in direct connection with buried sand and gravel deposits. In these areas, water containing tritium could travel deeper into the aquifer system.

Wells completed deeper than 100 feet generally had water with no tritium. For these wells, the radioactive isotope of carbon was used to estimate ground-water residence time. Nine samples were collected for carbon-14 (^{14}C) age dating in wells ranging from 109 feet to 453 feet deep (Table 2). In addition, a 61-foot-deep well containing tritium was also sampled to calibrate the carbon-14 model.

The age-dating results show that water more than 100 feet below the land surface generally has a residence time from 1,000 to 9,000 years before present. The relatively young waters found in aquifers within 100 feet below the land surface suggest the presence of local and intermediate flow systems that recharge and discharge over shorter distances and times. The much older waters in aquifers below 100 feet are more likely to be associated with regional flow systems, which can discharge many miles from where they receive recharge.

Ground-water source. The 10 samples listed in Table 2 were also analyzed for ratios of stable isotopes of hydrogen and oxygen. The results indicate that ground water in the deep regional flow systems largely originates from precipitation. The $\delta^{18}O$ values reflect the temperatures of the precipitation. Results show small variations that might be related to small climatic fluctuations. There is no indication of water originating from glacial meltwater, which is consistent with the calculated postglacial ground-water ages.

REFERENCES CITED

Alexander, S.C., and Alexander, E.C., Jr., 1989, Residence times of Minnesota groundwaters: Minnesota Academy of Sciences Journal, v. 55, no. 1, p. 48-52.

Clark, I.D., and Fritz, P., 1997, Environmental isotopes in hydrogeology: Boca Raton, Lewis Publishers, 328 p.

Delin, G.N., 1986, Hydrogeology of confined-drift aquifers near the Pomme de Terre and Chippewa rivers, western Minnesota: U.S. Geological Survey Water-Resources Investigations Report 86-4098, 70 p.

Kanivetsky, R., 1978, Hydrogeologic map of Minnesota, bedrock hydrogeology: Minnesota Geological Survey State Map Series S-3, 1 pl., scale 1:500,000.

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., 3 pls. in pocket, scale 1:126,720.

Magner, J.A., and Alexander, S.C., 1994, The Minnesota River basin–a hydrogeologic overview, 94 p., *in* Minnesota River Assessment Project Report, Volume II, Physical and chemical assessment, January 1994: St. Paul, Minnesota Pollution Control Agency, Report to the Legislative Commission on Minnesota Resources.

Minnesota Department of Natural Resources, 1997, Pre-settlement wet mineral soils and peatlands, Map 4, *of* Minnesota wetlands and surface water resources: St. Paul, Minnesota Department of Natural Resources, 1 pl.

Rittenour, T.M., Geiger, K.L., and Cotter, J.F.P., 1998, Glacial Lake Benson, west-central Minnesota, *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 97-102.

Setterholm, D.R., 1990, Geologic maps of the late Cretaceous rocks, southwestern Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-69, 2 pls., scale 1:750,000 and smaller.

Woodward, D.G., and Anderson, H.W., 1986, Hydrogeologic and water-quality characteristics of the Cretaceous aquifer, southwestern Minnesota: U.S. Geological Survey Water-Resources Investigations Report 84-4153, 2 pls.

MAP EXPLANATION

Water Table

1100 — Water table elevation (feet above sea level), contour interval 50 feet
Supplementary contours (25-foot interval)
General direction of ground-water movement

Well Symbols

Shape indicates aquifer type

▲ Quaternary water table
▼ Quaternary buried outwash
● Cretaceous sandstone
■ Cretaceous regolith

Color indicates tritium age

Recent—Waters with tritium concentrations of 8 tritium units (TU) or more entered the ground water after 1953.
Mixed—Waters with 0.9 to 8 TU are a mixture of recent and vintage.
Vintage—Waters with less than 0.8 TU entered the ground water before 1954.

Well Labels

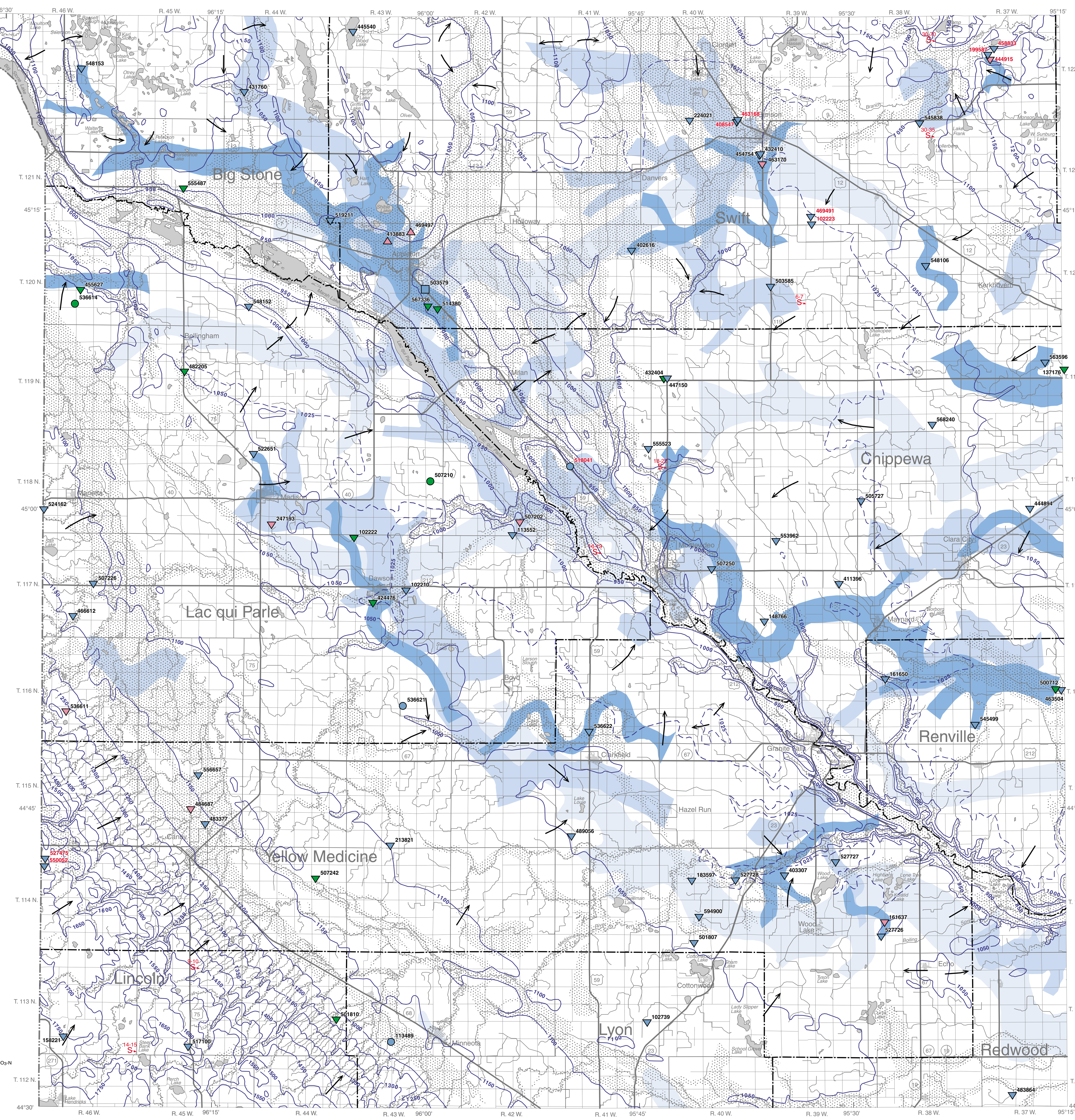
113552 Unique well number of well not sampled for carbon-14
408547 Unique well number of well sampled for carbon-14

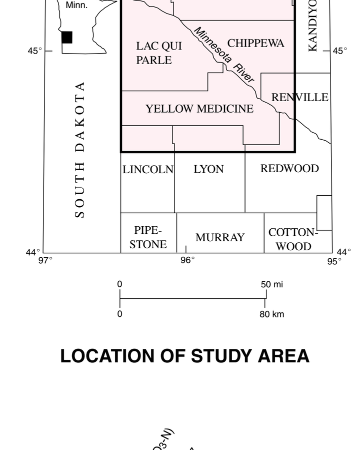
Relative Depths of Aquifers

Surficial sand and gravel. Map units Qdb, Qsd, Qsh, Qsld, Qssd, and Qsw as shown on Plate 1, Part A.
Shallow Quaternary buried aquifer, elevation 950 to 1000 feet
Quaternary buried aquifer, elevation 920 to 975 feet
Sub-Quaternary buried aquifer, elevation 750 to 920 feet.

Seismic Refraction

9-10 S→ Numbers indicate range of depth in feet to the water table; arrow points to location of the midpoint of transect.





LOCATION OF STUDY AREA

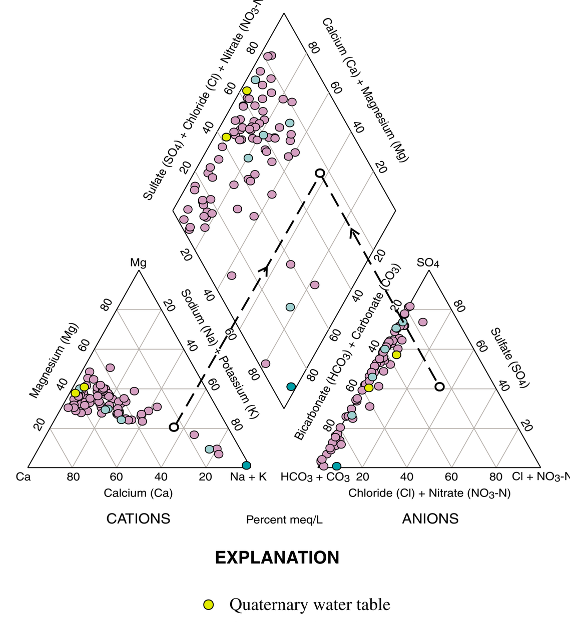


FIGURE 1. *Piper trilinear plot of major cations and anions by aquifer classification. Plotted on the lower left and right triangles are points representing the positively charged ions (cations) and negatively charged ions (anions), respectively. The diamond-shaped field combines the components in the triangular fields as shown by the hypothetical sample point.*

SCALE 1:200 000
5 0 5 10 Miles
5 0 5 10 Kilometers
Contour Interval 50 Feet
Supplementary Contours Shown in Selected Areas

Digital base map composite:
Roads and county boundaries - Minnesota Department of Transportation GIS Statewide Base Map (source scale 1:24,000)
Hydrologic features - U.S. Geological Survey Digital Line Graphs (source scale 1:100,000)
Digital base map annotation - Minnesota Geological Survey.

Project data compiled from 1997 to 1999 at the scale of 1:200,000. Universal Transverse Mercator projection, grid zone 15, 1983 North American datum. Vertical datum is mean sea level.

GIS and cartography by Randy McGregor. Edited by Nick Kroska. Digital assembly by Nordic Press.

GIS data and metadata available through the Ground Water Mapping Program website: http://www.dnr.state.mn.us/waters/programs/gw_section/cgarha/index.html

TABLE 1. Characteristics of natural waters by aquifer in the upper Minnesota River basin study area.

[Samples collected from 1997 to 1998 by Minnesota Department of Natural Resources staff; TDS, total dissolved solids, is the sum of cation and anion concentrations expressed in milligrams per liter (mg/L); Eh, redox potential expressed in millivolts (mV); TU, tritium units; alkalinity expressed as $CaCO_3$; nitrate (NO_3) expressed as nitrogen (N): 1 mg/L nitrogen = 4.4 mg/L nitrate; NA, not applicable; <, less than]

	Well depth (feet)	TDS (mg/L)	pH (pH unit)	Eh (mV)	Dissolved oxygen (mg/L)	Tritium (TU)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Iron (mg/L)	Manganese (mg/L)	Strontium (mg/L)	Barium (mg/L)	Aluminum (mg/L)	Alkalinity (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Nitrate as nitrogen (mg/L)	Bromide (mg/L)	Fluoride (mg/L)	Silicon (mg/L)	Total phosphorus (mg/L)
Quaternary Aquifer																							
Number of samples	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78
Number of samples below detection	NA	NA	NA	NA	67	56	0	0	0	0	1	0	0	0	9	0	0	0	54	6	0	0	13
Minimum	44	298	6.79	-88	<0.01	<0.8	24.6	9.75	5.39	1.96	<0.01	0.004	0.179	0.008	<0.001	212	0.03	0.34	<0.005	<0.015	0.08	9.3	<0.02
25th percentile	75	562	7.21	157	<0.01	<0.8	93	43.6	20.8	4.0	0.93	0.077	0.502	0.02	0.005	330	115	2.0	<0.005	0.034	0.25	14	0.03
Median	100	858	7.33	239	<0.01	<0.8	140	54.7	42.0	5.8	2.0	0.23	0.769	0.04	0.008	369	352	3.4	<0.005	0.054	0.29	15	0.06
75th percentile	142	1250	7.49	307	<0.01	1.3	190	79.2	95.7	8.0	3.0	0.54	1.14	0.10	0.01	408	607	10	0.009	0.099	0.35	16	0.1
Maximum	453	2599	7.86	644	6.2	30.1	521	183	243	16.2	11.0	3.149	3.033	0.685	0.172	581	1630	91	28.1	0.440	0.72	21.6	1.17
Cretaceous Aquifer																							
Number of samples	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Number of samples below detection	NA	NA	NA	NA	5	4	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	1
Minimum	47	549	7.12	39	<0.1	<0.8	3.0	0.66	22.6	2.1	0.03	0.005	0.077	0.006	0.012	304	0.43	0.67	<0.005	0.037	0.26	3.62	<0.02
Median	169	1107	7.33	216	<0.1	<0.8	170	56	142	7.1	2.1	0.041	1.47	0.04	0.016	408	497	8.4	<0.005	0.13	0.46	8.5	0.04
Maximum	375	1812	8.82	402	0.1	1.0	324	137.1	231	15.3	17.5	0.356	2.73	0.078	0.273	513	1030	30.5	0.039	0.240	2.02	19.5	1.59

TABLE 2. Summary of oxygen, hydrogen, and carbon isotope data for water samples.

[δ, ratio of the isotope to its element in the sample compared to the same ratio in an arbitrary standard and reported as parts per thousand or per mille (‰); B.P., before present; TU, tritium units; n.d., not determined; modern, greater than 50 but less than 200 years old; <, less than]

Unique well number	Well depth (feet)	$\delta^{34}S$ (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{13}C$ (‰)	^{14}C (percent modern)	Age (B.P., in 1000 years)	Tritium (TU)
Quaternary Aquifer								
550052	453	-11.0	-10.97	-79.1	-12.7	32.2	6	<0.8
469491	216	2.7	-10.44	-72.9	-12.4	23.5	8	<0.8
463168	243	n.d.	-10.24	-75.2	-11.3	30.2	7	<0.8
527475	195	-14.1	-10.20	-72.1	-12.3	54.9	1.5	<0.8
102223	150	n.d.	-10.08	-72.4	-12.5	27.3	7	<0.8
408547	152	n.d.	-9.83	-74.3	-13.6	33.9	6	<0.8
458833	109	n.d.	-8.70	-62.8	-10.3	50.9	3	<0.8
199587	220	n.d.	-8.53	-60.4	-11.5	39.3	4	<0.8
444915	61	-3.0	-8.40	-58.5	-6.9	76.8	modern	15.1
Cretaceous Aquifer								
518041	240	-14.6	-9.63	-68.2	-14.1	44.8	3	<0.8

The DNR Information Center
Twin Cities: (651) 296-6157
Minnesota Toll Free: 1-888-646-6367
Telecommunication Device for the Hearing Impaired (TDD): (651) 296-5484
TDD Minnesota Toll Free: 1-800-657-3929
DNR Web Site: http://www.dnr.state.mn.us

This information is available in an alternative format on request.

This map was compiled and generated using geographic information systems (GIS) technology. Digital data products are available from DNR Waters.

This map was prepared from publicly available information only. Every reasonable effort has been made to ensure the accuracy of the factual data on which this map interpretation is based. However, the Department of Natural Resources does not warrant the accuracy, completeness, or any implied uses of these data. Users may wish to verify critical information; sources include both the references here and information on file in the offices of the Minnesota Geological Survey and the Minnesota Department of Natural Resources. Every effort has been made to ensure the interpretation shown conforms to sound hydrogeologic and cartographic principles. This map should not be used to establish legal title, boundaries, or locations of improvements.

Equal opportunity to participate in and benefit from programs of the Minnesota Department of Natural Resources is available to all individuals regardless of race, color, national origin, sex, sexual orientation, marital status, status with regard to public assistance, age, or disability. Discrimination inquiries should be sent to: Minnesota DNR, 500 Lafayette Road, St. Paul, MN 55155-4031; or the Equal Opportunity Office, Department of the Interior, Washington, DC 20240.

REGIONAL HYDROGEOLOGIC ASSESSMENT
UPPER MINNESOTA RIVER BASIN, MINNESOTA