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QUATERNARY AND BEDROCK AQUIFER HYDROGEOLOGY

By John D. Barry

2014

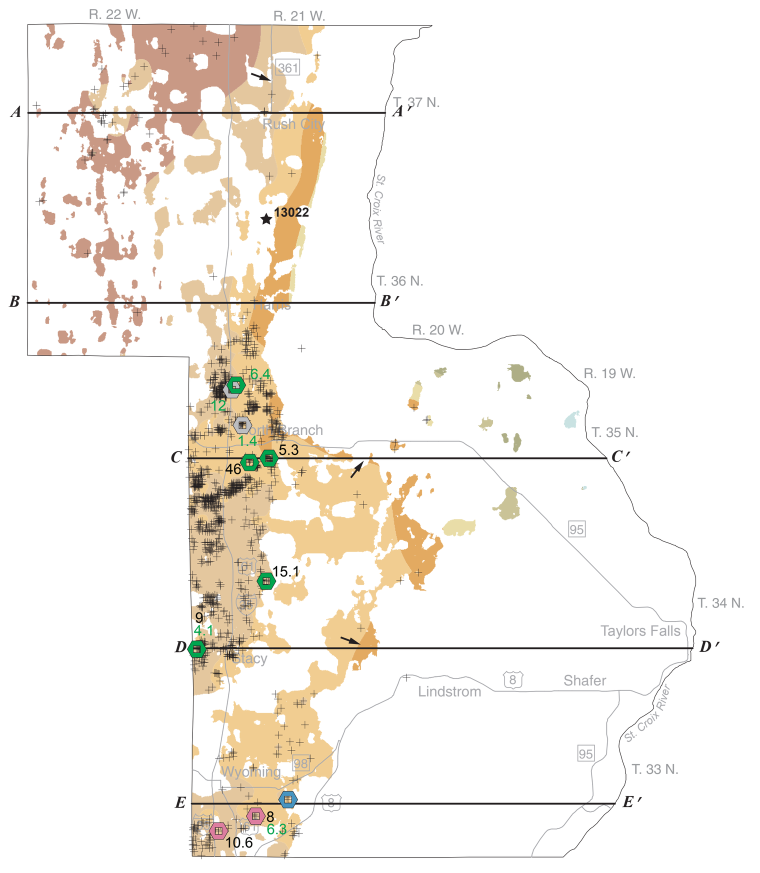


FIGURE 1. Potentiometric surface elevation and extent of the sl buried sand and gravel aquifer.

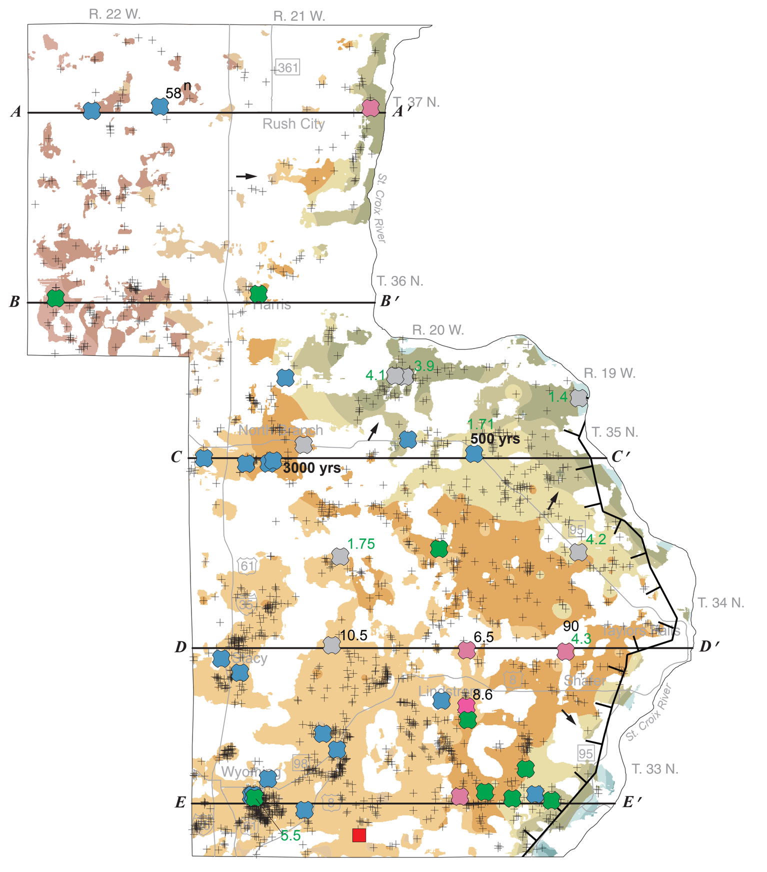


FIGURE 4. Potentiometric surface elevation and extent of the sx buried sand and gravel aquifer. This aquifer is unconfined (is a water-table aquifer) along a narrow strip in southeast Chisago County adjacent to the St. Croix River.

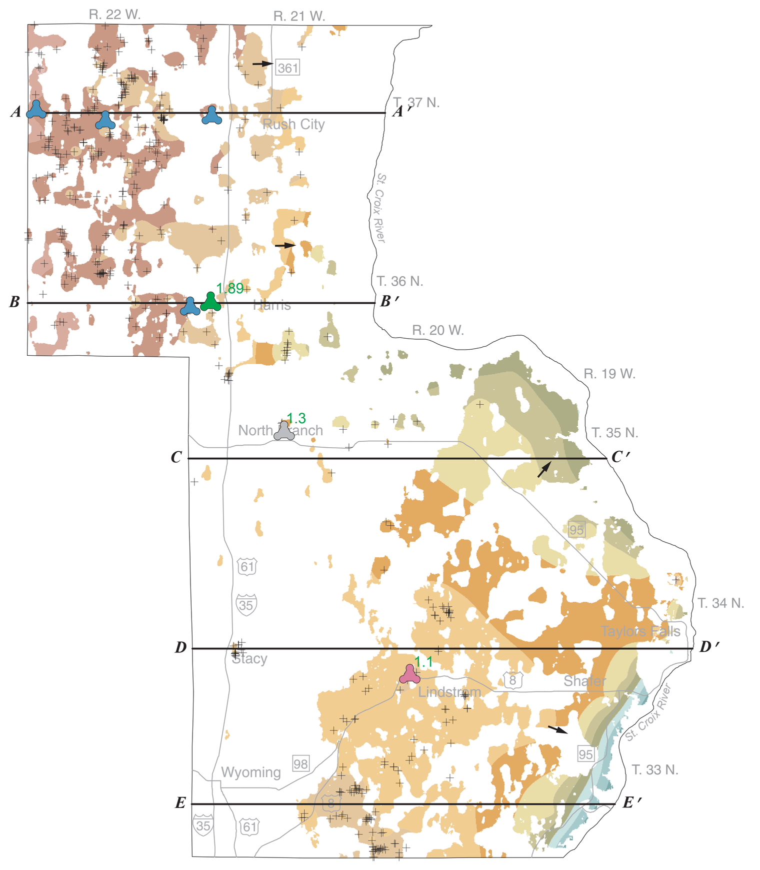


FIGURE 2. Potentiometric surface elevation and extent of the sc buried sand and gravel aquifer.

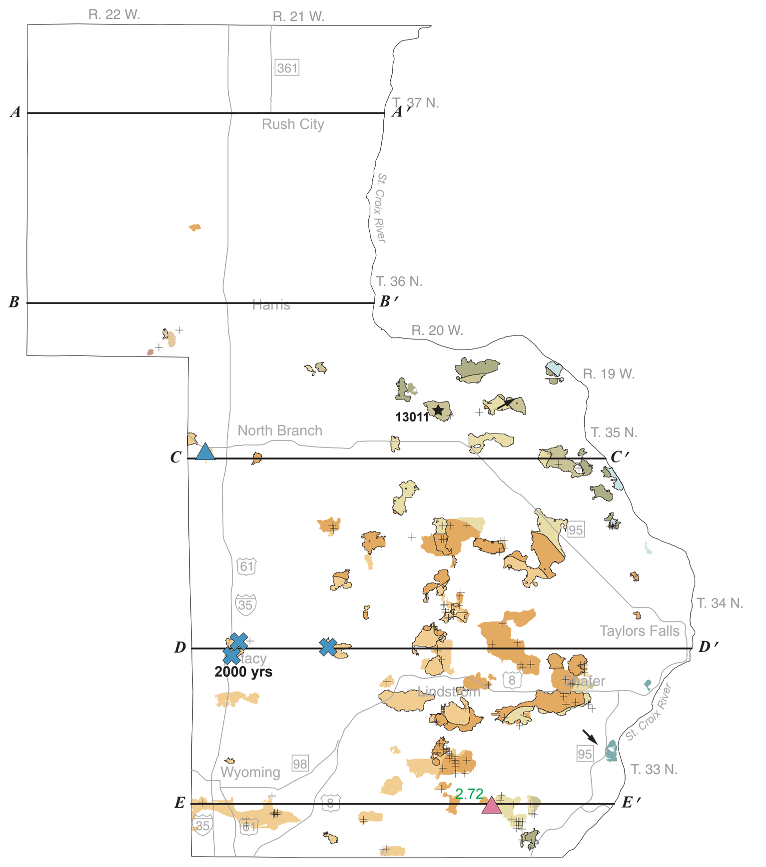


FIGURE 5. Potentiometric surface elevation of the sr and sp buried sand and gravel aquifer. The sr aquifer is stratigraphically above the sp aquifer. For clarity in the figure, the sp aquifer (shown with border) is positioned above the sr aquifer (shown without border), in reverse of their stratigraphic relationship.

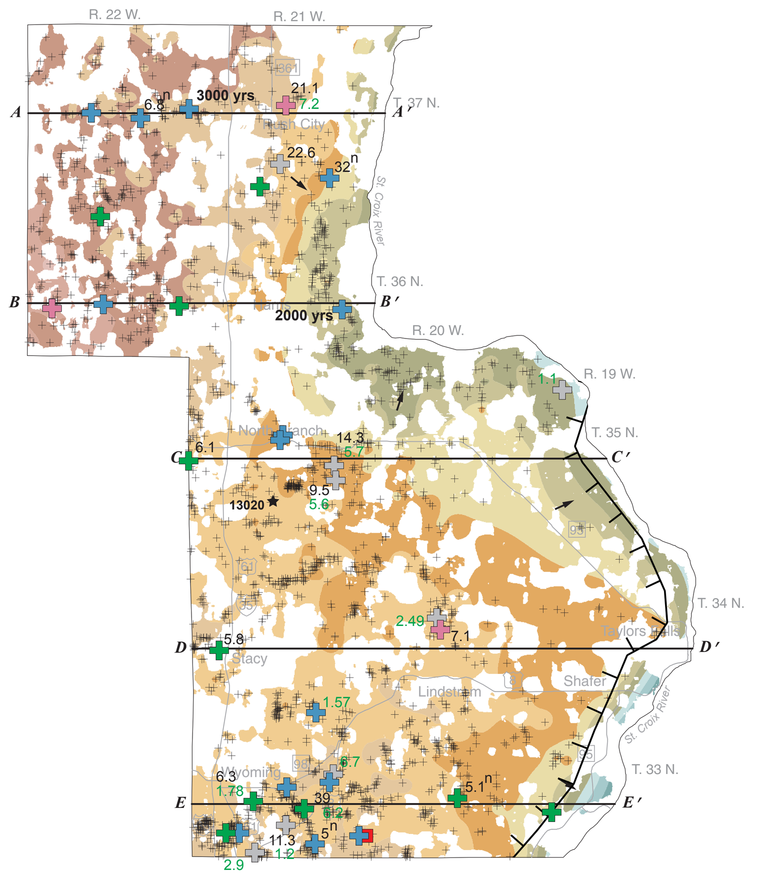


FIGURE 3. Potentiometric surface elevation and extent of the se buried sand and gravel aquifer. This aquifer is unconfined (is a water-table aquifer) along a narrow strip in southeast Chisago County adjacent to the St. Croix River.

MAP EXPLANATION
Figures 1–5

Potentiometric surface elevation of aquifers
(feet above mean sea level)

- > 965 to 1,000
- > 940 to 965
- > 915 to 940
- > 890 to 915
- > 865 to 890
- > 840 to 865
- > 815 to 840
- > 790 to 815
- > 765 to 790
- > 740 to 765
- > 715 to 740
- > 690 to 715
- > 665 to 690

MAP EXPLANATION
Figures 1–8

Tritium age

Symbol color indicates tritium age of water sampled in well.

- Cold War era—Water entered the ground during the peak period of atmospheric tritium concentration during nuclear bomb testing, 1958–1959 and 1961–1972 (greater than 15 tritium units [TU]).
- Recent—Water entered the ground since about 1953 (8 to 15 TU).
- Mixed—Water is a mixture of recent and vintage waters (greater than 1 TU to less than 8 TU).
- Vintage—Water entered the ground before 1953 (less than or equal to 1 TU).
- Well was not sampled for tritium.

Symbols and labels

- 21.1 If shown, chloride concentration equals or exceeds 5 parts per million. Naturally occurring chloride concentration greater than 5 parts per million is shown with a superscript n.
- 7.2 If shown, nitrate-nitrogen concentration equals or exceeds 1 part per million.
- 3000 yrs If shown, groundwater residence time in years estimated by carbon-14 (^{14}C) isotope analysis
- Static (non-pumping) water level data from the County Well Index (CWI)
- 13011 DNR groundwater level monitoring well. Label is well number.
- Aquifer test
- Direction of groundwater flow
- Boundary between confined and unconfined conditions, hachures toward confined conditions
- E—E′ Line of cross section

Sampled well and aquifer symbols

Symbol color indicates tritium age of water sampled in well.

Buried sand and gravel aquifers

- sl
- sc
- se
- sx
- sr
- sp

Bedrock well construction

- Upper Tunnel City
- Upper Tunnel City–Wonewoc
- Upper Tunnel City–Mt. Simon, Upper Tunnel City–Eau Claire
- Wonewoc, Wonewoc–Eau Claire
- Mt. Simon, Eau Claire–Mt. Simon, Wonewoc–Mt. Simon

SCALE 1:300 000
COMPILATION SCALE 1:100 000
1 0 1 2 3 4 5 MILES
1 0 1 2 3 4 5 6 7 8 9 KILOMETERS

TABLE 3. Water use reported by DNR groundwater appropriation permit holders for 2011 by aquifer
[Data from Minnesota Department of Natural Resources, Water Appropriation Permit Program; MGY, million gallons per year]

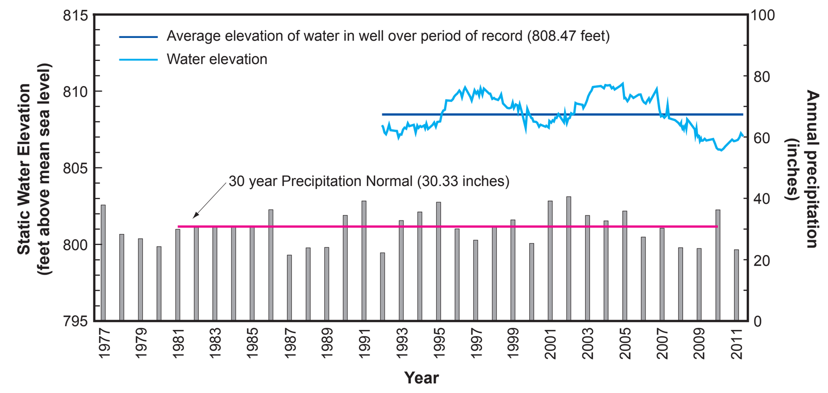
Aquifer	2011 Water Use (MGY)	Percent of Use
Surficial sand	5.6	0.5
Buried sand and gravel		
sc	15.6	1.5
se	35.5	3.5
sx	143.2	14.0
Bedrock aquifer		
St. Peter–Prairie du Chien–Mt. Simon	60.4	5.9
Jordan	2.4	0.2
Upper Tunnel City–Eau Claire	34.6	3.4
Upper Tunnel City–Wonewoc	79.7	7.8
Wonewoc	17.5	1.7
Upper Tunnel City–Mt. Simon	59.6	5.8
Wonewoc–Mt. Simon	5.3	0.5
Eau Claire–Mt. Simon	44.5	4.4
Mt. Simon	506.9	49.6
Mesoproterozoic sedimentary	10.2	1.0
Total	1021.0	100*

*Percentages do not add up to 100 due to rounding

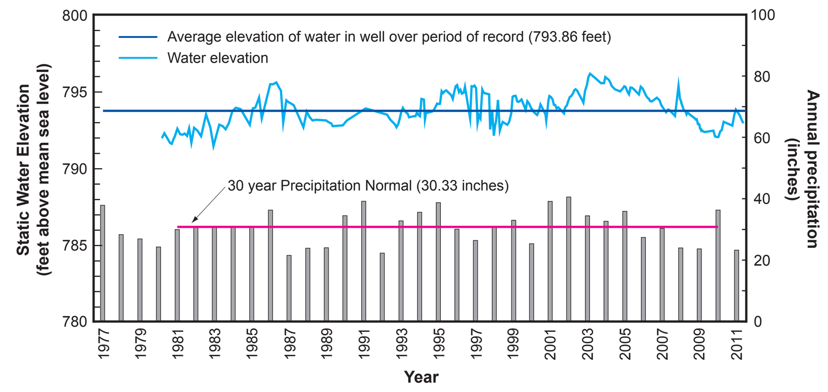
TABLE 1. Specific capacity from well development tests and transmissivity from aquifer tests for selected large-capacity wells
[gpm/ft, gallons per minute per foot; gpd/ft, gallons per day per foot; dash marks (--) indicate no data available]

	Specific Capacity (gpm/ft)[1]					Transmissivity from Aquifer Test (gpd/ft)[2]				
Aquifer	Well Diameter (inches)	Mean	Minimum	Maximum	No. of Tests	Well Diameter (inches)	Mean	Minimum	Maximum	No. of Tests
Surficial sand[3]	8	20	11	30	2	--	--	--	--	--
Buried sand and gravel										
sl	--	--	--	--	--	--	--	--	--	--
sc	--	--	--	--	--	--	--	--	--	--
se	12	20	--	--	1	12	137,000	--	--	1
sx	12–18	7	4	11	2	12	142,000	--	--	1
qu	18	102	--	--	1	--	--	--	--	--
Bedrock										
St. Peter–Prairie du Chien–Mt. Simon[4]	12	20	--	--	1	--	--	--	--	--
Upper Tunnel City–Eau Claire[4]	16	35	--	--	1	--	--	--	--	--
Upper Tunnel City–Wonewoc[4]	14	9	--	--	1	16	40,000	35,000	45,000	2
Wonewoc	18	47	--	--	1	18	104,000	--	--	1
Wonewoc–Mt. Simon[4]	18	9	--	--	1	--	--	--	--	--
Mt. Simon	12–18	17	8	26	12	12–24	20,100	8,100	32,000	2
Mt. Simon–Hinckley[4]	24	28	--	--	1	24	40,000	--	--	1
Volcanic rock[3]	6	0.008	0.004	0.013	7	--	--	--	--	--

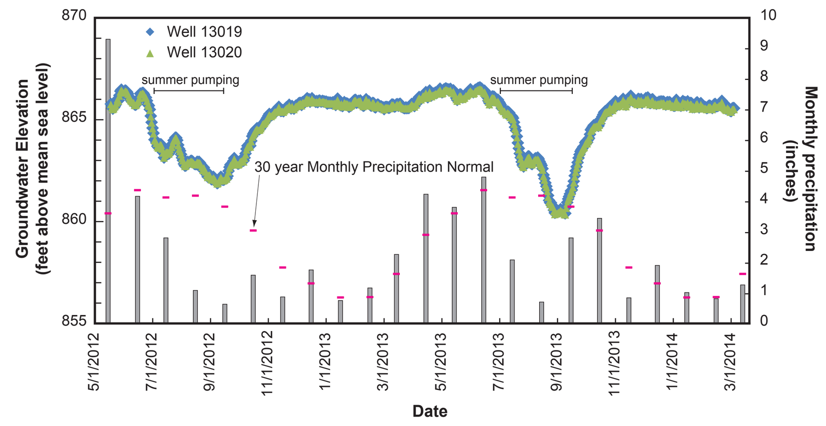
Wells selected for inclusion in the table were pumped for at least four hours and had a pumping water level a minimum distance of at least two feet above the well screen and inside the casing.
[1]Data adapted from the County Well Index.
[2]Data adapted from aquifer tests conducted for the Minnesota Department of Health.
[3]Less than 12-inch diameter wells constructed in surficial sand aquifer or Mesoproterozoic volcanic rock.
[4]Well constructed across more than one aquifer.



10a. Well 13011 (352 feet deep) in Sunrise Township is constructed in the sp buried sand and gravel aquifer. Water levels track with precipitation, but with a lag of roughly two years.



10b. Well 13006 (270 feet deep) in Amador Township is constructed in the Mt. Simon bedrock aquifer. Water levels track with precipitation with 2-year lag time similar to well 13011. The groundwater level elevation response to precipitaton in wells 13011 and 13006 indicates they are not directly influenced by short-term trends in precipitation, but follow a muted response to precipitation that is similar to long-term trends.



10c. Wells 13019 (270 feet deep) and 13020 (97 feet deep) in North Branch Township are constructed in the Mt. Simon aquifer and the se buried sand and gravel aquifer, respectively. The groundwater level change of these aquifers over time is very similar. Increased summer groundwater appropriation in nearby North Branch is evident, showing roughly six feet of drawdown during summer pumping in 2012 and 2013 followed by rapid recovery in the fall.

FIGURE 10a-c. Comparison of hydrographs of four DNR groundwater level monitoring wells to precipitation. Annual precipitation is shown by vertical gray bars. Precipitation was recorded from 1977–2011 at Wild River State Park (National Weather Service Station 218986).

TABLE 2. Water use reported by DNR groundwater appropriation permit holders for 2011 by use category
[Data from Minnesota Department of Natural Resources, Water Appropriation Permit Program; MGY, million gallons per year]

Use Category	Number of Wells	2011 Water Use (MGY)	Percent of Use
Municipal water supply	23	760.7	74.5
Major crop irrigation	8	120.7	11.8
Noncrop irrigation (golf course)	4	52.3	5.1
Commercial/institutional water	5	33.0	3.2
Special category (snow and ice making)	1	29.8	2.9
Private water supply	6	16.0	1.6
Crop irrigation (sod farms)	5	6.5	0.6
Industrial processing (sand and gravel washing)	1	2.0	0.2
Total	53	1021.0	100*

* Percentages do not add up to 100 due to rounding

MAP EXPLANATION
Figure 9

Water use reported by DNR groundwater appropriation permit holders for 2011
(millions of gallons per year)

- 0 to 15
- > 15 to 30
- > 30 to 45
- > 45 to 60
- > 60

DNR permitted groundwater use for 2011 by use category

- Municipal water supply
- Major crop irrigation
- Noncrop irrigation (golf course)
- Commercial/institutional water
- Special category (snow and ice making)
- Private water supply
- Crop irrigation (sod farms)
- Industrial processing (sand and gravel washing)

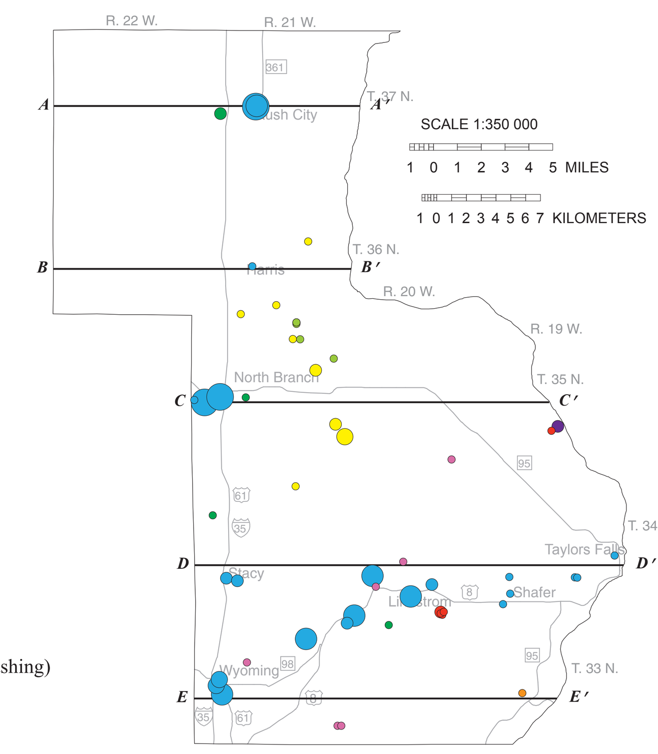


FIGURE 9. Distribution of DNR permitted groundwater appropriation by volume reported and use category for 2011. Municipal water supply accounts for the largest permitted groundwater use in Chisago County.

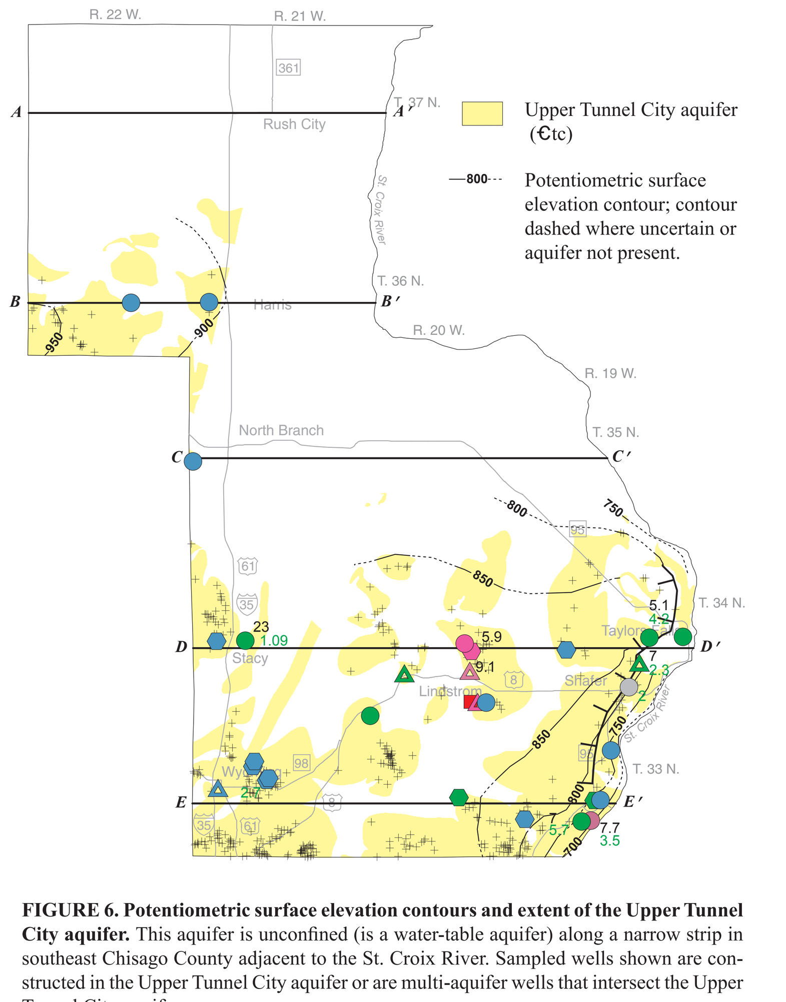


FIGURE 6. Potentiometric surface elevation contours and extent of the Upper Tunnel City aquifer. This aquifer is unconfined (is a water-table aquifer) along a narrow strip in southeast Chisago County adjacent to the St. Croix River. Sampled wells shown are constructed in the Upper Tunnel City aquifer or are multi-aquifer wells that intersect the Upper Tunnel City aquifer.

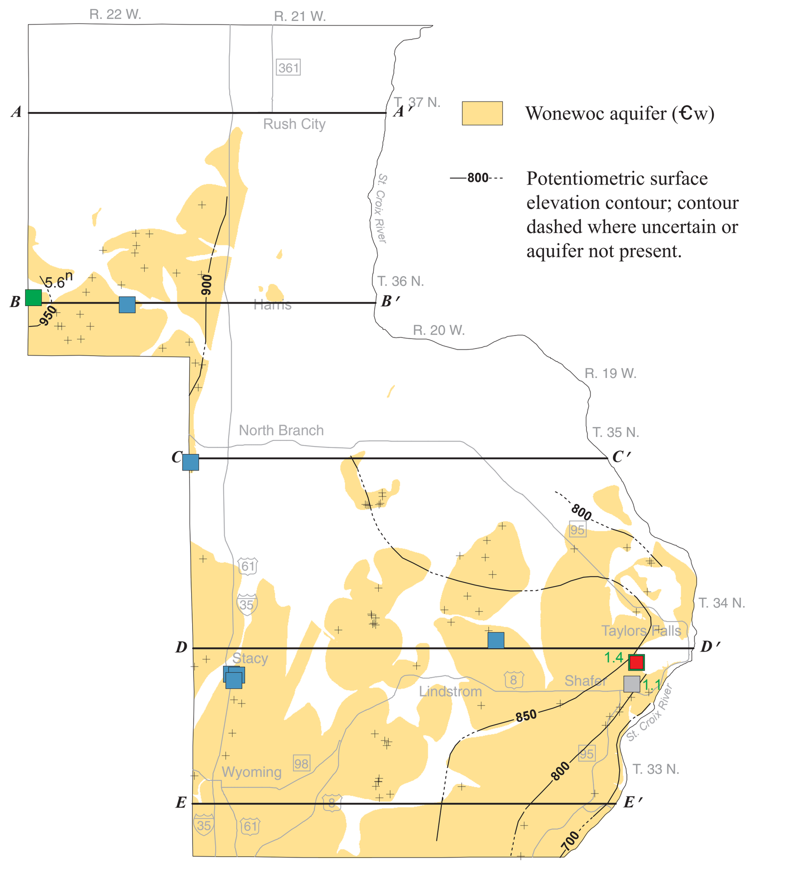


FIGURE 7. Potentiometric surface elevation contours and extent of the Wonewoc aquifer. Sampled wells shown are constructed in the Wonewoc aquifer or are multi-aquifer wells that intersect the Wonewoc aquifer.

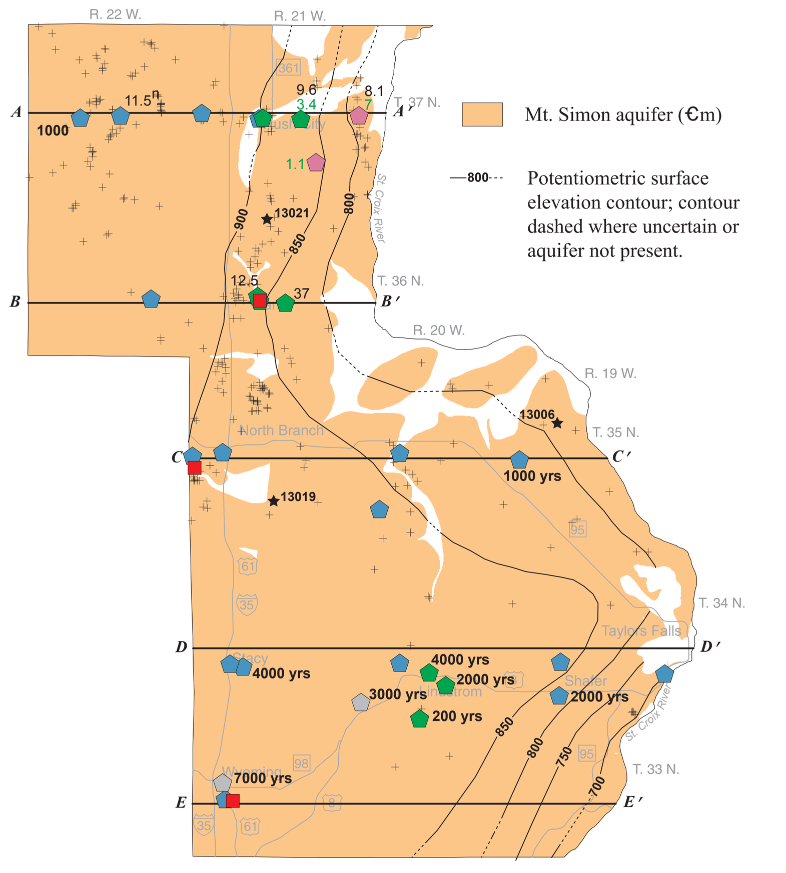


FIGURE 8. Potentiometric surface elevation contours and extent of the Mt. Simon aquifer. This aquifer is unconfined (is a water-table aquifer) along a narrow strip in eastern Chisago County adjacent to the St. Croix River near Rush City. Sampled wells shown are constructed in the Mt. Simon aquifer or are multi-aquifer wells that intersect the Mt. Simon aquifer.

INTRODUCTION

Groundwater resources provide drinking water to all of Chisago County. Approximately 79 percent of wells in Chisago County extract water from sand and gravel aquifers; nearly 19 percent extract water from bedrock aquifers (Part A, Plate 1). The remaining 2 percent of wells do not have aquifer designations. The laterally continuous sand and gravel units that are used as aquifers across the county were deposited during the last glaciations (Meyer and Lively, 2010). These units were deposited as layers of sand and gravel separated by lower-permeability till and other fine-grained sediments. These lower-permeability sediment layers partially protect the county's aquifers from surface contamination because the overlying sediments with relatively clay-rich textures slow the rate of aquifer recharge. Beneath the glacial sediments are a series of bedrock units, of which several have sufficient permeability and thickness to be important aquifers. The more important bedrock aquifers of the county are the Upper Tunnel City aquifer (formerly the Franconia), the Wonewoc aquifer (formerly the Ironton–Galesville aquifer), and the Mt. Simon aquifer.

QUATERNARY BURIED SAND AND GRAVEL AQUIFERS

The distribution and thickness of the six buried sand and gravel units that are considered aquifers in Chisago County were mapped by the Minnesota Geological Survey (MGS) and are published in Part A, Plate 5, Figures 3 through 9. Geologists from the MGS use County Well Index (CWI) drilling record logs and geologic understanding of glacial successions, deposition, and processes to map the extent, thickness, and depth of the various sand and gravel deposits in the county. These data are brought into a Geographic Information Systems (GIS) environment to create digital elevation models representing the tops and bottoms of the multiple sand and gravel units, the till and other fine-grained glacial units, and bedrock units across the county.

Water levels from wells completed in each of the buried sand and gravel aquifers were analyzed to determine the potentiometric surface of that aquifer. A potentiometric surface represents the elevation to which water will rise in a well cased in a confined aquifer (Fetter, 2000). These surfaces are also used to indicate key groundwater recharge and discharge areas and the direction of groundwater flow within the aquifer. Figures 1 through 5 depict the potentiometric surface elevation of the six mapped buried aquifers in Chisago County. The figures additionally show groundwater residence time and select chemistry data where available. The potentiometric surface of the mapped buried sand and gravel aquifers have similar elevations. They vary widely from west to east; with potentiometric elevation highs in the west and potentiometric elevation lows in the east along the St. Croix River. The potentiometric surface elevation of the buried sand and gravel aquifers, combined with the equipotential contours and groundwater chemistry displayed on the hydrogeologic cross sections displayed on Plate 9, describe a groundwater system that is recharged by the downward vertical movement of water. Groundwater then moves both vertically downward and laterally to the east to the regional groundwater discharge zone, the St. Croix River.

BEDROCK AQUIFERS AND AQUITARDS

The distribution of the bedrock geologic units of Chisago County is shown on Part A, Plate 2. MGS geologists use CWI drilling record logs and geophysical surveys to map the extent, thickness, and depth of the bedrock units that are present in the county. Not all bedrock units make good aquifers. Bedrock units that store and transmit water in appreciable quantities and rates are aquifers. Bedrock units that are generally not good aquifers or retard flow are aquitards. Some aquitards that impede water movement vertically may have horizontal fractures that enable the aquitard to yield sufficient water for residential use. Two regional aquitards, the St. Lawrence Formation and the Eau Claire Formation, are used in some locations for residential well supply.

Groundwater from bedrock units primarily comes from the Upper Tunnel City, the Wonewoc, or the Mt. Simon aquifer. In Chisago County it is also common for bedrock wells to intersect multiple bedrock aquifers. Figures 6 through 8 depict the lateral extent and groundwater potentiometric surface elevation contours of the three primary bedrock aquifers. The Upper Tunnel City aquifer has relatively high hydraulic conductivity in the fine- to medium-clastic sandstone part of the formation referred to as the Mazomanie. Lower hydraulic conductivity is found in the finer-grained glauconitic sandstone part of the formation referred to as the Lone Rock (Runkel, 2010). Both the Mazomanie and the Lone Rock are known to exhibit systematic and nonsystematic secondary porosity features such as bedding plane fractures and jointing that greatly increase the bulk hydraulic conductivity (Runkel and others, 2006). The Wonewoc and Mt. Simon aquifers primarily exhibit intergranular flow through fine- to coarse-grained quartz sandstone. Where bedrock aquifers are shallowly buried, within approximately 50 feet of the bedrock surface, groundwater flow through systematic and nonsystematic secondary porosity features such as fractures is common (Runkel and others, 2006). Secondary porosity can also occur in aquitards in shallow bedrock conditions, which can lessen the integrity of the aquitard in impeding water movement. Wells completed in aquifers with significant secondary porosity can exhibit much higher transmissivity values than wells completed in aquifers with primarily intergranular flow.

Nearly 90 percent of the wells constructed in bedrock aquifers in Chisago County are used for residential domestic water supply. The largest volume of groundwater use from bedrock aquifers in the county is by large municipalities; over half of these use the Mt. Simon aquifer for water supply.

AQUIFER HYDRAULIC PROPERTIES

Aquifer properties such as specific capacity and transmissivity are used to describe how water is transmitted by an aquifer. Specific capacity is a numerical value that describes the quantity of water produced from a well per unit depth of drawdown. Transmissivity is a numerical value that describes an aquifer's capacity to transmit water and is determined by multiplying the hydraulic conductivity of the aquifer material (the rate at which groundwater flows), by the thickness of the aquifer. Higher values of each of these properties indicate more productive aquifers. Table 1 lists specific capacity and transmissivity values for aquifers in the county. Specific capacity data were determined from short-term pumping or well development tests performed when the well was drilled. Specific capacity values listed in the table are from information listed in the CWI and include data for all wells with a casing diameter greater than or equal to 12 inches. Because no large-diameter wells are constructed in the surficial aquifer or volcanic rock, pumping data for smaller diameter wells constructed in these aquifers are included in Table 1. Transmissivity data were calculated from longer-term aquifer tests conducted for the Minnesota Department of Health. Longer-term aquifer tests generally pump wells at greater rates and for longer durations than individual well tests and are more representative of aquifer properties. Table 1 shows that the se and sx buried sand and gravel aquifers have the highest transmissivity values of the aquifers tested, with calculated transmissivity values of about 140,000 gallons per day per foot (gpd/ft). Although data from only a limited number of aquifer tests characterizing buried sand and gravel aquifers are available, the values are consistent with published hydraulic conductivity values for sand and gravel aquifers (Fetter, 2000). Transmissivity values of the bedrock aquifers range from 8,100 gpd/ft to 104,000 gpd/ft. High transmissivity values in bedrock aquifers are often related to secondary porosity influences in the aquifer (Runkel and others, 2006). Wells in Chisago County completed in volcanic rock have low specific capacity due to low matrix permeability and limited fracturing. These wells are often drilled to great depths to allow storage of water in the open hole between pump cycling events.

HIGH CAPACITY GROUNDWATER USAGE

The Minnesota Department of Natural Resources (DNR) maintains water use data through the water appropriation permit program to determine and regulate water use patterns across the state (DNR, 2012). Water users that withdraw more than 10,000 gallons per day or one million gallons per year are required to have a valid permit from the DNR and report their annual water use. Figure 9 shows the location, volume reported, and the use category of DNR permitted groundwater appropriators for 2011. Tables 2 and 3 show water use reported to the DNR by groundwater appropriation permit holders for the year 2011. The tables show water use by use category and by aquifer, respectively.

In 2011, the largest permitted groundwater use in Chisago County was for municipal water supply, which accounted for 74.5 percent of the total permitted groundwater withdrawal. Over half of this (55.7 percent) came from the Mt. Simon aquifer. Additional sources included a variety of bedrock and buried sand and gravel aquifers. The second largest permitted use was for major crop irrigation, accounting for 11.8 percent. Just under half (46 percent) of this was withdrawn from the Mt. Simon aquifer; the remaining 54 percent was extracted from other bedrock and buried sand and gravel aquifers. The third largest permitted use (5.1 percent) was for golf course irrigation, with the water supplied entirely from bedrock aquifers. The remaining water use categories together account for 8.5 percent of the total permitted groundwater used in 2011.

The total permitted annual groundwater withdrawal in Chisago County has been steadily increasing since 1988 (DNR, 2012). Municipal water supply is primarily responsible for this trend, with use increasing by 59.2 percent from 1988 to 2011. Other permitted water use categories vary in annual water use due to factors such as annual precipitation and economic conditions.

GROUNDWATER POTENTIOMETRIC SURFACE ELEVATION AND FLOW DIRECTION

Figures 1 through 5 show the potentiometric surface elevation of the mapped buried sand and gravel aquifers. Groundwater levels were used to construct the potentiometric surface for each of the buried sand and gravel aquifers on this plate. Levels were measured at the time of well construction and recorded in CWI. The groundwater surfaces and elevations depicted represent nonpumping conditions. In areas where high-volume groundwater appropriation occurs, local groundwater flow is radial towards the high capacity well.

The potentiometric surfaces represent the hydraulic head of the aquifer and are used to identify groundwater recharge and discharge areas and to interpret groundwater-flow direction. Groundwater moves from high elevations to lower elevations of the potentiometric surface in directions generalized by flow arrows. Figures 6 through 8 show the groundwater potentiometric surface elevation contours of the three primary bedrock aquifers. The shape and elevation of the potentiometric surfaces of the bedrock aquifers are similar to each other and to those of the buried sand and gravel aquifers. The Upper Tunnel City and Wonewoc aquifers are not present throughout the entire county; in these areas groundwater-elevation contours are absent. Most groundwater in Chisago County initially moves vertically downward and then flows east and southeast toward the St. Croix River. Groundwater also discharges to other features such as streams, lakes, and wetlands.

BURIED AND BEDROCK GROUNDWATER LEVEL AND AQUIFER RESPONSE TO PRECIPITATION

The hydrographs shown on this plate and on Plate 7 were produced from data retrieved from the DNR's groundwater level monitoring program (DNR, 2014). Figures 10a and 10b show the groundwater elevation hydrographs of two deep monitoring wells. Monitoring well 13011 (Figure 10a) is constructed to a depth of 352 feet in the sp buried sand and gravel aquifer and monitoring well 13006 (Figure 10b) is constructed to a depth of 270 feet in the Mt. Simon aquifer. These wells respond to long-term changes in precipitation, with responses lagging by approximately two years.

Wells close to each other and constructed in different aquifers are referred to as well nests. In 2012, three new well nests were installed in Chisago County comprising three buried sand and gravel wells and three bedrock wells. Although the period of record is too short to determine meaningful trends at these locations, these nests are already providing high resolution hydrologic data that provides insight into how these aquifers respond to recharge events, climatic conditions, and pumping stresses.

Continuous data (not shown) is collected at DNR observation wells 13021 and 13022 at the well nest located at Rose Wildlife Management Area north of Harris. These data show that the Mt. Simon aquifer in this area of the county has greater pressure head than the overlying buried sand and gravel aquifer and influences the water levels within the buried sand and gravel aquifer. Figure 10c shows continuous data collected at the nest located at Janet Johnson Wildlife Management Area southeast of North Branch. This hydrograph shows the Mt. Simon aquifer and buried sand and gravel aquifer have roughly the same pressure head. Each of the water levels in these wells rises and falls synchronously and shows the impacts of high volume water appropriation from wells in the vicinity of the city of North Branch. For the limited period of record, aquifer levels in this vicinity recover rapidly following maximum pumping during summer months.

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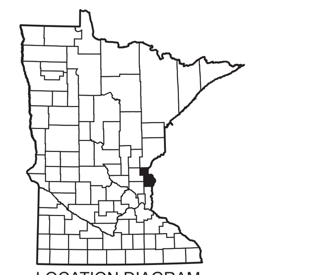

LOCATION DIAGRAM

This map was compiled and generated using Geographic Information Systems (GIS) technology. Digital data products, including chemistry and geophysical data, are available from the DNR Ecological and Water Resources Division at http://www.mndnr.gov/waters.

Base modified from Minnesota Geological Survey, Chisago County Geologic Atlas, Part A, 2010.

Project data compiled from 2010 to 2012 at a scale of 1:100,000. Universal Transverse Mercator projection, grid zone 15, North American Datum of 1983. Vertical datum is mean sea level.

GIS and cartography by John Barry, Shana Pascal, and Holly Johnson. Edited by Carrie Jennings, Ruth MacDonald, and Holly Johnson.