MINNESOTA DEPARTMENT OF NATURAL RESOURCES

GEOLOGIC ATLAS OF NICOLLET COUNTY, MINNESOTA

County Atlas Series C-25

PART B, HYDROGEOLOGY:

Report

Plate 7, Chemical Hydrogeology

Plate 8, Hydrogeologic Cross Sections

PART A, GEOLOGY was published separately by the Minnesota Geological Survey and contains the following:
Plate 1, Data-Base Map
Plate 2, Bedrock Geology
Plate 3, Surficial Geology
Plate 4, Quaternary Stratigraphy
Plate 5, Sand Distribution Model
Plate 6, Bedrock Topography and Depth to Bedrock

MNDNR

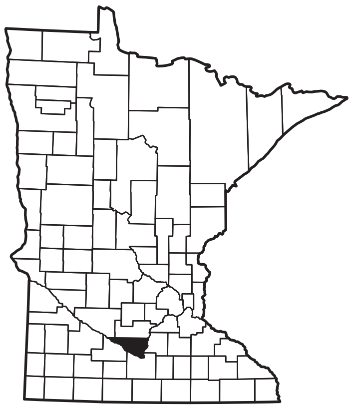
St. Paul
2016

This page intentionally left blank.

Geologic Atlas of Nicollet County, Minnesota

County Atlas Series C-25, Part B

By Vanessa M. Baratta and Todd A. Petersen



LOCATION DIAGRAM

Minnesota Department of Natural Resources

2016

Recommended Citation

Baratta, V.M. and Petersen, T.A., 2016, Geologic atlas of Nicollet County, Minnesota (Part B): Minnesota Department of Natural Resources, County Atlas Series C-25, report and pls. 7–8.

County Geologic Atlas Program

The Minnesota County Geologic Atlas series has been produced since 1982. Recent atlases are found in two parts. Part A covers the geology and is produced by the Minnesota Geological Survey (MGS). Part B covers the hydrogeology and is produced by the Minnesota Department of Natural Resources (DNR).

Explanations of the history and purpose of the program, atlas applications, and descriptions of the Part A and Part B components are available online:

Part A, MGS: mngs.umn.edu/county_atlas/countyatlas.htm
Part B, DNR: mndnr.gov/groundwatermapping

Report Contents

Report Figures

Report Tables

Plates

Acknowledgments

Guidance and technical assistance was provided by a number of colleagues during the production of this report. Jeremy Rivord and Avery Guertin performed the field data collection and early report work. Roberta Adams made the water table, depth to water table, and near-surface pollution sensitivity maps and provided technical editing on those sections. John Barry, Jim Berg, Meagan Harold, Paul Putzier, and Jeremy Rivord provided thoughtful insight, experience and technical review. Ruth MacDonald provided technical editing. Holly Johnson provided cartographic and graphical editing. Additional technical review was provided by: Mindy Erickson, Mike MacDonald, Tony Runkel, Julia Steenberg, and Bob Tipping.

Scott Alexander and Jim Lundy provided additional chemical and isotopic data. An additional thank you goes to Scott Alexander for his assistance in the calculation of the carbon-14 ages of groundwater samples.

Geologic Atlas of Nicollet County, Minnesota, Part B

By Vanessa M. Baratta and Todd A. Petersen

Introduction

This report and the two accompanying plates are **Part B** of the Nicollet County Geologic Atlas. Part B describes the hydrogeology and is produced by the Minnesota Department of Natural Resources (DNR). It builds on the geology described in Part A, which was published by the Minnesota Geological Survey (MGS).

The purpose of this atlas is to help users understand the hydrogeologic setting and inherent pollution sensitivity of the aquifers in the county. This information can be used to make land-use decisions that take aquifer sensitivity, water quality, and sustainability into account.

A Geologic Atlas User's Guide is available from the MGS for additional information on the history and purposes of the program, various atlas applications, and descriptions of the Part A components (Setterholm, 2014).

This report describes the hydrogeologic setting, water levels, chemistry, pollution sensitivity, and use of aquifers within the county. The accompanying plates illustrate the water chemistry (Plate 7) and show groundwater flow directions and residence time within the buried sand and gravel aquifers and bedrock aquifers along hydrogeologic cross sections (Plate 8).

The following information is incorporated into maps and cross sections to help visualize the distribution of aquifers, aquitards, groundwater recharge, and subsurface flow within the county.

Geology and physical hydrogeology outlines the characteristics of the geologic units from the land surface down to the bedrock. Hydrostratigraphic characteristics as aquifers or aquitards are identified with their corresponding geologic units from Part A.

Groundwater elevation maps give a broad look at the direction of groundwater flow in unconfined conditions (water-table elevation) and confined conditions (potentiometric elevation surfaces). A map of the depth to water table is included.

Chemical hydrogeology provides information about the water source, flow path, travel time, and residence time of groundwater. The groundwater chemistry is used to identify areas of interest, such as naturally elevated arsenic levels or high pollution sensitivity, and supports the results of the pollution sensitivity models.

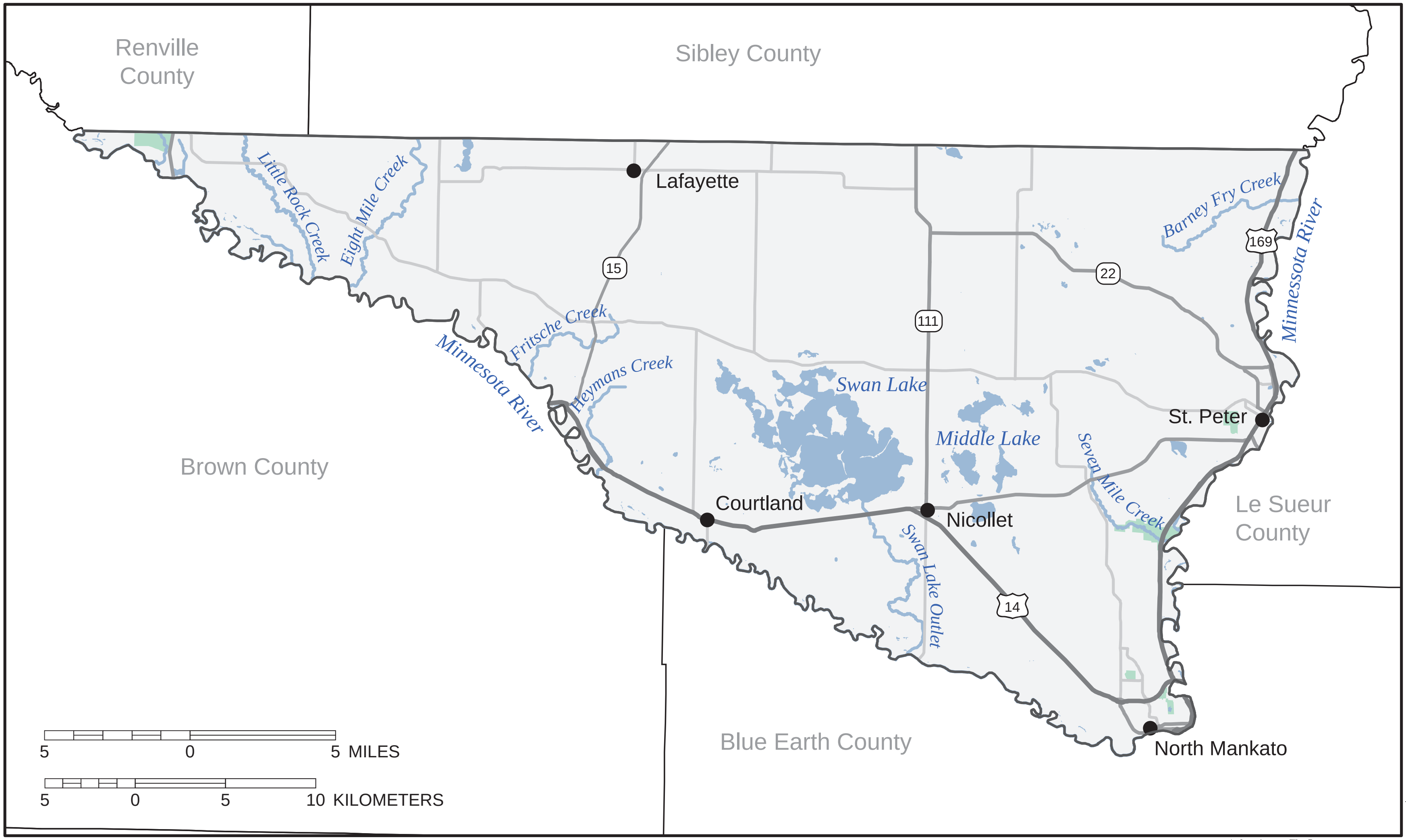
Hydrogeologic cross sections bring the physical hydrogeology and groundwater chemistry together to illustrate groundwater flow, residence time, and distribution of chemical characteristics. These cross sections help define areas of interest, such as important groundwater recharge and discharge areas, and pollution sensitivity.

Pollution sensitivity is modeled for the near-surface materials and for the mapped buried sand and gravel aquifers and the bedrock surface.

The sensitivity of *near-surface materials* is an estimate of the time it takes for water to infiltrate the land surface to a depth of 10 feet. This model is based on hydrologic soil groups and surficial geologic matrix textures.

The sensitivity of *buried sand and gravel aquifers and the bedrock surface* is based on the cumulative thickness of fine-grained sediment (aquitard material) overlying an aquifer or the bedrock surface. The pollution sensitivity ratings are compared to tritium and carbon-14 data for residence time, and to inorganic chemistry constituents that have traveled from the land surface. These comparisons allow us to evaluate the model results.

Groundwater use and aquifer characteristics summarize specific capacity tests, aquifer tests, and water use records (from groundwater appropriation permits) for each aquifer, where available. These data help hydrogeologists plan new wells to meet requirements for a given use. DNR groundwater level monitoring data is also summarized to identify monitoring efforts that are underway in the county.



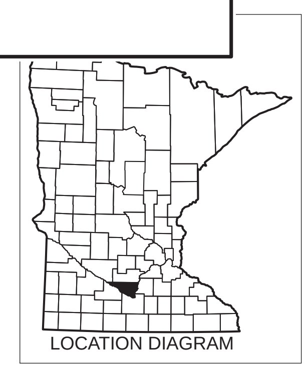


Figure 1. Nicollet County location map

Geology and physical hydrogeology

Nicollet County is located in south-central Minnesota (Figure 1) and spans two sub-basin-level surface watersheds (hydrologic unit code 8), both of which flow to the Minnesota River (Figure 2). Most of the county is in the Minnesota River–Mankato watershed. The north-central and northeastern parts of the county are in the Lower Minnesota River watershed. The Minnesota River has no major tributaries in Nicollet County. There are four minor tributaries: Seven Mile Creek, Eight Mile Creek, Barney Fry Creek, and Little Rock Creek.

The topography is level to rolling in most of the county, except along the southern and eastern borders where the Minnesota River and its tributaries are deeply incised into the surface, creating river gorges with wooded bluffs and tributary ravines.

Surficial geologic units and aquifers

Surficial deposits in Nicollet County are dominated by glacial sediment of the Des Moines Lobe (Part A, Plate 3). This sediment was deposited in multiple phases of advance and retreat resulting in multiple layers with slightly different lithologic compositions. After the Des Moines Lobe retreated, drainage from glacial Lake Agassiz created the glacial River Warren, which cut the 200-foot-deep valley that is currently occupied by the Minnesota River.

This large valley locally exposes bedrock along the southern and eastern border of the county along the steep valley walls. The sudden creation of this deep valley caused pre-existing tributaries to begin adjusting their gradients to the new local base level, a process that is ongoing. Gradual fluvial and slope processes have altered the sides of the Minnesota River valley that borders Nicollet County on two sides, creating ravines that lead to fans on the valley floor and gravitational failure of sediment and rock in steeper portions of the landscape.

The fine-grained sediment that covers most of the county at the land surface does not readily transmit water to wells and therefore is not considered an aquifer. The surficial sand and gravel aquifer is formed primarily from terrace deposits in the Minnesota River valley, where these deposits are saturated (Part A, Plate 5, Figure 2).

Water table

The water table is the surface between the unsaturated and saturated zones where the water pressure equals the atmospheric pressure. The water table occurs in both aquifer and nonaquifer sediment across the entire county.

The surficial sand and gravel (ss) aquifer is present where there is sufficient saturated thickness and yield to install a well and economically pump groundwater. It has limited extent and thickness in Nicollet County (primarily present along the river valleys) and is not often used as a water resource.

The water-table elevation (Figure 2) is estimated from several sources of data:

- Static water levels in surficial sand and gravel wells obtained from well records in the County Well Index database
- The elevation of surface-water bodies calculated from a digital elevation model (DEM) derived from Light Detection and Ranging (LiDAR) technology
- Estimates of wet soil conditions from polygon shapefiles and associated tabular data from the county soil survey by the Natural Resources Conservation Service (NRCS)

The depth to water table (Figure 3) is derived by subtracting the water-table elevation from the land-surface elevation.

More details on how both maps were constructed can be found in *Methods for estimating water-table elevation and depth to water table* (DNR, 2016a).

The water-table maps provide guidance for many applications but additional site-specific information should be used to further refine water-table information at local scales. There are conditions that can affect the fluctuation of the water table and create locally different results from the maps created using this procedure. Some of these include, but are not limited to, seasonal weather conditions, extent and composition of surficial geology units, land-use practices, vegetation composition and distribution, and pumping of large-capacity wells. There are also limited data along the valley walls of the high-relief Minnesota River valley. The resulting water-table elevation in those locations can be variable.

The water table generally follows the surface topography. Based on the above data, the water table is probably within ten feet of the land surface across most of the county. The depth to water table is likely greater than 10 feet near the upland valley edges and terraces within the Minnesota River valley.

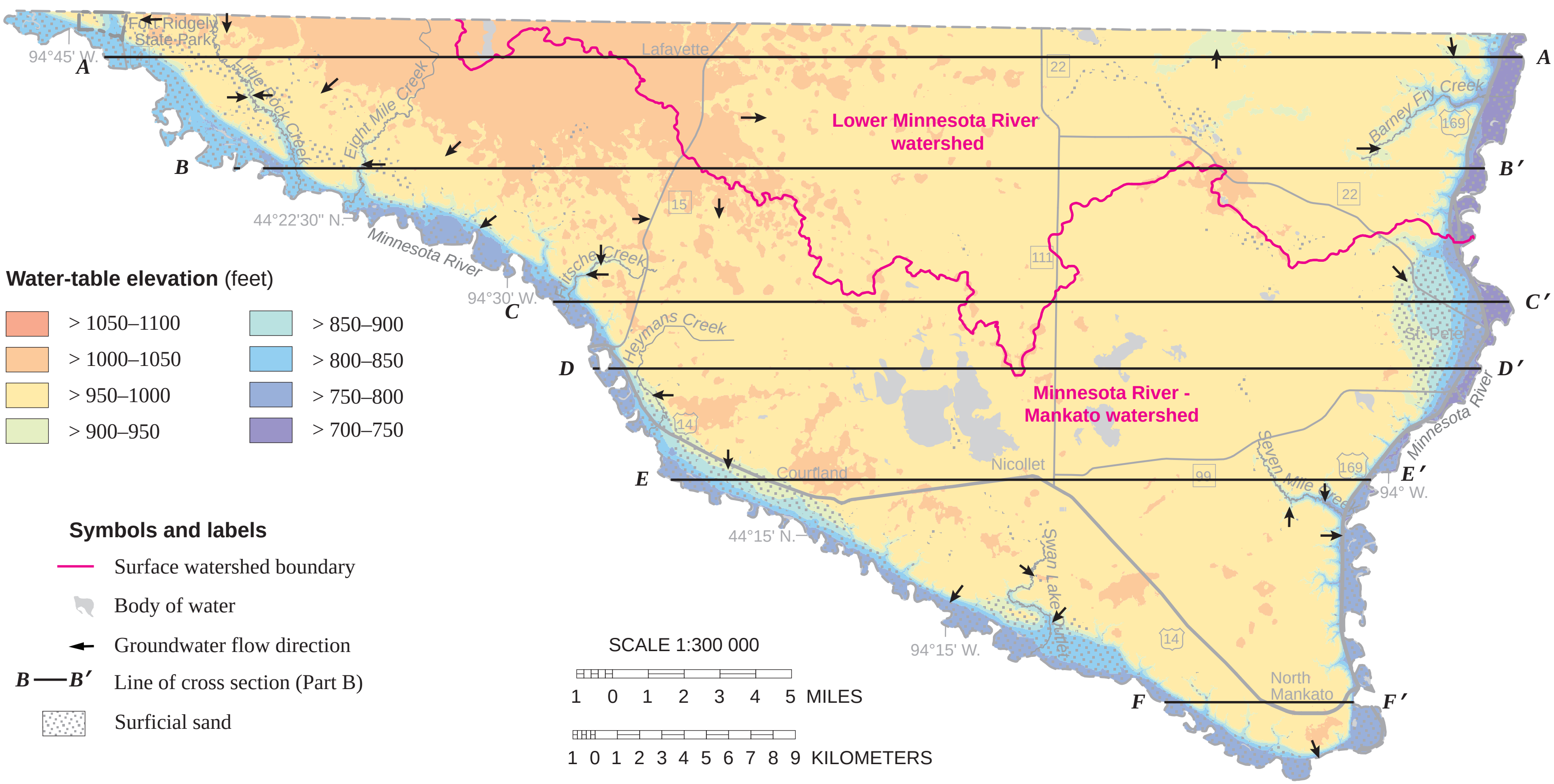


Figure 2. Water-table elevation and groundwater flow directions

Groundwater flows toward the Minnesota River and its minor tributary streams. Map modified from the Minnesota Hydrogeology Atlas HG-03.

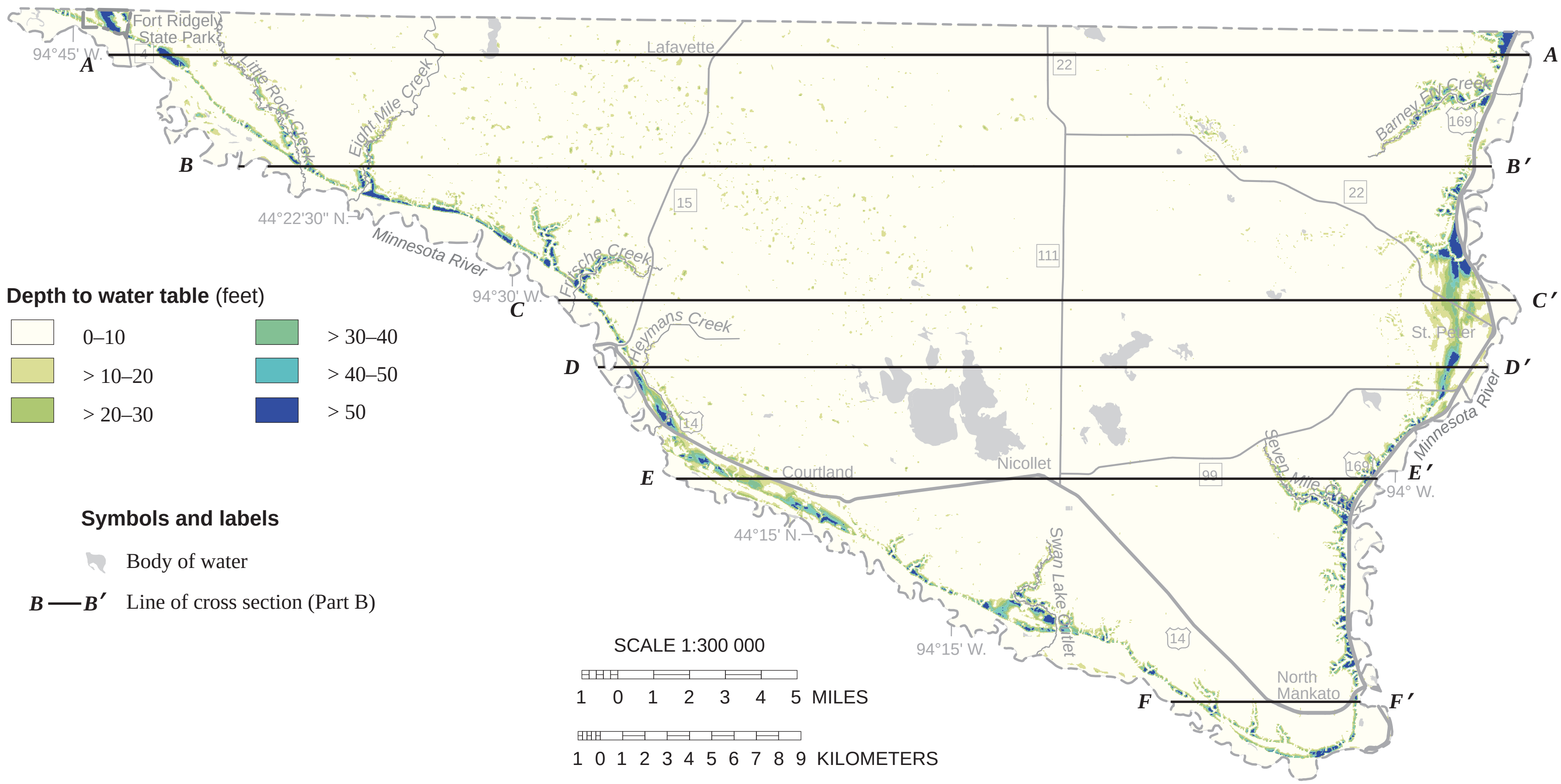


Figure 3. Depth to water table

The depth to water table is within 10 feet of the land surface across the majority of Nicollet County, with the exception of the Minnesota River valley, its minor tributary valleys, and in some of the large terrace deposits along the Minnesota River valley. Map modified from the Minnesota Hydrogeology Atlas HG-03.

Buried sand and gravel aquifers

Deeper sediment layers were deposited during multiple episodes of glaciation over the past 2 million years (Part A, Plates 4 and 5). An unsorted mixture of clay, silt, sand, and gravel (till) was deposited directly by the glaciers. In some places the sediment was sorted as it was deposited by meltwater streams (forming sand and gravel deposits) and lakes (forming silt and clay deposits) (Part A, Plate 5). Glacial deposits are highly variable and the associated sand and gravel aquifers are typically thin (20 to 40 feet thick) and discontinuous with lateral extents rarely exceeding several miles. Buried aquifers are typically surrounded by layers of fine-grained glacial sediment that form aquitards.

The unconsolidated sediment thickness in Nicollet County varies primarily because of the topography of the buried bedrock surface. However, in areas in the Minnesota River valley the sediment is often less than 50 feet thick because of erosion by the glacial River Warren. In the central portion of the county the sediment can be up to 450 feet thick where deep bedrock valleys have been filled with glacial sediment (Part A, Plate 6).

The stratigraphic column in Figure 4 summarizes the geologic units and hydrogeologic properties of the glacial sequence and correlates the corresponding Part A and B unit names and map labels. The Part B units are represented as follows:

- **Aquifers** are represented with *patterns* throughout this atlas (Figure 4 and Plate 8).
- **Aquitards** are shown as *shades of gray* to represent the relative hydraulic conductivity. This is based on the percentage of a sample that is sand less than 2 millimeters in size. Lighter shades of gray represent units with more sand, implying a higher hydraulic conductivity. Darker shades of gray represent units with less sand, implying a lower hydraulic conductivity.
- **Undifferentiated** sediment with an unknown texture is shown in *brown*.

There are some differences between this report and the Quaternary units presented in Part A. The differences are present because the Part A mapped units were reanalyzed by the MGS to create continuously mapped units across the Nicollet and Sibley county border where possible. New versions of the mapped units are available with the electronic data for this atlas.

The extent of aquifer sge is different than originally mapped, because small sections of aquifer sg3 were identified in Sibley County mapped across the border into Nicollet County. These have limited spatial extent and are stratigraphically similar to aquifer sge. For the purpose of this report the two units were combined and will be subsequently referred to as aquifer sge.

Another difference is that the sand unit associated with the Browerville Formation in Part A has a very limited extent and only a small number of wells are completed in it across Nicollet County (Part A, Plate 4). Because of this, it does not have a potentiometric surface or pollution sensitivity map in this report. One water sample was collected from the Browerville Formation and is designated aquifer sb within the chemistry section of this report.

	Part A	Part B
surficial sand and gravel		ss
clayey till	Quh	uh
sand and gravel	*Qsh/Qsv*	sh/sv
clayey till/till	*Qlh/Qvt*	lh/vt
sand and gravel	*Qsm*	sm
sandy till	*Qmt*	mt
sand and gravel	*Qst*	st
sandy till	*Qtt*	tt
sand and gravel	*Qsg*	sb
clayey till	*Qbt*	bt
sand and gravel	*Qs1*	sg1
clayey till	*Qg1*	g1
sand and gravel	*Qs2*	sg2
till	*Qg2*	g2
sand and gravel	*Qse*	sge
till	*Qet*	et
unknown sand and gravel		suu
undifferentiated sediment	*Qu*	ups
bedrock		

Figure 4. Hydrostratigraphy of Quaternary unconsolidated sediment

Aquifers are shown with patterns and aquitards are shown in shades of gray. Part B aquifer names are based on the name of the till underlying it in the Part A. Shades of gray on the aquitards correspond to the sand content within the till.

Potentiometric surfaces of buried sand and gravel aquifers

In confined aquifers, pressure causes water to rise in a well to a point higher than the top of the aquifer. Water levels measured in wells from a given aquifer are contoured to create a map of the *potentiometric surface* of that aquifer. The lines are similar to the contour lines of a topographic map, providing a visual model of the water surface.

The potentiometric surface of an aquifer represents the potential energy that is available to move groundwater. As groundwater moves from higher to lower potentiometric elevations it flows perpendicular to the potentiometric elevation contours.

Groundwater flows from recharge areas through the aquifer to discharge locations that can occur over a wide continuum of depth, distance, and time. Flow into, through, and out of shallow aquifers can take days to weeks to travel up to a mile. Flow in deeper aquifers can take centuries to millennia to travel dozens of miles. When combined with other information, high elevation areas on the potentiometric surface can indicate important recharge areas.

Potentiometric surface maps for Nicollet County incorporated water-level data from static (nonpumping) wells from the County Well Index, measurements made by DNR staff, and river elevation points along the Minnesota River (every 5 kilometers). River elevation points are included because the river is a regional discharge location for both the buried sand and gravel aquifers and the bedrock aquifers along the southern and eastern border of the county. Data from both Nicollet and Sibley counties were used together to increase the data coverage and ensure that the potentiometric surfaces were consistent across the county boundary. The County Well Index records used in the map development were measured from the 1960s to 2012 and represent various climatic and seasonal conditions over that time period.

A contour interval of 50 feet was used for the maps to account for some of the data variability, though some uncertainty is still present in the potentiometric surface elevations. The potentiometric contours are shown as solid lines inside mapped aquifers and dashed lines outside mapped aquifers. Although the potentiometric surfaces of the aquifers do not extend beyond its physical boundaries, the dashed lines help indicate general groundwater flow direction. The extent and thickness of buried sand and gravel aquifers are often not well constrained, especially for deeper aquifers, and the aquifers may extend over a broader area than shown.

Potentiometric surfaces are shown for four of the seven buried sand and gravel aquifers (Figures 5 through 8). Three of the buried aquifers have too few wells completed in them to reliably map a potentiometric surface (sh, sv, and sm). More information about these aquifers is presented in the sections, “Chemical hydrogeology” and “Pollution Sensitivity.”

All of the potentiometric surface maps indicate a general pattern of groundwater flow toward the Minnesota River valley, with an elevated region in the potentiometric surface northwest of Courtland. The elevated region is due to a high point in the underlying bedrock made up of relatively impermeable Sioux Quartzite. This prevents the groundwater in the overlying glacial sediment from continuing to move downward, forcing it to mound and move laterally along the surface of the quartzite. The deeply incised valleys of the Minnesota River and Seven Mile Creek are examples of low elevation areas that are typically discharge areas.

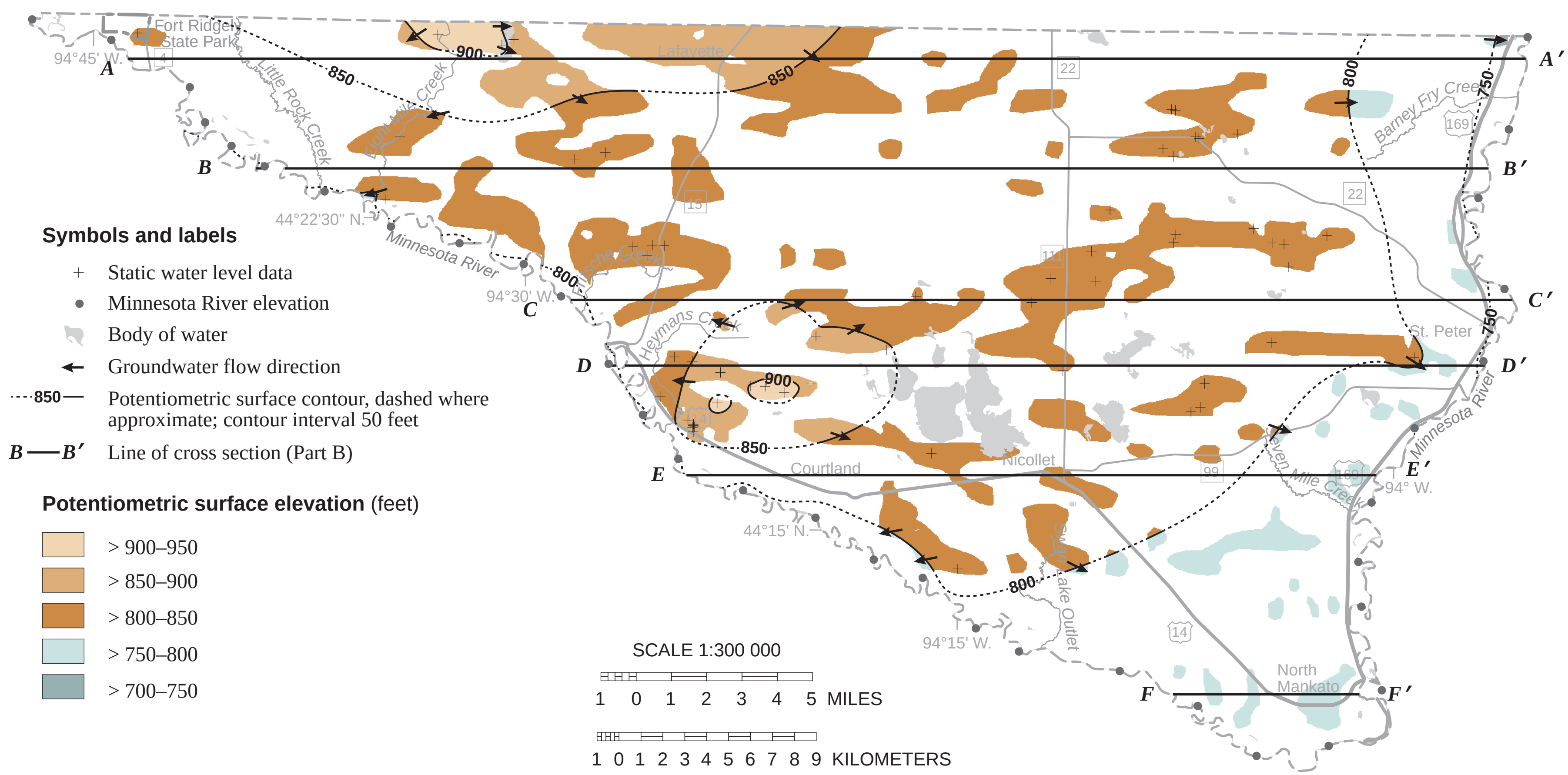


Figure 5. Potentiometric surface of the st aquifer

General groundwater flow direction is from the northwestern (upland) part of the county toward the Minnesota River, which forms the southern and eastern borders of the county. There is a high point in the potentiometric surface north of Courtland, indicating a localized area with flow away from the Minnesota River.

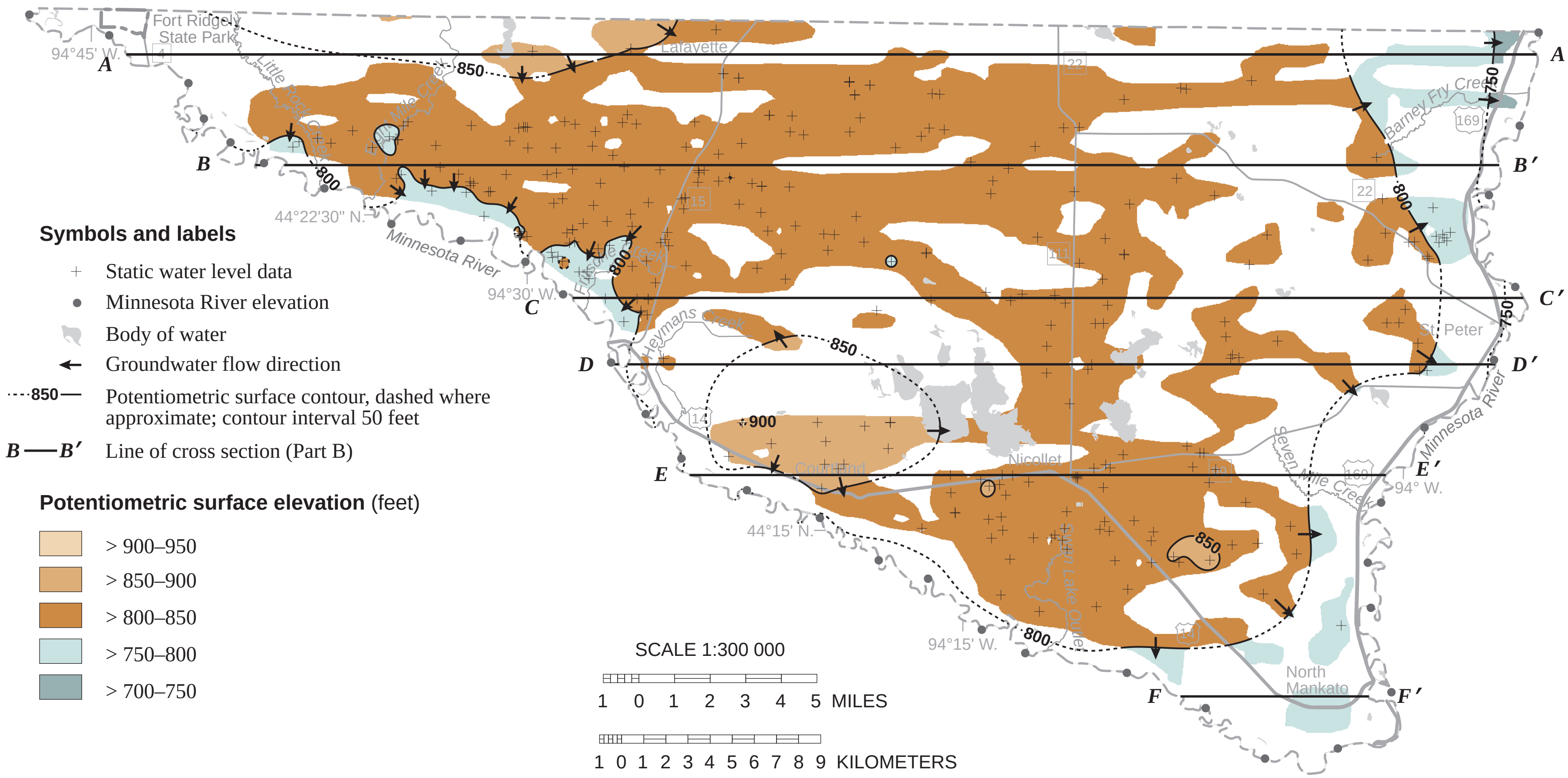


Figure 6. Potentiometric surface of the sg1 aquifer

General groundwater flow direction is from the northwestern (upland) part of the county toward the Minnesota River, which forms the southern and eastern borders of the county. There is a high point in the potentiometric surface north of Courtland, indicating a localized area with flow away from the Minnesota River.

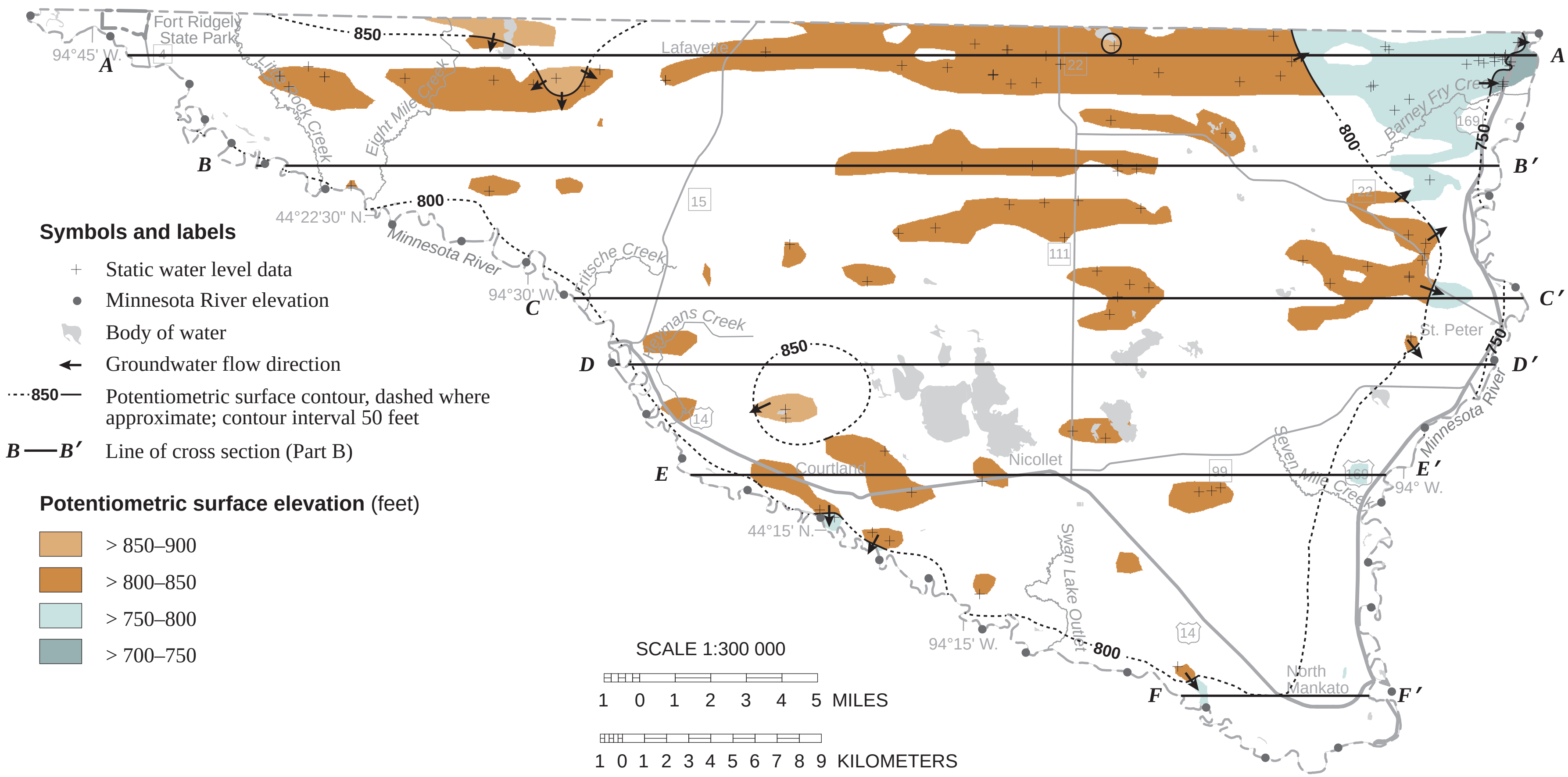


Figure 7. Potentiometric surface of the sg2 aquifer

General groundwater flow direction is from the northwestern (upland) part of the county toward the Minnesota River, which forms the southern and eastern borders of the county. There is a high point in the potentiometric surface north of Courtland, indicating a localized area with flow away from the Minnesota River.

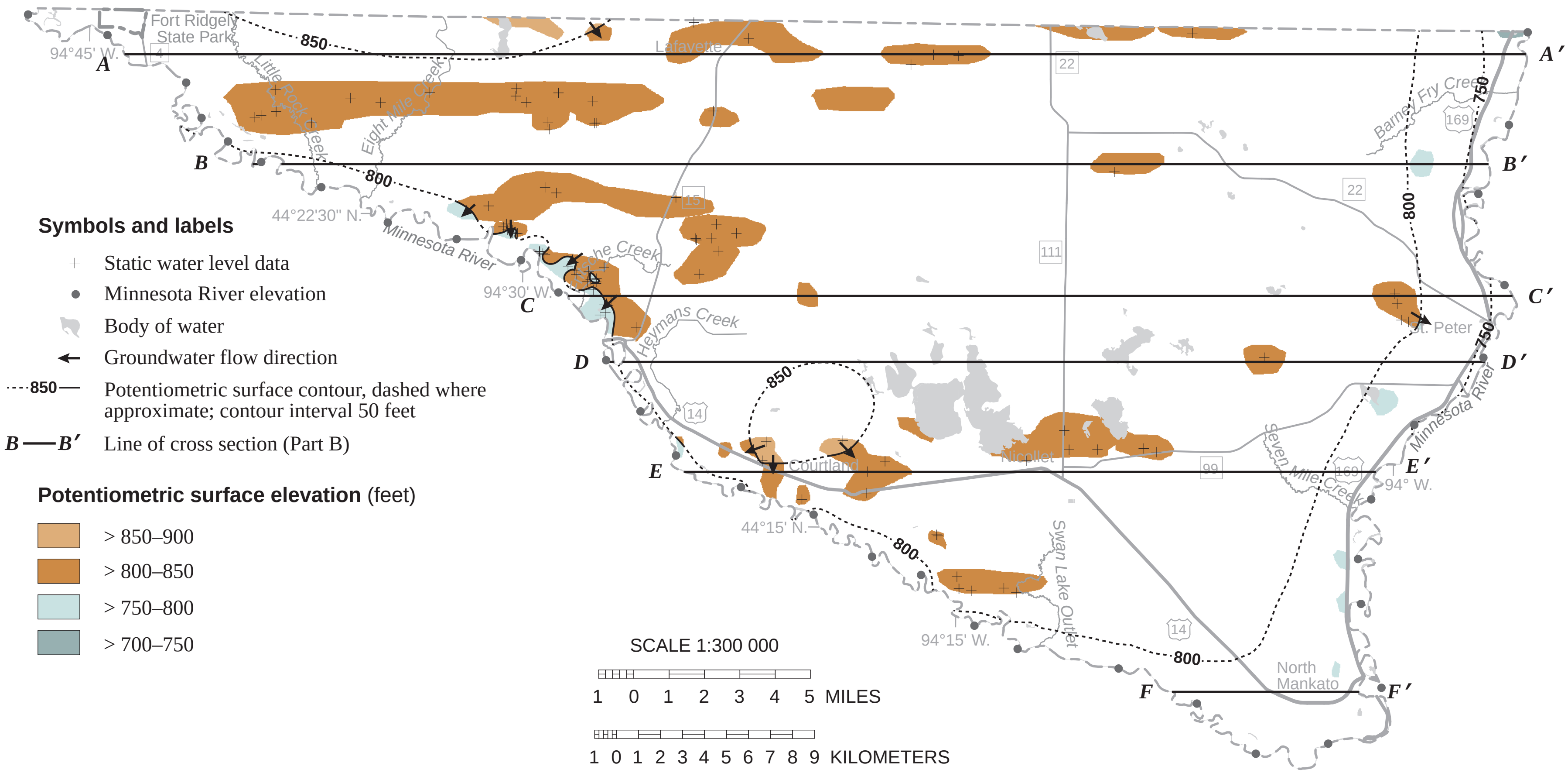


Figure 8. Potentiometric surface of the sge aquifer

General groundwater flow direction is from the northwestern (upland) part of the county toward the Minnesota River, which forms the southern and eastern borders of the county. There is a high point in the potentiometric surface north of Courtland, indicating a localized area with flow away from the Minnesota River.

Bedrock geologic units and aquifers

Several different bedrock units are present at the bedrock surface in Nicollet County (Part A, Plate 2). Paleozoic sedimentary units are at the bedrock surface in the eastern part of the county. These units dip gently toward the southeast. The oldest, stratigraphically lowest rocks of the sequence form the bedrock surface in the center of the county; the younger bedrock units form the bedrock surface to the east.

In the eastern part of the county, many of the Paleozoic sedimentary sandstone and carbonate units have a high enough permeability to be considered aquifers (Figure 9). In the western part of the county, sedimentary bedrock is not present and the principal formations are Precambrian crystalline rocks. These units have low permeability and are rarely used as aquifers. The Cretaceous Dakota Formation and the unnamed Ka unit have limited aquifer potential. The extent of these units is shown in Part A, Plate 2. The Cretaceous units appear on the cross sections of this report (Plate 8), but they are not shown on any of the bedrock potentiometric surface maps in this report.

The Paleozoic sandstone and carbonate aquifers are commonly used for water by municipalities and commercial operations because of their thickness, extent, and predictability. In sandstone aquifers such as the Jordan and Wonewoc, water moves through intergranular pore spaces and larger macropores such as fractures. Groundwater in the Prairie du Chien and Upper Tunnel City aquifers primarily moves through enlarged fractures. A potentiometric surface for the Wonewoc aquifer is not present in this report due to the small number of wells drilled into the Wonewoc in this region.

The St. Lawrence and Eau Claire formations generally have low permeability and only form aquifers where they are near the bedrock surface. An enhanced-permeability zone is generally found in approximately the uppermost 50 feet of the Paleozoic sedimentary bedrock units. It likely developed when the bedrock surface was at the land surface. The fractures in this zone generally increase the yield from aquifers but compromise the protective character of aquitards. The enhanced-permeability zone is not represented in the Precambrian or Cretaceous units in this report. The zone may exist in these units, but there is not enough information available at this time to say that it is present.

Both bedrock aquifers and aquitards are anisotropic with regard to hydraulic conductivity, with horizontal hydraulic conductivity higher than vertical hydraulic conductivity. This can be pronounced in some aquitards such as the St. Lawrence Formation, which can have bulk horizontal hydraulic conductivities similar to aquifer units, even in deep bedrock conditions (greater than 50 feet from the bedrock surface).

Geologic Unit		Hydrogeologic Unit	Hydrogeologic Unit Properties
Dakota Formation		Dakota aquifer	moderate intergranular permeability
Unnamed unit (Ka)		Ka aquifer	low to moderate intergranular permeability, thin sandstones interlayered with siltstone and claystone, probably low yielding
Prairie du Chien Group		Prairie du Chien aquifer	relatively low intergranular permeability, high fracture permeability
		aquitard	generally low permeability
Jordan Sandstone		Jordan aquifer	relatively high intergranular permeability
		aquitard	generally low permeability
St. Lawrence Formation		aquitard	generally low vertical permeability, moderate horizontal permeability
Tunnel City Group	Lone Rock Formation	Upper Tunnel City aquifer	relatively low intergranular permeability, moderate to high fracture permeability
		aquitard	generally low permeability
Wonewoc Sandstone		Wonewoc aquifer	moderate intergranular permeability
Eau Claire Formation		aquitard	generally low permeability
Mt. Simon Sandstone		Mt. Simon aquifer	moderate intergranular permeability

high permeability bedding fractures

Figure 9. Bedrock stratigraphy and hydrostratigraphy (not to scale)

Geologic stratigraphic units do not always correspond to hydrogeologic units. These characterizations are interpreted from hydrologic reports by Runkel and others, 2003 and Runkel and others, 2006.

Potentiometric surfaces of bedrock aquifers

Potentiometric surfaces for the Prairie du Chien–Jordan, Upper Tunnel City, and Mt. Simon aquifers indicate that overall bedrock groundwater flow is toward the Minnesota River (Figures 10 through 12). The potentiometric surfaces also indicate that there is discharge from the bedrock aquifers to the Minnesota River. The potentiometric surface for the Prairie du Chien and Jordan aquifers were mapped as one surface for this project due to limited data. The static water level data for the two aquifers was similar enough to combine the data, though it is possible that an aquitard may be present between the two aquifers locally.

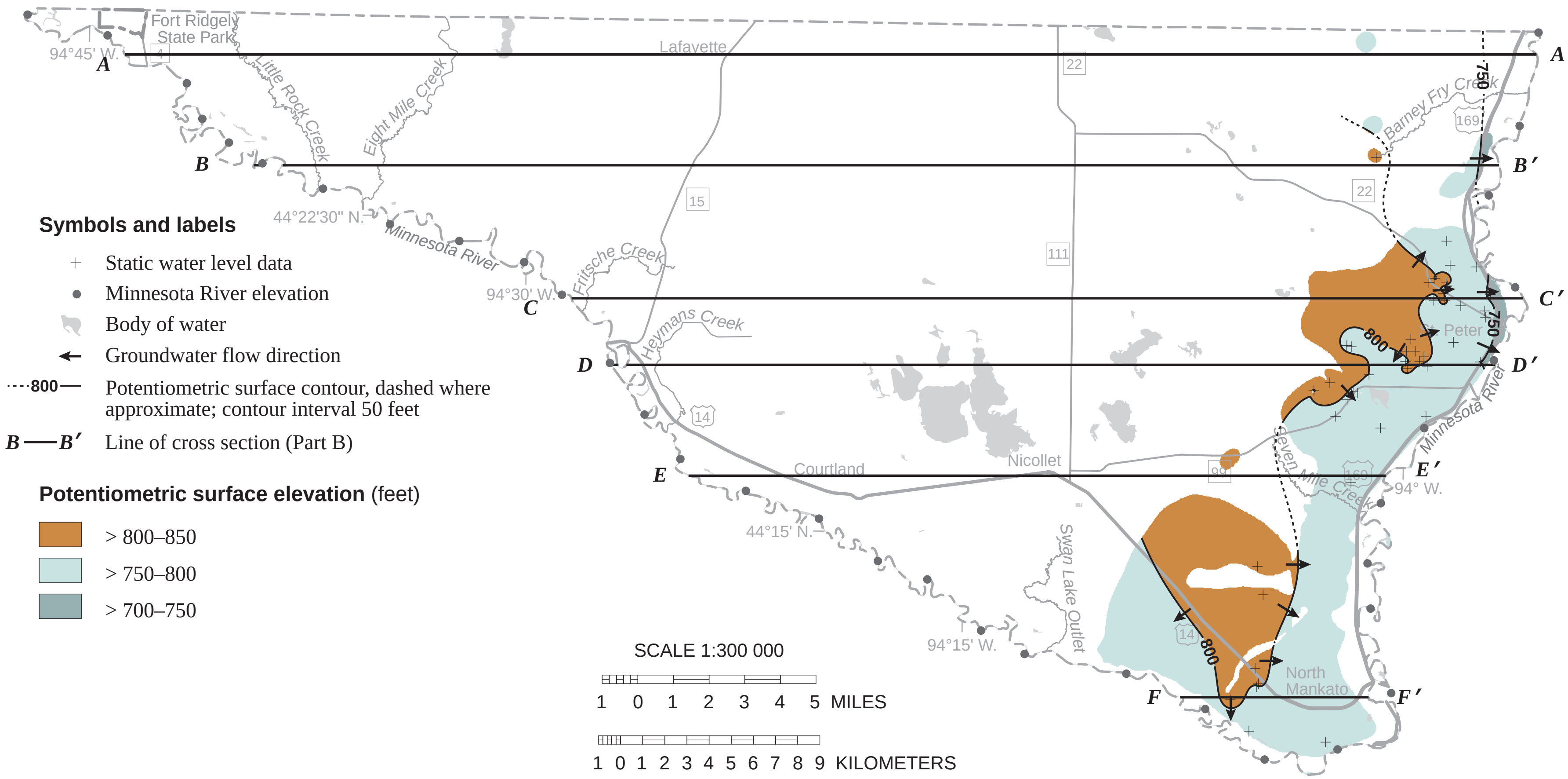


Figure 10. Potentiometric surface of the Prairie du Chien–Jordan aquifer

General groundwater flow direction is toward the Minnesota River, which forms the southern and eastern borders of the county.

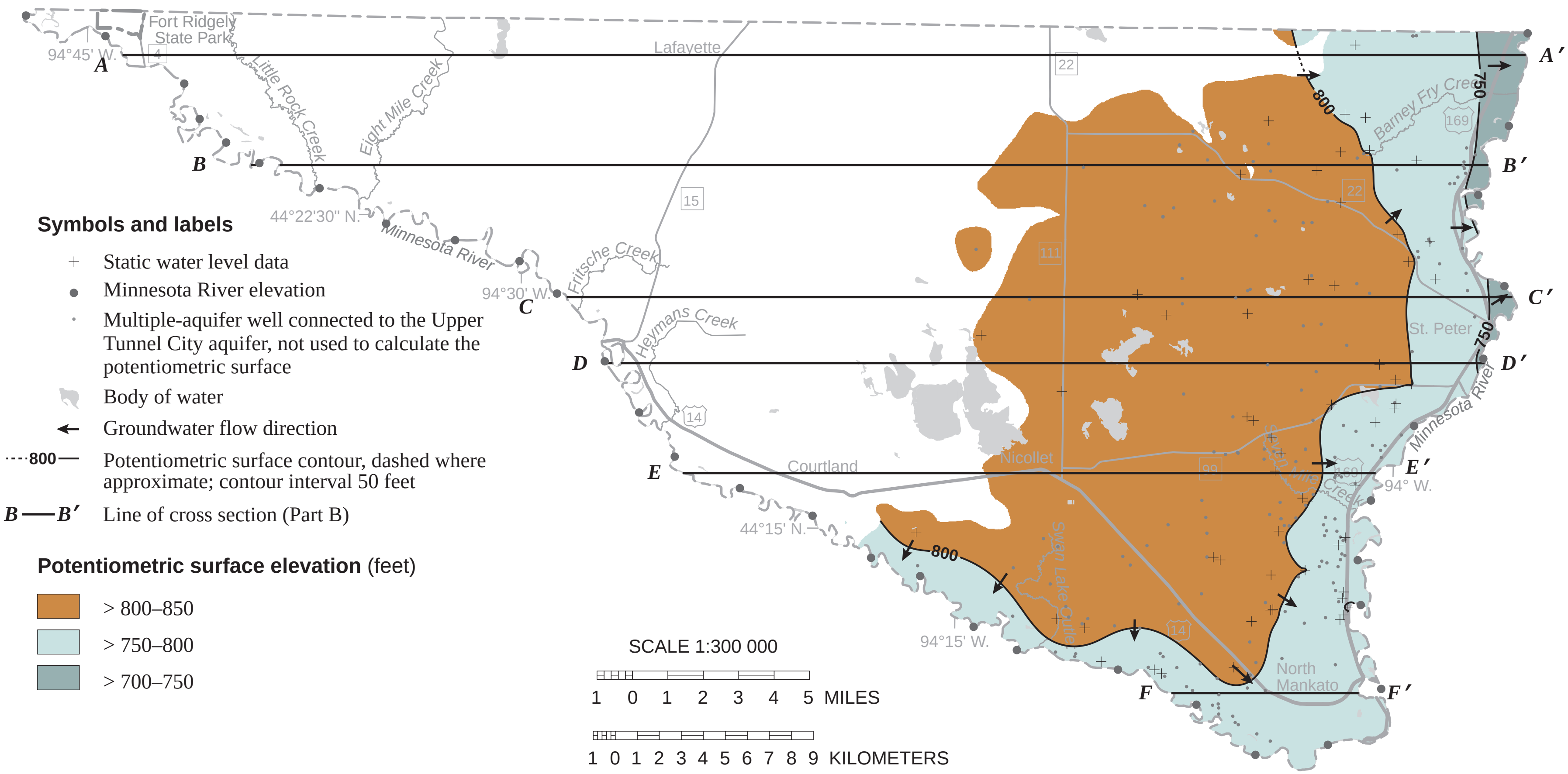


Figure 11. Potentiometric surface of the Upper Tunnel City aquifer

General groundwater flow direction is toward the Minnesota River, which forms the southern and eastern borders of the county.

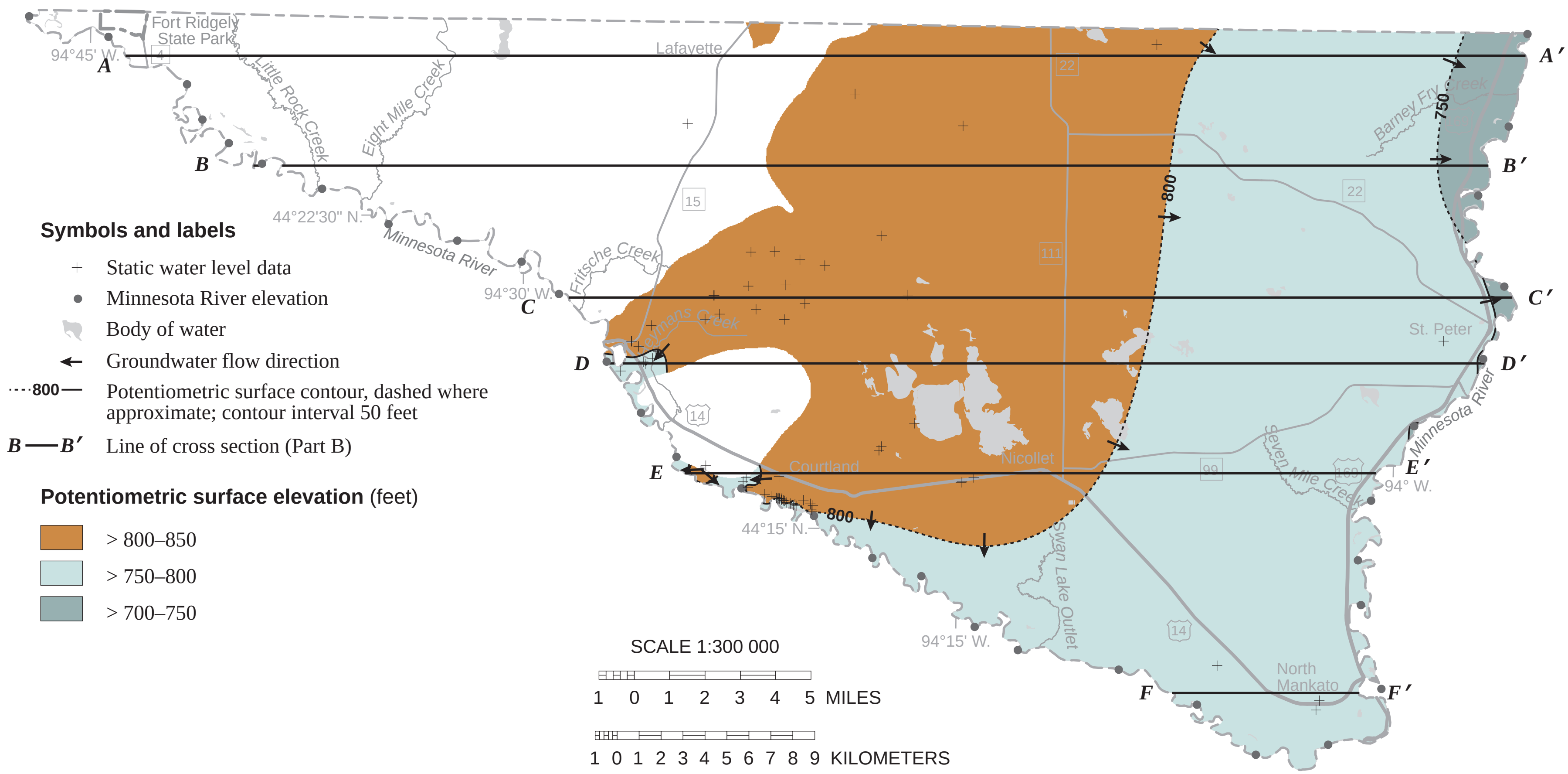


Figure 12. Potentiometric surface of the Mt. Simon aquifer

General groundwater flow direction is toward the Minnesota River, which forms the southern and eastern borders of the county.

Chemical hydrogeology - Plate 7

The types of dissolved elements and compounds in groundwater provide information about the recharge areas, the geologic layers that the water has flowed through, and approximately how long the water has been underground (residence time). All groundwater originated as precipitation or surface water that seeped into the ground, through the soil layer, and into the pores and crevices of aquifers and aquitards. Water moves into aquifers (recharge), through aquifers, and out of aquifers (discharge) in complicated but definable patterns. Water chemistry is used to provide information such as the following:

- Groundwater recharged from surface water can be identified from the effect of evaporation on the isotopes of hydrogen and oxygen.
- Groundwater residence time is estimated from tritium and carbon-14 isotopes. Tritium is used to identify where water has moved into the subsurface since the 1950s. Carbon-14 is used to determine groundwater residence times of centuries to millennia.
- The distribution of select naturally occurring elements can indicate areas where groundwater consumption is a potential concern to human health.

Groundwater sampling

To better understand groundwater movement and pollution sensitivity, 89 groundwater samples, 3 lake samples, 2 spring samples, and 1 river sample were collected from a wide range of aquifers and surface-water bodies across the county (Plate 7). Samples were collected using the protocols outlined in the Appendix.

Chemical data from collected water samples were used along with primary physical data (static water level and aquifer tests) to understand groundwater movement. Wells were selected for sampling based on their hydrogeologic setting. All aquifers that were significant for water supply were sampled.

The sampling network for this study is geographically distributed across the county, including the more populated areas near the cities of St. Peter and North Mankato. The sampling network includes wells near important surface-water features, such as the Minnesota River and multiple lakes.

Groundwater recharge sources

As water moves from precipitation to surface water to groundwater, chemical changes occur that can help determine whether groundwater was recharged directly from precipitation, lake water, or a mixture of the two. Stable isotopes of oxygen and hydrogen are useful for determining groundwater and surface-water interactions. Oxygen and hydrogen each have two main stable isotopes: ^{18}O and ^{16}O, and ^{2}H and ^{1}H. The different mass of the isotopes causes evaporation at different rates, which results in *fractionation*. This results in isotopic signatures that are unique to groundwater with different sources.

Water in lakes or open-water wetlands is subject to evaporative fractionation where the light isotopes evaporate into the atmosphere and move downwind. The water left in the lake or wetland has a heavier or *evaporative isotopic signature*.

Precipitation that infiltrates directly into the ground does not experience evaporation and therefore does not fractionate. The isotopic ratio does not change and it maintains its original *meteoric isotopic signature*.

To identify the source (precipitation or surface water) of a groundwater sample, oxygen and hydrogen isotopic data are plotted against each other (Figure 15). The x-axis represents the oxygen isotope value ($\delta^{18}O$) and the y-axis represents the hydrogen isotope value ($\delta^{2}H$). The measured ratio in the sample is divided by the ratio in in a standard (Vienna Standard Mean Ocean Water [VSMOW]). The $\delta^{18}O$ value is calculated from the $^{18}O/^{16}O$ ratio of the sample divided by the $^{18}O/^{16}O$ VSMOW standard. The $\delta^{2}H$ value is calculated from the ratio of $^{2}H/^{1}H$ ratio of the sample divided by $^{2}H/^{1}H$ VSMOW standard.

Definition of delta (δ)
The stable isotope composition of oxygen and hydrogen are reported as δ values. $\delta\ (^0/_{00}) = (R_x / R_s - 1)*1000$ where R represents the ratio of the heavy to light isotope, $^{18}O/^{16}O$ or $^{2}H/^{1}H$ and R_x represents the ratio of the sample and R_s represents the ratio in VSMOW. Delta values are reported in units of parts per thousand ($^0/_{00}$ or permil) relative to VSMOW.

Precipitation values for $\delta^{18}O$ and $\delta^{2}H$ generally plot along the meteoric water line. The North American meteoric water line was developed using North American precipitation averages from stations available through the Global Network of Isotopes in Precipitation (IAEA/WMO, 2006).

- Groundwater samples consistent with rapidly infiltrated **precipitation** plot near the **meteoric water line**.
- Groundwater samples that have been subjected to evaporation in **surface water** plot along an **evaporation line**,

which has a shallower slope than the meteoric water line. Samples that plot along the evaporation line are considered to have an evaporative signature.

The majority of the Nicollet County samples plot along the meteoric water line, in the center and left portions of the stable isotope graph. This suggests that precipitation infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies.

Six samples plot along the evaporation line: three lake samples collected from Annexstad, Sand, and Swan lakes; one from the Minnesota River, and two from wells (Plate 7). One of the well samples was from the relatively shallow sm aquifer downgradient of Annexstad Lake. The other was from the deeper sg1 aquifer downgradient from Swan Lake. The lakes are likely a source of recharge for these aquifers.

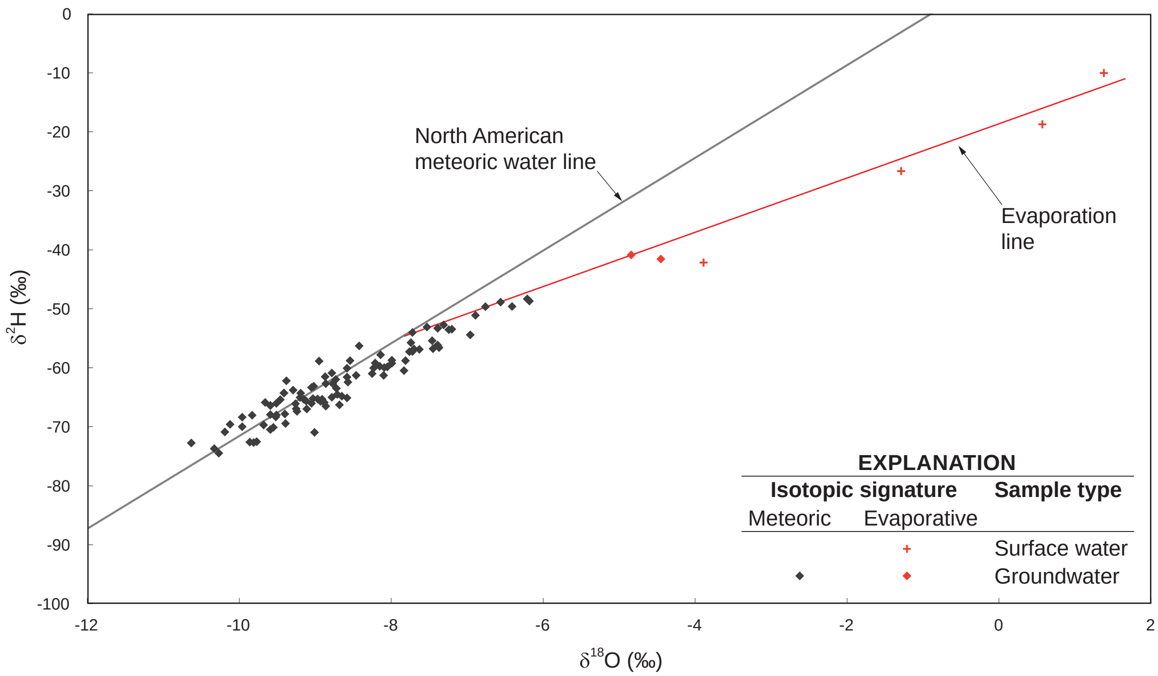


Figure 13. Graph of stable isotope values from water samples

Stable isotope values from groundwater samples relative to the meteoric water line. The red symbols denote water samples that have been affected by evaporation and plot along the evaporation line.

Groundwater residence time indicators

Groundwater residence time is the approximate time that has elapsed since water infiltrated the land surface to the time it was pumped from a well or discharged from a spring. In general, short residence time suggests high rates for groundwater flow velocity or short travel paths; long residence time suggests low rates for groundwater flow velocity or long travel paths. Isotopic analysis of the radioactive elements tritium and carbon-14 is used to estimate the residence time of the groundwater.

Tritium

Groundwater residence time can be interpreted from the concentration of tritium. Although tritium is a naturally occurring isotope of hydrogen, atmospheric concentrations were greatly increased between 1953 and 1963 by atmospheric testing of nuclear weapons (e.g., Alexander and Alexander, 1989). Hydrologists can estimate recharge timing using the tritium half-life of 12.32 years (Lucas and Unterweger, 2000).

Tritium age is important in the interpretation of the hydrogeologic cross sections (Plate 8) and pollution sensitivity maps. The pollution sensitivity maps are assessed by comparing groundwater chemistry (including tritium age, nitrate, and chloride values) with the calculated sensitivity (Figures 19 through 25).

Groundwater residence time is measured in tritium units (TU) and is divided into the following ranges of values.

- **Cold War era**: water entered the ground from the peak period of atmospheric tritium concentration from nuclear bomb testing, 1958–1959 and 1961–1972 (greater than 15 TU).
- **Recent**: water entered the ground since about 1953 (8 to 15 TU).
- **Mixed**: water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- **Vintage**: water entered the ground before 1953 (less than or equal to 1 TU).

Carbon-14

The carbon-14 (^{14}C) isotope is used to estimate the residence time for vintage and mixed tritium-age samples. This naturally occurring isotope has a half-life of 5,730 years, two orders of magnitude longer than tritium, and is used to estimate groundwater residence time ranging from 100 to 40,000 years (Alexander and Alexander, 1989).

Inorganic chemistry of groundwater

As soon as precipitation infiltrates the soil layer and becomes groundwater, the water begins dissolving minerals in the soil, sediment, and bedrock. Inorganic chemical analysis of groundwater samples is useful for characterizing the changes in water chemistry as it moves deeper into the earth and for identifying the presence of anthropogenic pollution sources. This report includes analyses of water samples for inorganic chemistry, primarily the major cations, major anions, and select elements that typically are found in trace amounts, in parts per billion (ppb). Information on Plate 7 includes chemical constituents that indicate anthropogenic impacts, a concern for human health, or spatial trends in the data.

Organic chemicals, which are usually of anthropogenic origin, were not studied (including pesticides and their breakdown products, solvents, degreasers, etc.). Studies of these organic chemicals in groundwater may be found at other state agencies.

Calcium and magnesium cations and bicarbonate anions (not shown on Plate 7) are dissolved by the groundwater in the glacial sediment of Minnesota. These are derived from limestone and dolomite bedrock sources (Freeze and Cherry, 1979) and are common in groundwater in the glacial aquifers of Nicollet County (Figure 14).

Sodium (not shown on Plate 7) is often present in deeper aquifers or at mineral interfaces. As groundwater moves through the aquifer systems, calcium and magnesium cations are exchanged for sodium ions (Hounslow, 1995). This is shown on the cation triangle in Figure 14, where the recent and mixed tritium-age samples plot with a lower proportion of sodium than the vintage tritium-age samples. One sample has higher magnesium and sodium and does not follow the general trend in the cation data. This sample was collected from a well completed in Sioux Quartzite, which is relatively isolated from the other groundwater.

Sulfate is largely naturally occurring, and is an important constituent of groundwater in parts of the county. High concentrations in groundwater can negatively affect the taste and may act as a laxative. Sulfate has a nonenforceable federal secondary maximum contaminant limit (SMCL) for public water systems of 250 ppm (EPA, [1996]).

Sulfate results: 50 of 109 samples (46 percent) analyzed for sulfate were above the SMCL for sulfate. There appears to be a spatial trend in samples with elevated sulfate. The Heiberg and Villard till units are at or near the surface across most of Nicollet County. Eighty-two sulfate samples were collected from units under the Heiberg till. There were elevated sulfate values in 47 of these 82 samples (57 percent). Samples collected from areas primarily covered by Villard till had elevated sulfate in only 3 of 27 samples (11 percent). The Heiberg till has a higher amount of Cretaceous shale than the Villard till. The Cretaceous shale may be the source of increased sulfate.

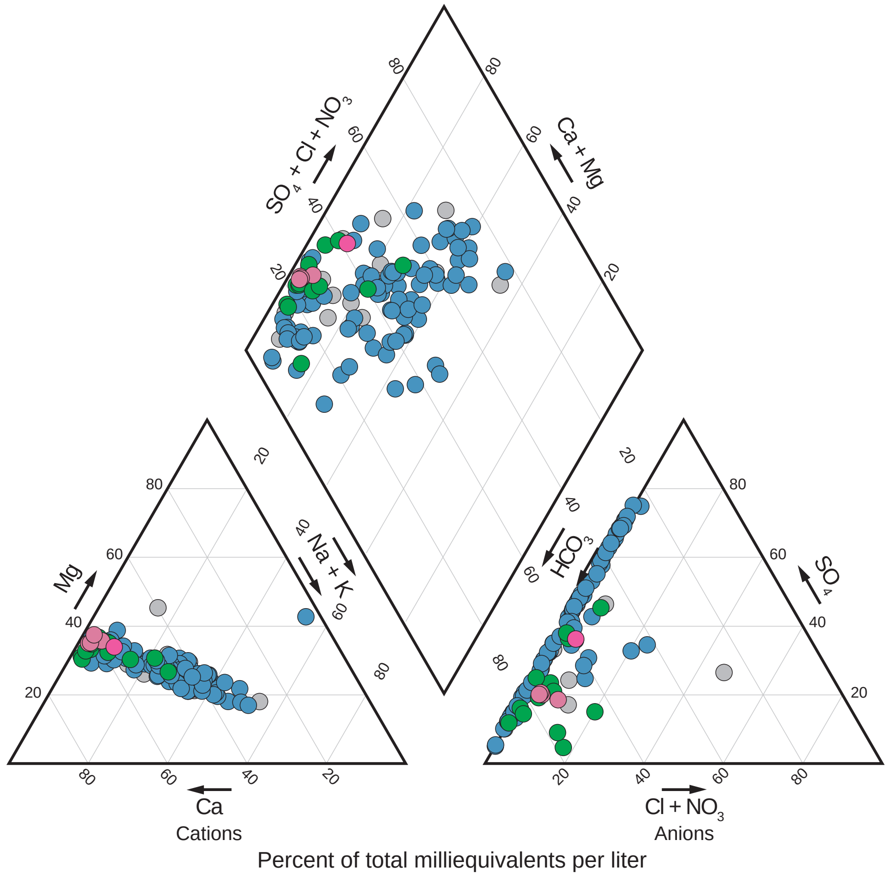
Chloride and nitrate-nitrogen concentrations can be used to indicate anthropogenic contamination from road salts, water softener salts, fertilizers, or animal and human waste. Their presence can indicate a short groundwater residence time. Possible anthropogenic impacts are indicated by elevated chloride concentrations above 5 ppm, with a chloride/bromide ratio above 300. Groundwater with an elevated nitrate-nitrogen concentration (greater than 1 ppm) likely entered the ground within the past few years to decades, and indicates anthropogenic sources and confirms high aquifer sensitivity. The maximum contaminant limit (MCL) for nitrate-nitrogen is 10 ppm (EPA, [1996]).

Chloride results: 35 of 109 samples (32 percent) had an elevated chloride concentration of more than 5 ppm (Plate 7). Many had chloride/bromide ratios under 300 and were collected from shallow bedrock aquifers or buried sand and gravel aquifers near the bedrock surface. The source of chloride in these samples may be the result of bedrock brine mixing with the groundwater and increasing the chloride. Elevated chloride concentrations without a high chloride/bromide ratio could also be the result of shallow groundwater evaporating and concentrating atmospheric chloride.

Nitrate-nitrogen results: 5 of 112 samples (4 percent) had more than 1 ppm nitrate-nitrogen, two of which were collected from the Jordan aquifer west of St. Peter. The Jordan aquifer in that area is overlain by a thick terrace deposit that results in rapid recharge from the surface to the buried sand and gravel and bedrock aquifers.

MCL (EPA): Maximum contaminant level: legally enforceable federal standards that apply to public water systems, to limit the levels of contaminants in drinking water.

SMCL (EPA): Secondary maximum contaminant level: nonenforceable guidelines for contaminants that may cause cosmetic effects or aesthetic effects in drinking water.



Tritium age

Symbol color indicates tritium age of water sample.

- Cold War era: water entered the ground during the peak period of atmospheric tritium concentration from nuclear bomb testing, 1958–1959 and 1961–1972 (greater than 15 TU).
- Recent: water entered the ground since about 1953 (8 to 15 TU).
- Mixed: water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).
- Not sampled for tritium.

Chemicals

Bicarbonate (HCO_3)

Calcium (Ca)

Chloride (Cl)

Magnesium (Mg)

Nitrate (NO_3)

Potassium (K)

Sodium (Na)

Sulfate (SO_4)

Figure 14. Piper diagram of water samples from the DNR and the Minnesota Pollution Control Agency

This diagram compares the relative proportions of cations and anions in the county water samples. The cations and anions are shown in the left and right triangles, respectively. The center diamond shows a composite of cations and anions. The cation triangle indicates that there is ion exchange taking place, which results from calcium and magnesium ions being exchanged for sodium through time. The anion triangle shows that samples with more sulfate primarily have a vintage tritium age. This indicates that the sulfate in these samples is from a natural source.

Naturally occurring elements of health concern

Although arsenic and manganese are found in smaller concentrations than the major constituents discussed previously, small concentrations of either element pose risks to human health (Table 1 and Plate 7). Exposure to arsenic has been linked to both cancer and noncancerous health effects (EPA, 2001). Low levels of manganese are a benefit to humans, but high exposures can harm the nervous system (MDH, 2012).

Arsenic

Arsenic is a naturally occurring element in Minnesota groundwater. Current science cannot predict which wells will have high arsenic concentrations, therefore newly constructed wells are tested for arsenic if they are used as a potable water supply, according to Minnesota Rule 4725.5650 (2008). The Environmental Protection Agency (EPA) requires that community water supplies not exceed 10 parts per billion (ppb) arsenic, but there is no such requirement for domestic wells. Well-water samples that had 5 ppb or more arsenic should be resampled to determine if the arsenic level of the first sample is a representative value.

- Arsenic concentrations greater than or equal to 10 ppb were found in 17 of the 100 (17 percent) water samples: 15 in buried sand and gravel aquifers and 2 in the Mt. Simon aquifer. The percentage of wells with elevated arsenic is greater than the average across the state of Minnesota (10.7 percent) (MDH, 2016).
- Arsenic concentrations greater than 5 ppb and less than 10 ppb were found in 15 water samples: 11 in buried sand and gravel aquifers, 2 in the Mt. Simon aquifer, 1 in the Dakota aquifer, and 1 from the Minnesota River near the northwestern corner of the county. The arsenic in the bedrock wells may be from the overlying glacial units.

The factors affecting elevated arsenic concentrations in groundwater are not completely understood. There is a strong correlation with wells completed in aquifers associated with glacial sediment bearing materials derived from rocks that lie northwest of Minnesota (Erickson and Barnes, 2005a). In this atlas these northwest provenance tills are subdivided into Riding Mountain and Winnipeg tills (Part A, Plate 4). Except for unit tt, all of the mapped fine-grained sediment in Nicollet County is from the northwest provenance. Research also indicates that arsenic concentrations are increased in wells that have short screened sections near the boundary of an aquitard and the aquifer (Erickson and Barnes, 2005b; McMahon, 2000).

The original arsenic reservoir is thought to be arsenic-bearing minerals from small shale particles in these tills. Some of this arsenic has been previously released and then adsorbed to surfaces of the mineral crystals and other small particles during earlier oxidizing conditions. This surface-adsorbed arsenic, the most chemically available form, is released to groundwater under reducing conditions (Erickson and Barnes 2005a; Nicholas and others, 2011; Thomas, 2007).

Manganese

The Minnesota Department of Health (MDH) Health Risk Limit (HRL) established for infants is 100 ppb; the standard for adults is 300 ppb.

A large proportion of groundwater samples (84 of 109 samples (79 percent)) contained manganese concentrations that exceeded 100 ppb. There were 52 of the 109 samples (48 percent) that exceeded 300 ppb. This indicates a natural water quality concern for most of the well owners in the county.

- All of the mapped aquifers had at least one water sample that exceeded 100 ppb.
- The sample group for the bedrock aquifers had the lowest percentage of samples that exceeded 100 ppb (54 percent).
- All samples from six of the aquifers had manganese values greater than 100 ppb (100 percent). These aquifers have a small number of samples, so this percentage may not accurately represent the aquifer as a whole.

A notable trend is present when the average manganese value (ppb) is considered.

- Stratigraphically higher sand and gravel deposits associated with the till sourced from northwest of Minnesota (Riding Mountain) had water samples with average manganese concentrations of 300–400 ppb.
- Water samples associated with tills sourced from north-northwest of Minnesota (Winnipeg) had average concentrations up to approximately 650 ppb.
- Water samples from bedrock had average manganese concentrations of 100–200 ppb. These concentrations are lower than water samples from the buried sand and gravel aquifers.

> **HRL (MDH)**: Health risk limit: the concentration of a groundwater contaminant, or a mixture of contaminants, that can be consumed with little or no risk to health and has been promulgated under rule.

Table 1. Summary of arsenic and manganese data

[-- indicates no data.]

Aquifer	Arsenic						Manganese					
	Number of Samples	Samples > 5 ppb	Samples ≥ 10 ppb	Minimum Value	Median Value	Maximum Value	Number of Samples	Samples > 100 ppb	Samples > 300 ppb	Minimum Value	Mean Value	Maximum Value
Surficial sand and gravel (ss)	1	0	0	--	1.9	--	1	1	1	--	790	--
Buried sand and gravel												
sh	1	0	0	--	3.4	--	1	1	1	--	461	--
sm	8	5	2	0.3	8.5	27.7	8	7	5	55	371	690
st	5	1	0	Tr	0.8	6.05	7	6	6	46	423	720
sb	1	1	0	--	8.5	--	1	1	0	--	254	--
sg1	27	14	7	Tr	5.66	27	30	28	20	70	622	1410
sg2	11	2	2	Tr	1.75	19.3	10	8	7	24	650	1815
sge	7	1	1	Tr	4.1	11.5	8	8	6	189	659	1667
unnamed	4	2	2	1.16	10.4	21	4	4	2	191	462	900
Buried sand and gravel totals	*64*	*26*	*14*	*Tr*	*4.1*	*27.7*	*69*	*63*	*47*	*24*	*564*	*1815*
Bedrock												
Mt. Simon	7	4	2	0.38	5.4	44.2	8	6	1	45	198	720
Other bedrock	25	1	0	Tr	0.29	7.7	29	14	3	1	140	860
Bedrock totals	*32*	*5*	*2*	*Tr*	*0.45*	*44.2*	*37*	*20*	*4*	*1*	*153*	*860*
Surface water	3	1	0	Tr	Tr	7.4	3	1	0	1	55	150
Total	**99**	**31**	**16**	**Tr**	**2.02**	**44.2**	**109**	**84**	**52**	--	--	--

Hydrogeologic cross sections - Plate 8

Six hydrogeologic cross sections (Plate 8) illustrate the horizontal and vertical extent of aquifers and aquitards, groundwater residence time, and general directions of groundwater flow. These were selected from a set of 35 regularly spaced, west-to-east cross sections created by the MGS, to display the higher density sections of chemistry data and a variety of recharge examples. These were constructed using a combination of well data from the County Well Index and the following sections of this atlas: the bedrock geology map (Part A, Plate 2), surficial geology map (Part A, Plate 3), and Quaternary stratigraphy plate (Part A, Plate 4). The well information for each cross section was from distances no greater than one-half kilometer. Residence time may have been projected from farther distances (up to 3 kilometers) if no data existed on the cross section.

Relative hydraulic conductivity

Hydraulic conductivity is a function of the porosity (volume of pores) and permeability (connectedness of pores) of a sediment or rock layer. Percent sand content in the glacial sediment matrix is a proxy for permeability because coarse grains typically add permeability to sediment. Glacial aquitards with a higher sand content are assumed to have a higher hydraulic conductivity than aquitards with lower sand content. This assumption does not account for the occurrence of larger clasts (pebbles, cobble, and boulders), the potential for fine sediment to fill pore spaces, or fractures in the shallow till units.

Glacial sediment layers that act as aquitards (till units) are shown in shades of gray on Plate 8. Lighter shades indicate aquitards with higher relative hydraulic conductivity, while the darker shades represent aquitards with lower relative hydraulic conductivity.

The percent sand in each of the aquitards is based on the average matrix texture of each till (Part A, Plate 4, Table 1). Till et (Figure 4) has two different sand percentages in Part A. The lower value (33 percent) is more representative in Nicollet County (Gary Meyer, verbal communication, March 2015).

Groundwater flow direction

Groundwater moves from areas with higher potential energy to areas with lower potential energy. The direction of groundwater movement is interpreted from the *equipotential contours* constructed from measured water levels in wells (Plate 8). These contours can be used to identify the groundwater flow direction, recharge zones, and discharge zones. The equipotential contours and flow arrows show that groundwater flow in Nicollet County is initially downward, then laterally toward the Minnesota River along the southern and eastern borders of the county. Large focused groundwater recharge zones are not common because of the low permeability glacial sediment at the land surface and generally level topography. Smaller focused groundwater recharge areas are identified in the following section where aquifers are interconnected and where tritium, chloride, or nitrate is elevated, indicating rapid recharge from the land surface (Plate 7 and 8).

Recharge interpretations

Most of Nicollet County has fine-grained glacial sediment at the land surface with relatively low permeability that limits groundwater recharge. A few areas are underlain by a relatively thick surficial sand and gravel aquifer or a stacked sequence of sand and gravel aquifers. These areas act as focused groundwater recharge zones and are shown on cross sections B–B′, C–C′, D–D′, and F–F′.

Recent or mixed tritium-age groundwater is found at depths greater than 100 feet in the subsurface in all of these zones. Examples of the specific types of recharge can be seen on the accompanying cross sections with recent or mixed tritium-age samples.

1. Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.

Water moving from the surface to shallow, relatively isolated occurrences of the surficial sand and gravel aquifer (ss) are interpreted as recharge areas where they have recent or mixed tritium ages. However, because the ss aquifer is generally not used as a water supply, limited chemistry data are available. One example of recharge to the ss aquifer is in the Minnesota River valley (western edge of D–D′).

2. Groundwater moves from an overlying surficial aquifer to a buried aquifer.

Groundwater moving from the ss aquifer to a buried sand and gravel aquifer is indicated by deeper occurrences of tritium. One example is shown on the west side of F–F′ near North Mankato, where the Jordan aquifer is being recharged by the overlying ss aquifer. This type of recharge is also shown on the eastern edge of C–C′ and D–D′, where a relatively thick coarse-grained terrace deposit near St. Peter permits groundwater to recharge underlying aquifers.

③ Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.

Groundwater moving from overlying buried aquifers to an underlying buried aquifer is interpreted in many places. An example is shown on the eastern side of cross section B–B′ where there is a series of stacked sand and gravel aquifers. This area is designated with high sensitivity because a water sample had a recent tritium age from a 250-foot deep well at the base of the stacked sand and gravel aquifers 3 kilometers north of the cross section. Another example is on the eastern end of C–C′ in the Minnesota River valley, just north of St. Peter, where the Jordan aquifer is being recharged by overlying aquifer units.

Ⓛ Groundwater flows laterally.

Predominantly lateral groundwater flow is found in multiple locations. In the northwestern part of the county there is an indication of lateral flow to the south from overlying aquifers to the sm aquifer (west end of A–A′). There are also indications of lateral flow in the western part of the county near Courtland (western side of D–D′), where water is infiltrating into the eastern edge of aquifer sh and moving laterally toward the Minnesota River.

Ⓤ The source of the recent tritium-age or mixed tritium-age groundwater is unknown.

Carbon-14 data

Carbon-14 samples were collected from 18 wells: 10 for this project and 8 historic samples collected prior to this project. There are 8 samples shown on the Plate 8 cross section; 6 are close to one other carbon-14 sample. Each of these sets of wells shows that carbon-14 age increases with depth:

East central portion of cross section B–B′:

Two samples collected during this study from wells approximately 6 miles apart. The shallower sample was from unmapped sand in unit tt (Figure 4) and had a carbon-14 age of 4,000 years. The deeper sample was from the Upper Tunnel City–Wonewoc aquifer downgradient from the first sample, with a carbon-14 age of 7,000 years.

West central portion of cross section C–C′:

Two samples were collected from wells close to each other by the DNR in 2009 during an investigation of the Mt. Simon aquifer. The shallower sample was from mt (Figure 4) and had a carbon-14 age of 8,000 years. The deeper sample was from the Mt. Simon aquifer with a carbon-14 age of 22,000 years.

West central portion of cross section E–E′:

Two samples were collected from wells close to each other by the DNR in 2009 during the investigation of the Mt. Simon aquifer. The shallower sample was from the sg1 aquifer and had a carbon-14 age of <500 years and also had stable isotope values that indicate there is recharge from surface water, most likely from Swan Lake that is upgradient from the well. The deeper sample was from the Mt. Simon aquifer with a carbon-14 age of 18,000 years.

Additional carbon-14 data samples are shown on the west central portion of cross section B–B′ and F–F′ showing the carbon-14 age of samples at varying depths.

Discharge interpretations

Ⓓ Groundwater discharges to a surface water.

Groundwater discharge to rivers, lakes, and wetlands supply water vital to aquatic ecosystems. Across Nicollet County the water table indicates that there is discharge from the ss aquifer to the lakes, streams, and wetlands. The equipotential lines on the cross sections indicate that all of the buried aquifer units discharge to the portion of the Minnesota River that forms the southern and eastern border of the county.

Pollution sensitivity

Pollution sensitivity maps generated on a county scale are intended to assist citizens and local government in protecting and managing groundwater resources. Pollution sensitivity is defined as the general potential for groundwater to be contaminated owing to the hydrogeologic properties of the material hosting or overlying it. Migration of contaminants dissolved in water through unsaturated and saturated sediment is a complex process that is affected by biological degradation, oxidizing or reducing condition, and other factors. The methods to interpret pollution sensitivity use the following generalizing assumptions:

- Flow paths are vertical and downward from the land surface through the soil and underlying sediment to an aquifer.
- A contaminant is assumed to travel at the same rate as water.
- A contaminant that is dissolved and moving within water from the surface is not chemically or physically altered over time.

Two models are used to estimate the pollution sensitivity, based on the different properties of the materials. The following assumptions apply to a specific model.

- **Near-surface sensitivity**: sediment texture is the primary property used to create a sensitivity map. The permeability of the sediment matrix texture is estimated based on hydrologic theory or empirical data to establish a downward flow rate. The rate multiplied by the vertical travel distance equals the estimate of the vertical travel time.
- **Buried aquifer sensitivity**: sediment above and between buried sand and gravel aquifers are fine grained with low hydraulic conductivity. The method only considers the cumulative thickness of fine-grained sediment overlying aquifers. It does not consider differences in sediment texture or permeability of nonaquifer materials.

Near-surface sensitivity

Methods

The sensitivity to pollution of near-surface materials is an estimate of the time of travel through the unsaturated zone to reach the water table, which is assumed to be 10 feet below land surface. The first 3 feet (0–3 feet) are assumed to be soil and the next 7 feet (3–10 feet) are assumed to be surficial geological material. If there is no soil data the transmission rate is based on 10 feet of the surficial geologic unit.

The transmission rate of a soil or surficial geologic unit will vary depending on the texture. The two primary inputs used to estimate transmission rate are the hydrologic soil group and the surficial geologic matrix texture. In general, coarse-grained materials have faster transmission rates than fine-grained materials. In this approach, attributes of the hydrologic soil group and surficial geologic matrix texture are both used to estimate the time of travel (Table 2) (USDA-NRCS, 2011; Part A, Plate 4). Further details of how the near-surface pollution sensitivity map was created are available in *Methods to Estimate Near-Surface Pollution Sensitivity* (DNR, 2016b).

The time of travel through the near-surface sediment varies from hours to approximately a year.

- Areas with a relatively short time of travel (hours to a week) are rated as having high sensitivity (Figure 15).
- Areas with a longer travel time of (weeks to a year) are rated low or very low.
- Areas of more than a year are rated ultra low, but are not present in the county.

Results

The near-surface pollution sensitivity map (Figure 16) indicates that the interior areas of the county have low to very low near-surface sensitivity. Moderate to high pollution sensitivity ratings are found throughout the Minnesota River valley along the southern and eastern borders. It is also distributed sporadically through the interior of the county, typically along stream valleys or in regions of buried stream sediment. Some small areas in the Minnesota River valley have a very low near-surface sensitivity rating where relatively impervious crystalline bedrock is exposed at the land surface.

Table 2. Transmission rates used to assess the pollution sensitivity rating of the near-surface materials

Hydrologic Soil Group (0–3 feet)		Surficial Geologic Texture (3–10 feet)		
Group*	**Transmission rate (in/hr)**	**Classification**	**Transmission rate (in/hr)**	**Surficial geology map unit (Plate 3)**
A, A/D	1	gravel, sandy gravel, silty gravel	1	Qat1, Qat2, Qat3, Qat4, Qat5, Qhb, Qs, Qsb, Qsc
		sand, silty sand	0.71	Not present in county
B, B/D	0.50	silt, loamy sand, units with eolian sand designation	0.50	Qa
		sandy loam	0.28	Qf
--	--	loess (Peoria)	0.218	Not present in county
C, C/D	0.075	silt loam, loam	0.075	Qtw, Qc, Qtm, Qtc, Qth, Qil, Qt, Qts
		sandy clay loam	0.035	Not present in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Qhl
--	--	glacial lake sediments of lakes Agassiz and Duluth	0.000011	Not present in county

*The Natural Resources Conservation Service (NRCS) defines hydrologic soil groups primarily based on texture and the occurrence of low permeability layers (USDA-NRCS, 2009):

Group A: water is freely transmitted. Soils are more than 90 percent sand and gravel.

Group B: soils are less permeable but water transmission is still unimpeded.

Group C: water transmission is somewhat restricted.

Group D: water movement is restricted or very restricted.

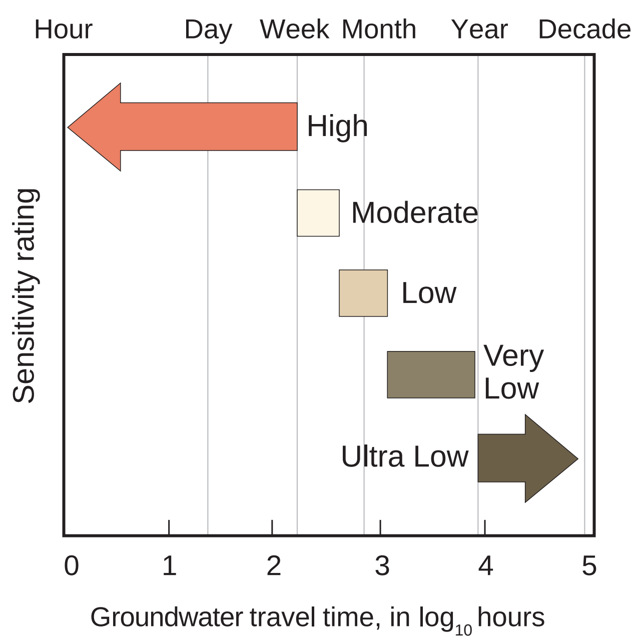


Figure 15. Geologic sensitivity rating for the near-surface materials

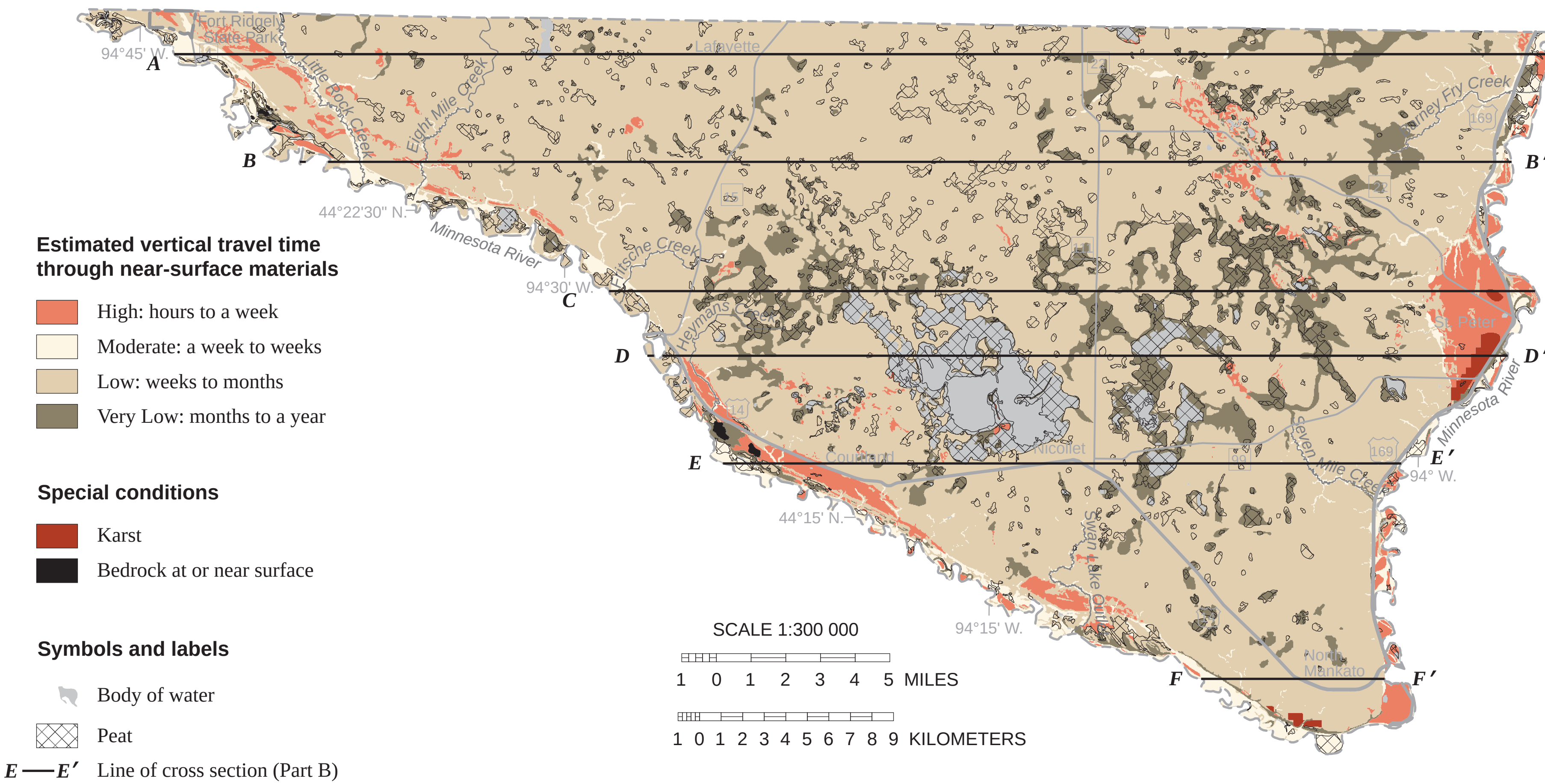


Figure 16. Near-surface pollution sensitivity

Low to very low pollution sensitivity ratings are common throughout most of the county. The exception is in river and stream valleys, which are primarily found along the southern and eastern border of the county (Minnesota River valley). Peat deposits from the Part A surficial geology map (Plate 3) are shown as an overlay on this map. The peat is not included in the travel-time estimate for the surficial geology across the county due to its unknown thickness. Map modified from the Minnesota Hydrogeology Atlas HG-02.

Buried sand and gravel aquifer and bedrock surface sensitivity

Methods

The sensitivity rating for the buried sand and gravel aquifers and the bedrock surface are based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). The travel time varies from days to thousands of years.

- Areas with relatively short travel times of less than a few years are rated high or very high.
- Areas with estimated travel times of decades or longer are rated low or very low.

The DNR developed a method using geographic information systems (GIS) for mapping pollution sensitivity of buried sand aquifers and the bedrock surface based on a simplified two-dimensional model.

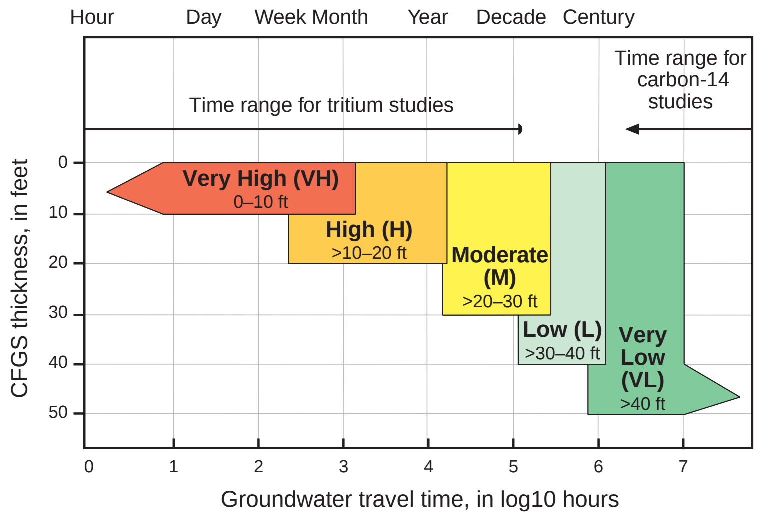


Figure 17. Geologic sensitivity rating for the buried sand and gravel aquifers and the bedrock surface

Defined by vertical travel time. Numbers following each rating represent the cumulative fine-grained sediment (CFGS) thickness overlying an aquifer.

The model is a representation of how water from precipitation infiltrates the land surface and recharges portions of deeper aquifers. The central concept of this process is focused (relatively rapid) recharge. Portions of the aquifers overlap and are connected by complex pathways that can allow surface water to penetrate into even the deepest aquifers.

The model assumes the thickness of fine-grained sediment overlying an aquifer is inversely proportional to the sensitivity of an aquifer (Figure 18). The thicker the fine-grained sediment overlying an aquifer, the longer it will take for water to move through it. GIS software is used to calculate a cumulative thickness of these sediment layers. Thicknesses of 10 feet or less are rated very high sensitivity, thicknesses greater than 40 feet are rated very low, and intermediate thicknesses have intermediate sensitivity ratings. Thicknesses are modified from discussion of fine-grained layers in *Criteria and Guidelines for Assessing Geologic Sensitivity of Ground Water Resources in Minnesota* (Geologic Sensitivity Workgroup, 1991) (Figure 17). A more detailed explanation is available in *Buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment (CFGS) thickness* (DNR, 2016c).

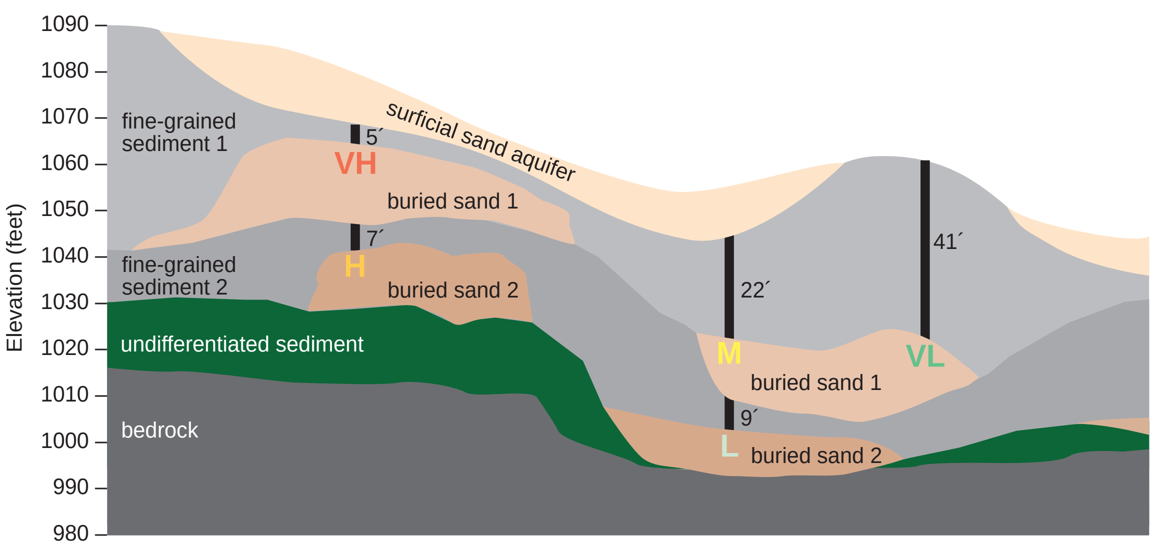


Figure 18. Cross section showing examples of pollution sensitivity ratings

Based on the cumulative thickness of overlying fine-grained sediment. Each of the vertical black lines in the figure is labeled with the thickness of fine-grained sediment. The letter at the base of the line indicates the sensitivity rating determined from the cumulative thickness.

Results

The following discussion of the aquifers is in stratigraphic order from the shallowest to the deepest. The model results described in the following section include groundwater flow direction derived from potentiometric surfaces to help the user understand the distribution of particular chemical constituents.

sh and sv aquifer (Figure 19)

Depth and thickness: the sh and sv aquifers are mapped jointly. The top of these aquifers is less than 100 feet below the land surface everywhere. Most of the aquifers are less than 50 feet below the land surface (Part A, Plate 5, Figure 3) and vary in thickness from 20 to 120 feet. Because it is such a shallow and nonextensive aquifer, only 12 wells are drilled in this aquifer across the county.

- Sensitivity: moderate to very high conditions are common.
- Chemistry: one sample from the sh aquifer
  Mixed tritium age: lateral flow from Swan Lake westward toward the Minnesota River could be contributing to the mixed tritium age of this sample. An elevated chloride concentration of 17.6 ppm is most likely due to the shallow depth of the aquifer.

sm aquifer (Figure 20)

- Depth and thickness: varies from relatively shallow (0 to 50 feet) to moderate (150 to 200 feet) depths below the land surface, with thicknesses that vary from 20 to 120 feet (Part A, Plate 5, Figure 4).
- Sensitivity: typically very low pollution sensitivity. Some high sensitivity ratings are found within river valleys (primarily in the Minnesota River valley) as well as in regions where the sm aquifer is overlain by thick deposits of the sv aquifer (e.g., northeast section of the county).
- Chemistry: eight samples
  Recent tritium age: one sample was from a well northwest of St. Peter near Annexstad Lake. The sample had an elevated chloride concentration, and also an evaporative stable isotope signature. Even though this is located in an area of low pollution sensitivity, the sample was collected downgradient from a high sensitivity area. The recent tritium age is most likely the result of downward migration of water from Annexstad Lake through the thick stack of the sh and sv aquifers that overlie the sm aquifer in this region.
  Mixed tritium age: three samples were collected in two different areas, in the northwestern corner of the county and in the west-central portion of the county northwest of Courtland. Both areas have low sensitivity ratings. The sample in the northwestern corner is most likely a result of lateral flow of water from the stream valley north and east of the wells moving toward the Minnesota River valley. The sample northwest of Courtland is most likely due to lateral flow of water from the Swan Lake area toward the Minnesota River valley.
  Vintage tritium age: four samples were collected from very low sensitivity areas of the county.

st aquifer (Figure 21)

- Depth and thickness: primarily 100 to 200 feet below the land surface, typically 20 to 60 feet thick (Part A, Plate 5, Figure 5).
- Sensitivity: very low sensitivity across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface, and in the northeastern portion of the county where there is a series of stacked aquifers.
- Chemistry: five samples
  Recent tritium age: one sample was from a well north of Courtland with an elevated chloride concentration. The recent tritium-age sample is most likely recharged from the overlying sh aquifer in an area of moderate sensitivity.
  Mixed tritium age: two samples were from the west-central part of the county. One was within a section of moderate sensitivity and is likely being recharged from the overlying sand layers as water flows toward the Minnesota River. The other was collected from a well to the east of the recent tritium-age sample and also has an elevated chloride concentration. This sample is being recharged from a moderate to low sensitivity area to the west. Flow in this region is eastward (away from the Minnesota River valley) due to a high area in the relatively impermeable crystalline bedrock that causes a high area in the buried sand and gravel potentiometric surfaces.
  Vintage tritium age: two samples were collected in the western part of the county in areas with very low pollution sensitivity. In these areas the depth to the aquifer is greater than 100 feet.

sg1 aquifer (Figure 22)

- Depth and thickness: 150 to 250 feet below the land surface, varies from 20 to 120 feet thick (Part A, Plate 5, Figure 6).
- Sensitivity: very low pollution sensitivity rating across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface.
- Chemistry: 27 samples
  Recent tritium age: one sample was from a well in the northeastern portion of the county. The recent tritium age is most likely due to the series of stacked aquifers overlying the aquifer at this location.

Mixed tritium age: one sample was from a well south of Swan Lake, and is most likely due to vertical recharge of water through a series of stacked aquifers overlying the aquifer in this area.

Vintage tritium age: 25 samples were collected in areas with a very low pollution sensitivity rating. Elevated chloride concentrations, with chloride to bromide ratios less than 300, were found in six vintage tritium-age samples as well as one sample that did not have a tritium value. The elevated chloride in these samples may be the result of deep source brine southwest of Lafayette. Four samples in this aquifer had carbon-14 ages varying from <500 to 22,000 years. The <500 year carbon-14 sample also had an evaporative signature showing that there is surface-water recharge to the aquifer near Nicollet.

sg2 aquifer (Figure 23)

- Depth and thickness: 150 to 300 feet below the land surface, typically 20 to 60 feet thick (Part A, Plate 5, Figure 7). However, in the north-central part of the county and a small area near Nicollet, the aquifer can be up to 120 feet thick.
- Sensitivity: very low sensitivity across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface.
- Chemistry: 11 samples.
  Vintage tritium age: all of the samples have vintage tritium ages, consistent with their location in areas with a very low pollution sensitivity rating. There is one sample with an elevated chloride concentration; it did not have an anthropogenic signature. Carbon-14 samples from two wells show the age of the samples is 2,300 and 4,000 years.

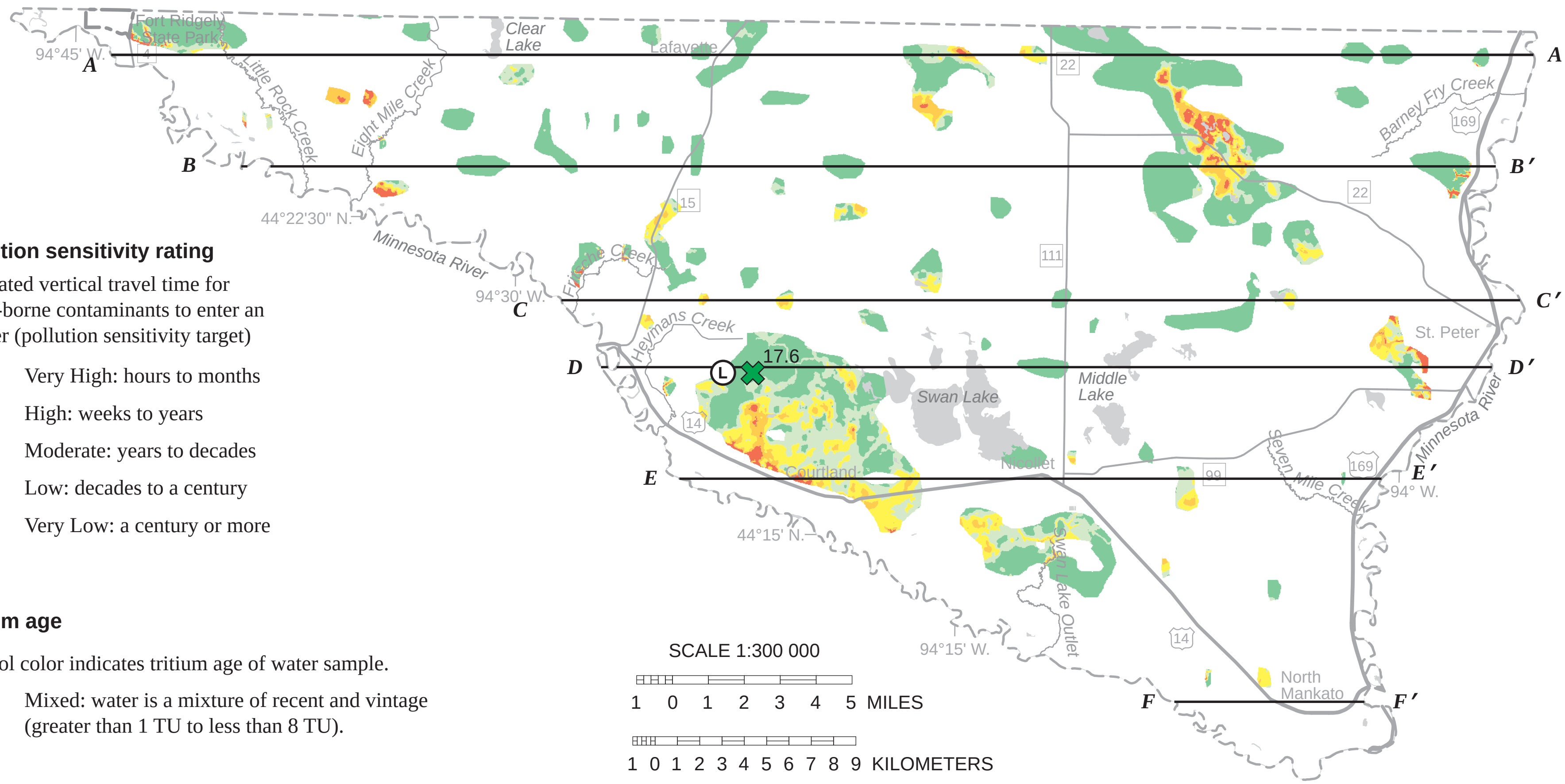
sge aquifer (Figure 24)

- Depth and thickness: 100 to 300 feet below the land surface, typically 20 to 100 feet thick (Part A, Plate 5, Figure 8).
- Sensitivity: very low sensitivity across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface.
- Chemistry: seven samples.
  Cold War era tritium age: one sample was collected with an elevated chloride concentration indicating an anthropogenic water source. The sampled well is located in the Minnesota River valley under a series of stacked aquifers, with recharge and lateral migration of water toward the Minnesota River valley as the likely source of the recharge water.
  Mixed tritium age: two samples were collected in areas with a very low pollution sensitivity rating. One was located in the northwest corner of the county. This well is recharged through the lateral flow of water toward the Minnesota River. The other sample was collected from a well in the west-central region of the county. The source of tritium in this well is unknown, though it should be noted that the tritium value was 1.2 TU, which is barely above the threshold for classifying the water as vintage tritium age. Both of these samples had elevated chloride concentrations with a high chloride to bromide ratio indicating an anthropogenic water source.
  Vintage tritium age: four samples were collected in areas of very low pollution sensitivity; two of the samples had an elevated chloride concentration without an anthropogenic signature.

Bedrock surface (Figure 25)

- Depth: 50 to 450 feet below the land surface (Part A, Plate 6).
- Sensitivity: largely rated as very low across the county, except near the Minnesota River valley.
- Chemistry: 32 water chemistry samples were collected from wells completed in bedrock aquifers.

  Recent tritium age: one sample was collected from a well in the Jordan aquifer in the southern part of the county. This sample had an elevated chloride concentration and was collected in an area of moderate pollution sensitivity in the Minnesota River valley where the bedrock surface is closer to the land surface.
  Mixed tritium age: three samples were collected in or near the Minnesota River valley where the bedrock surface is closer to the land surface. Two of the wells were completed in the Jordan aquifer, and the third well was completed in an undetermined bedrock unit. All of the samples had elevated chloride concentrations indicating an anthropogenic water source.
  Vintage tritium age: 28 samples were collected, 26 of which were constructed in areas with very low pollution sensitivity ratings. The remaining two samples were constructed in areas with a moderate to high pollution sensitivity rating along the southern border in the Minnesota River valley, where the wells were drilled into deeper bedrock aquifers that were protected by overlying geologic units. Ten carbon-14 samples were collected from bedrock aquifer wells, indicating that the water varies in age from <500–31,000 years.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed: water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).

Groundwater conditions

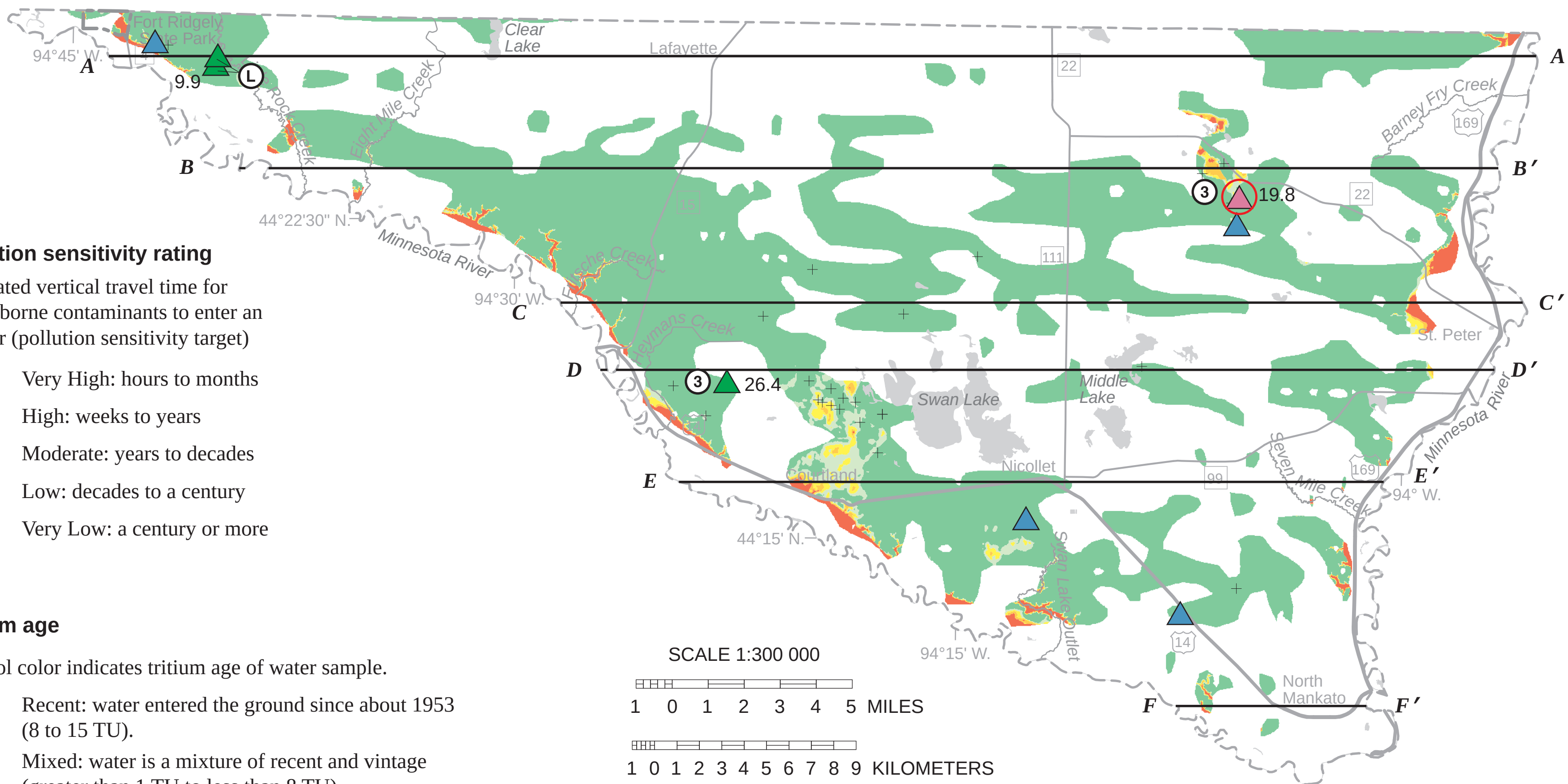
- (L) Groundwater flows laterally.

Symbols and labels

- 17.6 If shown, chloride concentration equals or exceeds 5 parts per million.
- Body of water
- B—B′ Line of cross section (Part B)

Figure 19. Pollution sensitivity of the buried sand and gravel aquifers sh and sv

The sh and sv aquifers are generally shallow (less than 50 feet), commonly exhibit moderate to very high sensitivity, and are not usually used for water supply purposes.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Recent: water entered the ground since about 1953 (8 to 15 TU).
- Mixed: water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).

Groundwater conditions

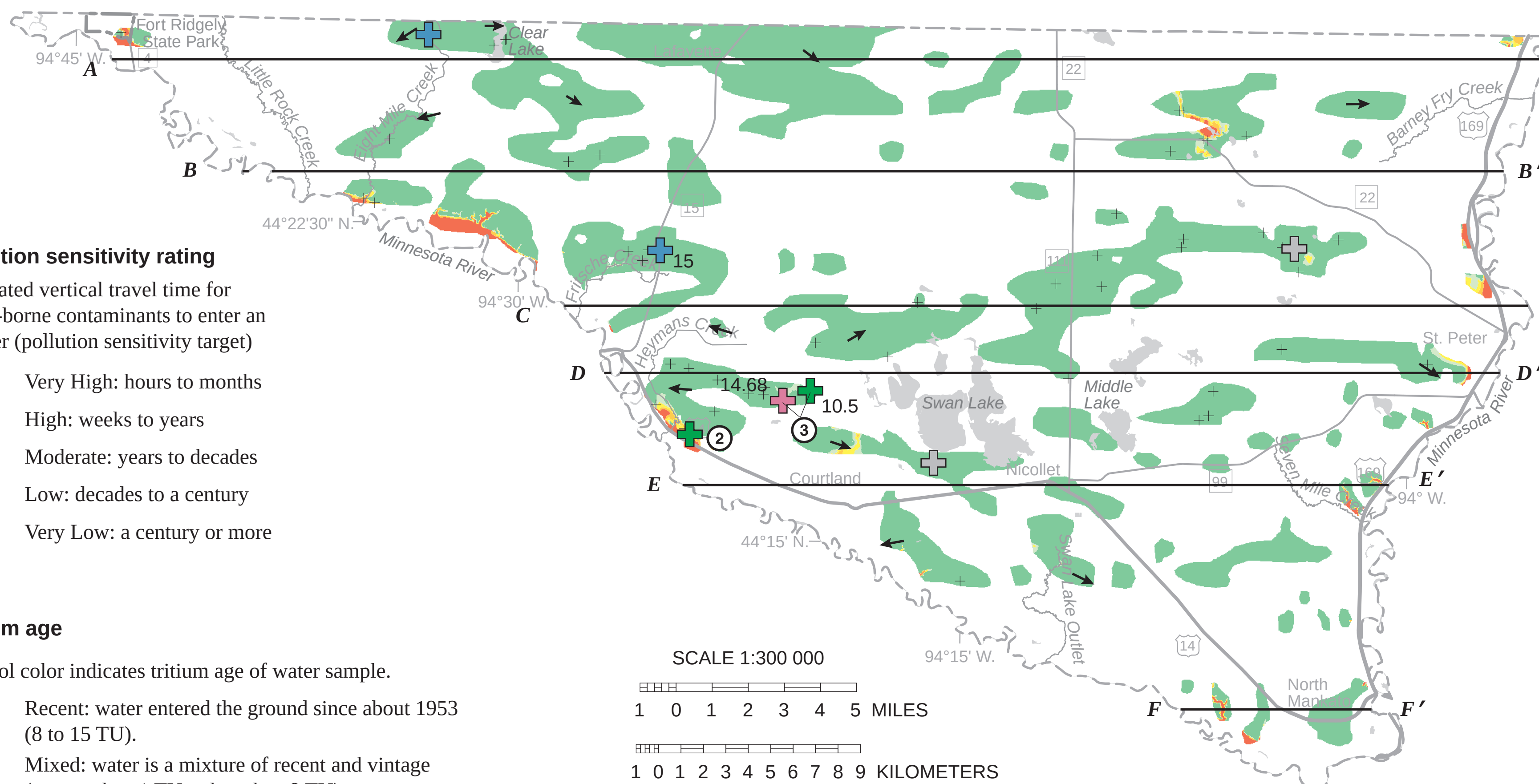
- 3 Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- L Groundwater flows laterally.

Symbols and labels

- 19.8 If shown, chloride concentration equals or exceeds 5 parts per million.
- \+ Static water level data
- Stable isotope evaporative signature
- Body of water

Figure 20. Pollution sensitivity of the buried sand and gravel aquifer sm

The sm aquifer typically has a very low pollution sensitivity rating except for shallower occurrences in the river valleys as well as in the northeast part of the county where there is a thick deposit of aquifer sv overlying the aquifer.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Recent: water entered the ground since about 1953 (8 to 15 TU).
- Mixed: water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).
- Not sampled for tritium.

Groundwater conditions

2 Groundwater moves from an overlying surficial aquifer to a buried aquifer.

3 Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.

Symbols and labels

10.5 If shown, chloride concentration equals or exceeds 5 parts per million.

\+ Static water level data

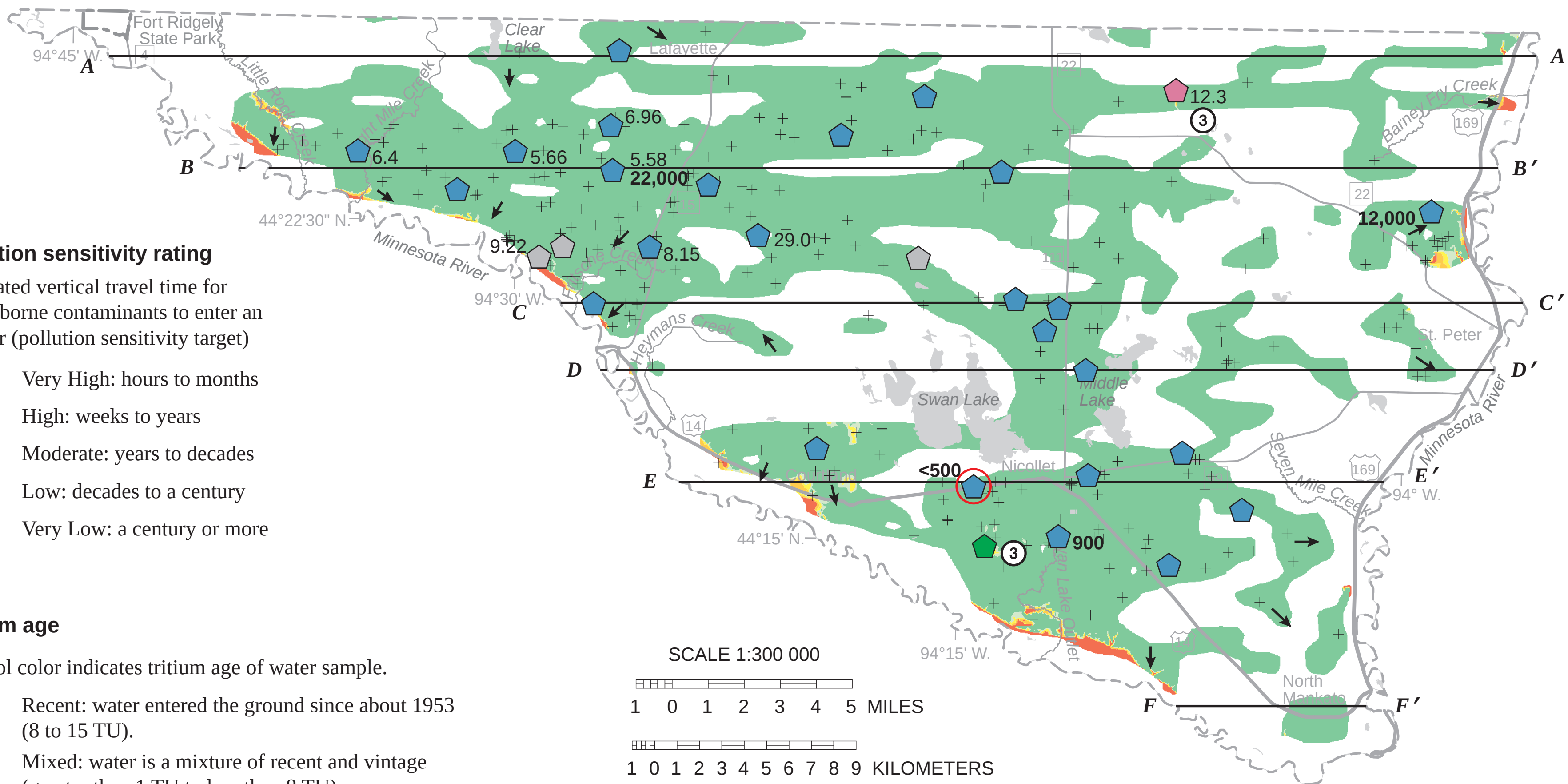
Body of water

← Groundwater flow direction

B—B′ Line of cross section (Part B)

Figure 21. Pollution sensitivity of the buried sand and gravel aquifer st

The st aquifer typically has a very low pollution sensitivity rating, except for shallower occurrences in the river valleys and the northeast part of the county where there are thick deposits of the overlying aquifers.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Recent: water entered the ground since about 1953 (8 to 15 TU).
- Mixed: water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).
- Not sampled for tritium.

Groundwater conditions

3 Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.

Symbols and labels

12.3 If shown, chloride concentration equals or exceeds 5 parts per million.

900 If shown, groundwater residence time in years estimated by carbon-14 (^{14}C) isotope analysis

\+ Static water level data

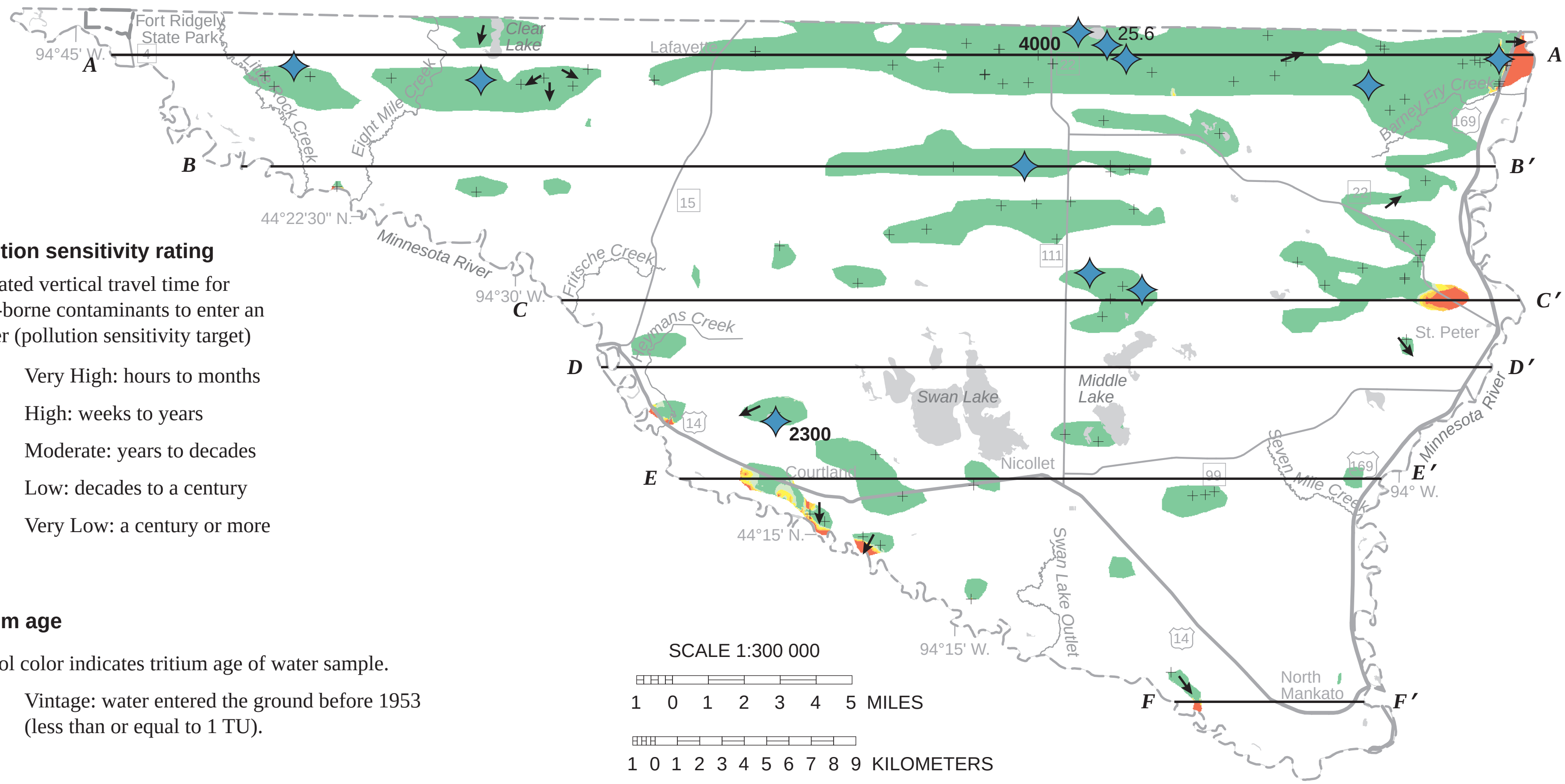
Body of water

Stable isotope evaporative signature

← Groundwater flow direction

Figure 22. Pollution sensitivity of the buried sand and gravel aquifer sg1

The sg1 aquifer typically has a very low pollution sensitivity rating, except for shallower occurrences in the river valleys and a small section in the northeast part of the county where there are thick deposits of overlying aquifers.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).

Symbols and labels

25.6	If shown, chloride concentration equals or exceeds 5 parts per million.
2300	If shown, groundwater residence time in years estimated by carbon-14 (^{14}C) isotope analysis
+	Static water level data
	Body of water
←	Groundwater flow direction
B——B′	Line of cross section (Part B)

Figure 23. Pollution sensitivity of the buried sand and gravel aquifer sg2

The sg2 aquifer typically has a very low pollution sensitivity rating, except for in the Minnesota River valley where the top of the aquifer is closer to the land surface.

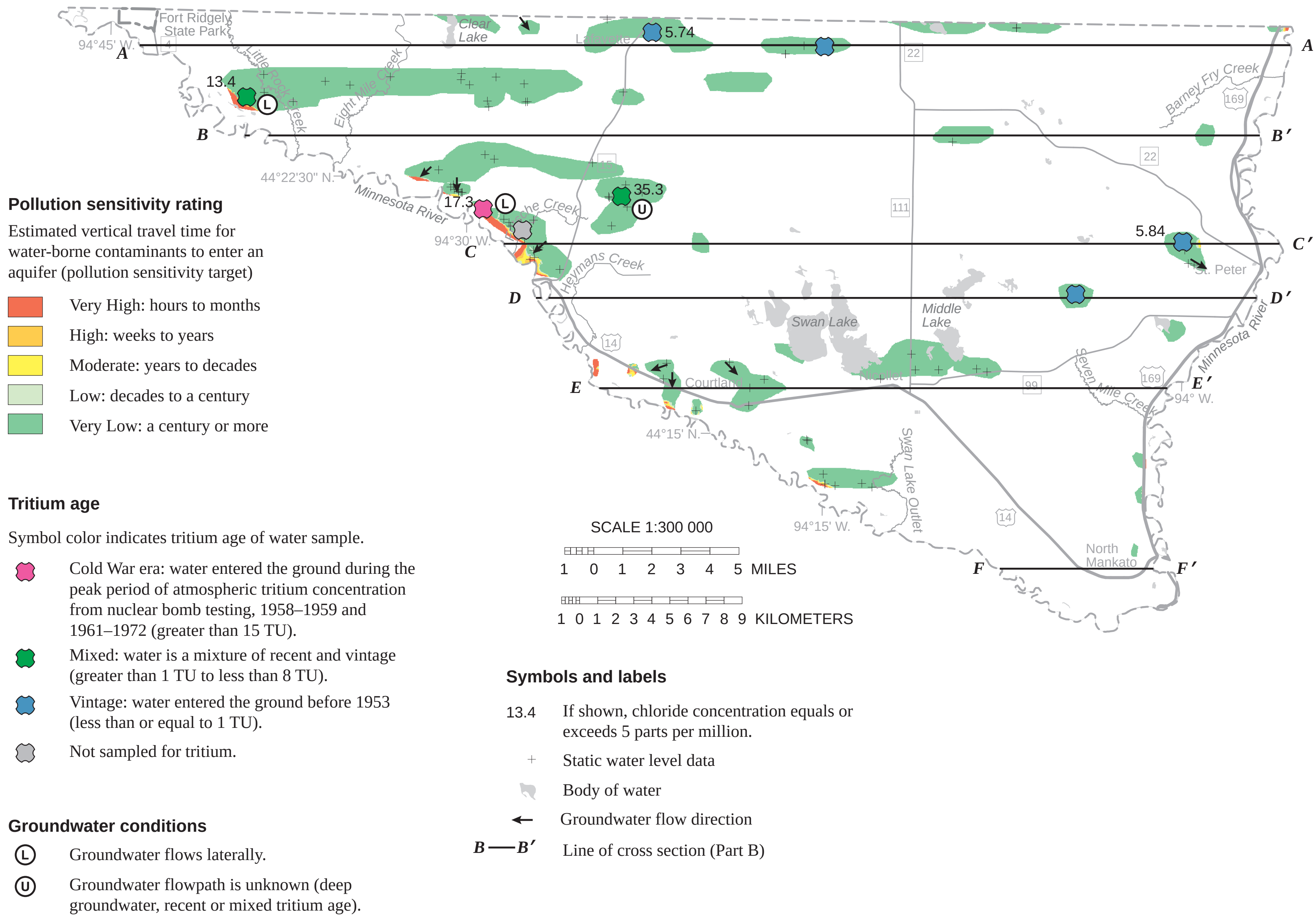
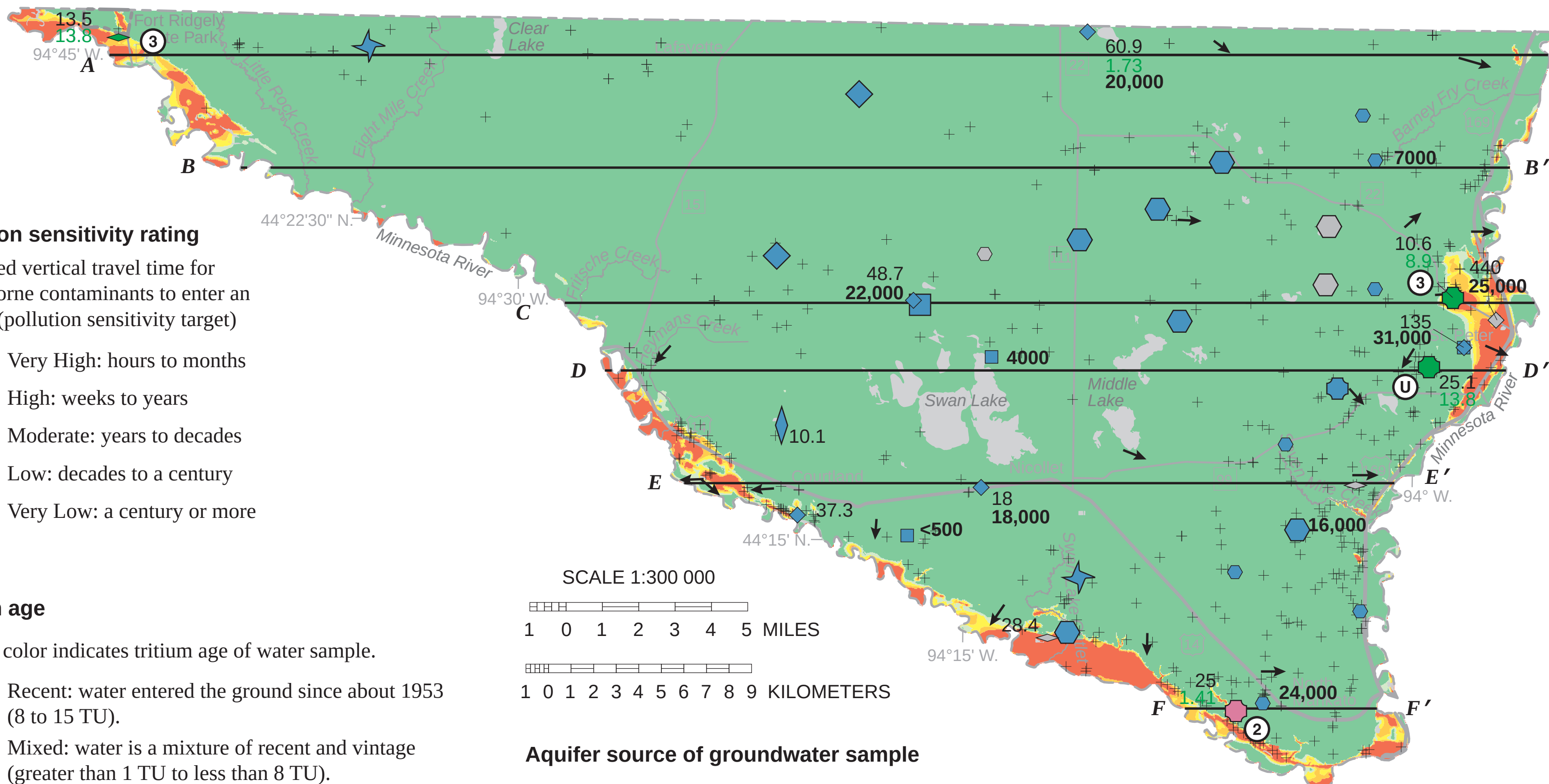


Figure 24. Pollution sensitivity of the buried sand and gravel aquifer sge

The sge aquifer typically has a very low pollution sensitivity rating, except for in the Minnesota River valley where the top of the aquifer is closer to the land surface.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

- Recent: water entered the ground since about 1953 (8 to 15 TU).
- Mixed: water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).
- Not sampled for tritium.

Groundwater conditions

- 2 Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- 3 Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- U Groundwater flowpath is unknown (deep groundwater, recent or mixed tritium age).

SCALE 1:300 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 6 7 8 9 KILOMETERS

Aquifer source of groundwater sample

- Jordan
- St. Lawrence, Upper Tunnel City, Upper Tunnel City–Wonewoc, Upper Tunnel City–Eau Claire
- Wonewoc, Wonewoc–Eau Claire
- Mt. Simon, Mt. Simon–Hinckley, Mt. Simon–Fond du Lac
- Cretaceous undifferentiated
- Sioux Quartzite
- Multiple, indeterminate

Large symbols: samples from the shallow bedrock aquifers
Small symbols: samples from the underlying bedrock aquifer

Symbols and labels

- 10.1 If shown, chloride concentration equals or exceeds 5 parts per million.
- 8.9 If shown, nitrate-nitrogen concentration equals or exceeds 1 part per million.
- **4000** If shown, groundwater residence time in years estimated by carbon-14 (^{14}C) isotope analysis
- \+ Static water level data
- Body of water
- ← Groundwater flow direction
- *B*—*B′* Line of cross section (Part B)

Figure 25. Pollution sensitivity of the bedrock surface

The pollution sensitivity of the bedrock surface is typically very low, except in the Minnesota River valley where the bedrock is closer to the land surface and is overlain by sand and gravel deposits.

Groundwater use and aquifer characteristics

For this study 1,216 wells in Nicollet County were assigned an aquifer unit based on the well aquifer information and the geology presented in Part A. Of these wells, 52 percent draw groundwater from buried sand and gravel aquifers, 44 percent draw from bedrock aquifers, and 4 percent draw from unknown units.

Groundwater use

A water-use appropriation permit from the DNR is required for all groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year. This provides the DNR with the ability to assess and regulate which aquifers are being used and for what purpose. DNR water appropriation permits require that the water usage be reported annually. Information pertaining to these permits is recorded using Minnesota Department of Natural Resources Permitting and Reporting System (MPARS). This helps the DNR track the volume, source aquifer, and type of water use.

The reported groundwater use for 2013 is categorized for all large capacity users in the county by the type of aquifer and type of use (Table 3 and Figure 26). Water-use permits are located primarily near towns, with a few exceptions for wells used for livestock watering in the central portion of the county.

Bedrock aquifers accounted for 75 percent of the water pumped in 2013, with the majority drawing from the Mt. Simon aquifer. Buried sand and gravel aquifers accounted for 16 percent for water supply usage, with over half of these from the sge aquifer. The ss aquifer accounted for only 8 percent of the reported 2013 water usage.

The primary use type in the county is for municipal water supplies, making up 85 percent of the pumped water. Livestock watering and agricultural processing account for 5 to 10 percent of overall pumping, and the remaining uses account for one percent each.

Table 3. Reported 2013 water use from DNR groundwater permit holders

[Data from MPARS; MGY, million gallons per year; dash marks (--) indicate no use in those categories]

Aquifer	Number of wells	Municipal/ public water supply	Livestock watering	Agricultural/ food processing	Agricultural crop irrigation	Landscape/ athletic field irrigation*	Total (MGY)	Total (percent)
Surficial sand and gravel (ss)	6	150.2	--	--	--	--	**150.2**	**8.0**
Buried sand and gravel								
sg1	4	31.1	4.8	4.2	--	--	**40.1**	**2.1**
sg2	3	11.6	4.3	--	--	--	**15.9**	**0.8**
sge	2	225.3	--	--	--	--	**225.3**	**12.0**
suu	1	14.4	--	--	--	--	**14.4**	**0.8**
unnamed	1	12.3	--	--	--	--	**12.3**	**0.7**
Buried sand and gravel total	*11*	*294.7*	*9.1*	*4.2*	--	--	**308.0**	**16.3**
Bedrock								
Jordan	3	87.2	--	--	--	--	**87.2**	**4.6**
St. Lawrence–Upper Tunnel City	1	2.9	--	--	--	--	**2.9**	**0.2**
Upper Tunnel City–Wonewoc	8	48.1	59.5	--	--	5.7	**113.3**	**6.0**
Upper Tunnel City–Eau Claire	3	--	60.5	--	--	--	**60.5**	**3.2**
Upper Tunnel City–Mt. Simon	1	195.8	--	--	--	--	**195.8**	**10.4**
Wonewoc	2	114.3	--	--	--	--	**114.3**	**6.1**
Wonewoc–Mt. Simon	4	125.9	11.8	--	18.4	--	**156.1**	**8.3**
Mt. Simon	5	455.2	--	96.1	--	17.4	**568.7**	**30.2**
Mt. Simon–Hinckley	2	127.8	--	--	--	--	**127.8**	**6.8**
Bedrock total	*29*	*1157.2*	*131.8*	*96.1*	*18.4*	*23.1*	**1426.6**	**75.7**
Total (MGY)	--	**1602.1**	**140.9**	**100.3**	**18.4**	**23.1**	**1884.8**	--
Total (percent)	--	**85.0**	**7.5**	**5.3**	**1.0**	**1.2**	--	--

*Includes golf course irrigation

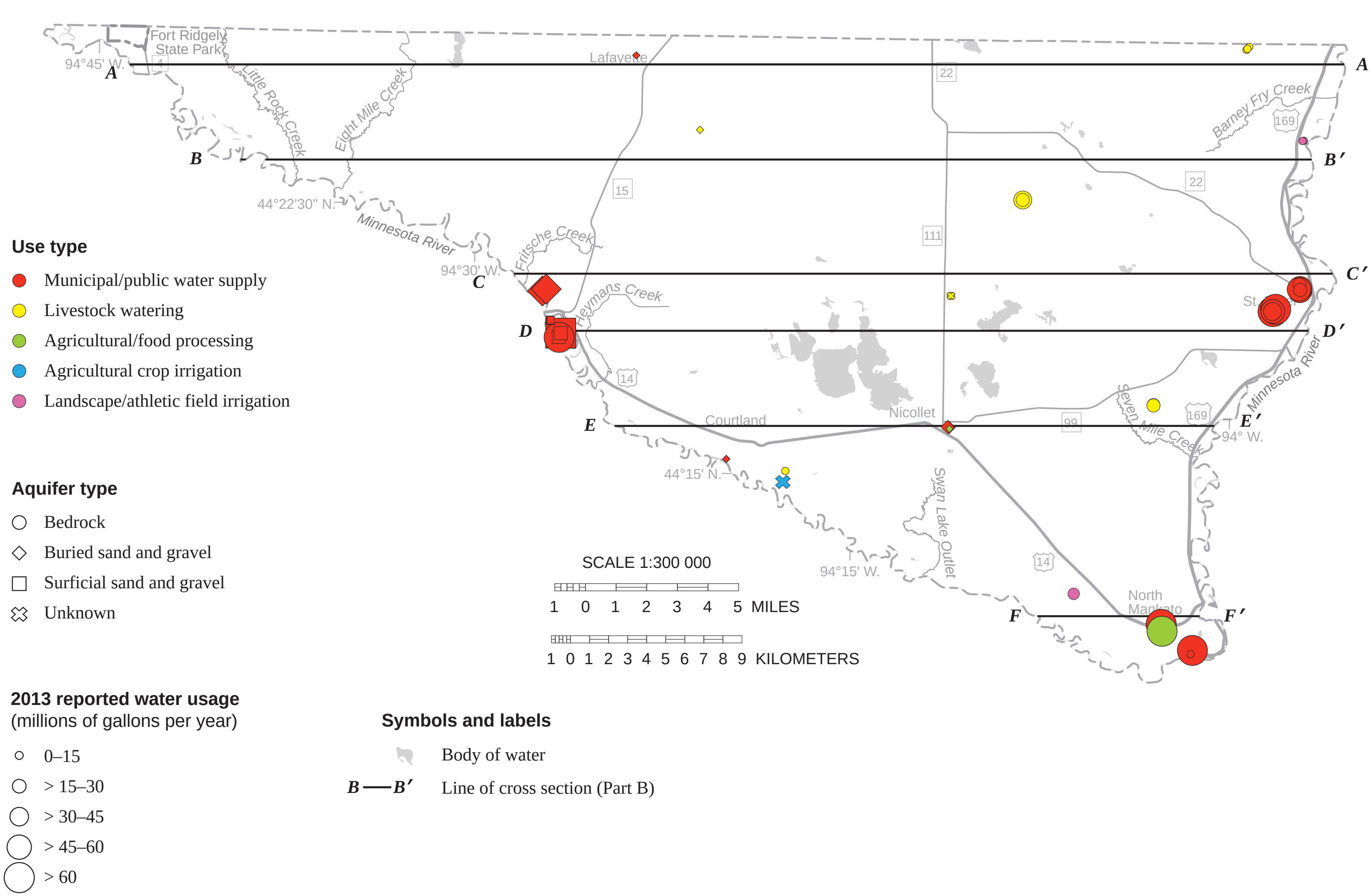


Figure 26. Location of wells with DNR groundwater appropriation permits

Where present, the bedrock aquifers are the primary source of permitted water usage. The primary use type for the permitted water is municipal/public water supply.

Groundwater level monitoring

The DNR maintains a statewide groundwater level monitoring program using observation wells for the following purposes: assessing groundwater resources, determining long term trends, interpreting impacts of pumping and climate, planning for water conservation, evaluating water conflicts, and otherwise managing water resources.

Nicollet County has ten DNR observation wells (Figure 27). Eight were drilled as part of an investigation of the Mt. Simon aquifer by the DNR in 2008–2009 (Berg and Pearson, 2011). The eight wells make up four different paired well nests (group of closely spaced wells) where one well was drilled into the Mt. Simon aquifer and a paired well was drilled into a buried sand and gravel aquifer that overlies the Mt. Simon aquifer.

The other two observation wells are both completed in the Mt. Simon aquifer and have only limited hand measurement data available (one was drilled in 1998, with consistent data collected between 2008–2012, and one was drilled in 2012). Long term trends in the aquifers and the response to precipitation are not identifiable at this time due to the limited amount of time for data collection, the depth of the wells, and in some cases the limited period of record.

Some shorter term trends are discussed in the DNR report on the Mt. Simon aquifer investigation. The report states that there are seasonal fluctuations in the well levels (lower in summer and higher in winter) and that all of the well nests in Nicollet County show that groundwater is flowing downward. These continue to be monitored by the groundwater level monitoring program of the DNR and data are available to be downloaded from the DNR Cooperative Groundwater Monitoring website (DNR, 2015).

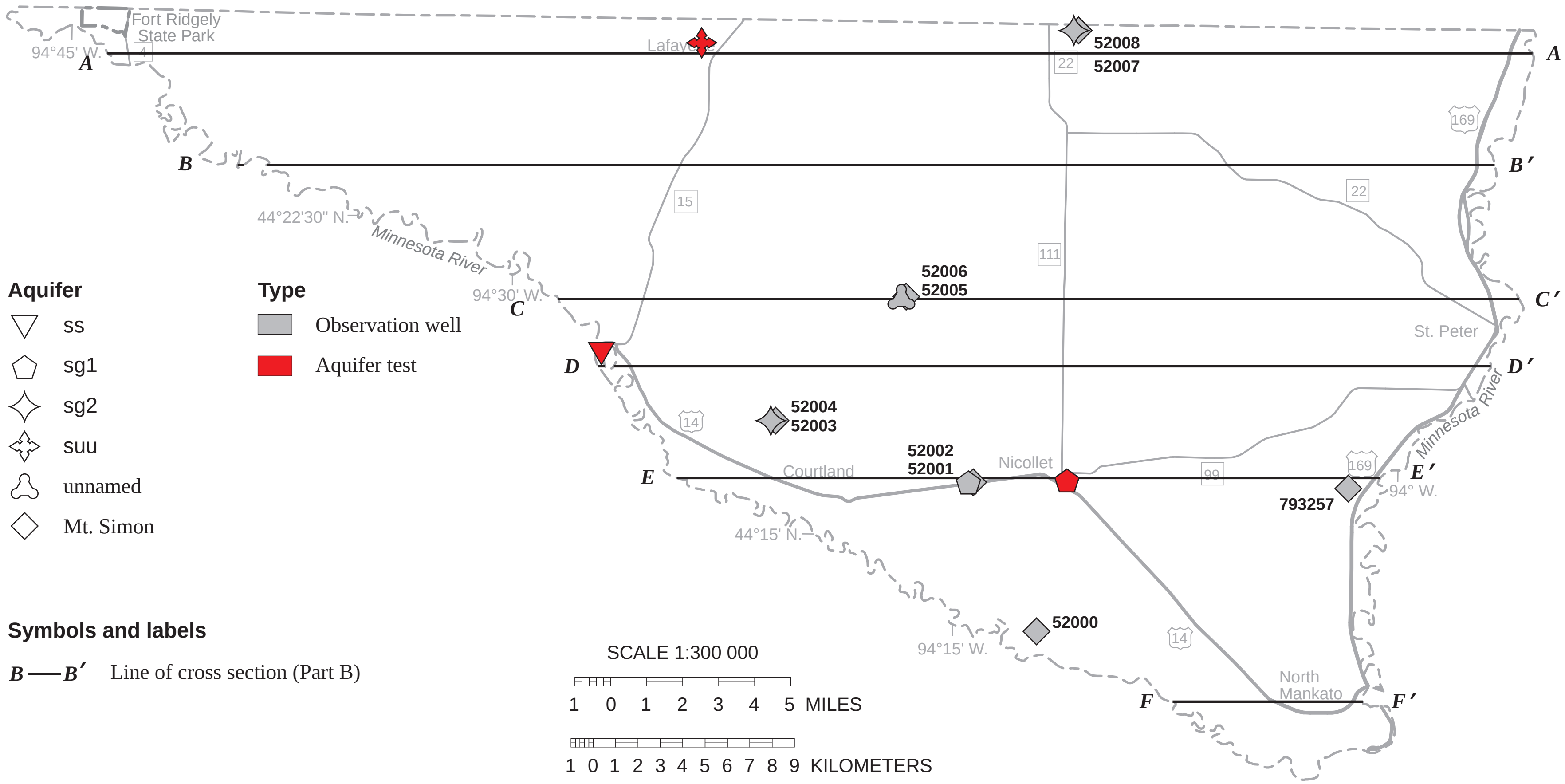


Figure 27. Location of aquifer tests and observation wells

Observation wells are labeled with identification numbers.

Aquifer specific capacity and transmissivity

Aquifer characteristics such as specific capacity and transmissivity are used to describe how water is transmitted by an aquifer. *Specific capacity* is the rate of discharge of water produced from a well per unit depth of drawdown, typically expressed in gallons per minute per foot (gpm/ft). *Transmissivity* is an aquifer's capacity to transmit water. It is determined by multiplying the hydraulic conductivity of the aquifer material (the rate at which groundwater flows through a unit cross section of an aquifer) by the thickness of the aquifer. Larger values of each of these parameters indicate more productive aquifers.

Specific capacity data were determined from short-term pumping or well-development tests performed when the well was drilled. To ensure that the data reflect actual pumping, the pumping-test data for specific capacity were obtained from the County Well Index for wells with the following conditions:

1. The casing diameter was at least 12 inches.
2. The well was pumped for at least 4 hours.
3. The pumping water level was inside the well casing, at least 2 feet above the well screen or open hole.

The ss aquifer had the highest mean specific capacity in Nicollet County (48.1 gpm/ft) (Table 4). The more commonly used buried sand and gravel aquifers have a lower mean specific capacity (19.4 gpm/ft). The specific capacity of the bedrock aquifers ranged from 3.2–17.5 gpm/ft.

Transmissivity data was calculated from longer-term and larger-scale aquifer tests that provide a more accurate representation of the aquifer properties. Transmissivity data provide more accurate aquifer parameters than specific capacity values determined at individual wells.

Three buried sand and gravel aquifers have aquifer test reports available, providing transmissivity values (Table 4 and Figure 27). The three tests were performed in aquifers ss, sg1, and suu, and had transmissivity values that ranged from 4,500–80,000 gallons per day per foot.

Table 4. Specific capacity and transmissivity of selected wells

[Specific capacity data adapted from the County Well Index. Transmissivity data are from aquifer test data compiled by the DNR. (--), no data; gpm/ft, gallons per minute per foot; gpd/ft, gallons per day per foot.]

Aquifer	Specific Capacity (gpm/ft)					Aquifer Tests	
	Number of tests	Well diameter (inches)	Min (gpm/ft)	Mean (gpm/ft)	Max (gpm/ft)	Well diameter (inches)	Transmissivity (gpd/ft)
Surficial sand and gravel (ss)	3	12–30	35.2	48.1	68.3	12	80,000
Buried sand and gravel							
sg1	--	--	--	--	--	20	4,500
sge	6	16	11.4	19.4	28.3	--	--
suu	--	--	--	--	--	10	21,750
Bedrock							
Jordan	2	12–18	4.4	8.45	12.5	--	--
Upper Tunnel City–Wonewoc	1	12	--	3.2	--	--	--
Wonewoc	2	12–18	4.3	5.9	7.5	--	--
Mt. Simon	3	12–18	12.6	15.8	17.5	--	--
Mt. Simon–Hinckley	1	18	--	12.2	--	--	--
Multiple	1	12	--	14.2	--	--	--
Unknown	1	12	--	5.5	--	--	--

Conclusions

Nicollet County is located in the central portion of southern Minnesota. The Minnesota River flows along the southern and eastern borders, and is the primary discharge for groundwater throughout the county.

The **surficial sand and gravel (ss) aquifer** is not extensive and not widely used as a water resource. The depth to water table map shows that the water table is within 10 feet of the surface across most of the county, with the exception of the upland valley edges and terrace sands in the Minnesota River valley. Seven **buried sand and gravel aquifers** are used in the county. The primary **bedrock aquifers** are the Prairie du Chien, Jordan, Upper Tunnel City, Wonewoc, and Mt. Simon and they are located in the eastern half of the county. **Potentiometric surface map**s compiled from static water level data from wells in Nicollet and Sibley counties indicate a general pattern of groundwater flow toward the Minnesota River valley. There is an elevated region in the potentiometric surface northwest of Courtland within the buried sand and gravel aquifers due to a high point in the bedrock surface made up of relatively impermeable bedrock beneath this area.

All but two of the groundwater samples have **stable isotope signatures** that indicate water from precipitation infiltrated directly into the groundwater. The water did not reside for long periods in lakes or other surface-water bodies. Two groundwater samples with evaporative signatures were collected from aquifers downgradient from Swan Lake and Annexstad Lake, indicating that both lakes probably recharge the underlying aquifer system.

Thirty-two percent of samples tested for **chloride** were above 5 ppm, many of which had low **Cl/Br ratios** indicating that there are some deep bedrock brines. Five samples had **nitrate-nitrogen** values above 1 ppm indicating an anthropogenic water source; two of the samples were collected from the Jordan aquifer west of St. Peter. Forty-six percent of samples analyzed for sulfate were above 250 ppm, from a natural source. There appears to be an increased percentage of elevated values under areas with Heiberg till versus areas with Villard till. The Heiberg till has a higher amount of Cretaceous shale than the Villard till. The Cretaceous shale may be the source of increased sulfate.

Both **arsenic** and **manganese** are naturally occurring elements of concern that are present in groundwater across the county. Arsenic concentrations greater than or equal to 10 ppb were found in 17 percent of the water samples analyzed for arsenic, which is greater than the average across the state of Minnesota (10.7 percent) (MDH, 2016). Elevated concentrations were present primarily in buried sand and gravel aquifers with a couple of elevated samples being from the Mt. Simon aquifer. Manganese concentrations that exceeded 100 ppb were found in 79 percent of the samples analyzed for manganese, with 48 percent exceeding 300 ppb. Concentrations greater than 300 ppb were primarily found in buried sand and gravel units with only a few being identified in wells completed in bedrock aquifers.

Residence-time analysis of groundwater samples using the radioactive isotope tritium along with other chemical data validated sensitivity models that were based on the cumulative thickness of fine-grained sediment overlying the aquifers. Groundwater samples with recent and mixed tritium ages were typically collected in areas of very high to moderate sensitivity and those with vintage tritium ages were collected from areas of low to very low sensitivity.

The **pollution sensitivity** ratings of the sh, sv, and sm aquifers are higher compared to the other aquifers in the county because they are located closer to the land surface. All of the other aquifers have very low pollution sensitivity ratings across the interior of the county with higher sensitivity ratings in the Minnesota River valley.

Wells with **DNR appropriation permits** across the county are located primarily near towns. Bedrock aquifers supplied 76 percent of the water pumped in 2013. Buried sand and gravel aquifers supplied 16 percent of the reported water use, and the surficial sand and gravel aquifer produced 8 percent. Municipal water supplies was the primary use type in the county, accounting for 85 percent of the pumped water.

References cited

Adams, R., 2016a, Water-table elevation and depth to water table: Minnesota Department of Natural Resources, Minnesota Hydrogeology Atlas Series HG-03, report and 2 pls.

Adams, R., 2016b, Pollution sensitivity of near-surface materials: Minnesota Department of Natural Resources, Minnesota Hydrogeology Atlas Series HG-02, report and plate.

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.

Berg, J.A. and Pearson, S.R., 2011, Southcentral Minnesota groundwater monitoring of the Mt. Simon aquifer, v.3.1: Minnesota Department of Natural Resources, Ecological and Water Resources Division.

DNR, 2015, Nicollet County observation well data: Cooperative Groundwater Monitoring Program, Minnesota Department of Natural Resources, accessed November 23, 2015 at <http://www.dnr.state.mn.us/waters/cgm/index.html>.

DNR, 2016a, Methods for estimating water-table elevation and depth to water table, GW-04: Minnesota Department of Natural Resources, <http://files.dnr.state.mn.us/waters/groundwater_section/mapping/gw/gw04_wt.pdf>.

DNR, 2016b, Methods to estimate near-surface pollution sensitivity, GW-03: Minnesota Department of Natural Resources, <http://files.dnr.state.mn.us/waters/groundwater_section/mapping/gw/gw03_ps-ns.pdf>.

DNR, 2016c, Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment (CFGS) thickness, GW-02: Minnesota Department of Natural Resources, <http://files.dnr.state.mn.us/waters/groundwater_section/mapping/gw/gw02_report.pdf>.

EPA, 2001, Arsenic rule: Environmental Protection Agency, accessed May 11, 2015, at <http://water.epa.gov/lawsregs/rulesregs/sdwa/arsenic/regulations.cfm>.

EPA, [1996], Secondary drinking water standards–guidance for nuisance chemicals: Environmental Protection Agency, accessed May 11, 2016, <https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals>.

Erickson, M.L., and Barnes, R.J., 2005a, Glacial sediment causing regional scale elevated arsenic in drinking water: Ground Water, November–December, v. 43, no. 6, p. 796–805.

Erickson, M.L., and Barnes, R.J., 2005b, Well characteristics influencing arsenic concentrations in ground water: Water Research, v. 39, p. 4029–4039.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, NJ, Prentice-Hall, 604 p.

Geologic Sensitivity Workgroup, 1991, Criteria and guidelines for assessing geologic sensitivity of ground water resources in Minnesota: Minnesota Department of Natural Resources, Division of Waters, 122 p., <http://files.dnr.state.mn.us/waters/groundwater_section/mapping/sensitivity/docs/assessing_geologic_sensitivity.pdf>

Hounslow, A.W., 1995, Water quality data: Analysis and Interpretation, CRC Press.

IAEA/WMO (2006), Global network of isotopes in precipitation: The GNIP database.

Lucas, L.L., and Unterweger, M.P., 2000, Comprehensive review and critical evaluation of the half-life of tritium: Journal of Research of the National Institute of Standards and Technology, v. 105, p. 541–549.

McMahon, P.B., 2001, Aquifer/aquitard interfaces: mixing zones that enhance biogeochemical reactions: Hydrogeology Journal, v. 9, p. 34–43.

MDH, 2012, Human health-based water guidance table: Minnesota Department of Health, <http://www.health.state.mn.us/divs/eh/risk/guidance/gw/table.html>.

MDH, 2016, Arsenic in private wells–facts & figures: Minnesota Department of Health, accessed August 2016 at <https://apps.health.state.mn.us/mndata/arsenic_wells>.

MPCA, 1998, Nitrate in Minnesota ground water–a GWMAP perspective: Minnesota Pollution Control Agency, accessed October 2015.

Nicholas, S.L., Toner, B.M., Erickson, M.L., Knaeble, A.R., Woodruff, L.G., and Meyer, G.N., 2011, Speciation and mineralogy of arsenic in glacial sediments and their effect on arsenic concentrations in groundwater [abs.]: Geological Society of America Abstracts with Programs [digital version], v. 43, no. 5.

Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., Green, J.A., Mossler, J.H., and Alexander, S.C., 2003, Hydrogeology of the Paleozoic bedrock in southeastern Minnesota: Minnesota Geologic Survey, RI-61, 105 p., 2 pls.

Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., and Alexander, S.C., 2006, Hydrostratigraphic characterization of intergranular and secondary porosity in part of the Cambrian sandstone aquifer system of the cratonic interior of North America–improving predictability of hydrogeologic properties: Sedimentary Geology, v. 184, p. 281–304.

Setterholm, D., 2014, Geologic atlas user's guide–using geologic maps and databases for resource management and planning: Minnesota Geological Survey, Open-File Report 12-1, <http://hdl.handle.net/11299/166713>.

Thomas, M.A., 2007, The association of arsenic with redox conditions, depth, and ground-water age in the glacial aquifer system: U.S. Geological Survey Scientific Investigations Report 2007-5036, 26 p.

USDA-NRCS, 2009, Part 630 hydrology, national engineering handbook: U.S. Department of Agriculture, Natural Resources Conservation Service, Hydrologic Soil Groups, Chapter 7.

USDA-NRCS, 2011, Soil Survey geographic database (SSURGO) for Nicollet County, Minnesota: USDA-NRCS, Web Soil Survey, accessed February 10, 2015 at <http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx>.

Glossary

anion—a negatively charged ion in which the total number of electrons is greater than the total number of protons, resulting in a net negative electrical charge.

anisotropic—a condition in which a property (e.g., hydraulic conductivity) varies with the direction of measurement at a point in a geologic formation (Freeze and Cherry, 1979, p. 32).

anthropogenic—of, relating to, or resulting from the influence of humans on nature.

aquifer—an underground layer of water-bearing permeable rock or unconsolidated materials (sand and gravel) from which groundwater can be extracted using a water well.

aquitard (or confining layers)—made up of materials with low permeability, such as layers of clay and shale, which prevent rapid or significant movement of water.

arsenic—a chemical element that is sometimes dissolved in groundwater and is toxic to humans. Natural arsenic contamination of groundwater is a problem that affects millions of people across the world, including over 100,000 people served by domestic wells in Minnesota.

bedrock—the consolidated rock underlying unconsolidated surface materials such as soil or glacial sediment.

buried aquifer (confined aquifer)—a volume of porous and permeable sediment (either sand or gravel or a mixture of the two) which is buried beneath the ground surface by a low permeability layer.

carbon-14 (^{14}C)—a radioactive isotope of carbon that has a half-life of 5,730 years. It is used to identify groundwater that entered the ground from 100–40,000 years before present.

cation—a positively charged ion in which the total number of electrons is less than the total number of protons, resulting in a net positive electrical charge.

County Well Index—a database developed and maintained by the Minnesota Department of Health and Minnesota Geological Survey containing basic information for wells drilled in Minnesota. Information includes location, depth, static water level, construction, and geological information. The database and other features are available through the Minnesota Well Index online mapping application.

equipotential line—a line along which the pressure head of groundwater is the same. Groundwater flow (shown on cross sections) is perpendicular to these lines in the direction of decreasing pressure.

formation—a fundamental unit of lithostratigraphy. A formation consists of a certain number of rock strata that have a comparable lithology, facies or other similar properties.

fractionation—a separation process in which a certain quantity of a mixture (solid, liquid, solute, suspension, or isotope) is divided up in a number of smaller quantities (fractions) in which the composition varies according to a gradient. Fractions are collected based on differences in a specific property of the individual components. Stable isotopes are fractionated by mass.

glacial—of, relating to, or derived from a glacier.

groundwater—water that collects or flows beneath the earth's surface, filling the porous spaces below the water table in soil, sediment, and rocks.

half-life—the time required for one half of a given mass of a radioactive element to decay.

hydrogeology—the study of subsurface water, including its physical and chemical properties, geologic environment, role in geologic processes, natural movement, recovery, contamination, and use.

hydraulic conductivity—the rate at which groundwater flows through a unit cross section of an aquifer.

infiltration—the movement of water from the land surface into the subsurface under unsaturated conditions.

isotope—variants of a particular chemical element. All isotopes of an element share the same number of protons, but each isotope has a different number of neutrons.

meteoric—of, relating to, or derived from the earth's atmosphere.

neutron—a subatomic particle contained in the atomic nucleus. It has no net electrical charge and a mass of approximately 1 (slightly greater than a proton).

nitrate—a polyatomic anion with the molecular formula NO_3^-. Nitrates are primarily derived from fertilizer. Humans are subject to nitrate toxicity, with infants being especially vulnerable to methemoglobinemia, also known as blue baby syndrome.

observation well —a well that is used to monitor the static water level of groundwater, but not used as a water source.

Paleozoic—an era of geologic time from about 542 to 251 million years ago.

potentiometric surface—a surface representing the total head of groundwater in an aquifer and defined by the levels to which water will rise in tightly case wells.

provenance—the area from which the constituent materials of glacial sediment are derived.

Quaternary—geologic time period that began 2.588 million years ago and continues to today. The Quaternary Period comprises the Pleistocene and Holocene epochs.

radioactive—a property of an element that spontaneously decays or changes to a different element through the emission of radioactive particles.

recharge—the process by which water enters the groundwater system.

residence-time indicators—a chemical and/or isotope used to interpret groundwater residence time.

specific capacity—the discharge of a well divided by the drawdown in the well.

stable isotope—chemical isotopes that are not radioactive (i.e., they do not spontaneously undergo radioactive decay).

static water level—the level of water in a well that is not affected by pumping.

stratigraphy—a branch of geology that studies rock layers and layering (stratification). It is primarily used in the study of sedimentary and layered volcanic rocks. Also used to refer to the sequence of rock layers in a region.

till—unsorted glacial sediment, deposited directly by ice, that is derived from the subglacial erosion and entrainment of rock and sediment over which the glacier has passed. It is no longer till if it has been modified or redeposited.

transmissivity—an aquifer's capacity to transmit water, determined by multiplying the hydraulic conductivity of the aquifer material by the thickness of the aquifer.

tritium (^3H)—a radioactive isotope of hydrogen. The nucleus of tritium contains one proton and two neutrons.

tritium unit (TU)—one tritium unit represents the presence of one tritium atom for every 1018 hydrogen atoms.

unconfined—an aquifer that has direct contact with the atmosphere through an unsaturated layer.

water table—the surface between the unsaturated and saturated zone where the water pressure equals the atmospheric pressure.

watershed—the area of land drained by a single stream or river.

well nest—two or more wells completed in different aquifers in close proximity to each other.

Appendix

Groundwater samples were collected from an outside faucet or hydrant. The wells were purged prior to sampling to remove stagnant water from the well bore and plumbing system. Samples were collected after field parameters such as temperature, conductivity, dissolved oxygen, and pH had stabilized. Each was filtered and preserved according to protocols listed below and submitted to laboratories for analysis. Samples were analyzed by DNR staff, the University of Minnesota Department of Earth Sciences Laboratory (U of M), or the University of Waterloo Environmental Isotope Laboratory (Waterloo). The well owners received a copy of the results including some background reference information regarding their meaning.

Groundwater field sample collection and handling details

Parameter	Enriched Tritium	^{18}O ^{2}H	Cations	Anions	Trace constituents	Alkalinity
Lab	Waterloo	Waterloo	U of M	U of M	U of M	DNR Staff
Sample container	500 ml HDPE	60 ml HDPE	15 ml, Fisherbrand BLUE cap	50 ml Argos BLACK bottle***	15 ml Sarstedt RED cap	500 ml plastic
Head space	yes	yes	yes	yes	yes	no
Rinse	no	no	yes*	yes*	yes*	yes**
Filter	no	no	yes	yes	yes	no
Preservative	no	no	1 drop 6N HCl	no	5 drops 15N HNO_3	no
Refrigeration	no	no	yes	yes	yes	Yes, if not analyzed onsite
Shelf life	long	long	2–3 weeks	2–3 weeks	2–3 weeks	24–48 hours
Field duplicate	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	none
Field blank	none	none	1 for every 20****	1 for every 20****	1 for every 20****	none
Storage duplicate	yes	yes	no	no	no	no

*Rinse the bottle three times with sample water prior to collecting the sample (filtered if sample is filtered). Rinsing means fill the bottle with sample water and then pour the contents out over the cap.

**Rinse the bottle three times with sample water prior to collecting the sample. Fill bottle submerged with cap in hand. Seal bottle submerged ensuring no remnant bubbles.

***Fill 50 ml anion bottle unless filtering is very difficult. Bottle must be at least 1/3 full.

****Use deionized (DI) water from small bottle for field blanks. Pour DI water into the back of the syringe when the plunger is removed. Fill bottles through filter.

Technical Reference

Maps were compiled and generated in a geographic information system (GIS). Digital data products, including chemistry data, are available from the Minnesota Department of Natural Resources (DNR), Ecological and Water Resources Division on the Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

Maps were prepared from publicly available information. Every reasonable effort has been made to ensure the accuracy of the factual data on which the report and map interpretations were based. However, the DNR 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 DNR. Every effort has been made to ensure the interpretations conform to sound geologic and cartographic principles. These maps should not be used to establish legal title, boundaries, or locations of improvements.

These bases were modified from Minnesota Geological Survey, Nicollet County Geologic Atlas, Part A, 2012.

Universal Transverse Mercator projection, zone 15, North American Datum of 1983. North American Vertical Datum of 1988.

GIS and cartography by Vanessa M. Baratta, Holly Johnson and Valerie Woelfel. Edited by Ruth MacDonald.

This page intentionally left blank.

Funding for this project was provided by the
Minnesota Environment and Natural Resources Trust Fund
and the Clean Water Fund.

The DNR Information Center

Minnesota Department of Natural Resources
Ecological and Water Resources Division
500 Lafayette Road
St. Paul, MN 55155-4025
For more information call 651-296-6157 or 888-646-6367
mndnr.gov