GEOLOGIC ATLAS OF SIBLEY COUNTY, MINNESOTA

County Atlas Series C-24

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

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NATURAL RESOURCES

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Geologic Atlas of Sibley 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 Sibley 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, previously 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.

The **report** describes the hydrogeologic setting, water levels, chemistry, pollution sensitivity, and use of aquifers within the county. The accompanying **plates 7 and 8** illustrate the chemical hydrogeology (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 illustrate 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).

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

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. To evaluate the model results, 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.

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.

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).

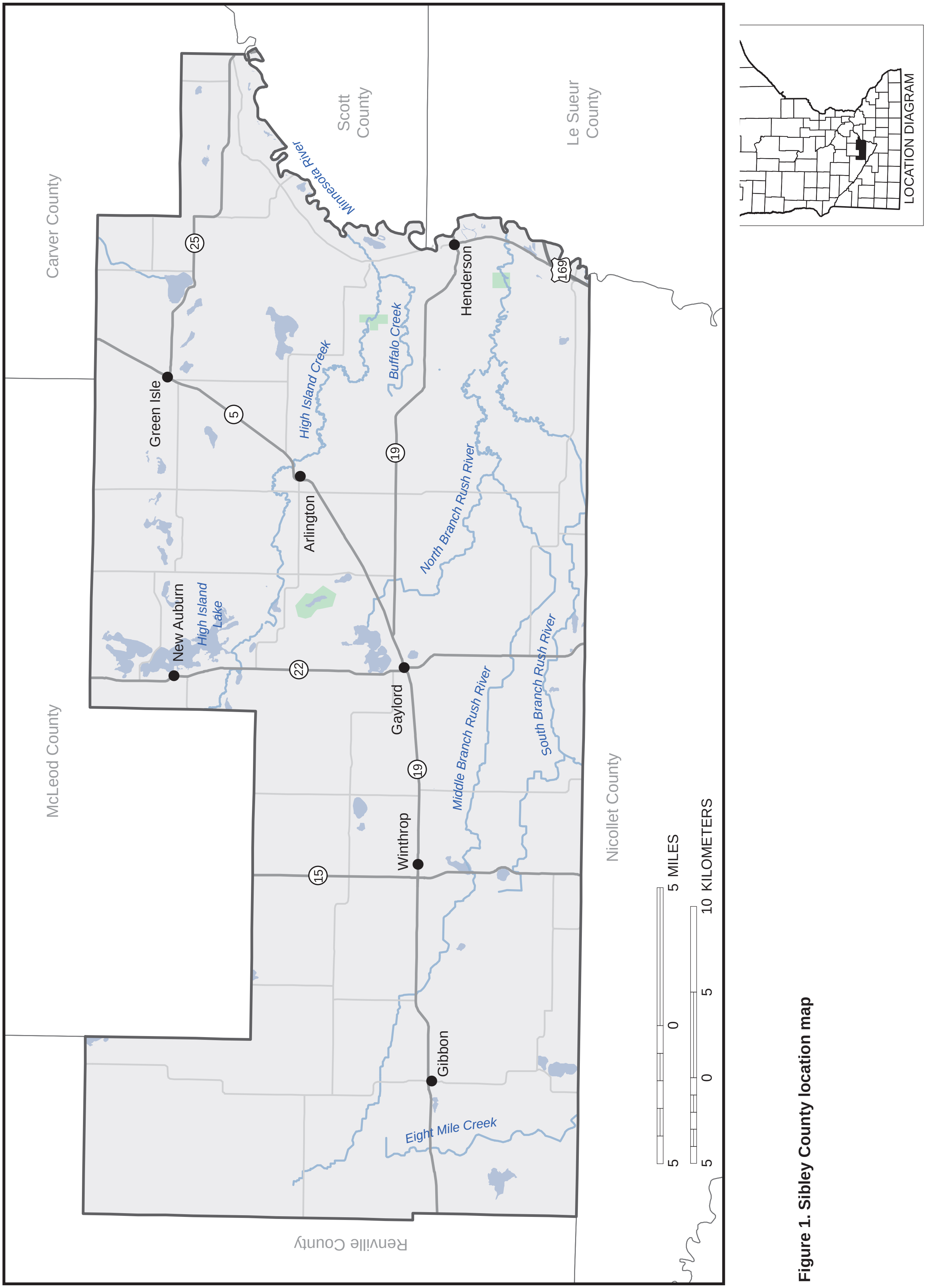


Figure 1. Sibley County location map

Geology and physical hydrogeology

Sibley County is located in south-central Minnesota (Figure 1); the topography is level to rolling in most of the county. Along the eastern border there are river gorges with wooded bluffs and tributary ravines where the Minnesota River and its tributaries are deeply incised into the surface.

Portions of three different subbasin-level surface watersheds (hydrologic unit code 8) are present in the county (Figure 2). The Minnesota River–Mankato watershed and the Lower Minnesota River watershed drain toward the Minnesota River (to the south and east) covering the majority of Sibley County. The South Fork Crow River watershed covers a small portion of the northern part of the county and drains to the north. Within the Lower Minnesota River watershed there are two primary streams draining the county, the Rush River and High Island Creek.

Surficial geologic units and aquifers

Surficial deposits in Sibley County are dominated by glacial sediment of the Des Moines lobe (Part A, Plate 3). This sediment was deposited in multiple phases of glacial 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 eastern border of the county, along the steep valley walls. The relatively rapid creation of this deep valley caused preexisting 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, creating ravines that lead to fans on the valley floor and gravitational failure of sediment and rock in steep portions of the landscape.

The surficial sand can be up to 100 feet thick in the broad valley now occupied by the Minnesota River. 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). Elsewhere in the county the surficial sand is of limited extent and thickness, and as a result the surficial sand and gravel aquifer is rarely used.

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 aquitard sediment across the entire county.

The surficial sand and gravel aquifer is present below the water table where there is sufficient saturated thickness and yield to install a well and economically pump groundwater. It has limited extent and thickness in Sibley County (primarily in 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:

- The elevation of surface-water bodies (such as rivers, perennial streams, lakes, and wetlands)
- Static water levels in surficial sand wells obtained from well records in the County Well Index database (converted to elevations*)
- Estimates of wet soil conditions from the Natural Resources Conservation Service county soil survey (converted to elevations*)

**Data were converted to elevations using a digital elevation model derived from Light Detection and Ranging technology.*

The depth to water table (Figure 3) is derived by subtracting the water-table elevation from the land-surface elevation. More details on how these maps were made 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 refine information at local scales. Certain conditions affect the fluctuation of the water table and can create locally different results from the maps that were 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 and is poorly constrained.

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

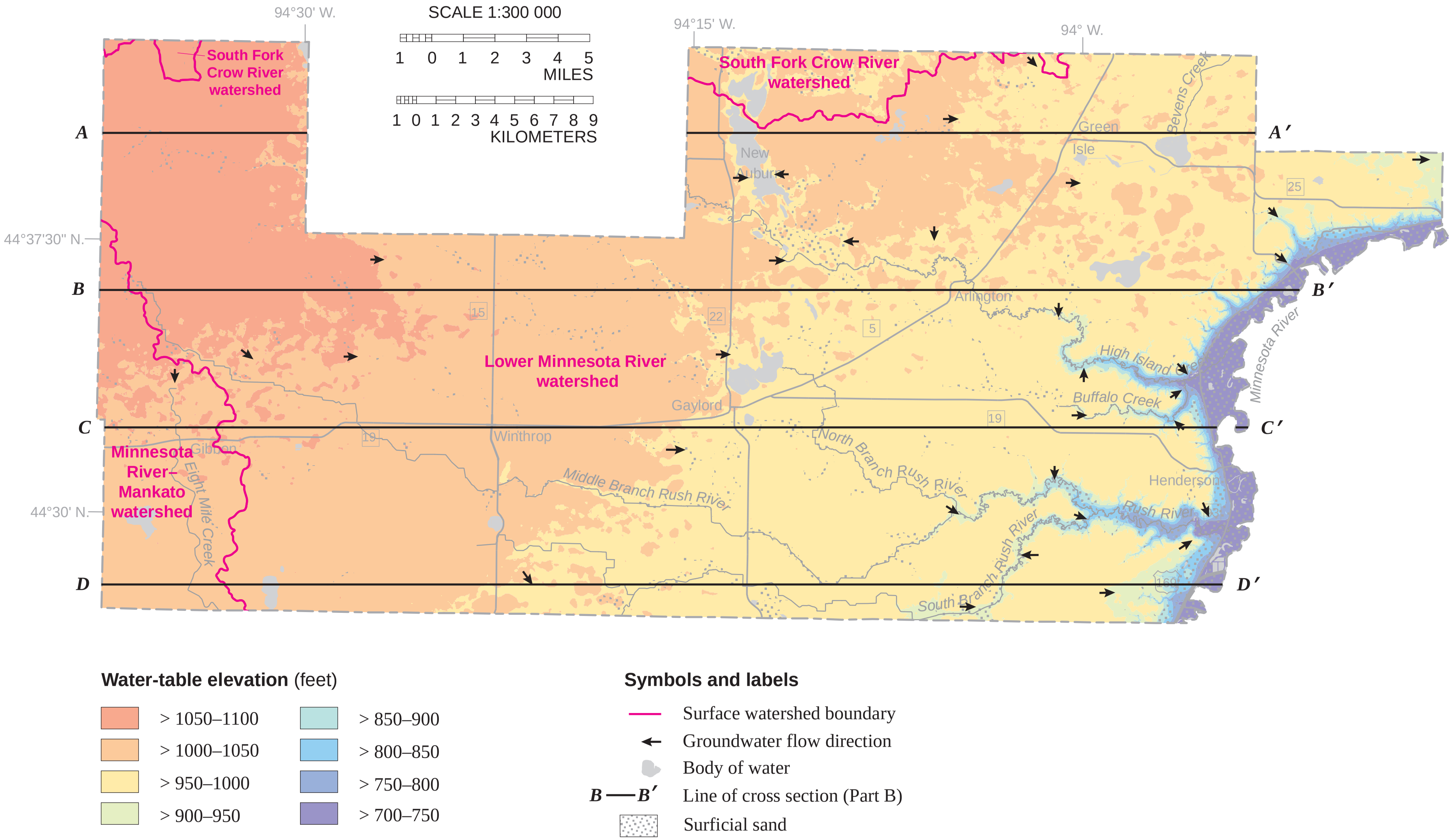


Figure 2. Water-table elevation and groundwater flow directions

Groundwater flows toward the Minnesota River and some of its minor tributary streams (map modified from Adams, 2016a, Plate 1).

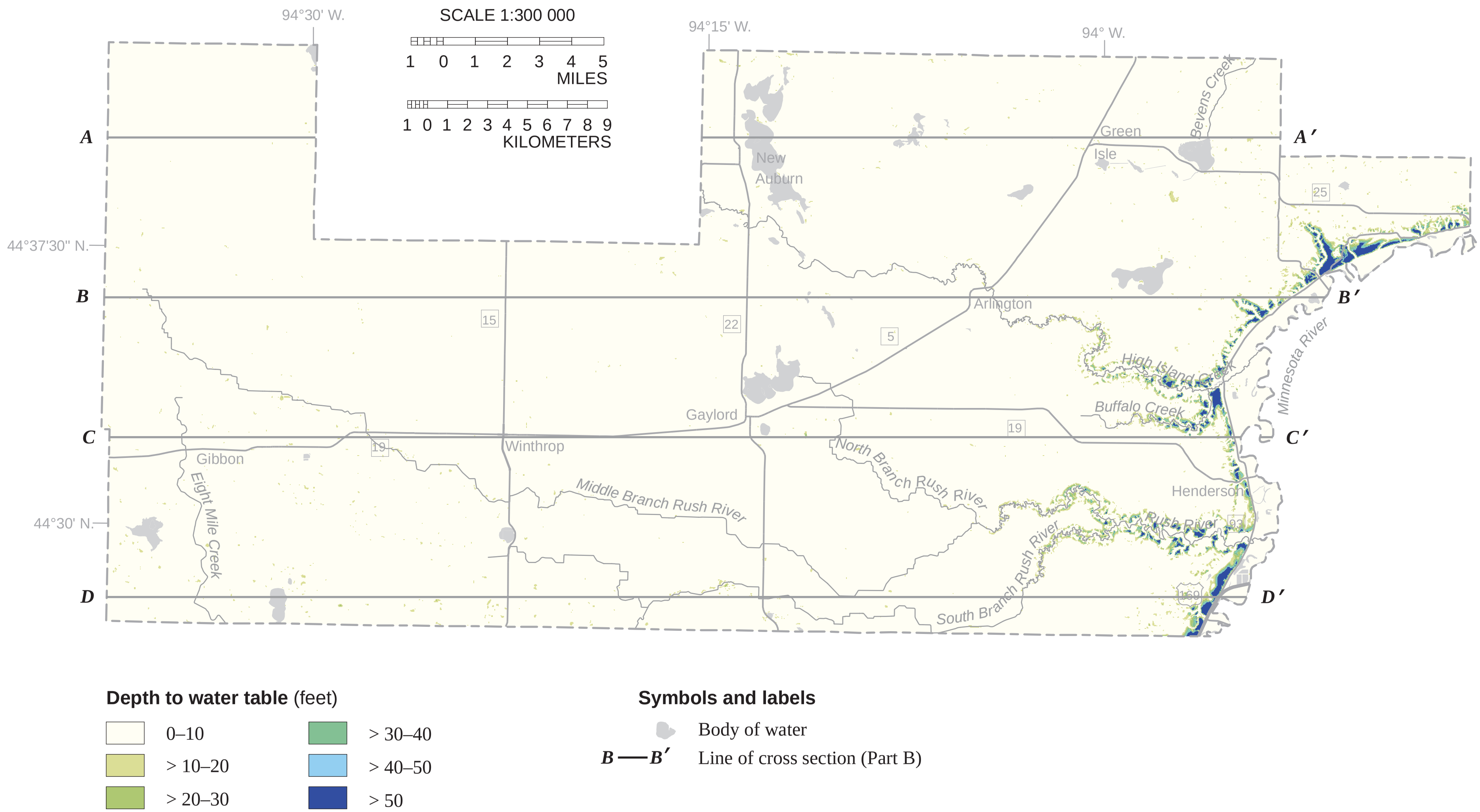


Figure 3. Depth to water table

The depth to water table is within 10 feet of the land surface across most of Sibley County, with the exception of the upland valley edges and tributary valleys of the Minnesota River valley (map modified from Adams, 2016a, Plate 2).

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 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 aquifers are typically thin (20 to 40 feet thick) and discontinuous with lateral extents rarely exceeding several miles. Buried aquifers are typically surrounded by fine-grained glacial-sediment layers (mostly till) that form aquitards.

The unconsolidated sediment thickness in Sibley 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 east central portion of the county the sediment can be greater than 500 feet thick where deep bedrock valleys have 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 as follows:

- **Aquifers** are represented with *patterns* (Figure 4, Figure 17, and Plate 8).
- **Aquitards** are shown as *shades of gray*, representing the relative hydraulic conductivity. Lighter shades represent units with more sand, implying a higher hydraulic conductivity. The shades of gray are based on the average sand content of the aquitard, which is determined from the portion that is less than 2 millimeter grain size.
- **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 map units were reanalyzed by the MGS to create continuously mapped units across the Sibley and Nicollet county border where possible. New versions of the map units are available with the electronic data for this atlas.

The sand unit associated with the Browerville Formation in Part A had a limited extent with only 28 wells in Sibley County (Part A, Plate 4). Because of this, it does not have a potentiometric surface or pollution sensitivity map in this report. Four water samples from the Browerville Formation are designated aquifer sb in the chemistry section (Plate 7) and are shown on cross sections B–B′ and C–C′ (Plate 8).

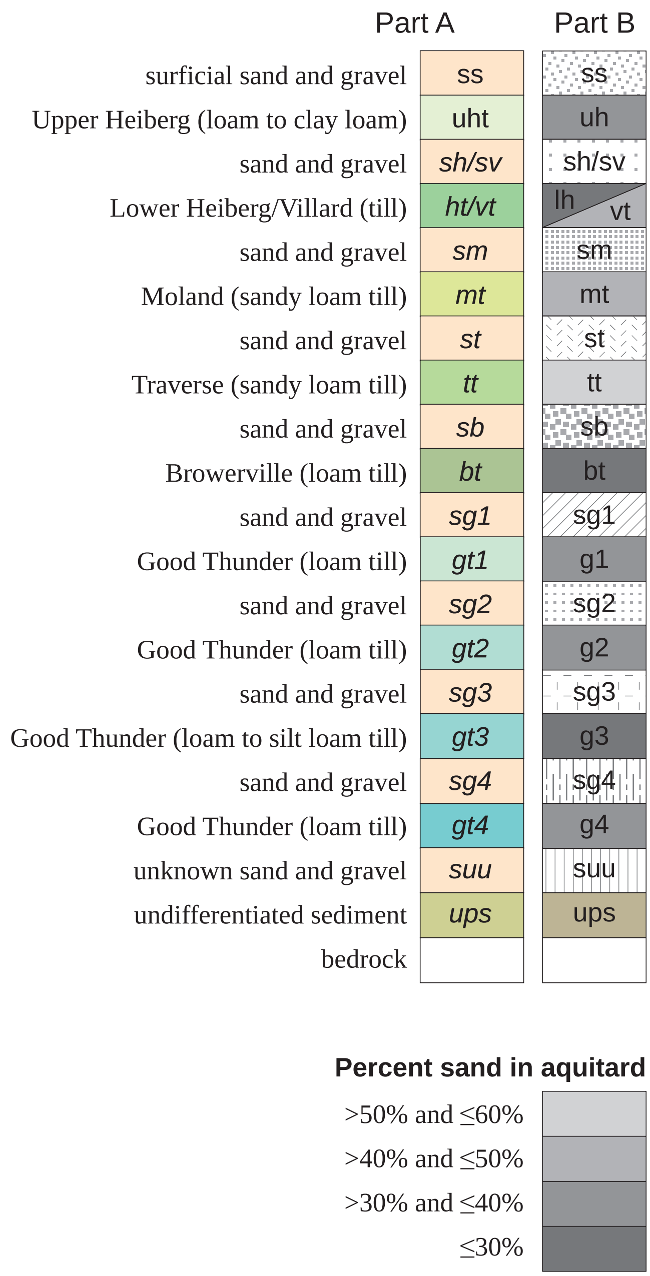


Figure 4. Hydrostratigraphy of Quaternary unconsolidated sediment

Aquifers are shown with patterns and aquitards are shown in shades of gray. These are used for the Part B hydrostratigraphic units on the Plate 8 cross sections and Figure 17. Shades of gray on aquitards correspond to the percent sand content indicating relative hydraulic conductivity. The Part A sediment texture description is shown on the left side for reference and unit identification only.

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 an aquifer. The lines are similar to 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 from centuries to millennia to travel tens of miles. When combined with other information, high elevation areas on the potentiometric surface can indicate important recharge areas.

Potentiometric surface maps for Sibley County incorporated static water-level data from the County Well Index (CWI), 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 eastern border of the county. Data from Sibley and Nicollet counties were used together to increase the data coverage and ensure that the potentiometric surfaces were consistent across the county boundary. The CWI 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 defined, especially for deeper aquifers, and the aquifers may extend over a broader area than shown.

Potentiometric surfaces are shown for six of the nine buried sand and gravel aquifers (Figures 5 through 10). 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 report sections, “Chemical hydrogeology” and “Pollution sensitivity.”

All of the potentiometric surface maps indicate a general pattern of groundwater flow toward the Minnesota River (to the east and south). There is a high point in the potentiometric surfaces between New Auburn and Green Isle that results in some local flow to the west. This flow is possibly the result of a deep buried bedrock valley (Part A, Plate 6) creating a local preferential flow. The deeply incised valleys of the Minnesota River, Rush River, and High Island Creek are examples of low-elevation areas that can be discharge areas.

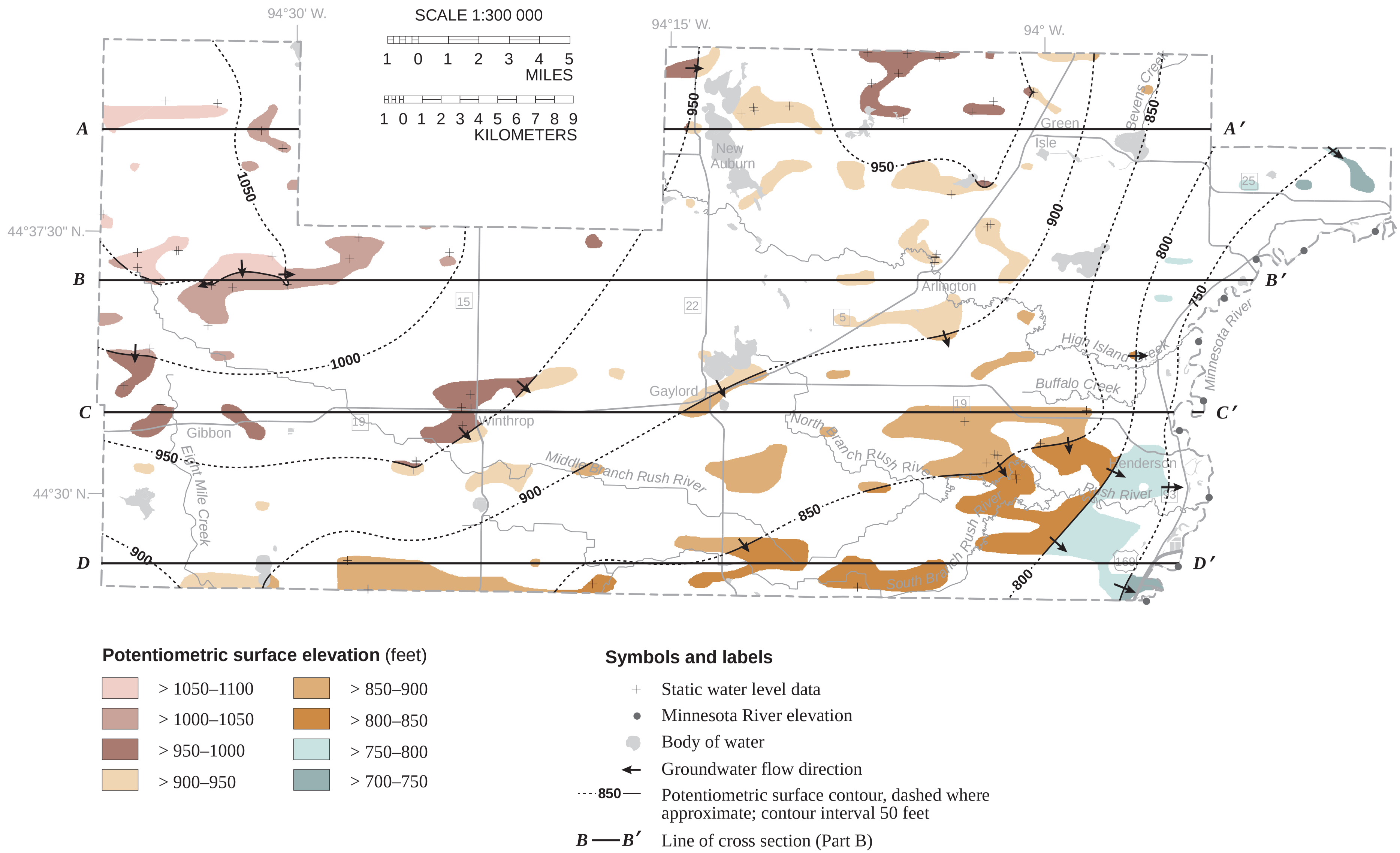


Figure 5. Potentiometric surface of the st aquifer

General groundwater flow direction is from the northwestern (upland) part of the county toward the Minnesota River, which forms the eastern border of the county. Flow in the southwestern part of the county is southward moving toward the Minnesota River along the southern border of neighboring Nicollet County.

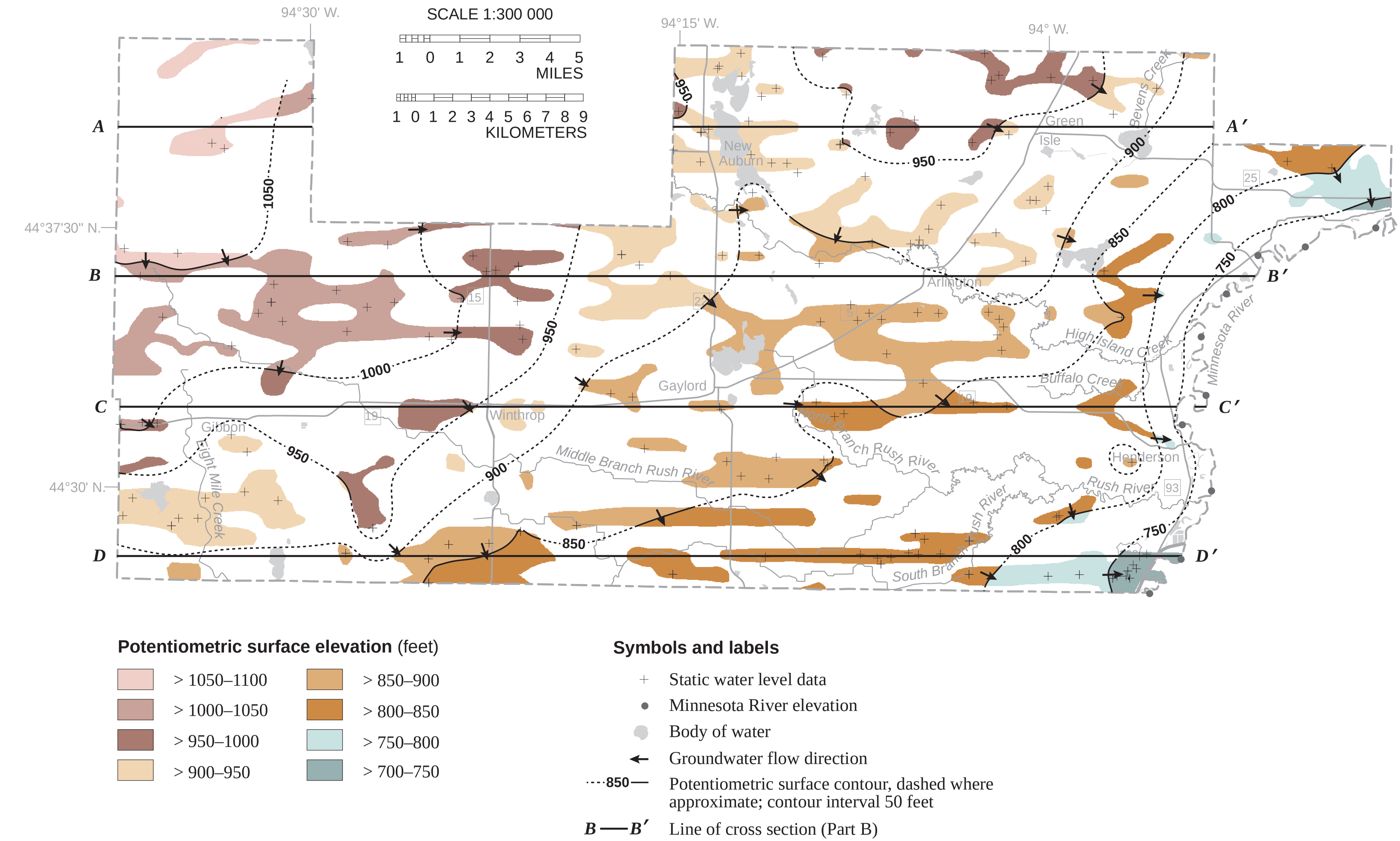
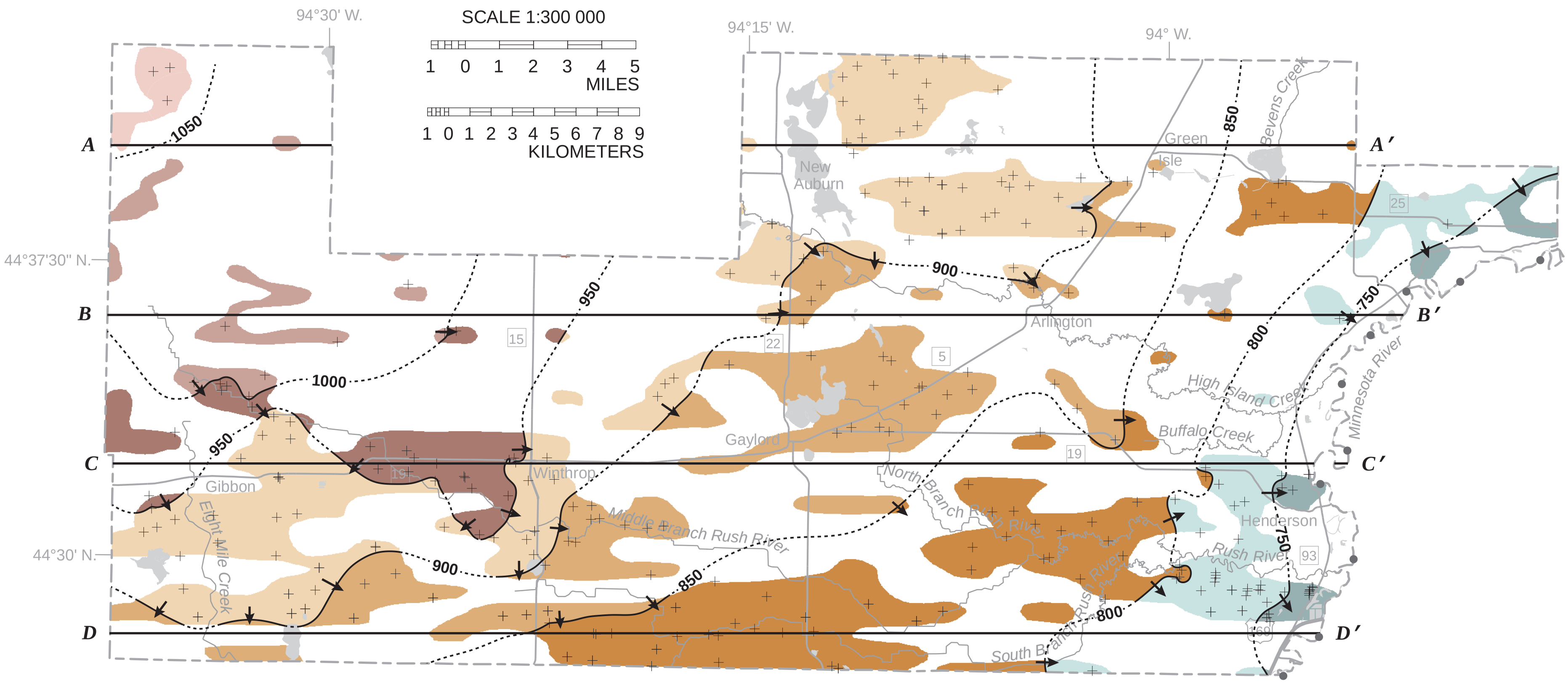


Figure 6. Potentiometric surface of the sg1 aquifer

General groundwater flow direction is from the northwestern (upland) part of the county toward the Minnesota River, which forms the eastern border of the county. Flow in the southwestern part of the county is southward moving toward the Minnesota River along the southern border of neighboring Nicollet County. Some localized flow in the north-central portion of the county flows away from the Minnesota River, this appears to be due to buried bedrock valleys in this area.



Potentiometric surface elevation (feet)

- > 1050–1100
- > 1000–1050
- > 950–1000
- > 900–950
- > 850–900
- > 800–850
- > 750–800
- > 700–750

Symbols and labels

- Static water level data
- Minnesota River elevation
- Body of water
- Groundwater flow direction
- 850 — Potentiometric surface contour, dashed where approximate; contour interval 50 feet
- B — B′ Line of cross section (Part B)

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 eastern border of the county. Flow in the southwestern part of the county is southward moving toward the Minnesota River along the southern border of neighboring Nicollet County.

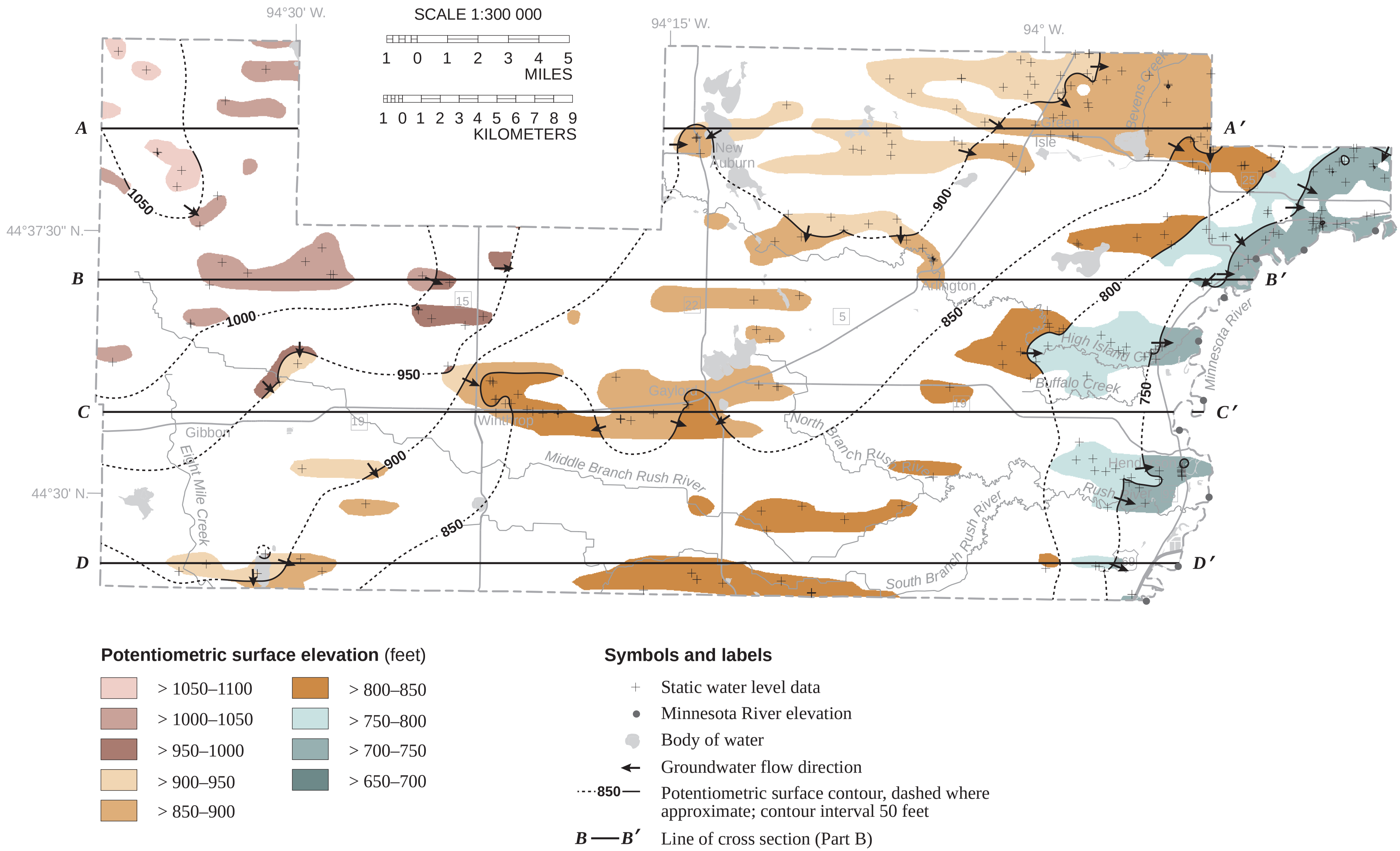


Figure 8. Potentiometric surface of the sg3 aquifer

General groundwater flow direction is from the northwestern (upland) part of the county toward the Minnesota River, which forms the eastern border of the county. Flow in the southwestern part of the county is southward moving toward the Minnesota River along the southern border of neighboring Nicollet County. Some localized flow in the north-central portion of the county flows away from the Minnesota River. This could be due to buried bedrock valleys in these areas. There is also some localized flow away from the Minnesota River in the center of the county between Winthrop and Gaylord. This change in flow direction could be the result of high volume pumping of water from this aquifer to supply municipal water for these cities (Figure 31).

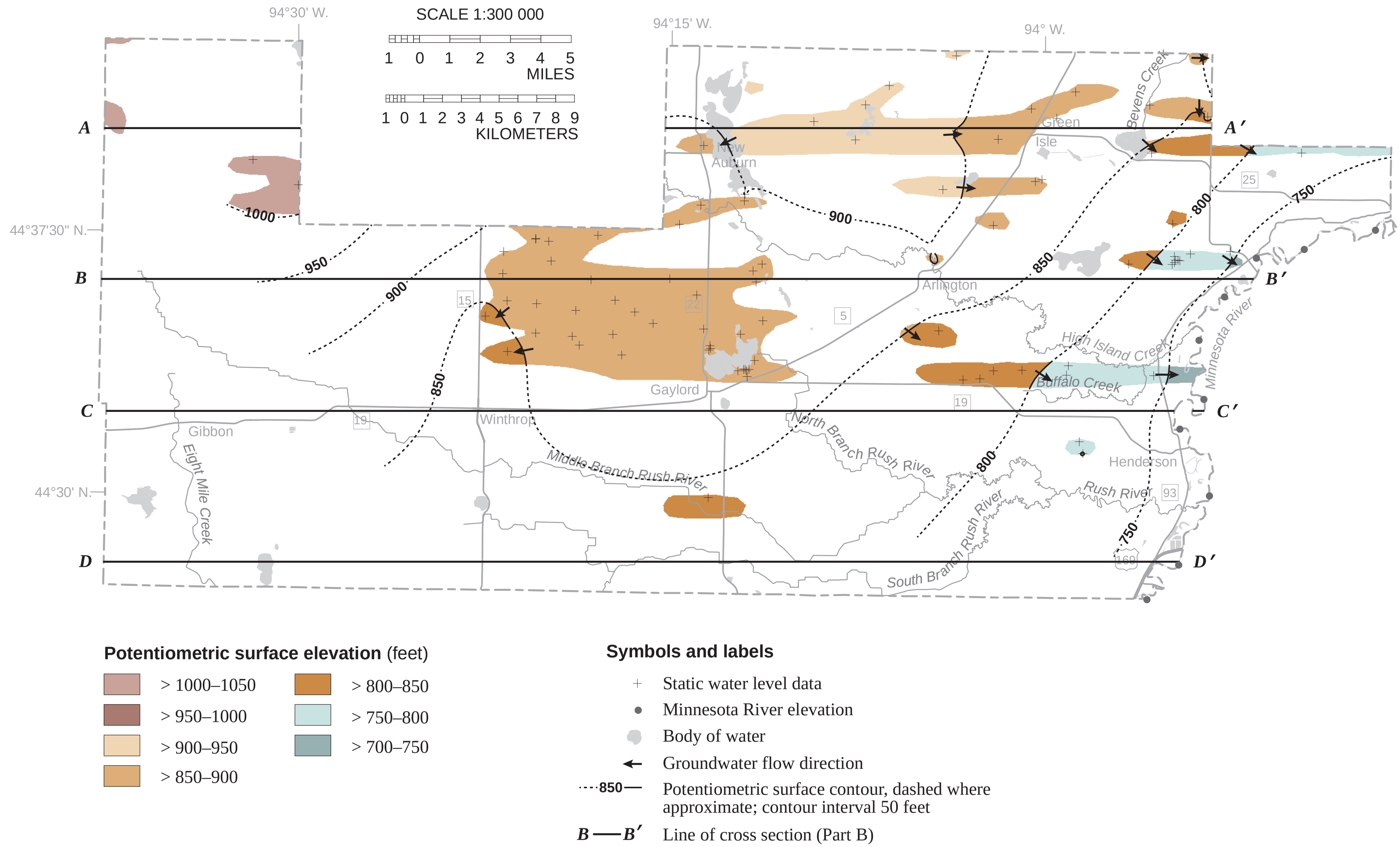
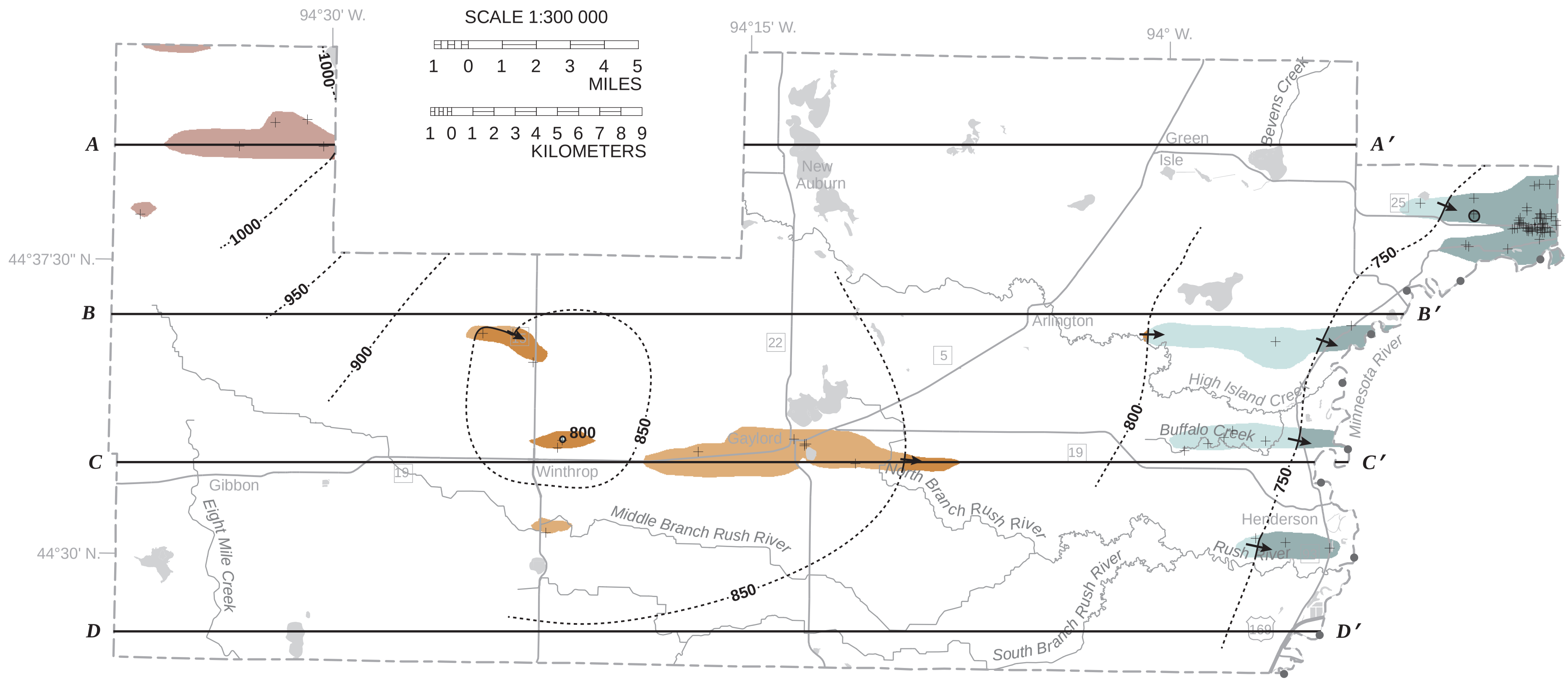


Figure 9. Potentiometric surface of the sg4 aquifer

General groundwater flow direction is from the northwest (upland) toward the east, to the Minnesota River along the eastern border of the county. Some localized flow in the central portion of the county flows away from the Minnesota River. This may be due to buried bedrock valleys in these regions.



Potentiometric surface elevation (feet)

- > 1050–1100
- > 1000–1050
- > 950–1000
- > 850–900
- > 800–850
- > 750–800
- > 700–750
- > 650–700

Symbols and labels

- \+ Static water level data
- ● Minnesota River elevation
- ← Groundwater flow direction
- Body of water
- ····850— Potentiometric surface contour, dashed where approximate; contour interval 50 feet
- *B*——*B′* Line of cross section (Part B)

Figure 10. Potentiometric surface of the suu aquifer

General groundwater flow direction is from the northwest (upland) toward the east, to the Minnesota River along the eastern border of the county. Some localized flow in the central portion of the county flows away from the Minnesota River. This may be the result of large volume pumping from municipal wells using water from the aquifer in this region.

Bedrock geologic units and aquifers

Several bedrock units are present at the bedrock surface in Sibley County (Part A, Plate 2). Paleozoic sedimentary units in the eastern part of the county dip gently towards the southeast. The oldest, stratigraphically lowest rock units of the sequence form the bedrock surface in the center of the county while the younger 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 11). In the western part, the Paleozoic sedimentary bedrock is not present and the principal bedrock units are Precambrian crystalline rock. These units have low permeability and are rarely used as aquifers. Limited data are available for the Cretaceous Dakota Formation and unnamed Ka unit in the western half of the county. Both of these units are composed of fine-grained materials that likely have limited aquifer potential. The extent of these units is shown in Part A, Plate 2. The Cretaceous units appear on the cross sections on Plate 8, but 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, Wonewoc, and Mt. Simon, water moves through intergranular pore spaces and larger macropores such as fractures. Groundwater primarily moves through enlarged fractures in the Prairie du Chien and Upper Tunnel City aquifers. The Wonowoc aquifer had too few wells to create a potentiometric surface for this report.

The St. Lawrence and Eau Claire formations generally have low permeability and are typically used as aquifers only 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 section (Runkel and others, 2006). It likely developed when the bedrock surface was at the land surface. The fractures in this zone generally increase the yield from aquifers and 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 was not enough information available at this time to say that it is present.

The hydraulic conductivity of most bedrock aquifers and aquitards varies with flow direction: horizontal hydraulic conductivity is generally higher than vertical hydraulic conductivity. This can be pronounced in some aquitards such as the St. Lawrence Formation, where hydraulically active bedding-plane fractures have bulk horizontal hydraulic conductivities similar to aquifer units, even in bedrock units greater than 50 feet below 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 11. Bedrock stratigraphy and hydrostratigraphy

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

Potentiometric surfaces of bedrock aquifers

Potentiometric surfaces for Prairie du Chien–Jordan, Upper Tunnel City, and the Mt. Simon aquifers indicate that overall groundwater flow in the bedrock aquifers is towards the Minnesota River (Figures 12 through 14). 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 because of limited data. The static water level data for the two aquifers was similar enough to combine the data, though it is likely that an aquitard may be present between the two aquifers locally (Tipping and others, 2006).

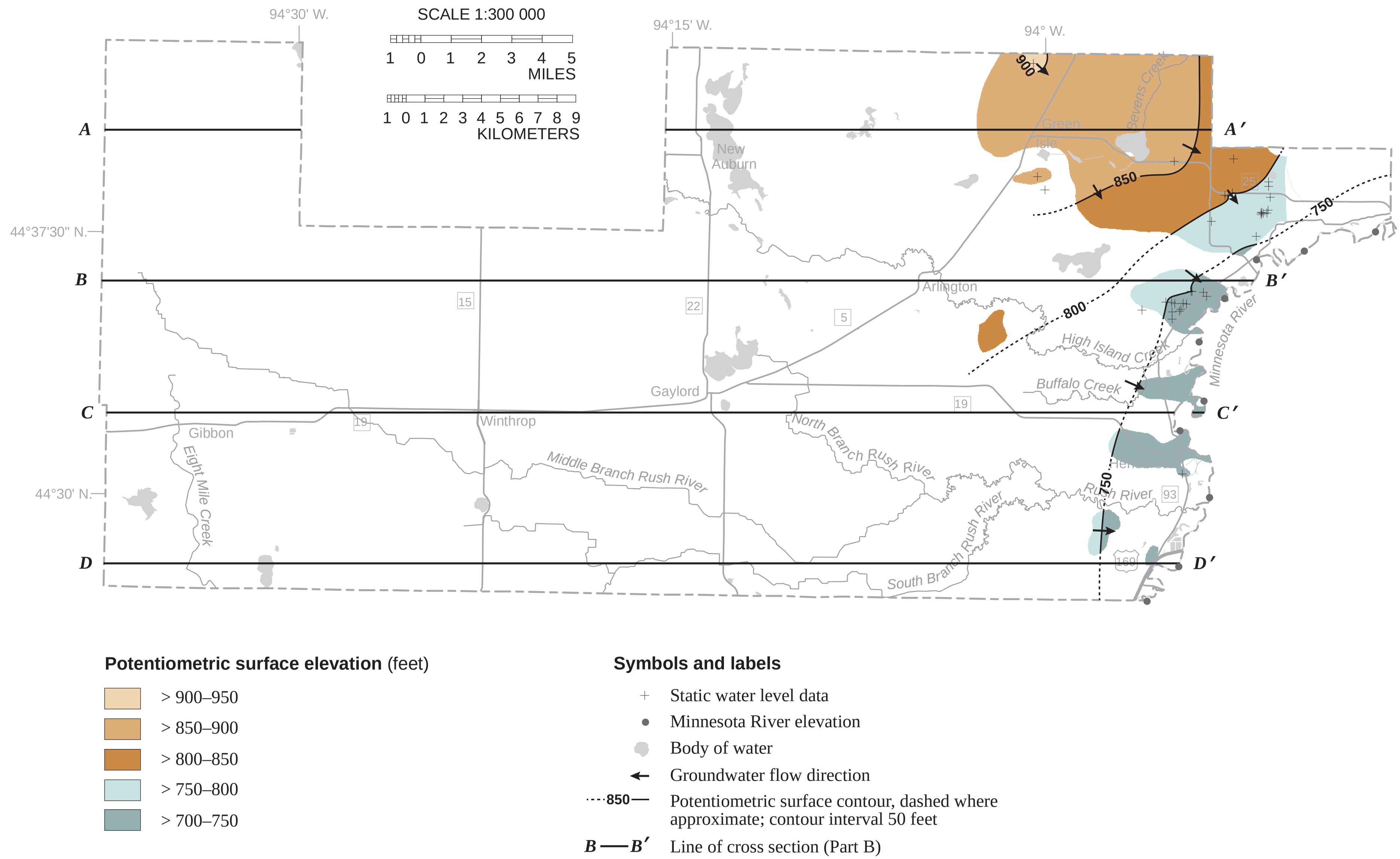
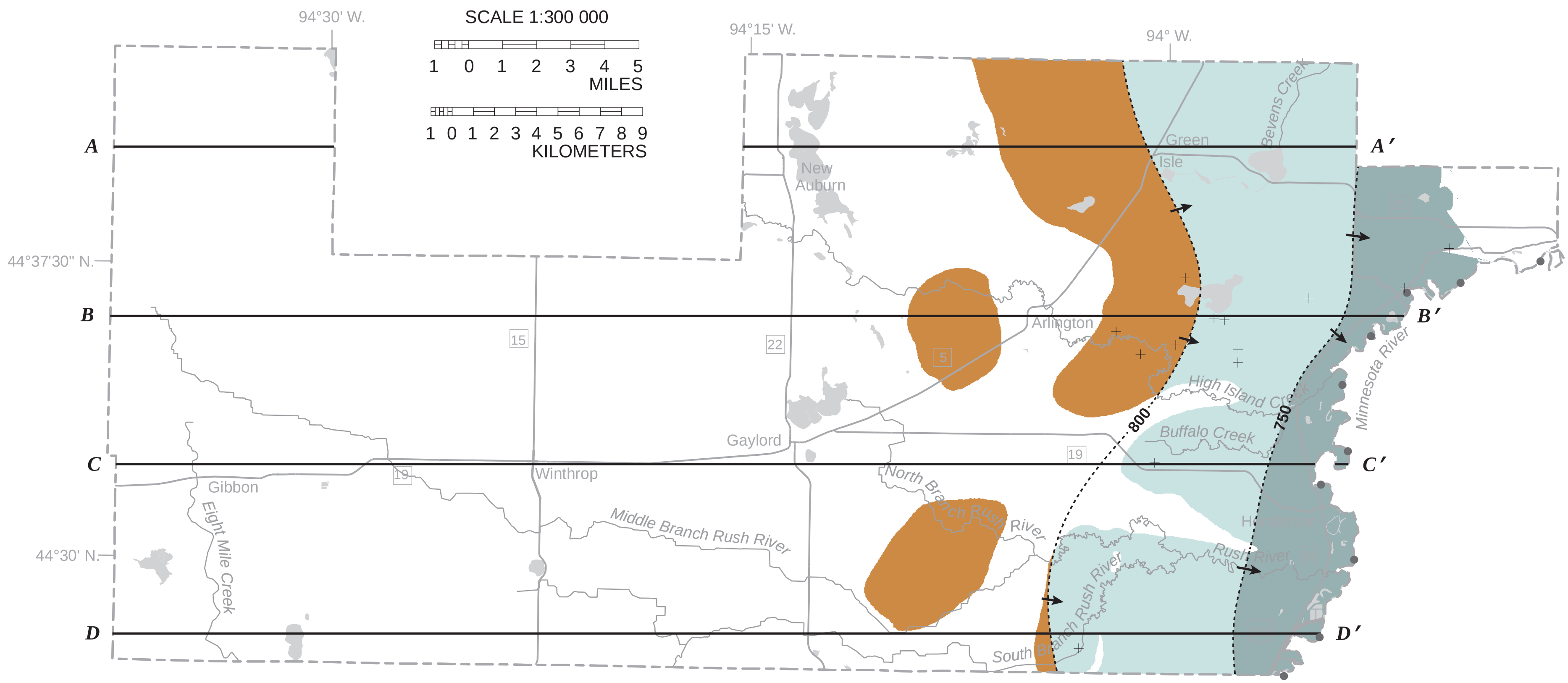


Figure 12. Potentiometric surface of the Prairie du Chien and Jordan aquifers

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



Potentiometric surface elevation (feet)

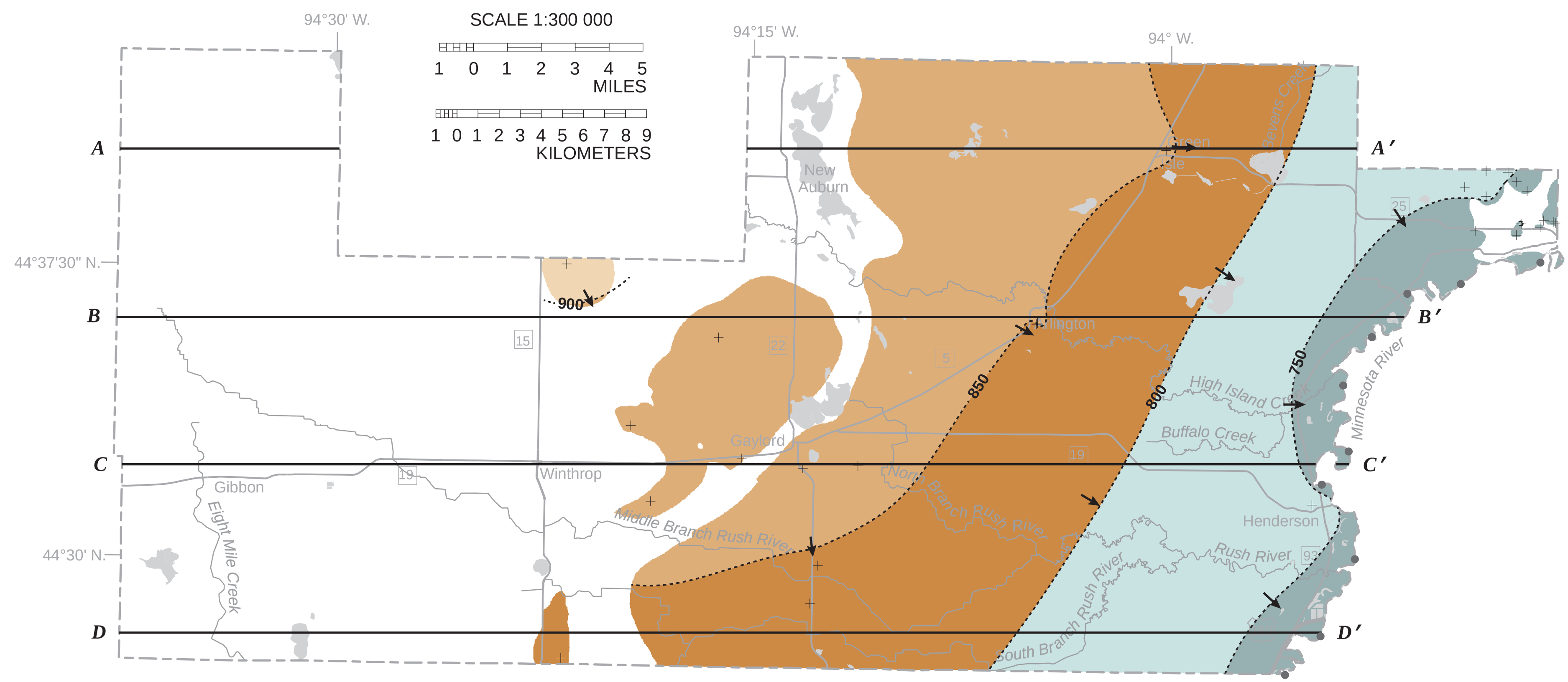
- > 800–850
- > 750–800
- > 700–750

Symbols and labels

- Static water level data
- Minnesota River elevation
- Body of water
- Groundwater flow direction
- 850 — Potentiometric surface contour, dashed where approximate; contour interval 50 feet
- B — B′ Line of cross section (Part B)

Figure 13. Potentiometric surface of the Upper Tunnel City aquifer

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



Potentiometric surface elevation (feet)

- > 900–950
- > 850–900
- > 800–850
- > 750–800
- > 700–750

Symbols and labels

- Static water level data
- Minnesota River elevation
- Body of water
- Groundwater flow direction
- ····850— Potentiometric surface contour, dashed where approximate; contour interval 50 feet
- *B*——*B′* Line of cross section (Part B)

Figure 14. Potentiometric surface of the Mt. Simon aquifer

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

Chemical hydrogeology - Plate 7

The types of dissolved elements and compounds in groundwater provide information about groundwater recharge areas, the geologic layers that the water has flowed through, and approximately how long the water has been underground–the *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 the 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.

Water sampling

To better understand groundwater movement and pollution sensitivity, 91 groundwater samples, 3 lake samples, and 1 river sample were collected from a 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 are 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 and aquifers were selected for their significance for water supply. The sampling network also 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 more of the light isotopes evaporate into the atmosphere. 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 so 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 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 $^{2}H/^{1}H$ ratio in the sample divided by the $^{2}H/^{1}H$ 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 from rapid filtration 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 from **surface water** sources has been subjected to evaporation; values 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 Sibley County samples plot along the meteoric water line, in the center and left portions of the stable isotope graph. This suggests precipitation infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies.

Five samples plot along the evaporation line: three lake samples collected from Clear, Titlow, and Swan lakes; one from the Minnesota River, and one from a well completed in the sg3 aquifer. The sample from the sg3 aquifer is directly downgradient from Severance Lake, though connectivity between the lake and the aquifer is not readily apparent.

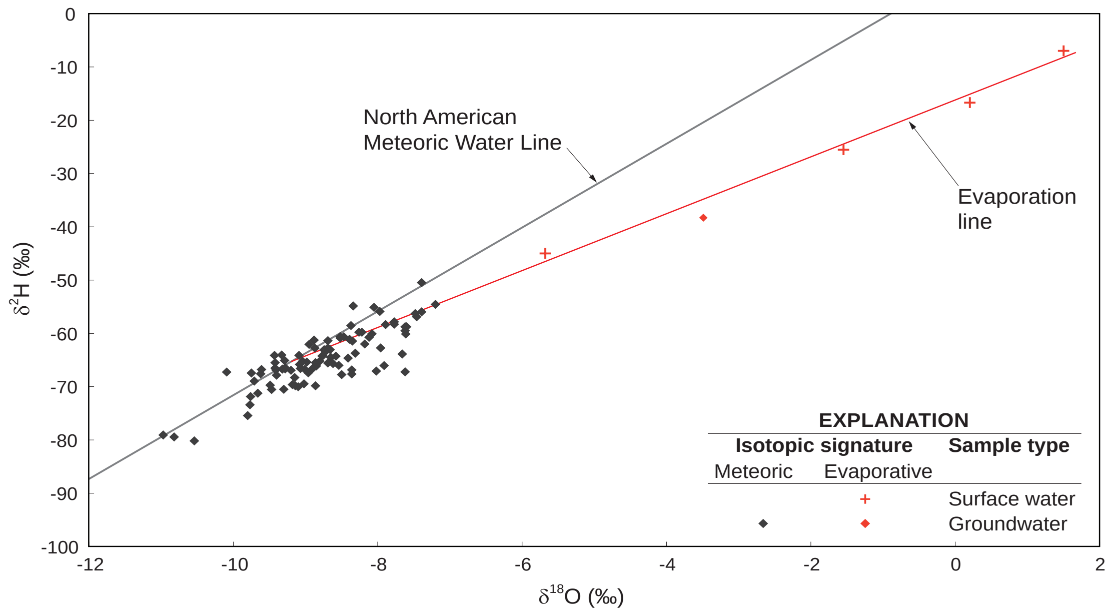


Figure 15. Graph of stable isotope values from water samples

Stable isotope values from water samples are compared to the meteoric water line. The red symbols are 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 a high groundwater flow velocity or short travel paths; long residence time suggests a low groundwater flow velocity or long travel paths. The residence time of groundwater is estimated using isotopic analysis of the radioactive elements tritium and carbon-14.

Tritium

Groundwater residence time can be interpreted from the concentration of tritium. Although tritium is a naturally occurring isotope of hydrogen, atmospheric concentrations of this isotope greatly increased between 1953 and 1963 by atmospheric testing of nuclear weapons (e.g., Alexander and Alexander, 1989). Hydrologists can estimate recharge timing using tritium's 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 concentrations of tritium, nitrate, and chloride) with the calculated sensitivity (Figures 22 through 30).

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 waters (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 and major anions, which are typically found in parts per million (ppm), and select elements that typically are found in trace amounts in parts per billion (ppb). Information shown on Plate 7 is for chemical constituents that indicate anthropogenic impacts, a concern for human health, or have 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 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 Sibley County (Figure 16).

Sodium 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 16, where the recent and mixed tritium-age samples plot with a lower proportion of sodium than the vintage tritium-age samples.

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

Sulfate results: 26 of 105 samples (25 percent) 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 Sibley County. Elevated sulfate values were found in 14 of the 19 samples (73 percent) collected from units under the Heiberg till. Samples collected from areas primarily covered by Villard till had elevated sulfate in only 13 of 86 samples (15 percent). The Heiberg till has a higher amount of Cretaceous shale than the Villard till (Part A, Plate 4). The Cretaceous shale may be the source of increased sulfate.

Chloride and nitrate-nitrogen (nitrate) 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. Chloride can also be elevated due to naturally occurring residual brines or from shallow groundwater evaporation concentrating atmospheric chloride. Possible anthropogenic impacts are indicated by elevated chloride concentrations above 5 ppm, with a chloride/bromide ratio above 300. Groundwater with an elevated nitrate concentration (greater than 1 ppm) likely entered the ground within the past few years to decades, indicates anthropogenic sources, and confirms high aquifer sensitivity. The maximum contaminant level (MCL) for nitrate is 10 ppm (EPA, [1996]).

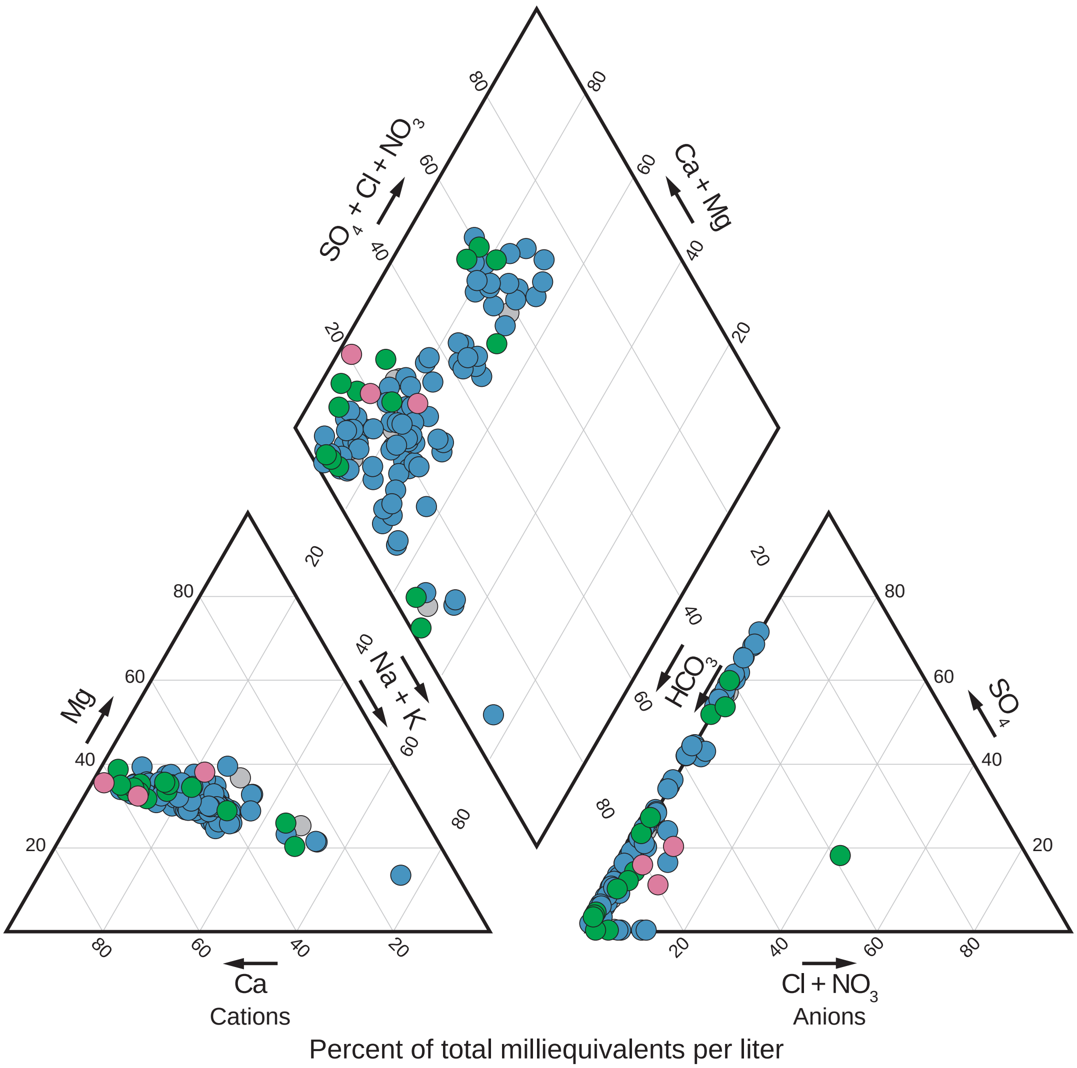
Chloride results: 25 out of 105 samples (24 percent) had an elevated chloride concentration above 5 ppm (Plate 7). Many of these had chloride/bromide ratios below 300 and were collected from shallow bedrock aquifers or buried sand and gravel aquifers near the bedrock surface. The source of chloride in these samples may be residual brine. Sample points indicate a brine source of chloride in the northwest and northeast corners of the county.

Nitrate results: Two samples had nitrate values above 1 ppm. Both were collected from aquifers with less than 50 feet of fine-grained sediment overlying the aquifer.

Environmental Protection Agency (EPA) standards

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

Secondary Maximum Contaminant Level (SMCL): nonenforceable guidelines for contaminants that may cause cosmetic 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 tritium units [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.

Chemistry

Bicarbonate (HCO_3)
Calcium (Ca)
Chloride (Cl)
Magnesium (Mg)
Nitrate (NO_3)
Sulfate (SO_4)

Figure 16. Piper diagram of water samples from the Minnesota Department of Natural Resources and Minnesota Pollution Control Agency

This diagram compares the relative proportions of cations and anions in the county water samples, 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 is from a natural source.

Naturally occurring elements of health concern

Although arsenic and manganese are found in lower concentrations than the major constituents discussed previously, low 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 concentrations 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 EPA requires that community water supplies not exceed 10 parts per billion (ppb) arsenic (EPA, 2001), but there is no such requirement for domestic wells. Well-water samples that have 5 ppb or more arsenic should be resampled to determine if the arsenic concentration of the first sample is a representative value.

- Arsenic concentrations greater than or equal to 10 ppb were found in 36 of the 95 water samples (38 percent). All of the samples that had 10 or more ppm arsenic were collected from buried sand and gravel aquifers. The percentage of wells with elevated arsenic is greater than the average across Minnesota (10.7 percent) (MDH, 2016).
- Arsenic concentrations greater than 5 ppb and less than 10 ppb were found in 15 water samples (16 percent): 13 in buried sand and gravel aquifers and 2 completed in bedrock (the Dakota aquifer and an undifferentiated Cretaceous aquifer).

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 to the northwest of Minnesota (Erickson and Barnes, 2005a). In part A of this atlas these are subdivided into Riding Mountain and Winnipeg provenance tills (Part A, Plate 4). Except for the Traverse till (tt) (Figure 4), all of the mapped till units throughout the county have a northwest provenance. Research also indicates that arsenic concentrations are greater in wells with short screened sections near the boundary of an aquitard and aquifer (Erickson and Barnes, 2005b; McMahon, 2000).

The source of the arsenic 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 is the most chemically available form, and is released under reducing conditions to groundwater (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.

Manganese concentrations exceeded 100 ppb in 62 of 105 groundwater samples (59 percent). Concentrations exceeding 300 ppb were found in 20 of the 105 samples (19 percent). This indicates a natural water quality concern for the majority of well owners in the county.

- All of the mapped aquifers had at least one water sample that exceeded the 100 ppb lower HRL.
- The sample group for the sg3 aquifer had the lowest percentage of samples that exceeded the limit (50 percent).
- All the samples from the sh and unnamed aquifers had manganese values greater than 100 ppb. These aquifers have a small number of samples, so this percentage may not accurately represent the aquifer as a whole.

Minnesota Department of Health standard

Health Risk Limit (HRL): 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

Aquifer	Arsenic						Manganese					
	Number of Samples	Samples ≥ 5 and < 10 ppb	Samples ≥ 10 ppb	Minimum Value	Median Value	Maximum Value	Number of Samples	Samples ≥ 100 and < 300 ppb	Samples ≥ 300 ppb	Minimum Value	Mean Value	Maximum Value
Buried sand and gravel												
sh	2	0	1	4.4	10.2	16	2	1	1	120	222	324
sm	4	1	2	1.66	19.25	40	4	2	1	70	197	510
st	12	1	10	1.8	26.5	40	13	5	1	3	122	318
sb	3	2	1	7.58	8.2	32	3	2	0	40	93	130
sg1	12	1	10	6.2	22	39	14	4	4	42	242	960
sg2	16	3	5	0.3	4.46	28	18	5	6	1	289	1230
sg3	13	2	4	0.29	5.5	22	14	5	2	19	161	473
sg4	5	2	0	0.42	6.5	8.3	5	2	1	40	206	520
suu	6	0	1	0.29	2	12	7	3	1	48	244	1040
unnamed	4	1	2	9.5	17	64.3	5	4	1	121	207	374
All buried sand and gravel totals	77	13	36	0.29	10.92	64.3	85	33	18	1	208	1230
All bedrock	18	2	0	0.3	1.88	6.4	20	9	2	13	137	630
All aquifers	95	15	36	0.29	5.6	64.3	105	41	20	1	194	1230

Hydrogeologic cross sections - Plate 8 and Figure 17

Four hydrogeologic cross sections (Plate 8) illustrate the horizontal and vertical extent of aquifers and aquitards, groundwater residence time, and general direction of groundwater flow. These were selected from a set of 30 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 CWI, and the following components of the Part A atlas: bedrock geology map (Plate 2), surficial geology map (Plate 3), and Quaternary stratigraphy plate (Plate 4). The well information for each cross section was projected 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.

Figure 17 is a unique example of recharge that is not shown on Plate 8.

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, cobbles, and boulders), the potential for fine sediment to fill pore spaces, or fractures in the shallow till units.

The percent sand in each of the aquitards is based on the average matrix texture of each fine-grained unit (Part A, Plate 4, Table 1). 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; darker shades represent aquitards with lower relative hydraulic conductivity.

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. 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 Sibley County is initially downward, then laterally toward the Minnesota River along the eastern border of the county (Plate 8 and Figure 17). There is a portion of the groundwater flow that is out of the cross section in the western part of the county, moving southward through neighboring Nicollet County toward the Minnesota River.

Large focused groundwater recharge zones are not common in the county because of the low permeability glacial sediment at the land surface and generally level topography. Small focused groundwater recharge areas are identified in the “Recharge interpretations” section where aquifers are interconnected. Rapid recharge from the land surface is indicated in areas of mixed or recent tritium age, or elevated chloride or nitrate (Plate 7 and Plate 8).

Most of the county has fine-grained glacial sediment at the land surface with relatively low permeability that limits groundwater recharge. Limited areas with relatively thick surficial sand and gravel deposits are rarely closely connected to underlying aquifers.

Recent or mixed tritium-age water may occur in the following recharge situations, indicated using the symbols shown below, on Plate 8, Figure 17, and Figures 22 through 30.

Recharge interpretations

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

Shallow, relatively isolated occurrences of the surficial sand and gravel (ss) aquifer are interpreted as recharge areas where they have recent or mixed tritium ages. However, because the ss aquifer is generally not used for water supply, no chemistry data were collected. One area of probable recharge is in the southeastern part of the county near the Minnesota River (eastern edge of D–D′ and Figure 17).

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 mixed or recent tritium-age groundwater. An example of this type of recharge is south of Gaylord (center of D–D′), where the sv aquifer is being recharged by the overlying ss aquifer. This type of recharge is also taking place along the southeastern border of the county (Figure 17) where the ss aquifer is recharging the st aquifer through a layer of unit g1 (Figure 4).

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

This condition only occurs in a few places across the county. An example is in the southeastern portion of the county (Figure 17). The st aquifer is recharging the sg2 aquifer through 40 feet of fine-grained sediment at this location. The recharge moving rapidly through the fine-grained sediment is most likely the result of a high gradient near the Minnesota River.

Ⓛ Groundwater is suspected to flow laterally.

Predominantly lateral groundwater flow was only identified in one location west of Green Isle. This location is not shown on the cross sections. In this area the sg2 aquifer is being recharged from a series of stacked sands to the west.

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

A mixed or recent tritium-age sample was collected from an aquifer that was overlain by more than 40 feet of fine-grained sediment, without an apparent connection to the surface. The source of mixed or recent tritium-age water may be due to: higher hydraulic conductivity within the fine-grained sediment than expected, presence of unmapped sand units, or improper well construction.

Carbon-14 data

Carbon-14 samples were collected from 16 wells: 10 for this project and 6 historic samples prior to this project. Plate 8 contains 13 samples. Two pairs of wells are close to another carbon-14 sample. The deeper groundwater sample from each pair (well nest) has an older carbon-14 age.

Two water samples were collected by the DNR during this study from wells located approximately 1.5 miles from each other (central portion of cross section B–B′). The shallower water sample was collected from the sb aquifer and had a carbon-14 age of 2,000 years The deeper sample was collected from the sg4 aquifer, upgradient from the first sample, and had a carbon-14 age of 13,000 years.

Two carbon-14 samples from nested wells were collected by the DNR in 2009 from the suu aquifer and the Mt. Simon aquifer (central portion of cross section C–C′). These two wells had similar carbon-14 ages (18,000 and 17,000 years respectively), indicating that the aquifers may be connected. A water sample collected from the shallower st aquifer upgradient of these nested wells had a carbon-14 age of 8,000 years Additional carbon-14 data samples are shown on the cross sections.

Discharge interpretations

Ⓓ Groundwater discharges to surface water.

Groundwater supplies water that is vital to aquatic ecosystems through discharge to rivers, lakes, and wetlands. Across Sibley County the water table indicates that there is discharge from the surficial sand and gravel aquifer to the lakes, streams and wetlands (Plate 8). The equipotential lines on the cross sections indicate that the buried aquifers discharge to the Minnesota River along the eastern border of the county.

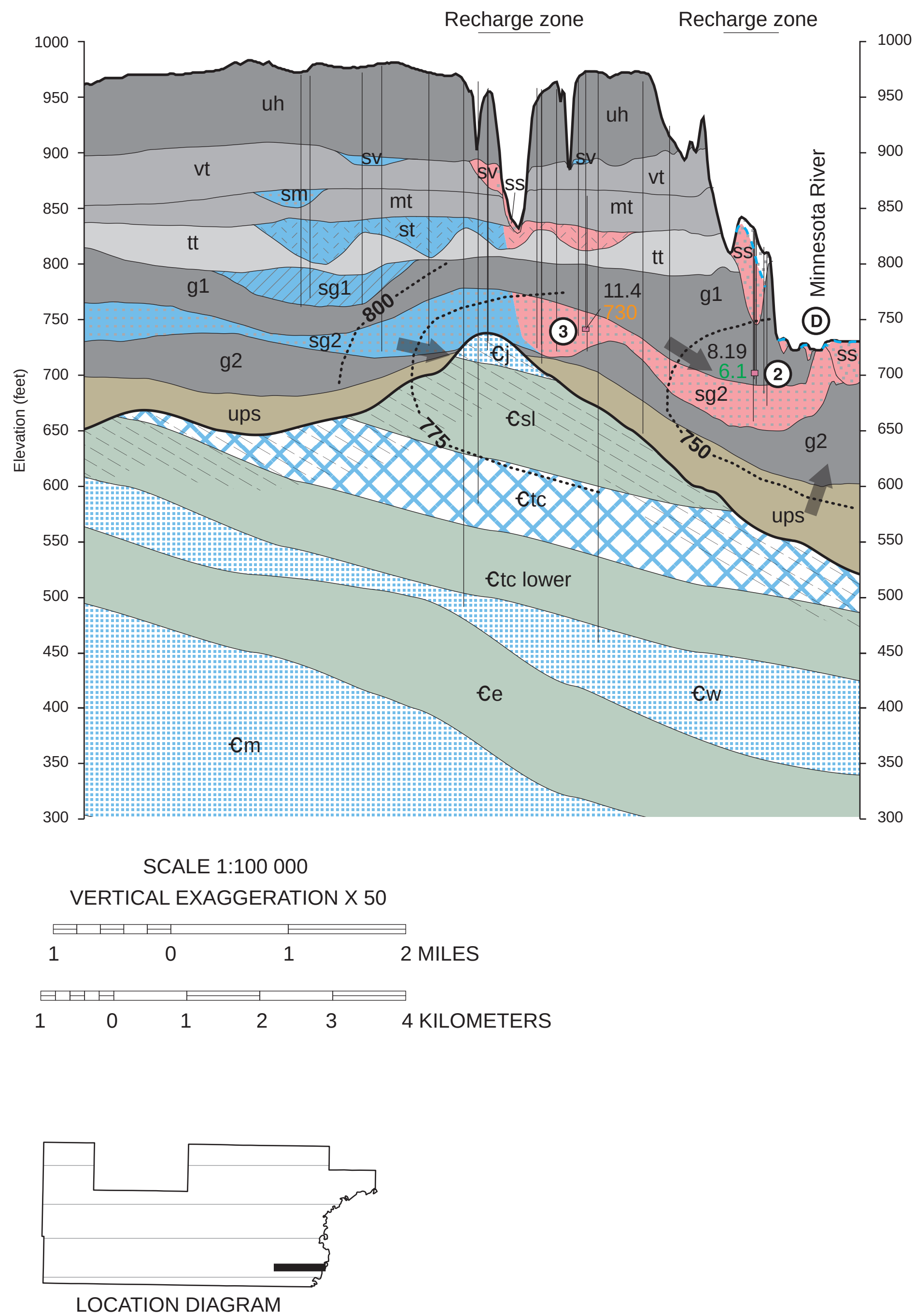


Figure 17. Example of a series of stacked sand and gravel aquifers

This cross section (not shown on plate 8) shows recharge into aquifer sg2 from a surficial aquifer and continued flow to the Minnesota River.

CROSS SECTION EXPLANATION

Aquifers and aquitards grouped by stratigraphy

Interpreted tritium age is indicated by background color

Interpreted tritium age is indicated by pattern color

Quaternary unconsolidated sediment (see Figure 4 for geologic unit correlation)

Surficial sand and gravel

- ss

Buried aquifers and aquitards

- uh
- sv
- vt
- sm
- mt
- st
- tt
- sg1
- g1
- sg2
- g2
- Undifferentiated sediment (ups)

Bedrock

- Ꞓj — Jordan
- Ꞓsl — St. Lawrence Formation
- Ꞓtc — Upper Tunnel City
- Ꞓtc lower — Lower Tunnel City Group
- Ꞓw — Wonewoc
- Ꞓe — Eau Claire Formation
- Ꞓm — Mt. Simon

Enhanced-permeability zone

Quaternary aquitards

Grouped by texture ranging from highest to lowest sand content indicating relative hydraulic conductivity.

Geologic unit code	Percent sand
tt	>50% and ≤60%
mt, vt	>40% and ≤50%
g1, g2, uh	>30% and ≤40%

Tritium age

Darker color in small vertical rectangle (well screen symbol) indicates tritium age of water sampled in well. Lighter color indicates interpreted age of water in aquifer.

Recent: water entered the ground since about 1953 (8 to 15 tritium unit [TU]).

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

Symbols and labels

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

6.1 If shown, nitrate-nitrogen concentration equals or exceeds 1 part per million.

730 If shown, manganese concentration equals or exceeds 100 parts per billion.

General groundwater flow direction

····750···· Approximate equipotential contour; contour interval 25 feet

Geologic contact

Land or bedrock surface

Water table

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.

(D) Groundwater discharges to a surface-water body.

Legend for Figure 17.

Pollution sensitivity

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 conditions, 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 each model.

- **Near-surface sensitivity (to a depth of 10 feet)**: sediment texture is the primary property used to create the map. The permeability of the sediment matrix texture is estimated based on hydrologic theory and 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 is 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 travel time through the unsaturated zone to reach the water table, which is assumed to be 10 feet below land surface. The first 3 feet are assumed to be soil and the next 7 feet (3–10 feet) are assumed to be surficial geologic 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. 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 travel time (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 travel time through the near-surface materials varies from hours to approximately a year (Figure 18).

- Areas with a relatively short travel time (hours to a week) are rated high sensitivity.
- Areas with a longer travel time (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 19) indicates that the interior of the county has low to very low near-surface sensitivity. Moderate to high pollution sensitivity ratings are found throughout the Minnesota River valley along the eastern border. It is also distributed sporadically through the interior of the county, typically along stream valleys or in regions of buried stream sediment.

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	Qat, Qat1, Qat2, Qat3, Qat4, 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, Qf
		sandy loam	0.28	Qvw
--	--	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, Qvh, Qvm, Qvc
		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 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.

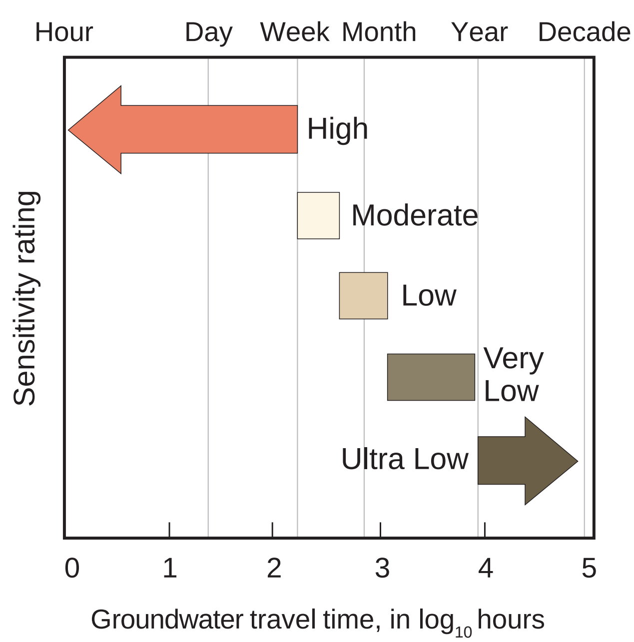


Figure 18. Geologic sensitivity rating for the near-surface materials

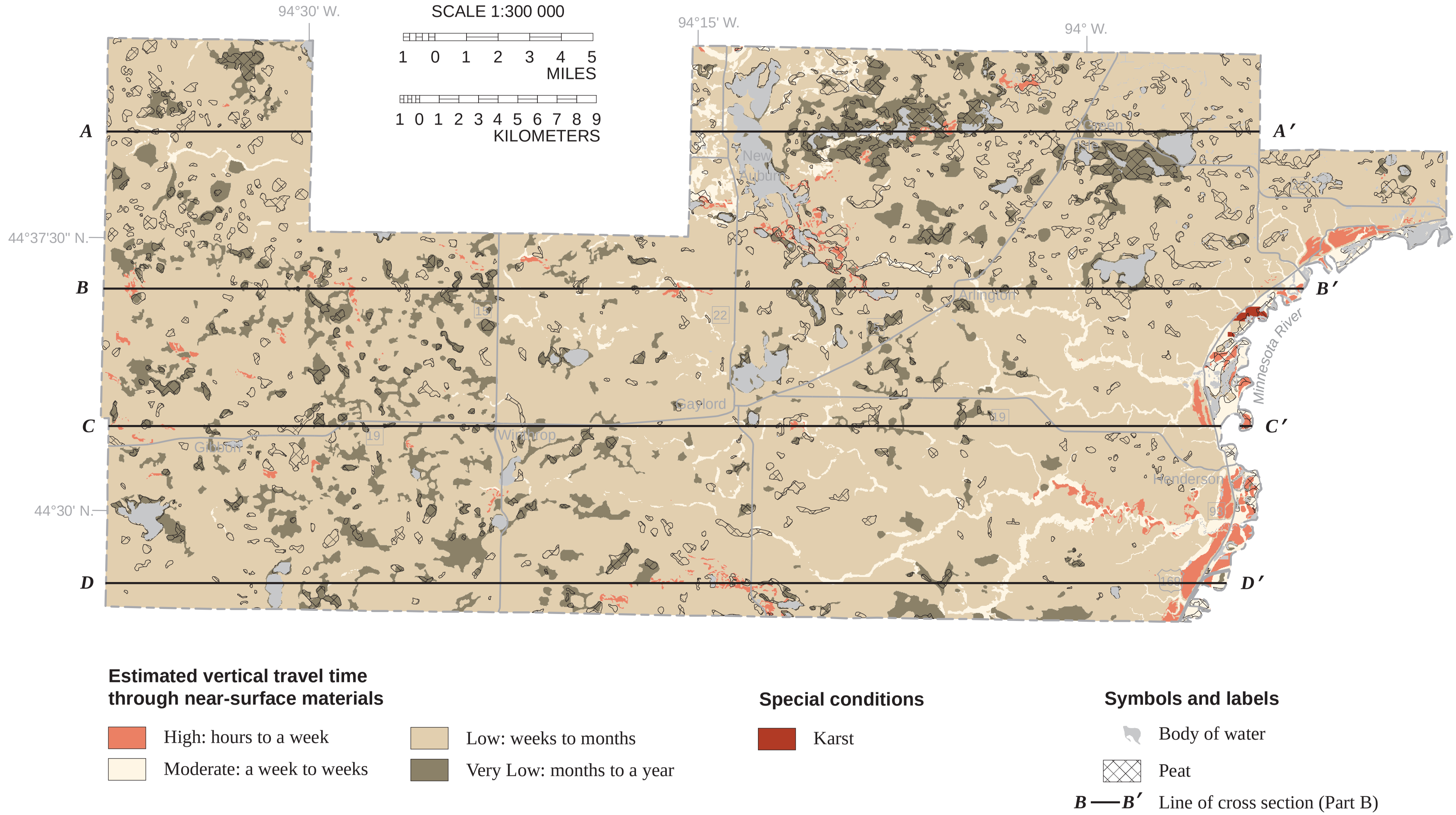


Figure 19. Near-surface pollution sensitivity

Low to very low pollution sensitivity ratings are common across most of the county. The exception is in river and stream valleys, which are primarily found along the eastern border (Minnesota River valley). Peat deposits from the Part A surficial geology map (Part A, 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 Adams, 2016b, Plate 1).

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 (Figure 20).

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

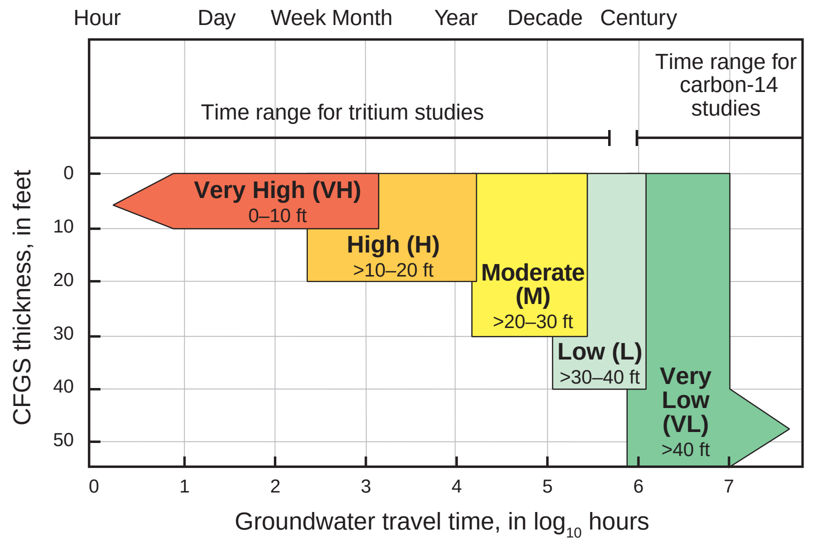


Figure 20. Geologic sensitivity rating for the buried sand and gravel aquifers and the bedrock surface

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 21). 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. 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)*. A more detailed explanation is available in *Buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment (CFGS) thickness* (DNR, 2016c).

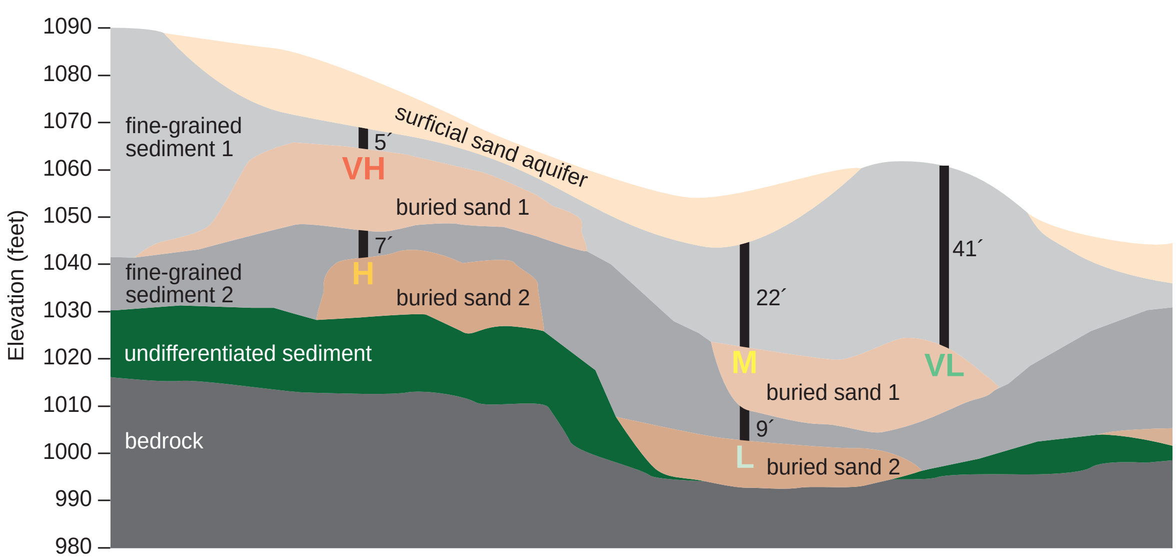


Figure 21. Cross section showing examples of pollution sensitivity ratings

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 illustrate the distribution of particular chemical constituents.

sh and sv aquifer (Figure 22)

- 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 aquifer is less than 50 feet below the land surface (Part A, Plate 5, Figure 3). The thickness of the aquifers vary from 20 to 120 feet. Because it is a shallow, nonextensive aquifer, there are only four of these wells in the county.
- Sensitivity: moderate to very high conditions are common.
- Chemistry: two samples from the sh aquifer
  Mixed tritium age: one sample, collected from a moderately sensitive area northwest of Gibbon, had a mixed tritium age and an elevated chloride value of 8.56 ppm, which is most likely due to the shallow depth of the aquifer.
  Vintage tritium age: one sample was collected from a very low sensitivity area south of Winthrop.

sm aquifer (Figure 23)

- Depth varies from shallow (0 to 50 feet) to moderate (150 to 200 feet) below the land surface. Thicknesses vary from 20 to 120 feet (Part A, Plate 5, Figure 4).
- Sensitivity: typically very low. Some high sensitivity ratings are found in river valleys (primarily the Minnesota River valley) as well as in regions where the sm aquifer is overlain by thinner fine-grained sediment layers (e.g., west central section of the county).
- Chemistry: four samples
  Vintage tritium age: four samples were collected in very low sensitivity areas of the county.

st aquifer (Figure 24)

- Depth is primarily 50 to 200 feet below the land surface. Thicknesses are typically 20 to 60 feet (Part A, Plate 5, Figure 5).
- Sensitivity: very low across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface.
- Chemistry: 12 samples
  Mixed tritium age: five samples were collected from across the county. One was from a well north of Green Isle, one from a well north of Arlington, two in the northwestern part of the county, and one from a well west of Henderson just north of the Rush River. The mixed tritium-age samples are located in regions with very low pollution sensitivity ratings. One of the samples collected from the northwestern part of the county has a tritium value of 5.2 TU, and a high chloride concentration with a high chloride/bromide ratio, indicating an anthropogenic source of chloride. The source of tritium is vertical recharge from the overlying sm aquifer. The other four samples have unknown sources of recharge because there is more than 40 feet of fine-grained sediment overlying them and no readily apparent source for recharge.
  Vintage tritium age: seven samples are located in parts of the aquifer with very low pollution sensitivity. A sample near Gaylord had a carbon-14 age of 8,000 years.

sg1 aquifer (Figure 25)

- Depth is from 50 to 150 feet below the land surface in the northern half of the county and 150 to 250 feet below the land surface in the southern half of the county. Thickness varies from 20 to 80 feet (Part A, Plate 5, Figure 6).
- Sensitivity: very low across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface and is overlain by surficial sand.
- Chemistry: 12 samples
  Mixed tritium age: one sample was collected from a well south of Winthrop. The sample tritium value was 1.4 TU, and does not have a readily identified source of tritium.
  Vintage tritium age: 11 samples were collected from areas with very low pollution sensitivity. The sample in the northwest corner of the county has an elevated chloride concentration, with a low chloride/bromide ratio. The elevated chloride could be the result of residual brine in this area. One of the samples in the southeastern corner of the county had a carbon-14 age of 8,000 years.

sg2 aquifer (Figure 26)

- Depth is 150 to 250 feet below the land surface; thickness is typically 20 to 80 feet (Part A, Plate 5, Figure 7).
- Sensitivity: very low across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface and is overlain by surficial sand.
- Chemistry: 16 samples.
  Recent tritium age: two samples were collected in the southeastern corner of the county near the Rush River. Tritium in these samples is the result of water recharging to a relatively shallow buried aquifer in the Minnesota River valley (Figure 17). Both of the samples have an elevated chloride concentration indicating an anthropogenic effect.
- *Mixed tritium age*: two samples were collected, one from the southeastern corner of the county and one from a well

north of Arlington. The sample from the southeastern corner had a tritium value of 1.3 and no readily apparent source for the tritium. The other sample had a tritium value of 1.6 TU. The most likely source of tritium for this well is lateral recharge from an area to the west that has a series of stacked aquifers overlying the sg2 aquifer.

Vintage tritium age: 12 samples were collected from areas with very low pollution sensitivity ratings. One sample in the northwestern corner of the county had an elevated chloride concentration that did not have an anthropogenic signature. The chloride in this sample is likely the result of residual brine mixing with the groundwater. A carbon-14 sample from one well near Buffalo Creek had an age of 15,000 years.

sg3 Aquifer (Figure 27)

- Depth is 150 to 300 feet below the land surface, with the exception of the river valleys where the aquifer is commonly within 100 feet of the land surface. Thickness runs typically 20 to 80 feet (Part A, Plate 5, Figure 8).
- Sensitivity: very low across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface and is overlain by surficial sand.
- Chemistry: 13 samples.
  Mixed tritium age: one sample was collected from a well northeast of Green Isle. The source of tritium in this well is unknown, though the tritium value was 1.2 TU, which is slightly above the threshold for classifying the water as vintage tritium age.
  Vintage tritium age: 12 samples were collected in areas of very low pollution sensitivity, three of the samples had an elevated chloride concentration without an anthropogenic signature, indicating some residual brines in the central and northeastern part of the county. Carbon-14 samples were collected from three wells in this aquifer with ages of 19,000 to 33,000 years.

sg4 Aquifer (Figure 28)

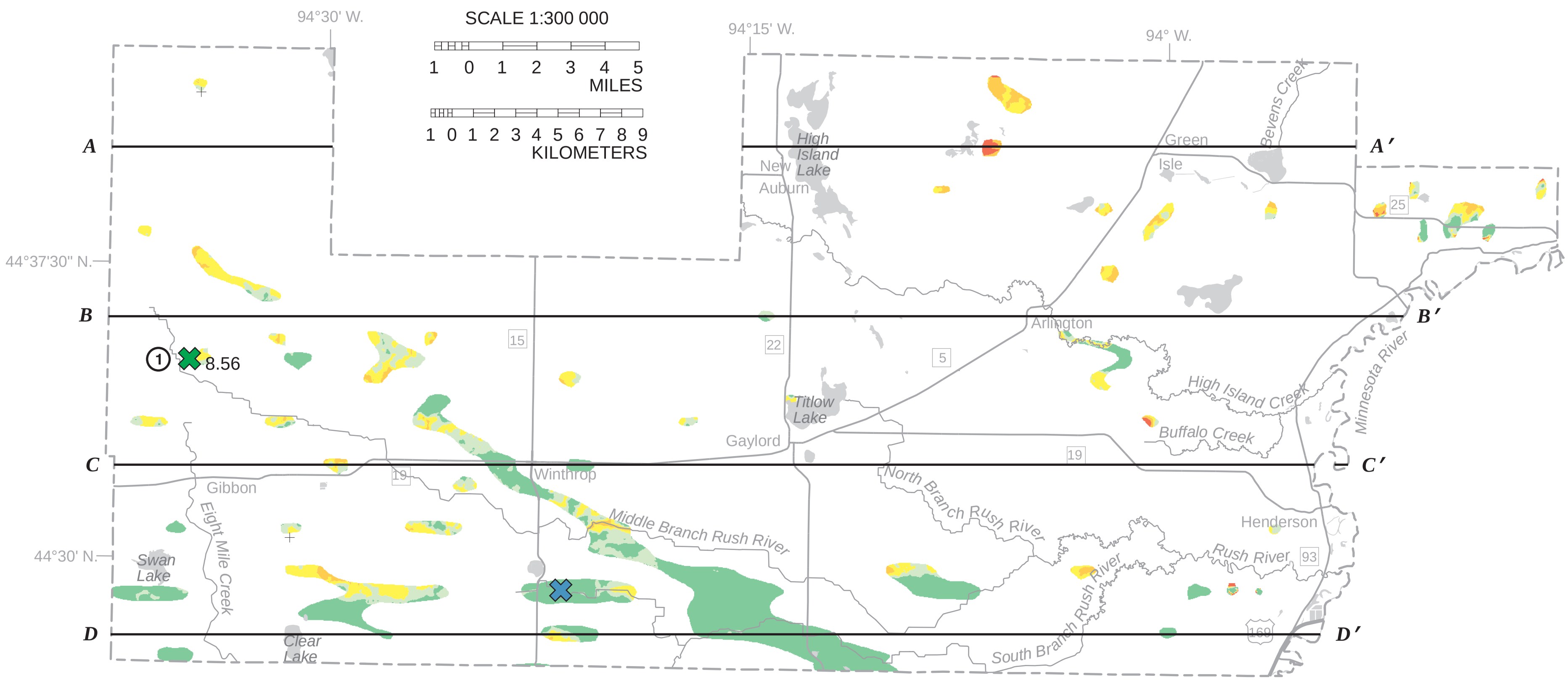
- Depth is 200 to 300 feet below the land surface, with the exception of the Minnesota River valley where the aquifer can be within 50 feet of the land surface. The thickness varies from 20 to 140 feet (Part A, Plate 5, Figure 8).
- Sensitivity: very low across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface and is overlain by surficial sand.
- Chemistry: five samples.
  Vintage tritium age: all five samples collected were from areas of very low pollution sensitivity. Carbon-14 samples were collected from two wells in this aquifer with ages of 5,000 and 13,000 years.

suu Aquifer (Figure 29)

- Depth is 200 to 350 feet below the land surface, with the exception of the river valleys where the aquifer can be within 100 feet of the land surface. Thickness varies from 0 to 200 feet (Part A, Plate 5, Figure 8).
- Sensitivity: very low across the county except in the Minnesota River valley, where the aquifer is located closer to the land surface and is overlain by surficial sand.
- Chemistry: seven samples.
  Vintage tritium age: all seven samples were collected from areas of very low pollution sensitivity. Elevated chloride concentrations with a low chloride/bromide ratio were found in four of the samples indicating residual brines in the northwest and northeast part of the county. Two carbon-14 samples were collected from this aquifer with ages of 18,000 and 40,000 years.

Bedrock surface (Figure 30)

- Depth is between 0 to 550 feet below the land surface (Part A, Plate 6).
- Sensitivity: rated as very low pollution sensitivity across the county, except a few small areas near the Minnesota River valley.
- Chemistry: 17 samples were collected from wells completed in bedrock aquifers.
  Recent tritium age: one water sample was collected from a well south of Green Isle. The source of the tritium in this well is unknown and could be the result of well construction issues. The well has elevated chloride concentration and a high chloride/bromide ratio indicating an anthropogenic source of chloride.
  Vintage tritium age: 16 samples were collected from bedrock aquifers in areas with very low pollution sensitivity ratings. In the northwest and the northeast corners of the county four wells had elevated chloride concentrations without an anthropogenic signature. This indicates that there may be residual brines in these areas. Carbon-14 samples were collected from five bedrock aquifer wells showing groundwater age from 8,000 to 19,000 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).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).

Groundwater conditions

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

Symbols and labels

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

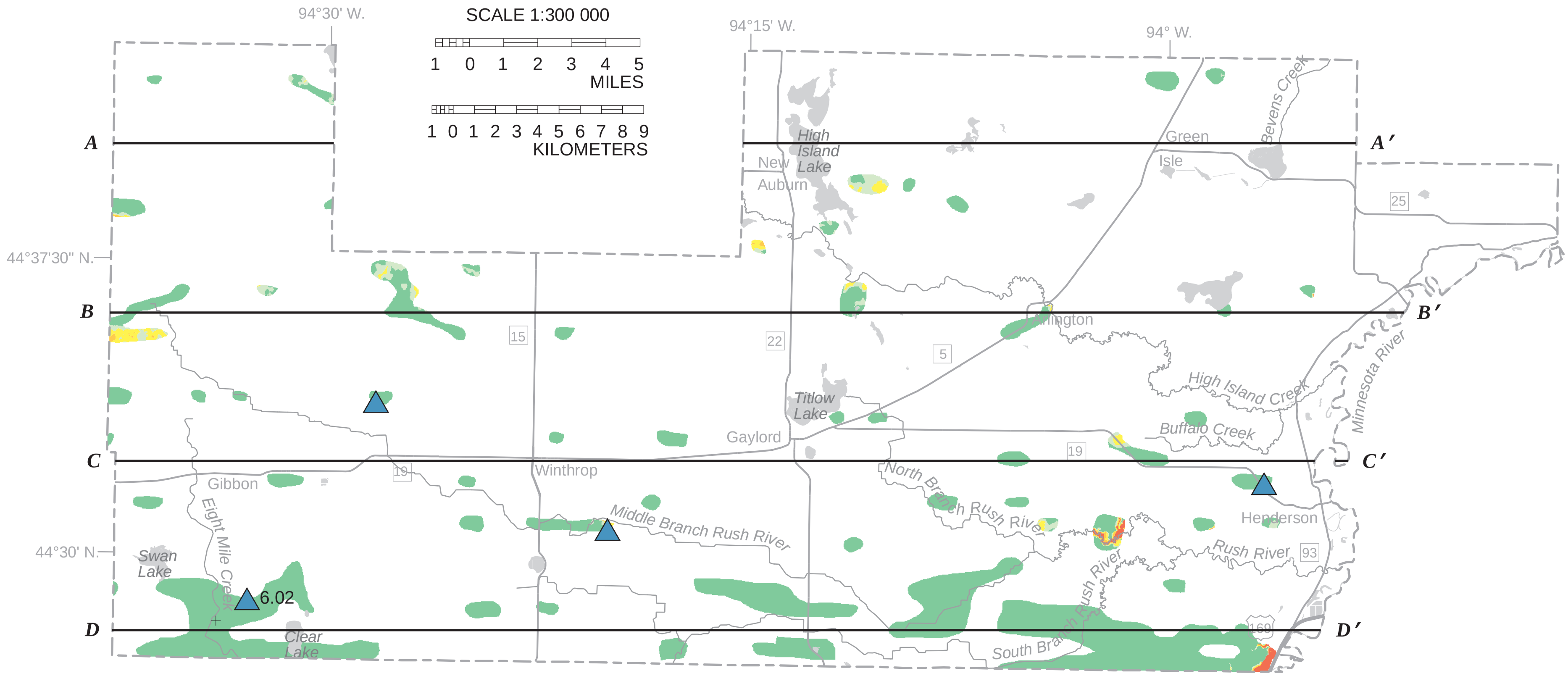
+ Static water level data

Body of water

B—B′ Line of cross section (Part B)

Figure 22. Pollution sensitivity of 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.



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.

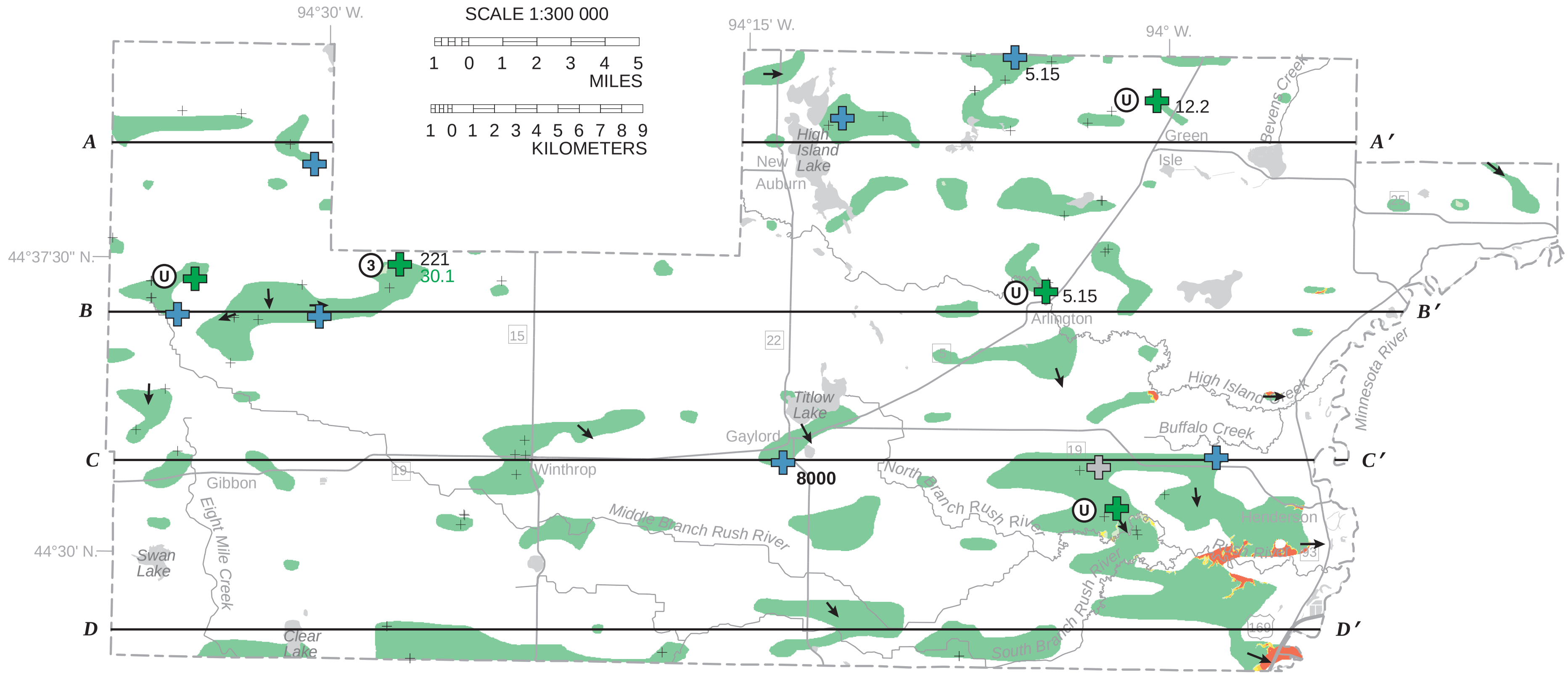
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).

Symbols and labels

- 6.02 — If shown, chloride concentration equals or exceeds 5 parts per million.
- + — Static water level data
- Body of water
- *B*——*B′* — Line of cross section (Part B)

Figure 23. Pollution sensitivity of 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 and in the west-central part of the county where the overlying till deposits are thinner.



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).
- 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.

U Groundwater flowpath is unknown (deep groundwater, recent or mixed tritium age).

Symbols and labels

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

30.1 If shown, nitrate-nitrogen concentration equals or exceeds 1 part per million.

8000 If shown, groundwater residence time in years estimated by carbon-14 (^{14}C) isotope analysis

Static water level data

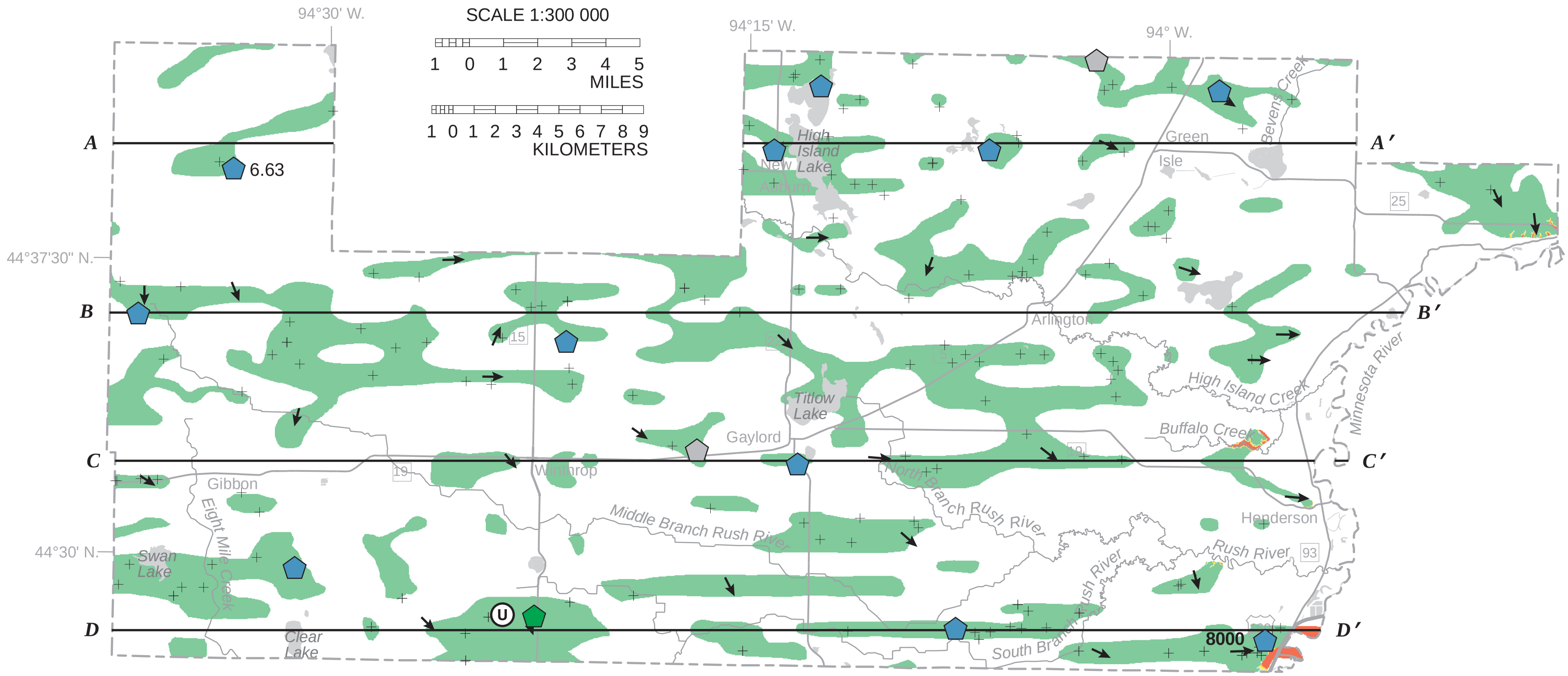
Body of water

Groundwater flow direction

B——*B′* Line of cross section (Part B)

Figure 24. Pollution sensitivity of 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.



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).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).
- Not sampled for tritium.

Groundwater conditions

U Groundwater flowpath is unknown (deep groundwater, recent or mixed tritium age).

Symbols and labels

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

8000 If shown, groundwater residence time in years estimated by carbon-14 (^{14}C) isotope analysis

Static water level data

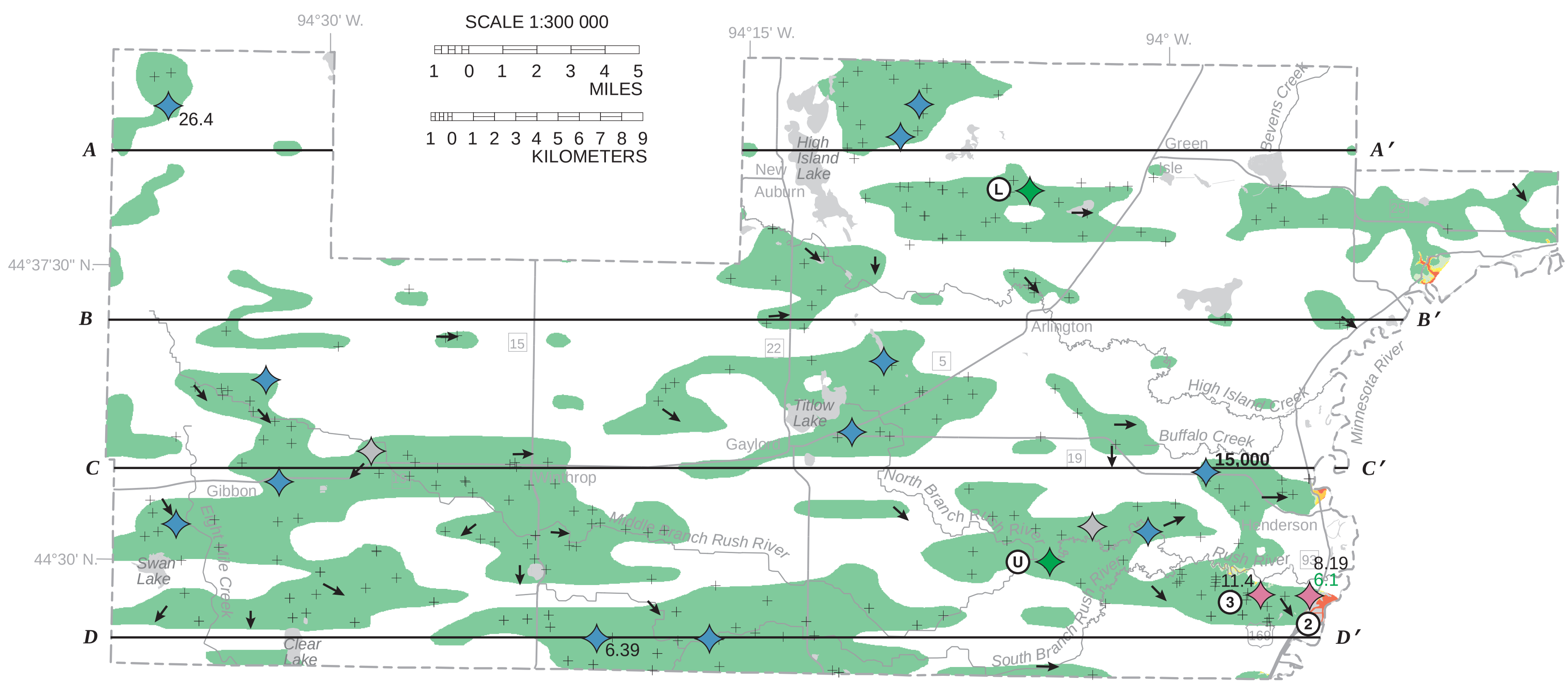
Body of water

Groundwater flow direction

B—B′ Line of cross section (Part B)

Figure 25. Pollution sensitivity of 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.



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

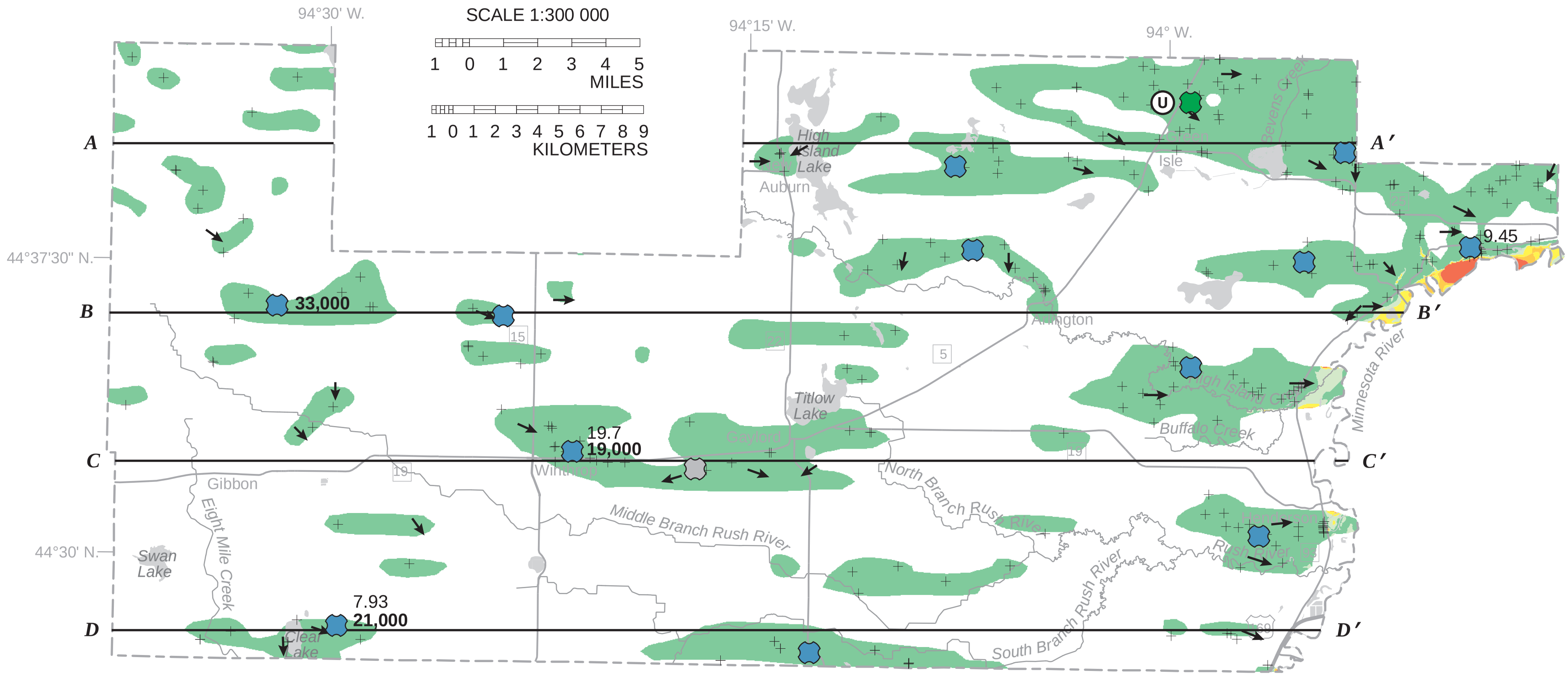
- 2 Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- 3 Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- L Groundwater flows laterally.
- U Groundwater flowpath is unknown (deep groundwater, recent or mixed tritium age).

Symbols and labels

- 11.4 If shown, chloride concentration equals or exceeds 5 parts per million.
- 6.1 If shown, nitrate-nitrogen concentration equals or exceeds 1 part per million.
- **15,000** 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 26. Pollution sensitivity of 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.



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).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).
- Not sampled for tritium.

Groundwater conditions

U Groundwater flowpath is unknown (deep groundwater, recent or mixed tritium age).

Symbols and labels

- 7.93 If shown, chloride concentration equals or exceeds 5 parts per million.
- **19,000** 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 27. Pollution sensitivity of buried sand and gravel aquifer sg3

The sg3 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.

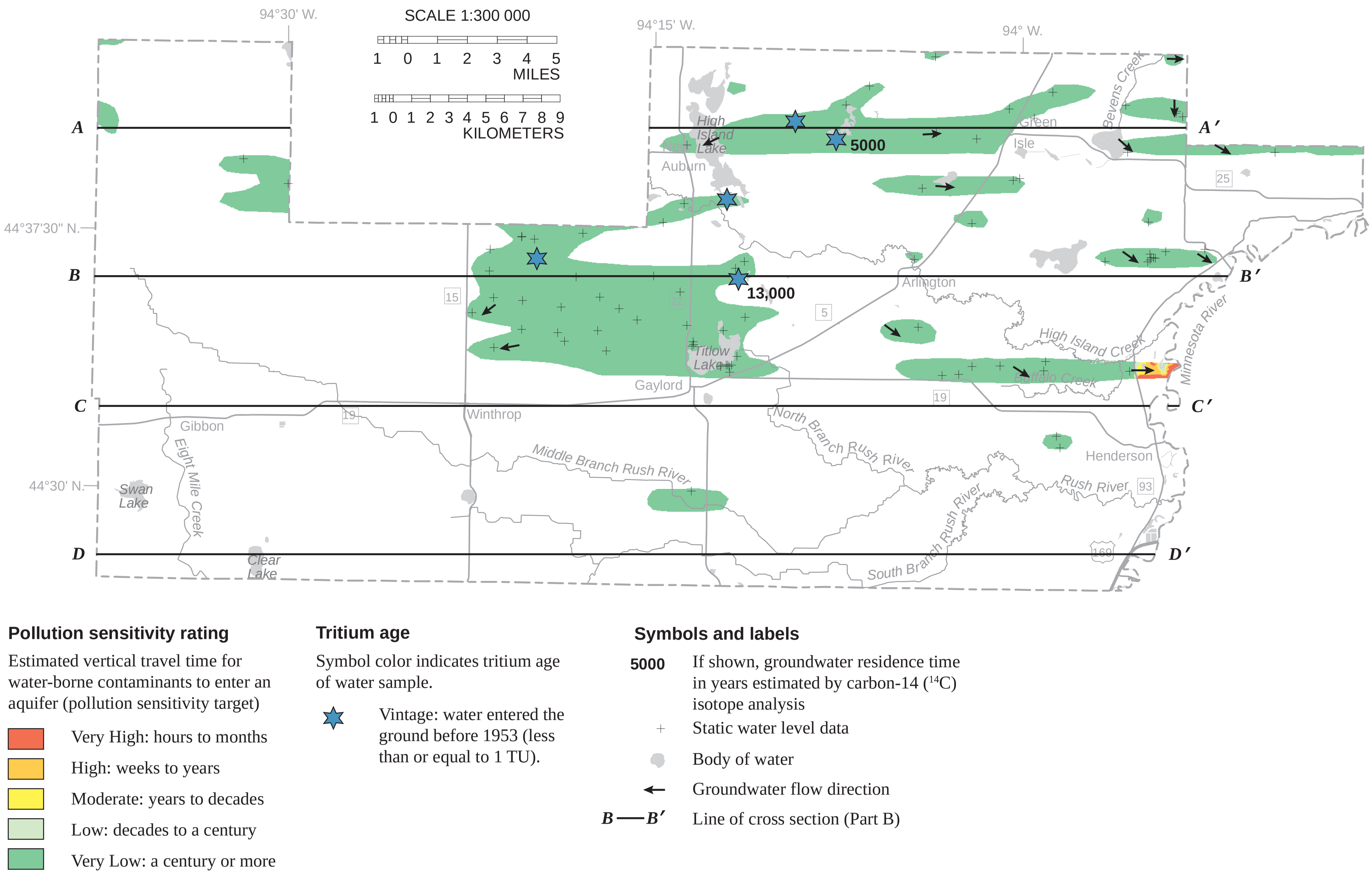
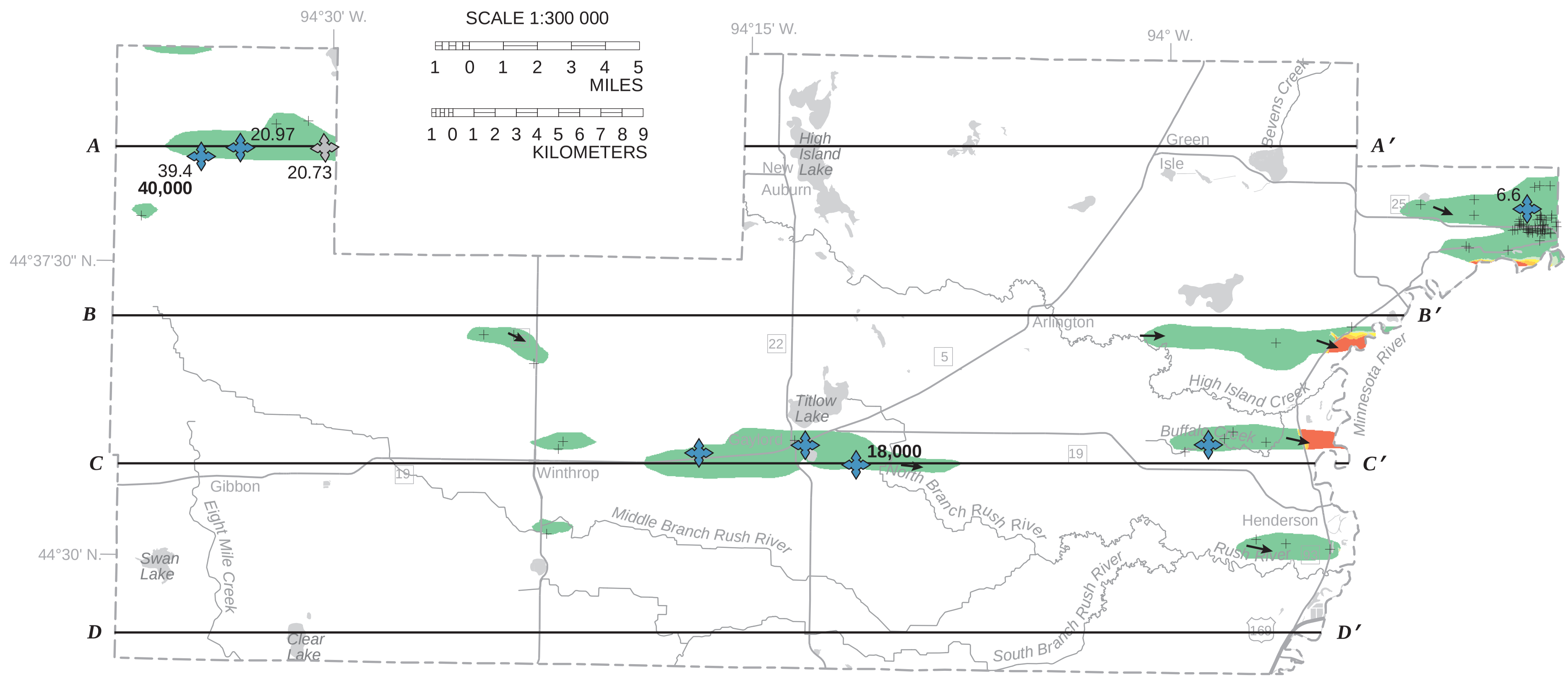


Figure 28. Pollution sensitivity of buried sand and gravel aquifer sg4

The sg4 aquifer has a very low pollution sensitivity rating except for in the Minnesota River valley in the east central part of the county, 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.

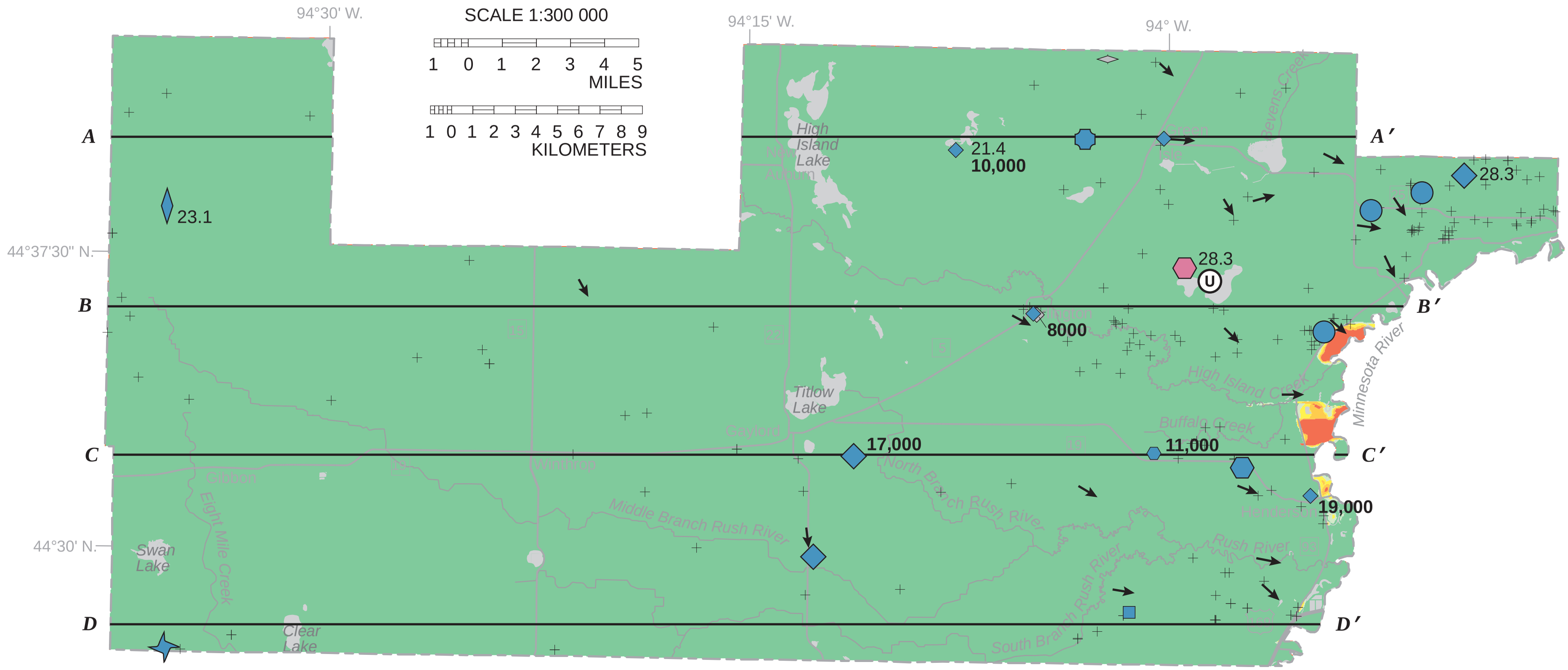
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).
- Not sampled for tritium.

Symbols and labels

6.6	If shown, chloride concentration equals or exceeds 5 parts per million.
18,000	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 29. Pollution sensitivity of buried sand and gravel aquifer suu

The suu aquifer has a very low pollution sensitivity rating except for in the Minnesota River valley in the east central part of the county, 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

Groundwater conditions

- (U) Groundwater flowpath is unknown (deep groundwater, recent or mixed tritium age).

Tritium age

Symbol color indicates tritium age of water sample.

- Recent: water entered the ground since about 1953 (8 to 15 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).
- Not sampled for tritium.

Aquifer source of groundwater sample

- Prairie du Chien, Prairie du Chien–Jordan
- 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

- 21.4 If shown, chloride concentration equals or exceeds 5 parts per million.
- **8000** 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 30. Pollution sensitivity of the bedrock surface

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

Groundwater use and aquifer characteristics

For this study 1,378 wells in Sibley County were assigned an aquifer unit based on the well log information and the geology presented in Part A. Of these wells, 77 percent draw groundwater from buried sand and gravel aquifers, 15 percent draw from bedrock aquifers, and 8 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. The permit requires that the water usage be reported annually. Information is recorded using Minnesota Department of Natural Resources Permitting and Reporting System (MPARS), which helps the DNR track the volume, source aquifer, and type of water use.

The reported groundwater use for 2013 is categorized for all large volume users in the county by the type of aquifer and type of use (Table 3 and Figure 31). Water use permits across Sibley County are located primarily near cities, with a few exceptions for wells used for ethanol production and livestock watering in the central portion of the county.

Buried sand and gravel aquifers accounted for 67 percent of the water pumped in 2013, with the majority drawing from the sg3 and suu aquifers. The remaining 33 percent of reported water use was pumped out of wells connected to the Mt. Simon aquifer.

The reported water was as follows: 72 percent for municipal water supplies, 24 percent for chemical processing, and 2 percent each for livestock watering and golf course irrigation.

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	Chemical Processing	Golf Course Irrigation	Total (MGY)	Total (Percent)
Buried sand and gravel							
sg1	1	--	6.8	--	--	6.8	**0.8**
sg2	4	31.6	--	--	16.6	48.2	**5.9**
sg3	7	121	7.9	--	--	128.9	**15.8**
suu_sg3	1	--	--	97.1	--	97.1	**11.9**
suu	4	265.8	--	--	--	265.8	**32.9**
Buried sand and gravel total	*17*	*418.4*	*14.7*	*97.1*	*16.6*	*546.8*	**67.2**
Bedrock							
Jordan–Mt. Simon	1	1.1	--	--	--	1.1	**0.1**
Eau Claire–Mt. Simon	1	45.7	--	--	--	45.7	**5.6**
Mt. Simon	5	119.7	--	100.9	--	220.6	**27.1**
Bedrock total	*7*	*166.5*	--	*100.9*	--	*267.4*	**32.8**
Total (MGY)		**584.9**	**14.7**	**198**	**16.6**	**814.2**	--
Total (percent)		**71.5**	**1.8**	**24.2**	**2.0**	--	--

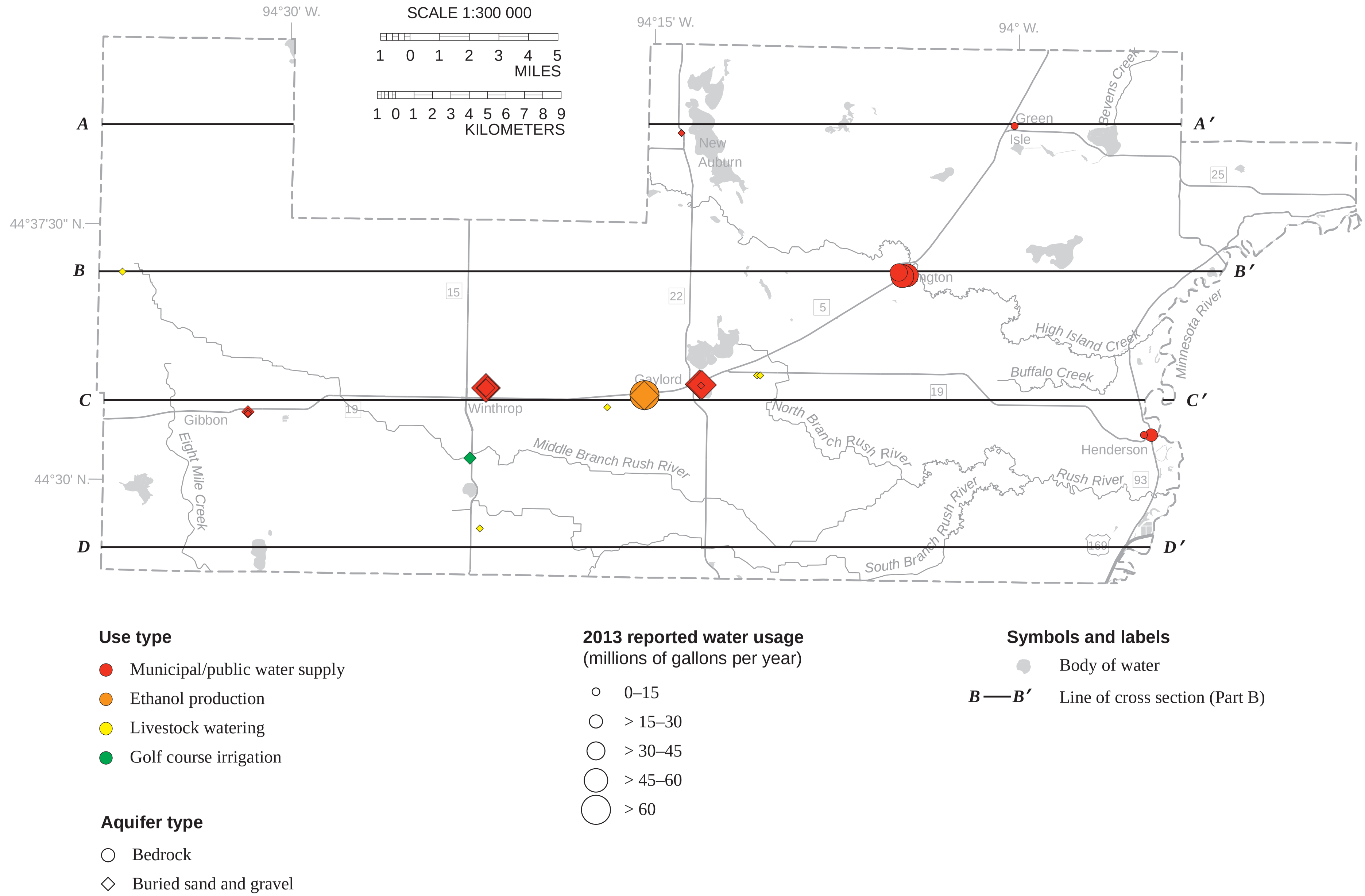


Figure 31. Wells with DNR groundwater appropriation permits

The primary use type for the permitted water is municipal/public water supply. Permitted water use was primarily from buried sand and gravel aquifers.

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, and evaluating water conflicts.

Sibley County has four DNR observation wells (Figure 32). All of the wells were drilled as part of an investigation of the Mt. Simon aquifer by the DNR in 2008–2009 (Berg and Pearson, 2011). The four wells make up two paired well nests 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. 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 and the depth of the wells.

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, which are lower in the summer and higher in the winter, and that all of the well nests show groundwater flowing downward. These continue to be monitored by the groundwater level monitoring program of the DNR. Data are available to be downloaded from the DNR Cooperative Groundwater Monitoring website (DNR, 2015).

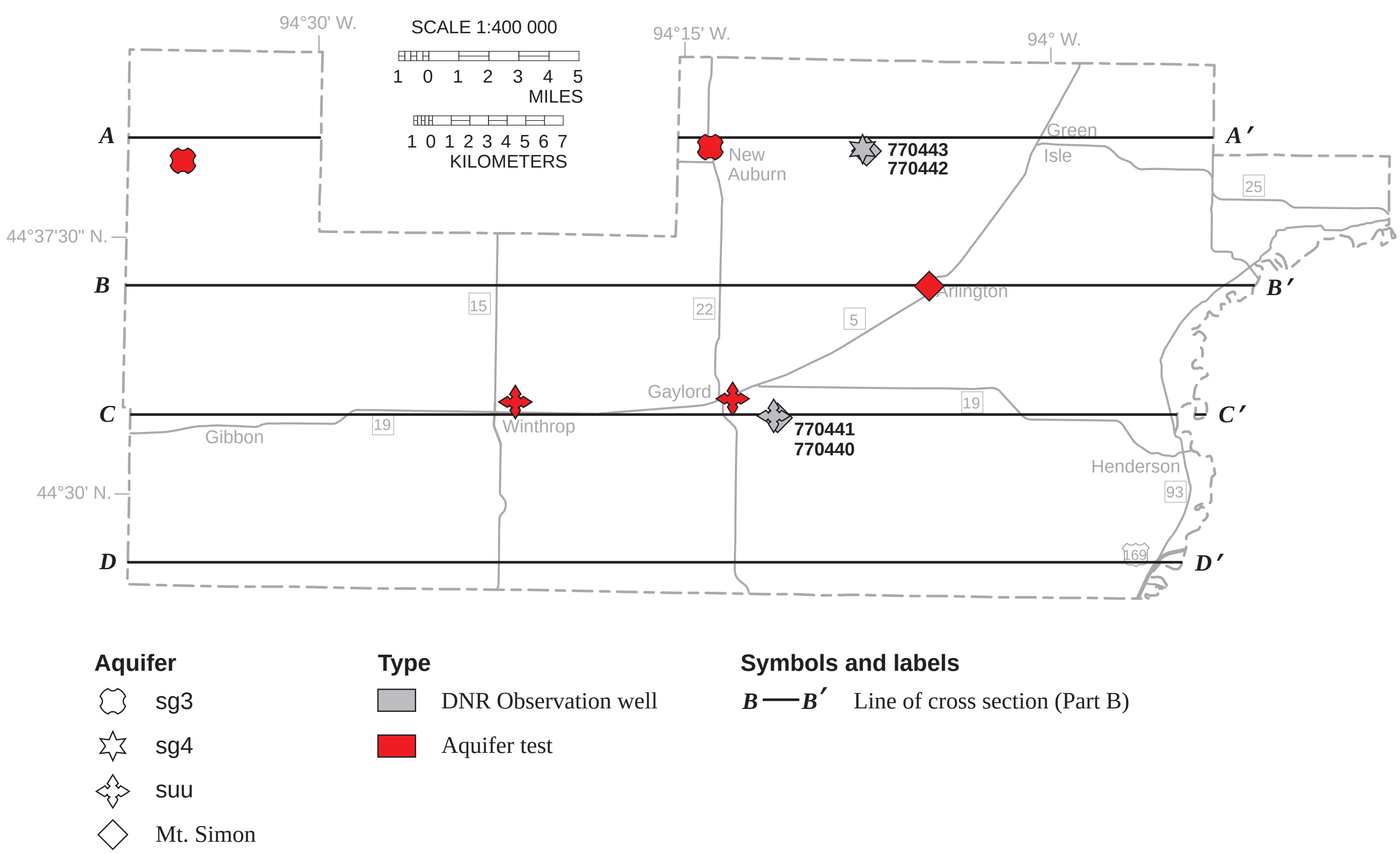


Figure 32. Aquifer tests and observation wells

Observation wells are labeled with identification number.

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 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. The pumping-test data for specific capacity were obtained from CWI for wells with the following conditions to make sure that the data reflect actual pumping:

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

The suu aquifer had the highest specific capacity value (Table 4) of the buried sand and gravel aquifers. The Mt. Simon aquifer ranged from 4.2 to 18.9 gpm/ft.

Transmissivity data was calculated from longer term and larger scale aquifer tests that provide a better test of the aquifer properties. Transmissivity data provide more accurate aquifer parameters than specific capacity values determined at individual wells. Five different aquifer tests in the sg3, suu, and the Mt. Simon aquifer have available transmissivity values in Sibley County (Table 4 and Figure 32). The suu aquifer had the highest transmissivity values: 47,800 and 60,000 gpd/ft.

Table 4. Specific capacity and transmissivity of selected wells

[Specific capacity data adapted from CWI; gpm/ft, gallons per minute per foot.
Transmissivity data are from aquifer test data compiled by the DNR; gpd/ft, gallons per day per foot.]

Aquifer	Specific Capacity					Aquifer Tests		
	Number of tests	Well diameter (inches)	Min (gpm/ft)	Mean (gpm/ft)	Max (gpm/ft)	Number of tests	Well diameter (inches)	Transmissivity (gpd/ft)
Buried sand and gravel								
sg3	5	12	6.4	15.4	33.8	2	12 8	15,300 20,600
sg3_suu	1	12	--	6.9	--	--	--	--
suu	1	16	--	105.8	--	2	18 12	47,800 60,000
Bedrock								
Mt. Simon	4	12–18	4.2	10.25	18.9	1	12	35,900

Conclusions

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

The surficial sand and gravel 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. Nine buried sand and gravel aquifers are used in the county. The primary bedrock aquifers are located in the eastern half of the county: the Prairie du Chien, Jordan, Upper Tunnel City, Wonewoc, and Mt. Simon. Potentiometric surface maps compiled from static water level data from wells in both Sibley and Nicollet counties indicate a general pattern of groundwater flow toward the Minnesota River.

All but one 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. The groundwater sample with an evaporative signature was collected from the sg3 aquifer downgradient from Severance Lake, indicating recharge from the lake to the aquifer system.

Twenty-four percent of samples tested for chloride were above 5 ppm, many of which had low chloride/bromide ratios indicating that there may be some deep residual brine in the northwest and northeast corners of the county. Two samples had nitrate values above 1 ppm indicating an anthropogenic water source. Both of these samples were collected from wells with less than 50 feet of fine-grained sediment overlying the aquifer.

Twenty-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 which may be the source of increased sulfate.

Both arsenic and manganese are naturally occurring elements of health concern that are present in groundwater across the county. Arsenic concentrations greater than or equal to 10 ppb were found in 38 percent of the water samples analyzed for arsenic, which is greater than the average across the state of Minnesota. All of the elevated arsenic concentrations were collected from buried sand and gravel aquifers. Manganese concentrations that exceeded 100 ppb were found in 59 percent of the samples analyzed for manganese, with 19 percent exceeding 300 ppb. Concentrations greater than 300 ppb were primarily found in buried sand and gravel units with only two 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. A number of samples with mixed tritium ages were collected from areas with low to very low sensitivity and the source of the tritium is unknown. Tritium could have reached this depth due to: higher hydraulic conductivity within the fine-grained sediment than expected, presence of unmapped sand units, or improper well construction.

The pollution sensitivity ratings of the sh, sv, and sm aquifers are high 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 cities. Buried sand and gravel aquifers supplied 67 percent of the water pumped in 2013. The remaining 33 percent of water was pumped from wells connected to the Mt. Simon aquifer. Municipal water supply accounts for 71 percent of the permitted water use in the county.

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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.

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

Arsenic (As)—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—a body of porous and permeable sediment or bedrock 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 (CWI)—a database developed and maintained by the Minnesota Geological Survey and the Minnesota Department of Health 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.

deuterium (^2H)—one of two stable isotopes of hydrogen. The nucleus of deuterium contains one proton and one neutron.

dolostone, or dolomite rock—a sedimentary carbonate rock that contains a high percentage of the mineral dolomite. Most dolostone formed as a magnesium replacement of limestone or lime mud prior to lithification. It is resistant to erosion and can either contain bedded layers or be unbedded. It is less soluble than limestone, but it can still develop solution features over time.

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 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—relating to water movement.

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 (NO3–)—a polyatomic anion. 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 water level of groundwater. It is 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 cased wells.

provenance—the place of origin of a glacier.

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.

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. It is derived from the erosion and entrainment of rock and sediment over which the glacier has passed.

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 10^{18} hydrogen atoms.

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

vadose zone (unsaturated zone)—the layer between the land surface and the top of the water table.

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 in close proximity completed in different aquifers.

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 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 and geophysical data, are available from the Department of Natural Resources (DNR), County Groundwater Atlas page (mndnr.gov/groundwatermapping).

Maps were prepared from DNR and other 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, Sibley 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 and Holly Johnson. Edited by Ruth MacDonald.

Conversion Factors

12 inches = 1 foot

5280 feet = 1 mile

1 foot = 0.3048 meters

1 meter = 1000 millimeters

1000 meters = 1 kilometer

1 kilometer = 0.621 miles

1 inch per hour = 7.056×10^{-6} meters per second

1 part per million = 1 milligram per liter

1 part per billion = 1 microgram per liter

1 milligram per liter = 1000 microgram per liter

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The DNR Information Center

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