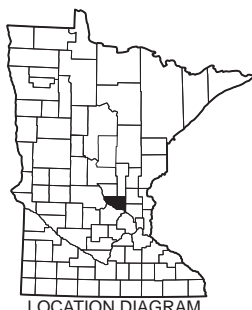


Geologic Atlas of Sherburne County, Minnesota

County Atlas Series C-32

Part B, Hydrogeology



LOCATION DIAGRAM

Report

To accompany these atlas components:

[Plate 6, Water Chemistry](#)

[Plate 7, Hydrogeologic Cross Sections](#)

m DEPARTMENT OF
NATURAL RESOURCES

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County Geologic Atlas Program

The Minnesota County Geologic Atlas series has been produced since 1982. Recent atlases are produced in two parts. For Sherburne County:

Part A covers the geology and was produced by the Minnesota Geological Survey (MGS) in 2013. It contains the following: Plate 1, Data-Base Map; Plate 2, Bedrock Geology; Plate 3, Surficial Geology; Plate 4, Quaternary Stratigraphy; Plate 5, Bedrock Topography, Depth to Bedrock, and Sand Distribution Model.

Part B: the Minnesota Department of Natural Resources (DNR) expanded on this information to cover the hydrogeology in this report.

Explanations of the history and purpose of the program, atlas applications, map sales, and descriptions of the atlas components are available online:

[Part A, MGS](http://www.mnngs.umn.edu/county_atlas/countyatlas.htm) (http://www.mnngs.umn.edu/county_atlas/countyatlas.htm)

[Part B, DNR](http://mndnr.gov/groundwatermapping) (mndnr.gov/groundwatermapping)

Technical Reference

Maps were compiled and generated in a geographic information system. Digital data products are available on the DNR County Geologic Atlas Program [page](http://mndnr.gov/groundwatermapping) (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 MGS 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.

The basemaps were modified from the MGS Sherburne County Geologic Atlas, Part A, 2013. Universal Transverse Mercator projection, zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion Factors

12 inches = 1 foot	1 kilometer = 0.621 miles
5280 feet = 1 mile	1 inch per hour = 7.056×10^{-6} meters per second
1 foot = 0.3048 meters	1 part per million = 1 milligram per liter
1 meter = 1000 millimeters	1 part per billion = 1 microgram per liter
1000 meters = 1 kilometer	1 milligram per liter = 1000 micrograms per liter

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Plates (separate inserts)

Plate 6, Water Chemistry

Plate 7, Hydrogeologic Cross Sections

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Geologic Atlas of Sherburne County, Minnesota, Part B

By James A. Berg

Introduction

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

The purpose of this atlas is to illustrate 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 into account aquifer sensitivity, water quality, and sustainability.

The **report** describes the hydrogeologic setting, water levels, chemistry, pollution sensitivity, and use of aquifers within the county, as well as the accompanying plates. **Plate 6** illustrates the water chemistry and **Plate 7** shows selected hydrogeologic cross sections to indicate groundwater flow directions and residence time within the buried sand and gravel aquifers and bedrock aquifers. The following information is incorporated to help visualize the distribution of aquifers, aquitards, groundwater recharge, and subsurface flow within the county.

Geology and physical hydrogeology outlines the characteristics of geologic units in the county. 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).

Water chemistry 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 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 locations of important groundwater recharge, discharge, and pollution sensitivity.

Pollution sensitivity is modeled for two conditions: 1) the near-surface materials and 2) the mapped buried sand and gravel aquifers and the bedrock surface.

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

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

Groundwater use and aquifer characteristics summarize specific capacity tests, aquifer tests, and water use records for each aquifer, where available. These data help hydrogeologists plan new wells to meet requirements for a given use.

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).

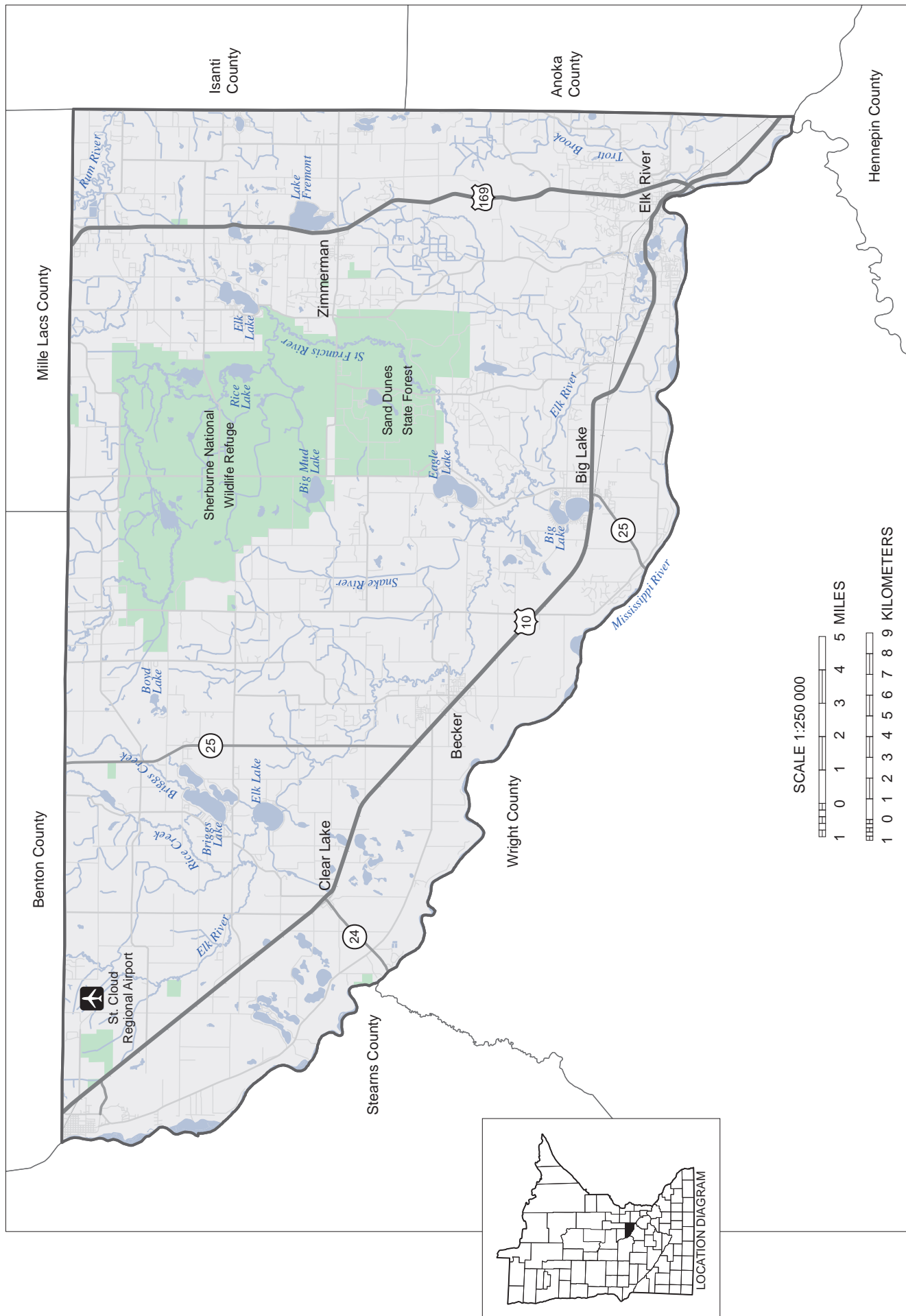


Figure 1. Sherburne County location map

Geology and physical hydrogeology

Sherburne County is located in east-central Minnesota (Figure 1). The southeastern portion of the county includes the northwestern fringe of the Twin Cities metropolitan area (Minneapolis and St. Paul). The county has a population of approximately 92,000 residents, according to a 2015 estimate (United States Census Bureau, 2016). A corridor along the western county boundary that parallels the Mississippi River has urban and suburban land use in the communities of Elk River, Big Lake, Becker, Clear Lake and a small

portion of eastern St. Cloud. A large state forest unit (Sand Dunes) and national wildlife refuge (Sherburne) occupy the east central portion of the county. The remainder of the county is mostly low density rural and small communities. The Mississippi River forms the western county border. The county lies within the watersheds of the Mississippi (St. Cloud and Twin Cities) and Rum rivers. The topography is level to rolling in most of the county.

Surficial geologic units and aquifers

The origin of the topography and surficial deposits can be traced back to late-glacial events (Part A, Plate 3) as ice retreated from the county and a proglacial lake formed. The relatively thick and widespread surficial sand and gravel of the Anoka sand plain is one of the most important geologic features controlling groundwater availability and the pollution sensitivity of underlying aquifers (Figure 2).

Two major glacial events set the stage for the abundant sand deposition in this area. The first event was the advance from the northeast and retreat of Superior lobe glaciers (Part A, Plate 3, Figure 4). These glacial episodes created the St. Croix moraine that dominates the topography of the counties that surround Sherburne County to the west, south, and east. This moraine is an area of thick glacial sediment and higher land elevations that were created as the edge of the glacier stagnated in and around the current Twin Cities metropolitan area.

In a second major event, another glacial ice lobe advanced into the region from the northwest (Des Moines lobe). A sublobe of this (Grantsburg sublobe) advanced to the northeast over the St. Croix moraine across the present-day Sherburne County and into Wisconsin. As this sublobe retreated, water from the melting glacial ice was trapped within the surrounding highlands of the St. Croix moraine, creating glacial Lake Anoka. Very fine to medium-grained sand accumulated in this glacial lake creating the sandy portion of the New Brighton Formation. This formation comprises most of the surficial sand in the eastern portion of the county. As the Grantsburg sublobe melted, outwash sand and gravel were deposited in a broad plain to the north and east of the retreating ice front.

Eventually the St. Croix moraine was breached by erosion, forming the present course of the upper Mississippi River. Early flow of glacial meltwater through the Mississippi River was much greater than current flow levels and created broad sand and gravel terraces several miles beyond

the present day Mississippi River valley. These deposits account for a major portion of the surficial sand and gravel in the southwestern portion of the county near the Mississippi River.

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.

Water-table elevation (Figure 3) is estimated from several sources of data:

- The elevation of surface-water bodies (e.g., 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 (NRCS) county soil survey (converted to elevations*)

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

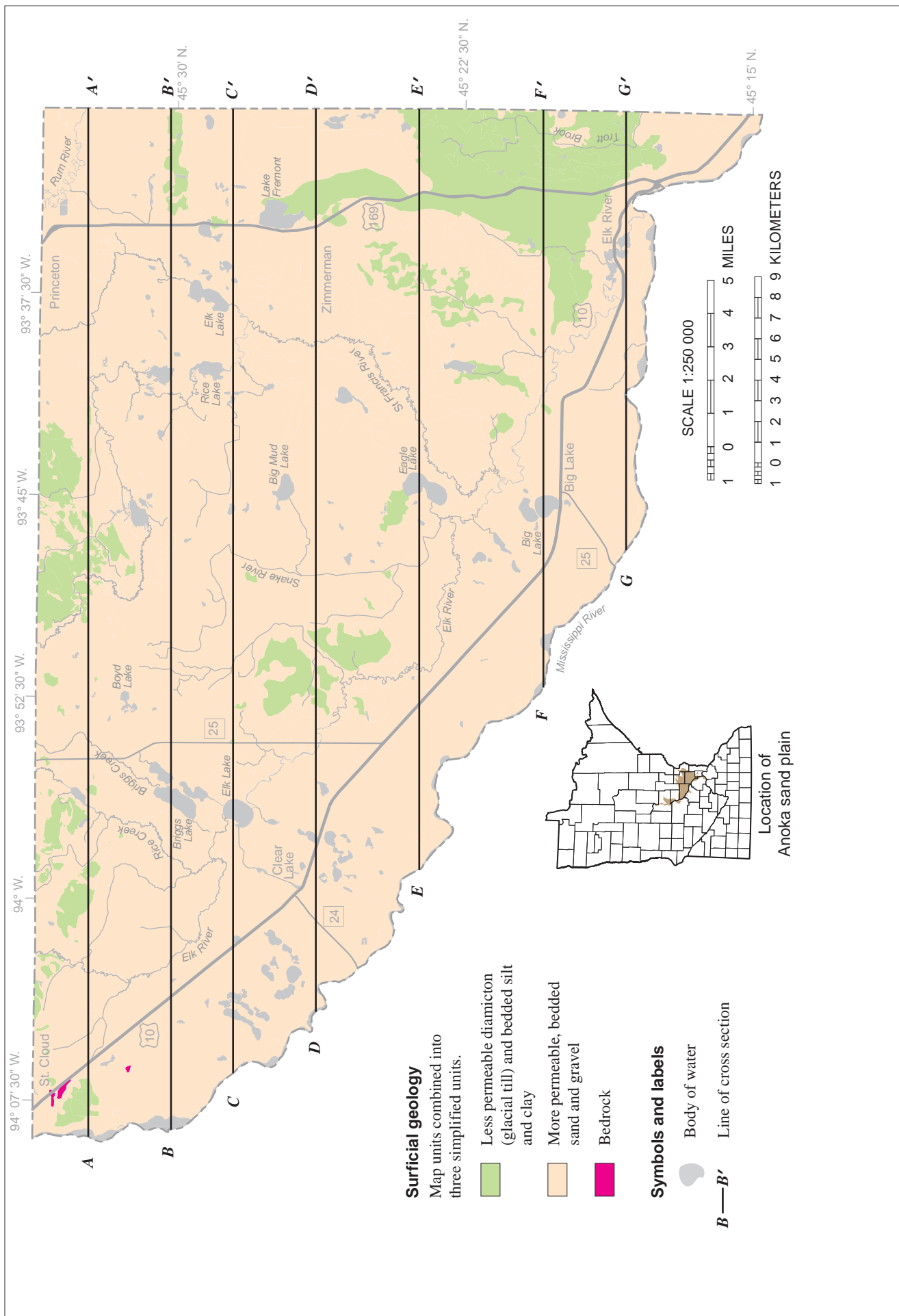
Groundwater flow directions in the water-table aquifer are controlled by the dominant groundwater discharge locations, including the Rum, Elk, and Mississippi rivers and associated tributaries.

Depth to water table is derived by subtracting the water-table elevation from the land-surface elevation (Figure 4).

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

conditions (0–10 feet) are common in the county with the exception of the higher land surface (upland) areas near portions of Briggs Creek; the St. Francis, Snake, Elk, and Mississippi rivers; and uplands in the eastern portion of the county.

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.



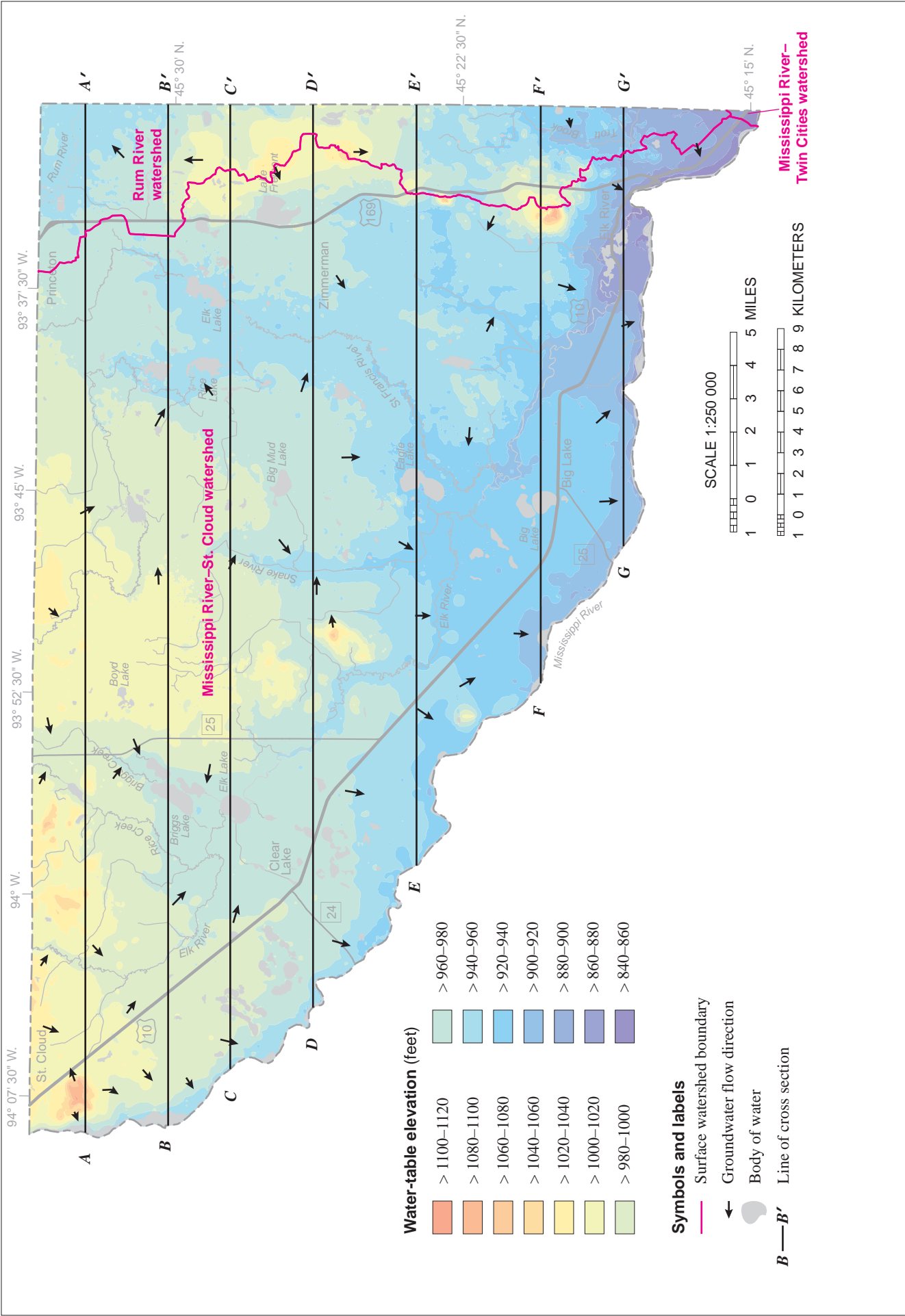


Figure 3. Water-table elevation and groundwater flow directions
Groundwater flows toward the major river valleys within the county. Map modified from Adams, 2016a.

Buried sand and gravel aquifers

The stratigraphic column in Figure 5 summarizes the geologic units and hydrogeologic properties of the glacial sequence and correlates the corresponding Part A and B unit names and map labels.

The Part B units are represented as follows:

- *Aquifers* are represented with *patterns* throughout this atlas (Figure 5 and Plate 7). Surficial sand units defined in Part A that only exist at the surface (**ss**, **nbs**, and **ns**) are shown with the same pattern. Portions of **csa**, **csr**, **cse**, and **scs** that are surficial or appear to be hydraulically connected to surficial units are shown on Plate 7 with another pattern to emphasize those hydraulic connections. The buried sand and gravel units that are not directly connected to surficial sands are shown with a pattern unique to each unit.
- *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 a 2 millimeter grain size.
- Units of undifferentiated Pleistocene sediment with an unknown texture are shown in *brown*.

	Part A	Part B
Silt and clay	sc	sc
Surficial sand and gravel	ss	ss
Sandy glacial lake deposits	nbs	ss
Sand and gravel	ns	ss
Till (New Ulm)	nt	nt
Sand and gravel	csa	csa
Till (Automba)	cta	cta
Sand and gravel	csr	csr
Till (St. Croix)	ctr	ctr
Sand and gravel	cse	cse
Till (Emerald)	cte	cte
Sand and gravel	scs	scs
Till (Sauk Centre)	sct	sct
Sand and gravel	fs1	fs1
Till (St. Francis)	ft1	ft1
Sand and gravel	mls	mls
Till (Meyers Lake)	mlt	mlt
Sand and gravel	fs2	fs2
Till (St. Francis)	ft2	ft2
Sand and gravel	suu	suu
Undifferentiated Pleistocene sediment	ups	ups
bedrock		


 Hydraulically connected combinations of surficial sand and buried sand layers

Figure 5. Hydrostratigraphy of Quaternary unconsolidated sediment

Aquifers are shown with patterns and aquitards are shown in shades of gray. Part B aquifer names are based on the name of the till underlying it in Part A. Shades of gray on aquitards correspond to the percent sand content indicating relative hydraulic conductivity, varying from light gray (high hydraulic conductivity) to dark gray (low hydraulic conductivity). The Part A sediment texture description is shown on the left side for reference and unit identification only. Aquifers csa, csr, cse, and scs sometimes directly underlie the surficial aquifer. In that case they are hydraulically connected to the surficial aquifer.

Potentiometric surfaces of buried sand and gravel aquifers

Note: the buried sand and gravel aquifers will subsequently be referred to as the buried sand aquifers.

In confined aquifers, pressure causes water to rise in a well to a level higher than the top of the aquifer. These levels are measured and contoured to create a map of the potentiometric surface for each aquifer. The resulting groundwater-level elevation maps show changes in water levels similar to the way topographic maps show changes in land-surface elevations.

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. Flow directions are shown as arrows in Figures 6 through 11.

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

Potentiometric surface maps were created from static water-level data from the County Well Index (CWI), measurements made by DNR staff, and river elevation points along the major rivers and streams. The CWI records represent various climatic and seasonal conditions from 1960 through 2014. This data variability creates some uncertainty in potentiometric surface elevations.

River elevation points are included because these features are typically groundwater discharge locations for the relatively shallow buried sand aquifers and the relatively shallow bedrock aquifers. Data from Sherburne and Anoka counties were used together to increase the data coverage and ensure that the potentiometric surfaces were consistent across the county boundary.

All the potentiometric surface maps (Figures 6–11 and 13) show a general pattern of groundwater flow toward the Mississippi River valley. Local flow toward the larger rivers and creeks in the county is evident on the buried sand potentiometric surface maps, such as the Elk and St. Francis rivers, and Briggs Creek. These maps indicate at least some groundwater discharge to the Mississippi and portions of its tributaries are from all the buried sand aquifers.



Figure 6. Potentiometric surface of the csa aquifer

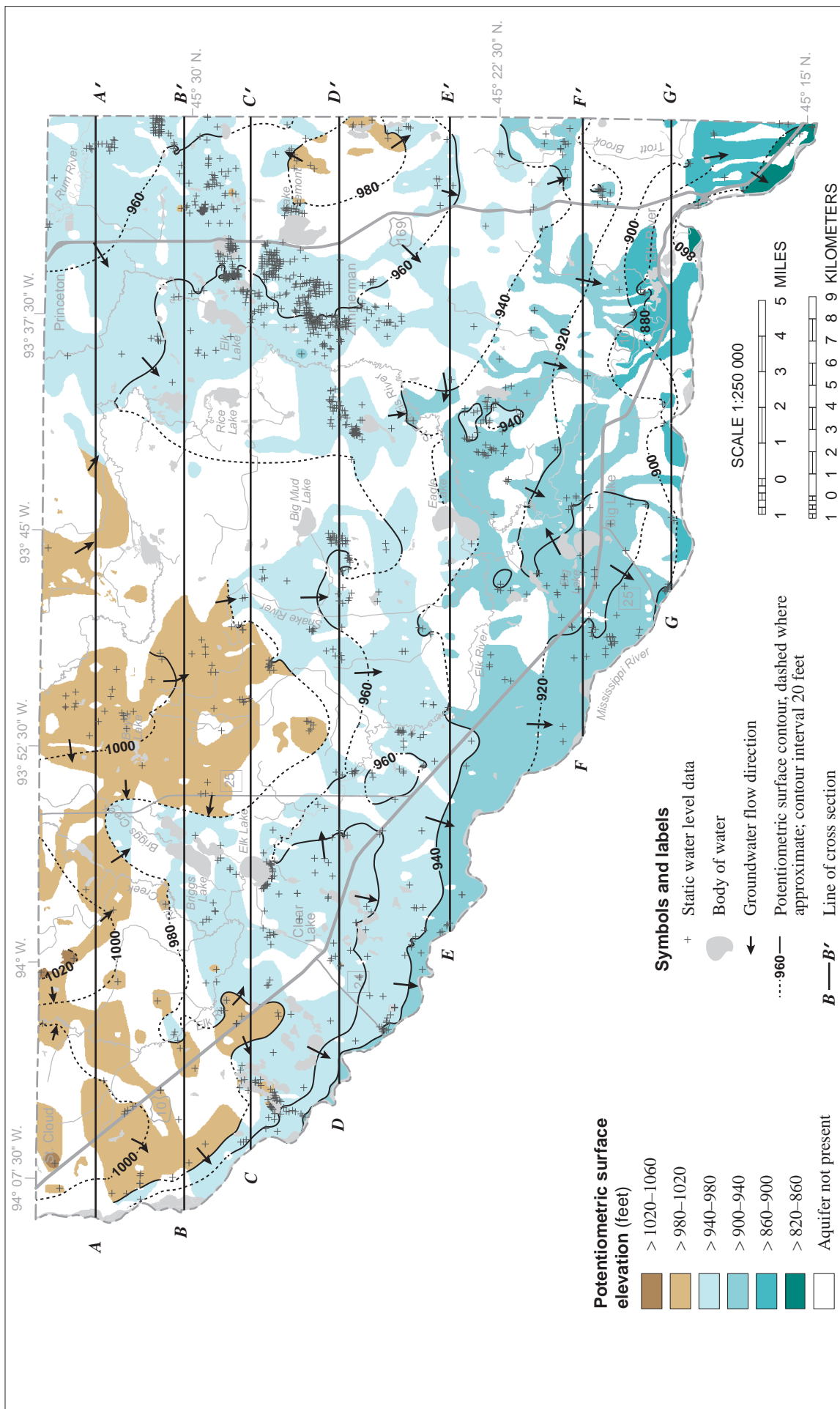


Figure 7. Potentiometric surface of the csr aquifer

Groundwater flow is toward the Mississippi River and locally toward the Elk and St. Francis rivers, and Briggs Creek.

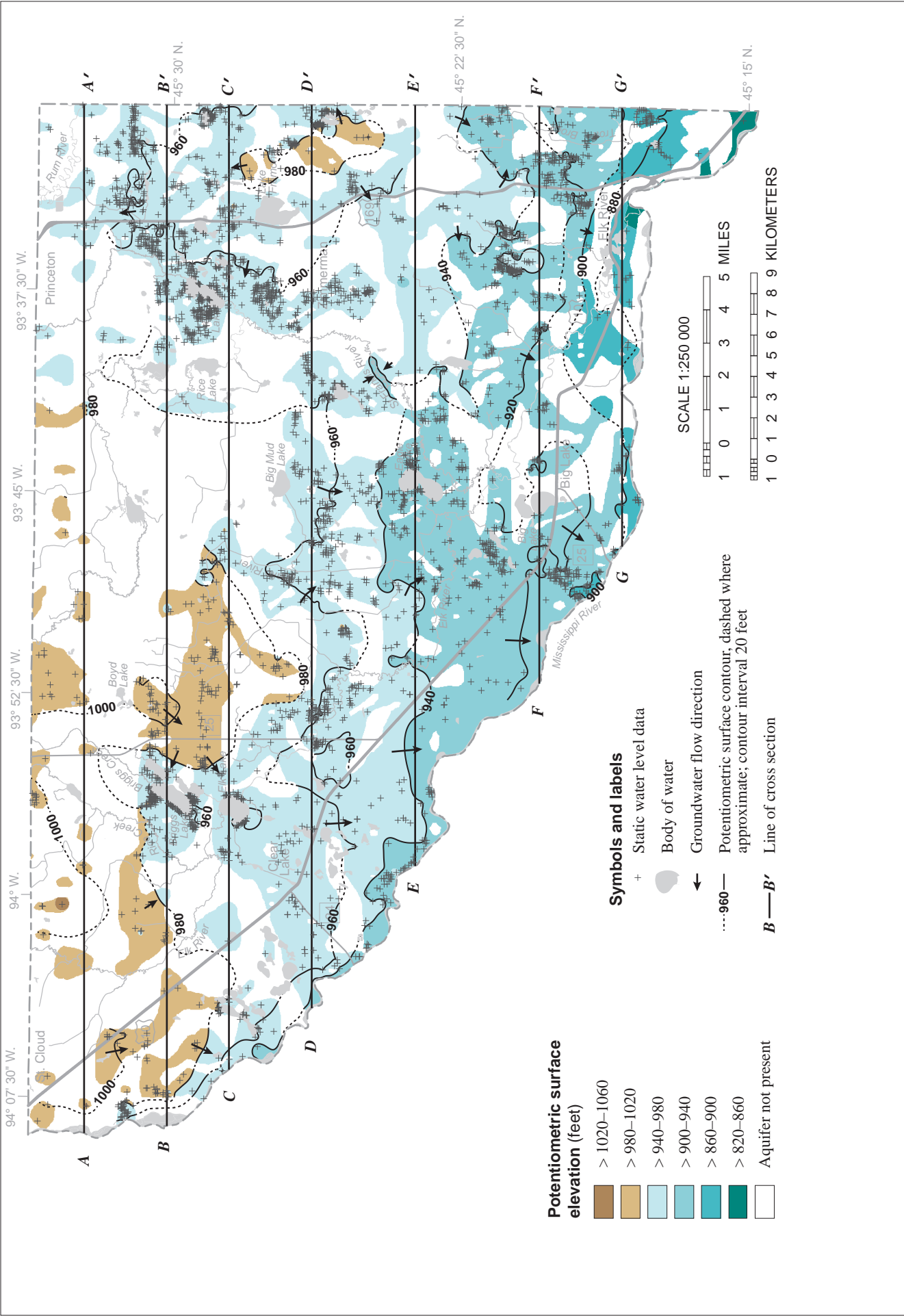


Figure 8. Potentiometric surface of the cse aquifer
Groundwater flow is toward the Mississippi River and locally toward the Elk and St. Francis rivers, and Briggs Creek.

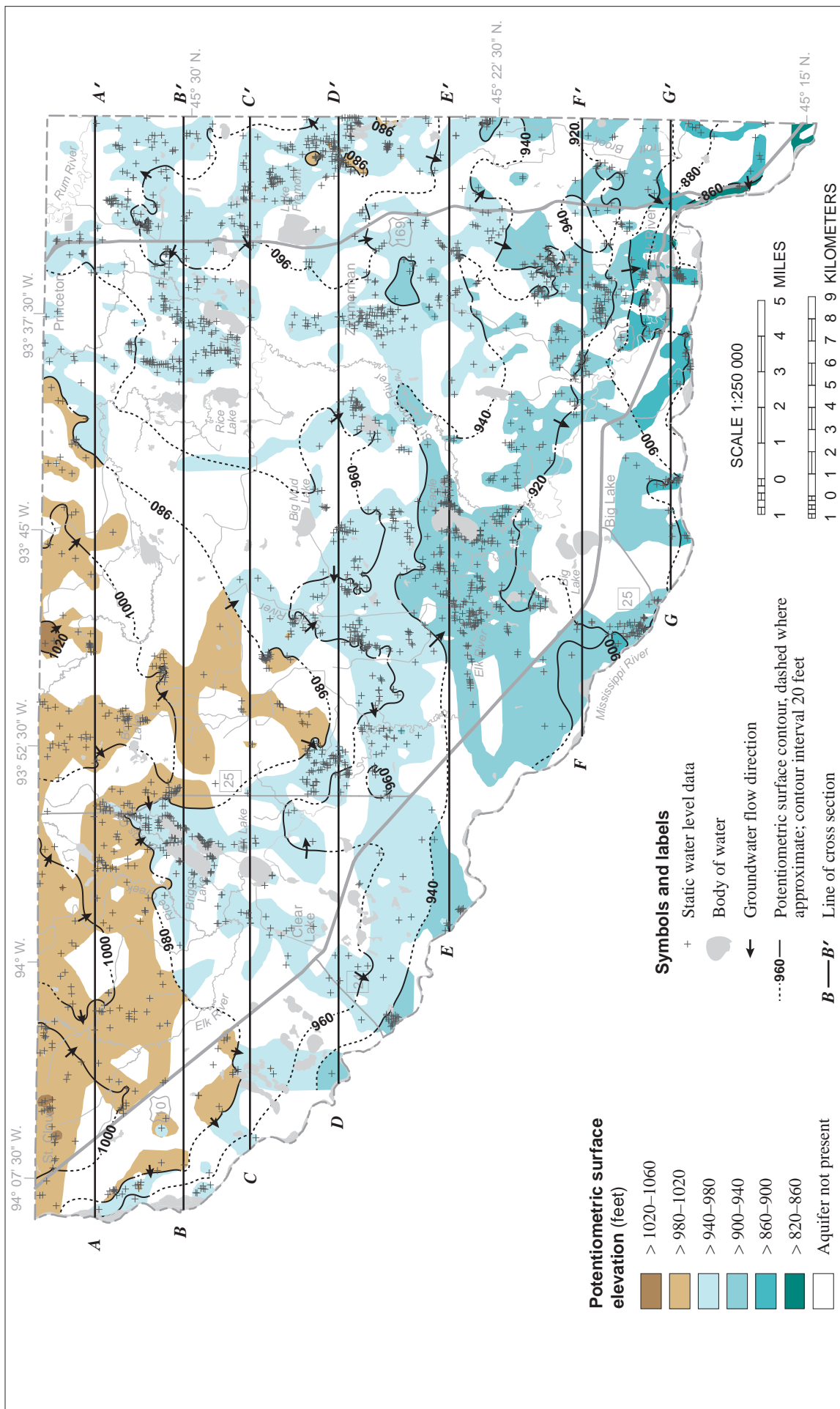
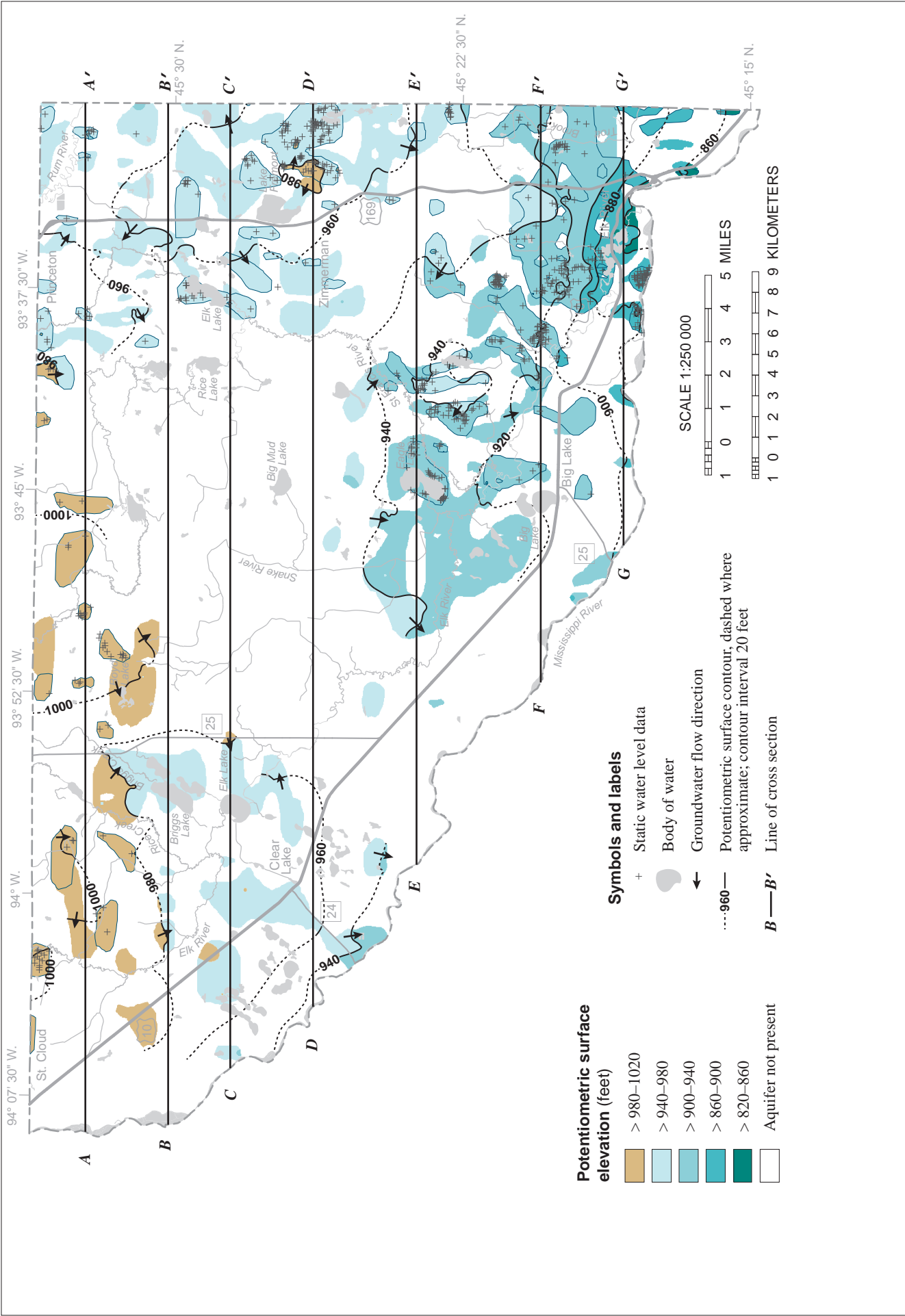


Figure 9. Potentiometric surface of the scs aquifer
Groundwater flow is toward the Mississippi River and locally toward the Elk and St. Francis rivers, and Briggs Creek.



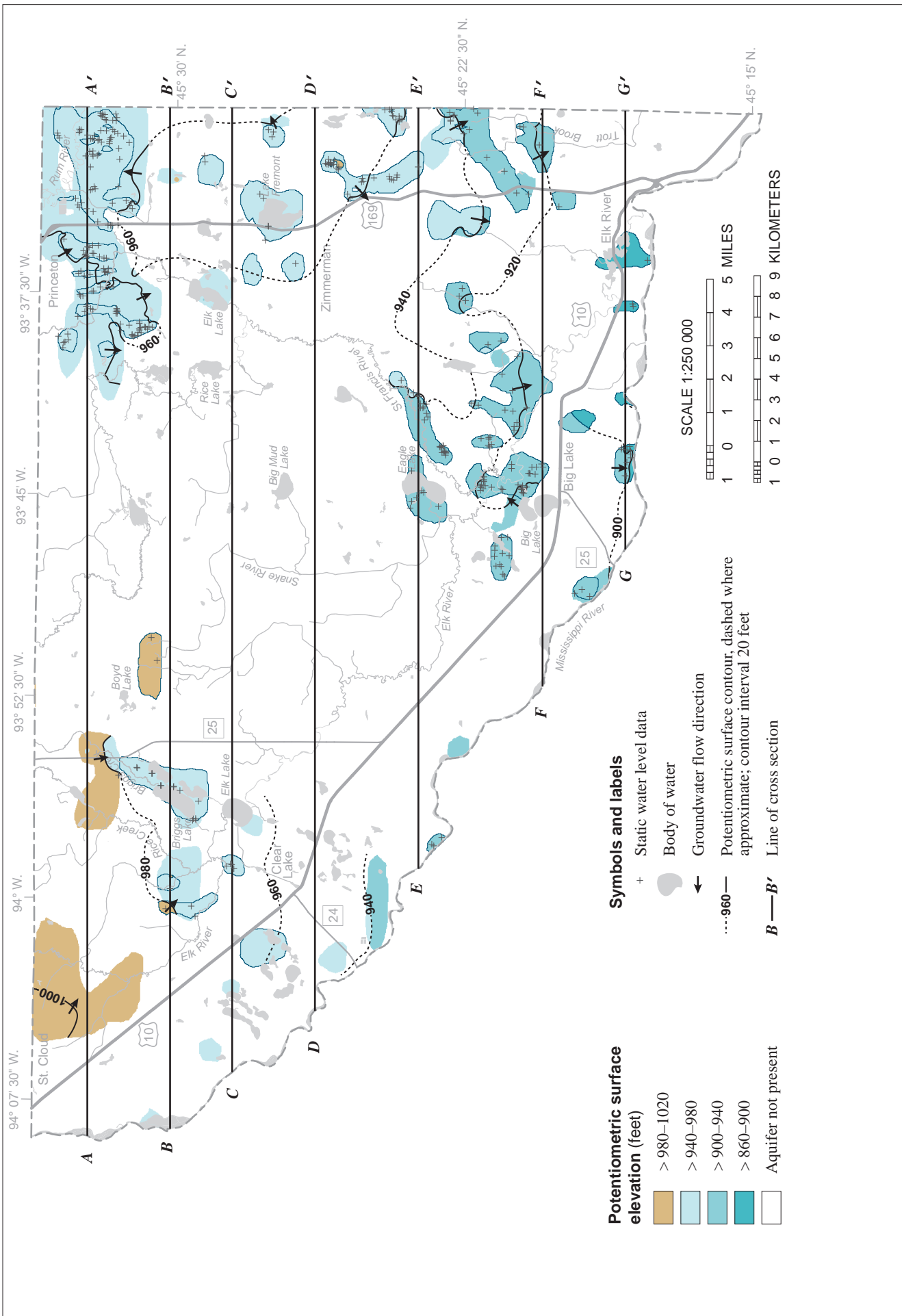


Figure 11. Potentiometric surface of the fs2 and suu aquifers

Groundwater flow is toward the Mississippi River and locally toward the St. Francis River. The fs2 aquifer (shown with outlines) is stratigraphically above the suu aquifer.

Bedrock geologic units and aquifers

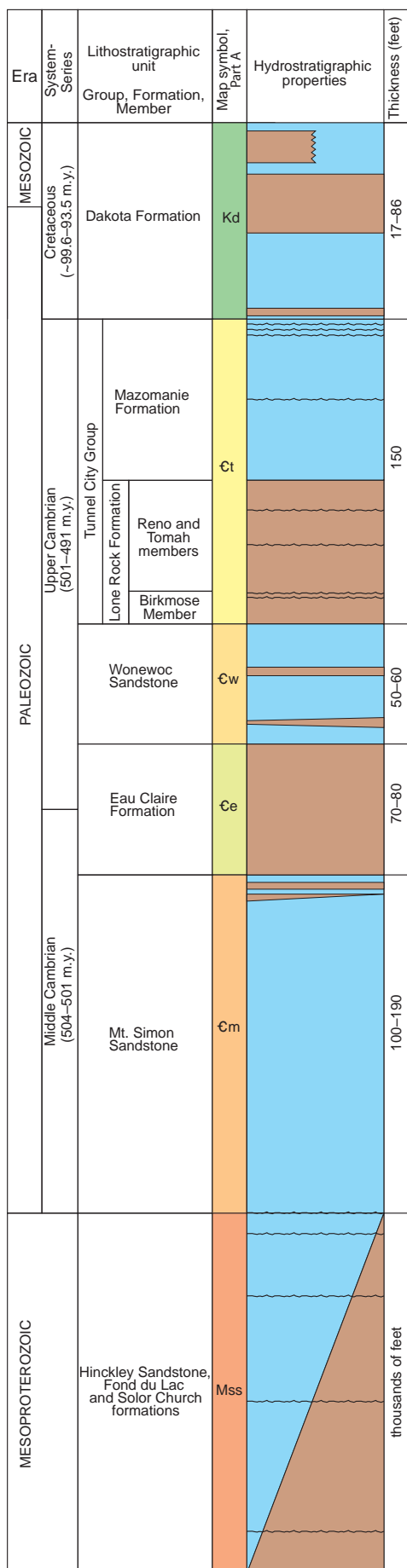
The bedrock formations of Sherburne County are at the northwestern edge of regionally extensive, gently dipping layers of sandstone, shale, and carbonate rock that range in thickness from 50 feet to greater than 200 feet (Figure 12 and Part A, Plate 2, Figure 3). These sedimentary rocks were originally deposited in mostly shallow marine settings during the Paleozoic era (Part A, Plate 2). Portions of these rocks endured periods of weathering while at or near the surface that affected the hydraulic properties. These Paleozoic formations are underlain by a much thicker and older group of Precambrian (Mesoproterozoic) sedimentary rock formations that are also used as aquifers, including the Hinckley Sandstone and Fond du Lac Formation. Since this group of bedrock units is often similar in appearance and difficult to differentiate in the subsurface, the terms “red clastics” or “Mesoproterozoic sedimentary rocks” (**Mss**) are used.

The formations include in ascending order (oldest to youngest): 1) the Mesoproterozoic: Fond du Lac Formation, Solor Church Formation, and Hinckley Sandstone; 2) the Cambrian: Mt. Simon Sandstone, Eau Claire Formation, Wonewoc Sandstone, and Tunnel City Group (Lone Rock and Mazomanie formations); and 3) the Cretaceous: Dakota Formation. The Dakota Formation has limited extent and is not a significant source of groundwater in the county. The combined Mt. Simon and **Mss** sandstones are commonly used and considered together as one aquifer. The bedrock aquifers are commonly used for water by municipalities and commercial operations because of their thickness, extent, predictability, and other features that affect water yield. In sandstone aquifers such as the Wonewoc and Mt. Simon–**Mss**, water moves through intergranular pore spaces and larger macropores such as fractures (Runkel and others, 2003).

An enhanced-permeability zone is generally found in approximately the uppermost 50 feet of sedimentary bedrock units (Runkel and others, 2006). It developed when the bedrock surface was at the land surface. The fractures in this shallow bedrock zone generally increase the yield from aquifers but may compromise the protective character of aquitards. Locally, weathered igneous and metamorphic Precambrian formations provide some groundwater to wells, especially in the northwestern portion of the county. However, these weathered Precambrian units are not a significant source of groundwater in the county.

Potentiometric surface of Mt. Simon–**Mss** aquifer

The extent of the Upper Tunnel City and Wonewoc aquifers is limited to the very southeastern portion of the county. With this limited extent and only limited water level data available, potentiometric maps have not been included in this county scale report. Similar to the buried sand potentiometric surface maps, the Mt. Simon–**Mss** aquifer map shows the same general pattern of groundwater flow toward the Mississippi River valley except in the very northeastern corner of the county where flow is northeasterly toward the Rum River (Figure 13). Local flow toward the Elk River is evident in the southern part of the county north of the city of Big Lake. This map indicates at least some groundwater discharge to the Mississippi River and portions of the Elk River are from the Mt. Simon–**Mss** aquifer.



Hydrostratigraphic properties

- Relatively high permeability (aquifer)
- Relatively low permeability except for fractures in the aquitard
- High permeability bedding fracture

Figure 12. Bedrock stratigraphy and hydrostratigraphy

Geologic stratigraphic units (formations or groups) do not always correspond to hydrogeologic units (aquifers and aquitards). In Sherburne County the Upper Tunnel City aquifer is equivalent to the Mazomanie Formation. Modified from Part A, Plate 2, Figure 3. Figure not to scale.



The general pattern of groundwater flow is toward the Mississippi River valley except in the very northeastern corner of the county where flow is northeasterly toward the Rum River. Local flow toward the Elk River is evident in the southern part of the county.

Water chemistry (Plate 6)

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

Groundwater sampling

To better understand groundwater movement and pollution sensitivity in the county, 92 samples were collected for this project from wells in a range of aquifers (protocols listed in the Appendix). The data were combined with water sample data from other agencies for analysis and interpretations in the following sections. Sources of samples include the Minnesota Department of Health (60 groundwater, 5 surface water), the Minnesota Pollution Control Agency (13 groundwater), an older DNR project (4 groundwater), and the Minnesota Geological Survey (1 groundwater, Lively and others, 1992).

Chemical data from well-water samples were used along with primary physical data (static water level and aquifer

tests) to understand water movement. Wells were selected based on their hydrogeologic setting and aquifers were selected for their significance for domestic water supply. An ideal well-sampling network is evenly distributed across the county, includes the more populated areas, and targets surface water and groundwater interaction in the vicinity of lakes and larger rivers. The network distribution depends on citizen willingness to participate. Approximately 1000 well owners were contacted through letters that included a description of the project and a reply card to return if they were willing to participate. Approximately 30 percent of those contacted gave permission for sampling.

Groundwater recharge sources

As water moves from precipitation 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 (Kendall and Doctor, 2003). Oxygen and hydrogen each have two main stable isotopes: ^{18}O and ^{16}O , and ^2H and ^1H . The different mass of the isotopes causes evaporation at different rates, which results in *fractionation*, leaving behind different ratios of heavy to light isotopes. This results in isotopic signatures that are unique to groundwater with different sources.

- Groundwater infiltrated directly from *precipitation* exhibits a *meteoric* isotopic signature. It infiltrates directly into the ground, leaving the isotopic ratio unchanged.
- Groundwater recharged from *open water* such as lakes or wetlands exhibits an *evaporative* isotopic signature. It has been subjected to fractionation where light isotopes

evaporate into the atmosphere, leaving a ratio favoring heavier isotopes.

To identify the source (precipitation or surface water) of a groundwater sample, oxygen and hydrogen isotopic data are plotted against each other (Figure 14). The x-axis represents the oxygen isotope value ($\delta^{18}\text{O}$) and the y-axis represents the hydrogen isotope value ($\delta^2\text{H}$). The measured ratio in the sample is divided by the ratio in a standard (Vienna Standard Mean Ocean Water [VSMOW]).

Definition of delta (δ)

The stable isotope composition of oxygen and hydrogen are reported as δ values. δ (0/00) = $(R_x/R_s - 1) \times 1000$ where R represents the ratio of the heavy to light isotope, $^{18}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$ 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.

County results are compared to the global meteoric water line, which was developed from precipitation data from around the world. The isotopic values display a linear correlation over the entire range for waters which have not undergone excessive evaporation (Craig, 1961).

The majority of Sherburne samples plot along the meteoric water line, in the center and left portions of the stable isotope graph (Figure 14). This suggests sources from precipitation (rain and snow melt) infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies for these samples.

One evaporative signature was found in a groundwater sample downgradient of Big Mud Lake in the central part

of the county (Figure 15). There are also some unnamed wetlands upgradient from this location which could be another possible source of surface water. This evaporative signature sample was collected from the relatively shallow (95 feet) **cse** buried sand aquifer. The absence of evaporative signatures from wells near other lakes or lake areas does not necessarily indicate that evaporative signature water is rare in Sherburne’s groundwater, but may be more of an artifact of the sampling strategy. Samples from wells at ideal locations and depths for detecting lake evaporative processes on groundwater characteristics are not always available because of accessibility limitations. Samples were limited to wells volunteered by homeowners.

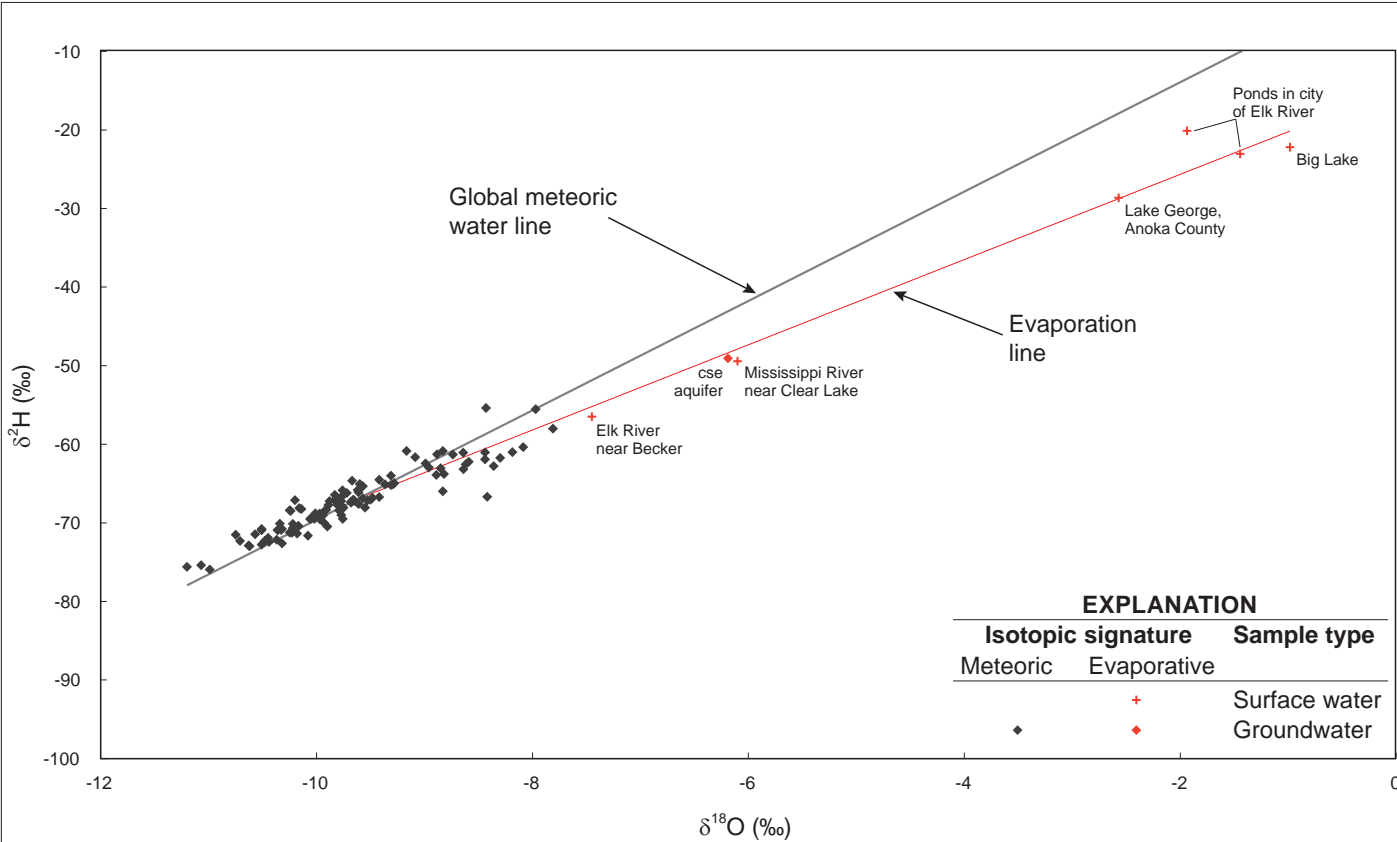


Figure 14. Stable isotope values from groundwater samples

Stable isotope values from groundwater samples are compared to the global meteoric water line. Precipitation values from direct infiltration generally plot along the meteoric water line. Groundwater recharged from surface water sources plots along an evaporation line, a shallower slope.

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 to a lake, river, wetland, or spring. Generally short residence time suggests high recharge rates or short travel paths; long residence time suggests low recharge rates 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 were greatly increased between 1953 and 1963 by atmospheric testing of nuclear weapons (e.g., Alexander and Alexander, 1989). This isotope decays at a known rate with a half-life of 12.32 years (Lucas and Unterweger, 2000).

Tritium concentrations and other groundwater chemistry (such as nitrate and chloride values) are compared with the estimated pollution sensitivity. The interpretations are used in maps for pollution sensitivity and the hydrogeologic cross sections. The concentrations are

presented in tritium units (TU) and are referred to as *tritium age* in the following categories.

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

Carbon-14

The carbon-14 (^{14}C) isotope is used to estimate the residence time for selected vintage and mixed tritium-age samples. This naturally occurring isotope has a half-life of 5,730 years, and is used to estimate groundwater residence time ranging from 100 to 35,000 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 (human caused) pollution sources. This report includes analyses of water samples for inorganic chemistry, including primarily the major cations and major anions that are typically found in concentrations of parts per million (ppm), and select elements that typically are found in trace amounts of parts per billion (ppb).

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

Calcium, magnesium, and sodium cations and bicarbonate anions are dissolved out of the glacial sediment by the groundwater. The constituents are derived from limestone and dolomite bedrock sources (Freeze and Cherry, 1979) and are common in groundwater in the glacial sediment aquifers.

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).

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

Chloride and nitrate-nitrogen (nitrate) can be used to indicate anthropogenic contamination and evaluate pollution sensitivity.

Elevated chloride can come from sources such as road salts, water softener salts, and fertilizers (Davis and others, 1998; Panno and others, 2006). Groundwater with a chloride concentration above 5 ppm with a chloride/bromide ratio above 250 may indicate anthropogenic sources and high pollution sensitivity. This anion is a significant contaminant in Sherburne County with 57 of 66 groundwater samples (86 percent) exceeding these limits. These elevated occurrences of chloride exhibit a relatively widespread distribution across the county in the ss aquifer, and most of the buried sand aquifers (csr, cse, scs, mls, fs2, and suu). Elevated chloride was also found in bedrock aquifers and an aquifer category including: Wonewoc, Mt. Simon,

Fond du Lac, and red clastics (Figure 16). Eight samples that contained elevated chloride were collected by the Minnesota Pollution Control Agency (MPCA) but were not analyzed for bromide. Since most of these samples were collected from depths of less than 100 feet they are likely from anthropogenic sources in this sand-rich geologic setting.

Elevated nitrate comes from sources such as fertilizer and animal or human waste. Groundwater nitrate concentration that equals or exceeds 1 ppm indicates anthropogenic sources and high aquifer sensitivity (MPCA, 1998; Wilson, 2012). The maximum contaminant level (MCL) for nitrate is 10 ppm (EPA, [1996]). Concentrations that equaled or exceeded the 1 ppm level were found in 35 of 115 groundwater samples (30 percent). All but two of these elevated occurrences were from samples that also contained elevated concentrations of anthropogenic chloride (Figure 16). Elevated nitrate concentrations were most common in the western portion of the county where agriculture is common, and were found in the ss, csr, cse, scs, fs1, and suu buried sand aquifers; the Mt. Simon and Fond du Lac aquifers, and the red clastic category.

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 effects or aesthetic effects in drinking water.

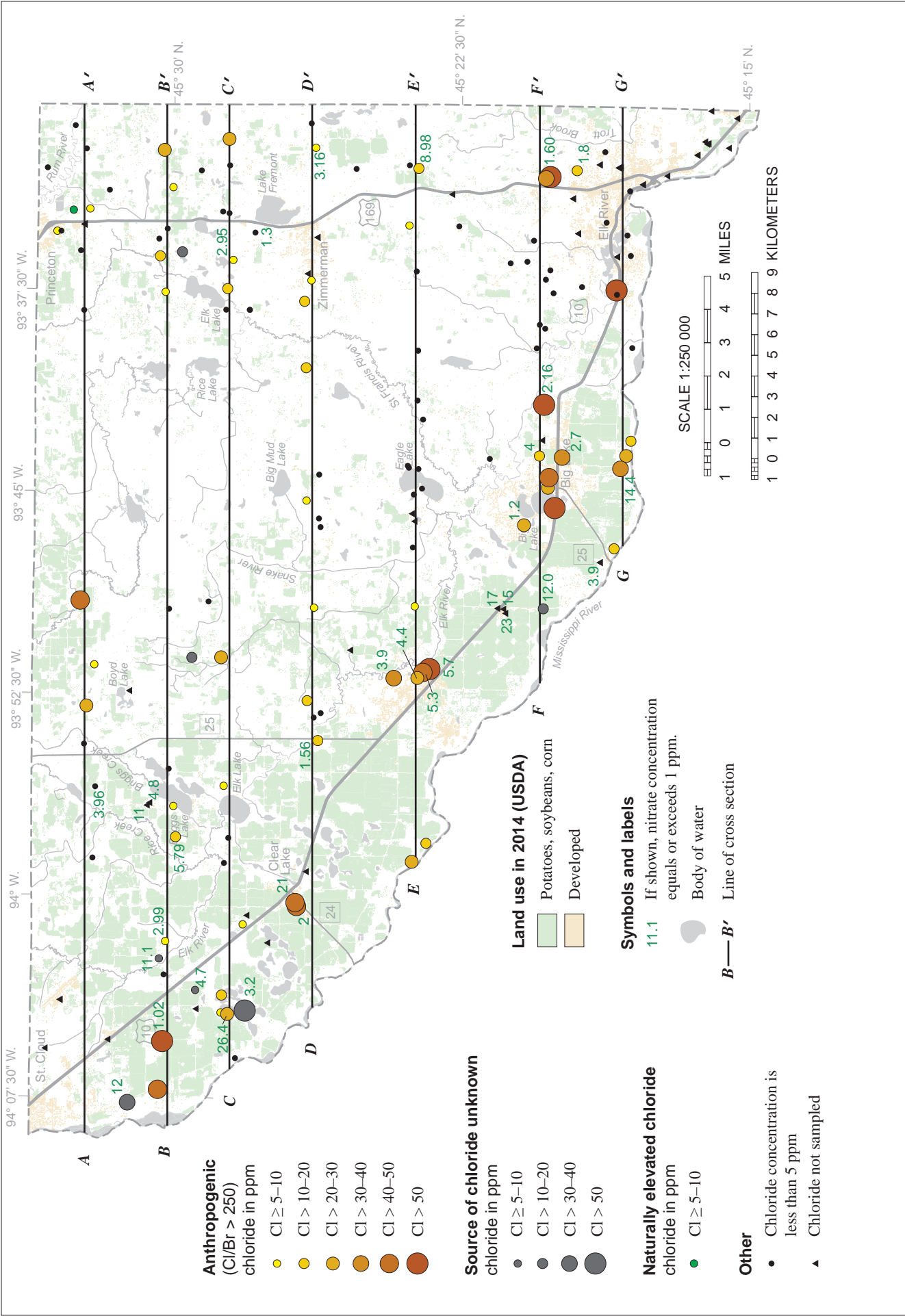


Figure 16. Elevated chloride and nitrate concentrations from groundwater samples

Elevated and anthropogenic (human caused) chloride concentrations (≥ 5 ppm and $\text{Cl}/\text{Br} > 250$) from groundwater samples are common and widespread in Sherburne County. Groundwater samples with elevated nitrate values (≥ 1 ppm) tend to be associated with agricultural areas that run parallel with the Mississippi River.

Naturally occurring elements of health concern

Some chemicals present in water may be naturally occurring but can potentially pose a human health risk in elevated concentrations. Exposure to arsenic has been linked to both cancer and noncancerous health effects (EPA, 2001). Low levels of manganese are a benefit to humans, but high exposures can harm the nervous system (MDH, 2012).

Arsenic

Arsenic is a naturally occurring element in Minnesota groundwater. Current science cannot predict which wells will have high arsenic concentrations, therefore newly constructed wells are tested for arsenic if they are used as a potable water supply, according to Minnesota Rule 4725.5650 (2008). The Environmental Protection Agency (EPA) requires that community water supplies not exceed 10 ppb arsenic (EPA, 2001), but there is no requirement for domestic wells. Well-water samples that exceed 5 ppb arsenic should be resampled to determine if the arsenic level of the first sample is a representative value.

The factors affecting elevated arsenic concentrations in groundwater are not completely understood. There is a strong correlation with wells completed in aquifers associated with glacial sediment bearing materials derived from rocks that lie northwest of Minnesota. Research also indicates that arsenic concentrations are increased in wells that have short screened sections near the boundary of an aquitard and the aquifer (Erickson and Barnes, 2005a; McMahon, 2000).

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

While generally not common in Sherburne County, elevated arsenic values (10 ppb or greater) were detected from wells in the **csr**, **cse**, **scs**, and **fs2** aquifers (Figure 17). Elevated arsenic detections occurred in five groundwater samples (6 percent). Statewide, from 2008 to 2015, approximately 11 percent of newly constructed potable wells have arsenic concentrations exceeding 10 ppb (MDH, 2016a).

Manganese

Manganese is a naturally occurring element in Minnesota groundwater. The Minnesota Department of Health (MDH) Health Risk Limit (HRL) is 100 ppb (MDH, 2016b). This is 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. For more details, see the Minnesota Ground Water Association white paper on manganese and groundwater (MGWA, 2015).

A large proportion of groundwater samples (88 of 129 samples, 68 percent) contained manganese concentrations that exceeded the lower MDH HRL established for infants (100 ppb) indicating a natural water quality issue for the majority of well owners in the county.

Manganese distribution in Minnesota groundwater is highly variable. Water-table and buried sand aquifers have the greatest median manganese concentrations, 155 and 160 ppb, respectively. In water-table aquifers, 57 percent of drinking water wells sampled have manganese concentrations that equal or exceed 100 ppb. In buried sand aquifers, 63 percent of drinking water wells sampled have manganese concentrations that equal or exceed 100 ppb (MDH, 2014).

Minnesota Department of Health standards

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.

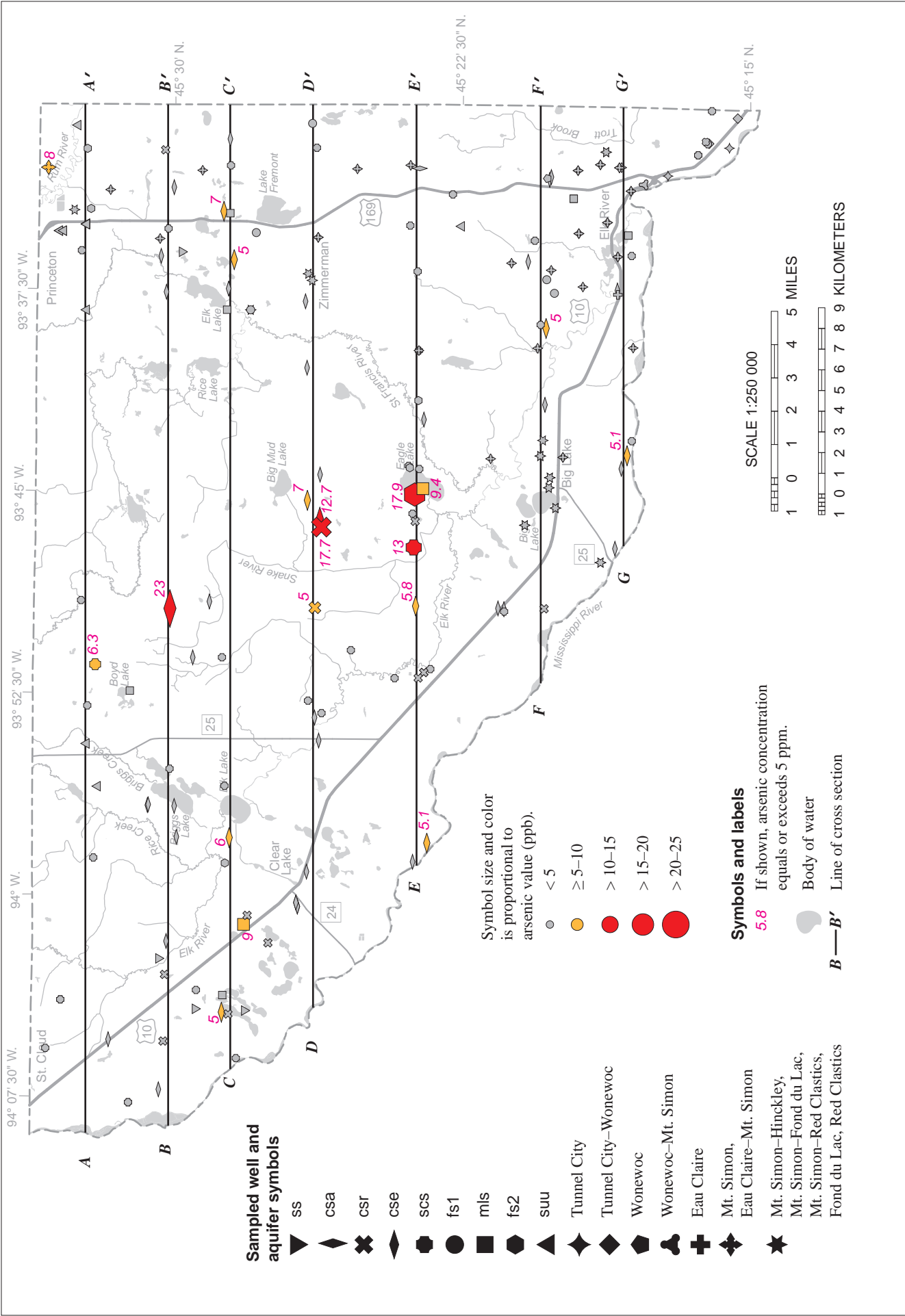


Figure 17. Arsenic values from buried sand and bedrock aquifers
Arsenic concentrations that equaled or exceeded federal drinking water standards (10 ppb) were found in five groundwater samples collected from buried sand aquifers. All arsenic values 5 ppb or greater are labeled for reference.

Hydrogeologic cross sections (Plate 7)

The hydrogeologic cross sections shown on Plate 7 illustrate the horizontal and vertical extent of aquifers and aquitards, groundwater residence time, and general directions of groundwater flow. It also includes a comparison of glacial geologic units that were defined in Part A and the corresponding hydrogeologic units (Figure 5).

The seven cross sections were selected from a set of 37 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 cross sections were constructed using a combination of well data from the CWI and the following sections of this atlas: the bedrock geology map (Part A, Plate 2), surficial geology map (Part A, Plate 3), and Quaternary stratigraphy plate (Part A, Plate 4). Well information was projected onto the trace of the cross section from distances no greater than one-half kilometer.

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 was used as a proxy for permeability because coarse grains typically add permeability to sediment. Glacial aquitards with a higher sand content are assumed to have a higher hydraulic conductivity than aquitards with lower sand content. This assumption does not account for the occurrence of larger clasts (pebbles, cobble, and boulders), the potential for fine sediment to fill pore spaces, or fractures in the shallow till units.

Glacial sediment layers that act as aquitards (till units) are shown in shades of gray on Plate 7. Lighter shades

indicate aquitards with expected higher relative hydraulic conductivity. Darker shades represent aquitards with lower relative hydraulic conductivity. The percent sand in each of the aquitards is based on the average matrix texture of each glacial aquitard (or till).

The tills with the highest sand content are the units of the Cromwell Formation (units **ctr**, **cte**, and **cta**), with 64–65 percent; and the St. Francis formations (**fs1** and **fs2**), 057 and 74 percent, respectively. The lowest sand content is found in the members of the Lake Henry Formation: **sct** at 22 percent and **mlt** at 31 percent.

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 the groundwater flow in Sherburne County is initially downward, then laterally toward the larger creeks and rivers.

Groundwater recharge zones exist across broad areas of the county due to the relatively thick and widespread surficial sand and generally level topography. Smaller discrete groundwater recharge areas are identified in the following section based on occurrences of connected aquifers and geochemical data such as tritium, chloride, and nitrate.

Recharge and discharge: interpreted groundwater residence time

Recharge interpretations

Cold War era, recent, or mixed tritium-age water may occur in the following situations. Each is indicated using the symbols below on the pollution sensitivity maps and Plates 6 and 7.

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

Due to the widespread sandy conditions in the county this condition is only present at one location at the far eastern side of B–B' where only a thin layer of nt till separates the underlying **csa** and **csr** buried sand aquifers from the surface.

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

This is the most common condition in the county due to the extensive surficial sand and common hydraulic connections to underlying aquifers. This condition is shown mostly on the central and western portions of cross sections B–B' through E–E' in the shallower buried aquifers **csr**, **cse** and to a lesser extent **scs**. Smaller clusters of locations with this condition are shown in the **cse** aquifer on the eastern portion of B–B' and C–C' and the western portion of G–G'.

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

Similar to the ② condition, this condition is almost as common due to extensive surficial sand and common hydraulic connections to underlying aquifers and to stratigraphically lower aquifers. This condition is common mostly on the central and eastern portions on cross sections A–A', D–D', and E–E' (buried sand aquifers **cse**, **scs**, **mls**, and **fs2**), and the western portion of F–F' (bedrock aquifers).

-
- Ⓐ Groundwater flows laterally.
-

This classification is necessary due to the limiting assumption of only vertical recharge used in the pollution sensitivity model. It is used where tritium detections occur in very low to low sensitivity areas. The likely source of water containing tritium is not from a direct vertical pathway, but from an upgradient (lateral) location. This condition is shown for most of the locations on A–A' (**scs** and **suu** aquifers), the eastern portion of C–C' (**cse** and **mls** aquifers), locations along F–F' (**scs** and bedrock aquifers), and other scattered locations.

-
- Ⓢ Groundwater flowpath is unknown.
-

The tritium detected in groundwater samples from these locations may be from unknown well conditions or unknown aquifer connections. This unknown designation is used when a recent or mixed classification can't be explained by any of the previously described recharge conditions. These anomalous conditions are sometimes due to old corroded well casing conditions that allow shallow recent water to leak directly into the well casing. In addition, sometimes older wells were not constructed to modern standards and lack a grout seal around the casing, allowing recent tritium-age water leakage directly to the screened or open-hole portion of the well. Five of these unknown locations are shown on the eastern portion of A–A' (**fs2** and **suu** aquifers), the western portion of C–C' (**fs2** aquifer), the eastern portion of D–D' (Mt. Simon aquifer), and the eastern side of F–F' (Eau Claire and Eau Claire–Mt. Simon).

Discharge interpretations

-
- Ⓣ Groundwater discharges to a surface-water body.
-

Groundwater discharge to rivers, lakes, springs, and wetlands is a common occurrence in Minnesota. It supplies water vital to aquatic ecosystems. Discharge or baseflow is most likely to occur where an underlying aquifer is connected to surface water.

The groundwater discharge (gaining) or recharge from surface water (losing) of surface-water bodies can vary depending on seasonal or climatic cycles. Evaluating this variability was beyond the scope of this study. The following designations of discharge are meant to recognize that groundwater discharge to surface-water bodies is likely to occur for at least part of each year.

A–A': west side, the Mississippi and Elk rivers; and Rice and Briggs creeks

B–B': west side, the Mississippi and Elk rivers, and Briggs Lake; east side, the St. Francis River and Battle Brook

C–C': west side, the Mississippi River and Elk Lake; east side, the St. Francis River

D–D': west side, the Mississippi and Elk rivers; east side, the Snake and St. Francis rivers

E–E': west side, the Mississippi and Elk rivers; east side, Eagle Lake

F–F' and G–G': the Mississippi and Elk rivers

Pollution sensitivity

Pollution sensitivity maps generated on a county scale are intended to assist citizens and local government in protecting and managing groundwater resources. Pollution sensitivity is defined as the potential for groundwater to be contaminated because of the hydrogeologic properties of the material hosting or overlying it. Migration of contaminants dissolved in water that flowed 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.
- River valleys are typically important groundwater discharge areas (see “Hydrogeologic cross sections”). Local upward groundwater movement is characteristic of these areas and the actual pollution sensitivity in these areas will be less than the rating.
- 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 these models.

Near-surface sensitivity (to a depth of 10 feet): sediment texture is the primary property used to create a sensitivity map. The permeability of the sediment matrix texture is estimated based on hydrologic theory 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 (aquitards) overlying aquifers. It does not consider differences in sediment texture or permeability of aquitard materials.

Pollution sensitivity of near-surface materials

Methods

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

The transmission rate of a soil or surficial geologic unit will vary depending on the texture. In general, coarse-grained materials have faster transmission rates than fine-grained materials. The two primary inputs used to estimate transmission rate are the hydrologic soil group and the surficial geologic matrix texture. Attributes of both are used to estimate the time of travel (Table 1) (USDA-NRCS, 2011; Part A, Plate 4). Further details are available in *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

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

- Areas with a relatively short travel time (hours to a week) are rated high sensitivity (Figure 18).
- Areas with a longer travel time (weeks to a year) are rated low or very low.

Results

High sensitivity conditions dominate the county (Figure 19) since the most common surficial material in the county is sand and gravel. Moderate sensitivity is the next most common category where sandy loam till exists at the surface. A large area of mostly moderate sensitivity exists in the area south of Zimmerman through most of the Elk River city limits. Smaller areas of mostly moderate sensitivity exist north of Becker and along the northern border of the county. One area of mostly low sensitivity exists at the center of the northern county border west of Princeton.

Table 1. Transmission rates used to assess the pollution sensitivity rating of the near-surface materials

[Note that peat is used as an overlay on the map due to variable and typically unknown thicknesses]

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
A, A/D	1	gravel, sandy gravel, silty gravel	1	Qa, Qbg, Qcc, Qci, Qco, Qno, Qtl, Qtu, Quc
		sand, silty sand	0.71	Qbs, Qe
B, B/D	0.50	silt, loamy sand, units with eolian sand designation	0.50	Qnl
		sandy loam	0.28	Qcd, Qct, Qnc, Qnt
C, C/D	0.075	silt loam, loam	0.075	Ql, Qng
D	0.015	sandy clay loam	0.035	Not mapped in the county
		clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Not mapped in the county

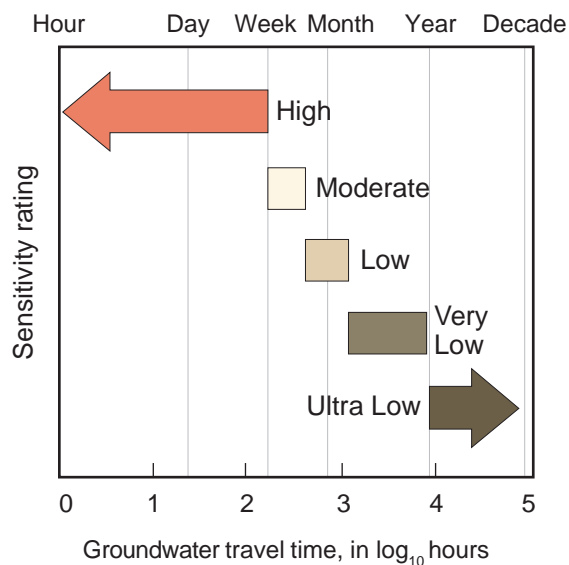
*The Natural Resources Conservation Service (NRCS) defines hydrologic soil groups primarily based on texture and the occurrence of low permeability layers (USDA-NRCS, 2009):

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

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

Group C: water transmission is somewhat restricted.

Group D: water movement is restricted or very restricted.

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

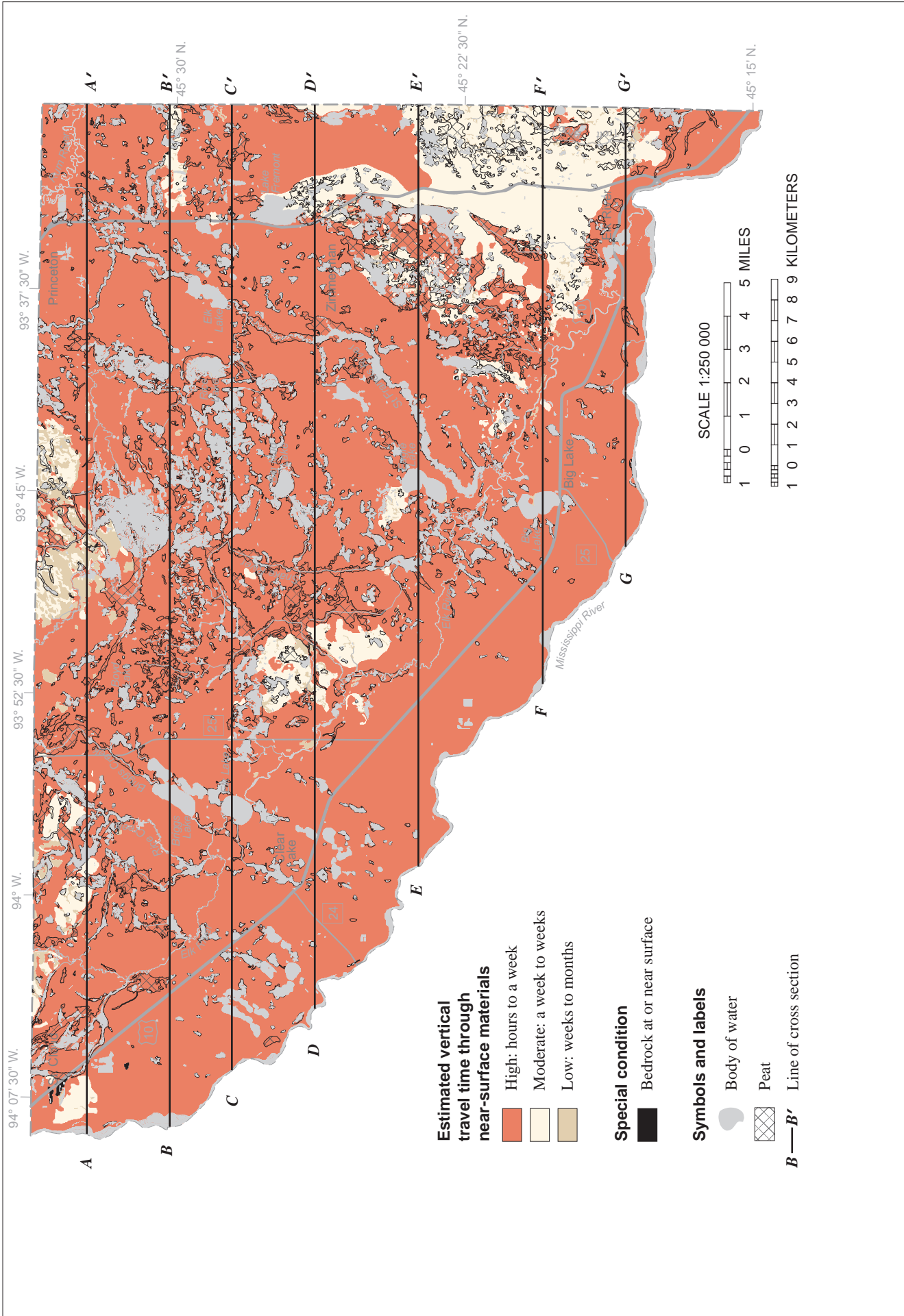


Figure 19. Pollution sensitivity of near-surface materials

This pollution sensitivity model assumes a 10-foot-deep water table and vertical travel of possible pollutants through unsaturated, near-surface materials. Map modified from Adams, 2016b.

Buried sand and gravel aquifer and bedrock surface sensitivity

Methods

The sensitivity rating for the buried sand aquifers and the bedrock surface are based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). The travel time varies from hours to thousands of years (Figure 20).

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

The DNR developed a method using geographic information systems (GIS) for mapping pollution sensitivity of buried sand aquifers and the bedrock surface based on a simplified two-dimensional model. 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, and intermediate thicknesses have intermediate sensitivity ratings. A more detailed explanation of this method is available in *Buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment (CFGs) thickness* (DNR, 2016c).

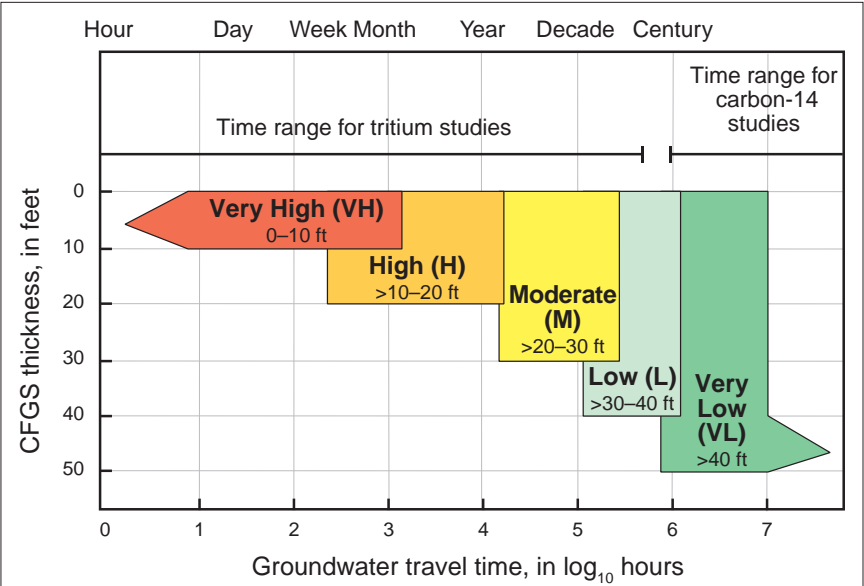


Figure 20. Geologic sensitivity rating for the buried sand aquifers and the bedrock surface
Sensitivity is defined by vertical travel time. The numbers following each rating represent the cumulative fine-grained sediment (CFGs) thickness overlying an aquifer.

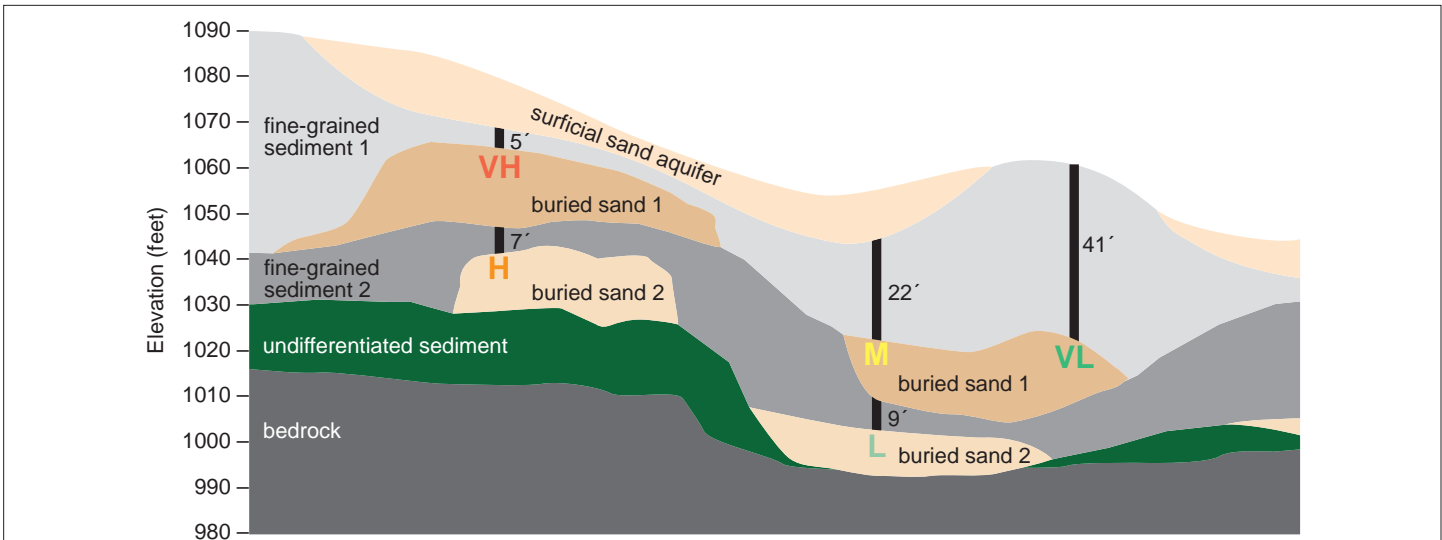


Figure 21. Cross section showing examples of pollution sensitivity ratings
Based on the cumulative thickness of overlying fine-grained sediment. Each vertical black line is labeled with the thickness of fine-grained sediment. The letter at the base of the line indicates the sensitivity rating determined from the cumulative thickness.

Results

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

The tritium dataset is a conglomeration of sampling efforts by the DNR and the Minnesota Department of Health (MDH) for several projects since 1989. None of these sampling plans were randomized in a way that would allow a statistical comparison to the results of the pollution sensitivity modeling. Therefore, the descriptions of groundwater chemistry and pollution sensitivity are mostly qualitative. Figure 20 suggests that tritium detections in groundwater samples should be a very rare occurrence from aquifers in areas mapped as very low sensitivity assuming that flow of recent water to the aquifer is vertical. In general, for the upper four aquifers, overlying interconnected sand layers are so extensive that almost all of the samples are mixed or recent tritium age despite directly overlying very low pollution sensitivity conditions. For the deeper aquifers there is a generally good match between tritium age and pollution sensitivity. In the following sections the pollution sensitivity values and spatial distributions are compared to tritium-age of groundwater (Cold War era, recent, mixed, and vintage) for each aquifer.

csa aquifer (Figure 22)

Sensitivity: The **csa** is a surficial or shallow buried sand aquifer and is unprotected in the northern portion of its extent. The New Ulm Formation (**nt**), with a loam to sandy loam texture, is the main protective layer (aquitard) for this aquifer in the southern portion of its extent. However, this till layer tends to have a thin and patchy distribution.

These geological circumstances create a pattern of mostly very high pollution sensitivity, especially in the northern portion, with local variations of very low to moderate sensitivity conditions in the southern portion. One groundwater sample had mixed tritium and elevated chloride and nitrate, and was collected from this aquifer near St. Francis shown on the east side of cross section E-E'.

csr aquifer (Figure 23)

Sensitivity: The **csr** aquifer, like the previously described **csa** aquifer, exhibits the entire range of pollution sensitivity conditions. This aquifer is overlain in many areas by the New Ulm Formation (**nt**) or the Cromwell Formation till (**cta**), or both. With these protective layers the **csr** aquifer exhibits more areas of very low to moderate pollution

sensitivity, especially in the eastern portion of the county, but overall is relatively sensitive to pollution.

Chemistry: All 10 of the groundwater samples analyzed for tritium were mixed, recent, or Cold War tritium age, which is consistent with the relatively sensitive nature of this aquifer. Of the 9 samples tested for chloride, 7 had elevated values ranging from 7.2 to 105 ppm. Of the 6 samples tested for nitrate, 5 had elevated values.

cse aquifer (Figure 24)

Sensitivity: The **cse** aquifer is relatively widespread and widely used in the county. It has large areas of moderate to very high pollution sensitivity because attributed to thin and patchy overlying aquitard protection. Only the eastern portion of the aquifer is mostly well protected. Similar to the overlying **csr** aquifer, very high pollution sensitivity conditions are common in the southwestern portion of the county where the overlying New Ulm Formation (**nt**) and Cromwell Formation till (**cta**) are absent, thin, or discontinuous.

Chemistry: Of the 35 samples that were tested for tritium, 33 had mixed or recent tritium age (94 percent). The two vintage samples are located at low to moderate sensitivity areas, respectively: west of Elk Lake shown on the west side of C-C' and east of the Elk River east of center F-F'. The vintage tritium-age sample east of the Elk River on F-F' had a carbon-14 age of 5,000 years which matches the very low to low pollution sensitivity of that area. The vintage tritium-age sample west of Elk Lake on C-C' had a carbon-14 age of 4,000 years, which doesn't match the moderate sensitivity of that area but suggests upwelling of older water in the vicinity of the Elk River valley.

Most of the mixed tritium-age samples matched with the low, moderate, and high sensitivities in the central, western, and southern parts of the county. A few of the mixed tritium-age samples matched with very low sensitivity areas in the eastern part of the county and are assumed to have been caused by lateral flow of mixed tritium-age water from upgradient, higher sensitivity locations. The recent tritium-age sample locations, associated with low to very high sensitivity areas, are scattered across all parts of the county with the exception of the eastern area.

Of the 39 samples that were tested for chloride, 26 (67 percent) had elevated concentrations of anthropogenic chloride (≥ 5 ppm), reflecting the more sensitive nature of this aquifer. Elevated chloride values ranged from 5.3 to 94.3 ppm and were found in all parts of the county. Of the 43 samples tested for nitrate, 13 (30 percent) had elevated concentrations (≥ 1 ppm) ranging from 1.5 to 21 ppm. These elevated values were widely scattered across most of the county.

scs aquifer (Figure 25)

Sensitivity: The **scs** aquifer is also relatively widespread and widely used in the county. It has many scattered areas of moderate to very high pollution sensitivity due to thin and patchy overlying aquitard protection. Similar to the overlying **cse** aquifer, very high pollution sensitivity conditions are common in the southwestern portion of the county where the overlying New Ulm Formation (**nt**) and Cromwell Formation till units (**cta** and **cte**) are absent, thin, or discontinuous.

Chemistry: Of the 33 samples tested for tritium, 29 were mixed or recent tritium age (88 percent). The four vintage samples in the eastern part of the county are located at very low to moderate sensitivity areas.

The 12 recent-age samples matched with the very low to moderate sensitivities throughout the county. Seven samples matched with very low sensitivity areas but were all close to upgradient areas of higher sensitivity suggesting lateral flow of mixed and recent tritium-age water from those upgradient locations. A similar situation was found for the mixed samples where 9 of the 17 were located in very low sensitivity areas but were all downgradient of an area of higher sensitivity, indicating lateral flow of recharge water from those areas. This relatively frequent association of detected tritium (mixed and recent tritium-age water) with local areas of very low and low sensitivity reflects the complexity of overlying hydraulic connections.

Of the 28 samples tested for chloride, 11 (39 percent) had elevated concentrations (≥ 5 ppm) of anthropogenic chloride, reflecting the more sensitive nature of this aquifer. Elevated chloride values ranged from 5.16 to 61.7 ppm and were found in all parts of the county. Of the 31 samples tested for nitrate, 6 (19 percent) had elevated concentrations (≥ 1 ppm) of 3.1 and 23 ppm.

fs1 aquifer (Figure 26)

Sensitivity: The **fs1** aquifer has a limited known extent. Mapped areas are mostly found in the eastern, southern, and northern parts of the county. This aquifer has a few scattered areas of moderate to very high pollution sensitivity due to local areas of hydraulically connected overlying sand bodies that have created areas of focused recharge.

Chemistry: Of the 4 samples that were tested for tritium, 2 were mixed and 2 were vintage. All of these samples were collected at locations in very low to low sensitivity areas. One sample located south of Elk Lake that was analyzed for carbon-14 residence time had an age of 7,000 years, which was consistent with the very low sensitivity of that area.

None of the five samples that were tested for chloride concentrations equalled or exceeded 5 ppm. One sample

located north of Zimmerman had a nitrate concentration of 1.3 ppm.

mls aquifer (Figure 27)

Sensitivity: Parts of the **mls** aquifer exist at locations across the county. Similar to the overlying **fs1** aquifer, the **mls** aquifer has a few scattered areas of moderate to very high pollution sensitivity due to local areas of hydraulically connected overlying sand bodies that have created areas of focused recharge. Most of these higher sensitivity areas are relatively small with the exception of a larger area northwest of Big Lake.

Chemistry: Of the eight samples tested for tritium, seven were vintage or mixed tritium age. One sample collected from the north-central part of the county near Boyd Lake had a recent tritium age and was associated with a moderate pollution sensitivity area. The four vintage samples are all located in very low sensitivity areas. The two vintage samples that were also analyzed for carbon-14 residence time had values of 4,000 and 5,000 years, respectively: west and east portions of cross section C–C'. One of the three mixed-age samples were located in very low sensitivity areas and can probably be attributed to lateral flow from upgradient areas of higher sensitivity. One of the mixed age samples was located in a high sensitivity area created by multiple overlying interconnected sand layers.

Of the six samples tested for chloride and nitrate, two had elevated concentrations (≥ 5 ppm) of anthropogenic chloride. Both were located northwest of Clear Lake and are shown on the west side of cross section C–C' between Elk Lake and Long Lake. Elevated chloride values were 5.89 and 10.0 ppm. None of the samples had elevated nitrate concentrations (≥ 1 ppm).

fs2 aquifer (Figure 28)

Sensitivity: Parts of the **fs2** aquifer exist at locations across the county. Similar to the overlying **fs1** and **mls** aquifers, the **fs2** aquifer has a few scattered areas of moderate to very high pollution sensitivity due to local areas of hydraulically connected overlying sand bodies that have created areas of focused recharge.

Chemistry: All of the six samples from this aquifer were mixed tritium age. One sample matched an area with very low sensitivity and probably represents lateral flow from higher sensitivity areas. Three of the mixed tritium-age samples were associated with low sensitivity areas and indicate focused recharge through multiple hydraulically connected overlying sand layers. Two of the mixed samples located in very low sensitivity areas had no apparent source of water that would contain detectable tritium and were classified with a recharge condition of unknown.

All of these samples were tested for chloride and nitrate. One sample located south of Princeton had an elevated (5.92 ppm) concentration of anthropogenic chloride. None of the samples had elevated nitrate concentrations.

suu aquifer (Figure 29)

Sensitivity: Parts of the **suu** aquifer exist mostly in the northern part of the county with scattered small locations in the south. Similar to the overlying **fs1**, **mls**, and **fs2** aquifers, the **suu** has a few scattered areas of moderate to very high pollution sensitivity due to local areas of hydraulically connected overlying sand bodies that have created areas of focused recharge.

Chemistry: Of the eight samples tested for tritium, two were vintage tritium age and two were recent. Both pairs of samples were located south of Princeton less than a mile apart. The vintage samples were associated with very low sensitivity. The recent samples, one with an elevated chloride value, were in an area of moderate to high sensitivity. These two pairs of contrasting samples and associated contrasting sensitivity conditions are good examples of the high variability of hydrogeologic conditions of glacial sediments at a local scale.

The four mixed samples matched areas with very low sensitivity and probably represent lateral flow from higher sensitivity areas. All of the mixed-age samples were tested for chloride and nitrate. One of the samples contained elevated chloride. One sample that had an elevated concentration of nitrate (3.96 ppm) is located east of St. Cloud, shown on A–A' east of Rice Creek.

Bedrock surface (Figure 30)

Sensitivity: Most of the bedrock aquifer usage and all of the groundwater samples are from the eastern part of the county, where the Paleozoic sandstones of the Mt. Simon and Wonewoc exist along with the underlying Mesoproterozoic clastic units such as the Hinckley and Fond du Lac. Within this eastern Paleozoic and Mesoproterozoic clastic bedrock area, pollution sensitivity is mostly very low with many small scattered areas of moderate to very high. Beyond this area to the west there are some much larger areas of higher sensitivity; especially in an area including Becker and adjoining areas along the Mississippi River where the overlying till units are absent, thin, or discontinuous.

Chemistry: Tritium data shown are only from wells with shallower open-hole constructions relative to the bedrock surface, with relatively short open-hole sections (bedrock surface to top of open hole ≤ 40 feet and length of open hole ≤ 80 feet). The purpose of this selection was to pick tritium data that were representative of the bedrock surface

conditions and the corresponding pollution sensitivity of the top bedrock surface.

Of the 12 tritium samples from wells that matched these criteria, six samples located in the eastern part of the county were mixed or recent tritium age, and six were vintage. These mixed and recent samples were associated with very low pollution sensitivity ratings and therefore are assumed to have originated by lateral groundwater movement from higher sensitivity areas or unknown circumstances. The five mixed and vintage samples that were also analyzed for carbon-14 residence time showed ages that ranges from 5,000 to 8,000 years, which is consistent with the very low pollution sensitivities of those areas.

Of the 12 samples that were tested for chloride, only one sample in the Elk River area contained an elevated concentration (34.9 ppm) of anthropogenic chloride. One sample located southwest of the city of Big Lake had an elevated nitrate concentration.

Deeper bedrock aquifers (Figure 31)

The selection of tritium data from wells constructed with open-hole portions in the deeper portions of the bedrock aquifers shows some groundwater samples with mixed tritium age (7 of 25). Most of these wells are located in areas of moderate to very high sensitivity for the bedrock surface (Figure 30) in the Big Lake area. This association suggests that in some areas the higher sensitivity conditions could extend to some of the deeper portions of the bedrock aquifers.

“Unknown” recharge conditions are shown for a recent tritium-age sample from the Mt. Simon aquifer in the southeastern portion of the county, and a mixed tritium-age Mt. Simon sample from Zimmerman. The age and condition of these wells may be a factor if older well construction methods or corrosion due to age have allowed leakage of shallow recent water into the well casings (shown with the “U” condition). Of the 16 samples that were tested for chloride, eight had elevated concentrations of anthropogenic chloride, including the areas of Big Lake, Princeton, and Zimmerman. Of the 23 samples tested for nitrate, five contained elevated concentrations, mainly in the Big Lake area.

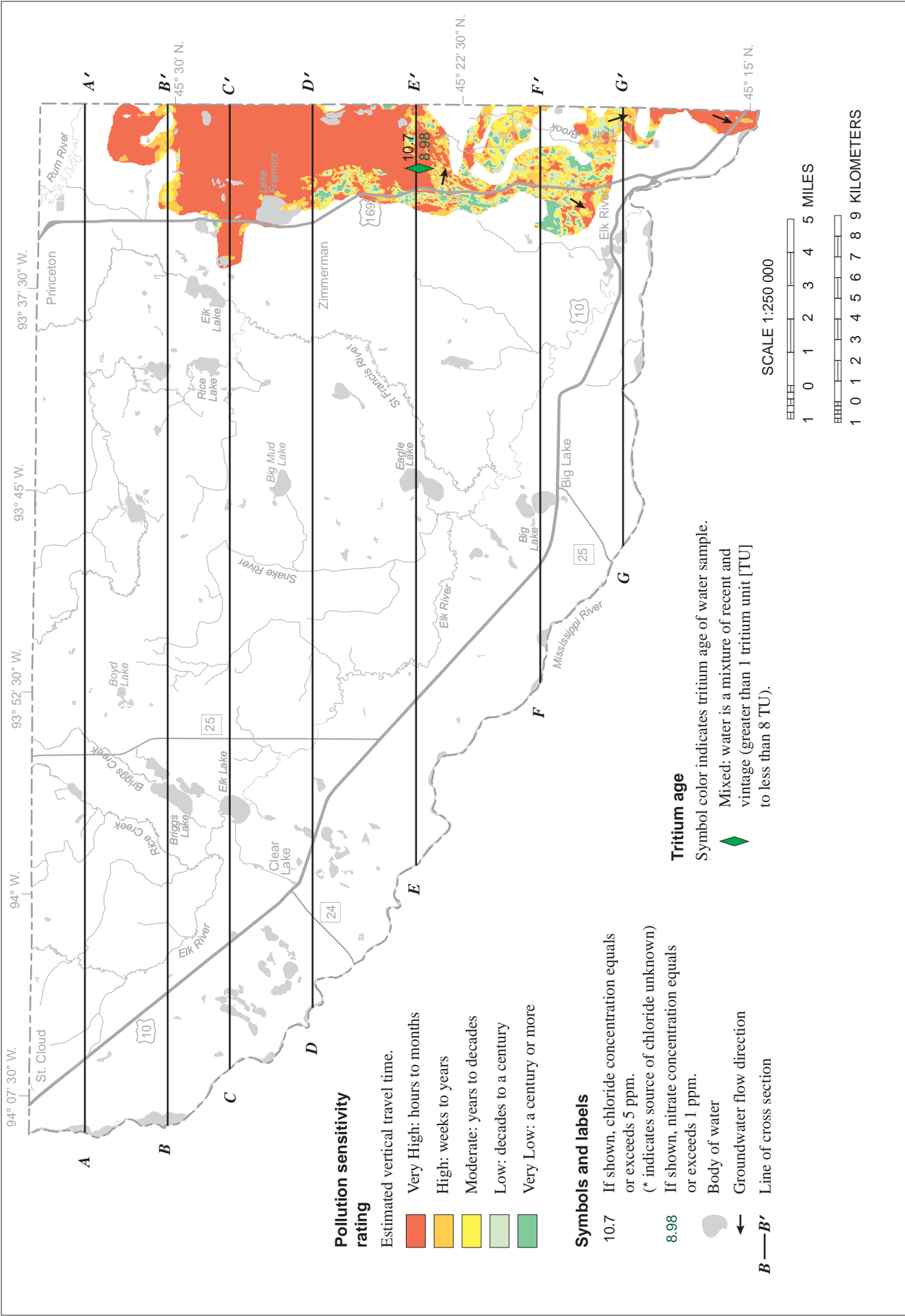


Figure 22. Pollution sensitivity of the csa aquifer and groundwater flow directions
Moderate to very high pollution sensitivity conditions are common.

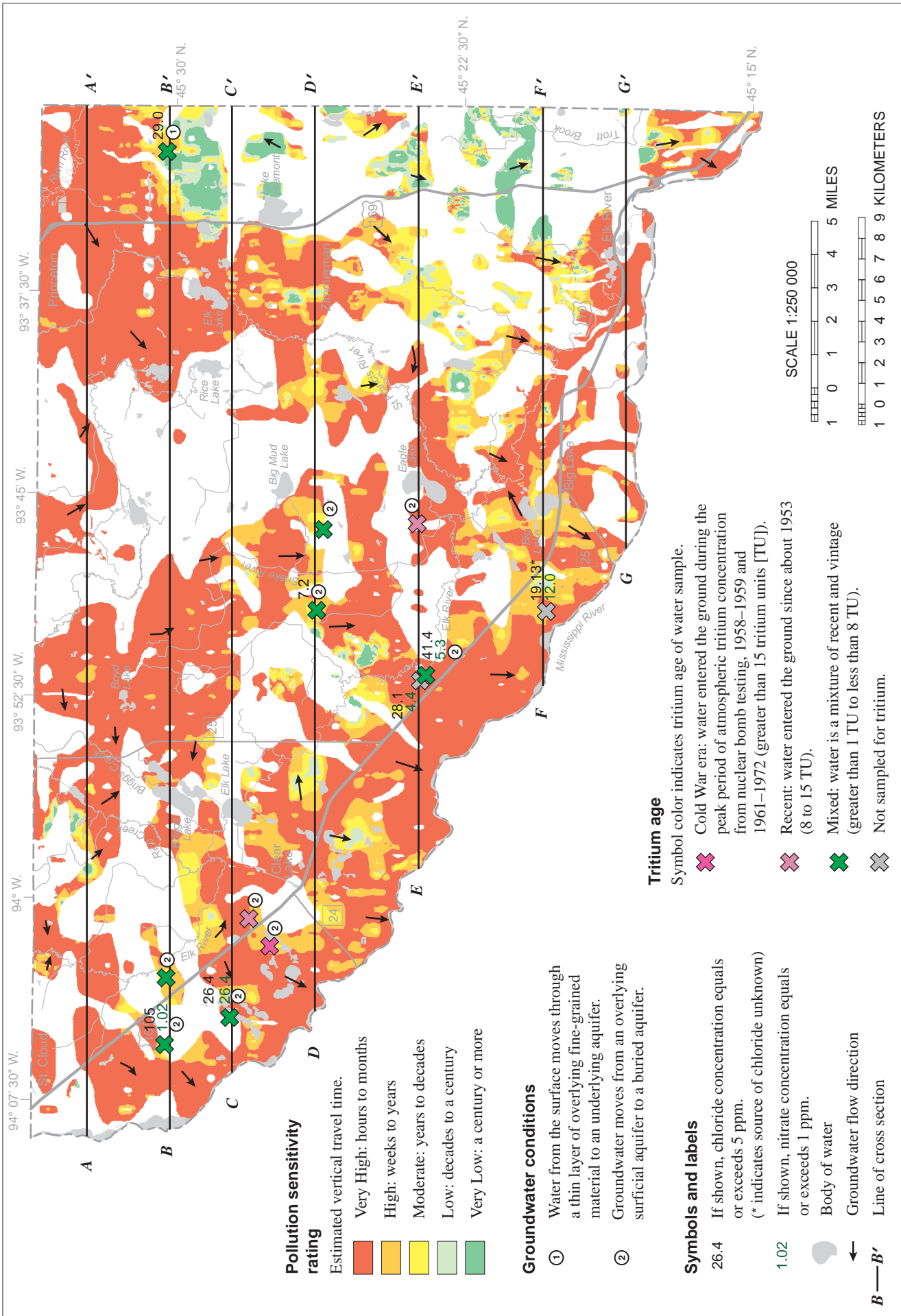


Figure 23. Pollution sensitivity of the CSR aquifer and groundwater flow directions

Moderate to very high pollution sensitivity conditions are common, with the exception of some areas in the eastern part of the county.

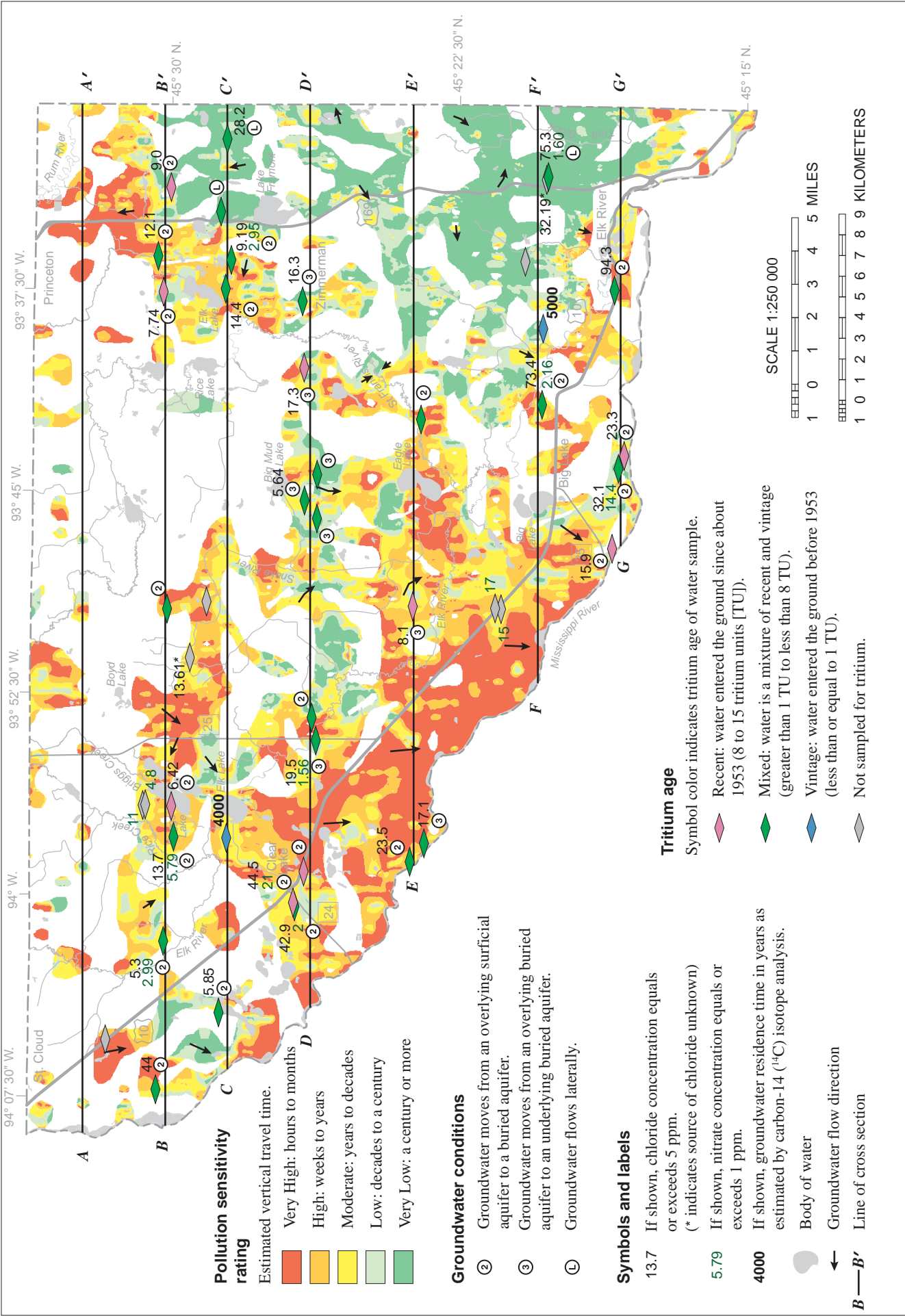
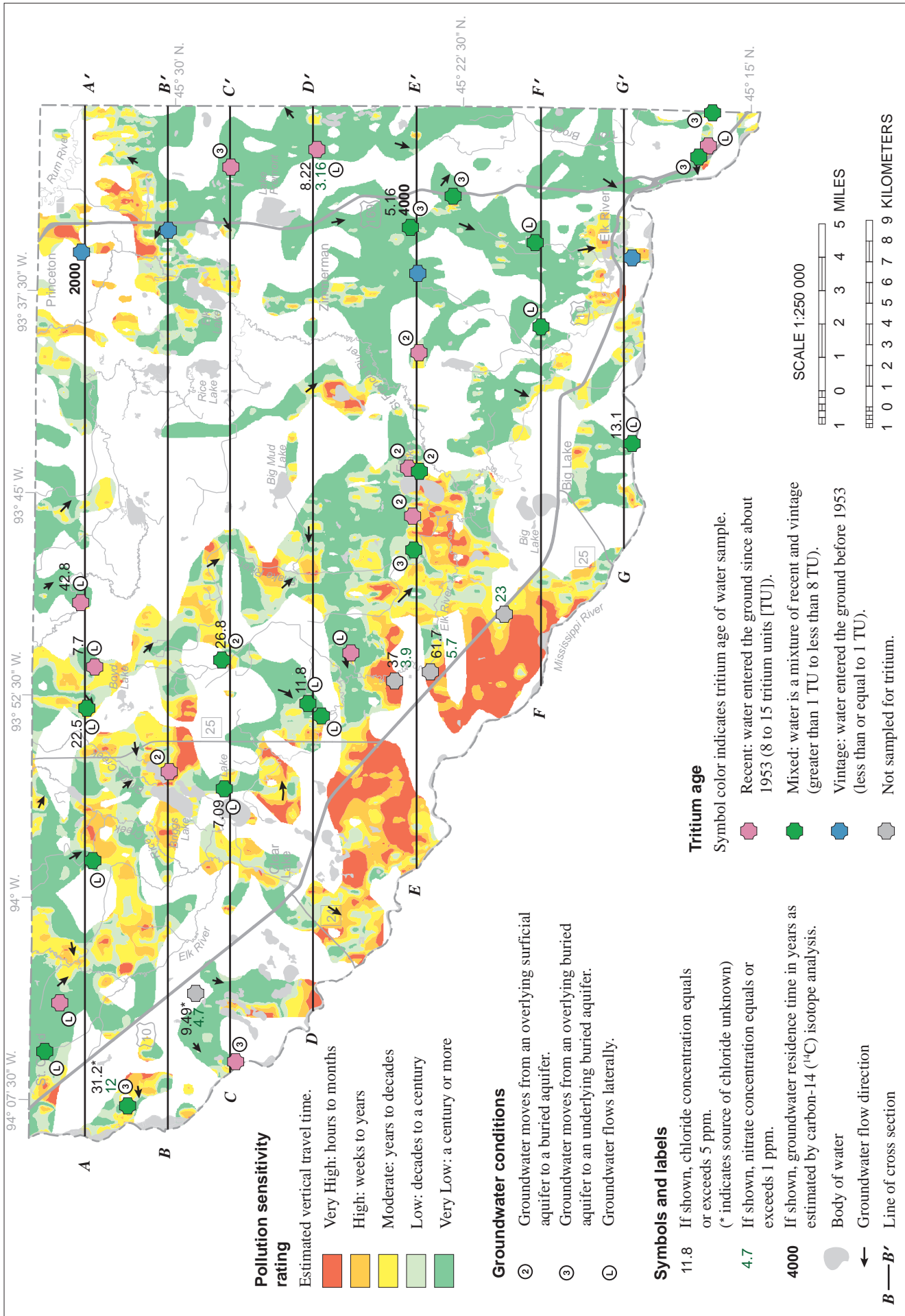


Figure 24. Pollution sensitivity of the cse aquifer and groundwater flow directions
This aquifer has large areas of moderate to very high pollution sensitivity due to thin and patchy overlying aquitard protection. Only the eastern portion of the aquifer is mostly well protected.





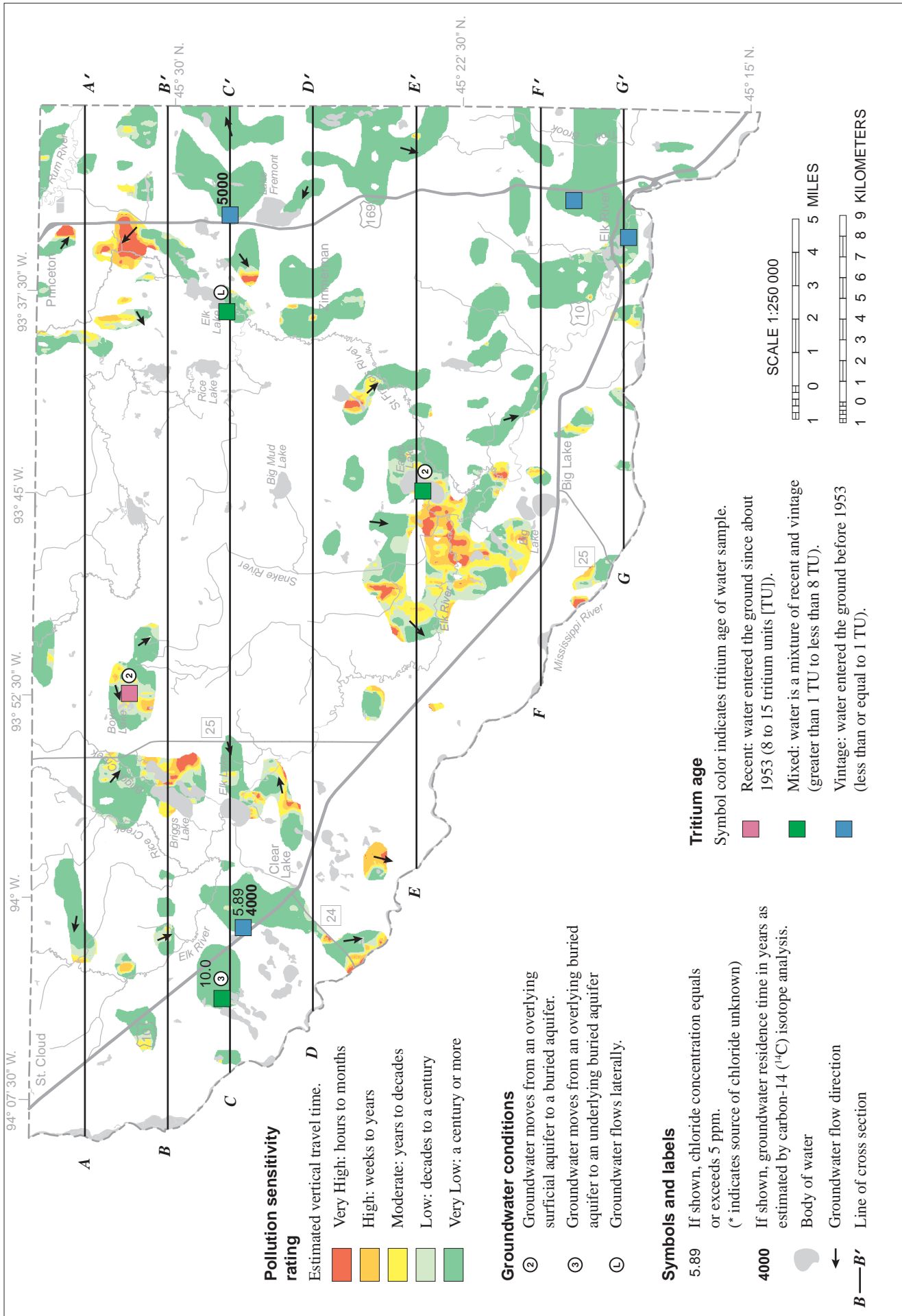


Figure 27. Pollution sensitivity of the mls aquifer and groundwater flow directions

This aquifer has a few scattered areas of moderate to very high pollution sensitivity due to local areas of hydraulically connected overlying sand bodies. Most of these higher sensitivity areas are relatively small with the exception of a larger area northwest of Big Lake.

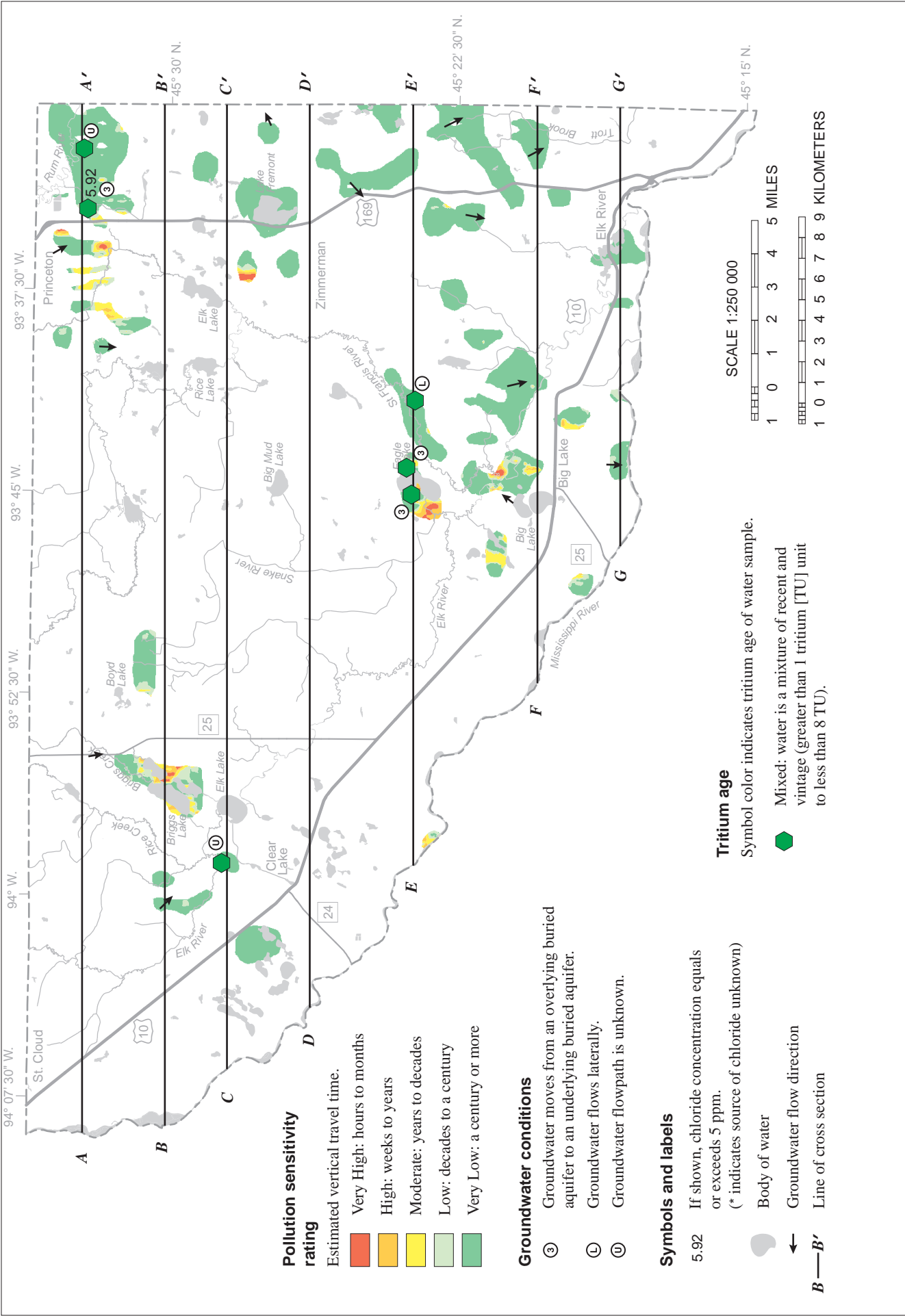


Figure 28. Pollution sensitivity of the fs2 aquifer and groundwater flow directions
This aquifer is mostly a very low sensitivity aquifer, except for scattered, relatively small areas of moderate to very high sensitivity.

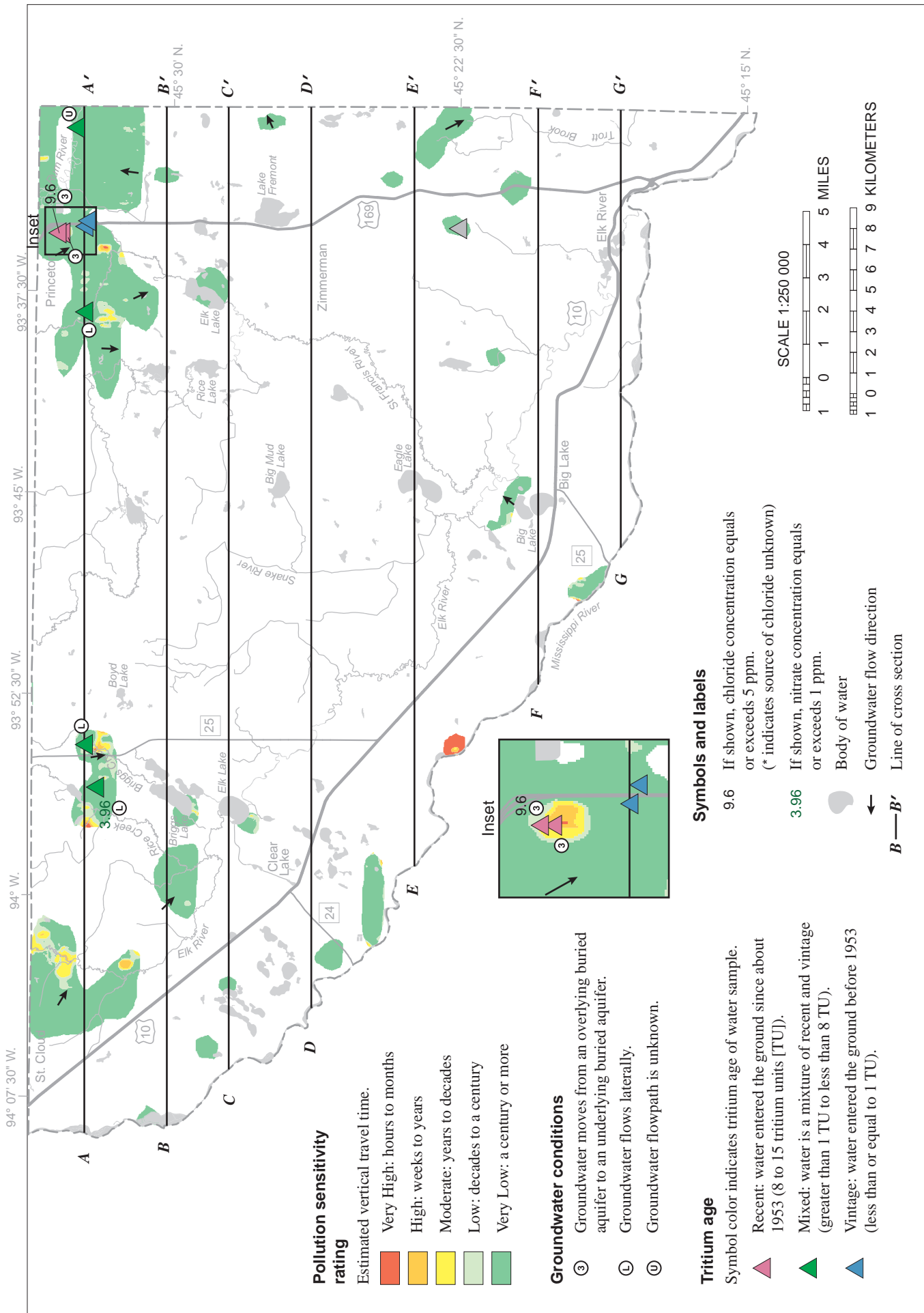
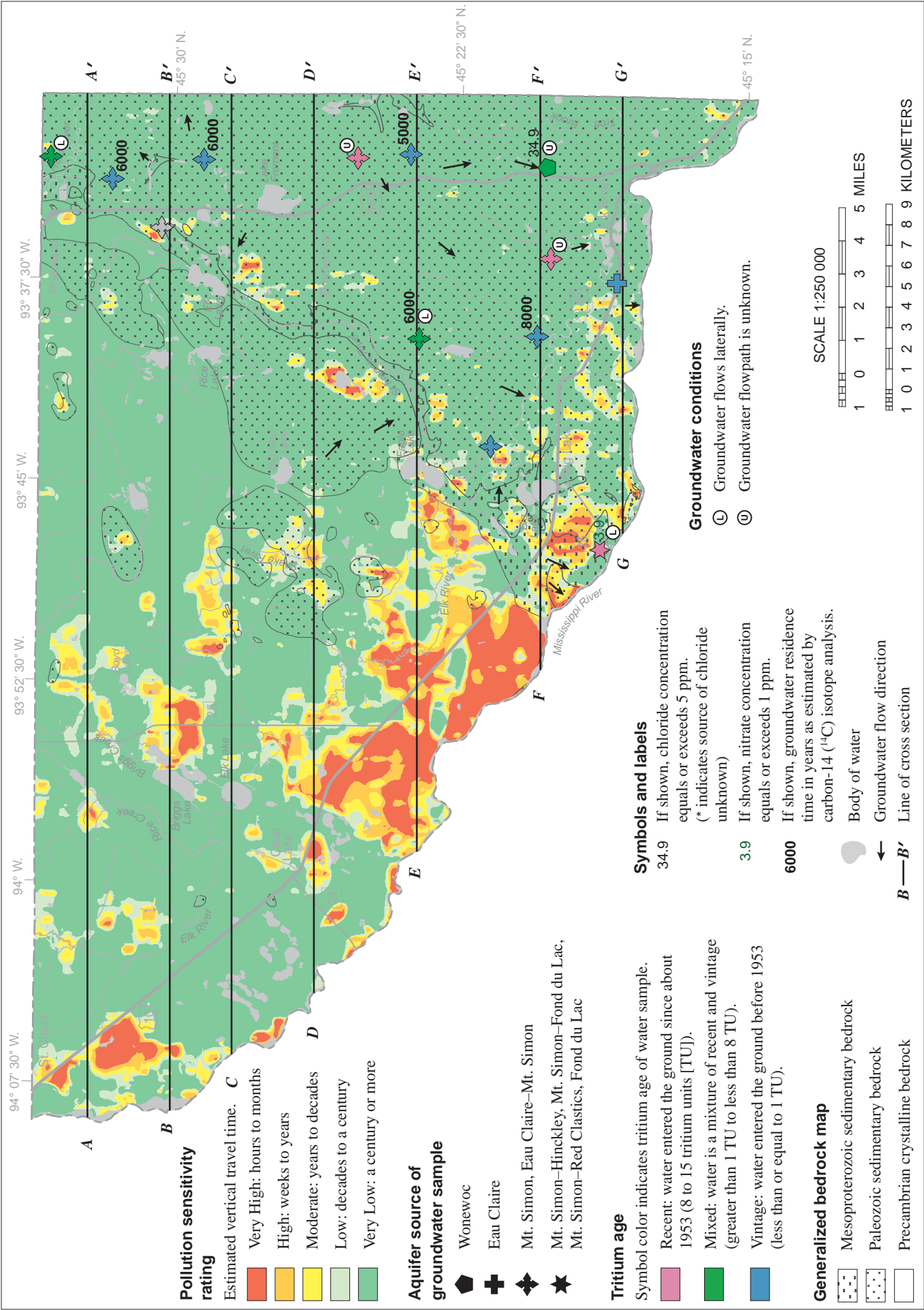


Figure 29. Pollution sensitivity of the suu aquifer and groundwater flow directions
 This aquifer is mostly a very low sensitivity aquifer, except for scattered, relatively small areas of moderate to very high sensitivity.



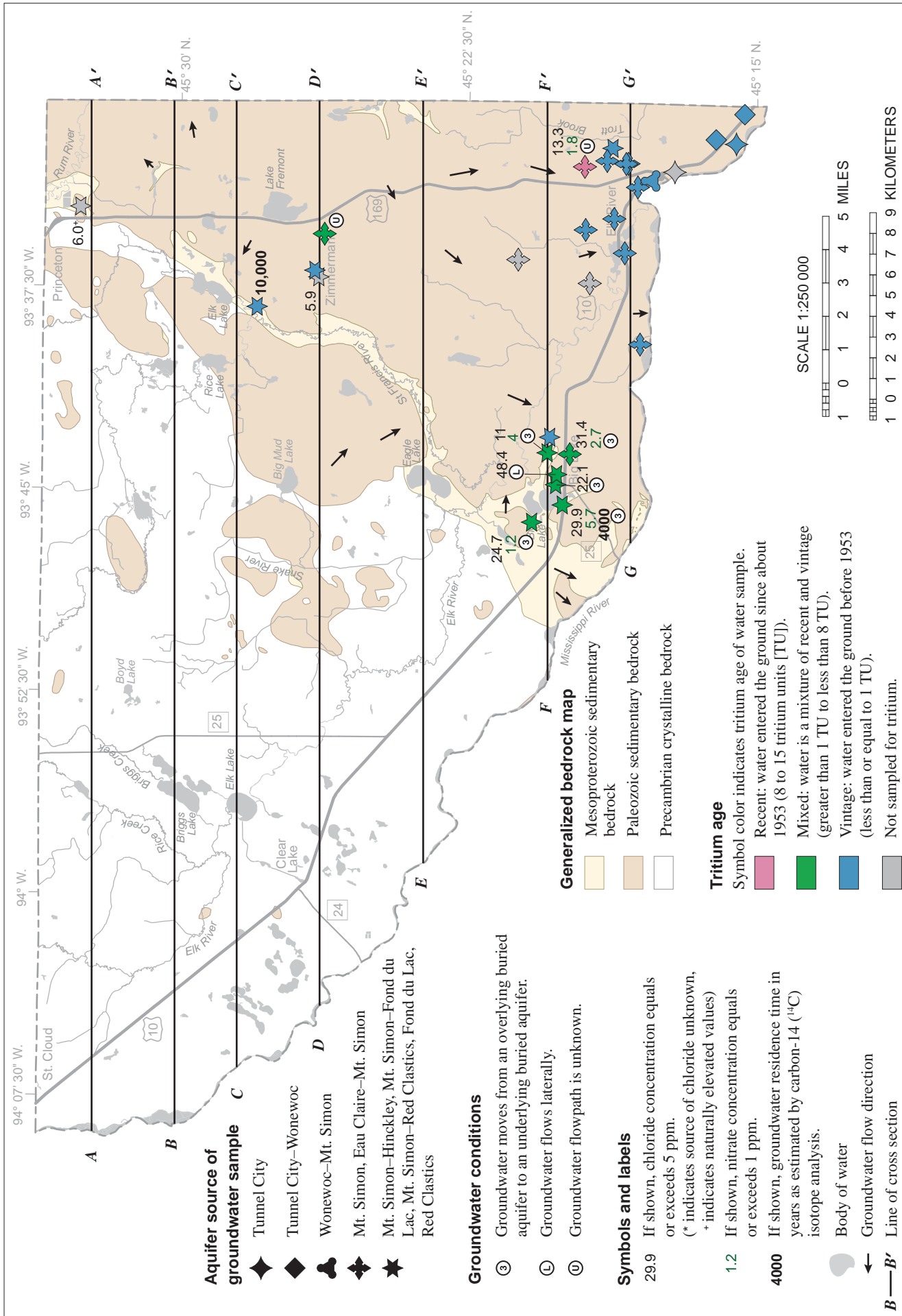


Figure 31. Deeper bedrock samples, tritium and other groundwater chemistry

Some of these deeper groundwater samples had a mixed tritium age which is associated with the moderate to very high sensitivity for the bedrock surface (Figure 30) in the Big Lake area. This association suggests that in some areas the higher sensitivity conditions could extend to some of the deeper portions of the bedrock aquifers.

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

Aquifer characteristics such as specific capacity and transmissivity are used to describe how water is transmitted by an aquifer. Larger values of each of these parameters indicate more productive aquifers.

Specific capacity is the discharge rate of water produced from a well per unit depth of drawdown. It is typically expressed in gallons per minute per foot (gpm/ft) and is determined from short-term pumping or well-development tests performed after a well was drilled. To ensure that the specific capacity values reflect actual pumping (not air-lifting), the pumping-test data were obtained from the County Well Index for wells with the following conditions:

- 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.

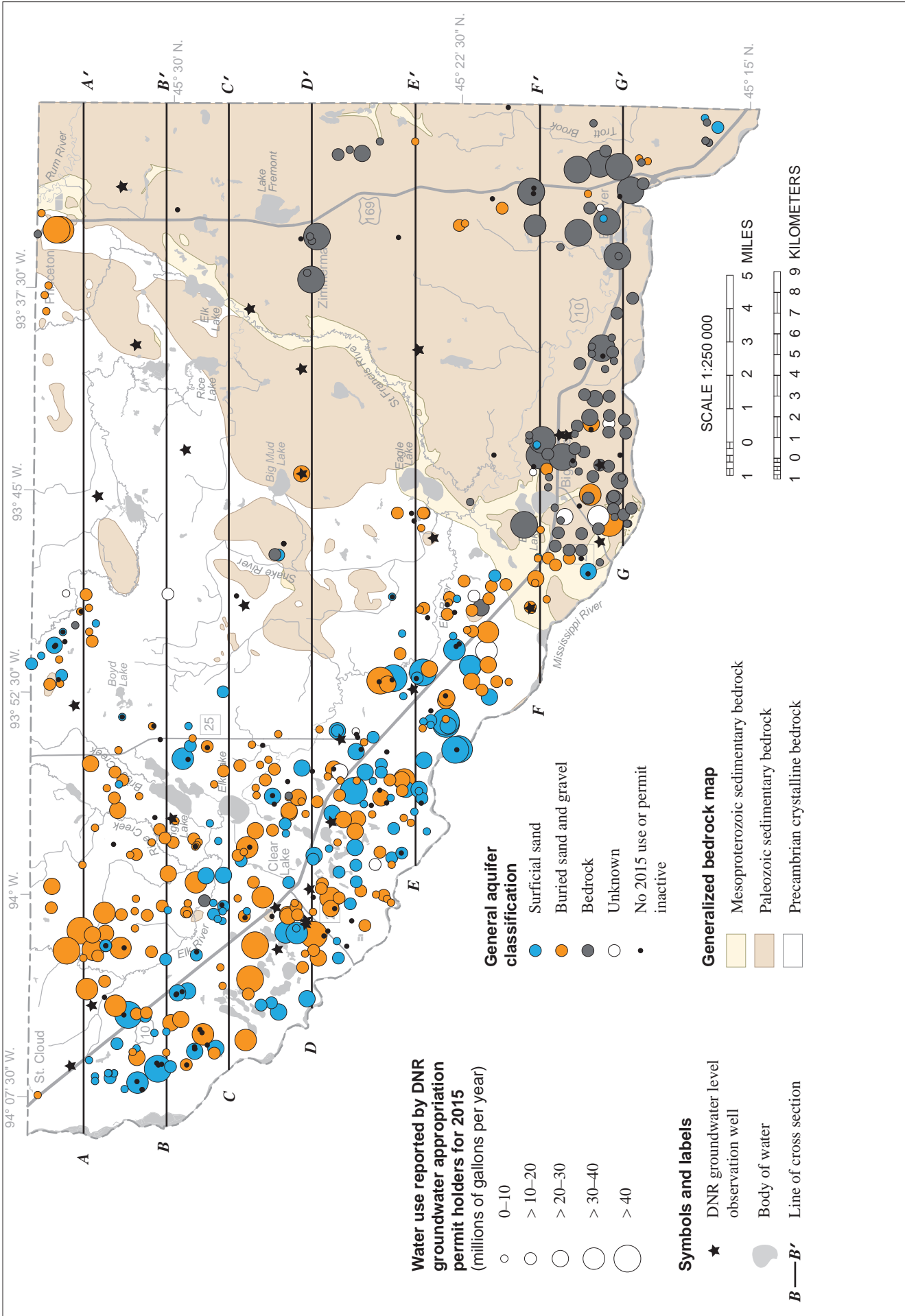
Transmissivity is an aquifer's capacity to transmit water. It is calculated from longer-term and larger-scale aquifer tests that provide a more accurate representation of the aquifer properties than specific capacity. It is determined by multiplying the thickness of the aquifer by the hydraulic conductivity of the aquifer material (the rate at which groundwater flows through a unit cross section of an aquifer).

Data from aquifer pumping tests are within a narrow range of values from approximately 4,600 ft²/day (surficial sand and gravel) to approximately 9,500 ft²/day (Mt. Simon). Two tests from wells that were constructed in the Mt. Simon and an underlying Mesoproterozoic clastic unit (Hinckley or Fond du Lac) had slightly lower transmissivities possibly due the less porous and permeable nature of these bedrock units.

Table 2. Specific capacity and transmissivity of selected wells

[Specific capacity data adapted from the County Well Index; gpm/ft, gallons per minute per foot. Transmissivity data are from MDH and U.S. Geological Survey (USGS) tests compiled by the DNR; ft²/day, feet squared per day, -- means no data, * means no tests available.]

Aquifer (CWI Code)	Specific capacity (gpm/ft)					Transmissivity (ft ² /day)		
	Casing diameter (inches)	Mean	Min	Max	Number of tests	Casing diameter (inches)	Mean	Number of tests
Unconsolidated aquifers								
Surficial sand and gravel (QWTA)	12–16	29.9	14.6	50.0	8	12	4,583	5
Buried sand and gravel (QBAA)	12–20	31.7	2.1	161.4	48	4–12	7,456	16
Bedrock aquifers								
Eau Claire–Mt. Simon (CEMS)	12–16	14.9	7.7	18.4	4	*	--	--
Mt. Simon (CMTS)	12–18	21.6	10.3	32.5	13	12–18	9,533	3
Mt. Simon–Hinckley (CMSH)	12–18	29.2	7.4	51.3	5	12–18	8,320	1
Mt. Simon–Fond du Lac (CMFL)	12–18	17.6	5.6	35.3	7	18	6,423	1
Mt. Simon–red clastics (CMRC)	12	27.1	5.3	47.4	4	*	--	--
Mid. Proterozoic Sed. (PMSU)	12	4.3	1.5	7.1	2	*	--	--
Multiple (MTPL)	12–16	24.4	10.4	36.8	4	*	--	--
Total bedrock	12–18	21.1	1.5	51.3	39	18	8,668	5



Groundwater use

A water-use appropriation permit from the DNR is required for groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year (with some exceptions). This provides the DNR with the ability to assess and regulate which aquifers are being used and for what purpose.

DNR water appropriation permits require that the water usage be reported annually. Information pertaining to these permits is recorded using Minnesota Department of Natural Resources Permitting and Reporting System (MPARS). This helps the DNR track the volume, source aquifer, and type of water use.

The reported water use for 2015 is categorized in Table 3 for all large capacity users in the county by the type of aquifer (Figure 32) and type of use (Figure 33).

The majority (70 percent) of the permitted water use is for irrigation and is drawn from the surficial sand (QWTA) and buried sand and gravel aquifers (QBAA). Water supply is the second most common use category (20 percent) with

bedrock and buried sand and gravel aquifers as the most important sources. Industrial processing (4 percent) uses water mostly from buried sand and bedrock sources. Noncrop irrigation (3 percent) and power generation (4 percent) use water mostly from buried sand and surficial sand sources.

There are no reporting requirements in Minnesota for well owners that use quantities of groundwater less than 10,000 gallons per day or 1 million gallons per year. However, the aquifer being used can be determined in many cases by comparing the well constructions with all of the closely spaced cross sections produced by the MGS. Of the approximately 14,600 active wells in the county with identified aquifers, most wells are completed in the buried sand aquifers (64 percent), followed by the sedimentary bedrock aquifers (21 percent). Only 15 percent are completed in the surficial sand aquifer. The large majority of wells in the county are domestic wells (88 percent), followed by irrigation (4 percent), and public supply (2 percent).

Table 3. Reported 2015 water use from DNR groundwater permit holders

[Data from Minnesota Permitting and Reporting System (MPARS). MGY, million gallons per year; Dash marks (--) indicate no use in those categories. Percentages may not total 100 due to rounding.]

Use category	Surficial sand (QWTA)	Buried sand and gravel (QBAA)	Bedrock	Unknown	Total (MGY)	Total (percent)
Crop irrigation	2572	2604	715	532	6423	70
Water supply	190	231	1384	--	1805	20
Industrial processing	21	248	117	2	387	4
Thermoelectric power generation	127	201	13	--	342	4
Noncrop irrigation	60	118	55	15	248	3
Dust control, livestock watering	--	1	2	--	3	0.04
Total (MGY)	2970	3404	2286	549	9210	
Total (percent)	32	37	25	6	100	

QWTA, Quaternary water table aquifer (surficial sand aquifer)

QBAA, Quaternary buried artesian aquifer



Conclusions

Groundwater flow directions in the water-table aquifer are controlled by the dominant groundwater discharge locations, including the Rum, Elk, and Mississippi rivers and associated tributaries. Shallow water-table conditions (0–10 feet) are common in the county with the exception of the higher land-surface areas near portions of Briggs Creek; the St. Francis, Snake, Elk, and Mississippi rivers; and uplands in the eastern portion of the county.

Potentiometric surface maps show a general pattern of groundwater flow toward the Mississippi River valley. Local flow toward the larger rivers and creeks in the county is evident on all the buried sand potentiometric surface maps, such as the Elk and St. Francis rivers, and Briggs Creek. These maps indicate at least some groundwater discharge to the Mississippi River and portions of its tributaries from all the buried sand aquifers.

Chemical characteristics of groundwater revealed important information regarding groundwater source, human health risk, residence time, and pollution sensitivity implications. One groundwater sample with an evaporative signature was collected downgradient of Big Mud Lake. These data are evidence of surface water to groundwater connections in this area.

- **Chloride** is a significant contaminant in Sherburne County groundwater samples. Of the 66 groundwater samples, 57 (86 percent) exceeded background concentrations for chloride, had elevated chloride to bromide ratios, and were therefore considered anthropogenic. These elevated occurrences of chloride were a relatively widespread across the county in the **ss** aquifer, most of the buried sand aquifers (**crs**, **ces**, **scs**, **mls**, and **fs2**), and also two detections in bedrock aquifers: Wonewoc and red clastics.
- **Nitrate** was found in 35 of 115 groundwater samples (30 percent) with concentrations that exceeded an approximate background concentration of 1 ppm. Nitrate has an EPA MCL of 10 ppm. Elevated nitrate concentrations were most common in the western portion of the county and were found in the **ss**, **csr**, **cse**, **scs**, **fs1**, and **suu** buried sand aquifers and the Mt. Simon, Fond du Lac, and red clastic bedrock aquifers.
- **Arsenic** was found in elevated concentrations (≥ 10 ppb) in 5 groundwater samples, in the **csr**, **cse**, **scs**, and **fs2** aquifers.
- **Manganese** concentrations that equaled or exceeded the lower MDH HRL established for infants (100 ppb) was found in a large proportion of groundwater samples

(88 samples, 68 percent) indicating a natural water quality issue for the majority of well owners in the county.

- **Carbon-14** residence time data from 14 wells within the county showed that ages in buried sand and upper bedrock aquifers ranged from approximately 2,000 to 8,000 years. A deeper bedrock aquifer residence time of 10,000 years was reported from the Fond du Lac.

Buried sand aquifer pollution sensitivity: The **csa**, **csr**, and **cse** buried sand aquifers are relatively sensitive to pollution with the exception of portions in the eastern part of the county where sensitivity is commonly very low to moderate. Most of the samples from these aquifers contained Cold War era, recent, or mixed tritium age. Most of the samples from these aquifers contained elevated chloride concentrations.

- The **scs** buried sand aquifer, similar to the overlying aquifers, is relatively sensitive to pollution and the majority of the groundwater samples from this aquifer contained mixed or recent tritium. However, the eastern portion appears to be better protected with fewer and smaller areas of moderate to very high sensitivity and four locations with vintage tritium age. Fewer than half of the samples contained elevated concentrations of chloride.
- The **fs1**, **mls**, **fs2**, and **suu** buried sand aquifers have large areas that appear to be well protected and exhibit very low pollution sensitivity ratings with the exception of a larger moderate to very high pollution sensitivity area in between Becker and Big Lake. Only three recent-age samples were detected in the group of 28 samples collected from these aquifers, and approximately a third of the groundwater samples that were analyzed for tritium had a vintage age. Elevated chloride was detected in only 4 of 24 samples (17 percent). Elevated nitrate was detected in 2 of 26 samples (8 percent).

Bedrock surface pollution sensitivity shows well-protected conditions with large areas of very low pollution sensitivity ratings in the eastern part of the county. However, dense clusters of moderate to very high pollution sensitivity areas exist along the southern portion of the county where agriculture and urbanization are common. Elevated anthropogenic chloride values with mixed-age tritium are especially common in the Big Lake area for the deeper bedrock wells. For groundwater samples collected from wells with shallower open-hole constructions, only a few groundwater samples contained mixed or recent tritium. Of the 12 samples that were tested for chloride, only one sample in the Elk River area had an elevated concentration

(34.9 ppm) of anthropogenic chloride. One sample southwest of the city of Big Lake had an elevated nitrate concentration (3.9 ppm).

Water use: the majority of the reported water use (70 percent) is for crop irrigation and mainly draws from the surficial sand (QWTA) and buried sand aquifers (QBAA). Water supply is the second most common use category (20 percent) with bedrock and buried sand aquifers as the most important sources.

Appendix

Groundwater samples were collected from an outside faucet or hydrant. The wells were purged prior to sampling to remove stagnant water from the well bore and plumbing system. Samples were collected after field parameters such as temperature, conductivity, dissolved oxygen, and pH had stabilized. Each was filtered and preserved according to protocols listed below and submitted to laboratories for analysis.

Samples were analyzed by DNR staff, the University of Minnesota Department of Earth Sciences Laboratory

(U of M), or the University of Waterloo Environmental Isotope Laboratory in Canada. The well owners received a copy of the results including some background reference information regarding their meaning.

Email county.groundwater.atlas.dnr@state.mn.us for additional information.

Groundwater field sample collection and handling details

Parameter	Enriched Tritium	^{18}O ^2H	Cations	Anions	Trace constituents	Alkalinity	^{14}C
Lab	Waterloo	Waterloo	U of M	U of M	U of M	DNR Staff	U of M
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	30 gallon barrel
Head space	yes	yes	yes	yes	yes	NO	yes
Rinse	no	no	yes*	yes*	yes*	yes**	no
Filter	no	no	yes	yes	yes	no	yes
Preservative	no	no	1 drop 6N HCl	no	5 drops 15N HNO ₃	no	NH ₄ OH added to adjust pH
Refrigeration	no	no	yes	yes	yes	Yes, if not analyzed onsite	no
Shelf life	long	long	2–3 weeks	2–3 weeks	2–3 weeks	24–48 hours	years
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	none
Field blank	none	none	1 for every 20****	1 for every 20****	1 for every 20****	none	none
Storage duplicate	yes	yes	no	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.

References

- Adams, R., 2016a, Water-table elevation and depth to water table: Minnesota Department of Natural Resources, Minnesota Hydrogeology Atlas Series HG-03, report and 2 pls.
- Adams, R., 2016b, Pollution sensitivity of near-surface materials: Minnesota Department of Natural Resources, Minnesota Hydrogeology Atlas Series HG-02, report and 1 pl.
- Alexander, S.C., and Alexander, E.C., Jr., 1989, Residence times of Minnesota groundwaters: Minnesota Academy of Sciences Journal, v. 55, no.1, p. 48–52.
- Craig, H., 1961, Isotopic variations in meteoric waters: Science, 133, p. 1702–1703.
- Davis, S.N., Whittemore, D.O., and Fabrryka-Martin, J., 1998, Uses of chloride/bromide ratios in studies of potable water: Ground Water, March–April, v. 36, no. 2, p. 338–350.
- DNR, 2016a, Methods for estimating water-table elevation and depth to water table: Minnesota Department of Natural Resources, GW-04, <http://files.dnr.state.mn.us/waters/groundwater_section/mapping/gw/gw04_wt.pdf>.
- DNR, 2016b, Methods to estimate near-surface pollution sensitivity: Minnesota Department of Natural Resources, GW-03, <http://files.dnr.state.mn.us/waters/groundwater_section/mapping/gw/gw03_ps-ns.pdf>.
- DNR, 2016c, Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment (CFGs) thickness: Minnesota Department of Natural Resources, GW-02, <http://files.dnr.state.mn.us/waters/groundwater_section/mapping/gw/gw02_report.pdf>.
- Erickson, M.L., and Barnes, R.J., 2005a, Glacial sediment causing regional-scale elevated arsenic in drinking water: Ground Water, November–December, v. 43, no. 6, p. 796–805.
- Erickson, M.L., and Barnes, R.J., 2005b, Well characteristics influencing arsenic concentrations in ground water: Water Research, v. 39, p. 4029–4039.
- EPA, 2001, Arsenic rule: Environmental Protection Agency, accessed May 11, 2015, <<http://water.epa.gov/lawsregs/rulesregs/sdwa/arsenic/regulations.cfm>>.
- EPA, [1996], Secondary drinking water standards—guidance for nuisance chemicals: Environmental Protection Agency, accessed May 11, 2016, <<https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals>>.
- Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, NJ, Prentice-Hall, 604 p.
- Geologic Sensitivity Workgroup, 1991, Criteria and guidelines for assessing geologic sensitivity of ground water resources in Minnesota: Minnesota Department of Natural Resources, 122 p., <http://files.dnr.state.mn.us/waters/groundwater_section/mapping/sensitivity/docs/assessing_geologic_sensitivity.pdf>.
- Hounslow, A.W., 1995, Water quality data: Analysis and Interpretation, CRC Press, p. 71–128.
- Kendall, C., and Doctor, D., 2003, Stable isotope applications in hydrologic studies, Holland, H.D., and Turekian, K.K., eds., chap. 11 of Surface and ground water, weathering, and soils, in treatise on geochemistry: Amsterdam, The Netherlands, Elsevier, Inc., v. 5, p. 319–364.
- Lively, R.S., Jameson, R., Alexander, E.C. Jr., Morey, G.B., 1992, Radium in the Mt. Simon-Hinckley aquifer, east-central and southeastern Minnesota: Minnesota Geological Survey, Information Circular 36, <<http://hdl.handle.net/11299/59391>>.
- Lucas, L.L., and Unterweger, M.P., 2000, Comprehensive review and critical evaluation of the half-life of tritium: Journal of Research of the National Institute of Standards and Technology, v. 105, p. 541–549, <<http://dx.doi.org/10.6028/jres.105.043>>.
- McMahon, P.B., 2001, Aquifer/aquitard interfaces—mixing zones that enhance biogeochemical reactions: Hydrogeology Journal, v. 9, p. 34–43.
- MDH, 2012, Human health-based water guidance table: Minnesota Department of Health, <<http://www.health.state.mn.us/divs/eh/risk/guidance/gw/table.html>>.
- MDH, 2014, Manganese in drinking water: Minnesota Department of Health, Minnesota Well Management News, v. 34, no. 1.
- MDH, 2016a, Arsenic in private wells—facts & figures: Minnesota Department of Health, accessed August 2016 <https://apps.health.state.mn.us/mndata/arsenic_wells>.
- MDH, 2016b, Drinking water quality: Minnesota Department of Health, <<https://data.web.health.state.mn.us/web/mndata/drinkingwater>>.

- MGWA, 2015, Manganese in Minnesota's groundwaters emphasizing the health risks of manganese in drinking water: Minnesota Groundwater Association, White Paper, 37 p., accessed May 5, 2017, <http://www.mgwa.org/documents/whitepapers/01_manganese/Manganese_in_Minnesotas_Groundwaters.pdf>.
- MPCA, 1998, Nitrate in Minnesota ground water—a GWMAP perspective: Minnesota Pollution Control Agency, accessed October 2015.
- MPCA, 2005, The Minnesota stormwater manual: Minnesota Pollution Control Agency, <<http://www.pca.state.mn.us/index.php/view-document.html?gid=8937>>.
- Nicholas, S.L., Toner, B.M., Erickson, M.L., Knaeble, A.R., Woodruff, L.G., and Meyer, G.N., 2011, Speciation and mineralogy of arsenic in glacial sediments and their effect on arsenic concentrations in groundwater [abs.]: Geological Society of America Abstracts with Programs [digital version], v. 43, no. 5.
- Panno, S.V., Hackley, K.C., Hwang, H.H., Greenberg, S.E., Krapac, I.G., Landsberger, S., and O'Kelly, D.J., 2006, Characterization and identification of Na-Cl sources in ground water: Ground Water, March–April, v. 44, no. 2, p. 176–187.
- Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., Green J.A., Mossler, J.H., Alexander, S.C., 2003, Hydrogeology of the Paleozoic bedrock in southeastern Minnesota: Minnesota Geological Survey, Report of Investigation 61, 105 p.; 2 pls.
- Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., and Alexander, S.C., 2006, Hydrostratigraphic characterization of intergranular and secondary porosity in part of the Cambrian sandstone aquifer system of the cratonic interior of North America—improving predictability of hydrogeologic properties: Sedimentary Geology, v. 184, p. 281–304.
- Setterholm, D., 2014, Geologic atlas user's guide—using geologic maps and databases for resource management and planning: Minnesota Geological Survey, Open-File Report 12-01.
- Thomas, M.A., 2007, The association of arsenic with redox conditions, depth, and ground-water age in the glacial aquifer system: U.S. Geological Survey Scientific Investigations Report 2007-5036, 26 p.
- USDA-NRCS, 2009, Hydrologic soil groups, chapter 7 in Part 630 hydrology, national engineering handbook: U.S. Department of Agriculture, Natural Resources Conservation Service.
- USDA-NRCS, 2011, Web soil survey geographic database (SSURGO) for Sherburne County, Minnesota: U.S. Department of Agriculture, Natural Resources Conservation Service, accessed January 5, 2015 at <<http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx>>.
- USDA-NRCS, 2011, Soil data access: <<http://sdmdataaccess.nrcs.usda.gov>>.
- United States Census Bureau, 2016, accessed August 26, 2016, <<https://www.census.gov/quickfacts/table/PST045215/27003,00>>.
- Wilson, J.T., 2012, Water-quality assessment of the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey Scientific Investigations Report 2011-5229, 154 p.

Glossary

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

anisotropic—a condition in which a property (e.g., hydraulic conductivity) varies with the direction.

anthropogenic—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 100–35,000 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—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 (nitrate-N, NO_3^-)—humans are subject to nitrate toxicity, with infants being especially vulnerable to methemoglobinemia, also known as blue baby syndrome.

Elevated nitrate (≥ 1 ppm) is primarily from fertilizer sources.

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 542–251 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 that has a half-life of 12.32 years. The nucleus of tritium contains one proton and two neutrons. It is used to identify groundwater that entered the ground since the 1950s.

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.

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