MINNESOTA DEPARTMENT OF NATURAL RESOURCES

GEOLOGIC ATLAS OF ANOKA COUNTY, MINNESOTA

County Atlas Series C-27

PART B, HYDROGEOLOGY:

Report

Plate 7, Water Chemistry

Plate 8, Hydrogeologic Cross Sections

Plate 9, Hydrogeologic Cross Section

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

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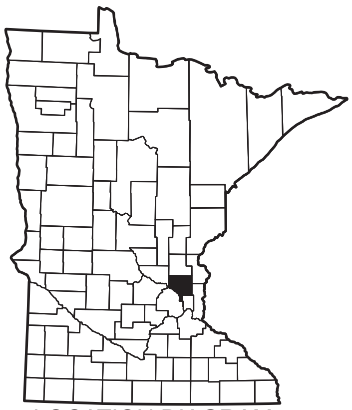
Geologic Atlas of Anoka County, Minnesota

County Atlas Series C-27, Part B

By James A. Berg



Minnesota Department of Natural Resources

2016

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County Geologic Atlas Program

The Minnesota County Geologic Atlas series has been produced since 1982. Atlases after 1996 are found in two parts. Part A covers the geology and is produced by the Minnesota Geological Survey (MGS). Part B covers the hydrogeology and is produced by the Minnesota Department of Natural Resources (DNR).

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

Part A, Geology, MGS (http://www.mngs.umn.edu/county_atlas/countyatlas.htm)
Part B, Groundwater, DNR (mndnr.gov/groundwatermapping)

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Geologic Atlas of Anoka County, Minnesota, Part B

by James A. Berg

Introduction

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

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

Additional information is available regarding the history and purposes of the program, various atlas applications, and descriptions of the Part A components (Setterholm, 2014).

The report describes the hydrogeologic setting, water levels, chemistry, pollution sensitivity, and use of aquifers within the county. The accompanying plates illustrate the water chemistry (Plate 7) and show groundwater flow directions and residence time within the buried sand and gravel aquifers and bedrock aquifers (hydrogeologic cross sections, Plates 8 and 9).

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

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

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

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

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

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

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

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

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

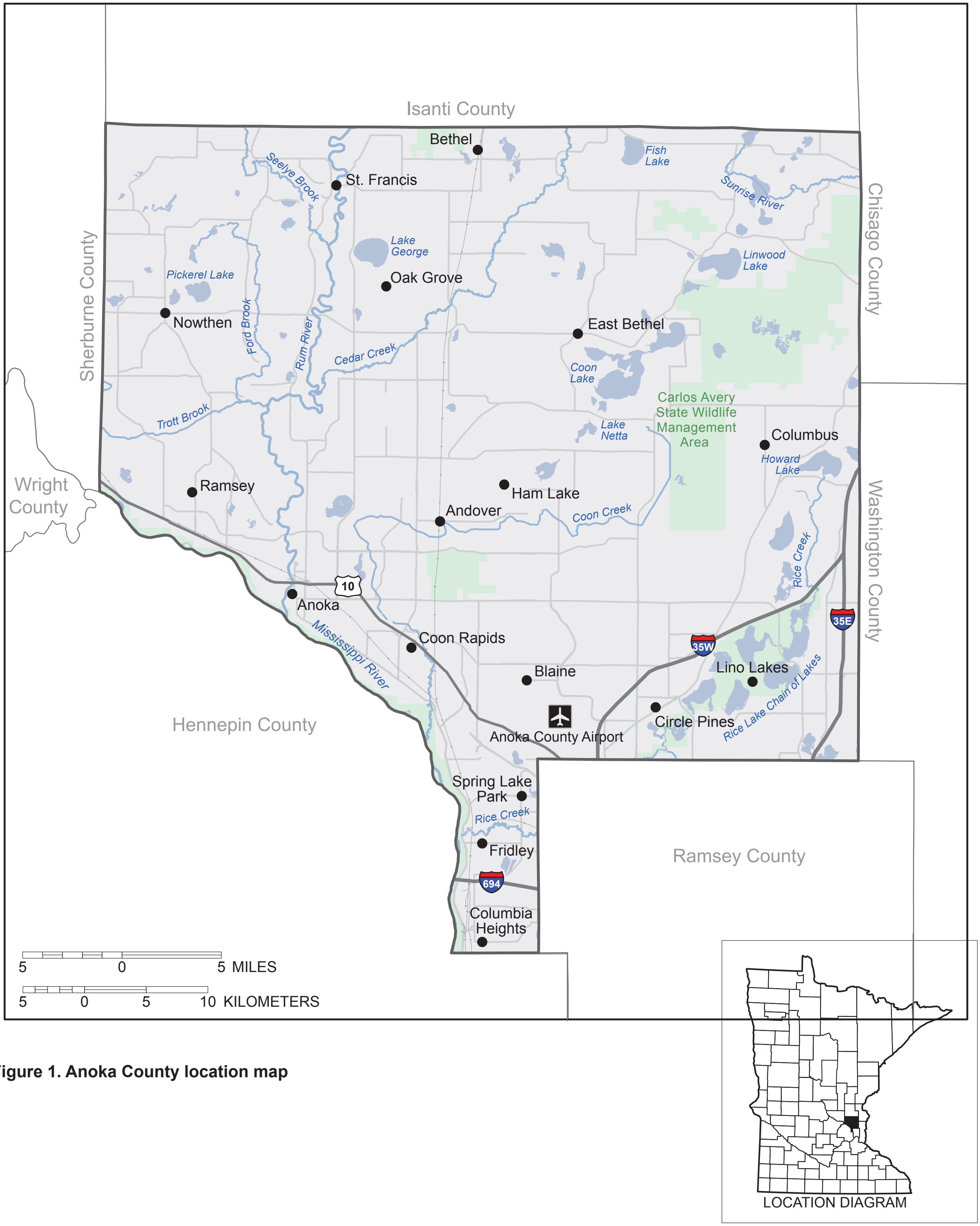


Figure 1. Anoka County location map

Geology and physical hydrogeology

Anoka County is located in east central Minnesota (Figure 1). The southern portion of the county includes the northern portion of the Twin Cities (Minneapolis and St. Paul) metropolitan area. According to a 2015 estimate (United States Census Bureau, 2016), the county is the fourth most populous in the state with over 344,000 residents. The southern and southwestern parts of the county are characterized by relatively high density urban and suburban settings and land use. The remainder of the county is mostly low density rural and small communities.

The Mississippi River forms more than half of the western county border and drains the western and southern parts of the county. The county lies within the watersheds of the Mississippi (Twin Cities), Rum, and Lower St. Croix rivers. The topography is level to rolling in most of the county with the exception of the hilly northwestern corner of the county, and the southernmost Columbia Heights area.

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 Anoka 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 Anoka County area and into Wisconsin. As this sublobe retreated, water from the melting glacial ice was trapped for hundreds of years 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 central and eastern portion of the county.

Eventually the St. Croix moraine was breached, 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 (Langdon and Richfield) 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.

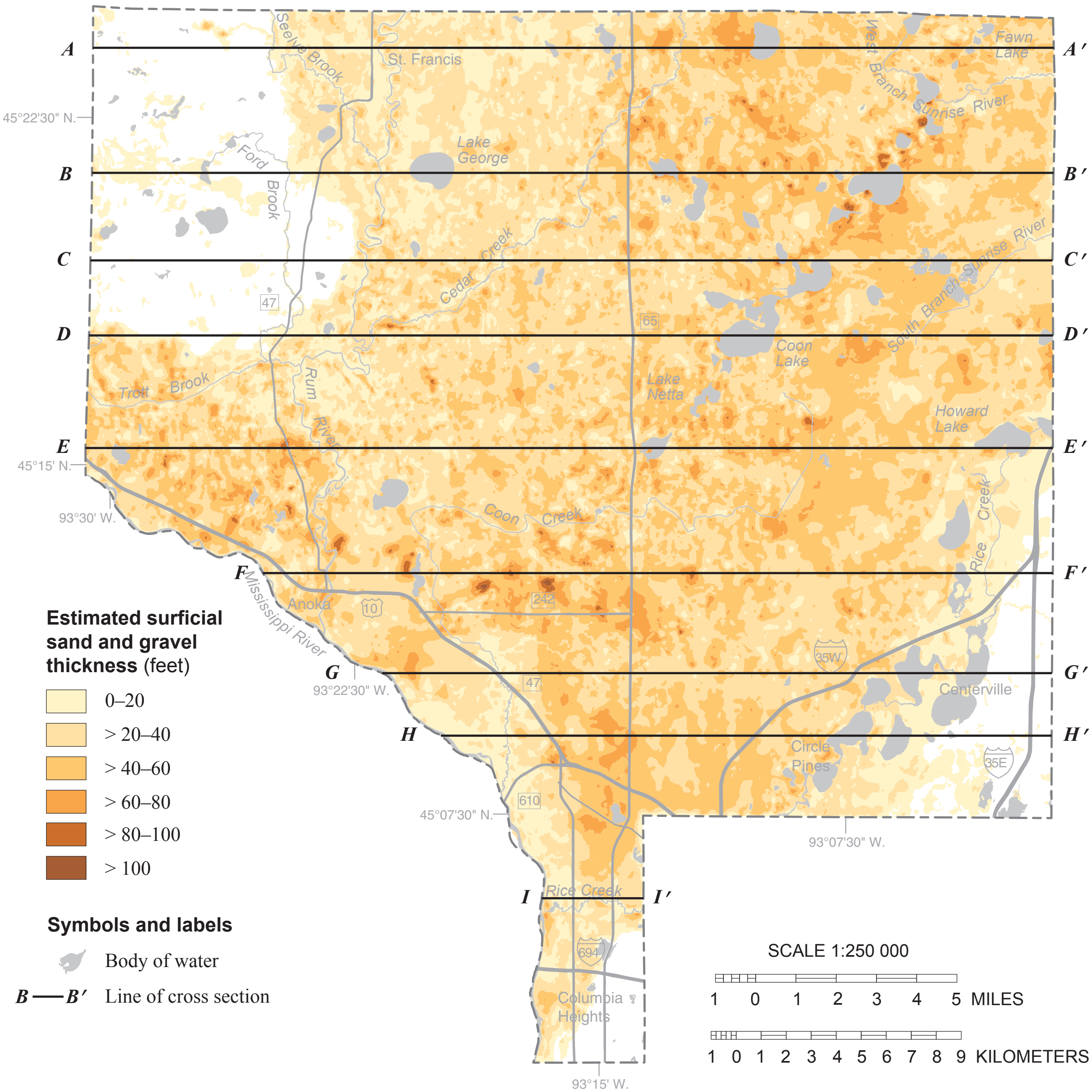


Figure 2. Surficial sand and gravel thickness

The thickness of the surficial sand and gravel is highly variable but commonly exceeds 20 feet across much of the county. The water-table aquifer in this layer is a minor source of human water supply, but is a major factor for the recharge and pollution sensitivity characteristics of the underlying aquifers that are major sources of human water supply.

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 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 (DNR, 2016a):

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

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

Depth to water table (Figure 4) is derived by subtracting the water-table elevation from the land-surface elevation. More details on how the maps were constructed can be found in *Methods for estimating water-table elevation and depth to water table* (DNR, 2016a).

The water-table maps provide guidance for many applications but additional site-specific information should be used to further refine water-table information at local scales. Certain conditions that affect the fluctuation of the water table create locally different results from the maps created using this procedure. Some of these include, but are not limited to, seasonal weather conditions, extent and composition of surficial geology units, land-use practices, vegetation composition and distribution, and pumping of large-capacity wells.

Water-table elevation controls groundwater flow directions. The lakes and streams that intersect the surficial sand aquifer are assumed to represent the water-table elevation at that location because most streams and lakes in this area receive groundwater contributions.

Water-table divides (areas where groundwater flow is divergent) are typically very similar to the surface divides, so the watershed boundaries may be considered to approximate groundwater flow divides for the water-table system. Groundwater flow directions in the water-table aquifer are controlled by the dominant groundwater discharge locations, including the Rum River and its tributaries (northwest), the Mississippi River (southwest), the St. Croix River (northeast), and associated tributaries. Another much broader topographic low area and groundwater discharge feature is occupied by a trend of lakes (Rice Creek chain of lakes) and wetlands in the southeastern part of the county that extends from Circle Pines northeast to Howard Lake (Figure 3).

Maps of water-table elevation can be useful in scoping groundwater pollution investigation plans where groundwater flow direction and velocity are required. Groundwater flow gradients are derived from maps of water-table elevation and used with other geologic information to estimate groundwater flow velocity.

Shallow water-table conditions (0–10 feet) are common in the county, with the exception of the valley edges of the Rum River and Cedar Creek, terraces of the Mississippi River, and uplands in the northwestern and southernmost portions of the county (Figure 4). In these areas the depth to water table is probably greater than the estimated shallow conditions for the rest of the county.

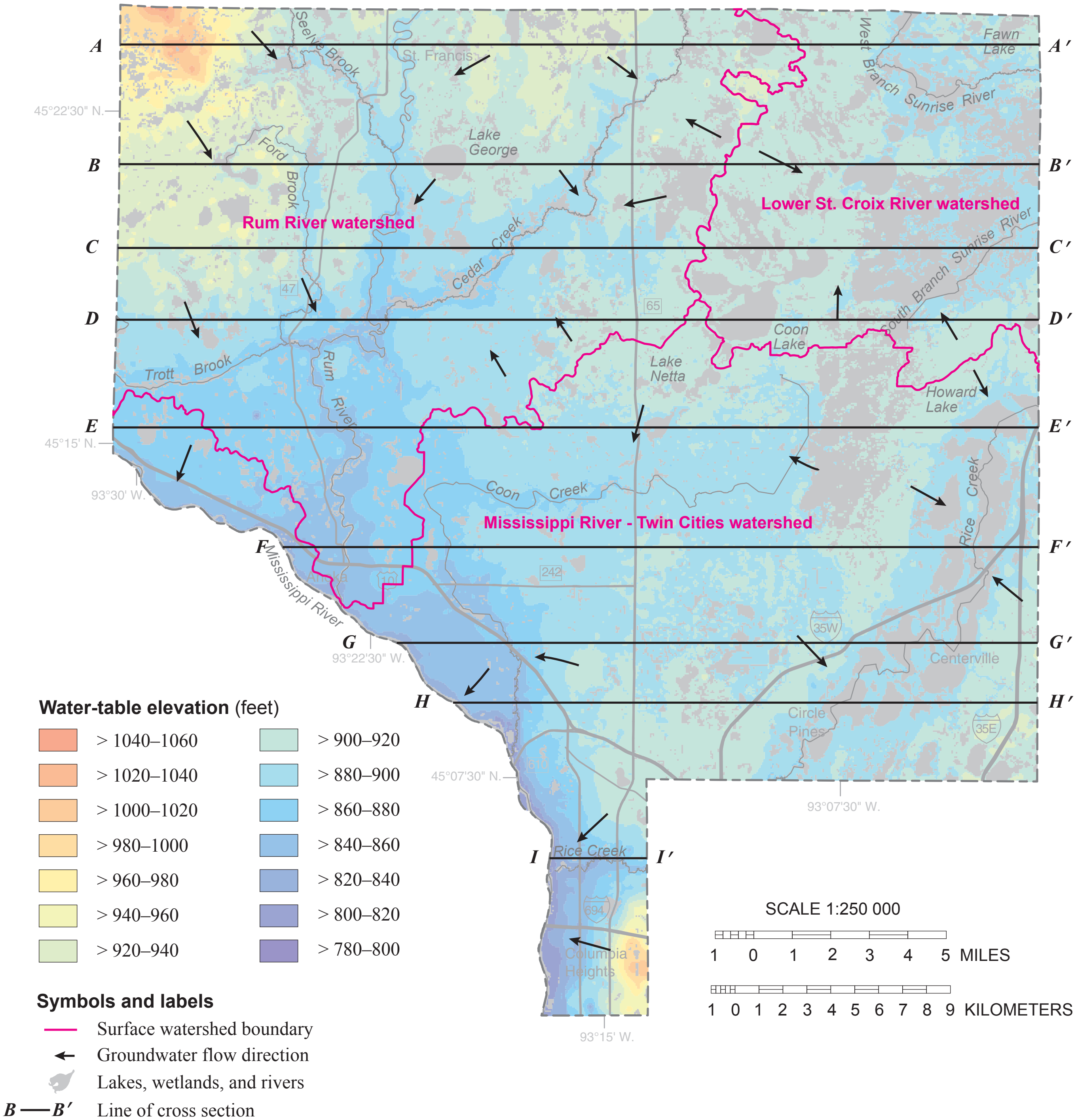


Figure 3. Water-table elevation and groundwater flow directions

Groundwater flows toward the major river valleys within the county. Surficial watersheds are labeled.

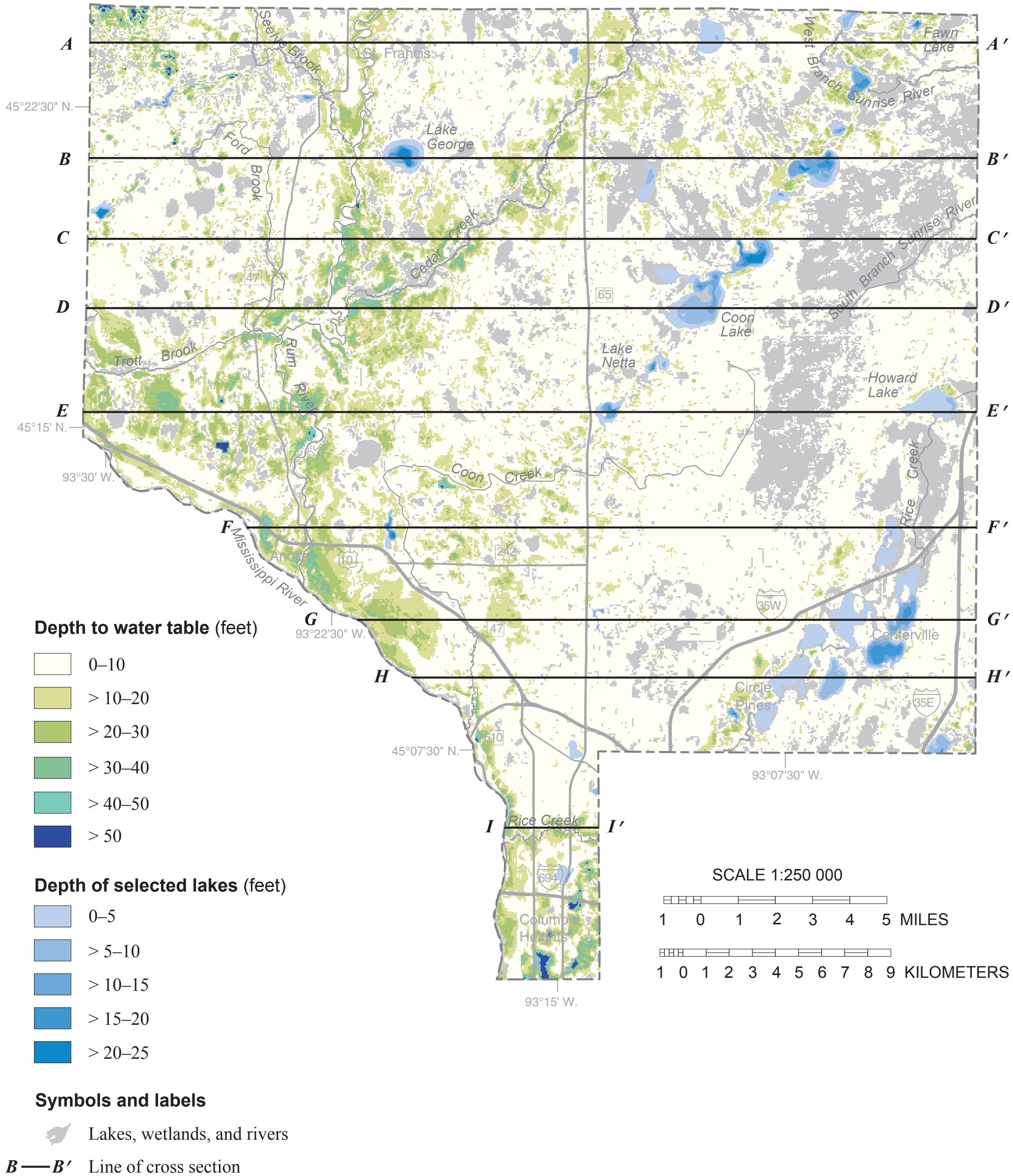


Figure 4. Depth to water table

Shallow water-table conditions are common in the county. Exceptions include the valley edges of major rivers. Most lakes and wetlands can be thought of as an exposed portion of the shallow water table.

Buried sand and gravel aquifers

Deeper sediment layers were deposited during multiple episodes of glaciation during the past 2 million years (Part A, Plates 4 and 5). An unsorted mixture of clay, silt, sand, and gravel was brought to the region by glaciers and was deposited directly by the ice (till). In some areas the glacial sediment was sorted as it was deposited by meltwater streams (primarily sand and gravel) and lakes (primarily silt and clay) (Part A, Plate 4 and Part B, Plate 7).

Glacial deposits are highly variable. The associated sand and gravel aquifers are typically thin (20 to 50 feet thick), and may be discontinuous with lateral extents rarely exceeding several miles, or may be more laterally continuous depending on the unit and location. Buried aquifers are typically surrounded by fine-grained, lake- and glacial-sediment layers that serve as aquitards.

A stratigraphic column that summarizes the material and hydrogeologic properties of the glacial sequence shows the corresponding Part A and B unit names and map labels (Figure 5). Part B maps and cross sections build on the geologic framework developed in Part A and GIS map elements to describe the hydrogeology of the subsurface.

- **Aquifers** are represented with *patterns* in this atlas (Figure 5 and Plates 8 and 9).
- **Aquitards** are shown as *shades of gray* to represent the presumed relative hydraulic conductivity based on sand content from representative samples collected from the unit by the MGS. Lighter shades of gray represent units with more sand, implying a higher hydraulic conductivity. Darker shades of gray represent units with less sand, implying a lower hydraulic conductivity.
- Units of **undifferentiated sediment** with an unknown texture are shown in *brown*.

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

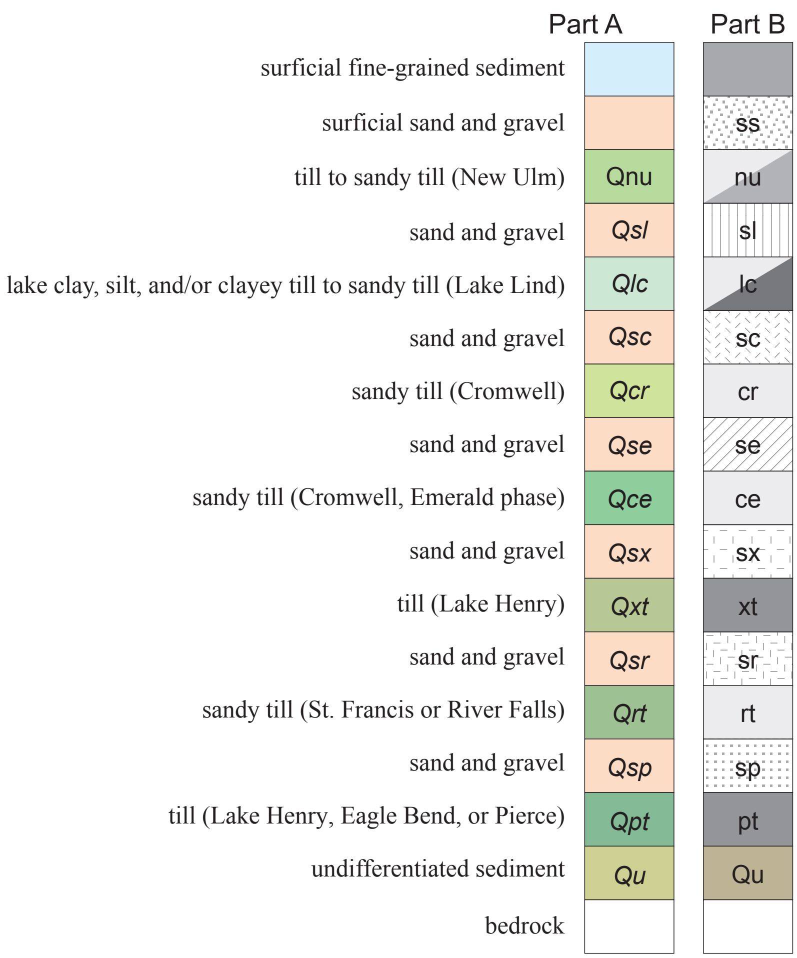


Figure 5. Hydrostratigraphy of Quaternary unconsolidated sediments

Patterns shown for Part B hydrostratigraphic units are used on Plate 8 and 9 cross sections. Shades of gray on aquitards (till and lake sediment) correspond to the percentage sand content.

Potentiometric surfaces of buried sand and gravel aquifers

In confined aquifers, pressure causes water to rise in a well to a point higher than the top of the aquifer. Measured levels are contoured to create a map of the *potentiometric surface* for each aquifer. The resulting groundwater-level elevations are similar to a topographic map, providing a visual model of the water surface.

The potentiometric surface of an aquifer represents the potential energy that is available to move groundwater. As groundwater moves from higher to lower potentiometric elevations it flows perpendicular to the potentiometric elevation contours. Flow directions are shown as arrows in Figures 6 through 10.

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 vary from days to weeks over short distances of up to a mile. Flow in deeper aquifers can take centuries or millennia across dozens of miles. When combined with other information, high elevation areas on the potentiometric surface can indicate important recharge areas. Incised rivers valleys are examples of low elevation areas that are typically discharge areas.

Potentiometric surface maps for the county 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. Stream elevation points are included because these features are groundwater discharge locations for both the buried sand aquifers and the relatively shallow bedrock aquifers along the Mississippi and Rum rivers. Data from both Anoka and Sherburne counties were used together to increase the data coverage and ensure that the potentiometric surfaces were consistent across the county boundary. The CWI records represent various climatic and seasonal conditions from the 1970s to 2013. This data variability creates some uncertainty in potentiometric surface elevations.

All the potentiometric surface maps (Figures 6 through 10) show a general pattern of groundwater flow toward the Mississippi River valley in the western half of the county and flow toward the St. Croix River in the east and northeast portions. Local flow toward the larger rivers in the county is evident on all the buried sand potentiometric surface maps, such as the Rum River, Cedar Creek, and to a lesser extent Coon Creek. These maps indicate at least some groundwater discharge to the Mississippi and portions of its tributaries from all the buried sand aquifers.

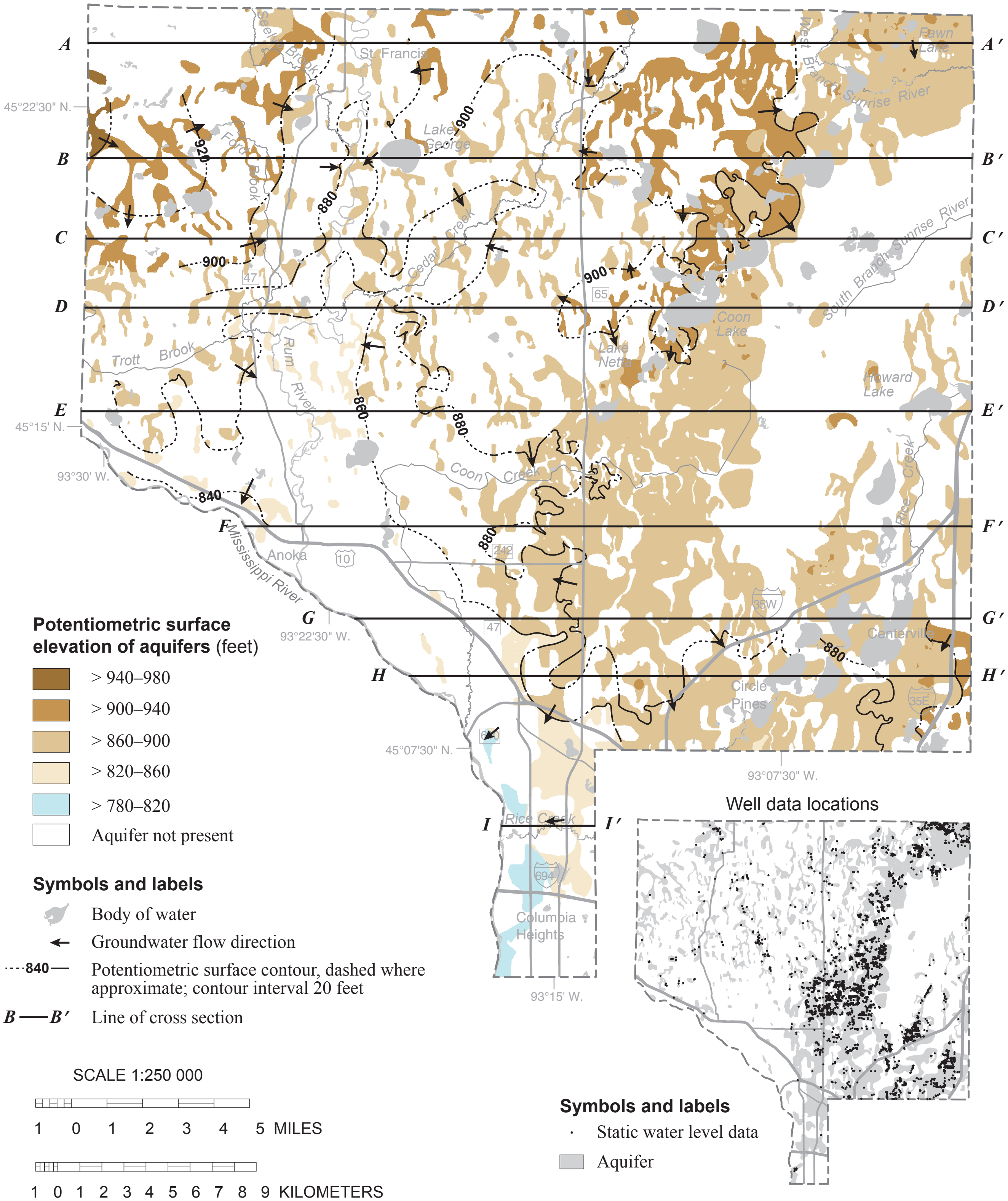


Figure 6. Potentiometric surface of the sl aquifer

Groundwater flow is toward the Mississippi River and locally toward the Rum River and Cedar Creek.

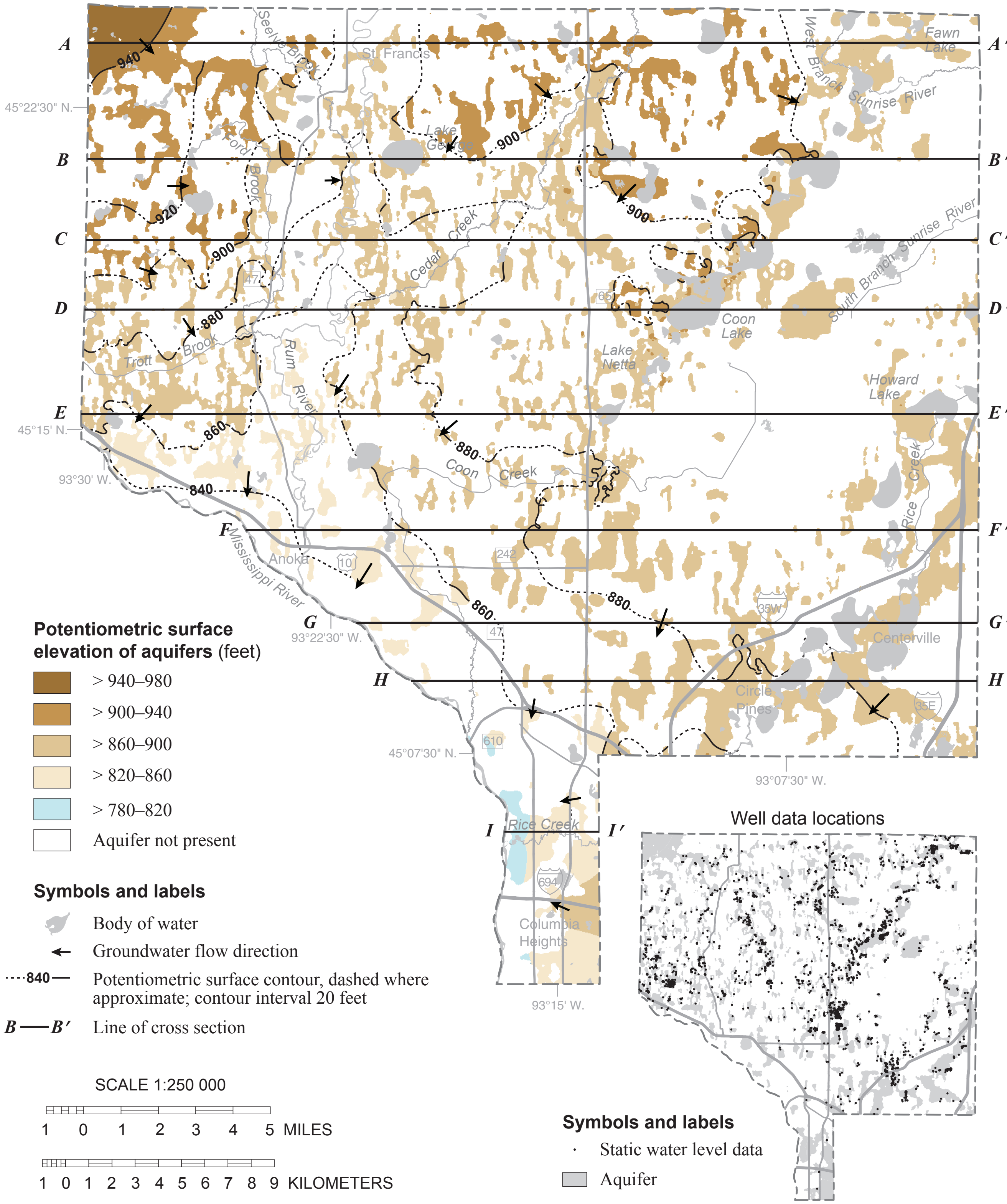


Figure 7. Potentiometric surface of the sc aquifer

Groundwater flow is toward the Mississippi River and locally toward the Rum River, Cedar Creek, and Coon Creek.

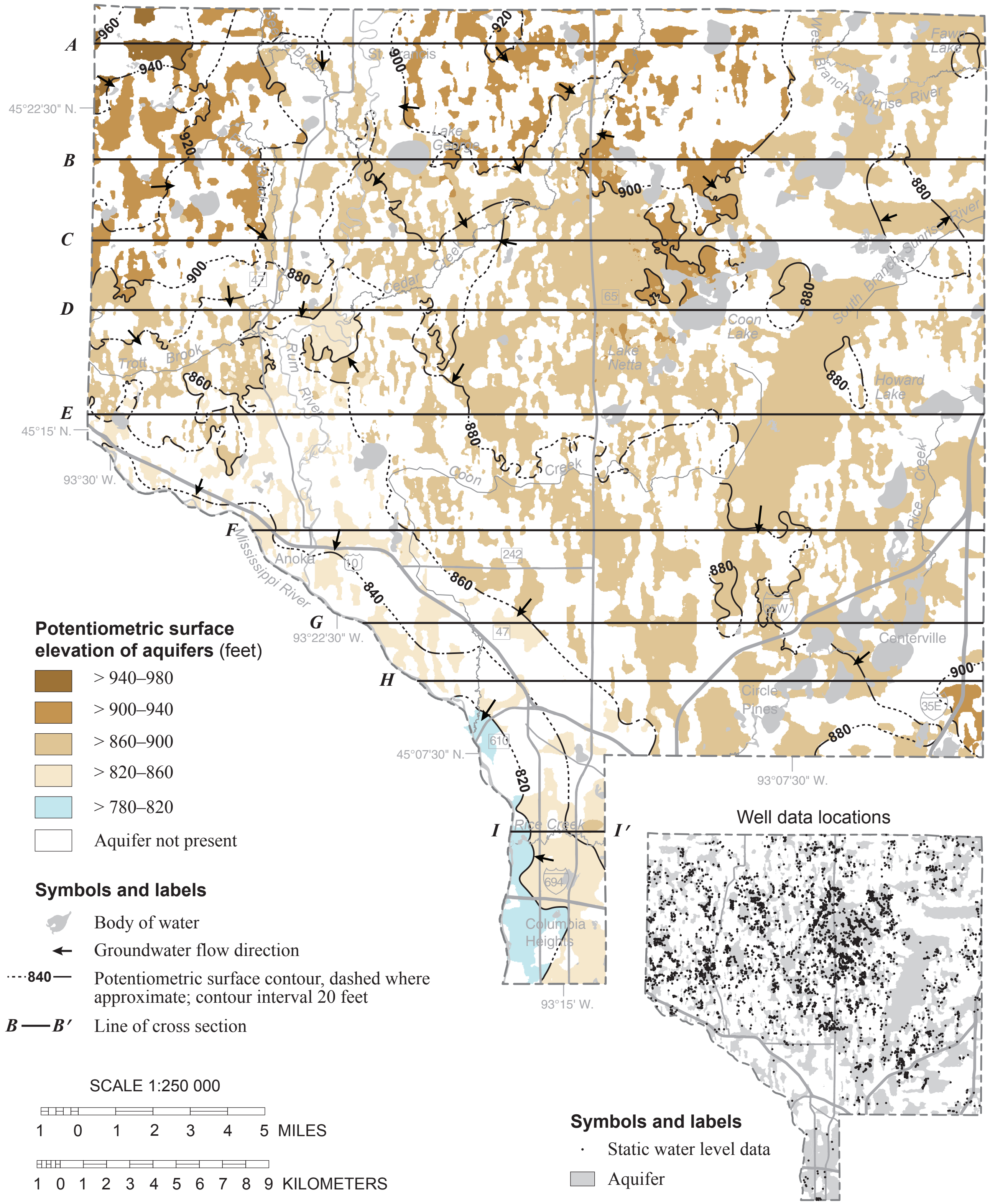


Figure 8. Potentiometric surface of the se aquifer

Groundwater flow is toward the Mississippi River and locally toward the Rum River and Cedar Creek.

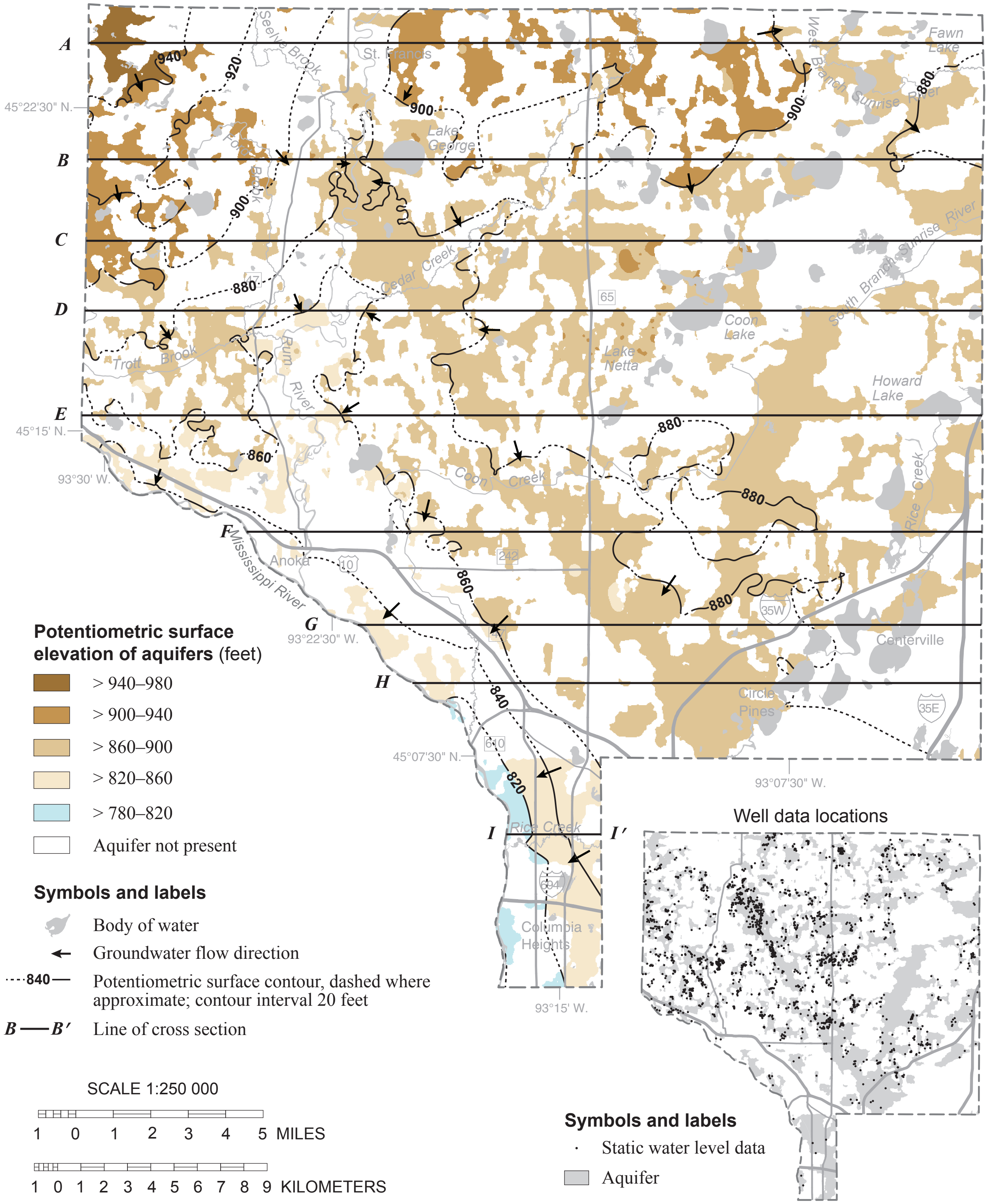


Figure 9. Potentiometric surface of the sx aquifer

Groundwater flow is toward the Mississippi and St. Croix rivers and locally toward the Rum River and Cedar Creek.

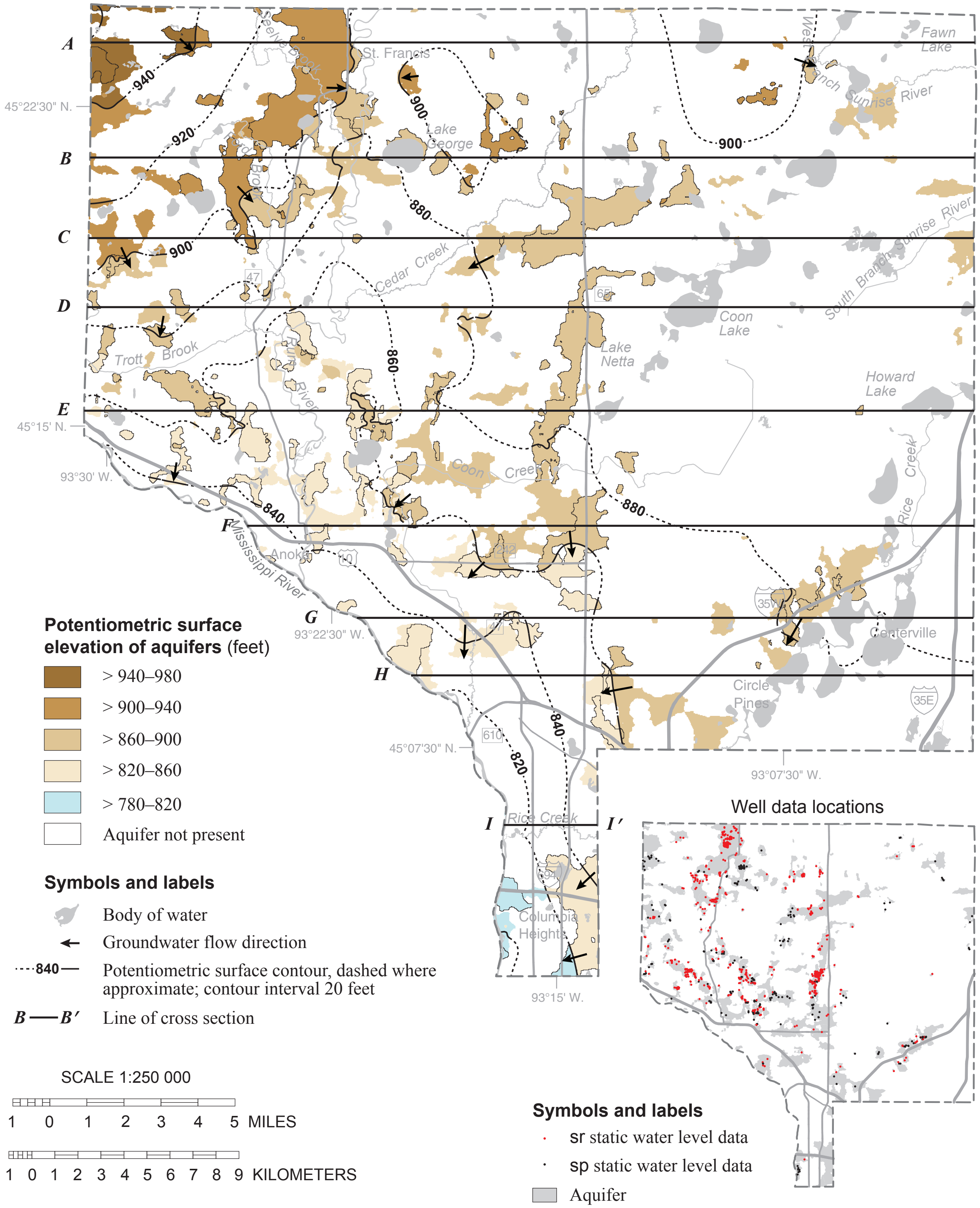


Figure 10. Potentiometric surface of the sr and sp aquifers

Groundwater flow is toward the Mississippi River and locally toward the Rum River. The sr aquifer (shown with outline) is stratigraphically above the sp aquifer.

Bedrock geologic units and aquifers

The bedrock formations of Anoka County are regionally extensive, gently dipping layers of sandstone, shale, and carbonate rock that range from 50 feet to greater than 200 feet in thickness (Figure 11 and Part A, Plate 2, Figure 1). 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 formations include in ascending order (oldest to youngest) the Cambrian Mt. Simon Sandstone, Eau Claire Formation, Wonewoc Sandstone, Tunnel City Group (Lone Rock and Mazomanie), St. Lawrence Formation, and the Jordan Sandstone. The stratigraphically higher and younger layers (Ordovician age) comprise mostly carbonate rock (limestone and dolostone) and include units such as the Prairie du Chien Group (Oneota Dolomite and Shakopee Formation). The upper most units in this stratigraphic succession include limited occurrences of the Ordovician St. Peter Sandstone in the southeastern and southern portions of the county which is locally overlain by one subcrop of the Glenwood and Platteville formations in the southern part of the county.

The aquifers associated with the bedrock layers are commonly used for water by municipalities and commercial operations because of their thickness, extent, predictability, and features that affect water yield. In sandstone aquifers such as the Jordan and Wonewoc, water moves through intergranular pore spaces and larger macropores such as fractures (Runkel and others, 2003). Groundwater in the Prairie du Chien and Upper Tunnel City aquifers mainly moves through enlarged fractures or macropores. An enhanced-permeability zone is generally found in approximately the uppermost 50 feet of all 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. Most of the bedrock wells in the county produce water from this uppermost 50-foot enhanced permeability zone.

Potentiometric surfaces of bedrock aquifers

Potentiometric surfaces for the St. Peter–Prairie du Chien–Jordan, Upper Tunnel City, Wonewoc, and Mt. Simon aquifers are shown in Figures 12 through 15. The St. Peter–Prairie du Chien–Jordan group of aquifers (Figure 11) were combined into one map because of the limited extent of these units in the county and the limited number of wells in these aquifers. This combined map is useful for determining county-scale generalized groundwater flow directions. For any local applications these units should be considered as separate aquifers unless extensive fracturing or karst conditions of aquitards create hydraulic connections between the separate aquifers.

Similar to the buried sand potentiometric surface maps, the bedrock aquifer maps (with the exception of the Mt. Simon aquifer) show the same general pattern of groundwater flow toward the Mississippi River valley in the western half of the county, and flow to the St. Croix River in the east and northeast portions (Figures 12 through 14). Local flow toward the larger rivers such as the Rum River and Cedar Creek, and to a lesser extent Coon Creek, are evident on Upper Tunnel City and Wonewoc potentiometric surface maps (Figures 13 and 14). Southerly flow toward the center of the Twin Cities metropolitan area in the southern portion of the county is apparent for the Wonewoc and Mt. Simon potentiometric surface maps (Figures 14 and 15).

These maps indicate at least some groundwater discharges to the Mississippi and portions of its tributaries (Rum River, Cedar and Coon creeks) from the Upper Tunnel City and the Wonewoc aquifers. The Mt. Simon aquifer appears to be mostly isolated from the area rivers, with the exception of the Rum River and a portion of the Mississippi River upstream from the confluence of the Rum and Mississippi rivers. Limited data indicate flow toward the clusters of high-capacity pumping wells in the Mt. Simon aquifer that are associated with municipal and industrial use in the Twin Cities metropolitan area (Sanocki and others, 2009; Berg and Pearson, 2013).

Geologic Period	Geologic Unit		Hydrogeologic Unit	Hydrogeologic Unit Properties
Ordovician		Platteville Formation		relatively low intergranular permeability with high permeability fractures
		Glenwood Formation	aquitard	
		St. Peter Sandstone (Osp)	St. Peter aquifer	moderate intergranular permeability
	Prairie du Chien Group	Shakopee Formation (Os)	Prairie du Chien aquifer	relatively low intergranular permeability with high permeability fractures
		Oneota Dolomite (Oo)	aquitard	aquifer in shallow conditions
Cambrian		Jordan Sandstone (€j)	Jordan aquifer	relatively high intergranular permeability with high permeability fractures
			aquitard	aquifer in shallow conditions
		St. Lawrence Formation (€sl)	aquitard	aquifer in shallow conditions
	Tunnel City Group	Mazomanie Formation (€tc)		moderate intergranular permeability
		Lone Rock Formation (€tc)	Upper Tunnel City aquifer	relatively low intergranular permeability with high permeability bedding fractures
		Lone Rock Formation (€tc lower)	aquitard	aquifer in shallow conditions
		Wonewoc Sandstone (€w)	Wonewoc aquifer	moderate intergranular permeability
		Eau Claire Formation (€e)	aquitard	aquifer in shallow conditions
		Mt. Simon Sandstone (€m)	Mt. Simon aquifer	moderate intergranular permeability

High permeability bedding fractures

Figure 11. Bedrock stratigraphy and hydrostratigraphy

Geologic stratigraphic units (formations or groups) do not always correspond to hydrogeologic units (aquifers and aquitards). Stratigraphic column not to scale.

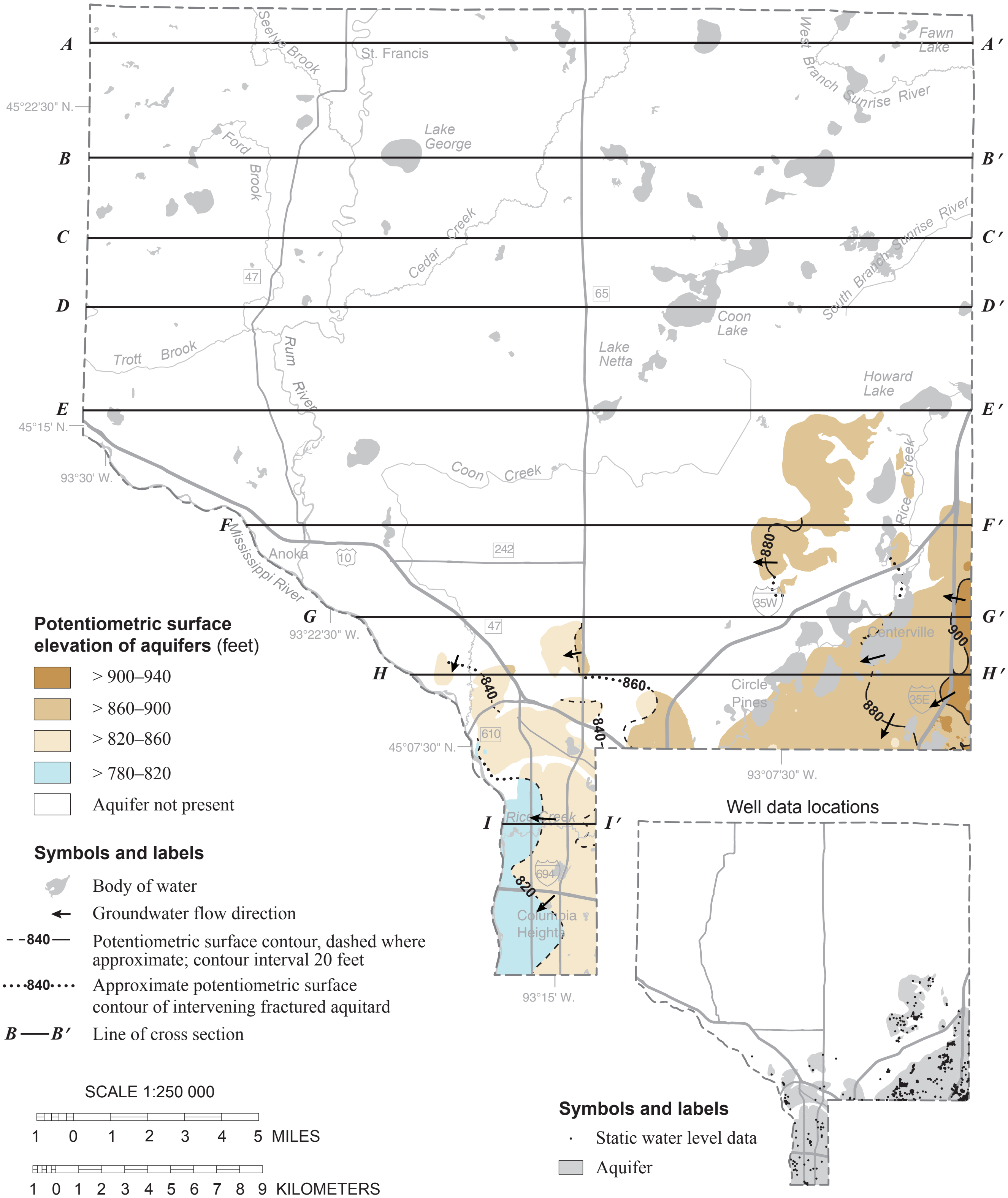


Figure 12. Potentiometric surface of the St. Peter, Prairie du Chien, and Jordan aquifers

General groundwater flow directions are toward the Mississippi River.

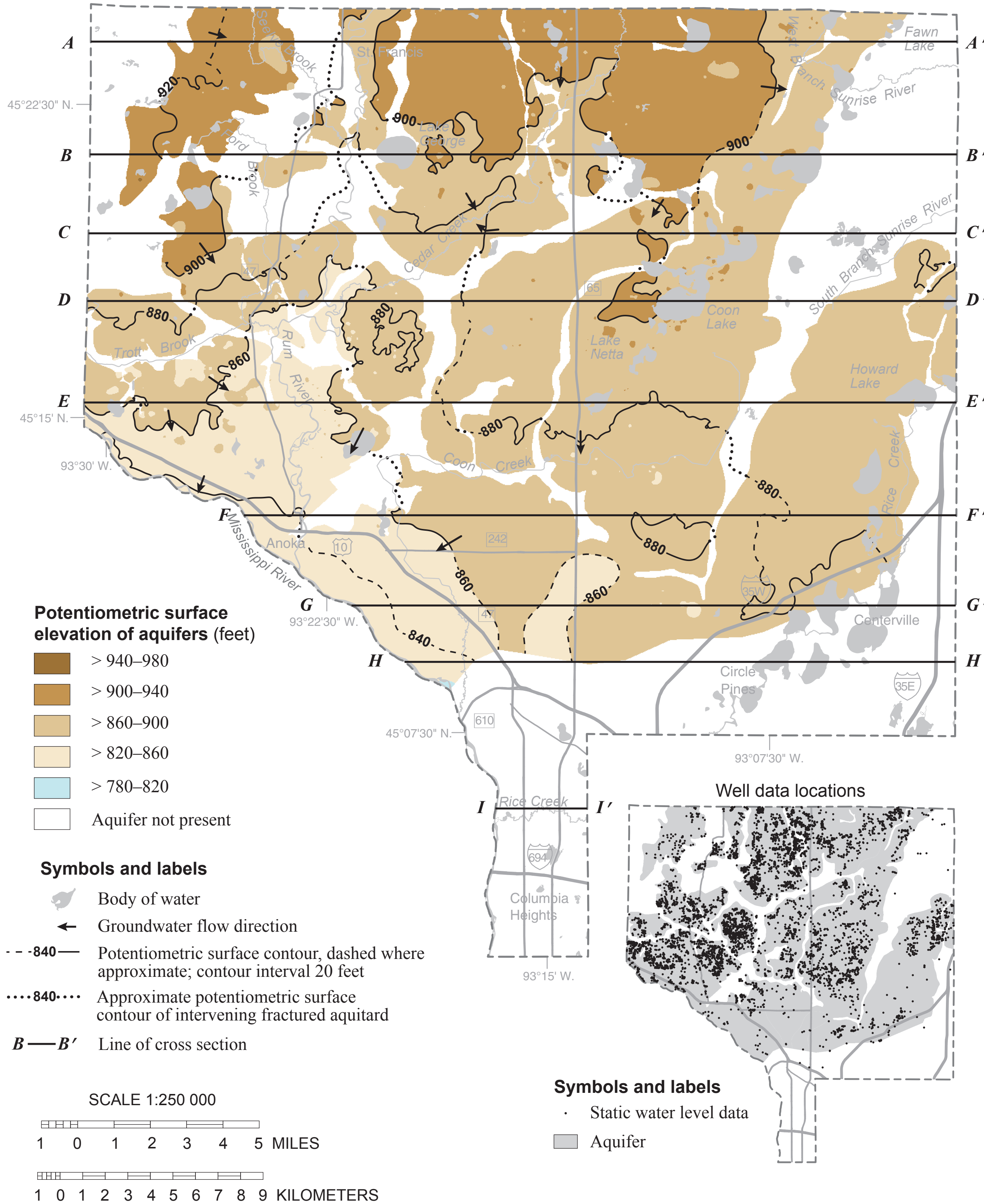


Figure 13. Potentiometric surface of the Upper Tunnel City aquifer

General groundwater flow directions are toward the Mississippi River, with the exception of the northeastern portion of the county where general flow directions are easterly toward the St. Croix River. Discharge to the Rum River creates locally convergent flow.

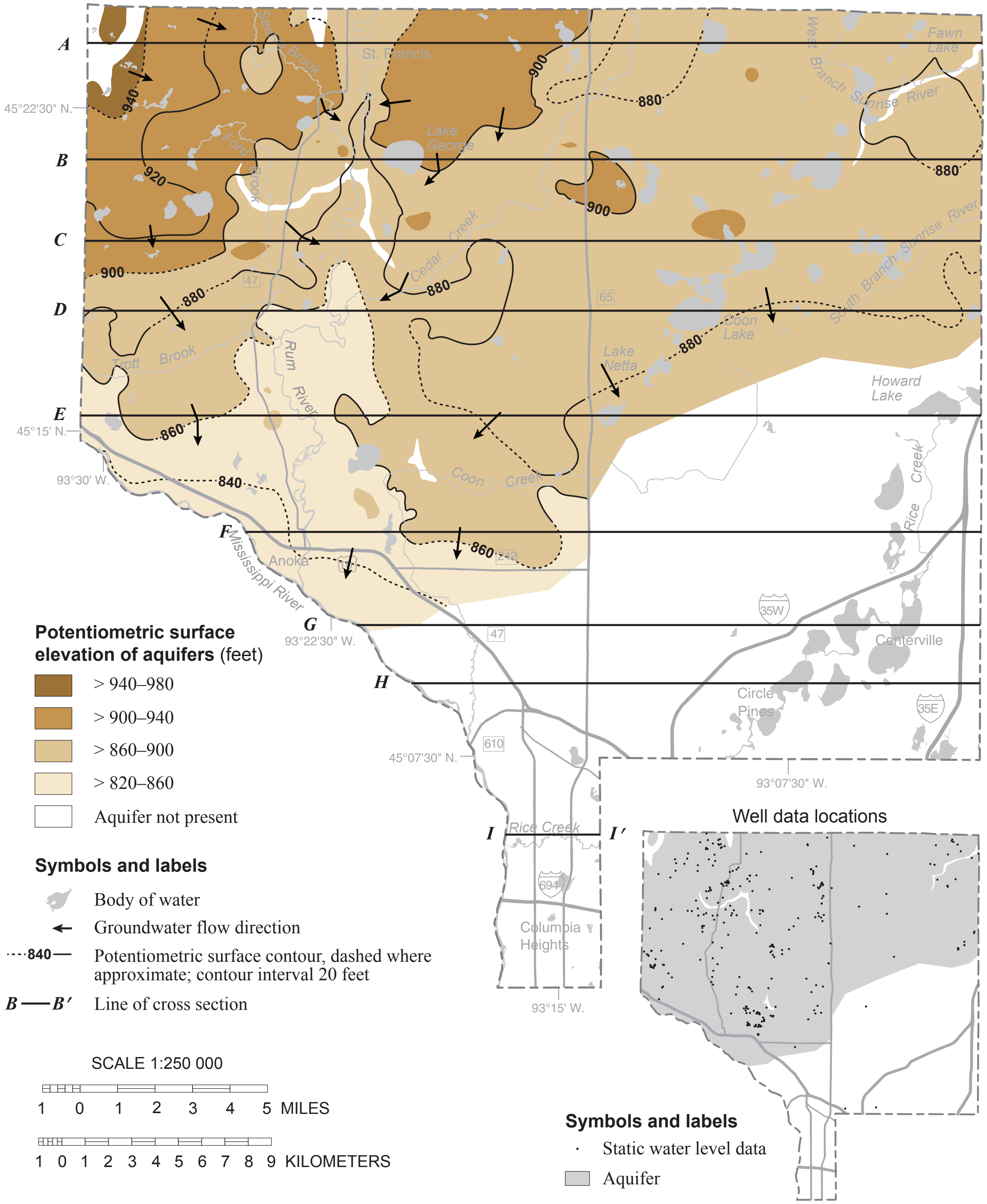


Figure 14. Potentiometric surface of the Wonewoc aquifer

General groundwater flow directions are toward the Mississippi River valley. Discharge to the Rum River creates locally convergent flow.

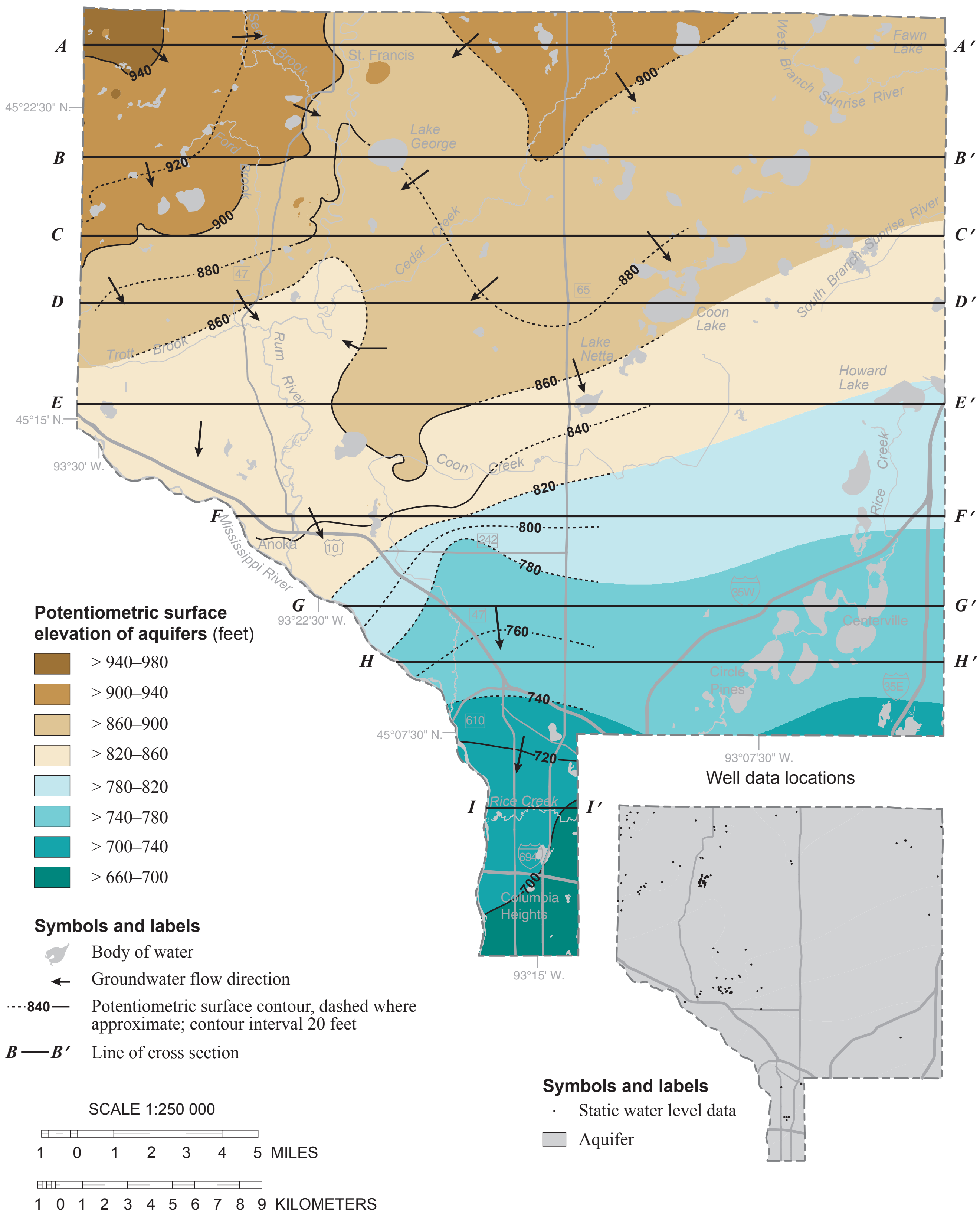


Figure 15. Potentiometric surface of the Mt. Simon aquifer

Groundwater flows toward the center of the Twin Cities basin, with the exception of local flow toward the Mississippi River valley in the area of the city of Anoka.

Water chemistry (Plate 7)

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

- Groundwater recharged from surface-water bodies 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 naturally occurring elements can indicate areas where consumption of groundwater is a potential concern to human health.

Groundwater sampling

To better understand groundwater movement and pollution sensitivity in the county, 92 groundwater samples were collected from wells in a range of aquifers (Plate 7). Details of the methods are listed in the Appendix.

Evaluations were also made from previously collected data from the following: the DNR (Berg and Pearson, 2013), the Minnesota Department of Health (MDH), MGS (Lively and others, 1992), Minnesota Pollution Control Agency (MPCA), and Anoka County (Marsh, 1996).

Chemical data from well-water samples were used along with primary physical data (static water levels and aquifer tests) to understand water movement. Wells were selected for sampling based on their hydrogeologic setting. All aquifers that were significant for domestic water supply were sampled. 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 surface water to groundwater, chemical changes occur that can help determine whether groundwater was recharged directly from precipitation, lake water, or a mixture of the two. Stable isotopes of oxygen and hydrogen are useful for determining groundwater and surface-water interactions. Oxygen and hydrogen each have two main stable isotopes: ^{18}O and ^{16}O, and ^{2}H and ^{1}H. The different mass of the isotopes causes evaporation at different rates, which results in *fractionation*. This results in isotopic signatures that are unique to groundwater with different sources.

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

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

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

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

Precipitation values for δ18O and δ2H generally plot along the meteoric water line. The North American meteoric water line was developed using North American precipitation averages from stations available through the Global Network of Isotopes in Precipitation (IAEA/WMO, 2006).

- Groundwater samples consistent with rapidly infiltrated **precipitation** plot near the **meteoric water line**.
- Groundwater samples that have been subjected to evaporation in **surface water** plot along an **evaporation line**, which has a shallower slope than the meteoric water line. Samples that plot along the evaporation line are considered to have an *evaporative signature.*

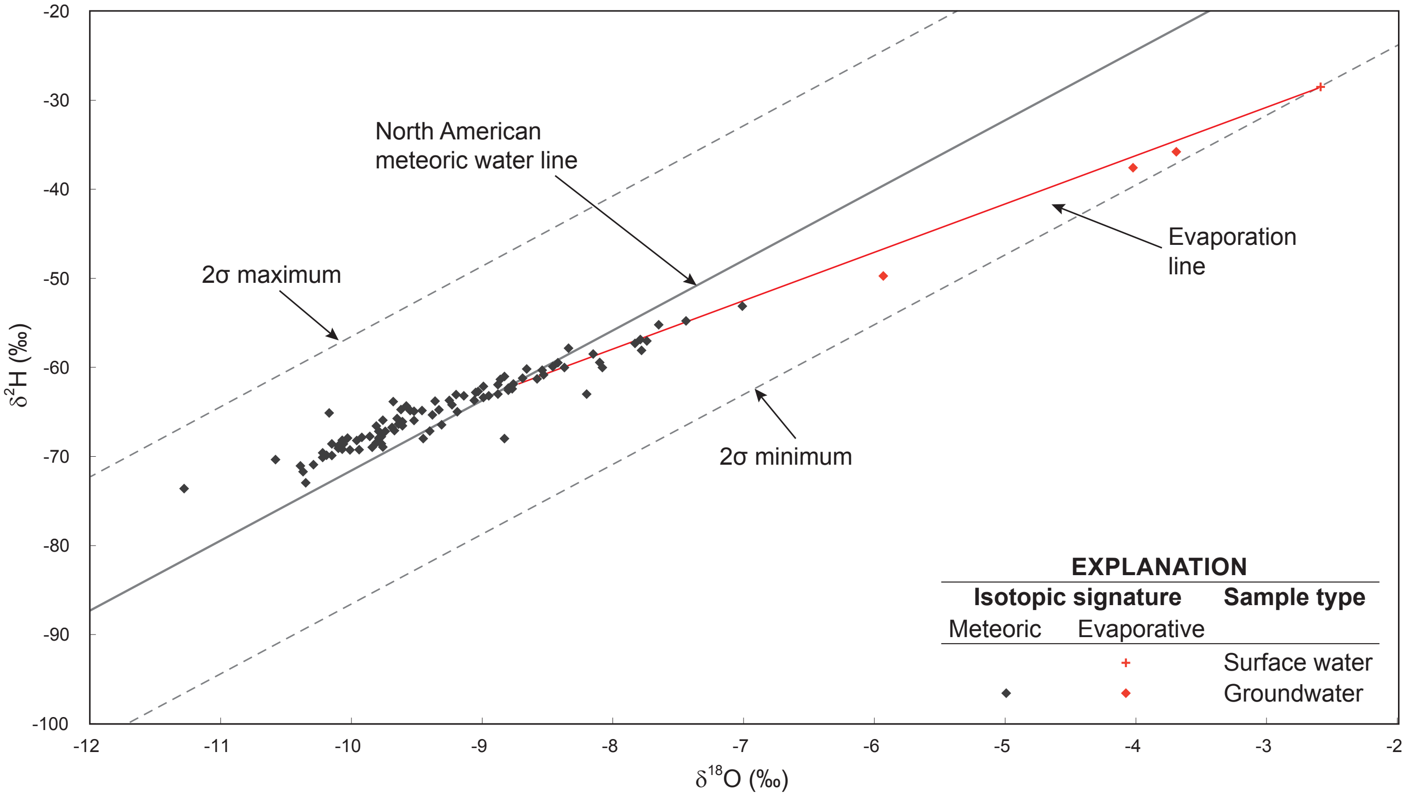


Figure 16. Graph of stable isotope values from groundwater samples

Stable isotope values from groundwater samples are compared to the meteoric water line. The red symbols that plot beneath the meteoric water line in the upper right portion of the graph represent water with an evaporative signature (also shown on Figure 17). Lake George, Coon Lake, and the Fawn Lake areas appear to have been the evaporative source for the three groundwater samples shown on this figure with evaporative signatures.

The majority of Anoka samples plot in the center and left portions of the stable isotope graph, along the meteoric water line (Figure 16). 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.

Three groundwater samples with evaporative signatures were collected downgradient of Lake George, Coon Lake, and the Lake Fawn areas (Figure 17). All of these occurrences are from the relatively shallow sl and se buried sand aquifers. The absence of evaporative signatures from wells near other lakes or lake areas does not necessarily indicate that evaporative signature water is rare in groundwater but may be more of an artifact of the opportunistic nature of our sampling strategy. In other words, we could not always sample wells at ideal locations and depths for detecting lake evaporative processes on groundwater characteristics because we are limited to samples from homeowners who volunteer their wells.

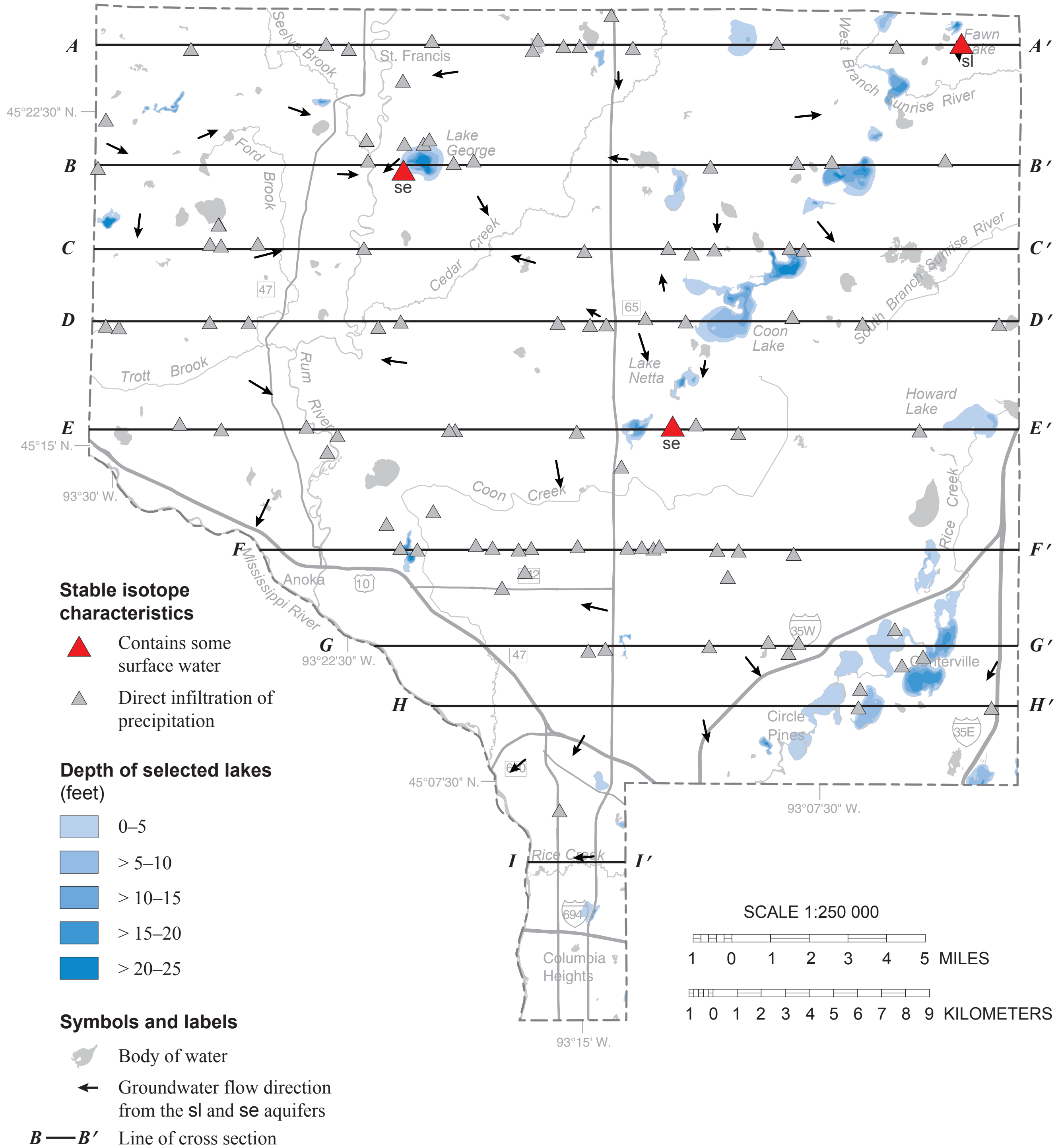


Figure 17. Stable isotope characteristics of groundwater samples

Most groundwater samples collected within the county appear to have originated as direct infiltration of precipitation. A group of groundwater samples located in the northern part of the county (red symbols) contains some water with an evaporative signature.

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 the aquifer or discharged at a lake, river, wetland, or spring. In general, short residence time suggests high recharge rates or short travel paths; long residence time suggests low recharge rates or long travel paths. Isotopic analysis of the radioactive elements tritium and carbon-14 is used to estimate the residence time of the groundwater.

Tritium

Groundwater residence time can be interpreted from the concentration of tritium. Although tritium is a naturally occurring isotope of hydrogen, atmospheric concentrations were greatly increased between 1953 and 1963 by above-ground detonation of hydrogen bombs (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). The relative age of groundwater can be estimated by the concentration of tritium in water samples, referred to in this atlas as *tritium age*.

The tritium age is useful in the interpretation of the hydrogeologic cross sections (Plates 8 and 9) and pollution sensitivity maps. The pollution sensitivity maps are evaluated by comparing groundwater chemistry (including tritium concentration, nitrate-nitrogen, and chloride values) with the estimated pollution sensitivity.

Groundwater residence time is determined by the tritium concentrations and is presented in tritium units (TU). These tritium data are used 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).

A large amount of historical data (sample dates from 1991 to 1996) have been used in the residence time interpretations of this report. Many of the tritium samples (36) were originally classified as Cold War era. More than 20 years later the aquifers that yielded these samples should no longer be characterized as Cold War era due to groundwater movement and recharge. These samples have, therefore, been reclassified as recent.

Carbon-14

The carbon-14 (^{14}C) isotope is used to estimate the residence time for selected vintage and mixed tritium-age samples (Figures 25–27, 29–31, and Plates 7–9). This naturally occurring isotope has a half-life of 5,730 years, much longer than tritium, and is used to estimate groundwater residence time ranging from 100 to 40,000 years (Alexander and Alexander, 1989).

Inorganic chemistry of groundwater

As soon as precipitation infiltrates the soil layer and becomes groundwater, the water starts to dissolve 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, major anions, and select elements that typically are found in trace amounts (parts per billion).

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

Calcium, magnesium, and sodium cations and bicarbonate anions are dissolved out of the glacial sediment by the groundwater. The calcium, magnesium, and bicarbonate constituents are derived from limestone and dolomite bedrock sources (Freeze and Cherry, 1979) and are common in groundwater in the glacial sediment aquifers. The most common type of water in Anoka County contains calcium as the predominant cation and bicarbonate as the most common anion (Figure 18).

Sodium is often present in deeper aquifers or mineral interfaces. As groundwater moves through the aquifer systems, calcium and magnesium cations are exchanged for sodium ions (Hounslow, 1995).

Three samples from the southwestern portion of the county have elevated sodium and chloride from bedrock and buried sand aquifers that possibly originated from deeper sodium and chloride-rich sources. Another group of samples were more like sodium and potassium type water and mostly from buried sand aquifers in the eastern portion of the county.

Chloride and nitrate-nitrogen (nitrate) concentrations can be used to indicate anthropogenic contamination from road salts, water softener salts, fertilizers, or animal and human waste. Their presence can indicate a short groundwater residence time. Possible anthropogenic impacts are indicated by chloride values above 5 ppm with a chloride to bromide ratio above 250. Groundwater with an elevated nitrate concentration (greater than 1 ppm) likely entered the land surface within the past few years to decades, and indicates anthropogenic sources and high aquifer sensitivity. The maximum contaminant limit (MCL) for nitrate is 10 ppm (EPA, [1996]).

In Anoka County, chloride to bromide ratios less than approximately 250 indicate chloride is likely from a deep natural source, based on comparisons with other chemical data and published references (Davis and others, 1998; Panno and others, 2006). Elevated nitrate concentrations can be related to fertilizer application or animal and human waste.

Chloride results: This anion is a significant contaminant in Anoka County groundwater samples with 40 groundwater samples (34 percent) that exceeded the upper limit background concentration for chloride of 5 ppm and an elevated chloride to bromide ratio. These elevated occurrences of chloride exhibit a relatively widespread distribution across the county and are most common in the upper (shallowest) two buried sand aquifers (sl and sc) but were also detected in all the underlying buried sand aquifers and the uppermost bedrock aquifers, the St. Lawrence Formation and Tunnel City Group (CSLT and CTCG, Figure 19). Several elevated chloride samples with low chloride to bromide ratios occur mostly in a cluster in and around the city of Anoka near the Rum and Mississippi rivers. Most of these apparently natural chloride occurrences are from bedrock aquifers suggesting upward groundwater flow from deep bedrock sources through the Douglas and Pine fault zones to these major rivers (Part A, Plate 2, main map and Figure 3) (Lively and others, 1992).

Nitrate results: Six groundwater samples (5 percent) contained concentrations of nitrate that exceeded an approximate background concentration of 1 ppm (MDH, 1998 and Wilson, 2012). Nitrate has a health risk limit (HRL) of 10 ppm (MDH, 2012). All but one of these elevated nitrate occurrences were from samples that also contained elevated concentrations of anthropogenic chloride (Figure 19). Elevated nitrate concentrations were all detected in the western portion of the county in buried sand (sc and se) and upper bedrock (CSLT and CTCG) aquifers.

Environmental Protection Agency (EPA)

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

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

Minnesota Department of Health (MDH)

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

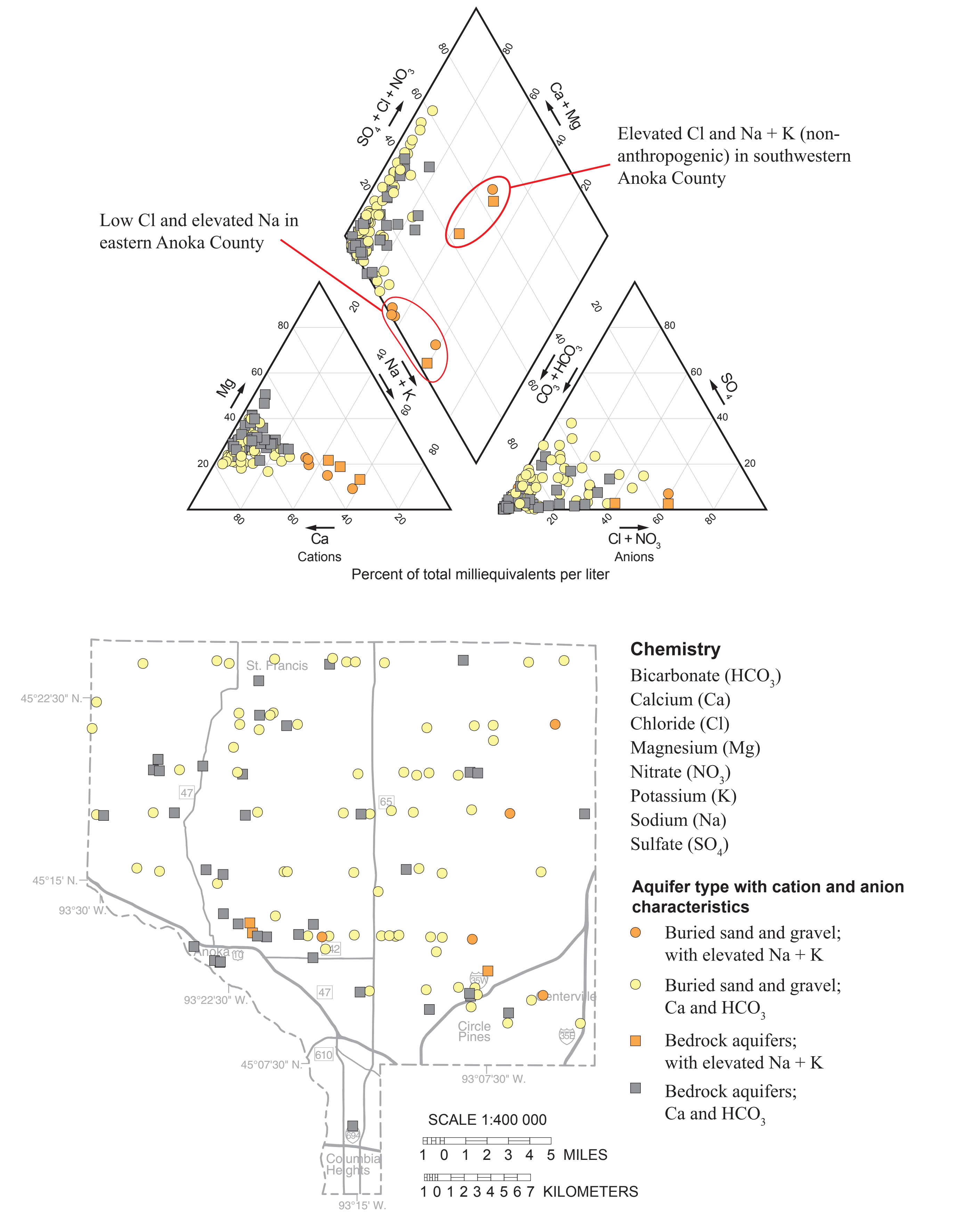


Figure 18. Ternary (Piper) diagram of groundwater samples from the DNR and MPCA

This diagram compares the relative proportions of cations and anions in groundwater from all the sampled wells. Most of the groundwater samples are the calcium and magnesium (Ca + Mg) and bicarbonate (HCO_3) type. The cations and anions are shown in the left and right triangles, respectively. The center diamond shows a composite of cations and anions.

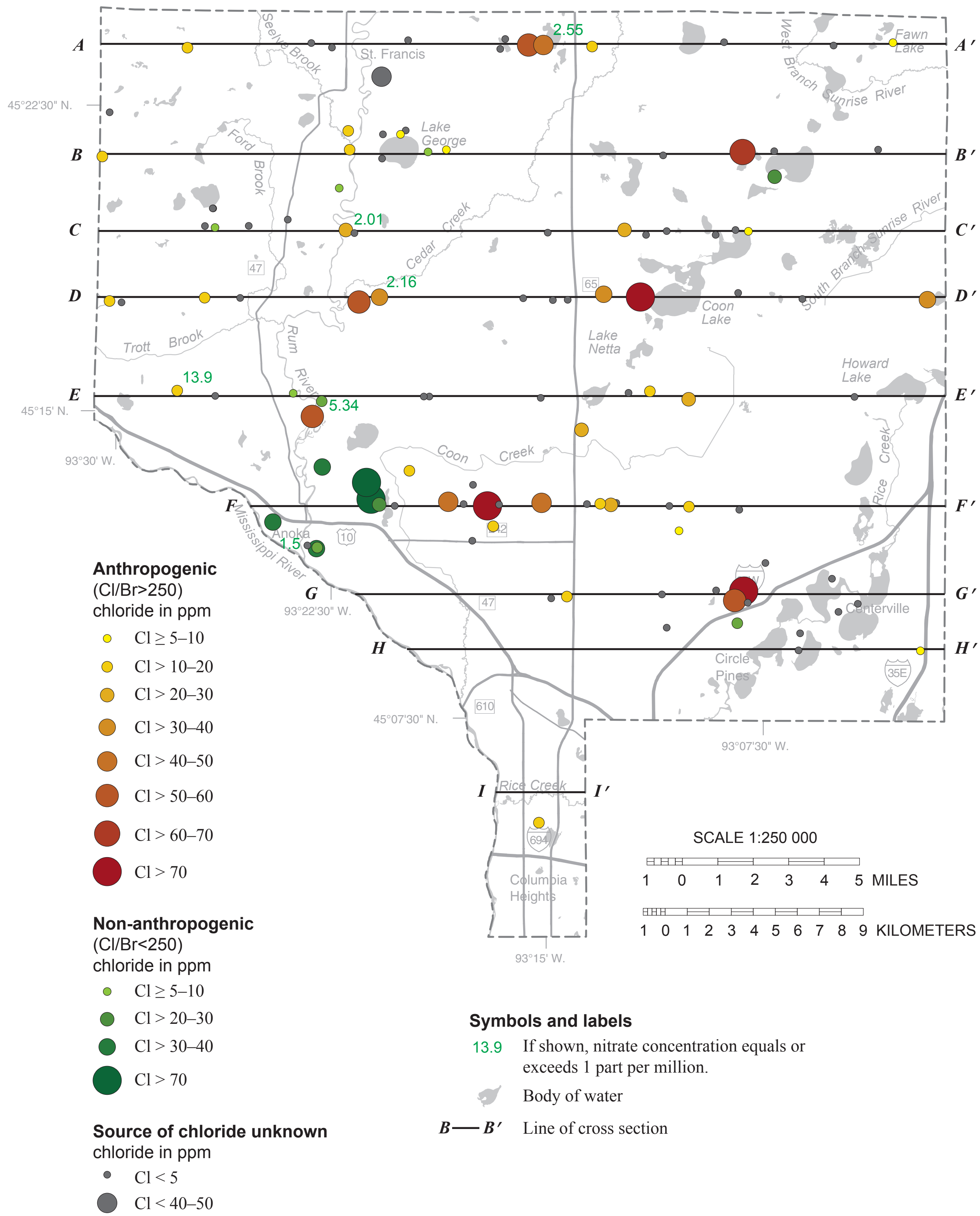


Figure 19. Elevated chloride and nitrate concentrations from groundwater samples

Elevated and anthropogenic (human caused) chloride concentrations (>5 ppm and Cl/Br >250) from groundwater samples are common and widespread in Anoka County. Groundwater samples with elevated nitrate values (>1 ppm) were limited to six samples in the western part of the county.

Naturally occurring elements of health concern

Some chemicals present in water, such as arsenic, manganese, and radium (Lively and others, 1992) may be naturally occurring but can potentially pose a human health risk.

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). One source of arsenic is from minerals in glacial sediment (Erickson and Barnes, 2005). However, elevated arsenic occurrences from buried sand aquifers are rare in Anoka County.

The Environmental Protection Agency (EPA) requires that community water supplies not exceed 10 parts per billion (ppb) arsenic (EPA, 2001), but there is no such requirement for domestic wells. Well-water samples that had 5 ppb or more arsenic should be resampled to determine if the arsenic level of the first sample is a representative value.

While generally not common, elevated arsenic values from groundwater samples were most common from wells with some hydraulic connection to the St. Lawrence and Tunnel City Group aquitards and aquifers (CSLT and CTCG). Elevated arsenic detections (10 ppb or greater) occurred in 10 groundwater samples (11 percent) with seven of the ten from bedrock aquifers (Figure 20). Statewide, from 2008 to 2015, approximately 11 percent of newly constructed potable wells have arsenic concentrations exceeding 10 ppb (MDH, 2016).

Manganese

Low levels of manganese are a benefit to humans, but high exposures can harm the nervous system (MDH, 2012). The MDH HRL established for infants is 100 ppb; the standard for adults is 300 ppb.

A large proportion of groundwater samples (87 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.

For a statewide comparison, manganese distribution in Minnesota groundwater is highly variable. Water table and buried sand aquifers had the greatest median manganese concentrations, 155 and 160 ppb, respectively. In water-table aquifers, 57 percent of drinking water wells sampled had manganese concentrations greater than 100 ppb. In buried sand aquifers, 63 percent of drinking water wells sampled had manganese concentrations greater than 100 ppb (MDH, 2014).

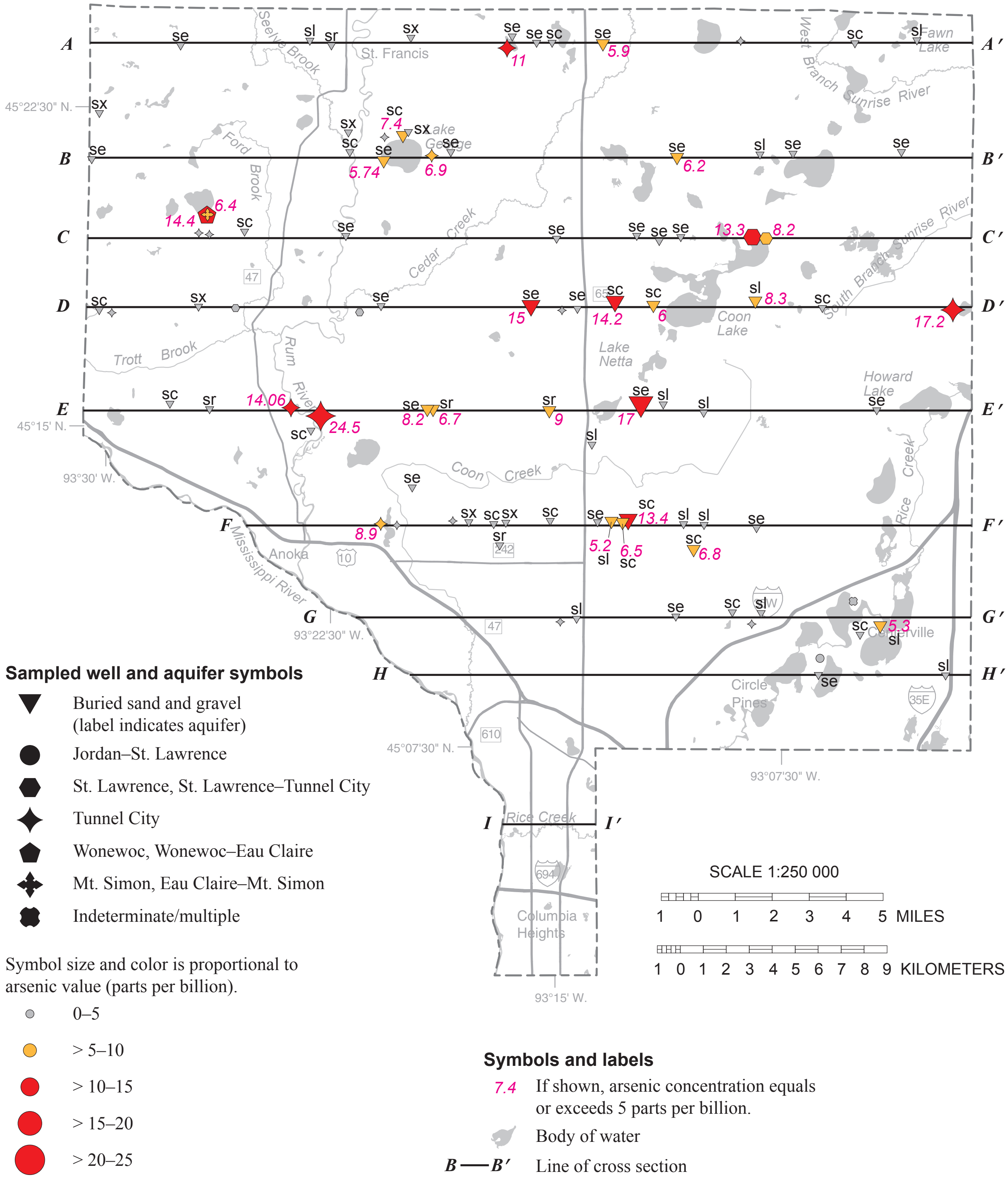


Figure 20. Arsenic values from buried sand and bedrock aquifers

Arsenic concentrations that equaled or exceeded federal drinking water standards (10 ppb) were found in 10 groundwater samples (11 percent) collected from buried sand and bedrock aquifers. All arsenic values 5 ppb or greater are labeled for reference.

Hydrogeologic cross sections (Plates 8 and 9)

The nine hydrogeologic cross sections shown on Plates 8 and 9 (Part B insert) illustrate the horizontal and vertical extent of aquifers and aquitards, groundwater residence time, and general directions of groundwater flow.

These cross sections were selected from a set of 87 regularly spaced (0.3 miles or 0.5 kilometers), west-to-east cross sections. These were constructed using a combination of well data from the CWI, bedrock geology map (Part A, Plate 2), surficial geology map (Part A, Plate 3), and Quaternary stratigraphy plate (Part A, Plate 4) of this atlas.

The well information for each cross section was projected onto the trace of the cross section from distances no greater than one-half kilometer. The locations of the nine cross sections in the county are shown in the inserts to this atlas, Plates 8 and 9, along with a comparison of glacial geologic units that were defined in Part A and the corresponding hydrogeologic units (Figure 5).

Relative hydraulic conductivity

Hydraulic conductivity is a function of the porosity (volume of pores) and permeability (connection of pores) of a sediment or rock layer. Percent sand content (Part A, Plate 4, Table 1) in the glacial sediment matrix is a proxy for permeability because coarse grains add permeability to sediment. Glacial aquitards with a higher sand content are assumed to have a higher hydraulic conductivity than aquitards with lower sand content. This assumption does not account for the occurrence of larger clasts (pebbles, cobbles, and boulders), the potential for fine sediment to fill pore spaces, or fractures in the shallow till units.

Glacial sediment layers that act as aquitards (till units) are shown in shades of gray on Plates 8 and 9. Lighter shades indicate aquitards with higher relative hydraulic conductivity; darker shades represent aquitards with lower relative hydraulic conductivity.

The tills with the highest sand content are the Cromwell Formation (unit Qcr) and Cromwell Formation–Emerald phase (unit Qce), both 64 percent; and the St. Francis or River Falls formations (unit Qrt, 66 percent). The lowest sand content is found in the clayey lacustrine unit (Qlc, 20 percent) of the Cromwell Formation and the pre-Wisconsin Qxt and Qpt units (33 percent).

The New Ulm Formation glacial till unit Qnu has a loamy portion and a sandy loam portion (Part A, Plate 4, Table 1 and cross sections) with average sand content of 46 percent and 59 percent, respectively. The Cromwell Formation unit (Qlc) also has the previously noted clayey loam portion (20 percent sand) and a sandy loam portion (64 percent sand). The different texture of these two units is represented on the Part B cross section A–A′ through F–F′ on Plates 8 and 9 (Gary Meyer, MGS, verbal communication, October 2016).

Groundwater-flow direction

Groundwater moves from areas with higher potential energy to areas with lower potential energy. Groundwater flow direction is indicated by the gray arrows in the cross sections (Plates 8 and 9) and is interpreted from the equipotential contours constructed from measured static (nonpumping) 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 Anoka 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 nitrates.

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 7 through 9.

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 not present.

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

sl aquifer

The following are shown on the cross sections: the St. Francis area west of the Rum River (left side A–A′); two locations east of Mud Lake (right side A–A′), two locations west of Linwood Lake (right side B–B′), and west of Coon Lake (right side C–C′); two locations in the Ham Lake area east of Ham Lake (right of center E–E′); three locations west of Lexington Avenue (near center F–F′); and one in the Lino Lakes area, east of Lochness Park (right side G–G′).

sc aquifer

The following are shown on the cross sections: in the Bethel area (center A–A′); the northwestern Ramsey area east of Trott Brook (left side D–D′); and two locations in the Bunker Hills Park area, near the Andover and Ham Lake border (near center F–F′).

se aquifer

Two locations the St. Francis area (left side A–A′).

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

sc aquifer

The following are shown on the cross sections: two locations in the Blaine area, near Lochness Park (right side G–G′).

se aquifer

The following are shown on the cross sections: west of Seelye Brook (left side A–A′); Bethel area (center A–A′); Oak Grove area, east of the Rum River (left side C–C′); and Andover area, east of the Rum River (left of center E–E′).

Upper bedrock zone

The following are shown on the cross sections: west of Bethel (left of center A–A′); Nowthen area (left side C–C′); and Ramsey area, west of Ford Brook (left side D–D′).

Ⓛ Groundwater is suspected to flow laterally.

This classification is necessary due to the limiting assumption of only vertical recharge used in the pollution sensitivity model. This classification is used where tritium detections occurs in very low to low sensitivity areas. In these areas the likely source of water containing tritium is not from a directly vertical pathway, but from some upgradient (lateral) location.

sl aquifer

Locations were identified in the southern portion of the aquifer extent where conditions are mixed moderate to high sensitivity and very low to low sensitivity. The following are shown on the cross sections: east of Bunker Hills Park (center F–F′); two locations in the Blaine area (left and right sides G–G′); and one location near the southeastern corner of Centerville, east of Sherman Lake (right side H–H′).

sc aquifer

Locations were identified in the central and northern portions of the county. The following are shown on the cross sections: east of Bethel (center A–A′); Oak Grove area, west of the Rum River (left side B–B′); Nowthen area, west of Ford Brook (left side C–C′); two locations in the Ham Lake area west of Coon Lake (right side D–D)′ and near Andover (left of center E–E′); and west of Lexington Avenue (center F–F′).

se aquifer

Locations were identified in the northwestern portion of the county. The following are shown on the cross sections: the Bethel area (center A–A′); six locations along the left and central portions of B–B′; two locations west of Coon Lake (right side C–C′); northern Andover area, east of Cedar Creek (left side D–D′); Ham lake area, east of Ham Lake (right side E–E′); and west of Bunker Hills Park (left of center F–F′).

sx aquifer

Locations were identified in the western portion of the county. The following are shown on the cross sections: the St. Francis area east of the Rum River (left side A–A′); northern Ramsey area west of the Ford Brook (left side D–D′), and the Andover area west of Bunker Hills Park (left side F–F′).

Bedrock

Locations were identified in the central and western portions of the county. The following are shown on the cross sections: east of Bethel (near center A–A′); the Oak Grove area, east of Lake George (left side B–B′) east of Mud Lake (left side C–C′); east of Cedar Creek (left of center D–D′); and the northern Andover area.

Ⓟ High-volume pumping creates an artificially steep gradient resulting in recent or mixed tritium age water at greater depths than expected.

This condition is common in Anoka County with its large number of high-capacity wells. This is typical of the deeper buried aquifers and aquifers in the upper bedrock zone because wells for public and commercial use tend to be constructed in the deeper aquifers to ensure a better long-term water supply, and to avoid interfering with the shallower domestic wells in the area.

se aquifer

Locations were identified in the the northern and western parts of the county (Plate 7). None are illustrated on the cross sections.

sx aquifer

The following are shown on the cross sections: the Ramsey area, west of the Rum River (left side E–E′); the Coon Rapids area, near the Mississippi River (left side H–H′); and the Fridley area (left side I–I′).

sr and sp aquifers

Locations were identified in the western portion of the county. One location is shown on the cross sections: the Coon Rapids area, east of Coon Creek (left side G–G′).

Bedrock

Many locations were identified in the southwest and southern populated areas (Plate 7). Most are not shown on the cross sections. The locations in this category that are shown on cross sections include: the Bethel area (center A–A′); the Ford Brook area (left side D–D′); east of the Rum River (left side F–F′); two locations in the Andover area in Bunker Hills Park (left of center F–F′); and the Columbus area, west of Rondeau Lake (right side F–F′).

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

Carbon-14 data

Carbon-14 residence time data are available from 23 wells (10 samples for this study and 13 from previous studies) within the county (Plates 7 through 9). Typical residence times for the buried sand and upper bedrock aquifers range from 1,000 to 5,000 years. The deeper bedrock aquifer residence times range from 5,000 to > 40,000 years.

Ten samples were collected for this project. Nine are illustrated on the cross sections: the St. Francis area, west of the Rum River (left side A–A′); two locations in the northeastern corner of the county, Linwood Lake area (right side B–B′); northern Ramsey, west of the Rum River (left side D-D′); the Ham Lake area, west of Coon Lake (center D–D′); and two locations in the Columbus area, east of Coon Lake (right side D–D′); the Ham Lake area, east of Bunker Hills Park (right side F–F′); and the Blaine area, west of Lochness Park (center G–G′).

Discharge interpretations

Ⓓ Groundwater discharges to surface water.

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 appears to be connected to the base of rivers or the base of the surficial sand aquifer associated with the rivers, or the hydraulic head in lower aquifers is at or above river elevation. The gaining (discharge) or losing (recharge) nature of surface water bodies can be a complicated phenomenon that can vary depending on seasonal or climatic cycles.

Evaluating this variability was beyond the scope of this study. Therefore, 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.

Cross sections include the following: the Rum River (left side A–A′ through E–E′), Cedar Creek (near center B–B′), and the Mississippi River (left side F–F′ through I–I′).

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 due to the hydrogeologic properties of the material hosting or overlying it. Migration of contaminants dissolved in water through unsaturated and saturated sediment is a complex process that is affected by biological degradation, oxidizing or reducing conditions, and other factors. The methods to interpret pollution sensitivity use the following generalizing assumptions:

- Flow paths are vertical and downward from the land surface through the soil and underlying sediment to an aquifer. Some places along river valleys are important groundwater discharge areas (see Hydrogeologic cross sections). Local upward groundwater movement is characteristic of these areas and will tend to lower the actual pollution sensitivity in these areas.
- 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 specific models.

Near-surface sensitivity: sediment texture is the primary property used to create a sensitivity map. The permeability of the sediment matrix texture is estimated based on hydrologic theory or empirical data to establish a downward flow rate. The rate multiplied by the vertical travel distance equals the estimate of the vertical travel time.

Buried aquifer sensitivity: sediment above and between buried sand aquifers are fine grained with low hydraulic conductivity. The method only considers the cumulative thickness of fine-grained sediment overlying aquifers. It does not consider differences in sediment texture or permeability of aquitard materials.

Near-surface sensitivity

Methods

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

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

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

- Areas with a relatively short time of travel (hours to a week) are rated as having high sensitivity (Figure 21).
- Areas with a longer time of travel (weeks to a year) are rated very low or low.
- Areas of more than a year are rated ultra low, but are not present in the county.

Results

The map (Figure 22) shows the combined travel-time estimate for the soil and surficial geologic materials.

- The slower infiltration rates (very low to low pollution sensitivity) are common in the northwestern, southeastern and southern portions of the county where surficial sand and gravel is thin or absent.
- Higher infiltration rates (moderate to high pollution sensitivity) dominate the central portion of the county where sandier soil and sediment are common at the surface.

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	Qci, Qwr, Qwl, Qwd, Qwn, Qbg, Qcp, Qco, Qni, Qt
		sand, silty sand	0.71	Qbs, Qbt, Ql, Qe
B, B/D	0.50	silt, loamy sand, units with eolian sand designation	0.50	Qlc, Qbc, Qa, Qns
		sandy loam	0.28	Qna
C, C/D	0.075	silt loam, loam	0.075	Qnd, Qnt, Qwf, Qwc, Qnt
		sandy clay loam	0.035	Not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Qm

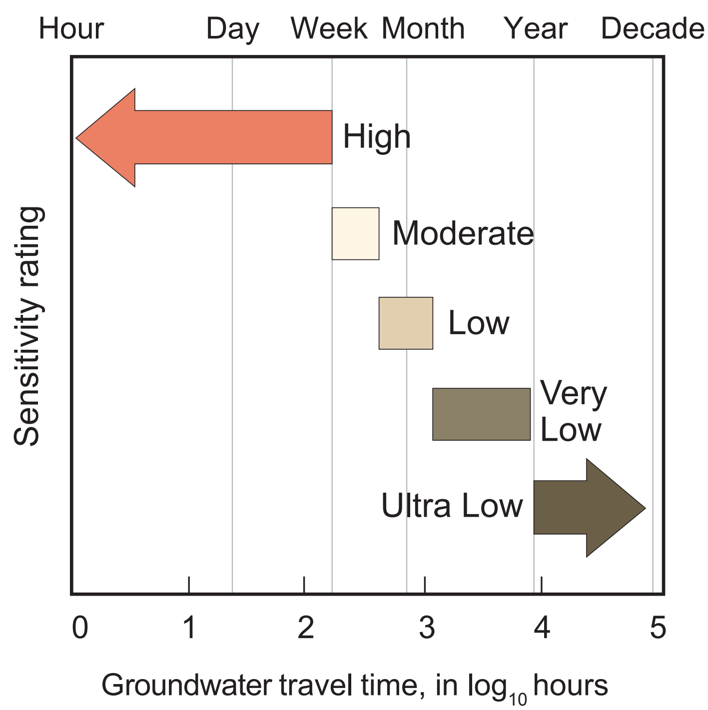


Figure 21. Geologic sensitivity rating for the near-surface materials

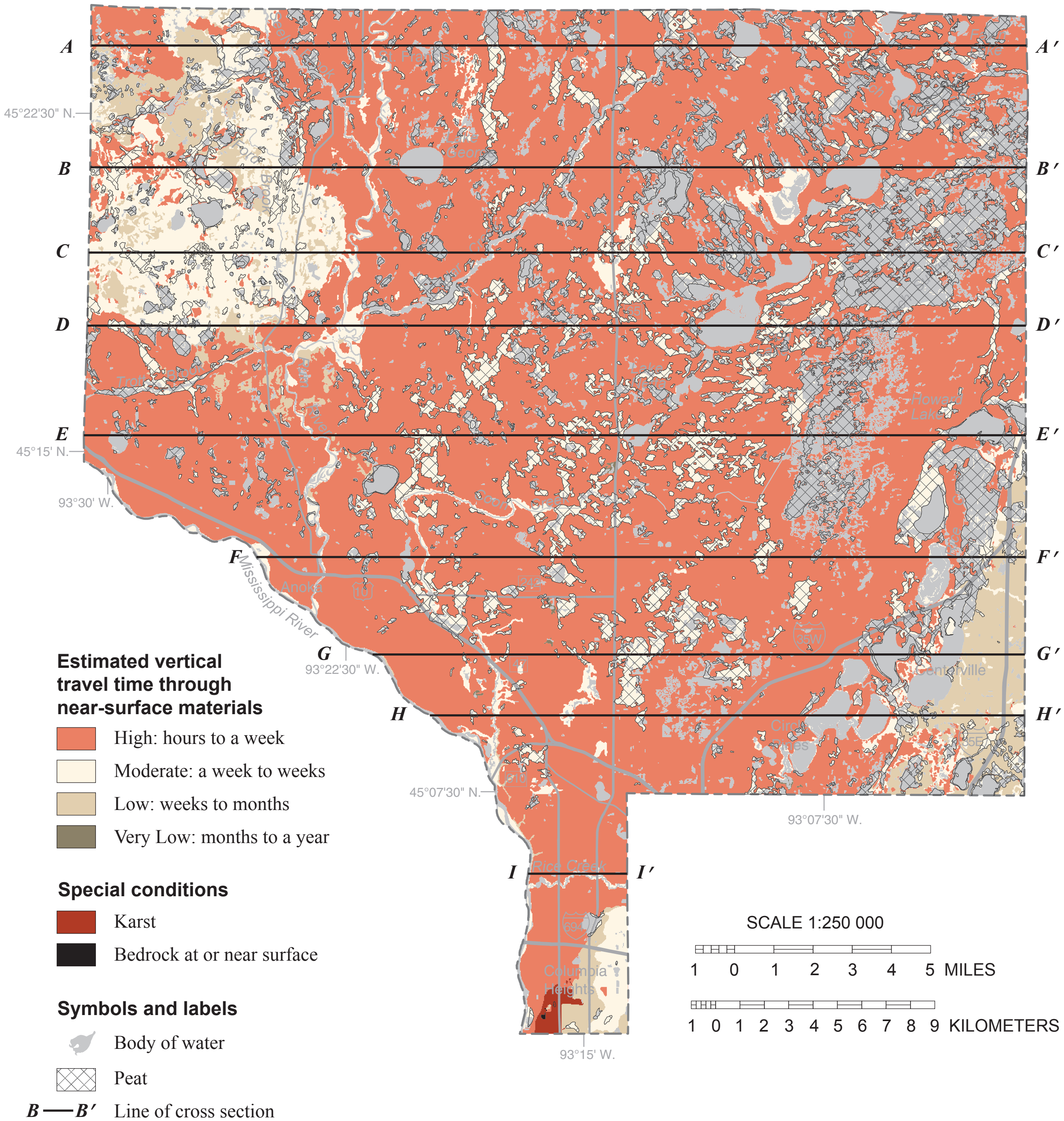


Figure 22. Pollution sensitivity of near-surface materials

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

Buried sand and gravel aquifer and top of bedrock 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 days to thousands of years.

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

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

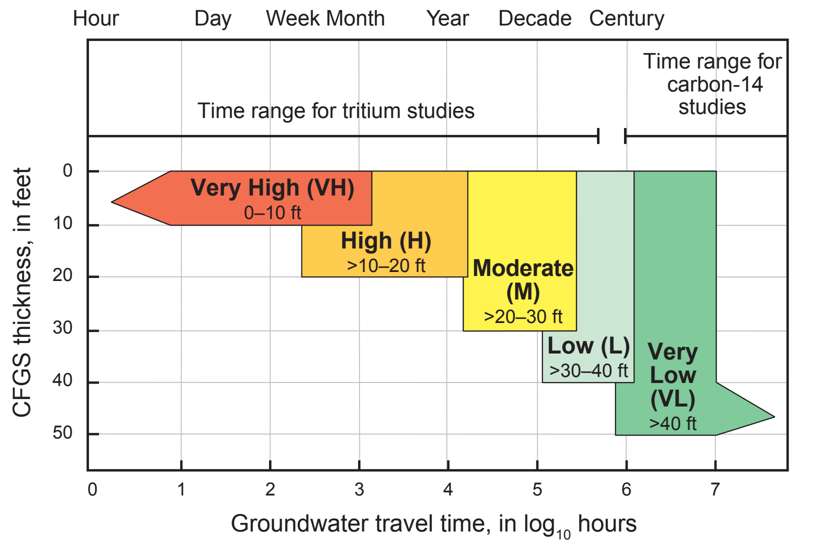


Figure 23. Geologic sensitivity rating for the buried sand and gravel aquifers and the bedrock surface

Sensitivity is defined by vertical travel time. Numbers following each rating represent the cumulative thickness of fine-grained sediment overlying an aquifer.

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

The model assumes the thickness of fine-grained sediment overlying an aquifer is inversely proportional to the sensitivity of an aquifer (Figure 24). 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, thicknesses greater than 40 feet are rated very low, and intermediate thicknesses have intermediate sensitivity ratings.

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

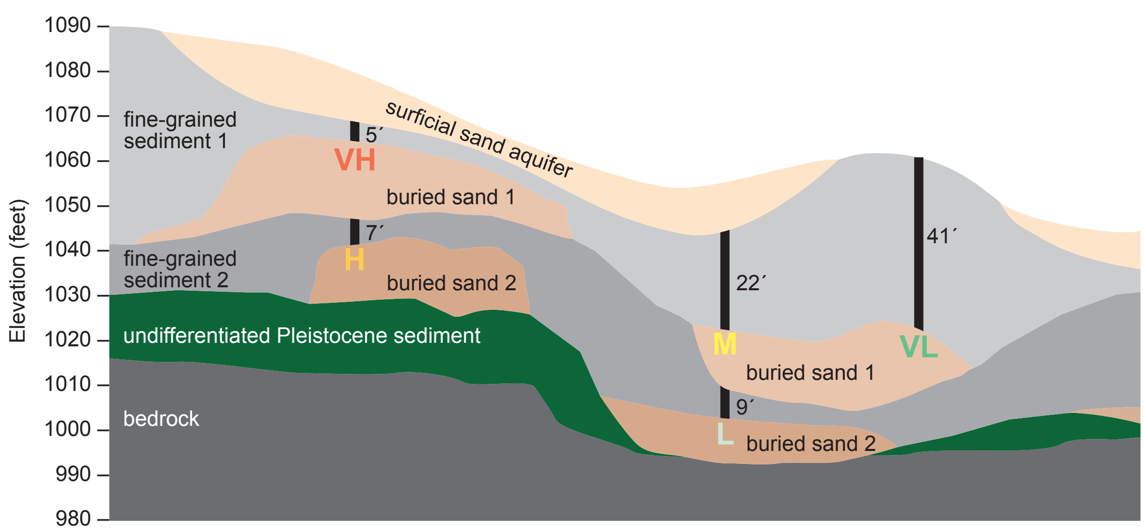


Figure 24. Cross section showing examples of pollution sensitivity ratings
Based on the cumulative thickness of overlying fine-grained sediment. Each of the vertical black lines in the figure is labeled with the thickness of fine-grained sediment. The letter at the base of the line indicates the sensitivity rating determined from the cumulative thickness.

Results

Results and maps in the following discussion of the aquifers are considered 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. These assist in understanding the distribution of particular chemical constituents. In the following sections the pollution sensitivity values and spatial distributions are compared to occurrences of "nonvintage" tritium-aged groundwater (Cold War era, recent, and mixed).

The tritium data set is a conglomeration of sampling efforts by the DNR, MDH, and Anoka County for several projects since 1991. None of these sampling plans were randomized in a way that would allow a statistical comparison to the results of the pollution sensitivity modeling. However, Figure 23 suggests that tritium detections in groundwater samples should be a very rare occurrence from aquifers in areas mapped as very low sensitivity. Considering these limitations and all the assumptions of the pollution sensitivity model, we found a good correspondence between tritium age and pollution sensitivity.

sl aquifer (Figure 25)

Sensitivity: The sl aquifer is relatively shallow (less than 50 feet) and unprotected in the northern and western portions of the county and transitions to deeper (up to approximately 100 feet) and better protected conditions in the southeastern part of the county. The New Ulm Formation, with a loam to sandy loam texture, is the main protective layer (aquitard) for this aquifer. This till layer tends to have a thin and patchy occurrence in the northern and western portions of the county; it is thicker and more continuous in the southeastern portion of the county.

These geological circumstances create a pattern of mostly low to very high pollution sensitivity (91 percent of the aquifer area) throughout the extent of the sl aquifer. The south-central and southeastern portions do not follow this trend as very low to moderate sensitivity conditions are common in this area.

Chemistry: Most of the samples from this aquifer were Cold War, recent, or mixed tritium age (20 of 29 samples) which is consistent with the more sensitive nature of this aquifer. These tritium detection locations generally corresponded to areas of moderate to very high pollution sensitivity in the northeastern and south-central parts of the county. The vintage tritium samples generally correspond to the southeastern area with very low to moderate sensitivity, with the exception of three samples in the northeastern portion of the county near Coon and Linwood Lakes. These vintage samples from areas of high to very high sensitivity may be due to locally isolated stratigraphic conditions that are beyond the resolution of our data. Elevated chloride detections tend to correspond to areas of moderate to very high sensitivity, with the exception of two samples in the southern part of the county (Blaine area, west of Club West Lake, left side G–G′; and southeastern Centerville, right side H–H′) where chloride sources may be from upgradient sources transported by lateral flow.

sc aquifer (Figure 26)

Sensitivity: The sc aquifer, like the previously described sl aquifer, exhibits the entire range of pollution sensitivity conditions. This aquifer is overlain in many areas by the New Ulm Formation (Qnu) or the Cromwell Formation lake clay unit (Qlc), or both. With this additional protective layer the sc aquifer exhibits more areas of very low pollution sensitivity (sc at 35 percent versus sl at 9 percent of total aquifer area) but overall is relatively sensitive to pollution (low through very high rating areas, 65 percent of total aquifer area).

Chemistry: The majority of the groundwater samples from this aquifer were mixed or recent tritium age (22 of 29 samples) which is consistent with the relatively sensitive nature of this aquifer. The higher sensitivity areas are in the southwestern part of the county (left side E–E′ and F–F′) where the New Ulm Formation (Qnu) is mostly absent and the Cromwell Formation lake clay unit (Qlc) is thin and discontinuous. The six tritium samples in this area from northwestern Ramsey through Andover, to the western part of Ham Lake, have tritium ages in the mixed and recent age range. Five of these samples contained elevated chloride concentrations ranging from approximately 12 to 184 ppm. Two of these elevated tritium concentration samples in this western area also had elevated nitrate concentrations of 5.3 and 13.9 ppm.

The eastern and southeastern parts of the county have mixed and vintage tritium conditions corresponding to the mostly very low to moderate sensitivity in these areas, including Columbus, southern Ham Lake, Blaine, Lino Lakes, and Centerville. In the central and northern portions of the county pollution sensitivity conditions vary locally, corresponding to an equally complex distribution of tritium conditions and elevated chloride occurrences ranging from 8 to 130 ppm and nitrate at 2.55 ppm at a location east of Bethel.

se aquifer (Figure 27)

Sensitivity: The se aquifer is relatively widespread and widely used in the county. It has large areas that appear to be generally well protected and exhibit very low pollution sensitivity ratings (82 percent of aquifer area). There are also less extensive areas of low to very high pollution sensitivity (18 percent of aquifer area).

Similar to the overlying sc aquifer, moderate to very high pollution sensitivity conditions are common in the southwestern portion of the county where the overlying New Ulm Formation (Qnu) and Cromwell Formation lake clay unit (Qlc) are absent, thin, discontinuous, or sandier.

Chemistry: More than half (35 of 60) of the samples were Cold War era, mixed, or recent tritium age. However, as a comparison to the pollution sensitivity model that only considers downward static flow conditions, a more representative value might be 22 of 60 samples, or approximately a third of the groundwater samples were nonvintage tritium age.

Since public wells tend to be deeper wells (greater than approximately 100 feet), higher capacity pumping from public wells at this general depth, and deeper, may have been an important factor causing capture of recent and mixed groundwater by the pumping well. In other words, 9 of the 35 groundwater samples that were nonvintage tritium age were not useful for evaluating our simple pollution sensitivity model for this aquifer due to pumping effects.

In addition, some of the groundwater samples containing tritium are from older wells (4 of 35, drilled from 1976 to 1987). Tritium detections in these wells may be due to older well construction procedures or corroded casings that may have caused leakage of shallow recent groundwater into the well casings. Most of the vintage groundwater samples from this aquifer were in the eastern part of the county where this aquifer is dominantly very low to low sensitivity.

The central and northwestern parts of the county have pollution sensitivity conditions that vary locally in complex patterns. Most of the 16 samples occur in this area with Cold War era, mixed, or recent tritium age, and all nine of the samples with elevated chloride. The elevated chloride concentrations range from 5.29 to 57 ppm. One elevated nitrate value with a concentration of 2.01 ppm is shown southwest of Lake George along C–C′.

sx aquifer (Figure 28)

Sensitivity: The sx aquifer is mostly a very low sensitivity aquifer (97 percent of aquifer area) except for scattered, relatively small areas of moderate to very high sensitivity.

Chemistry: Only 3 of 34 groundwater samples were mixed or recent tritium age if values are excluded from high-capacity pumping wells and some older wells that might have leaky casings. Possible pumping influences creating anomalously high tritium values (7 of 34 groundwater samples) were common in the western and southern parts of the county from wells owned by municipalities, businesses, and county facilities. Only two groundwater samples contained elevated concentrations of anthropogenic chloride at locations in the northwestern part of the county with values of 13.1 and 15.3 ppm.

sr and sp aquifers (Figure 29)

The sr and sp aquifers are shown together on the same figure since they both have limited extents, similar pollution sensitivity ratings, and mostly don't overlap.

Sensitivity: Similar to the overlying sx aquifer, the sr and sp aquifers exhibit mostly very low sensitivity conditions (97 percent and 99 percent of aquifer area, respectively) with relatively small scattered areas of moderate to very high sensitivity in mostly the western and southern portions of the county.

Chemistry: Few of the groundwater samples were mixed or recent tritium age (6 of 27 samples) and most of those tritium occurrences (5 of 6 samples) may be due to tritium capture from high-capacity pumping of public wells (municipal and county facilities).

Top of bedrock (Figure 30)

Sensitivity: Very low pollution sensitivity is the dominant rating for the top of the bedrock surface (98 percent of bedrock surface area) with low through very high pollution sensitivity areas scattered throughout the county. Pollution sensitivity conditions other than very low are rare in the eastern and south-central parts of the county.

Chemistry: The tritium data set for bedrock aquifers shown in Figure 30 is a subset of all the bedrock aquifer tritium data. Data shown are only from wells with shallower open-hole constructions: relative to the top of the bedrock, with relatively short open-hole sections (top of bedrock 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 top of bedrock conditions and the corresponding pollution sensitivity of the top bedrock surface.

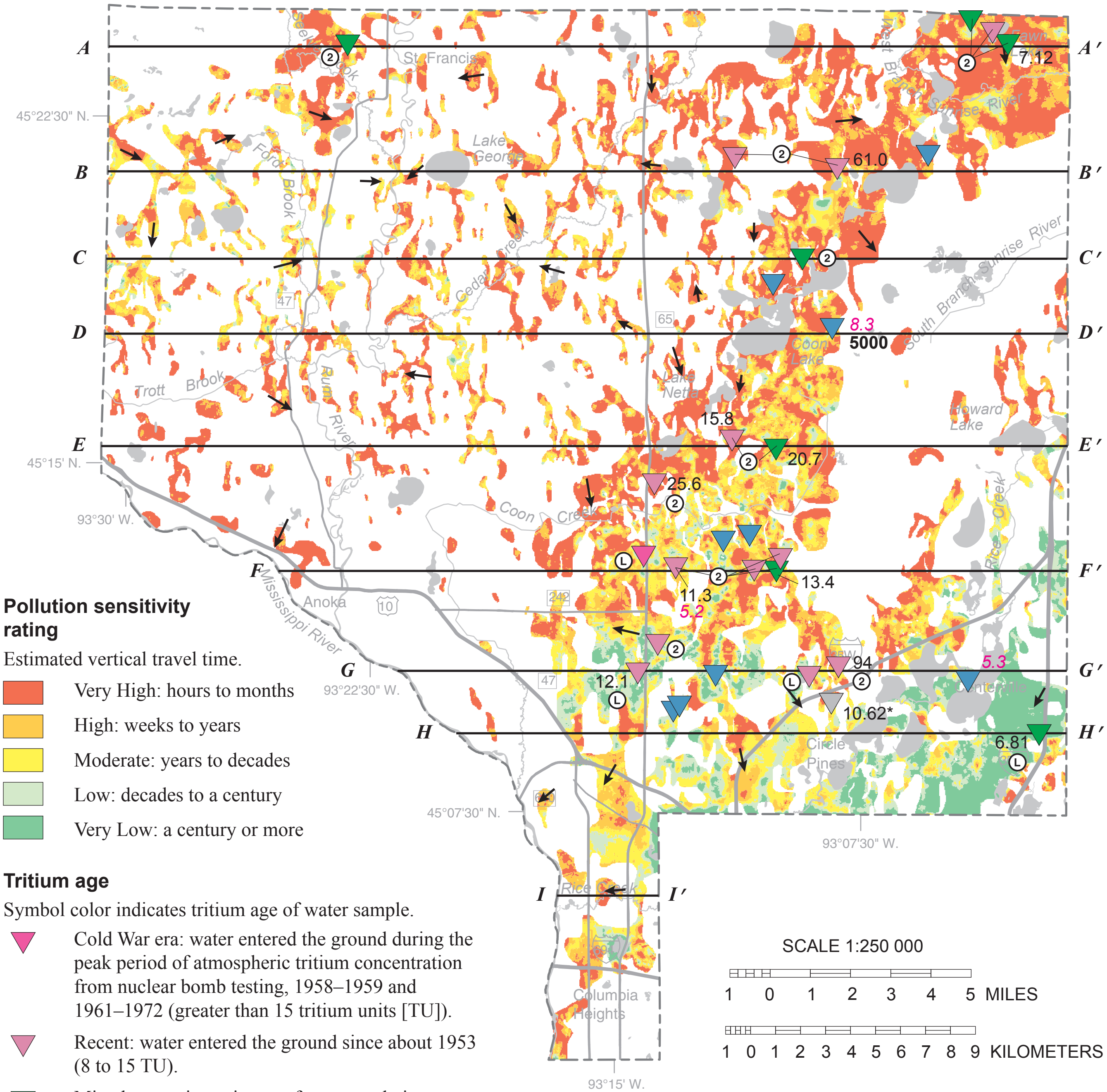
Of the 91 tritium samples from wells that matched these well construction criteria, 23 samples were mixed or recent tritium age. Most were located in the central, western, and southern parts of the county. Most of the nonvintage tritium ages (14 of 23 samples) were mixed.

Similar to the overlying se, sx, sr, and sp buried sand aquifers, the mixed or recent tritium-age water (5 of the 23 nonvintage samples) can probably be attributed to high-capacity pumping from public wells. For several other groundwater samples from older wells the source and pathways of the groundwater containing tritium is unclear (9 of the 23 mixed or recent samples) and may be due to corroded well casings that allow recent groundwater to leak into these wells. Seven groundwater samples containing tritium in the central, north-central, and western parts of the county can probably be attributed to recharge through multiple buried sand aquifers or lateral groundwater movement from higher sensitivity areas.

Deeper bedrock aquifers (Figure 31)

The selection of tritium data from wells constructed with open-hole portions in deeper aquifers shows some groundwater samples with mixed tritium age (13 of 32 samples). Most of these wells are located in the southern highly populated part of the county. All of these samples are from high-capacity municipal and county wells that may have drawn shallow recent and mixed water to deeper portions of the aquifer (the “P” condition). This would normally not occur under natural, nonpumping groundwater flow conditions.

The age and condition of these wells may be another 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). Some of these wells were constructed with the open-hole portion of the well spanning multiple aquifers. These types of well-construction designs were prohibited for new construction by the MDH well code of 1974 due to the risk of creating hydraulic connections between different aquifers through the open borehole.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

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

Groundwater conditions

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

SCALE 1:250 000

1 0 1 2 3 4 5 MILES

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

Symbols and labels

13.4	If shown, chloride concentration equals or exceeds 5 parts per million. (* indicates naturally elevated values)
5.3	If shown, arsenic concentration equals or exceeds 5 parts per billion.
5000	If shown, groundwater residence time in years as estimated by carbon-14 (^{14}C) isotope analysis.
	Body of water
←	Groundwater flow direction
B—*B′*	Line of cross section

Figure 25. Pollution sensitivity of the sl aquifer and groundwater flow directions

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

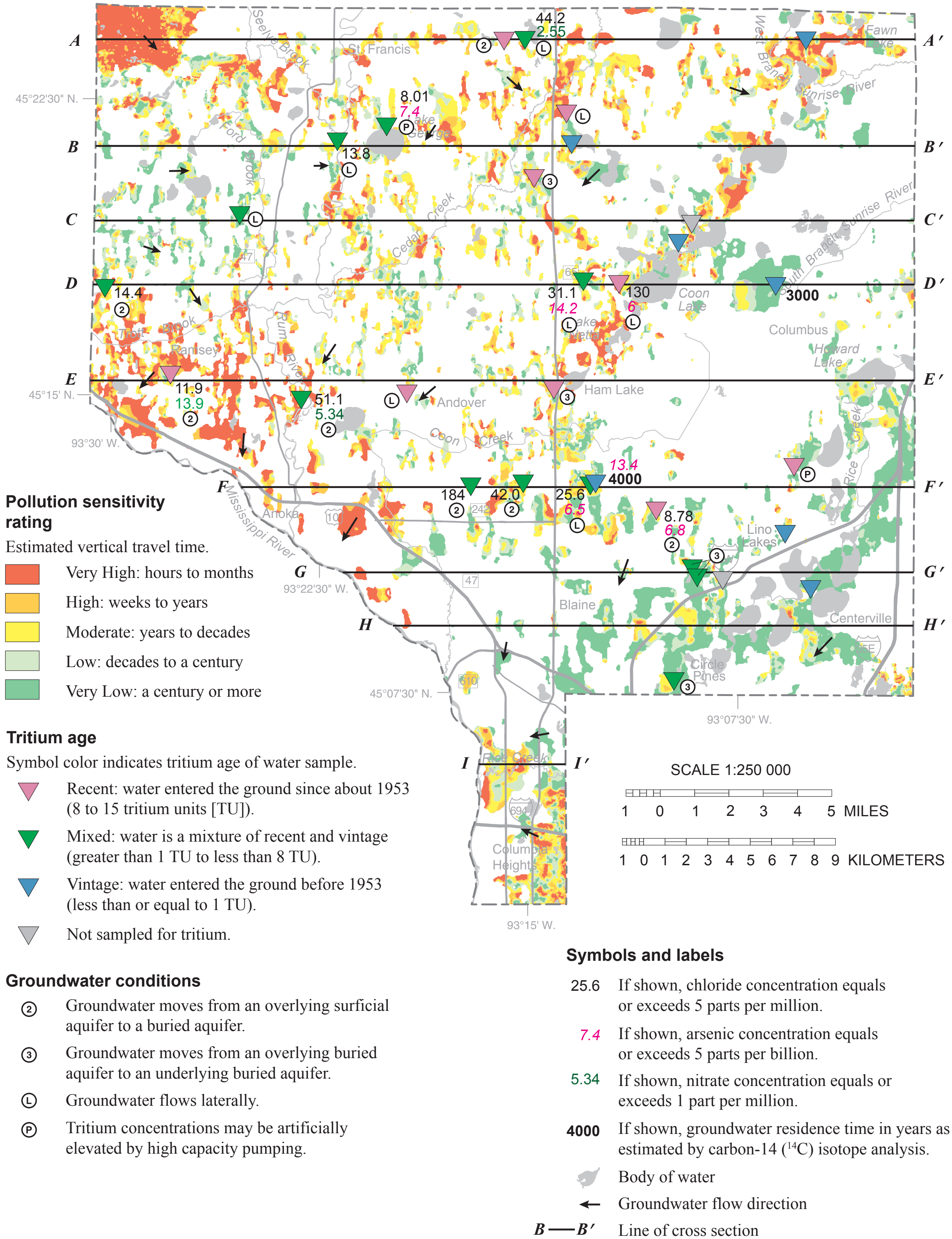
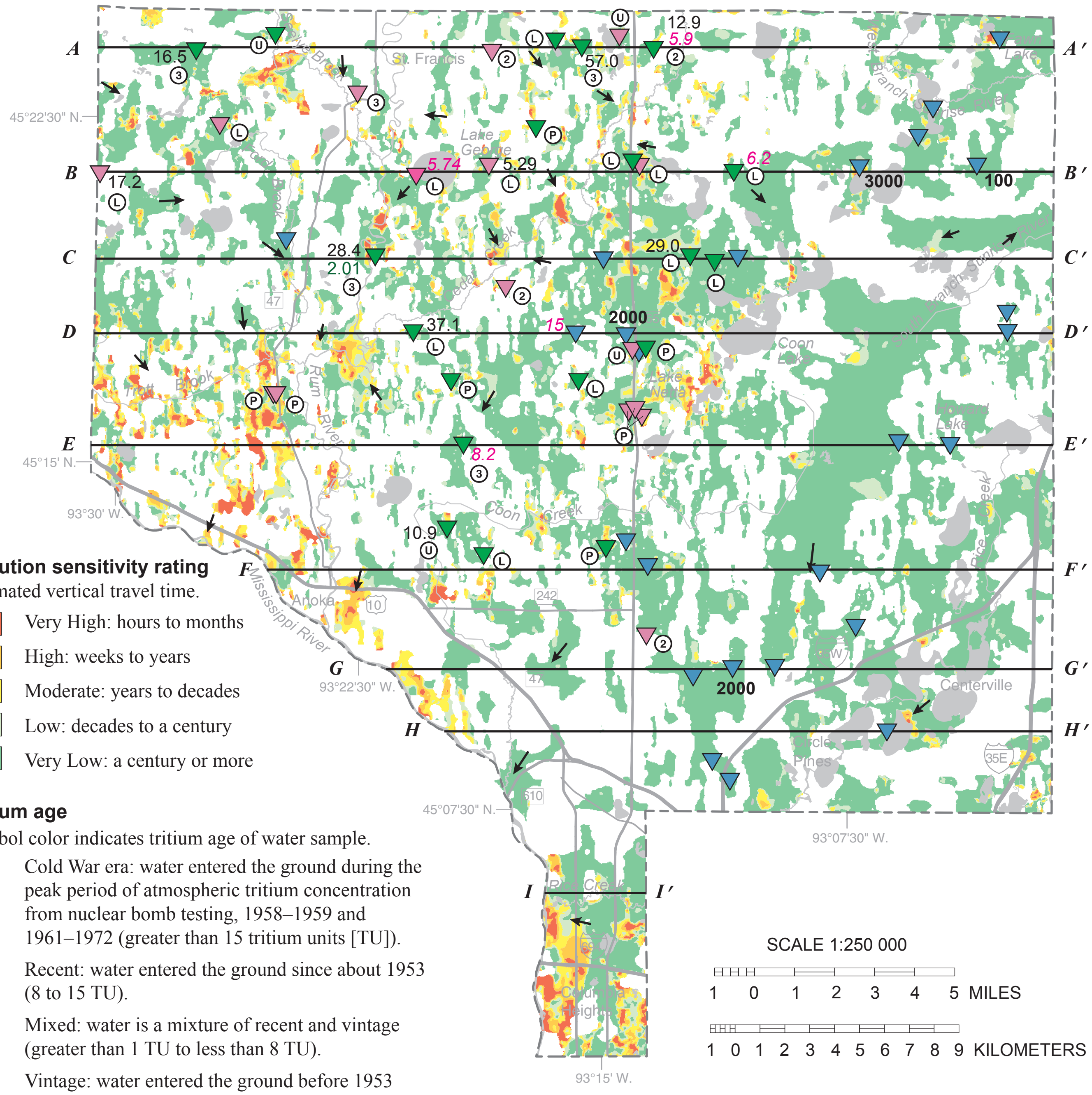


Figure 26. Pollution sensitivity of the sc aquifer and groundwater flow directions

The higher sensitivity areas are in the southwestern part of the county. The eastern and southeastern parts of the county have mixed and vintage tritium conditions corresponding to the mostly very low to moderate sensitivity in these areas.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

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

Symbols and labels

- 17.2 If shown, chloride concentration equals or exceeds 5 parts per million.
- 2.01 If shown, nitrate concentration equals or exceeds 1 part per million.
- 5.9 If shown, arsenic concentration equals or exceeds 5 parts per billion.
- **3000** If shown, groundwater residence time in years as estimated by carbon-14 (^{14}C) isotope analysis.
- Body of water
- Groundwater flow direction
- *B*——*B′* Line of cross section

Groundwater conditions

- ② Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- ③ Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- Ⓛ Groundwater flows laterally.
- Ⓟ Tritium concentrations may be artificially elevated by high capacity pumping.
- Ⓤ Groundwater flowpath is unknown.

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

Large areas of this aquifer exhibit very low pollution sensitivity, although moderate to very high pollution sensitivity conditions are common in the southwestern portion of the county.

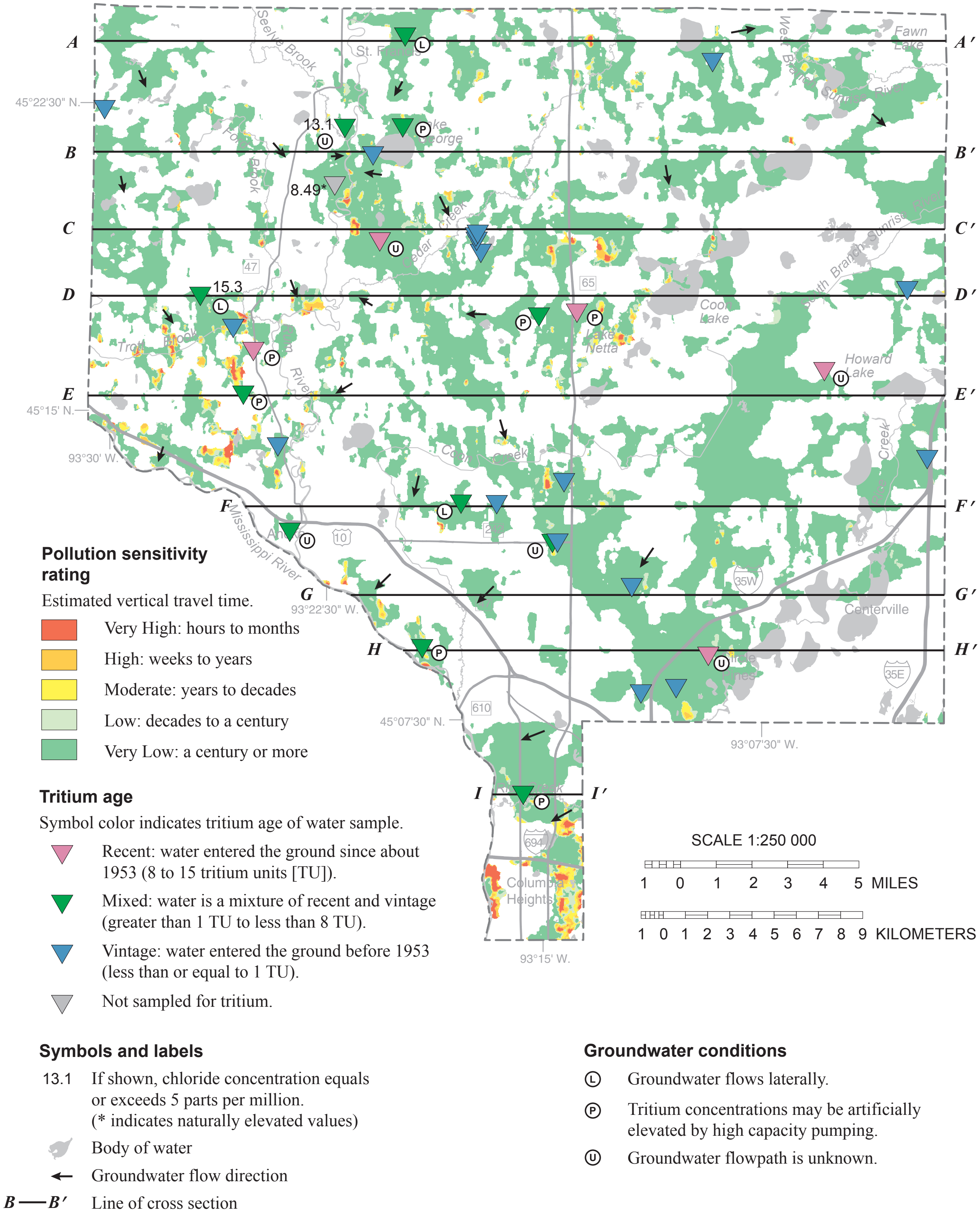


Figure 28. Pollution sensitivity of the sx aquifer and groundwater flow directions

The sx aquifer is mostly a very low sensitivity aquifer, except for scattered, relatively small areas of moderate to very high sensitivity.

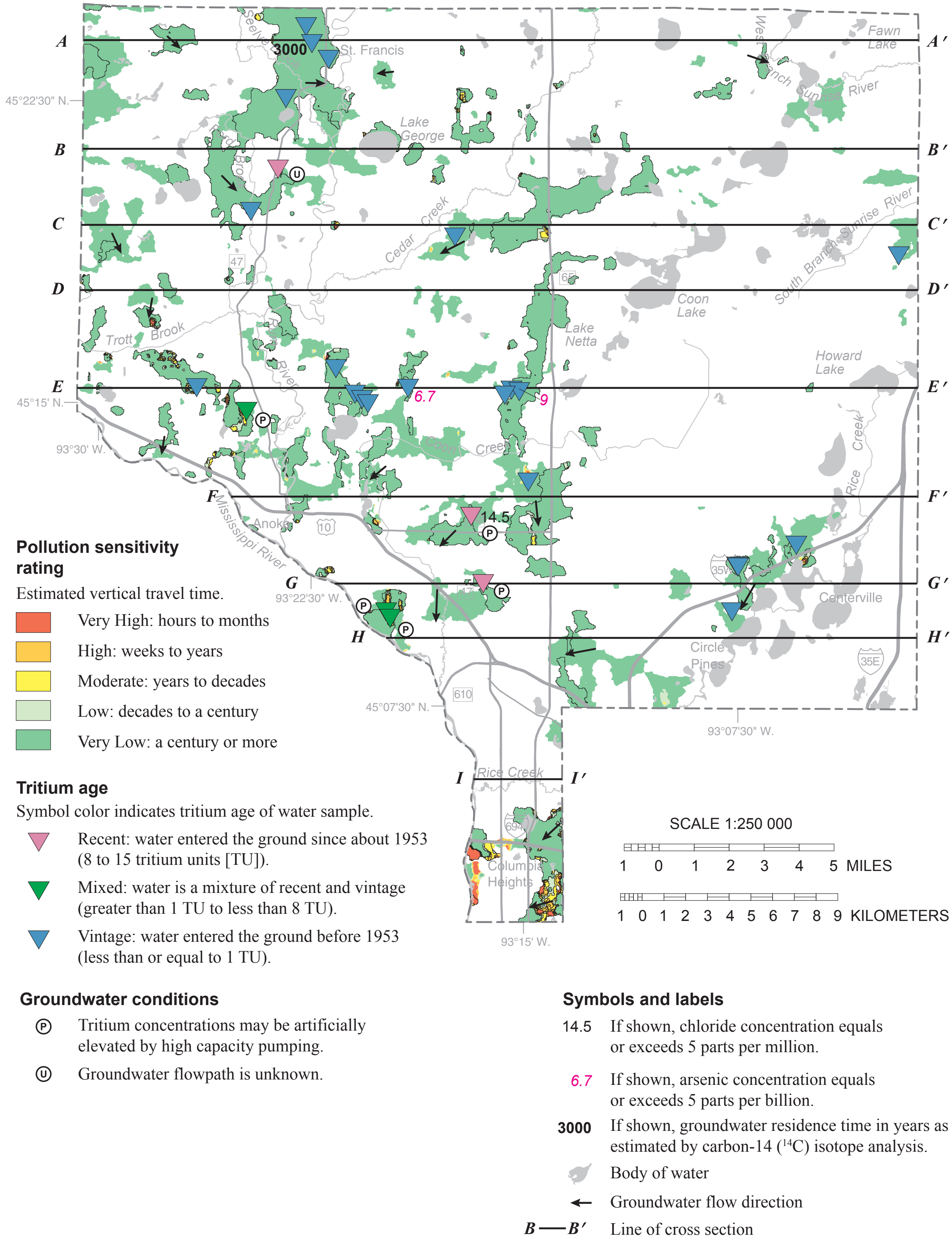


Figure 29. Pollution sensitivity of the sr and sp aquifers and groundwater flow directions

Similar to the overlying sx aquifer, these aquifers exhibit mostly very low sensitivity conditions. Relatively small scattered areas of moderate to very high sensitivity exist in mostly the western and southern portions of the county. The sr aquifer (shown with outline) is stratigraphically above the sp aquifer.

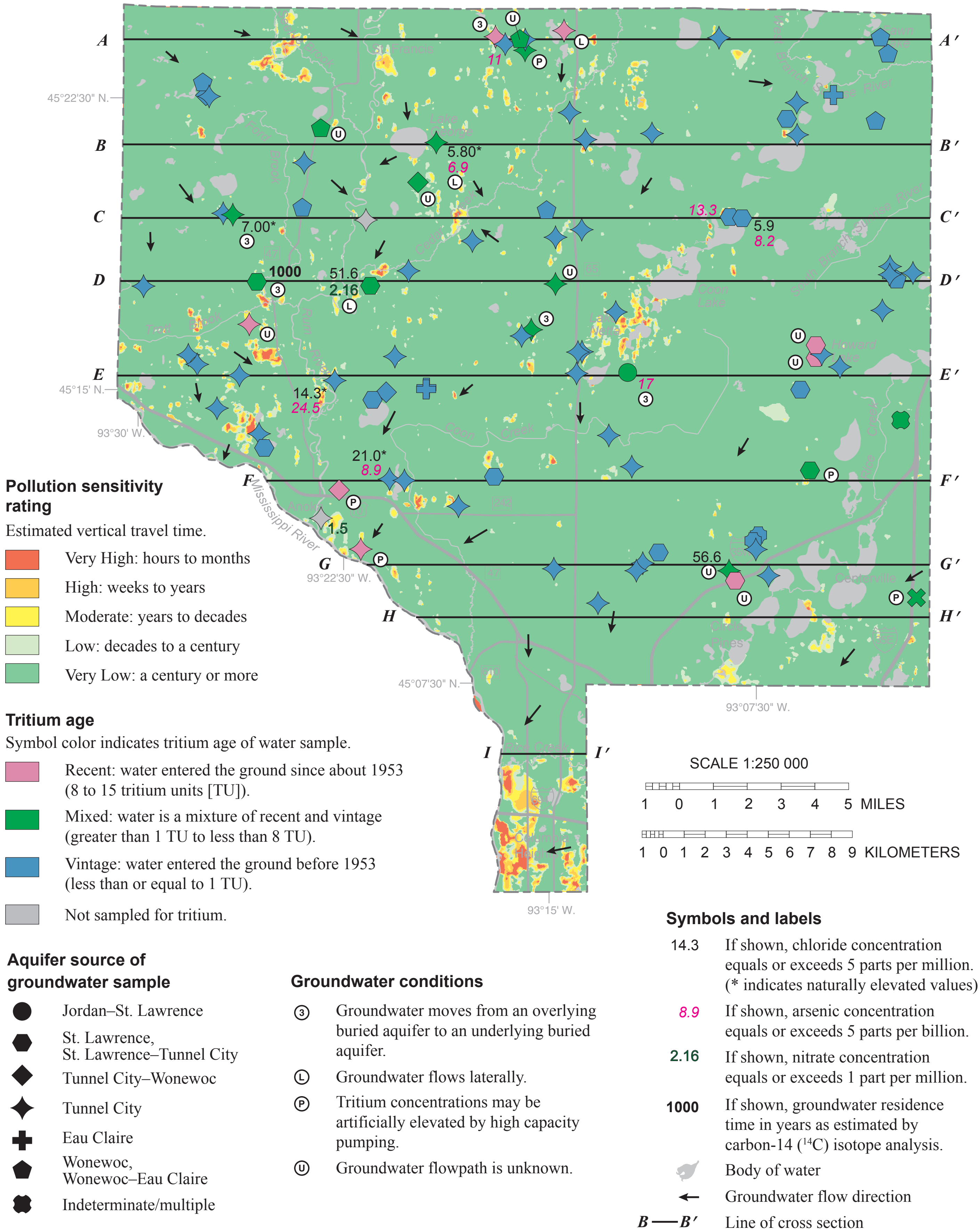


Figure 30. Pollution sensitivity of the top of bedrock and groundwater flow directions

Very low pollution sensitivity is the dominant rating for the top of the bedrock surface. Significant moderate through very high pollution sensitivity areas are scattered throughout the central, western, and southern parts of the county.

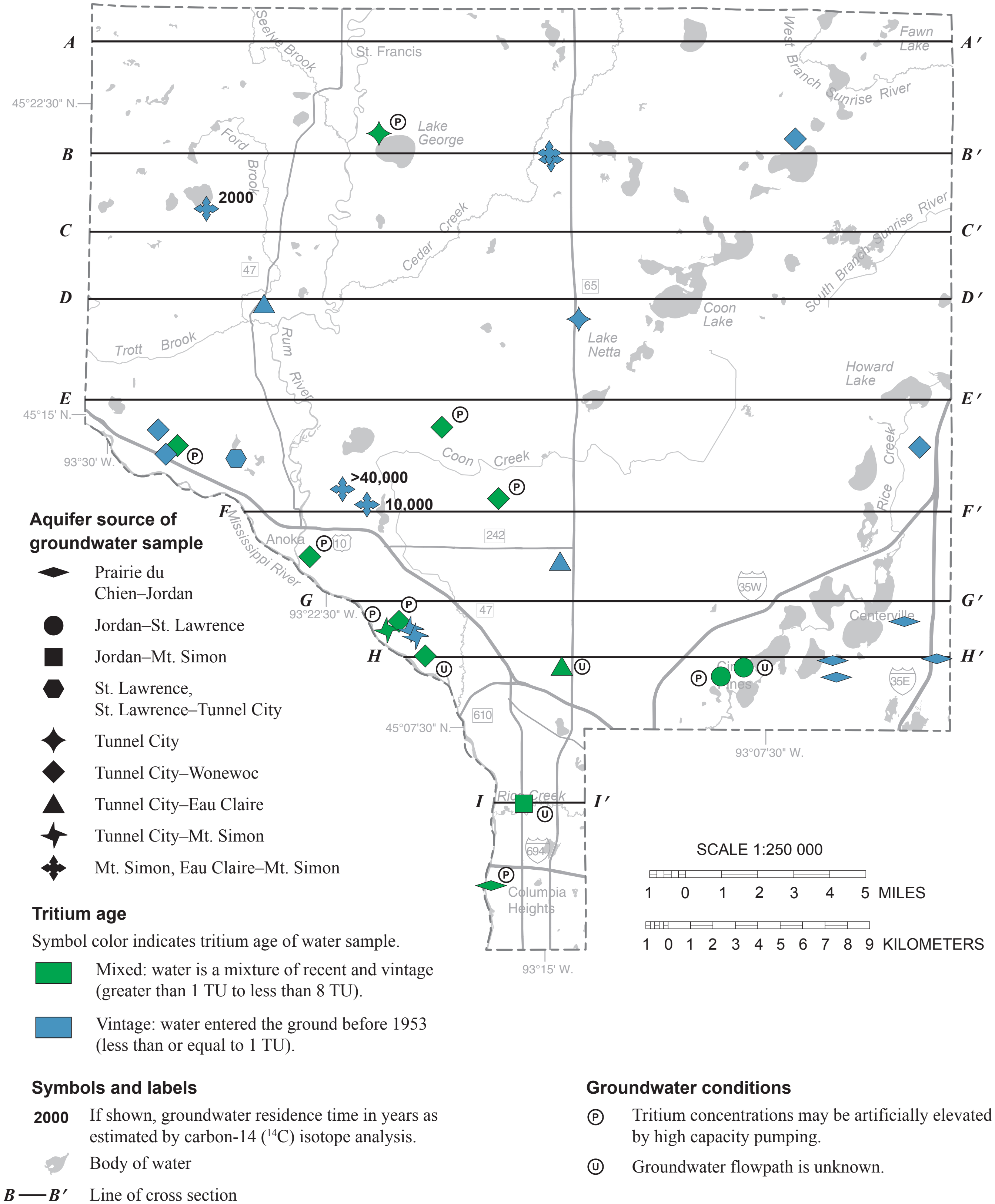


Figure 31. Deeper bedrock tritium and carbon-14 age

All of these tritium and carbon-14 samples are from high-capacity municipal and county wells. Groundwater samples with mixed tritium age may have drawn shallow, elevated tritium water deeper than would normally occur under natural, low pumping groundwater flow conditions.

Groundwater use and aquifer characteristics

A water-use appropriation permit from the DNR is required for all groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year (with some exceptions). This provides the DNR with the ability to assess and regulate which aquifers are being used and for what purpose. Combined with an understanding of aquifer characteristics (specific capacity and transmissivity), it is possible to project whether the supply is adequate and uses are sustainable.

Groundwater use

The reported water use for 2015 (Table 2) is categorized for all large capacity users in the county by the type of aquifer (Figure 32) and type of use (Figure 33).

The majority (85 percent) of the water used is water supply and mainly draws from the bedrock aquifers and the buried sand aquifers (QBAA). Water supply is not an important use category for the surficial aquifer. Noncrop irrigation is a small percentage (5 percent) of water use although probably a significant portion of water supply (municipal) use in the summer time. These wells draw primarily from buried sand and bedrock aquifers also located in the urbanized western and southern portions of the county. Industrial processing (3 percent) uses water mostly from buried sand sources. Pollution containment (4 percent) reflects the urban nature of the western and southern portions of the county. These wells use water mostly from the surficial sand and buried sand aquifers. Crop irrigation is a minor portion of groundwater use (<1 percent) in the county.

There are no reporting requirements in Minnesota for well owners that use smaller quantities of groundwater, but the aquifer being used can be determined in many cases. Of the approximately 24,000 active wells in the county with identified aquifers, most wells are completed in the buried sand aquifers (53 percent) followed by the sedimentary bedrock aquifers (38 percent). Only 6 percent are completed in the surficial sand aquifer. Approximately 3 percent are unclassified. The large majority of wells in the county are domestic wells (91 percent), followed by public supply (2 percent), pollution containment and monitoring (1 percent), irrigation (<1 percent), commercial/industrial (<1 percent), and other minor categories.

Table 2. Reported 2015 water use from DNR groundwater permit holders

Data from the Minnesota DNR Permit 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)
Water supply	279	1,791	7,448	--	9,518	85
Noncrop irrigation	32	172	345	21	571	5
Industrial processing	1	248	91	1	340	3
Pollution containment	183	186	114	--	482	4
Other	--	--	6	207	212	2
Crop irrigation	2	8	24	1	35	0.3
Total (MGY)	497	2,405	8,027	230	11,158	
Total (percent)	4	22	72	2		

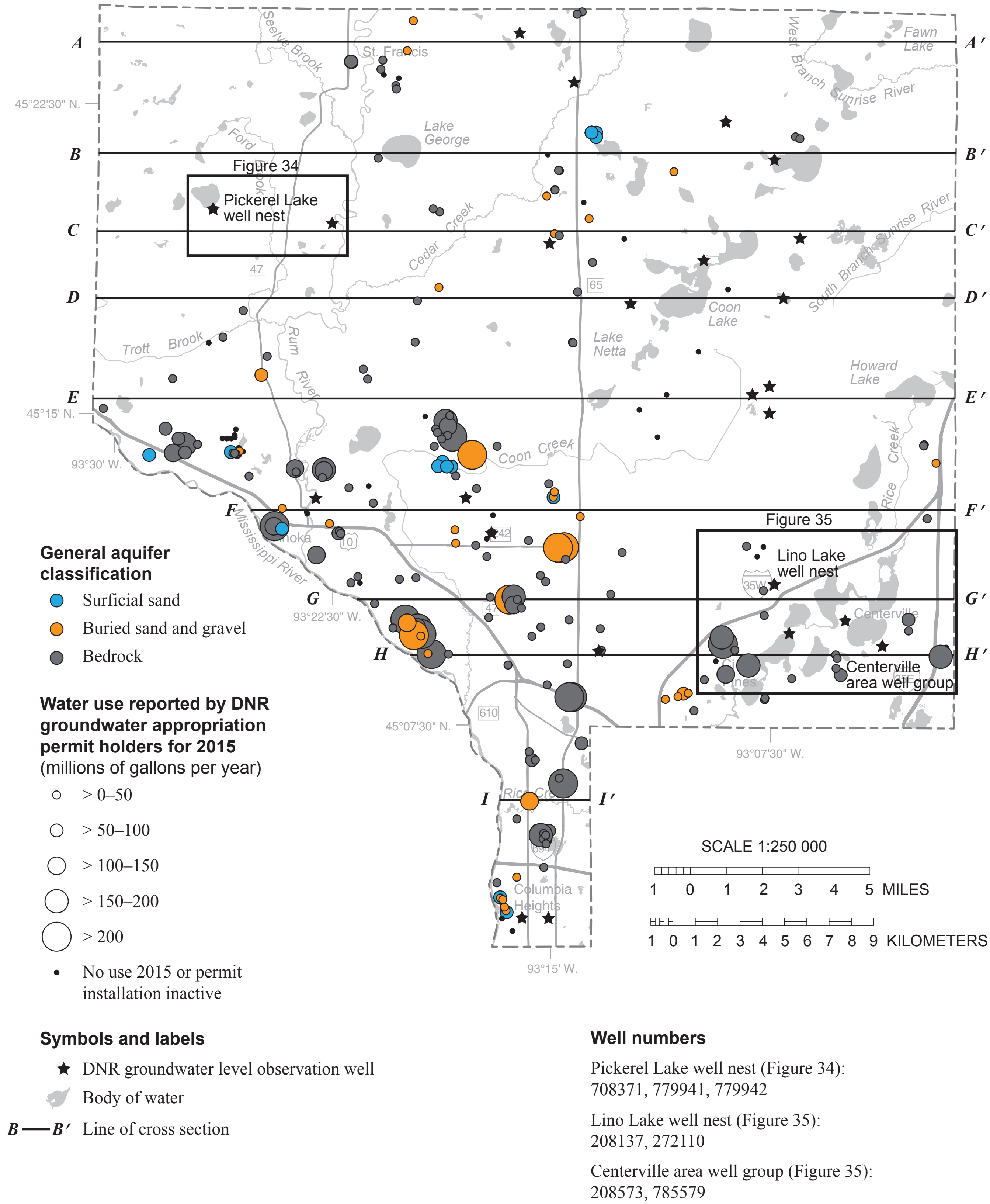


Figure 32. Locations of DNR groundwater appropriation permit holders by general aquifer classification

Symbols represent aquifer type and reported 2015 water-use amount. Water supply use is mainly from the bedrock and buried sand aquifers in the southern and southwestern portions of the county.

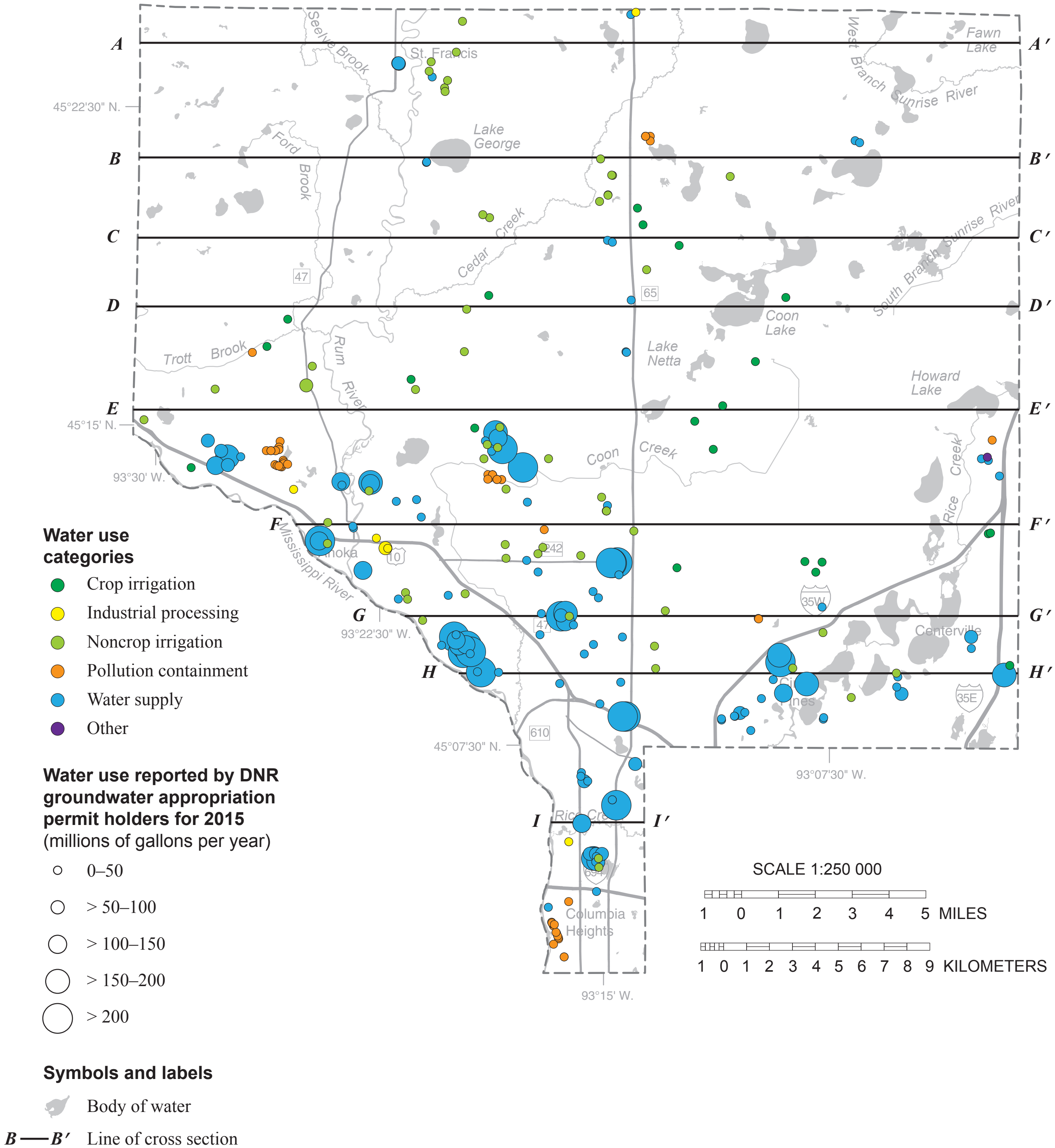


Figure 33. Locations of DNR groundwater appropriation permit holders by water use

Symbols represent water-use type and reported 2015 water-use amount. Water supply is the largest use.

Groundwater level monitoring

The DNR maintains a statewide groundwater level monitoring program using observation wells for the purpose of assessing groundwater resources, determining long term trends, interpreting impacts of pumping and climate, planning for water conservation, evaluating water conflicts, and otherwise managing the water resource. Anoka County is ideally situated to provide examples of both natural and man-made effects on multiple aquifers because of the dual nature of county land use (rural and urban), and an adequate amount of archived water level data with continuous readings at useful locations.

The Pickerel Lake area in the relatively rural northwestern portion of the county has had an observation well nest consisting of Mt. Simon, Wonewoc, and water table wells since 2010. This location is not near any large groundwater appropriations that might affect water level elevation trends (Figure 32). Figure 34 shows a comparison of the water level elevations from these three aquifers with the interpolated monthly precipitation records from that location. The patterns of water levels in all the wells are responding to changes in precipitation and increased recharge to the water-table aquifer and subsequent pressure loading of the underlying bedrock aquifers

The relationship between precipitation and water-table elevation trends is a result of the direct hydraulic connection of this aquifer to the land surface. The Wonewoc and Mt. Simon elevations (hydraulic head values) are lower than the water table indicating downward movement of water. Aquitards isolate these aquifers, limiting direct flow of groundwater from the surface downward to the Mt. Simon aquifer. During wet periods, pressure is likely exerted from the increased load from the overlying water-table aquifer. This is suggested by the isolated nature of the bedrock aquifers and the lack of lag time between precipitation peaks and elevation spikes. The affect has been noted in well nests from similar geologic settings across southern Minnesota (Berg and Pearson, 2013).

These natural water level trends are contrasted with aquifers that are affected by large-capacity pumping of groundwater (Figures 32 and 35). In the Lino Lakes and Centerville area of southeastern Anoka County, water level trends within the buried sand (QBAA), Jordan, and Mt. Simon aquifers follow the pumping patterns of the combined appropriation of 20 bedrock wells (Mt. Simon, Upper Tunnel City, St. Lawrence, Jordan, and Prairie du Chien).

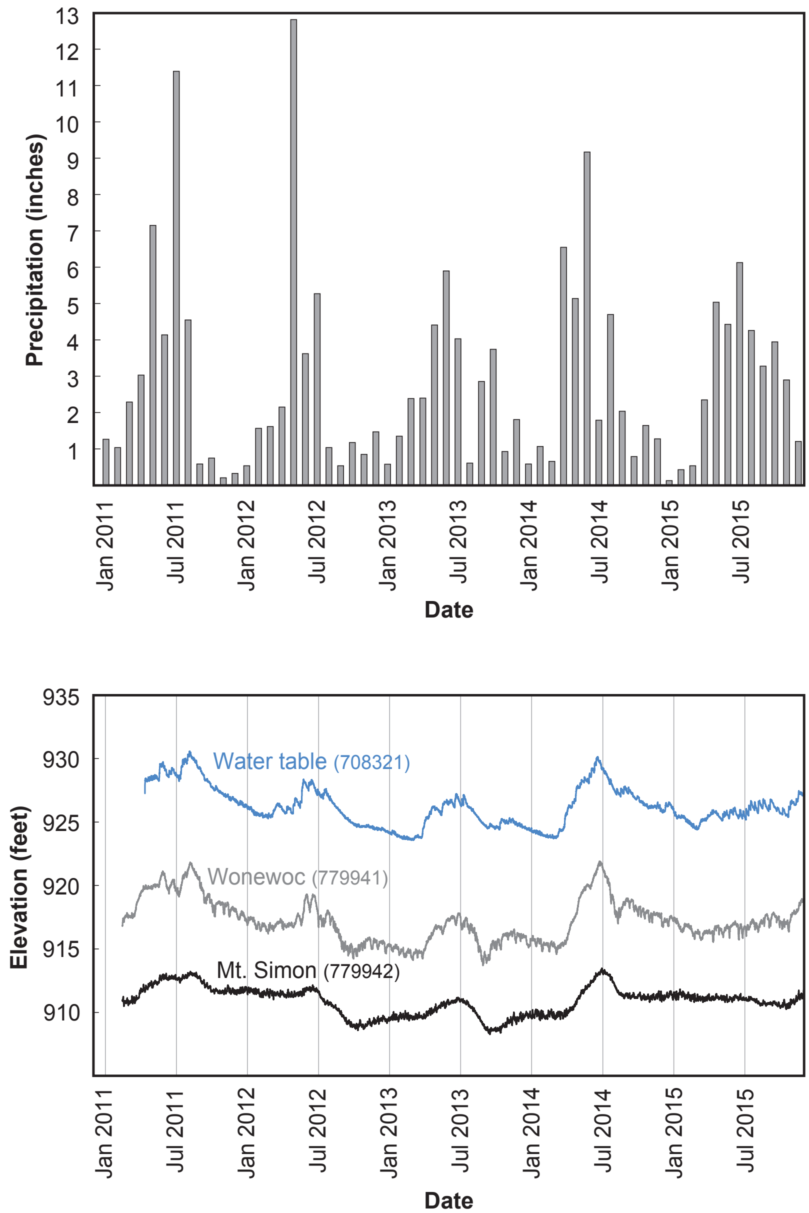


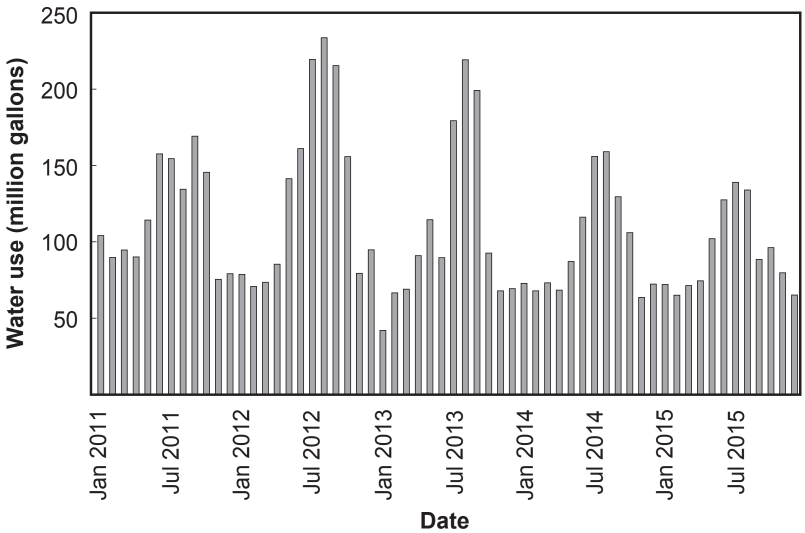
Figure 34. Pickerel Lake area

Top: Monthly precipitation

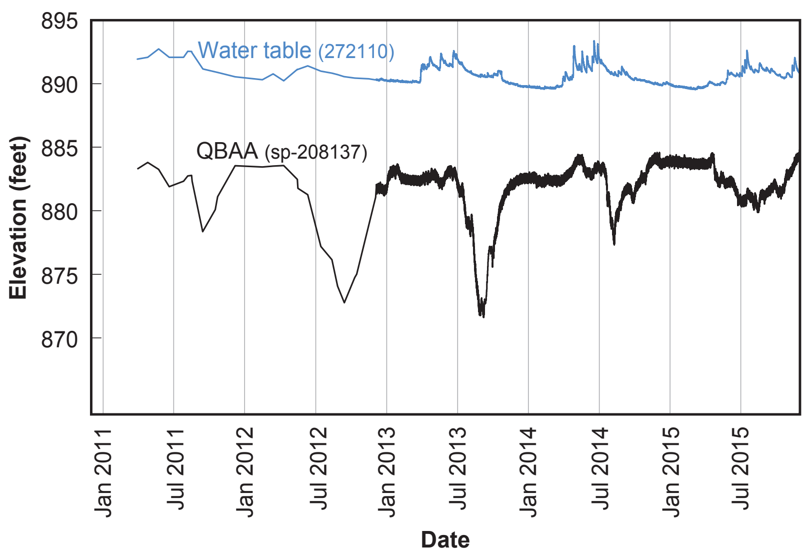
Bottom: Hydrograph of the water table, Wonewoc, and Mt. Simon aquifers showing seasonal fluctuation in a low groundwater-use area.

Figure 35. Lino Lakes and Centerville area

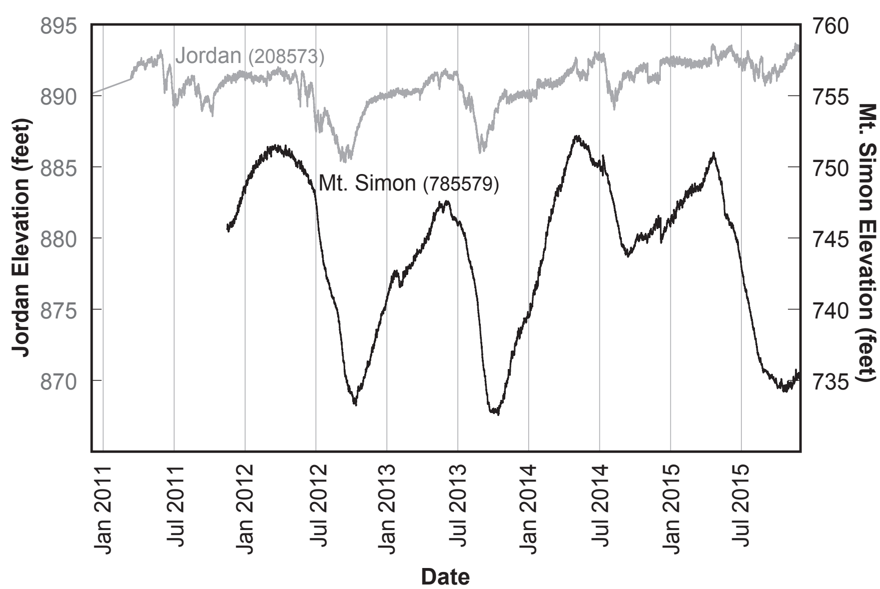
Seasonal high water use corresponds to periods of lower water elevations in all the buried aquifers.



Monthly groundwater use from 20 wells in the Lino Lake and Centerville area.



Hydrograph of the water table and sp (QBAA - buried sand) aquifers from the Centerville area.



Hydrograph of the Jordan and Mt. Simon aquifers in the Lino Lakes area.

Aquifer specific capacity and transmissivity

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

Specific capacity data were determined from short-term pumping or well-development tests performed after the well was drilled (Table 3). To ensure that the data reflect actual pumping, the pumping-test data for specific capacity were obtained from the County Well Index for wells with the following conditions:

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

The commonly used buried sand aquifers (mean specific capacity value of 31) and bedrock aquifers (mean specific capacity value of 25) had comparable mean values and a relatively large range of values.

Transmissivity data were calculated from longer-term and larger-scale aquifer tests that provide better information about the aquifer properties. Data from aquifer pumping tests are available from only two wells in buried sand aquifers. These very high values may not be representative of average conditions in the county (Table 3). The aquifer test data from a combined database kept by the DNR, MDH, and the U.S. Geological Survey (USGS) suggests that the combined Prairie du Chien and Jordan aquifers might have significantly higher transmissivity values than all the underlying aquifers. However, only one test from this aquifer group was available from Anoka County.

Table 3. 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 USGS tests compiled by the DNR; gpd/ft, gallons per day per foot, -- means no data, * means no tests available.

Aquifer (CWI Code)	Specific Capacity (gpm/ft)					Transmissivity (gpd/ft)		
	Casing Diameter (inches)	Mean	Min	Max	Number of Tests	Casing Diameter (inches)	Mean	Number of Tests
Unconsolidated units								
Surficial sand and gravel (QWTA)	12	25	--	--	1	*	--	--
Buried sand and gravel (QBAA)	12–30	31.4	4	83.3	13	12–20	226,000	2
Bedrock units								
Prairie du Chien–Jordan (OPCJ)	12–18	44	9	168	7	14	112,000	1
Jordan–St. Lawrence (CJSL)	24	33	--	--	1	*	--	--
Jordan–Mt. Simon (CJMS)	24	11	11	11	2	*	--	--
Wonewoc (CWOC)	18	15	--	--	1	*	--	--
Wonewoc–Mt. Simon (CWMS)	16–18	25	24	27	4	24	14,000	1
Tunnel City (CTCG)	14	35	--	--	1	14	10,000	1
Tunnel City–Wonewoc (CTCW)	12–24	31	8	138	17	18–24	35,000	3
Tunnel City–Eau Claire (CTCE)	12–18	22	8	44	4	16	22,000	1
Tunnel City–Mt. Simon (CTCM)	12–20	18	8	28	13	*	--	--
Eau Claire–Mt. Simon (CEMS)	12	17	--	--	1	*	--	--
Mt. Simon (CMTS)	12–24	21	13	31	11	14–18	22,000	6
Mt. Simon–Hinkley (CMSH)	18	19	--	--	1	*	--	--
Multiple (MTPL)	18	11	--	--	1	*	--	--

Summary and conclusions

Groundwater flow directions in the water-table aquifer are controlled by the dominant groundwater discharge locations, including the Rum River and its tributaries (northwest), the Mississippi River (southwest), and the St. Croix River (northeast). Another much broader topographic low and groundwater discharge feature is occupied by a trend of lakes and wetlands in the southeastern part of the county that extends from Circle Pines northeast to Howard Lake. Shallow water-table conditions (0–10 feet) are common in the county with the exception of the valley edges of the Rum River and Cedar Creek, terraces of the Mississippi River, and uplands in the northwestern portion of the county.

Potentiometric surface maps of buried aquifers show a general pattern of groundwater flow toward the Mississippi River valley in the western half of the county and flow toward the St. Croix River in the east and northeast portions. Local flow toward the larger rivers in the county such as the Rum River and Cedar Creek, and to a lesser extent Coon Creek, is evident on all the buried sand and upper bedrock potentiometric surface maps. Southerly flow toward the center of the Twin Cites structural basin is apparent on the Wonewoc and Mt. Simon potentiometric surface maps.

The chemical characteristics of groundwater revealed important information regarding groundwater source, human health risk, residence time, and pollution sensitivity implications.

- Three groundwater samples with evaporative signatures of oxygen and hydrogen stable isotopes were collected downgradient of Lake George, Coon Lake, and the Lake Fawn areas from shallow buried sand aquifers. These data are evidence of surface water to groundwater connections in these areas.
- Chloride is a significant contaminant in Anoka County groundwater samples, with 40 groundwater samples (34 percent) apparently from anthropogenic sources such as road and water softener salt. These elevated occurrences of chloride exhibit a relatively widespread distribution across the county. These data also indicate abundant pathways for surface water recharge to shallow buried sand aquifers.
- Nitrate was found in six groundwater samples (5 percent) with concentrations that exceeded an approximate background concentration of 1 ppm. Elevated nitrate concentrations were all detected in the western portion of the county.
- Arsenic was found in elevated concentrations (>10 ppb) in 10 groundwater samples (11 percent), with 7 of these from bedrock aquifers. While generally not common, elevated arsenic values from groundwater samples were most common from wells with some hydraulic connection to the St. Lawrence and Tunnel City Group aquitards and aquifers.
- Manganese concentrations that exceeded the lower MDH HRL established for infants (100 ppb) was found in a large proportion of groundwater samples (87 samples, 68 percent) indicating a natural water quality issue for the majority of well owners in the county.
- Carbon-14 residence time data from 23 wells within the county showed that ages in buried sand and upper bedrock aquifers ranged from 1,000 to 5,000 years. The deeper bedrock aquifer residence times range from 5,000 to >40,000 years.

We found a good correspondence between tritium age and pollution sensitivity, as follows:

- The sl buried sand aquifer overall is relatively sensitive to pollution (91 percent of aquifer area) with the exception of south-central and southeastern portions where sensitivity is commonly very low to moderate sensitivity. Most of the samples from this aquifer contained Cold War era, recent, or mixed tritium age. Elevated chloride detections tend to correspond to areas of moderate to very high sensitivity.
- The sc buried sand aquifer overall is relatively sensitive to pollution (low through very high rating areas, 65 percent of aquifer area). The majority of the groundwater samples from this aquifer contained mixed or recent tritium.
- The se buried sand aquifer has large areas that appear to be generally well protected and exhibit very low pollution sensitivity ratings (82 percent of aquifer area). Approximately a third of the groundwater samples that were analyzed for tritium contained mixed or recent tritium, after excluding values from high-capacity pumping wells and some older wells that might have leaky casings.
- The sx buried sand aquifer has large areas that appear to be generally well protected and exhibit very low pollution sensitivity ratings (97 percent of aquifer area). Only 3 of 34 groundwater samples contained mixed or recent tritium after excluding values from high-capacity pumping wells and some older wells that might have leaky casings.
- The sr and sp buried sand aquifers have large areas that appear to be generally well protected and exhibit very low pollution sensitivity ratings (97 percent and 99 percent of aquifer area, respectively). Mixed or recent tritium occurrences were rare and most of those detections may

be attributed to groundwater capture by high-capacity pumping of public wells (municipal and county facilities).

- The top of the bedrock surface appears to be generally well protected and exhibits very low pollution sensitivity ratings (98 percent of bedrock surface area). For groundwater samples collected from wells with shallower open-hole constructions only a few groundwater samples contained mixed or recent tritium, after values from high-capacity pumping wells and some older wells that might have leaky casings are excluded.

Most (89 percent) of the permitted water used in Anoka County is for water supply, which is mainly drawn from the bedrock aquifers and the buried sand aquifers. Pollution containment, noncrop and crop irrigation, and industrial processing are low percentage categories of water use. Most nonpermitted wells are completed in the buried sand aquifers (53 percent) followed by the sedimentary bedrock aquifers (38 percent), and are mostly used for domestic consumption.

The commonly used buried sand aquifers and bedrock aquifers had comparable specific capacity mean values (31 and 25 gpm/ft, respectively) and a relatively large range of values. Limited aquifer test results suggest that the combined Prairie du Chien and Jordan aquifers might have significantly higher transmissivity values than the underlying aquifers.

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Glossary

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

anthropogenic—of, relating to, or resulting from the influence of human beings 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 or shale, which prevent any rapid or significant movement of water.

arsenic—a chemical element with symbol As and atomic number 33. Arsenic occurs in many minerals. It is sometimes dissolved in groundwater and is toxic to humans. Natural arsenic contamination of groundwater is a problem that affects millions of people across the world, including over 100,000 people served by domestic wells in Minnesota.

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

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

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

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

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

deuterium (D or ^2H)—also known as heavy hydrogen, one of two stable isotopes of hydrogen.

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 in weakly acidic groundwater, but it can still develop solution features over time.

equipotential lines—lines of equal hydraulic potential.

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

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

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

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

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

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

hydraulic—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.

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

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

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

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

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 has not been 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 subglacial erosion and entrainment of rock and sediment over which the glacier has passed. It is no longer till if it has been modified or redeposited.

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

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

tritium unit (TU)—one tritium unit represents the presence of one tritium atom for every 10^{18} hydrogen atoms.

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

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

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

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

Appendix

Groundwater sampling methods

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 the following field parameters had stabilized: temperature, conductivity, dissolved oxygen, pH, and ORP. Each sample was filtered and preserved according to protocols listed below and submitted to laboratories for analysis.

Samples were analyzed by DNR staff, the University of Minnesota Department of Earth Sciences Laboratory (U of M), or the University of Waterloo Environmental Isotope Laboratory (Waterloo).

The well owners received a copy of the results including some background reference information regarding the meaning.

Field sample collection and handling details

Parameter	Enriched Tritium	^{18}O ^{2}H	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 HNO3	no	NH_4OH to pH 8.5
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	1 for every 20	1 for every 20	1 for every 20	1 for every 20	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 (use filtered water if sample is filtered). Rinsing means fill the bottle with sample water and then pour the contents out over the cap.

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

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

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

Technical Reference

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

Maps were prepared from publicly available information. Every reasonable effort has been made to ensure the accuracy of the factual data on which the report and map interpretations were based. However, the DNR does not warrant the accuracy, completeness, or any implied uses of these data. Users may wish to verify critical information; sources include both the references here and information on file in the offices of the Minnesota Geological Survey and the DNR. Every effort has been made to ensure the interpretations conform to sound geologic and cartographic principles. These maps should not be used to establish legal title, boundaries, or locations of improvements.

These bases were modified from Minnesota Geological Survey, Anoka County Geologic Atlas, Part A, 2013.

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

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