Groundwater Atlas of Isanti County, Minnesota

County Atlas Series C-44, Part B - Hydrogeology

Report

To accompany these atlas components:

Plate 7, Water Chemistry

Plate 8, Hydrogeologic Cross Sections

DEPARTMENT OF NATURAL RESOURCES

St. Paul 2025

mndnr.gov/groundwatermapping

The County Atlas Series

The Minnesota County Geologic Atlas (CGA) Series has been produced since 1982. Recent atlases come in two parts: Part A: Geology and Part B: Groundwater (this atlas). Before 2019, Part B was titled the "*Geologic* Atlas of X County - Hydrogeology." The title was changed to "*Groundwater* Atlas of X County" to better distinguish the content.

Part A - Geologic Atlas

The precursor to this atlas is the Geologic Atlas of Isanti County, Minnesota, C-44, Part A (Chandler and others, 2017), published by the Minnesota Geological Survey. It contains Plate 1, Data-Base Map (Pettus and Chandler); Plate 2, Bedrock Geology (Runkel); Plate 3, Surficial Geology (Hougardy and Meyer); Plate 4, Quaternary Stratigraphy (Meyer); Plate 5, Sand-Distribution Model (Meyer and Hamilton); and Plate 6, Bedrock Topography and Depth to Bedrock (Runkel).

Information is available on the Minnesota Geological Survey page (cse.umn.edu/mgs/county-geologic-atlas).

Part B - Groundwater Atlas

This atlas was published by the Minnesota Department of Natural Resources, expanding on the geologic information from Part A. Completed atlases, chemistry data, and more information are available through the Minnesota Department of Natural Resources, Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

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Acknowledgments

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Special thanks to all the well owners who graciously offered to let us collect water samples from their wells. Without their voluntary participation, this program could not achieve its goals.

Report Contents

Report Figures

Report Tables

Plates (accompanying folded inserts)

Technical reference

Maps were compiled and generated in a geographic information system. Digital data products are available from the Minnesota Department of Natural Resources Groundwater Atlas Program through the CGA page. (mndnr.gov/groundwatermapping).

Maps were prepared from Minnesota Department of Natural Resources and other publicly available information. Every reasonable effort has been made to ensure the accuracy of the data on which the report and map interpretations were based. However, the Minnesota Department of Natural Resources 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 Minnesota Department of Natural Resources. 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 titles, boundaries, or locations of improvements.

Base maps were modified from the *Minnesota Geological Survey, Geologic Atlas of Isanti County, Minnesota*, 2017. Universal Transverse Mercator projection, Zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion factors

1 inch per hour = 7.056×10^{-6} meter per second
1 part per million = 1 milligram per liter
1 part per billion = 1 microgram per liter
1 $foot^2$ per day = 7.48 gallons per day per foot

Groundwater Atlas of Isanti County, Minnesota

by Vanessa M. Baratta-Person, James A. Berg, and J. Wes Rutelonis

Executive summary

This report and the accompanying plates, produced by the Minnesota Department of Natural Resources (DNR), describe the county's groundwater characteristics. They build on the geology previously described in Part A by the Minnesota Geological Survey (MGS) (Chandler and others, 2017).

The atlas illustrates the hydrogeologic setting using maps, plates, figures, tables, and text. Principal products include groundwater flow maps, illustrations summarizing the results for select water chemistry constituents, aquifer pollution sensitivity maps, and geologic cross sections. This section highlights key elements and findings.

Physical setting and climate (pages 3 and 4) describes the location of the county, its average temperatures and precipitation, and lays the framework for how these influence groundwater recharge.

Isanti County is in east-central Minnesota, and its primary land use is a mixture of agriculture and small communities. It has a humid-continental climate with average temperatures of 68.4° Fahrenheit (°F) in the summer and 16.3°F in the winter. The average annual precipitation is approximately 31.7 inches.

Hydrogeology and groundwater flow (pages 5 to 17) describes the aquifers and aquitards and identifies their hydrostratigraphic characteristics and 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-surface elevation).

The county lies within three surface watersheds: the Rum River, Snake River, and Lower St. Croix River. The topography and surficial deposits of Isanti County are composed mainly of sands and tills. The areas with sand and gravel at the surface primarily represent the extent of glacial Lake Anoka and can be used as a water resource. Groundwater flow in these shallow sands and gravels generally follows the surface watersheds, with most groundwater flowing toward the Rum River, which flows throughout the county, and to the St. Croix River in the county's southeast corner.

Multiple glacial and bedrock aquifers lie under the surficial deposits. Water level elevations within the glacial aquifers show a similar groundwater flow pattern to the shallow sands and gravels; flow is generally toward the Rum, Snake, and St. Croix rivers. More deeply buried bedrock aquifers start displaying a general trend of groundwater flowing toward the southeast.

Water chemistry (pages 18 to 29, Plate 7) provides information about the following.

Groundwater recharge pathways: recharge from direct infiltration of precipitation is distinguished from recharge via surface water.

Groundwater is primarily recharged by direct infiltration of precipitation; however, evidence of recharge from surface water was found downgradient of some lakes.

Groundwater residence time: the time elapsed since water infiltrated the land surface to when it was sampled. It is estimated using tritium and carbon-14 analysis.

There is a high proportion of tritium detection (indicating shorter residence time) that reflects the relatively permeable nature of glacial sediment and bedrock. Groundwater with tritium ages reflecting recharge after 1953 was common in surficial sand, buried sand and gravel, and bedrock aquifers over 150 feet below the land surface in areas with sand at the surface and over 100 feet below areas with till at the surface. Carbon-14 residence times for a subset of samples ranged from 550 to 5,500 years.

Inorganic chemistry: Human (anthropogenic) sources are useful indicators for identifying where groundwater is being impacted by land use activities.

Chloride in groundwater is relatively widespread in the county and is mostly anthropogenic (human-caused). The highest concentrations were found near the cities of Cambridge and Isanti. Affected aquifers include shallow buried sand and gravel aquifers and multiple bedrock aquifers. Nitrate was not commonly found, likely due to limited row crop agriculture.

There are a variety of naturally occurring chemicals in water. Some can affect aesthetics, while others may pose a health concern.

Naturally sourced chloride, possibly from a deep bedrock brine source, was identified in a sample collected from a Mt. Simon–Hinckley well in central Isanti County. Arsenic was detected in over 85% of the well water samples. Eight of 104 samples exceeded the drinking water standard of 10 parts per billion (ppb). Manganese exceeded the health-based drinking water guideline of 100 ppb in approximately 85% of the samples and was found in most of the mapped sand and gravel and bedrock aquifers.

Pollution sensitivity (pages 30 to 45) is the time required for a contaminant to travel vertically from the land surface to the water table, a buried aquifer, or the bedrock surface. Two models are used to estimate it. Pollution sensitivity of the near-surface materials calculates travel time to the water table; pollution sensitivity of buried aquifers and the bedrock surface estimates travel time to a buried aquifer or the bedrock surface.

The pollution sensitivity of near-surface materials includes areas of high to moderate sensitivity across much of the county, with some low and very low sensitivity areas in the north and southwest. High and moderate sensitivity are associated with extensive sand and gravel deposits. Low and very low sensitivity are associated with loamy till deposits and lower-permeability soils.

The pollution sensitivity of buried sand and gravel aquifers ranges from very high to very low, depending on the thickness of the fine-grained sediment above the aquifer. Buried aquifers closest to the land surface have higher pollution sensitivity, as do deeper aquifers overlain by sand and gravel. Deep-buried sand and gravel aquifers overlain by fine-grained sediment are typically less sensitive to pollution. The pollution sensitivity of the bedrock surface is mostly very low, with scattered areas of very high to moderate pollution sensitivity in areas with overlapping sands above the bedrock surface.

Hydrogeologic cross sections (pages 46 and 47, Plate 8) illustrates the horizontal and vertical extent of aquifers and aquitards, the relative hydraulic conductivity of aquitards, general groundwater flow direction, groundwater residence time, and areas of groundwater recharge and discharge.

Aquifer characteristics and groundwater use (pages 48 to 58) summarizes specific capacity tests, aquifer tests, groundwater level monitoring data, and groundwater use records.

Domestic wells are the most common well type in the county and usually do not withdraw enough water to require a water use permit. The DNR requires water appropriation permits for wells that withdraw over 10,000 gallons per day or 1 million gallons per year.

Municipal water supply is the largest permitted user of groundwater, followed by irrigation. In 2022, these two categories made up about 92% of permitted groundwater use.

Physical setting and climate

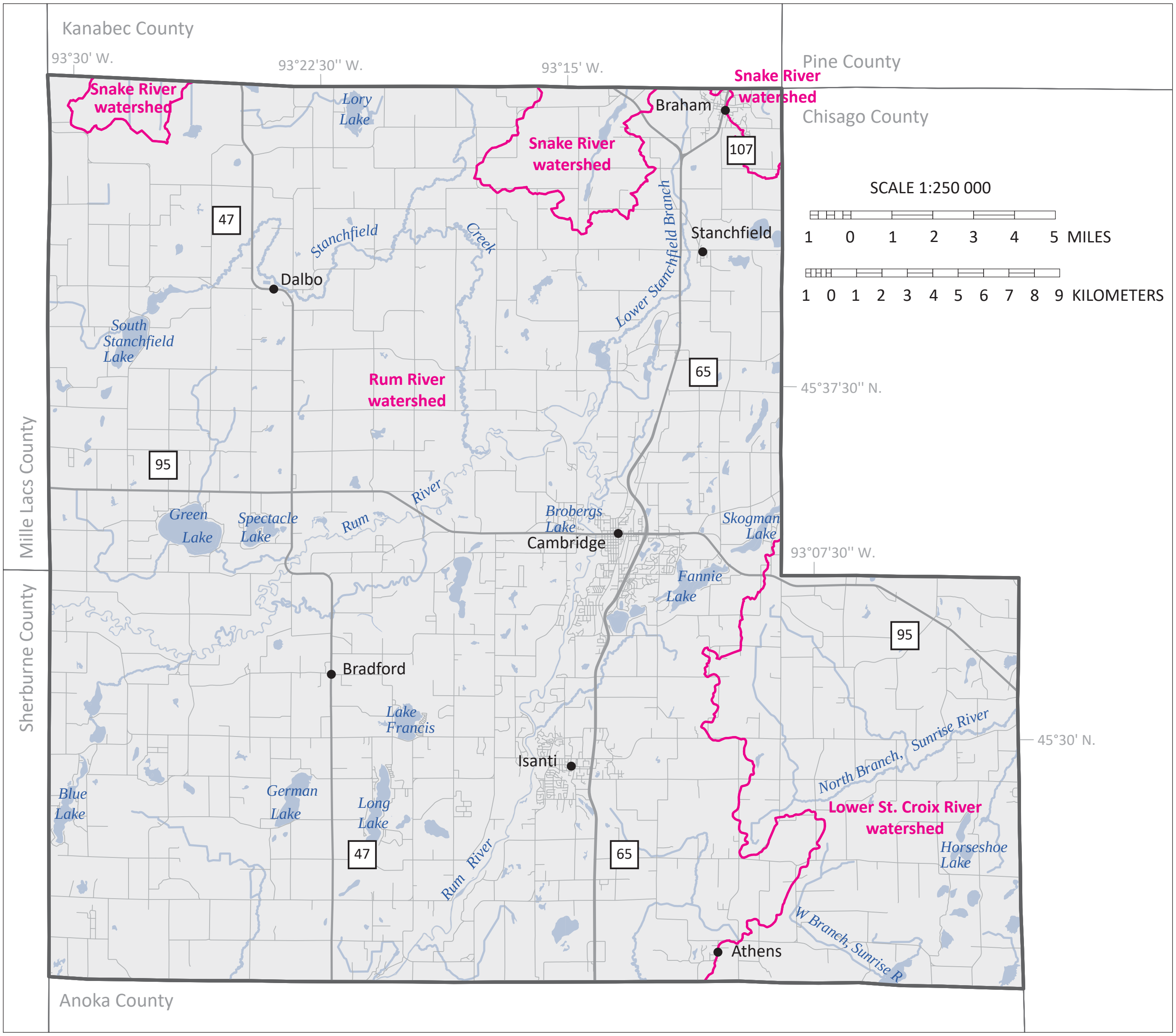
Minnesota is a headwaters state where surface water and groundwater are replenished solely by precipitation. Surface-water flow and groundwater levels vary with wet and dry years, and water levels may fluctuate rapidly in rivers and water-table aquifers following precipitation. It takes longer for water to travel to deeply buried aquifers, which often delays changes. Surface water leaves the state by a network of rivers that flow north to the Red River basin, east to the Great Lakes basin, southwest to the Missouri River basin, or southeast to the Mississippi River basin. Groundwater primarily provides baseflow to streams and major river systems.

Isanti County is in east-central Minnesota (Figure 1), with an estimated population of 41,135 in 2020 (U.S. Census Bureau, 2021). The county lies within portions of the Rum, Snake, and Lower St. Croix river watersheds, each of which ultimately drains into the Mississippi River basin. The primary land use is a mixture of agriculture and small communities.

Isanti County's climate is humid-continental, with warm to hot summers, cold winters, and an annual temperature range typically greater than 125°F. Based on 1991 to 2020 climate normals, the June-through-August average temperature is 68.4°F, with December through February averaging 16.3°F (DNR, 2023). Average annual precipitation is approximately 31.7 inches, placing Isanti County in the upper half of the statewide range of 21 to 38 inches (DNR, 2023). The region has pronounced wet and dry seasons, with precipitation during the summer nearly five times greater than during winter.

From 1895 through 2023, average annual temperatures increased by 3.1°F, which matches the statewide average temperature increase during the same period. The increases were fastest during winter, at night, and especially since 1970, when daily minimum temperatures have risen about 45% faster than daily maximum temperatures and average winter temperatures have risen four times faster than average summer temperatures. Annual precipitation has increased by 3.9 inches since 1895, and intense rainfall events producing daily totals exceeding 1, 2, and 3 inches were more common since 1990 than during any other period on record.

Climate projections summarized in the 2014, 2017, 2018, and 2023 National Climate Assessments, and others available for Minnesota, predict that Isanti County will warm by an additional 2.5 to 5°F by 2050, while annual precipitation could increase by 1 to 2 inches. Short-term variations are likely, leading to episodes of cooler conditions and drought, even as trends toward warmer and wetter conditions continue (Pryor and others, 2014; Vose and others, 2017; Easterling and others, 2017; Jay and others, 2018; Marvel and others, 2023; Wilson and others, 2023).



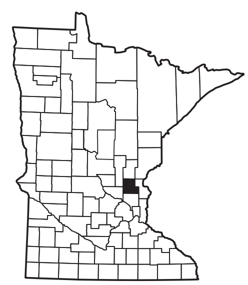


Figure 1. Isanti County, Minnesota

Hydrogeology and groundwater flow

Hydrogeology

Quaternary hydrostratigraphy

The Quaternary is the most recent geologic period, encompassing the last 2.6 million years, and hydrostratigraphy describes how different geologic layers affect groundwater flow. In Minnesota, sediment deposited during this timeframe includes glacial and postglacial deposits. A stratigraphic column (Figure 2) shows the vertical sequence of unconsolidated geologic units found in the county, with the oldest units on the bottom and the youngest on top. The hydrostratigraphic column (labeled Part B in Figure 2) shows these units as aquifers or aquitards based on their ability to transmit water.

Aquifers readily transmit water and are generally coarse-grained outwash sand and gravel deposits, where the saturated thickness yields sufficient water for the intended use.

Aquitards do not readily transmit water and generally fall into one of these textural categories.

1. A sediment mixture of sand, silt, clay, and gravel, referred to as till or diamicton.
2. Fine-grained silt and clay deposited in ice-walled lakes and depressions.

Surficial sand aquifers

The topography and surficial deposits of Isanti County are composed primarily of Late Wisconsinan Age sands and tills (Part A, Plate 3) from glacial advances and retreats. The sediment includes a wide range of grain sizes, textures, and distributions, which impacts their ability to transmit water (permeability) and influences the rate and amount of precipitation that can infiltrate the land surface and become groundwater. Areas of sand and gravel are likely locations of rapid infiltration (hours to days), while areas of clay or till infiltrate much slower (months to a year). For a more detailed examination of the glacial history and surficial geology, see Part A, Plate 3.

Most (62%) of the material at the surface of Isanti County is coarse-grained (sand and gravel), while the remainder (38%) is either fine-grained (silt and clay) or poorly sorted till (Figure 3). Areas with sand and gravel at the surface primarily represent the extent of glacial Lake Anoka and are part of the larger area known as the Anoka Sand Plain (Part A, Plate 3, Figure 3). Approximately 7% of the wells in the county are completed in surficial sand and gravel aquifers.

In this atlas, the ***surficial sand and gravel*** aquifers will be referred to as ***surficial sand*** aquifers.

Buried sand aquifers

Beneath the surficial geologic deposits are alternating layers of sand, gravel, and fine-grained material from earlier glacial advances. This atlas names the buried sand and gravel aquifers based on the underlying till unit described in the Part A atlas.

Meltwater from ice lobes deposited multiple sequences of sand and gravel through successive glacial advances and retreats. The buried sand and gravel bodies are confined by aquitards that were deposited as unsorted sediment directly by the ice (till) and bedded sediment of clay, silt, and fine-grained sand in ponds and lakes (Part A, Plate 5, Sand-Distribution Model–Introduction). These till units tend to be more laterally extensive than the buried sand and gravel layers. Approximately 67% of the wells in the county are completed in buried sand and gravel aquifers.

In this atlas, the ***buried sand and gravel*** aquifers will be referred to as ***buried sand*** aquifers.

Bedrock aquifers

Under the glacial deposits are a variety of saturated bedrock units (Figure 4 and Part A, Plate 2). The physical and mechanical properties of the rocks dictate whether they behave as aquifers or aquitards. The bedrock formations of Isanti County are part of regionally extensive, gently dipping layers of Paleozoic sandstone, shale, and siltstone that range from 30 to 200 feet in thickness (Part A, Plate 2, Figure 1). These sedimentary rocks were originally deposited in shallow marine settings during the Paleozoic Era (Part A, Plate 2). Portions of these bedrock layers endured periods of weathering while at or near the surface, which increased their ability to accommodate flow.

Paleozoic-aged formations are primarily sandstones and siltstones and include in descending order (youngest to oldest) the Jordan Sandstone, St. Lawrence Formation, Tunnel City Group (Mazomanie and Lone Rock formations), Wonewoc Sandstone, Eau Claire Formation, and Mt. Simon Sandstone. There are two tongues of the Mazomanie Formation (Upper Tunnel City aquifer) in the county, including an upper 40-to-50-foot layer and a lower 20-to-30-foot layer (Part A, Plate 2).

Under the Paleozoic bedrock is a thick sequence of Mesoproterozoic rocks (Figure 4 and Plate 8). They include the sandstone, siltstone, and shale of the Hinckley Sandstone and Fond du Lac Formation. Beneath them are older Paleoproterozoic units, composed mostly of basalt and other volcanic rocks that are not often used as a water resource due to their limited porosity and permeability. Limited subsurface data makes the distribution of these units less certain than the Paleozoic formations.

Approximately 26% of Isanti County's wells are completed in bedrock aquifers. Municipalities and commercial operations commonly use bedrock aquifers because of their thickness, extent, predictability, separation from the land surface, and hydrologic characteristics that typically allow for high water yields. In sandstone aquifers, water moves through intergranular pore spaces and larger macropores, such as fractures in the Jordan, Upper Tunnel City, Wonewoc, and Mt. Simon. In siltstone and shale aquitards, water does not move readily through the unit vertically, such as in the St. Lawrence, portions of the Tunnel City, and the Eau Claire. The Jordan Sandstone is present but not a significant water source; due to its limited extent, there are no wells completed in this aquifer in the county.

In the past, some high-volume wells were completed across multiple formations to increase yield. Typical combinations for multi-aquifer wells included the Upper Tunnel City and Wonewoc, the Mt. Simon and Hinckley, and the Mt. Simon through the Fond du Lac. Since 2008, the Minnesota Well Code prevents new wells from interconnecting aquifers separated by confining layers (Minnesota Administrative Rule, 4725.2020, Subpart 1).

In shallow bedrock conditions (less than 50 feet below the bedrock surface), fractures are more abundant, better connected, and larger compared to conditions of deeper burial (Barry and others, 2023; Runkel and others, 2018). However, using 50 feet to distinguish shallow and deep bedrock conditions is somewhat arbitrary as these changes are transitional and will vary across rock units and spatially throughout the county. While fracturing can increase an aquifer's ability to transmit water, it can also degrade an aquitard's ability to protect underlying aquifers. Fracturing typically decreases with depth below the bedrock surface.

Formation	Sediment type	Part A	Part B	Groundwater flow figure	Pollution sensitivity figure
	Surficial fine-grained sediment	sc	sc		
	Surficial sand and gravel	ss	ss	Figure 5	Figure 17
New Ulm Formation, Grantsburg sublobe	Loamy till	nt	nt		
Cromwell Formation, Automba phase	Sand and gravel	csa	csa		Figure 21
Cromwell Formation, Automba phase	Sandy till	cta	cta		
Cromwell Formation, St. Croix phase	Sand and gravel	csr	csr	Figure 7	Figure 22
Cromwell Formation, St. Croix phase	Sandy till	ctr	ctr		
Cromwell Formation, Emerald phase	Sand and gravel	cse	cse		Figure 23
Cromwell Formation, Emerald phase	Sandy till	cte	cte		
Henderson Formation	Sand and gravel	rs	rs		Figure 24
Henderson Formation	Sandy till	rt	rt		
Lake Henry Formation, Sauk Centre Member	Sand and gravel	scs	scs		Figure 25
Lake Henry Formation, Sauk Centre Member	Loamy till	sct	sct		
St. Francis Formation	Sand and gravel	fs1	fs1		
St. Francis Formation	Sandy till	ft1	ft1		
Lake Henry Formation, Meyer Lake Member	Sand and gravel	mls	mls	Figure 8	Figure 26
Lake Henry Formation, Meyer Lake Member	Sandy till	mlt	mlt		
St. Francis Formation	Sand and gravel	fs2	fs2		
St. Francis Formation	Sandy till	ft2	ft2		
Mulligan Formation	Sand and gravel	wrs	wrs		
Mulligan Formation	Sandy till	wrt	wrt*		
	Sand and gravel	uss	uss*		
	Undifferentiated sediment	ups	ups	-	-

* indicates unit is not shown on published cross sections.
Dash (-) indicates limited or no data.

Figure 2. Hydrostratigraphy of Quaternary unconsolidated sediment

This hydrostratigraphic column connects the unconsolidated geologic units from Part A, Plate 5, Figure 2, with the hydrogeologic units in Part B as follows:

- ***Sand and gravel*** units from Part A are ***aquifers*** in Part B, shown as ***patterns***.
- ***Till*** units from Part A are usually ***aquitards*** in Part B, shown in ***shades of gray***. The shades represent the relative hydraulic conductivity. Lighter shades are units with more sand, indicating a higher hydraulic conductivity. The shades of gray are based on the average sand content of the aquitard, determined from the matrix texture (the portion less than a 2-millimeter grain size).

Percent sand in aquitard

>60%
>50% and ≤60%
>40% and ≤50%
>30% and ≤40%
≤30%

- ***Undifferentiated sediment*** is shown as ***brown***.

The right columns show the grouping of mapped buried sands used to produce the potentiometric surface maps and pollution sensitivity maps.

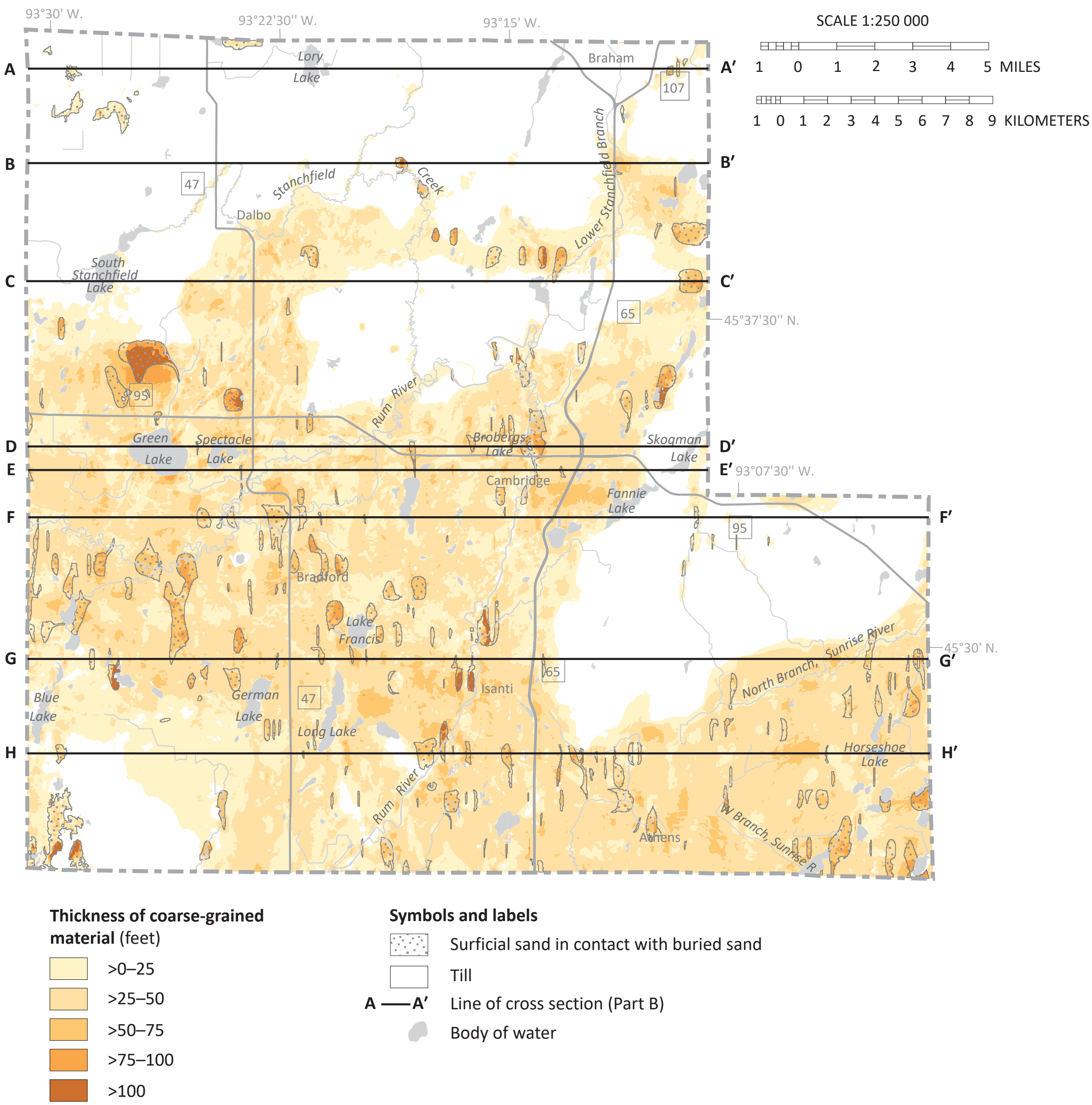


Figure 3. Simplified surficial geology with cumulative thickness of coarse-grained material

Coarse-grained material (sand and gravel) blankets most of Isanti County. In some places (dashed outlines), surficial sand is underlain by additional glacial sand layers (Wisconsinan Age) cumulatively up to 175 feet below the surface. The cumulative thickness of coarse materials was calculated by adding the individual thicknesses of vertically adjacent sand layers. White areas on the map are where till is present at the surface.

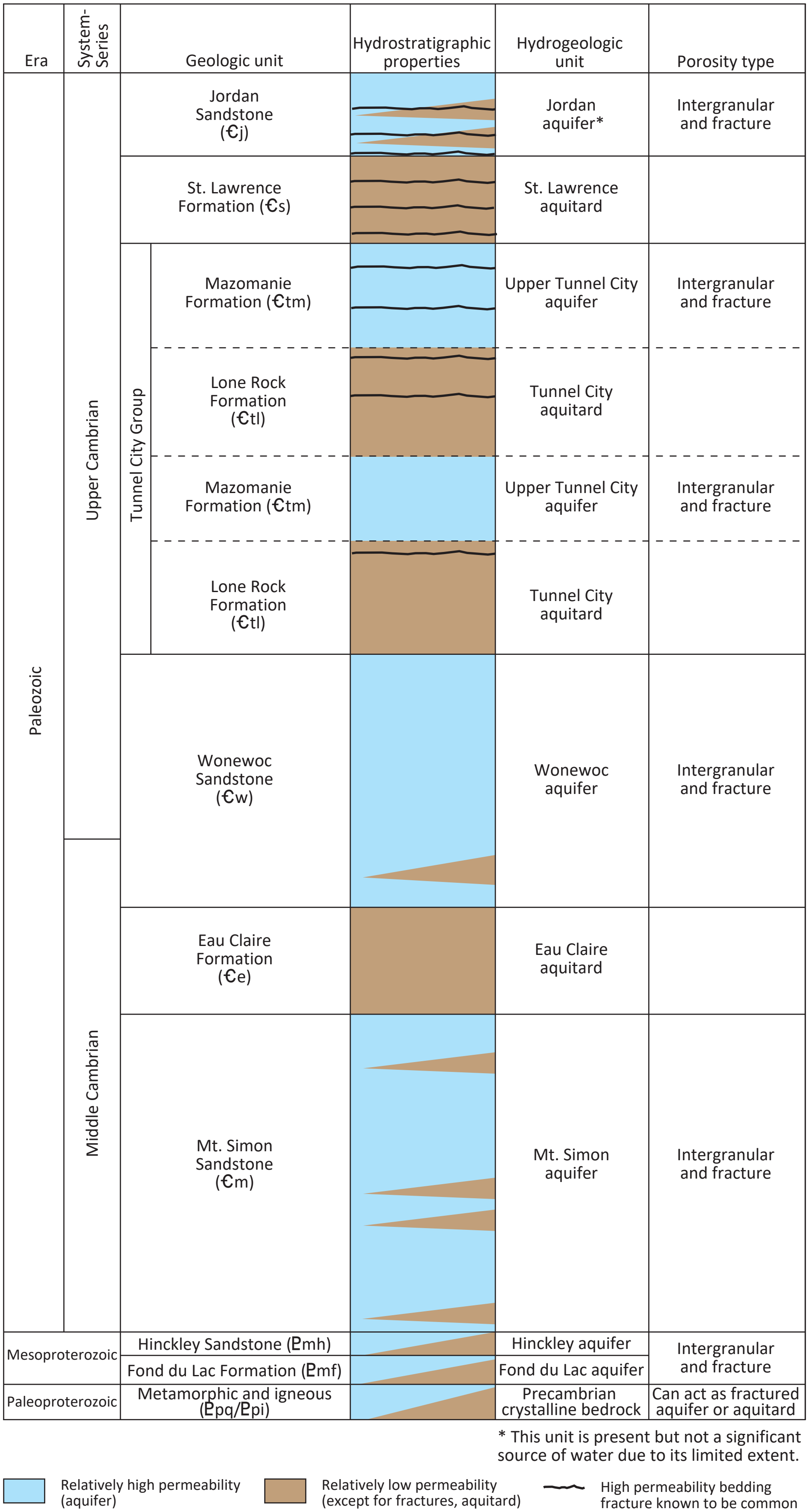


Figure 4. Bedrock stratigraphy and hydrostratigraphy

A generalized stratigraphic column portraying bedrock geologic units, hydrostratigraphy, and porosity type. Geologic stratigraphic units (formations or groups) do not always correspond to hydrogeologic units (aquifers and aquitards). Figure not to scale.

Groundwater flow

In this report, two map types illustrate groundwater flow.

1. The **water-table map** (Figure 5) shows shallow groundwater flow where it is unconfined and at equilibrium with atmospheric pressure. Groundwater flows from higher to lower elevations.
2. **Potentiometric surface maps** (Figures 7 to 10) describe groundwater flow for buried aquifers where it is confined and hydrostatic pressure exceeds atmospheric pressure. Groundwater flows from higher to lower pressure.

In both map types, groundwater elevations are contoured similarly to land-surface elevations on a topographic map.

Water table

The *water table* is the surface between the unsaturated and saturated zones, where water pressure equals atmospheric pressure. The water table occurs in both aquifer and aquitard sediment across the county. Surficial sand aquifers are present where there is sufficient saturated thickness and yield to install a well and pump water.

The **water-table elevation** is generally a subdued expression of the surface topography, with flow directions typically consistent with surface-water flow and watershed boundaries. Locally, the flow direction is from topographic highs to river tributaries, lakes, and wetlands.

While the maps can help guide many applications, site-specific information is needed at local scales. Although the water table is shown as a static surface, it is a dynamic system that varies in response to changes in recharge and discharge, including seasonal weather conditions, land-use practices, vegetation composition and distribution, and large groundwater withdrawals.

Water-table elevation was estimated from several sources of data.

- Elevation of surface-water bodies, like rivers, perennial streams, lakes, and open-water wetlands
- Static water levels in water-table wells obtained from the County Well Index (CWI) database*
- Estimates of depth to wet soil conditions from the Natural Resources Conservation Service (NRCS) county soil survey (2020)*

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

Depth to water table was determined by subtracting the water-table elevation from the land-surface elevation. More details can be found in *Methods for estimating water-table elevation and depth to water table* (DNR, 2016a).

Regionally, a large portion of groundwater in the surficial aquifer (water table) flows toward the Rum River. Exceptions include the southeastern part of the county, with flow toward the North and West branches of the Sunrise River, and small areas in the north that flow toward the Snake River. Locally, groundwater flows toward the tributaries of larger rivers (Stanchfield Creek and others) and to lakes and smaller water bodies (Figure 5).

Shallow water-table depths (0 to 20 feet) are common in the county (Figure 6). Most deeper water-table areas (greater than 30 feet) are in the east-central portion along the Rum River and the southwestern corner. Deeper water tables are typical of surficial sand areas with high topographic relief.

Potentiometric surface

Potentiometric surface maps show the general direction of groundwater flow in an aquifer. In confined aquifers, hydrostatic pressure is greater than atmospheric pressure, causing the water level in a well to rise above the top of an aquifer.

The potentiometric surface of an aquifer represents its potential energy to move groundwater. As groundwater moves from higher to lower potentiometric elevations, it flows perpendicular to the contours, depicted with arrows on the maps. At a local scale, high-volume pumping wells can draw groundwater toward the well screen or open hole and change groundwater flow direction.

Potentiometric surface maps were created using static water-level data from the CWI, measurements made by DNR staff, and LiDAR-derived surface elevation points along the major rivers and streams where a hydraulic connection with the aquifer being contoured is likely. The CWI records represent water levels collected under various climatic and seasonal conditions from 1950 to 2017 (MGS and MDH, 2018). This data variability creates some uncertainty in potentiometric surface elevations.

An evaluation of individual buried sand aquifers showed very similar groundwater flow direction patterns dominated by flow to the south toward the Rum River and to the southeast toward the St. Croix River. Therefore, only two maps of upper and lower groups of buried aquifers were created for simplicity and ease of use (Figures 7 and 8).

Potentiometric surface maps of the bedrock aquifers (Figures 9 and 10) show similar flow patterns toward the Rum River throughout most of the county, except for the southeast, where flow is to the southeast toward the St. Croix River.

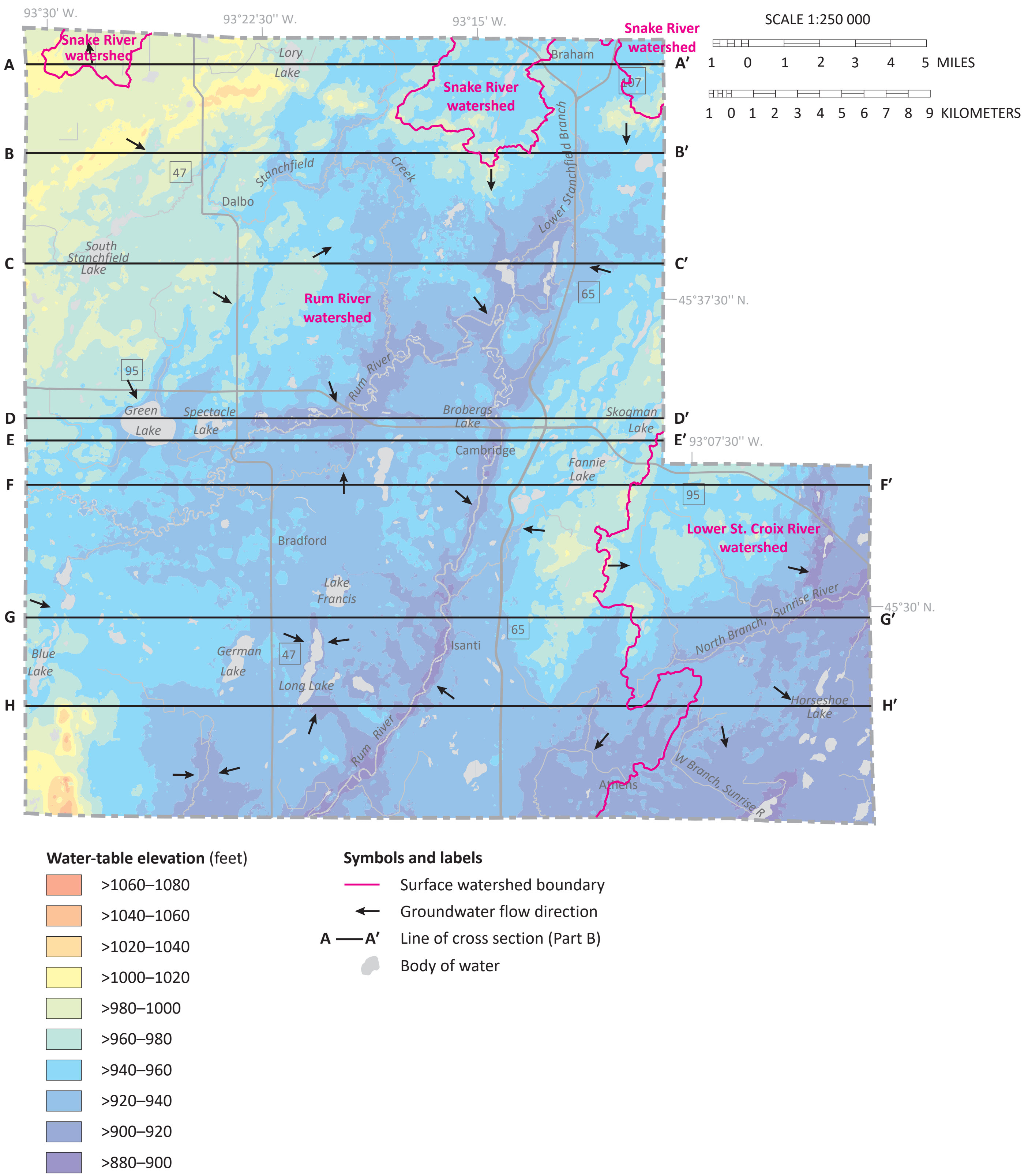


Figure 5. Water-table elevation and groundwater flow directions

A large portion of groundwater in the surficial aquifer (water table) flows toward the Rum River. Small areas in the north flow north toward the Snake River; in the county's southeastern corner, groundwater flows southeast toward streams that drain to the St. Croix River.

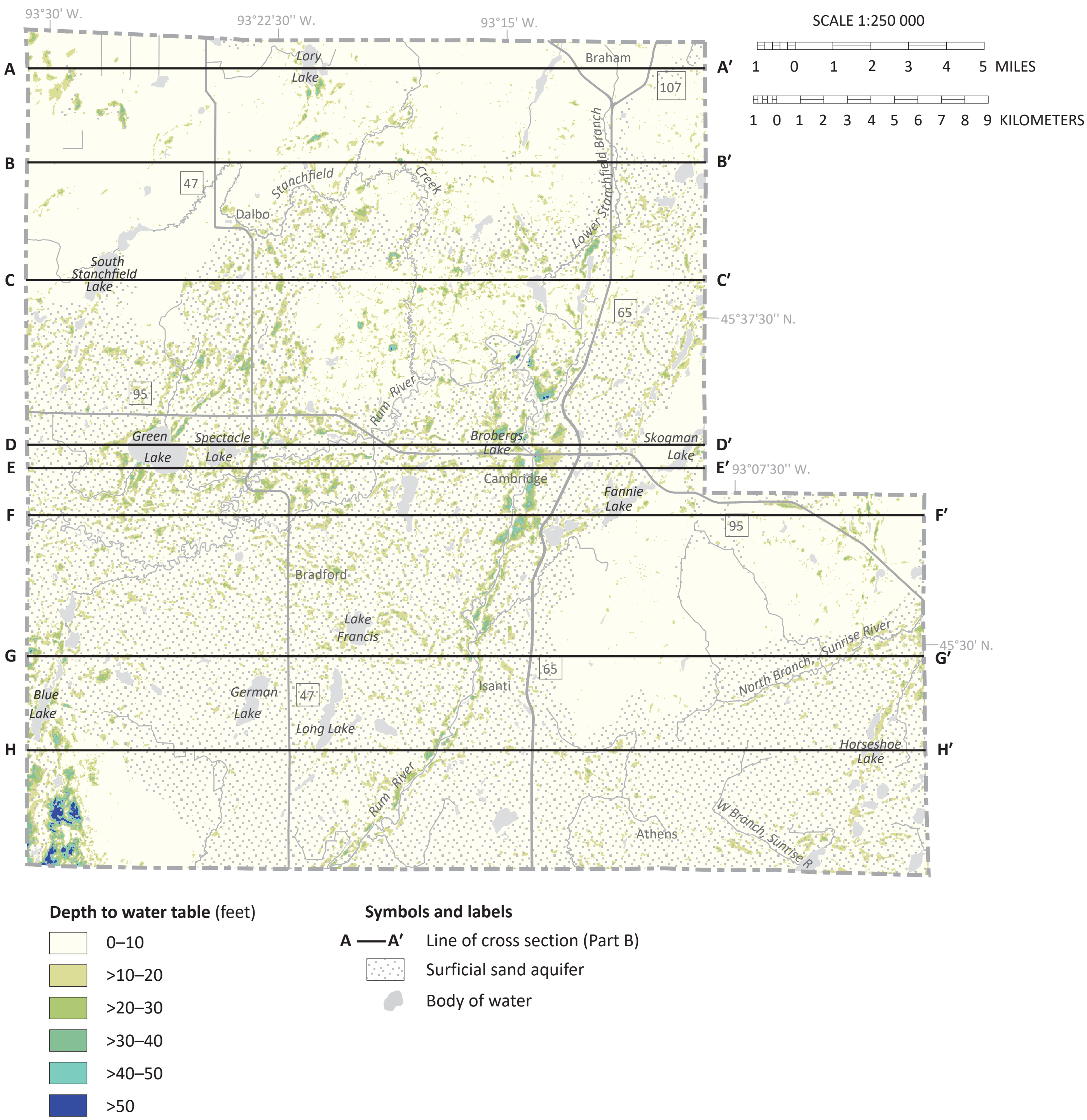
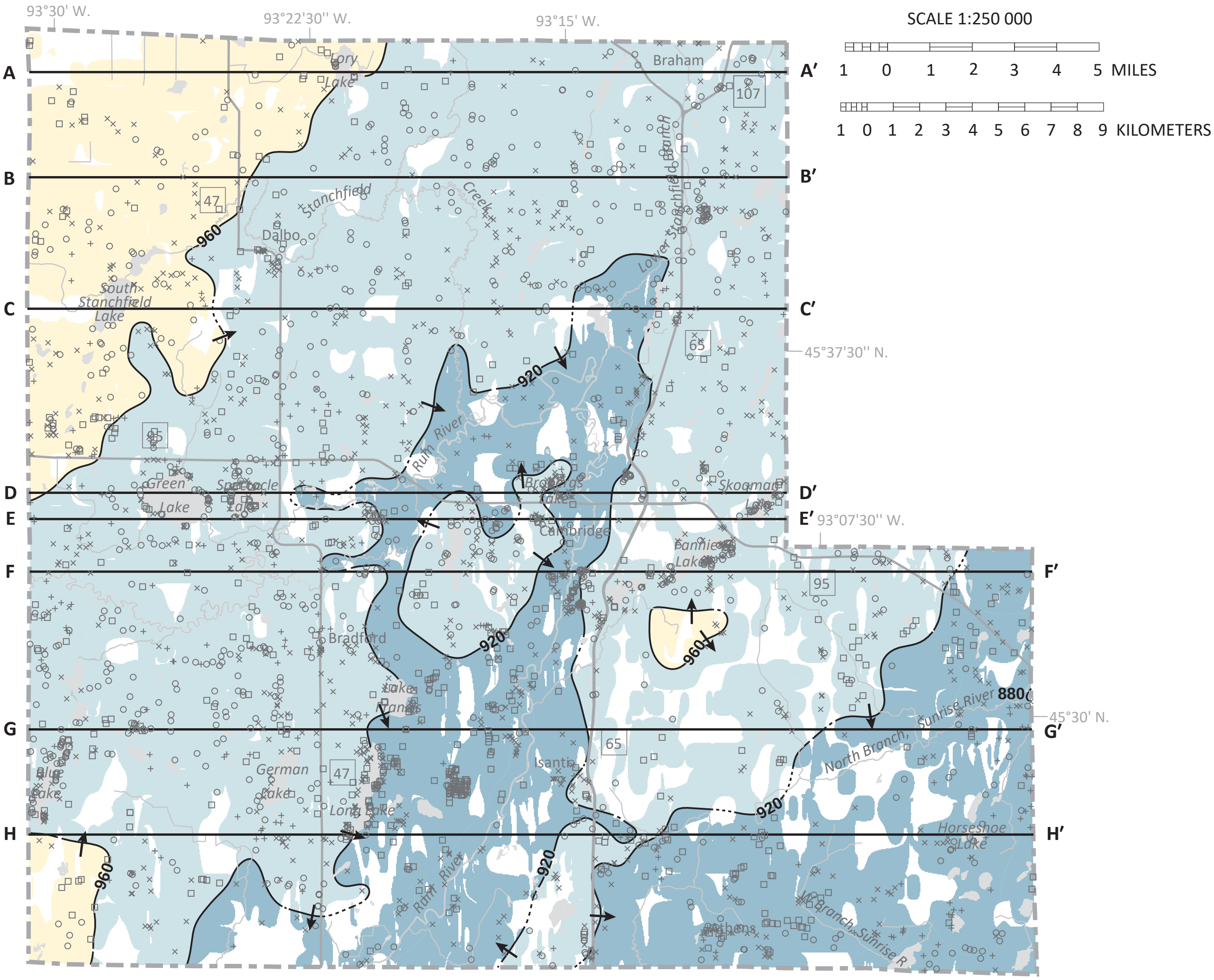


Figure 6. Depth to water table

Shallow water-table depths (0 to 20 feet) are common. Most of the deeper water-table areas (greater than 30 feet) are in the east-central portion, along the Rum River and the southwestern corner.



Potentiometric surface elevation (feet)

- >960–1000
- >920–960
- >880–920
- >840–880
- Aquifer not present

Static water level data

- csa
- csr
- cse
- rs

Symbols and labels

- Groundwater flow direction
- ····920— Potentiometric surface contour, dashed where approximate; contour interval 40 feet
- A —— A′ Line of cross section (Part B)
- Body of water

Figure 7. Potentiometric surface of the upper Quaternary buried sand aquifers

The upper group of Quaternary buried sand aquifers includes csa, csr, cse, and rs. Each is distributed countywide and is laterally extensive (Part A, Plate 5, Figures 5 through 8). Most flow in these aquifers is toward the Rum River, except for the southeast, where flow is generally toward the southeast.

Two areas show local flow divides (divergent flow). The Rum River has a sharp bend to the north in the Cambridge area, where the river changes direction from northeast to southwest. An area of divergent flow is on the inside of this bend. Another area of divergent flow is a groundwater divide east of Cambridge, where groundwater flows west toward the Rum River and southeast toward the North Branch of the Sunrise River.

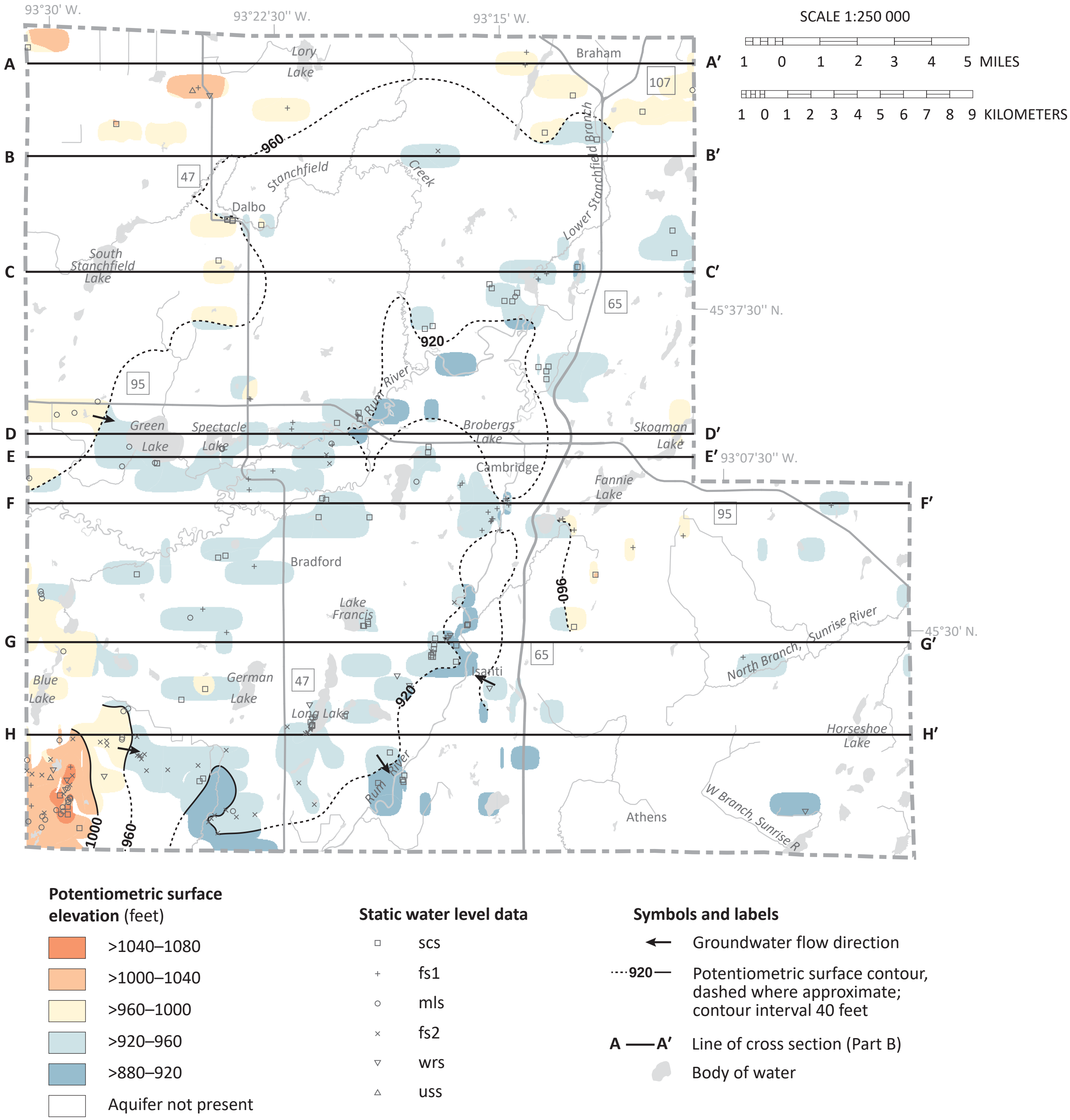


Figure 8. Potentiometric surface of the lower Quaternary buried sand aquifers

The lower group of Quaternary buried sand aquifers includes scs, fs1, mls, fs2, wrs, and uss. Their mapped extent is likely limited due to fewer wells completed in these deeper units, except for the southwestern part of the county. The general groundwater flow directions are similar to those of the overlying upper Quaternary aquifers, with the dominant flow pattern toward the Rum River. Flow direction in the southeastern corner of the county is less clear, as there are a limited number of wells completed in this area.

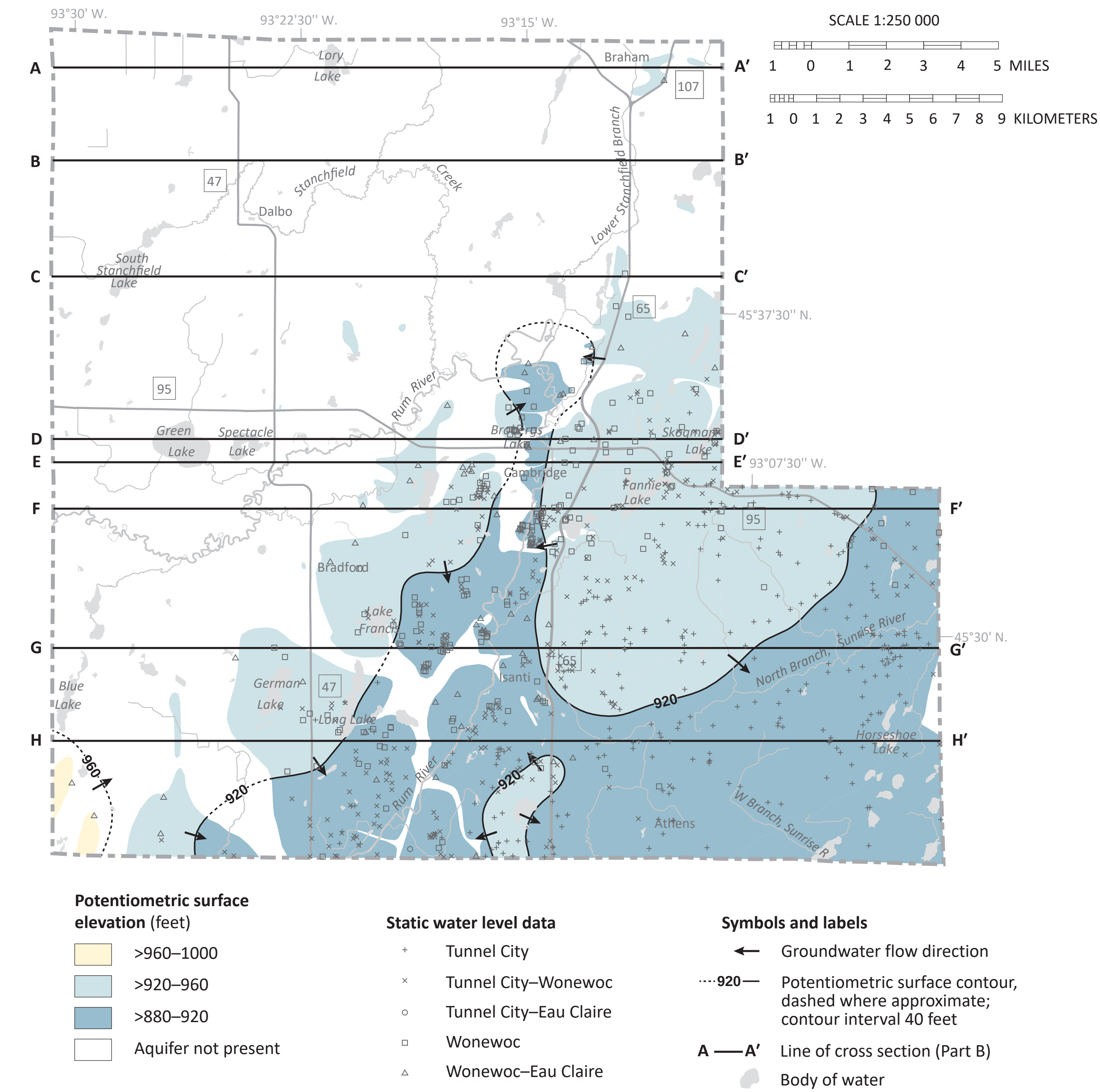
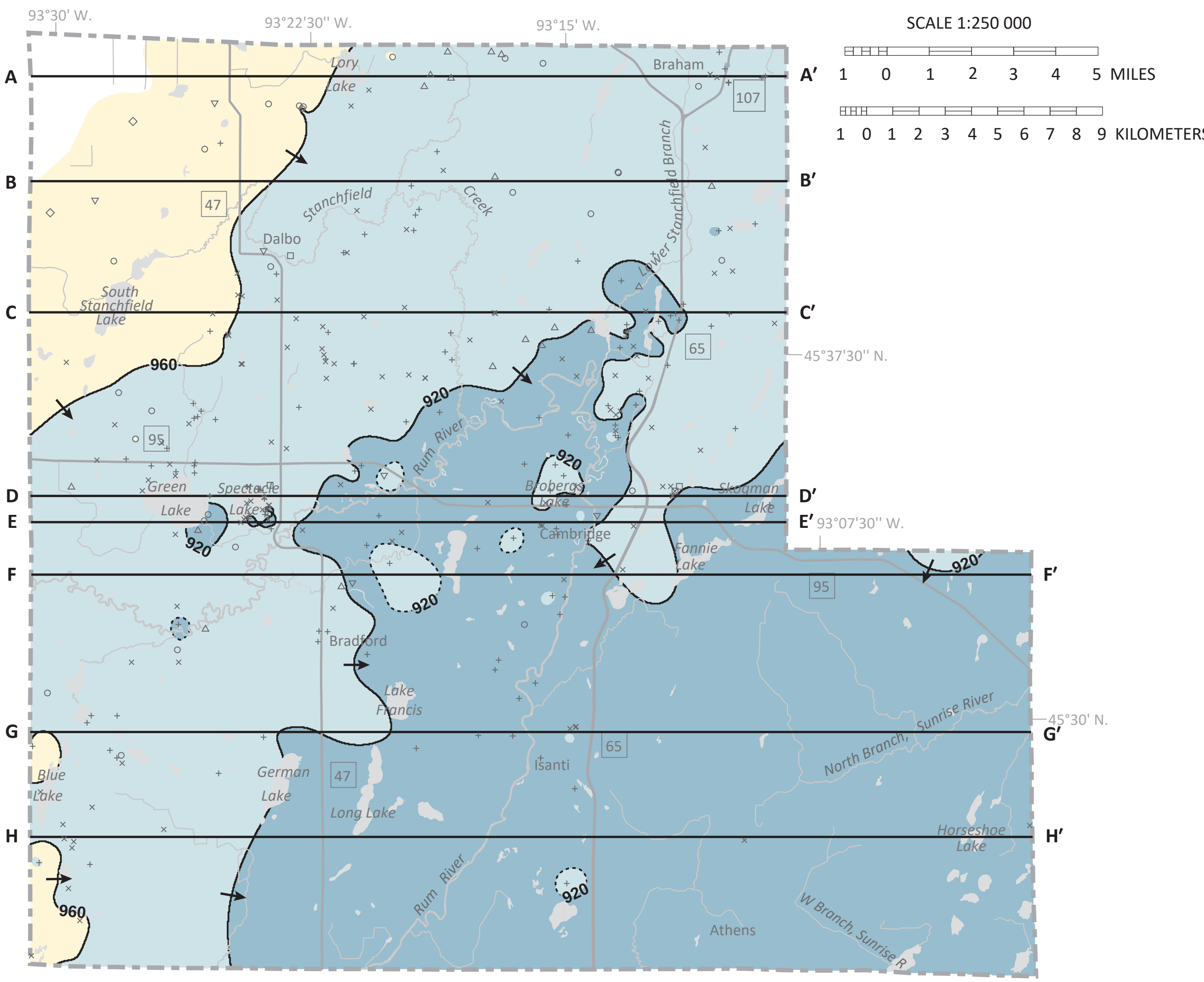


Figure 9. Potentiometric surface of the Upper Tunnel City and Wonewoc aquifers

The Upper Tunnel City and Wonewoc aquifers are present in the southern part of the county. Many wells are completed in both aquifers to gain maximum yield. This figure combines groundwater elevations from both aquifers as a single potentiometric surface. The dominant flow directions follow the pattern found in overlying aquifers, with flow toward the Rum River in the south-central part of the county and southeasterly toward the St. Croix River in the southeastern part.



Potentiometric surface elevation (feet)

- >960–1000
- >920–960
- >880–920
- Aquifer not present

Static water level data

- + Eau Claire–Mt. Simon
- × Mt. Simon
- ○ Mt. Simon–Hinckley
- □ Mt. Simon–Fond du Lac
- △ Hinckley
- ▽ Hinckley–Fond du Lac
- ◇ Fond du Lac

Symbols and labels

- ← Groundwater flow direction
- ····920— Potentiometric surface contour, dashed where approximate; contour interval 40 feet
- A —— A' Line of cross section (Part B)
- Body of water

Figure 10. Potentiometric surface of the Mt. Simon–Hinckley aquifer

Wells penetrate various depths into the Mt. Simon and Hinckley aquifers. No aquitards separate these formations, so it is considered the same aquifer. This combined aquifer is the deepest commonly used aquifer in the county, following similar flow patterns as the overlying groups of aquifers, with the dominant flow directions toward the Rum River in the south-central part of the county. Flow direction in the county's southeastern corner is hard to identify due to the limited number of wells finished in this unit within that area, but previous mapping suggests it is to the southeast toward the St. Croix River (Berg and Pearson, 2013).

Water chemistry (Plate 7)

Chemical constituents in groundwater can provide information about the source of groundwater recharge, the chemical evolution along groundwater flow paths, and approximately when the precipitation entered the ground (residence time). All groundwater originated as precipitation or surface water that infiltrated through soil layers into pores and crevices of aquifers and aquitards.

Water chemistry provides information about the following:

- **Groundwater recharge pathways**: direct infiltration of precipitation can be distinguished from recharge through surface water using stable isotopes.
- **Residence time**: time elapsed from when water entered the ground to when it was pumped from a well.
- **Chemical constituents of concern**: those that may pose a potential health risk.
- **Anthropogenic indicators**: chemicals that have been introduced by human activities.

Water sampling

Samples were collected from wells in aquifers used for domestic water supply. Wells were selected to get an even distribution across the county, include populated areas, and target surface-water and groundwater interaction around lakes and larger rivers. Groundwater samples were collected according to the protocols outlined in Appendix A. Approximately 1,000 well owners were contacted for permission to sample; the final sample network depended on their willingness to participate.

Water chemistry data for the Isanti County atlas included wells sampled by the DNR for this report and historical water samples incorporated into its interpretations. A total of 121 groundwater samples were used: 93 DNR-collected samples from 2010 and summer 2018, and 28 Minnesota Department of Health (MDH)-collected samples from 1989 to 2017. Additionally, 11 surface-water samples (1 MDH and 10 DNR) were included, with dates from 2007 and 2018.

Groundwater recharge pathways

Stable isotopes of oxygen and hydrogen are used to distinguish groundwater recharged by direct infiltration of precipitation at the land surface from groundwater recharged through lakes or open-water wetlands. Surface water that is open to the atmosphere can evaporate, which will change the isotopic composition through the process of *fractionation*.

Fractionation occurs because oxygen and hydrogen each have isotopes of different masses (^{18}O and ^{16}O, and ^{2}H and ^{1}H). This causes each isotope to evaporate at different rates, leaving the water with different ratios of heavy to light isotopes, resulting in unique isotopic signatures for groundwater with different recharge pathways (Kendall and Doctor, 2003).

- **Meteoric isotopic signature**: groundwater recharged from unevaporated precipitation. The water infiltrated directly into the ground, leaving the isotopic ratio unchanged.
- **Evaporative isotopic signature**: groundwater recharged through surface water, such as lakes or open-water wetlands. This water was subjected to fractionation by evaporation, resulting in lake water with a heavier isotopic ratio.

To identify the source of a groundwater sample, oxygen and hydrogen isotopic data are plotted against each other. 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. The standard used is Vienna Standard Mean Ocean Water (VSMOW).

Definition of delta (δ)

The stable isotope composition of oxygen and hydrogen are reported as δ values: $\boldsymbol{\delta\ (^0/_{00}) = (R_x / R_s - 1) * 1000}$.

- R represents the ratio of the heavy to light isotope, e.g., $^{18}O/^{16}O$ or $^{2}H/^{1}H$.
- R_x represents the ratio of the sample.
- R_s represents the ratio in the standard.

Delta values are reported in units of parts per thousand ($^0/_{00}$ or permil).

Results

Most of the groundwater samples plot along the global meteoric water line (GMWL) in the left portion of the stable isotope graph (Figure 11). This suggests these samples are sourced from precipitation (rain and snow melt) that infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies.

In Figure 11, the evaporation line was established by drawing a trendline using stable isotope values from 10 lakes sampled for this study (Figure 12). The Bloomgren Lake sample collected by MDH is shown but was not used to develop this trendline.

The degree of evaporation, and thus fractionation, is primarily related to the residence time of water in the lake. With longer residence time, lake water is subject to greater evaporation, leading to greater fractionation and a distinct trendline.

There are seven groundwater samples that plot along the evaporation line. Groundwater samples that plot along the evaporation line have lake water as a portion of their recharge. Each sample's position is based on the initial $\delta^{18}O$ value of the lake source and the proportion of lake water and precipitation that recharged the aquifer. Wells with $\delta^{18}O$ values greater than -7.27 (plotting to the right of) have an evaporative signature. As samples plot closer to the GMWL it becomes increasingly difficult to distinguish those that receive a portion of their recharge from a lake source.

Watershed to lake area ratio is a screening tool that can indicate the relative importance of groundwater flow to the water balance of a lake. Lakes with small watershed to lake area ratios typically have significant groundwater input, longer lake water residence times, and more fractionation. Lakes with large watershed to lake area ratios generally have surface-water inflows, shorter lake water residence times, and less fractionation.

Lakes with watershed to lake area ratios greater than 10 are likely surface-water dominated. Lakes with ratios between 5 and 10 may be groundwater dominated, especially if the sediment around the lake is predominantly sandy. Lakes with ratios less than 5 are very likely groundwater dominated, either through relatively large groundwater inflow, outflow, or both. If the sediment surrounding the lake is clayey, there may be little interaction between the lake water and groundwater (DNR, 2025).

German and Spectacle lakes have small watershed to lake area ratios (6 and 3, respectively) with longer residence times and more fractionation, indicating that they are likely groundwater dominated. Blue and Green lakes have larger ratios (23 and 19, respectively) with shorter residence times and less fractionation, indicating they are likely surface-water dominated.

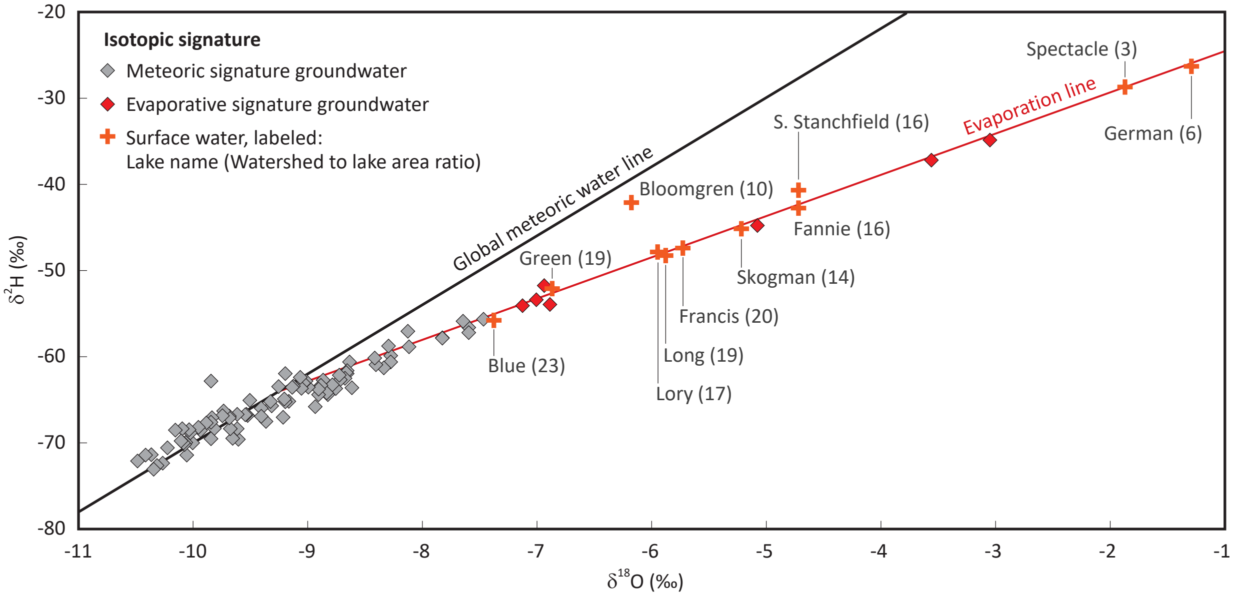


Figure 11. Stable isotope values from water samples

The **meteoric water line** represents the isotopic composition of precipitation. Groundwater that plots on the meteoric water line indicates recharge of directly infiltrated precipitation. The **GMWL** was developed using precipitation samples from around the world and is described by the following equation: $\delta^2H = 8.0\ \delta^{18}O + 10.0$ (Craig, 1961).

The **evaporation line** represents the isotopic composition of surface water fractionated by evaporation. Groundwater that plots on the evaporation line indicates recharge through surface water. The local evaporation line is described by the equation $\delta^2H = 4.8\ \delta^{18}O - 19.8$, calculated from surface-water samples collected for this study. The farther to the right on the line that the sample falls, the farther its distance from the GMWL, indicating a larger evaporative component.

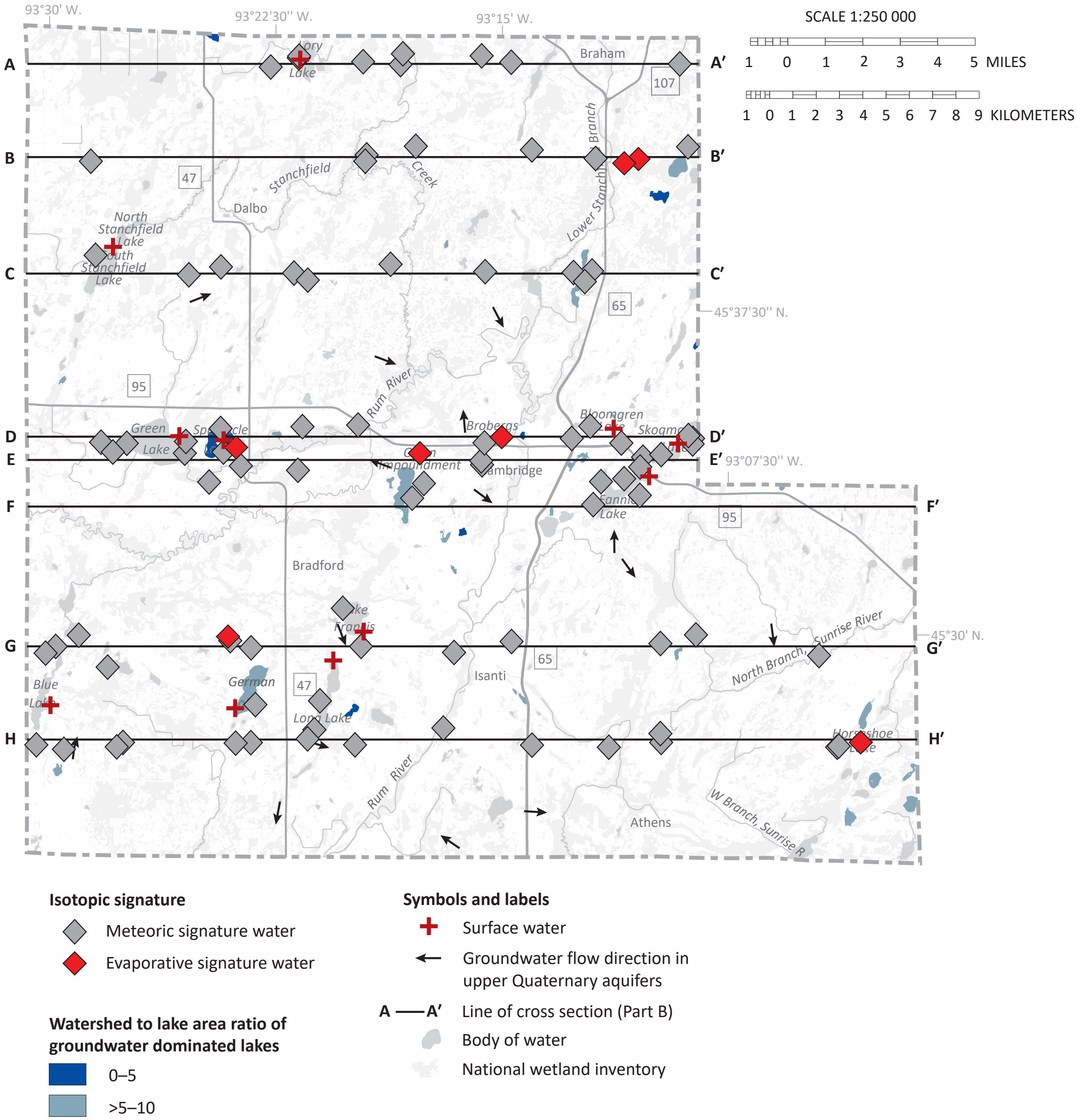


Figure 12. Stable isotope characteristics of groundwater samples

Groundwater that is partially sourced from lakes and other surface-water features is present in the county. Seven groundwater samples exhibited evaporative signatures that demonstrate some recharge from surface-water sources.

Groundwater residence time

Groundwater residence time is the approximate time elapsed since water infiltrated the land surface to when it was pumped from a well or discharged to a lake, river, wetland, or spring. Short residence time generally suggests short travel paths or high recharge rates; long residence time suggests long travel paths or low recharge rates. The residence time of groundwater was estimated using analysis of two radioactive isotopes: tritium and carbon-14.

Tritium

Tritium concentration helps estimate groundwater residence time from before the 1950s to today. Although tritium is a naturally occurring isotope of hydrogen, atmospheric concentrations greatly increased from atmospheric testing of nuclear weapons between 1953 and 1963 (Alexander and Alexander, 1989). Tritium has a half-life of 12.32 years (Lucas and Unterweger, 2000).

Groundwater residence time was estimated using the location and tritium concentration of the sample and the history of tritium deposition from precipitation at that general location. A complete description of the tritium-age method is in the procedures document *Tritium age classification: revised method for Minnesota* (DNR and MDH, 2020).

- **Modern**: water entered the ground after 1953.
- **Mixed**: water is a mixture of modern and premodern.
- **Mostly premodern**: water entered the ground before 1953 but may contain a small amount of modern water.
- **Premodern**: water entered the ground before 1953.

For hydrogeologic interpretation, ***premodern*** includes ***mostly premodern***.

Data shown on figures and plates uses both ***premodern*** and ***mostly premodern***.

Tritium was analyzed in 116 wells and 2 surface water samples to assist in residence time interpretations. Of the 118 samples analyzed for tritium, 57 were premodern, 25 were mixed, and 36 were modern tritium age. More details by aquifer are found in the pollution sensitivity results section and on Plate 7, Water Chemistry.

Carbon-14

Selected wells with premodern tritium-age results were further sampled for carbon-14 (^{14}C) to estimate longer residence times: less than 100 to greater than 40,000 years. This naturally occurring isotope has a half-life of 5,730 years. Carbon-14 sample collection, analysis, and modeling are described in Alexander and Alexander, 2018.

When precipitation infiltrates the unsaturated zone, it absorbs carbon dioxide, including carbon-14, from biospheric soil gases, forming carbonic acid. This mildly acidic water dissolves calcite and dolomite in the soil or bedrock. Plant communities present at the time of infiltration determine soil $\delta^{13}C$ ratios used within the model to estimate the groundwater residence time. Approximately half of the dissolved carbon in the groundwater comes from atmospheric carbon in the soil zone during infiltration, and half comes from very old bedrock sources, where carbon-14 has decayed completely.

Carbon-14 was analyzed from samples collected at 16 wells, 10 collected for this study and 6 from previous studies. Three samples from buried sand aquifers had residence times between 550 and 1,900 years, 1 sample from a Tunnel City–Wonewoc well had a residence time of 800 years, and 12 samples from Mt. Simon and Mt. Simon–Hinckley had residence times ranging from 950 to 5,500 years. Further details on carbon-14 residence times are found by aquifer in the pollution sensitivity results section and on Plate 7, Water Chemistry.

Inorganic chemistry of groundwater

Water begins dissolving minerals in the soil, sediment, and bedrock as soon as precipitation infiltrates the soil layer. Groundwater chemistry changes as water moves along the flow paths.

Groundwater naturally contains some contaminants. The Safe Drinking Water Act defines contaminant as any physical, chemical, biological, or radiological substance or matter in water (SDWA, et seq., 1974). The presence of contaminants does not necessarily indicate that the water poses a health risk. Some contaminants may be harmful if consumed above specific levels in drinking water, while others may negatively affect the aesthetics of water, such as taste or color.

Groundwater contaminants can be anthropogenic or from the dissolution of naturally occurring geologic material. For a select group of dissolved contaminants, this atlas uses the following guidelines.

Drinking Water Guidelines

U.S. Environmental Protection Agency
(EPA, 2023 January; EPA, 2023 February)

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

Maximum Contaminant Level Goal (MCLG): nonenforceable health goals set on possible health risks from exposure over a lifetime.

Secondary Maximum Contaminant Level (SMCL): nonenforceable guidelines for contaminants that can cause aesthetic effects or taste and odor problems in drinking water.

Minnesota Department of Health (MDH, 2023)

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

Health Based Value (HBV): derived using the same algorithm as HRLs; however, they have not yet been promulgated as rules.

Risk Assessment Advice (RAA): technical guidance concerning exposures and risks to human health. RAA values contain more uncertainty than HRLs.

Chemical descriptions and results

This section describes inorganic groundwater constituents and compares sample results to drinking water guidelines. Major cations and anions are reported in units of parts per million (ppm). Trace elements are reported in parts per billion (ppb).

Chloride

SMCL 250 ppm

Chloride can occur naturally from deep sources, such as brine, or be from anthropogenic sources, like road salt, water softener salt, or fertilizer (Panno and others, 2006). Concentrations above the SMCL can cause a salty taste in drinking water.

Samples at or above 5 ppm chloride are assigned an anthropogenic or natural source using the following conditions (Davis and others, 1998).

- Anthropogenic if the chloride/bromide ratio is greater than or equal to 300.
- Natural if the chloride/bromide ratio is less than 300.

Sampling results

Of the 109 wells sampled and analyzed for chloride, 29 had elevated chloride, and 28 were from anthropogenic sources (Figure 13). None of the samples exceeded the SMCL. Anthropogenic chloride in groundwater is found throughout the county and is pronounced in the Cambridge area. Chloride concentrations are often highest in shallow wells in areas of dense roads (Sander and others, 2008). The majority of affected aquifers are shallow buried sand aquifers (cse, csr, and rs) and bedrock aquifers near the bedrock surface (such as the Upper Tunnel City, Wonewoc, and Mt. Simon–Hinckley aquifers).

All elevated chloride samples likely had anthropogenic sources, except for a sample collected from a well completed in the Mt. Simon–Hinckley aquifer located east of Green Lake in the western part of the county, likely caused by a deep source of brine.

Nitrate-nitrogen (nitrate)

MCL and HRL 10 ppm

Nitrate can occur naturally, but concentrations greater than 1 ppm can indicate anthropogenic impacts from fertilizer or animal and human waste (MDH, 1998; Wilson, 2012). Nitrate concentrations may lessen with time (denitrification) when there is little oxygen in the groundwater. In Minnesota, groundwater with long residence time typically has little available oxygen and little to no nitrate.

Nitrate concentrations are classified as follows.

- Anthropogenic if greater than 1 ppm.
- Natural if less or equal to 1 ppm.

Sampling results

Of the 112 well samples analyzed for nitrate, 5 had elevated concentrations indicative of anthropogenic sources (Plate 7). Anthropogenic samples were from 1 surficial sand aquifer well, 3 buried sand aquifer wells (cse, csr, and rs), and 1 Mt. Simon aquifer well. Four of the five samples were collected from wells near or downgradient of cultivated crops. None were above the MCL (10 ppm).

Arsenic

MCL 10 ppb; MCLG 0

Arsenic is a naturally occurring element linked to negative health effects, including cancer. If arsenic is present, the MDH advises domestic well owners to treat drinking water (MDH, 2019). Current science cannot predict which wells will have high arsenic concentrations; therefore, water from all newly constructed drinking-water wells is tested for arsenic per Minnesota Administrative Rule 4725.5650 (Minnesota Legislature, 2008).

The factors affecting arsenic concentrations in groundwater are not completely understood. There is a strong correlation between arsenic in groundwater and glacial sediment derived from rocks northwest of Minnesota (Erickson and Barnes, 2005a).

The Riding Mountain provenance tills (New Ulm Formation) in Isanti County have a higher average relative percentage of shale than the tills associated with other glacial advances, pointing to these tills as a possible arsenic reservoir (Part A, Plate 3, Figure 4).

Research also indicates that arsenic concentrations are higher in wells with short-screened sections near the boundary of an aquifer and aquitard (Erickson and Barnes, 2005b; Erickson and others, 2018).

Sampling results

Of the 104 well samples analyzed for arsenic, 90 exceeded the reporting limits, and 8 exceeded the MCL (10 ppb). The majority of elevated arsenic samples were collected from buried sand aquifers. However, 29 samples from bedrock aquifers had elevated arsenic levels, likely from recharge through overlying New Ulm Formation tills. Those at or above the MCL were from scattered locations across the county (Figure 14).

Manganese

HBV 100 ppb; SMCL 50 ppb

Manganese is a naturally occurring element beneficial to humans at low levels, but at high levels can harm the nervous system (MDH, 2021). In addition to health effects, concentrations above the SMCL can have negative secondary effects, such as poor taste, odor, and water discoloration (stained laundry and plumbing fixtures).

Statewide, manganese concentrations were greater than the HBV in drinking-water wells for 57% of water-table aquifers and 63% of buried sand aquifers sampled (MDH, 2012). Although there are no clear patterns of manganese distribution across most of Minnesota, the MDH has found that southeastern Minnesota tends to have low levels of manganese (below 50 ppb), and southwestern Minnesota tends to have higher levels (some over 1,000 ppb).

Sampling results

Of the 101 well samples analyzed for manganese, 86 were greater than or equal to the HBV (100 ppb). The values above the HBV ranged from 102 to 1,180 ppb and were found throughout the county. Elevated levels were found in most of the mapped buried sand aquifers and all the bedrock aquifers (Plate 7).

Boron

RAA 500 ppb

Boron is a naturally occurring element linked to negative health effects. The MDH developed the RAA for boron in drinking water at 500 ppb to protect formula-fed infants (MDH, 2017).

Sampling results

Of the 93 well samples analyzed for boron, none were greater than the RAA of 500 ppb.

Sulfate

SMCL 250 ppm

Sulfate is largely naturally occurring and produced from the oxidation of sulfide minerals and dissolution of gypsum. Minor amounts are introduced from the burning of fossil fuels (Crawford and Lee, 2015). High concentrations in groundwater can negatively affect taste and act as a laxative.

Sampling results

Of the 105 well samples analyzed for sulfate, none were greater than the MCL of 250 ppm.

Calcium, Magnesium, Sodium, Potassium, and Bicarbonate

No drinking water guidelines. Reported in ppm.

Calcium, magnesium, sodium, and potassium cations and bicarbonate anions are dissolved out of sediment and bedrock by groundwater. The calcium, magnesium, and bicarbonate constituents are derived from limestone and dolomite bedrock sources (Hem, 1985) and are common in groundwater. Bicarbonate is also derived from carbon dioxide in the atmosphere and soil above the water table.

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

Potassium is naturally released from the weathering of silicate minerals (Hem, 1985). In agricultural areas, fertilizers provide an additional source of potassium.

Water with higher concentrations of calcium and magnesium is considered hard. Though not required, many residents soften their water to limit the build-up of minerals (scale) on plumbing fixtures, the insides of pipes, and water heaters.

Results are discussed in the Piper diagram section of this report.

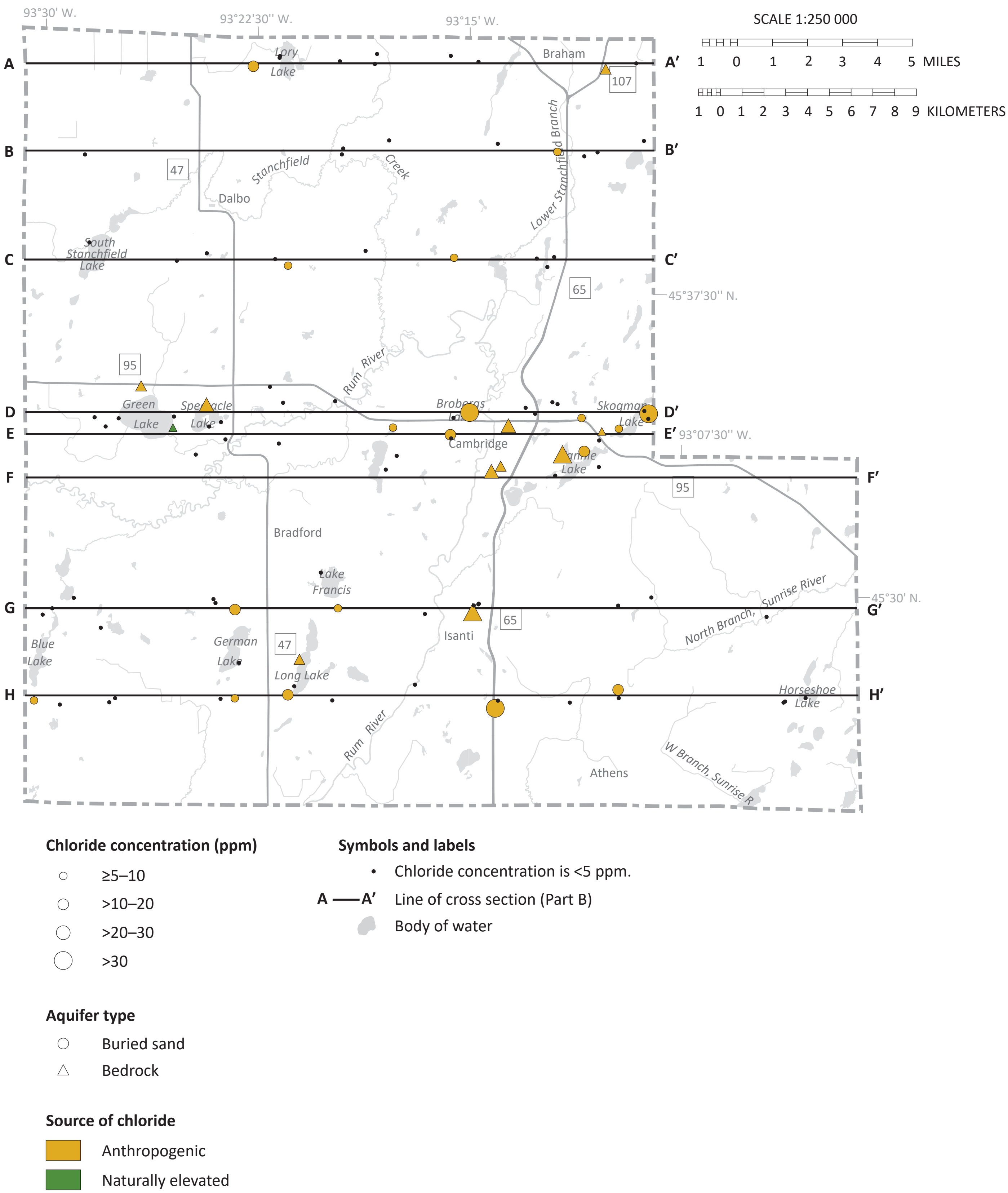


Figure 13. Chloride concentrations from groundwater samples

Anthropogenic chloride in groundwater is relatively widespread in the county, with an increased density of samples in the east-central region of the county near Cambridge.

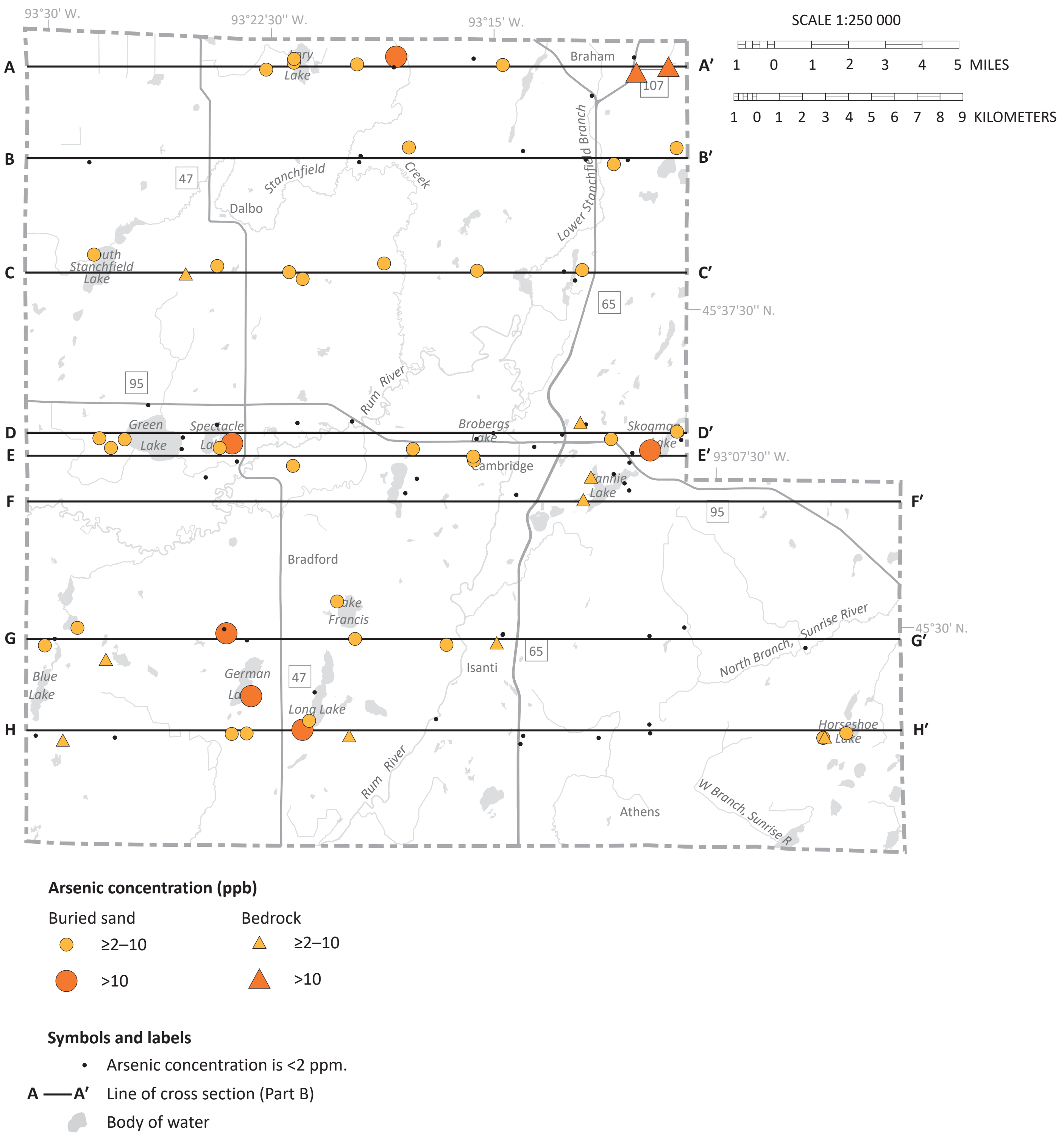


Figure 14. Arsenic concentrations from groundwater samples

Eight samples exceeded the MCL of 10 ppb for arsenic. Those above the MCL were scattered across the county and mostly from buried sand aquifers.

Piper diagram

The Piper diagram (Figure 15) graphically represents the chemistry of each sample for the most common ionic constituents in natural waters: calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and nitrate. The diagram can reveal information about the following:

- The source of dissolved chemicals
- Water chemistry changes along a groundwater flow path due to cation exchange, dissolution of minerals, and mixing of different water types

The Piper diagram has three components: a cation triangle, an anion triangle, and a central diamond. The cations and anions are shown in the left and right triangles, respectively. The center diamond shows a composite of cations and anions.

The general type of water prevalent in the county is calcium-magnesium bicarbonate (Figure 15). One buried sand aquifer sample, shown on the anion triangle at area 1, is slightly shifted toward the chloride+nitrate corner. This sample, located near the east end of D–D′ (Figure 13), had a modern tritium age, the highest chloride concentration found in the county (94 ppm), and the second highest nitrate concentration (4.87 ppm). These elevated concentrations show the sample was impacted by anthropogenic effects.

The two bedrock samples shown on the anion triangle at area 2, slightly shifted toward the sulfate corner, were from wells completed in the Upper Tunnel City aquifer. Both wells contained some of the highest sulfate concentrations in the county (37.5 and 109 ppm); however, these concentrations were still well below the sulfate SMCL of 250 ppm.

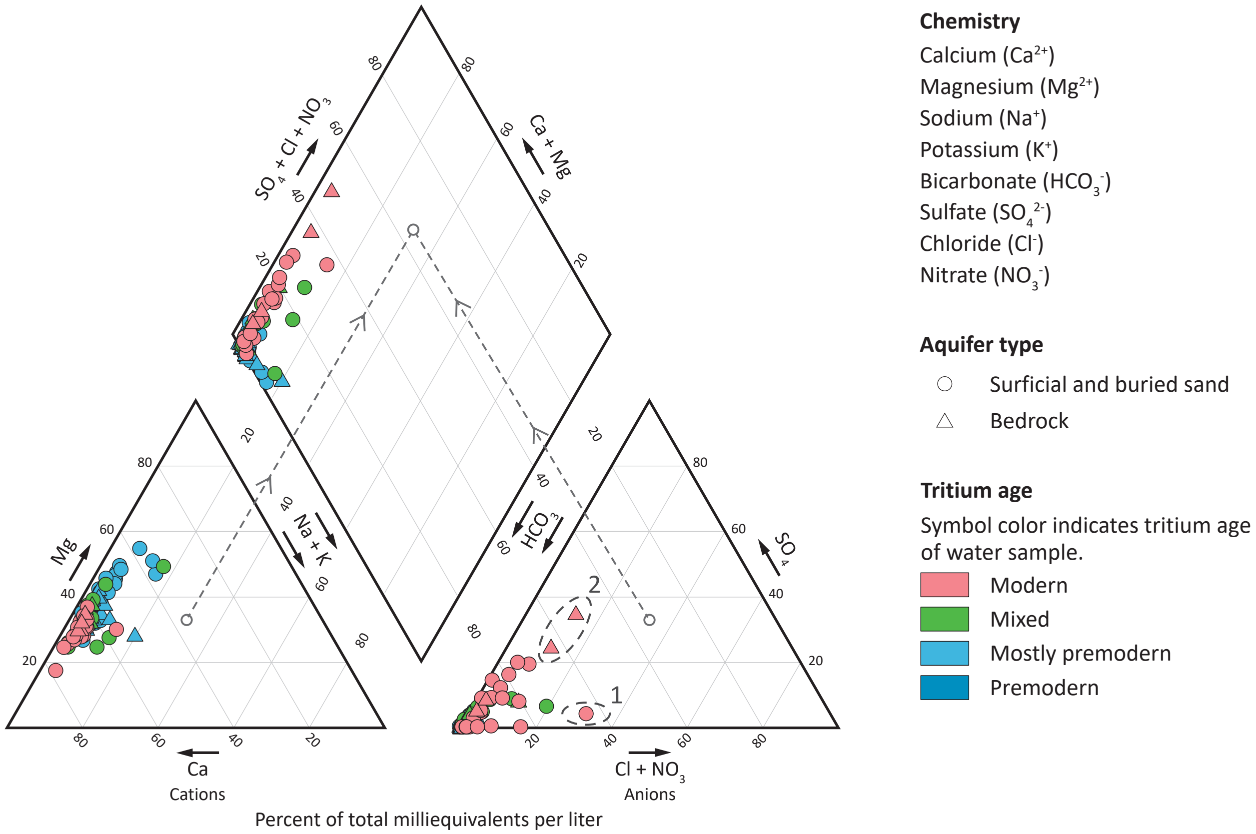


Figure 15. Piper diagram of groundwater sampled by DNR staff

This diagram compares the relative proportions of major cations and anions in groundwater from all the sampled wells.

The Piper diagram has three components: a cation triangle, an anion triangle, and a central diamond. Samples are represented by one data point on each component. The sample points on each triangle reflect the relative percentages of the major cations (lower left triangle) and anions (lower right triangle). These are projected onto the diamond grid. The sample points in the figure are color-coded according to tritium age to show chemical relationships.

Generally, a calcium-magnesium bicarbonate water type was prevalent throughout the county. In the anion triangle, there are two circled areas of interest. Area 1 is a buried aquifer sample shifted toward the chloride+nitrate corner, which is impacted by anthropogenic effects. Area 2 showcases two Upper Tunnel City aquifer samples with the highest sulfate concentrations in the county.

Pollution sensitivity

This report defines pollution sensitivity as the time it takes for a contaminant to travel from the land surface to a specific target: the water table, a buried aquifer, or the bedrock surface. There are two pollution sensitivity models:

1. The **near-surface materials model** estimates travel time to the water table.
2. The **buried sand aquifers and bedrock surface model** estimates travel time to the respective surfaces.

Both models estimate travel time, but each uses a different method.

Both methods include the following general assumptions:

- Flow paths are vertical and downward from the land surface through the soil and underlying sediment to the water table, a buried aquifer, or the bedrock surface.
- A contaminant travels at the same rate as water.
- A dissolved contaminant moves with water from the surface and is not chemically or physically altered over time.

Areas of high sensitivity can be associated with areas of high recharge. Land cover also affects potential recharge (Smith and Westenbroek, 2015) but is not included in the models.

Near-surface materials model

Methods

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

The transmission rate varies depending on the texture; coarse-grained materials generally have faster rates than fine-grained materials. The two primary inputs used to estimate the transmission rate are the hydrologic soil group (Natural Resources Conservation Service, 2009) and the surficial geologic matrix texture (Part A, Plate 3). Attributes of both are used to estimate the time of travel (Table 1).

Travel time varies from hours to approximately a year; ratings are shown in Figure 16. For more details, see *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

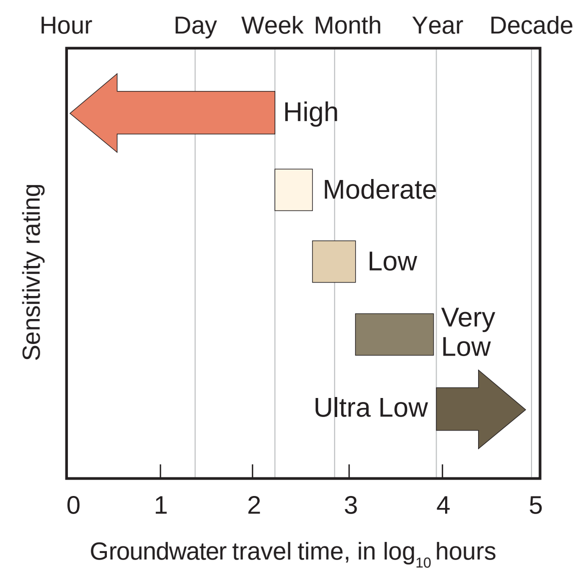


Figure 16. Pollution sensitivity of near-surface materials: travel time and ratings

Results

The broad patterns of pollution sensitivity include high and moderate conditions across much of the county, except for the northern, east-central, and southwest portions, where low and very low conditions are common. The high sensitivity areas mostly match the areas of sand and gravel shown in Figure 3. A consistent zone of low and very low pollution sensitivity dominates this northern area of extensive fine-grained lake sediment and loamy to silty loam till deposited in Lake Grantsburg of the Grantsburg sublobe. That ice lobe also deposited loamy till in the low sensitivity area of the east-central and southwestern parts (Part A, Plate 3, Figure 3).

Table 1. Transmission rates through unsaturated materials

Used to assess the pollution sensitivity rating of the near-surface materials

Hydrologic soil group (0 to 3 feet)		Surficial geologic texture (3 to 10 feet)		
Group*	**Transmission rate (in/hr)**	**Classification**	**Transmission rate (in/hr)**	**Surficial geology map unit (Part A, Plate 3)**
A, A/D	1	gravel, sandy gravel, silty gravel	1	ci, co, nbg, nta, nti, nto
		sand, silty sand	0.71	al, eo, ls, nbs, nfd
B, B/D	0.50	silt, loamy sand	0.50	ntw
		sandy loam, peat	0.28	ct, ntc
C, C/D	0.075	silt loam, loam	0.075	ntm, ntt
		sandy clay loam	0.035	Not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	ll, nfc, nfl, ntl

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

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

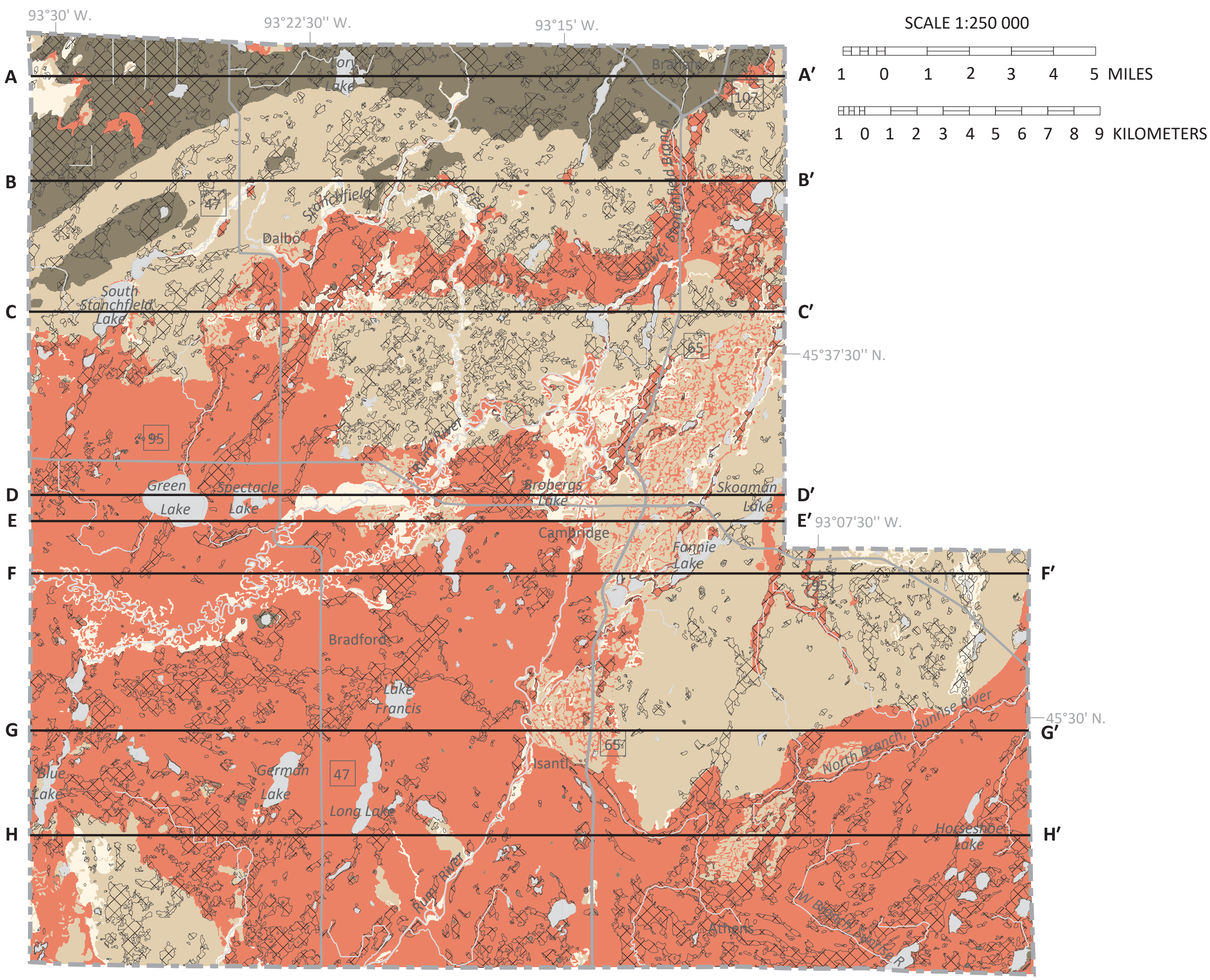
Group A: Water is freely transmitted. Soils are more than 90% sand and gravel.

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

Group C: Water transmission is somewhat restricted.

Group D: Water movement is restricted or very restricted.

Dual hydrologic groups (A/D, B/D, or C/D) are assigned by the NRCS to soils with the water table within 24 inches of the surface that can be adequately drained. The first letter describes drained conditions; the second describes undrained.



Estimated vertical travel time through near-surface materials

- High: hours to a week
- Moderate: a week to weeks
- Low: weeks to months
- Very low: months to a year

Symbols and labels

- A —— A′ Line of cross section (Part B)
- Peat
- Body of water

Figure 17. Pollution sensitivity of near-surface materials

High and moderate pollution sensitivity exists across much of the county, except for the northern, east-central, and southwest portions, where low to very low conditions are common. Peat is used as an overlay on the map due to variable and typically unknown thicknesses.

Buried sand aquifer and bedrock surface model

Method

The pollution sensitivity of buried sand aquifers and the bedrock surface estimates the time it takes for water to travel from the land surface to the buried aquifer or bedrock surface (travel time). This was defined by the Geologic Sensitivity Workgroup (1991).

The model applies to unconsolidated geologic sediment and assumes that all sediment above and between buried sand aquifers and down to the bedrock surface is an aquitard: fine-grained with low hydraulic conductivity. The estimate of travel time is assumed to be proportional to the cumulative fine-grained sediment (CFGS) thickness overlying a buried sand aquifer or the bedrock surface (Figures 18 and 19). The thicker the fine-grained sediment, the longer it takes for water to move through it. The model does not consider differences in sediment texture or permeability of aquitard materials. For more details, see *Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment thickness* (DNR, 2016c).

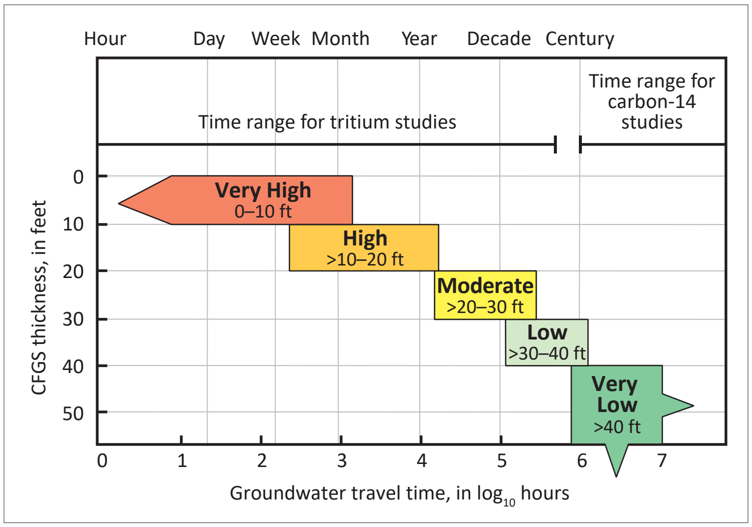


Figure 18. Pollution sensitivity rating for the buried sand aquifers and the bedrock surface

Sensitivity is defined by estimated vertical travel time. The numbers following each rating represent the CFGS thickness overlying an aquifer.

This model has five classes of pollution sensitivity based on overlapping time of travel ranges (very high, high, moderate, low, and very low). Areas with very high or high ratings have relatively short estimated travel times of less than a few years. Low or very low-rated areas have estimated travel times of decades or longer. Travel time varies from hours to thousands of years.

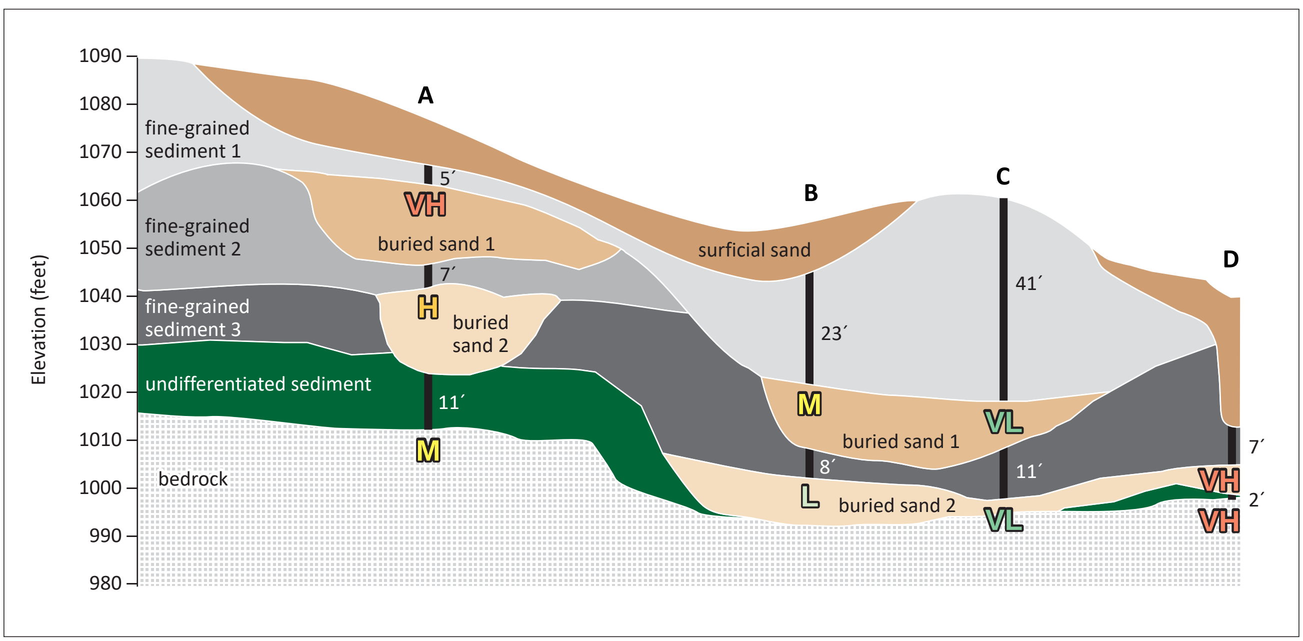


Figure 19. Cross section illustration of the pollution sensitivity model

The pollution sensitivity model assigns sensitivity ratings to buried sands and the bedrock surface based on the cumulative thickness of overlying fine-grained sediment. Sites A–D indicate aquitard thicknesses from the land surface to the bedrock surface. For example, site A pollution sensitivity ratings are assigned as follows:

Site A: 5 feet (buried sand 1: Very High) + 7 feet = 12 feet (buried sand 2: High) + 11 feet = 23 feet (bedrock surface: Moderate)

The pollution sensitivity of buried sands and the bedrock surface varies with overlying cumulative aquitard thickness.

Groundwater conditions

The modeled pollution sensitivity results are compared to groundwater residence times from tritium and carbon-14 samples and to the presence of anthropogenic chemical indicators (nitrate and chloride). In general, aquifers with *higher pollution sensitivity* have *mixed or modern* tritium-age water and anthropogenically sourced chemicals if a source is present.

Aquifers with *very low pollution sensitivity* ratings generally have *premodern* tritium-age water. Where this is not the case, the following groundwater conditions provide alternative explanations for how modern or mixed tritium-age water has traveled to an aquifer.

Ⓛ **Lateral flow:** the aquifer may have received lateral recharge from upgradient areas of higher pollution sensitivity.

Ⓟ **Pumping:** high-volume pumping may have enhanced recharge rates and changed local groundwater flow directions.

Ⓤ **Unknown:** neither the pollution sensitivity model nor groundwater conditions explained the presence of modern or mixed tritium-age water.

Where aquifers with *higher sensitivity* have *premodern* tritium-age water, the following condition may be present.

Ⓓ **Discharge:** older water upwelled from deep aquifers to shallow aquifers or the surface.

Groundwater flow directions derived from potentiometric surfaces are included to aid in identifying areas where lateral groundwater flow may be introducing water from higher sensitivity areas to downgradient areas of low or very low sensitivity. Equipotential contours aid in identifying areas where upwelling older groundwater interacts with aquifers near the surface.

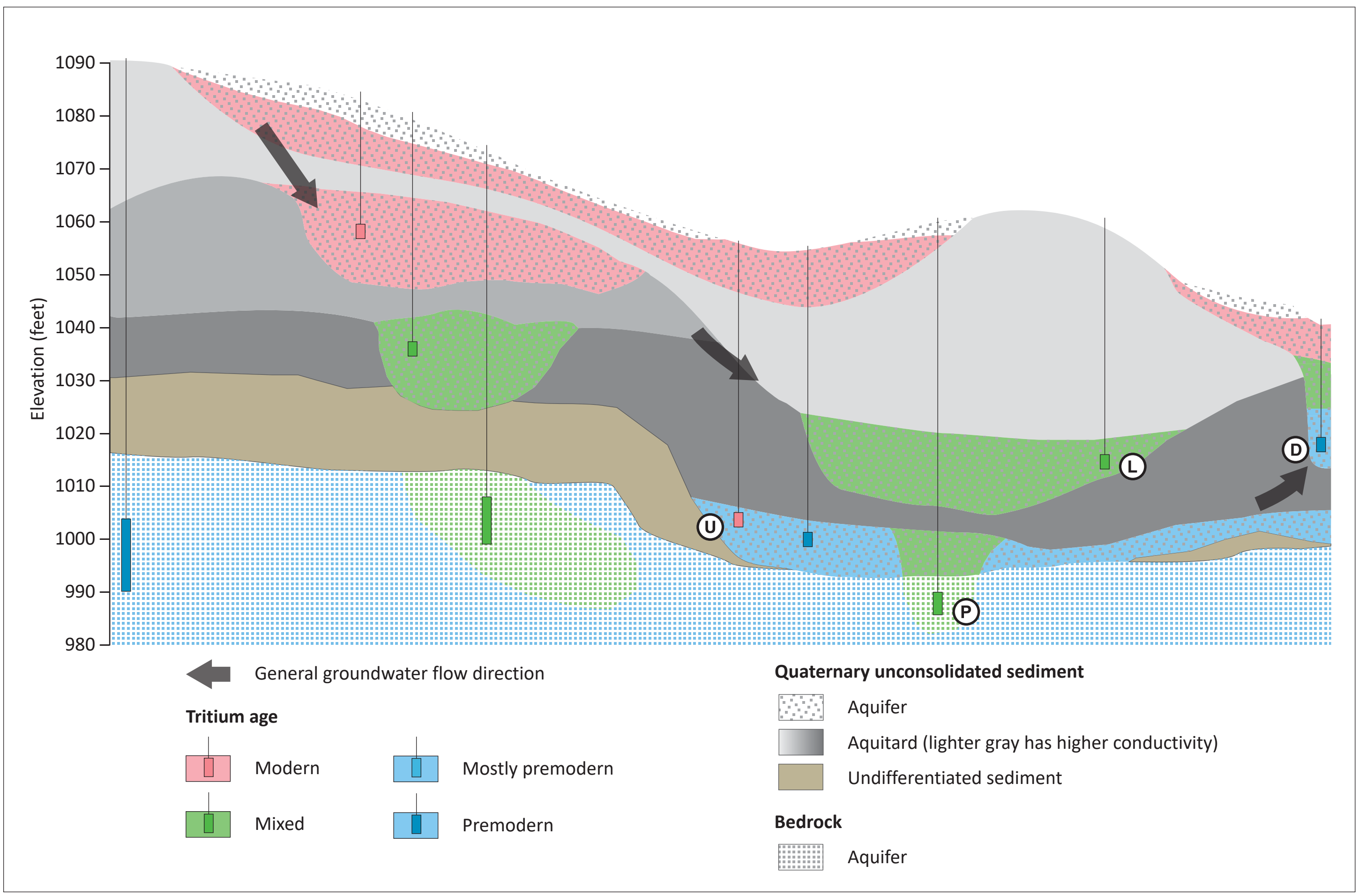


Figure 20. Cross section illustration of groundwater conditions

This illustration shows interpretations of why tritium might be present in groundwater samples under different conditions.

Results

The following section provides general characterizations of the buried aquifers in stratigraphic order (Figure 2) and the bedrock surface. Descriptions include aquifer depth and spatial distribution, pollution sensitivity, and the approximate percentage of wells completed in aquifers associated with each figure.

The modeled pollution sensitivity results are compared to groundwater residence times from tritium and carbon-14 samples and to the presence of anthropogenic chemical indicators (nitrate and chloride).

csa aquifer (Figure 21)

- *Extent*: The csa aquifer is found throughout the county.
- *Depth*: Depths range from 0 to 60 feet.
- *Thickness*: Mean thickness of 12 feet, with a maximum thickness of approximately 50 feet.
- *Use*: Approximately 5% of wells.
- *Pollution sensitivity*: Pollution sensitivity is mostly very high to moderate, with some low to very low areas, mainly in the northern part.
- *Residence time*: Of the 3 samples collected, all were analyzed for tritium with the following results: 1 modern, 1 mixed, and 1 premodern tritium age.
- *Anthropogenic chemical indicators*: Of the 2 samples analyzed for chloride, neither were elevated. Of the 2 samples analyzed for nitrate, both were below the detection limit.
- *Summary*: Of the 2 modern and mixed tritium-age samples, both were located near areas of very high to moderate sensitivity. The 1 premodern sample was in a low to very low sensitivity area. All samples were consistent with the pollution sensitivity model.

csr aquifer (Figure 22)

- *Extent*: The csr aquifer is found throughout the county.
- *Depth*: Depths range from approximately 20 to 90 feet.
- *Thickness*: Mean thickness is 15 feet with a maximum thickness of approximately 50 feet.
- *Use*: Approximately 20% of wells.
- *Pollution sensitivity*: Pollution sensitivity has a complex distribution of very high to very low, with some larger very high to moderate areas in the west-central and southeast.
- *Residence time*: All 22 samples collected were analyzed for tritium with the following results: 7 modern, 4 mixed, and 11 premodern tritium age. Two premodern samples had carbon-14 residence times of 1,600 and 1,900 years.
- *Anthropogenic chemical indicators*: Of the 22 samples analyzed for chloride, 5 were elevated from anthropogenic sources. Of the 22 samples analyzed for nitrate, 1 was elevated east of Skogman Lake in the eastern part (D–D′).
- *Summary*: Most of the 11 modern and mixed tritium-age samples were in high to low sensitivity areas, and 5 of the samples contained elevated chloride concentrations. Four samples were in areas of very low pollution sensitivity downgradient from areas of higher pollution sensitivity, which could have been the source of detected tritium due to lateral groundwater flow.

  Of the 11 premodern samples, 9 were in low to very low sensitivity areas, and 2 were in areas of moderate sensitivity. One of those locations is near the Rum River west of Cambridge, and the other is in the northeastern part of the county near the Lower Stanchfield Branch Creek. In these areas, water is likely discharging to the streams, reducing the amount that is moving further into the subsurface.

cse aquifer (Figure 23)

- *Extent*: The cse aquifer is found throughout the county.
- *Depth*: Depths range from approximately 50 to 130 feet.
- *Thickness*: Mean thickness of 15 feet with a maximum thickness of approximately 60 feet.
- *Use*: Approximately 22% of wells.
- *Pollution sensitivity*: Pollution sensitivity is mostly very low, with scattered areas of higher sensitivity.
- *Residence time*: Of the 29 samples collected, all were analyzed for tritium with the following results: 9 modern, 8 mixed, and 12 premodern tritium age. One premodern sample had a carbon-14 residence time of 550 years.
- *Anthropogenic chemical indicators*: Of the 28 samples analyzed for chloride, 8 were elevated due to anthropogenic sources. One of the 28 samples analyzed for nitrate was elevated.
- *Summary*: Of the 17 modern and mixed tritium-age samples, 14 were in low or very low pollution sensitivity areas, most downgradient of higher sensitivity areas, which is likely the source of the detected tritium through lateral groundwater flow. Half of these samples also had elevated chloride concentrations. The remaining samples had unknown recharge conditions that may be from more rapid infiltration than modeled or well construction issues.

Of the 12 premodern samples, all but 2 were in low to very low pollution sensitivity areas. One exception is located west of Isanti near the Rum River, where water is likely discharging to the river and reducing the amount of water moving further into the subsurface. The other sample, located northwest of German Lake, does not have a clear explanation for being in the high sensitivity area.

rs aquifer (Figure 24)

- *Extent*: The rs aquifer is found throughout the county.
- *Depth*: Depths range from approximately 70 to 170 feet.
- *Thickness*: Mean thickness of 14 feet with a maximum thickness of approximately 55 feet.
- *Use*: Approximately 13% of wells.
- *Pollution sensitivity*: Pollution sensitivity is mostly very low, with scattered areas of very high to moderate pollution sensitivity.
- *Residence time*: Of the 10 samples collected, 9 were analyzed for tritium with the following results: 6 modern, 2 mixed, and 1 premodern tritium age.
- *Anthropogenic chemical indicators*: Of the 10 samples analyzed for chloride, 5 were elevated from anthropogenic sources. Of the 10 samples analyzed for nitrate, 1 was elevated (located south of Isanti).
- *Summary*: Of the 8 modern and mixed tritium-age samples, 2 were in areas of high to low sensitivity. The remaining 5 samples were in very low sensitivity areas but downgradient of higher sensitivity areas, which may have been the sources of the detected tritium through lateral groundwater flow. The 1 premodern sample was in a very low pollution sensitivity area in the southwest.

scs aquifer (Figure 25)

- *Extent*: The scs aquifer has a sporadic and limited extent.
- *Depth*: Depths range from approximately 80 to 200 feet.
- *Thickness*: Mean thickness of 11 feet with a maximum thickness of approximately 40 feet.
- *Use*: About 1% of wells.
- *Pollution sensitivity*: Pollution sensitivity is mostly very low, with a few scattered higher sensitivity areas.
- *Residence time*: The 1 sample collected was premodern tritium age.
- *Anthropogenic chemical indicators*: The 1 sample collected was analyzed for nitrate and chloride; neither was elevated.
- *Summary*: The premodern sample was in an area of very low pollution sensitivity and had no indication of anthropogenic impacts.

Combined lower Quaternary aquifers (fs1, mls, fs2, wrs, and uss aquifers) (Figure 26)

- *Extent*: The combined lower Quaternary aquifers are found sporadically throughout the county and are most prevalent in the southwest.
- *Depth*: Depths range from approximately 70 to 300 feet.
- *Thickness*: Mean thickness of all units is approximately 11 feet, with a mean maximum thickness of approximately 37 feet.
- *Use*: Approximately 3% of wells.
- *Pollution sensitivity*: Pollution sensitivity is mostly very low.
- *Residence time*: Of the 4 samples collected, all were analyzed for tritium with the following results: 2 mixed and 2 premodern tritium age.
- *Anthropogenic chemical indicators*: Of the 4 samples, 3 were analyzed for nitrate and chloride; none were elevated.
- *Summary*: The 2 mixed tritium-age samples were in areas of very low pollution sensitivity. The source of the detected tritium is unknown. The 2 premodern samples were in areas of very low pollution sensitivity.

Bedrock surface (Figure 27)

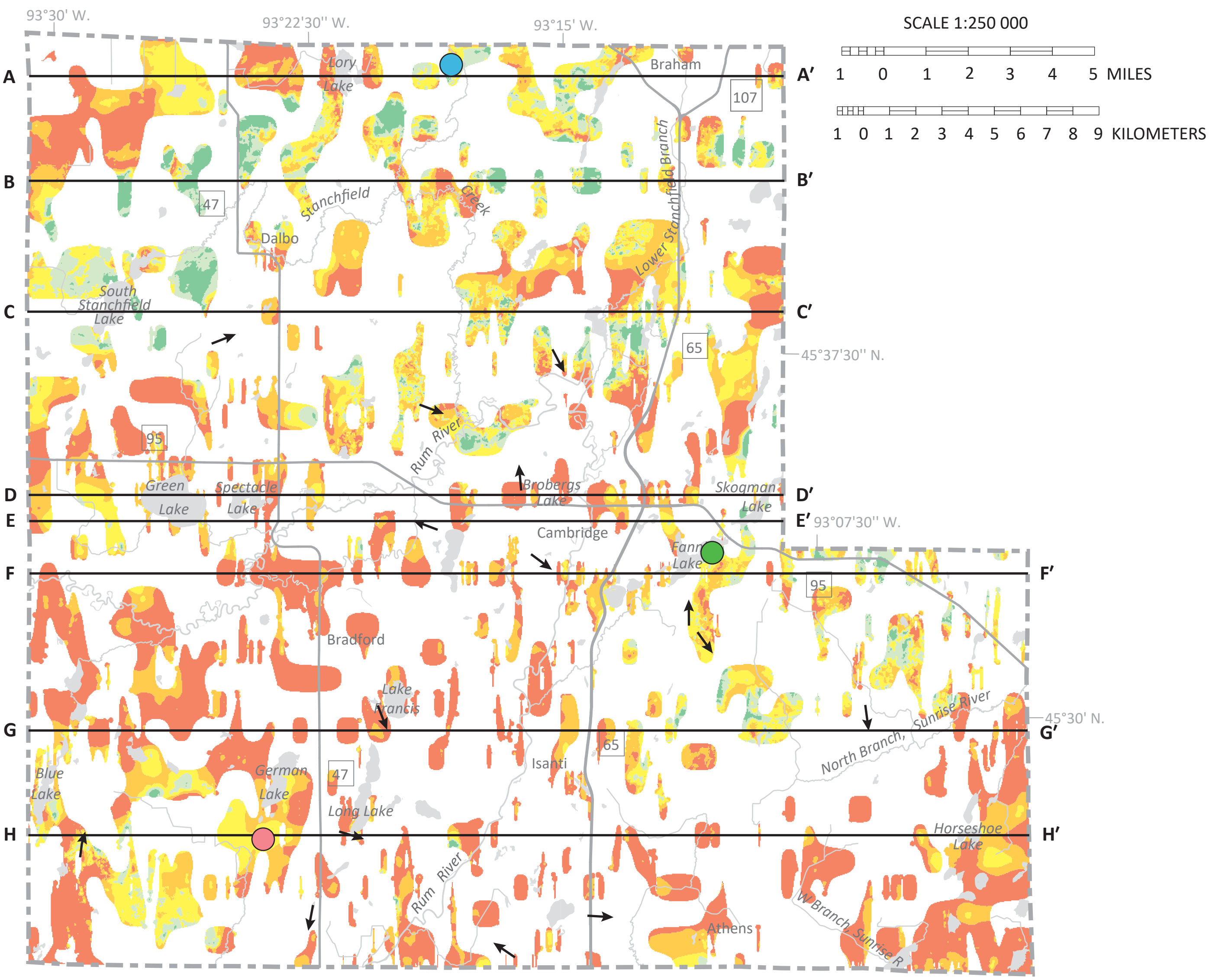
- *Depth*: Depths to the bedrock surface range from approximately 50 to 400 feet.
- *Use*: Approximately 26% of wells are completed in bedrock aquifers.
- *Pollution sensitivity*: Pollution sensitivity is mostly very low, with many scattered areas of very high to moderate pollution sensitivity.
- *Residence time*: Of the 50 samples collected from bedrock aquifers, 47 were analyzed for tritium with the following results: 10 modern, 8 mixed, and 29 premodern tritium age. Thirteen premodern samples had carbon-14 residence times ranging from 800 to 5,500 years.
- *Anthropogenic chemical indicators*: Of the 43 samples analyzed for chloride, 11 were elevated, with 10 from anthropogenic sources. Of the 45 samples analyzed for nitrate, 1 was elevated.
- *Summary*: Of the 18 modern and mixed tritium-age samples, 3 were in areas of high to low sensitivity. The remaining 15 samples, collected from very low sensitivity areas, are likely the result of lateral groundwater flow, high-volume groundwater pumping, or unknown sources. Areas of lateral flow are designated where samples were collected downgradient

of higher sensitivity areas. Tritium concentrations may be artificially elevated by high-capacity pumping near cities with high-volume pumping. In Isanti and Cambridge, recent tritium-age water is found at depths greater than expected. High-volume groundwater pumping in these areas has likely steepened gradients, bringing recent tritium-age water to greater depths. Elevated chloride and nitrate in this area also support the high sensitivity model result and provide further evidence of pumping impacts.

Of the 29 premodern tritium-age samples, all were in areas of low to very low sensitivity. One of these samples had naturally elevated chloride, collected from the Mt. Simon–Hinckley aquifer near Green Lake, and may indicate the presence of old brine-rich groundwater.

Cumulative pollution sensitivity of buried aquifers (Figure 28)

This map was made by layering all of the previously described pollution sensitivity maps in stratigraphic order to display the pollution sensitivity of the uppermost aquifer at any location. It shows that many parts of the county have high and moderate pollution sensitivity for the first buried aquifer.



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

Symbols and labels

- ← Groundwater flow direction in upper Quaternary aquifers
- A ——A′ Line of cross section (Part B)
- Body of water

Tritium age

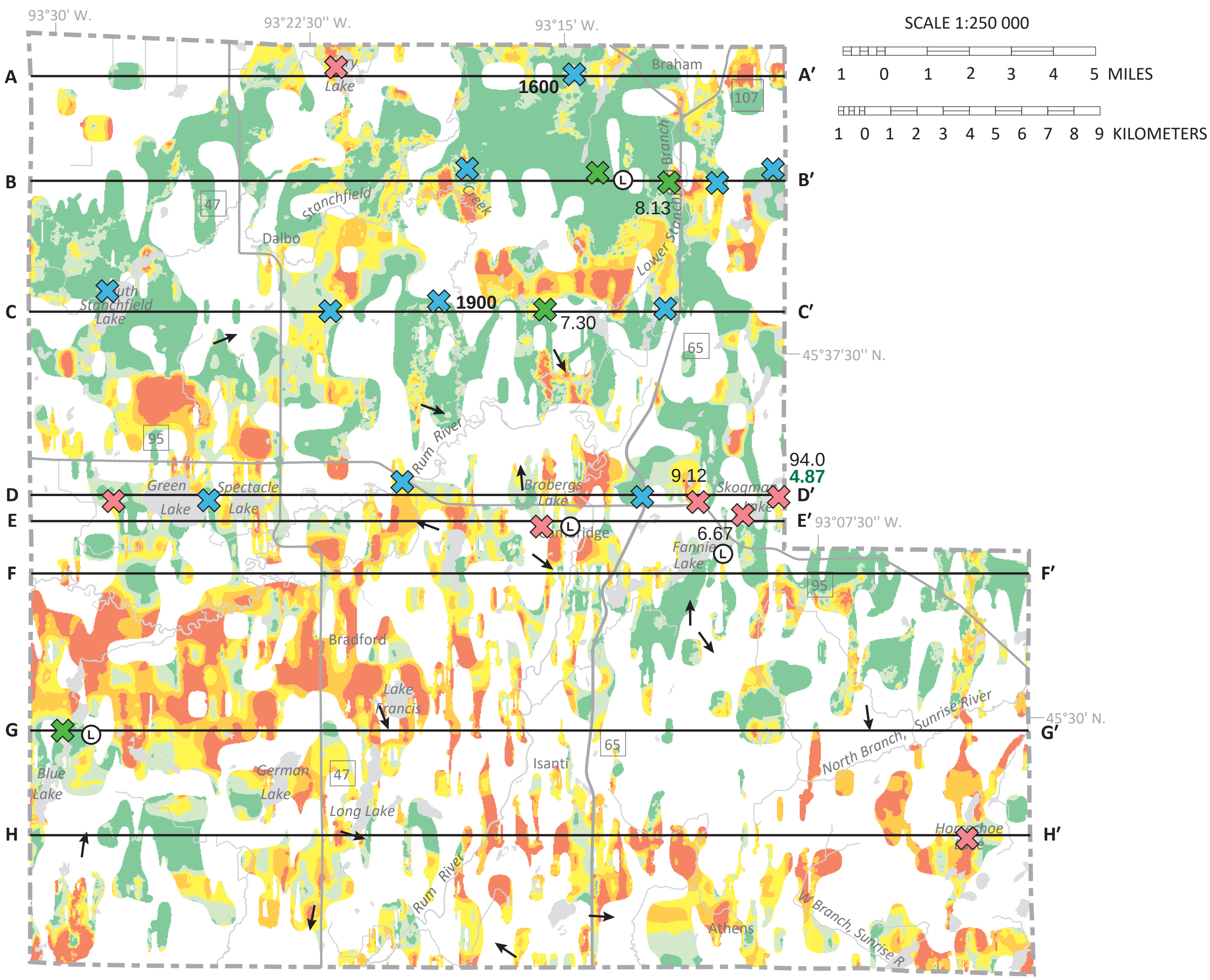
Symbol color indicates tritium age of water sample.

- Modern
- Mixed
- Mostly premodern

View hydrostratigraphy

Figure 21. Pollution sensitivity of the csa aquifer

Sensitivity is mostly very high to moderate, with some low to very low areas, mainly in the north. Approximately 5% of the county’s wells are completed in this aquifer.



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.

- Modern
- Mixed
- Mostly premodern

Symbols and labels

8.13	Chloride: if shown, concentration is ≥5 ppm.
4.87	Nitrate: if shown, concentration is ≥1 ppm.
1600	Carbon-14 (^{14}C): estimated groundwater residence time in years
←	Groundwater flow direction in upper Quaternary aquifers
A —A′	Line of cross section (Part B)
	Body of water

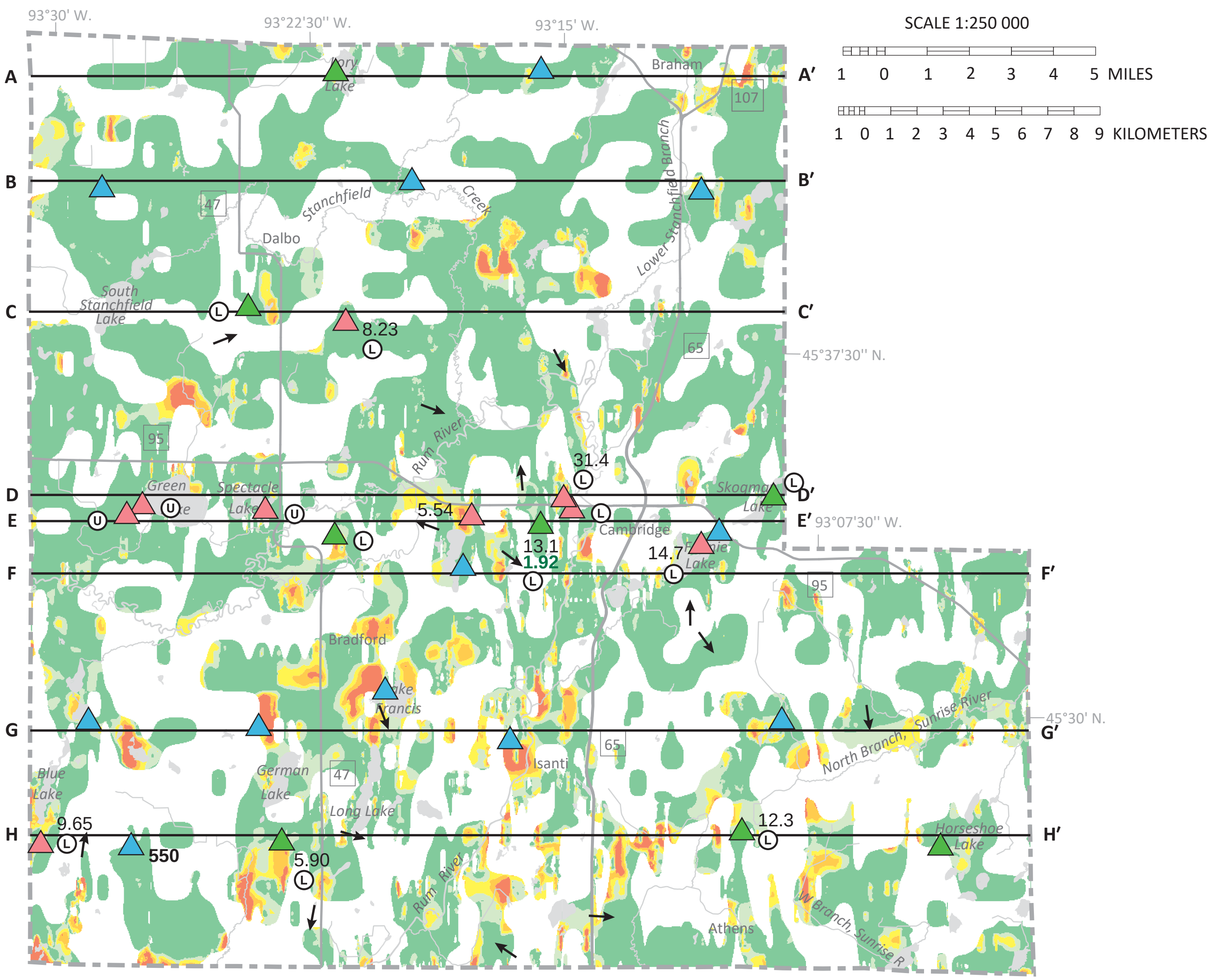
Groundwater conditions

(L) Lateral flow

View hydrostratigraphy

Figure 22. Pollution sensitivity of the csr aquifer

Sensitivity has a complex distribution of very high to very low, with some larger mostly very high to moderate areas in the west-central and south. Approximately 20% of the county's wells are completed in this aquifer.



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.

- Modern
- Mixed
- Mostly premodern

Symbols and labels

- 14.7 Chloride: if shown, concentration is ≥5 ppm.
- 1.92 Nitrate: if shown, concentration is ≥1 ppm.
- **550** Carbon-14 (^{14}C): estimated groundwater residence time in years
- ← Groundwater flow direction in upper Quaternary aquifers
- A —A′ Line of cross section (Part B)
- Body of water

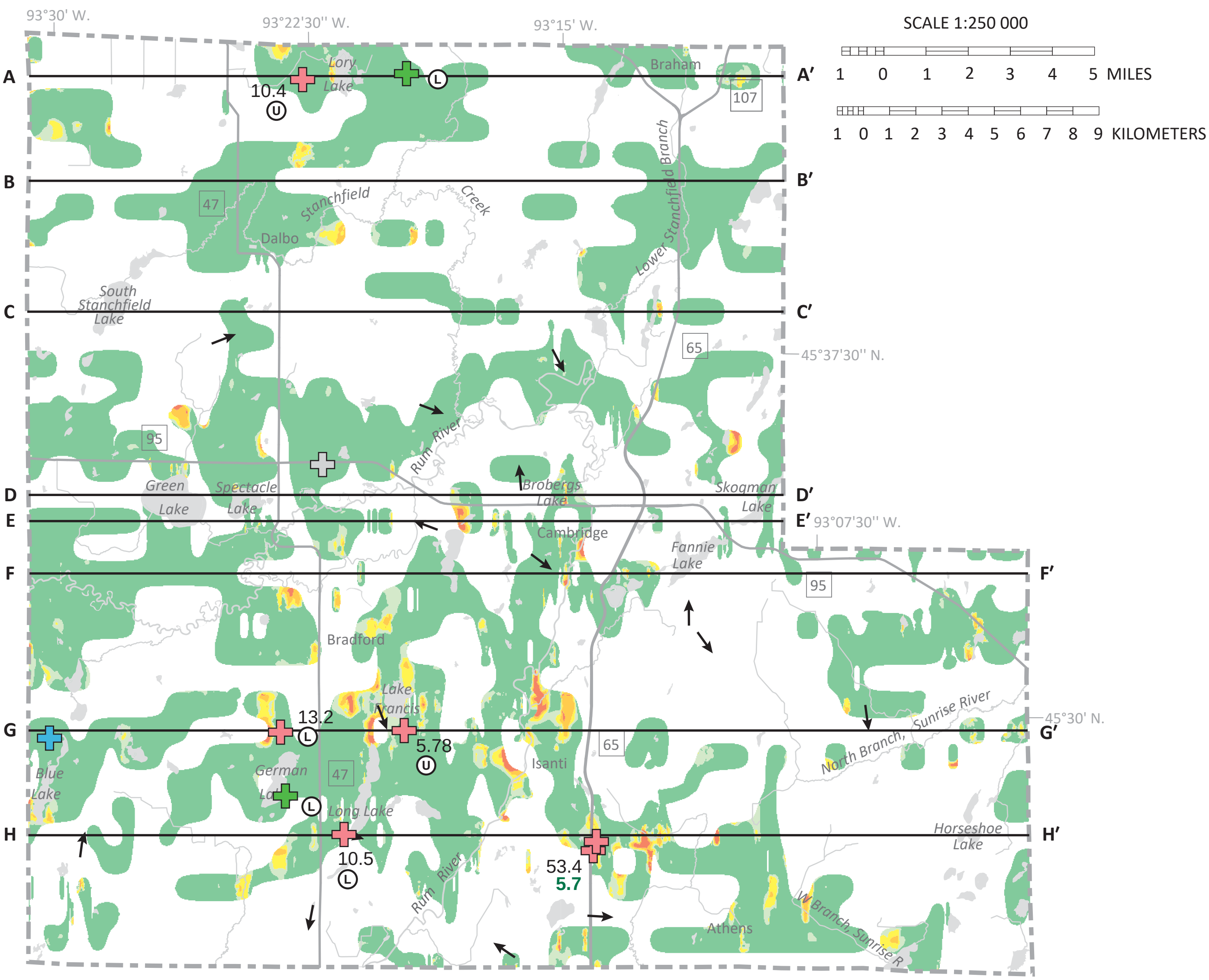
Groundwater conditions

- (L) Lateral flow
- (U) Unknown

View hydrostratigraphy

Figure 23. Pollution sensitivity of the cse aquifer

Sensitivity is mostly very low, with scattered areas of higher sensitivity throughout the county. Approximately 22% of the county's wells are completed in this aquifer.



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.

- Modern
- Mixed
- Mostly premodern
- Not sampled for tritium

Symbols and labels

- 10.4 Chloride: if shown, concentration is ≥5 ppm.
- 5.7 Nitrate: if shown, concentration is ≥1 ppm.
- Groundwater flow direction in upper Quaternary aquifers
- A —— A′ Line of cross section (Part B)
- Body of water

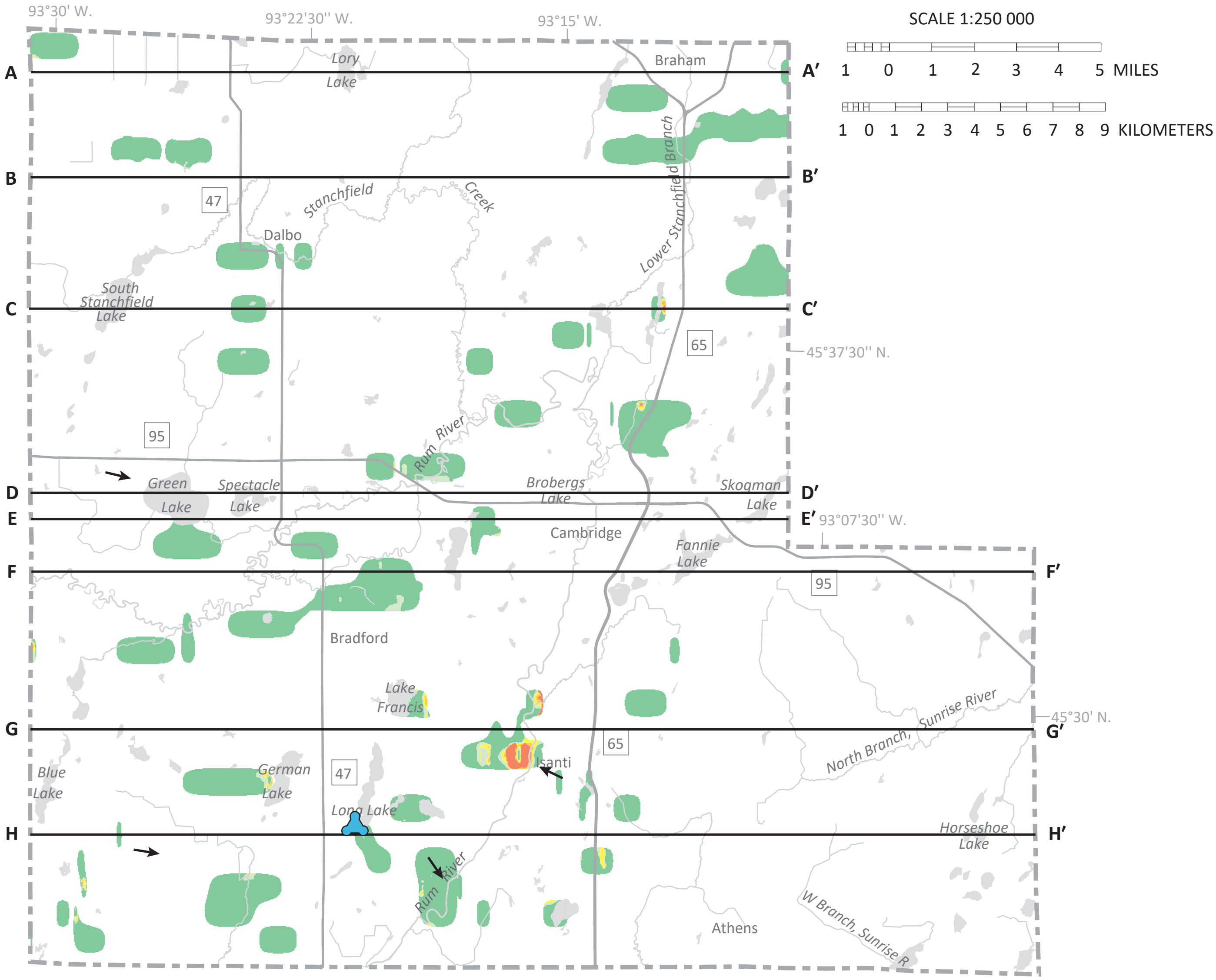
Groundwater conditions

- (L) Lateral flow
- (U) Unknown

View hydrostratigraphy

Figure 24. Pollution sensitivity of the rs aquifer

Sensitivity is mostly very low, with scattered areas of very high to moderate pollution sensitivity. Approximately 13% of the county's wells are completed in this aquifer.



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

Symbols and labels

- Groundwater flow direction in lower Quaternary aquifers
- A —— A' Line of cross section (Part B)
- Body of water

Tritium age

Symbol color indicates tritium age of water sample.

- Mostly premodern

View hydrostratigraphy

Figure 25. Pollution sensitivity of the scs aquifer

Sensitivity is mostly very low, with a few scattered higher sensitivity areas. Approximately 1% of the county's wells are completed in this aquifer.

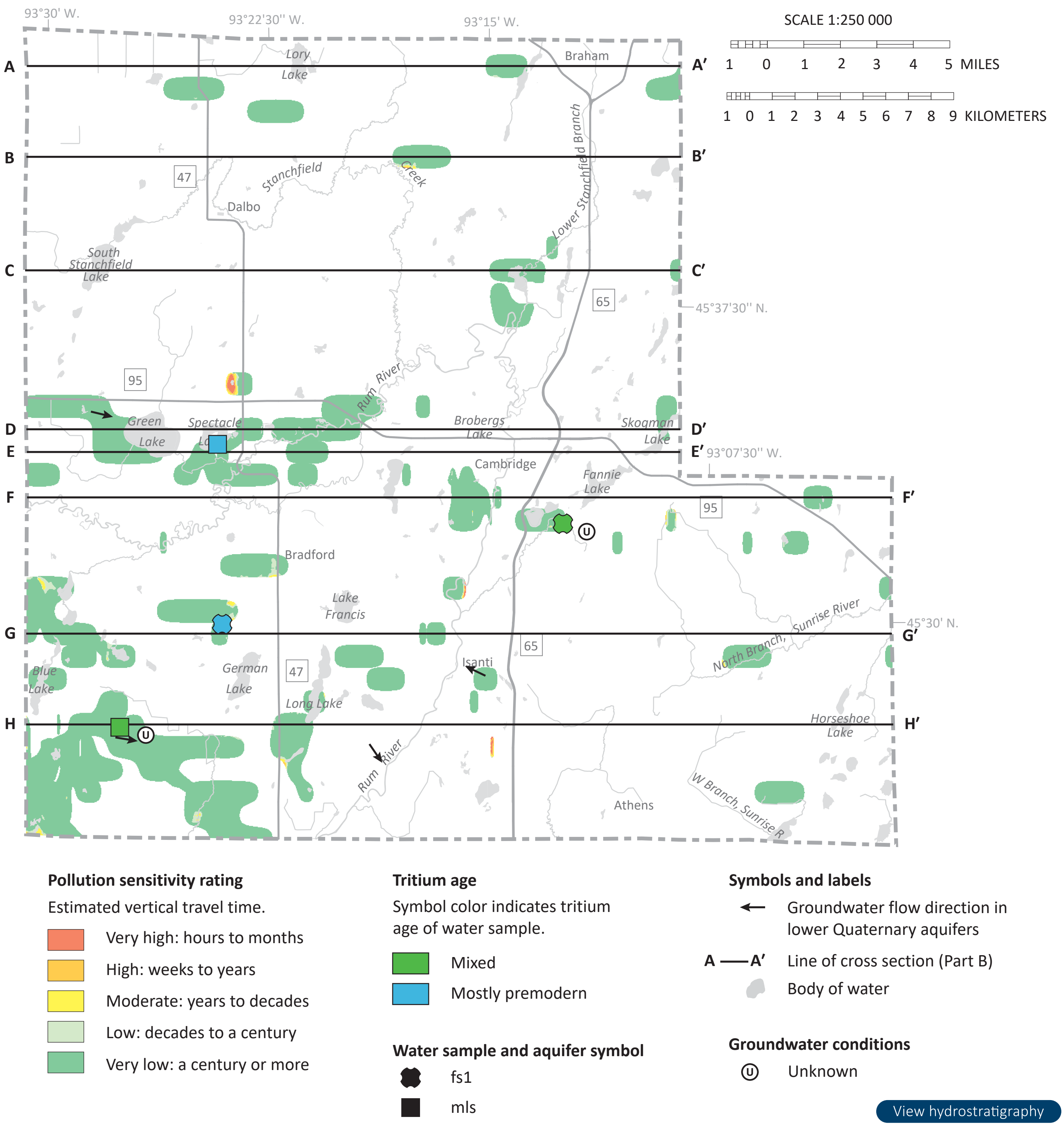
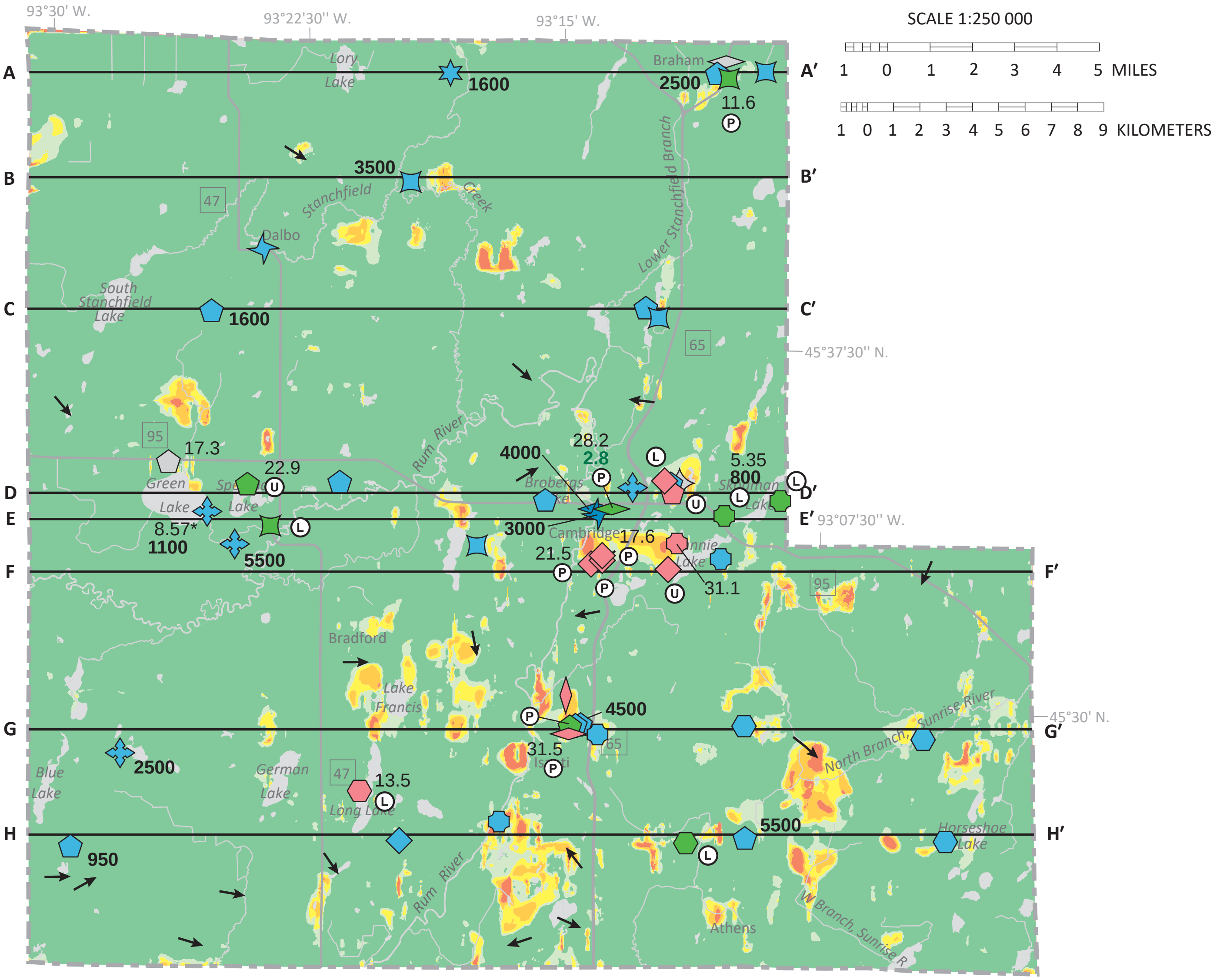


Figure 26. Pollution sensitivity of the lower Quaternary aquifers

The sensitivity of the combined fs1, mls, fs2, wrs, and uss aquifers is mostly very low. Approximately 3% of the county's wells are completed in these aquifers.



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.

- Modern
- Mixed
- Mostly premodern
- Premodern
- Not sampled for tritium

Water sample and aquifer symbol

- Tunnel City
- Tunnel City–Wonewoc
- Wonewoc
- Wonewoc–Eau Claire
- Wonewoc–Mt. Simon
- Eau Claire–Mt. Simon
- Mt. Simon
- Mt. Simon–Hinckley
- Mt. Simon–Fond du Lac
- Hinckley
- Hinckley–Fond du Lac

Symbols and labels

- 28.2 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
- 2.8 Nitrate: if shown, concentration is ≥1 ppm.
- **3500** Carbon-14 (^{14}C): estimated groundwater residence time in years
- ← Groundwater flow direction in Upper Tunnel City, Wonewoc, and Mt. Simon–Hinckley aquifers
- A —— A' Line of cross section (Part B)
- Body of water

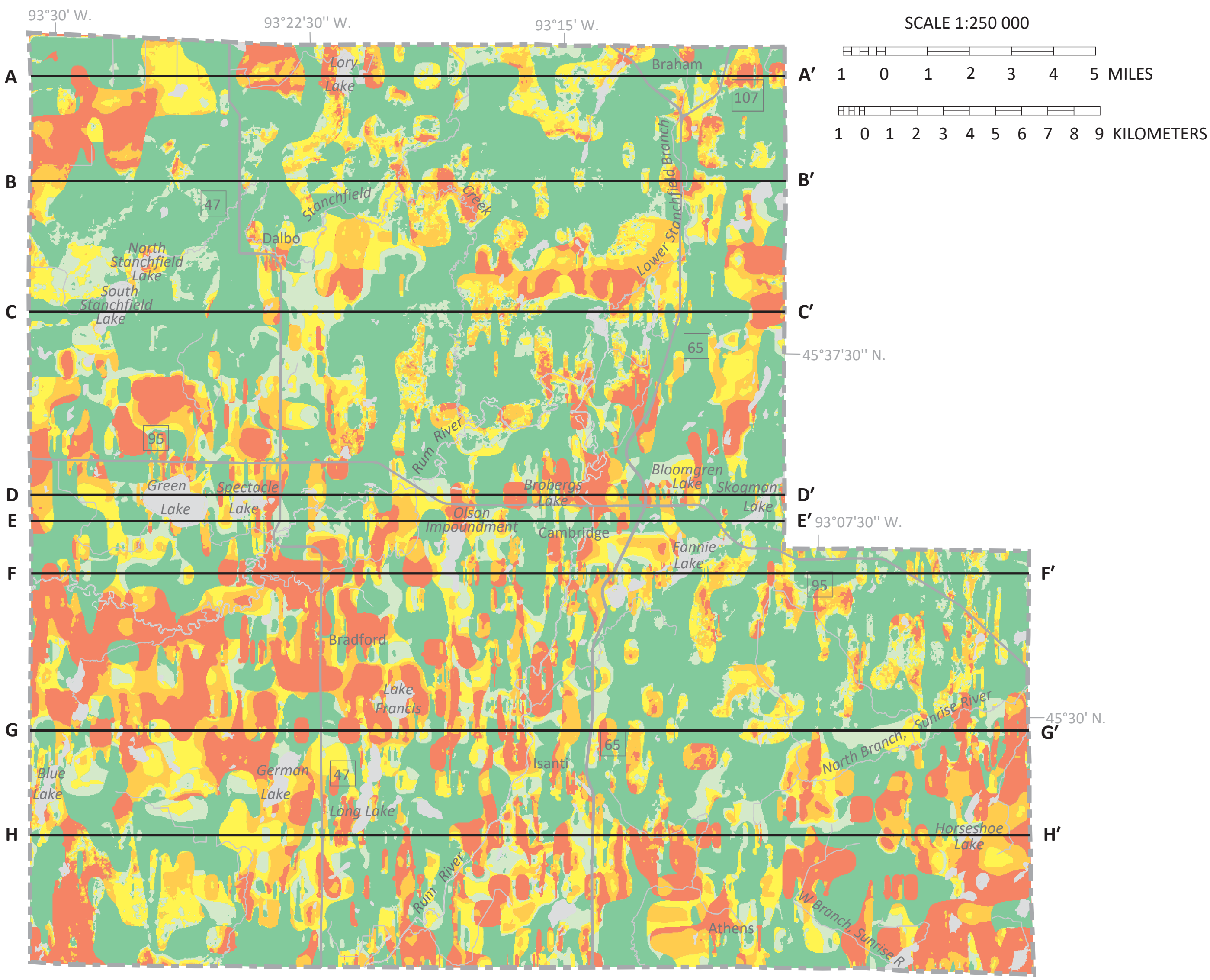
Groundwater conditions

- (L) Lateral flow
- (P) Pumping
- (U) Unknown

View hydrostratigraphy

Figure 27. Pollution sensitivity of the bedrock surface

Sensitivity is mostly very low, with many scattered areas of very high to moderate pollution sensitivity. Approximately 26% of the county's wells are completed in bedrock aquifers.



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

Symbols and labels

- A —— A′ Line of cross section (Part B)
- Body of water

View hydrostratigraphy

Figure 28. Cumulative pollution sensitivity of buried aquifers

This pollution sensitivity map of all the units in stratigraphic order shows the sensitivity of the uppermost layer at any location. It highlights that most of the county has high and moderate pollution sensitivity for the first buried aquifer encountered.

Hydrogeologic cross sections (Plate 8)

The hydrogeologic cross sections illustrate the horizontal and vertical extent of aquifers and aquitards, the relative hydraulic conductivity of aquitards, general groundwater flow direction, groundwater residence time, and areas of groundwater recharge and discharge.

The cross sections were selected from a set of regularly-spaced (1 kilometer) west-to-east cross sections created by the MGS. Each was constructed in geographic information systems (GIS) using a combination of well data from CWI and GIS stratigraphy provided by the MGS. Well information was projected onto the trace of the cross section from distances no greater than 1/2 kilometer.

Relative hydraulic conductivity of aquitards

Hydraulic conductivity represents water's relative ease in moving through sediment or bedrock. It is affected by porosity and permeability.

Groundwater is found in voids (porosity) between sediment grains in unconsolidated sediment and bedrock or in fractures or dissolution channels in bedrock. The relative ease of water movement through sediment or bedrock is a function of the connectedness of these pores (permeability).

Sediment that makes up the Quaternary aquitards (typically till) is shown on the cross sections as shades of gray based on its assumed ability to transmit water. Hydraulic conductivity values are not available for each Quaternary aquitard; therefore, percent sand content is used as a proxy for hydraulic conductivity. Aquitards with higher sand content (lighter shades of gray) are assumed to transmit water more readily and, therefore, have a higher hydraulic conductivity. Percent sand is based on the average matrix texture of each aquitard (Part A, Plate 4, Table 1).

Groundwater flow and residence time

The direction of **groundwater flow** is interpreted on the cross sections as *equipotential contours* constructed from measured water levels in wells. The water-level data are contoured to show groundwater flow along the cross section. The contours can be used to identify the groundwater flow direction, recharge zones, and discharge zones.

Aquifers shown on cross sections were shaded with one of three colors representing estimated **groundwater residence time**. Residence time was assigned based on available chemistry data (tritium age, chloride, and nitrate). Where chemistry data were not available, residence time was assigned by other means, including interpreting penetration depths of modern tritium-age water, pollution sensitivity of the aquifer, and relative permeability of aquitards.

A–A'

Buried sand aquifers are the primary groundwater source along this cross section, with some wells completed in the Mt. Simon aquifer in the center. Groundwater flow is primarily downward and laterally from west to east. Samples collected from buried sand aquifers in the western half of the cross section near Lory Lake showed modern and mixed tritium-age waters. Premodern tritium-aged water and a 1,600-year carbon-14 estimate from wells between Ties Creek and Minnesota Highway 65 (MN65) indicate an area of low sensitivity, likely due to the thick fine-grained sc till unit at the surface in this area. On the eastern edge of the cross section, stacked sands and high-volume municipal pumping steepen groundwater flow gradients in the area, bringing mixed tritium-age water to greater depths than would be present under natural conditions.

B–B'

Buried sand aquifers are the primary groundwater source along this cross section, with some wells completed in the Mt. Simon and Hinckley aquifers in the center. Groundwater flow is primarily downward and from west to east across the western half of the cross section. Along the eastern half of the cross section, the flow is primarily downward, with some localized flow toward the west in the center near Ties Creek. Mixed tritium ages and anthropogenic chloride up to depths of 100 feet west of MN65 indicate an area of increased sensitivity. Elsewhere, premodern tritium-aged water and an estimated carbon-14 age of 3,500 years suggests lower sensitivity.

C–C'

Buried sand aquifers are the primary groundwater source along this cross section, with the Mt. Simon aquifer also used in the center and east. Groundwater flow is primarily from west to east across most of the cross section. Near its eastern edge, flow is from east to west toward Little Stanchfield Lake and the deep bedrock valley buried beneath it. Near Minnesota Highway 47 (MN47) and in between Stanchfield Creek and Little Stanchfield Lake, surficial sands and thin intervening tills appear to influence buried sand sensitivity, evident from modern and mixed tritium-age waters and elevated chloride. Elsewhere, premodern tritium-age waters and estimated carbon-14 ages of 1,600 to 1,900 years suggest lower sensitivity.

D–D′ and E–E′

Buried sand aquifers are the primary groundwater source along these cross sections, with some wells completed in the Upper Tunnel City, Wonewoc, and Mt. Simon aquifers. Groundwater flow is primarily from west to east across the western halves of the cross sections. Along the eastern halves, flow is primarily from east to west toward the Rum River, which intersects the cross sections multiple times near their centers.

Both cross sections are dominated by a thick layer of surficial sand (Anoka Sand Plain), which commonly connects to buried sand aquifers. Residence time and anthropogenic indicators are widely variable and found up to depths greater than 200 feet, especially on the eastern sides of the cross sections near Cambridge, where high-volume pumping is likely bringing modern and mixed tritium-age waters to greater depths than present under natural conditions. A sample collected between Spectacle Lake and MN47 on cross section D–D′ had an evaporative signature that indicated recharge from a water source at the land surface, which may be near Spectacle or Green lakes.

Tritium data collected from wells in the center of cross section D–D′ showed an area of lower sensitivity, which could be from older waters moving upwards toward the Rum River in this area. Across both cross sections, there were also premodern tritium-age samples collected from deeper, more protected aquifer sources. One sample near Green Lake on cross section E–E′ also had naturally sourced chloride and an estimated carbon-14 age of 1,100 years, which may indicate a source of brine. Typically, deeper groundwater is older. This trend is shown on the east side of E–E′, where the shallower Wonewoc groundwater sample of 800 years was younger than the deeper Mt. Simon–Hinckley groundwater sample of 1,100 years, collected from the west end of the cross section.

F–F′ and G–G′

Buried sand aquifers are the primary groundwater source along these cross sections, with some wells completed in the Upper Tunnel City, Wonewoc, and Mt. Simon aquifers. Groundwater flow is primarily from west to east, except near the centers where groundwater flow directions are toward the Rum River. Both cross sections are dominated by a thick layer of surficial sand, which connects to buried sand aquifers in the western half of F–F′ and the eastern half of G–G′. High-volume pumping is likely bringing modern tritium-age waters to greater depths than would be present under natural conditions near Cambridge and Isanti.

Premodern tritium-aged water generally exists at 150 to 200-foot depths; however, modern tritium was found intermittently at similar depths. One sample from a well completed in the Mt. Simon, near Isanti on cross section G–G′, had an estimated carbon-14 age of 4,500 years.

H–H′

Buried sand aquifers are the primary groundwater source along this cross section, with some wells completed in the Upper Tunnel City, Wonewoc, and Mt. Simon aquifers. Groundwater flow is primarily west to east across the western portion to the Rum River. East of the Rum River, groundwater flow is to the east-southeast. The cross section is dominated by a thick layer of surficial sand, which connects to buried sand aquifers in the center and east.

A sample collected near Horseshoe Lake on the eastern end of the cross section had an evaporative signature that indicates it recharged from a surficial water source, which could be near Horseshoe Lake.

Modern and mixed tritium-aged waters were commonly found in buried sand aquifers to depths of over 100 feet, except for a sample west of Seelye Brook, where thick glacial till protects buried sand aquifers. A sample collected from the Upper Tunnel City aquifer near Cedar Creek in the east showed some indications of higher sensitivity due to the stacked sands overlying the bedrock or possibly impacts from high-volume pumping in this area. One deep sample collected at the western end of the cross section had a mixed tritium age with a higher sensitivity than expected. Possible reasons may be a corroded or ungrouted well casing leaking shallow groundwater to greater depths, or unknown hydraulic connections to the surface.

Tritium and carbon-14 data collected from wells near the western end of the cross section indicated an area of lower sensitivity, which could be from the presence of thick stacked glacial tills. This lower sensitivity is evident with the estimated carbon-14 dates of samples. The shallow cse groundwater sample is estimated to be 550 years and the deep Mt. Simon–Hinckley sample is 950 years. An even deeper Mt. Simon–Hinckley groundwater sample collected east of Cedar Creek was one of the oldest samples collected in the county, with an estimated residence time of 5,500 years.

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

Specific capacity and transmissivity describe how easily water moves through an aquifer. Larger values indicate more productive aquifers.

Specific capacity is usually determined by pumping a single well and is the pumping rate per unit depth of drawdown. It is typically expressed in gallons per minute per foot (gpm/ft) and determined from short-term pumping or well-development tests performed after a well is drilled.

To ensure that the specific-capacity values reflect actual pumping (not air-lift pumping), the pumping-test data were obtained from the CWI for wells with the following criteria:

- The casing diameter was at least 8 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.

Wells completed in the Wonewoc–Mt. Simon have the highest mean value (34 gpm/ft), followed by the Mt. Simon and Mt. Simon combinations with Hinckley and Fond du Lac (25 gpm/ft). The other aquifers have lower values (3 to 16 gpm/ft) (Table 2).

Transmissivity is an aquifer's capacity to transmit water. It provides a more accurate representation of aquifer properties than specific capacity because it is from longer-term and larger-scale aquifer tests. It is determined by multiplying the thickness of the aquifer by the hydraulic conductivity of the aquifer material (the rate groundwater flows through a unit cross section). Limited aquifer test data is available for wells in Isanti County. The only aquifer test data available were for wells completed in the Mt. Simon and combinations with Hinckley and Fond du Lac with a mean value of 4,500 square feet per day (ft^2/day).

Table 2. Specific capacity and transmissivity of selected wells

Aquifer	Specific capacity (gpm/ft)					Transmissivity (ft^2/day)				
	Casing diam (in.)	Mean	Min	Max	No. of tests	Casing diam (in.)	Mean	Min	Max	No. of tests
Unconsolidated										
Water table	12	11	-	-	1	-	-	-	-	-
Confined buried sand	12	7	5	9	2	-	-	-	-	-
Bedrock										
Tunnel City–Wonewoc	12	14	12	16	2	-	-	-	-	-
Tunnel City–Mt. Simon	10	11	-	-	1	-	-	-	-	-
Wonewoc–Eau Claire	12	16	15	18	3	-	-	-	-	-
Wonewoc–Mt. Simon	8–16	34	17	45	6	-	-	-	-	-
Mt. Simon and combinations with Hinckley and Fond du Lac	10–18	25	4	37	12	16–24	4,500	1,600	7,000	3
Hinckley–Fond du Lac	12	3	-	-	1	-	-	-	-	-

Specific capacity data adapted from the CWI.
Transmissivity data are from aquifer properties data (DNR, 2022)
Dash (-) means no data

Regional recharge evaluation of the Mt. Simon–Hinckley aquifer

The Mt. Simon–Hinckley aquifer is one of the major bedrock sources of groundwater, not only for Isanti County but also a large portion of the Twin Cities Metropolitan Area (TCMA) (Berg and Pearson, 2013).

Even though this aquifer has a large regional extent, multiple overlying glacial till and bedrock aquitards limit recharge. Recharge still occurs, with the best potential where the aquifer directly underlies (subcrops) glacial sediment, shown in Figure 29 with pollution sensitivity colors.

Within the subcrop area, surficial sand hydraulically connected to underlying buried sand aquifers creates areas of enhanced recharge, shown as small areas with very high to moderate pollution sensitivity.

Scattered modern and mixed tritium-age samples indicate some enhanced recharge. The gray area to the southeast represents the portion of the aquifer overlain by at least one bedrock aquitard. Modern and mixed tritium-age water in this area, where the aquifer is hydraulically isolated by one or more bedrock aquitards, is rare.

The mixed tritium-age samples near the cities of Cambridge and Braham and the modern and mixed tritium-age samples in the city of Isanti may be caused by high-volume pumping that can bring groundwater with shorter residence times to greater depths.

Carbon-14 residence time estimates (Figure 30) also indicate that the Mt. Simon–Hinckley subcrop has the best potential for aquifer recharge. From northeastern Wright County to southern Kanabec County, carbon-14 residence times in the subcrop area are 350 to 6,000 years, with most values in the 950 to 2,500-year range.

Outside the subcrop area, values are 1,500 to greater than 40,000 years. Values of 10,000 to greater than 40,000 years are very common in the core TCMA of southern Anoka, eastern Hennepin, and Ramsey counties. In these core areas, the Mt. Simon–Hinckley aquifer was recharged from the areas of northeastern Wright, eastern Sherburne, and northwestern Isanti counties over many millennia.

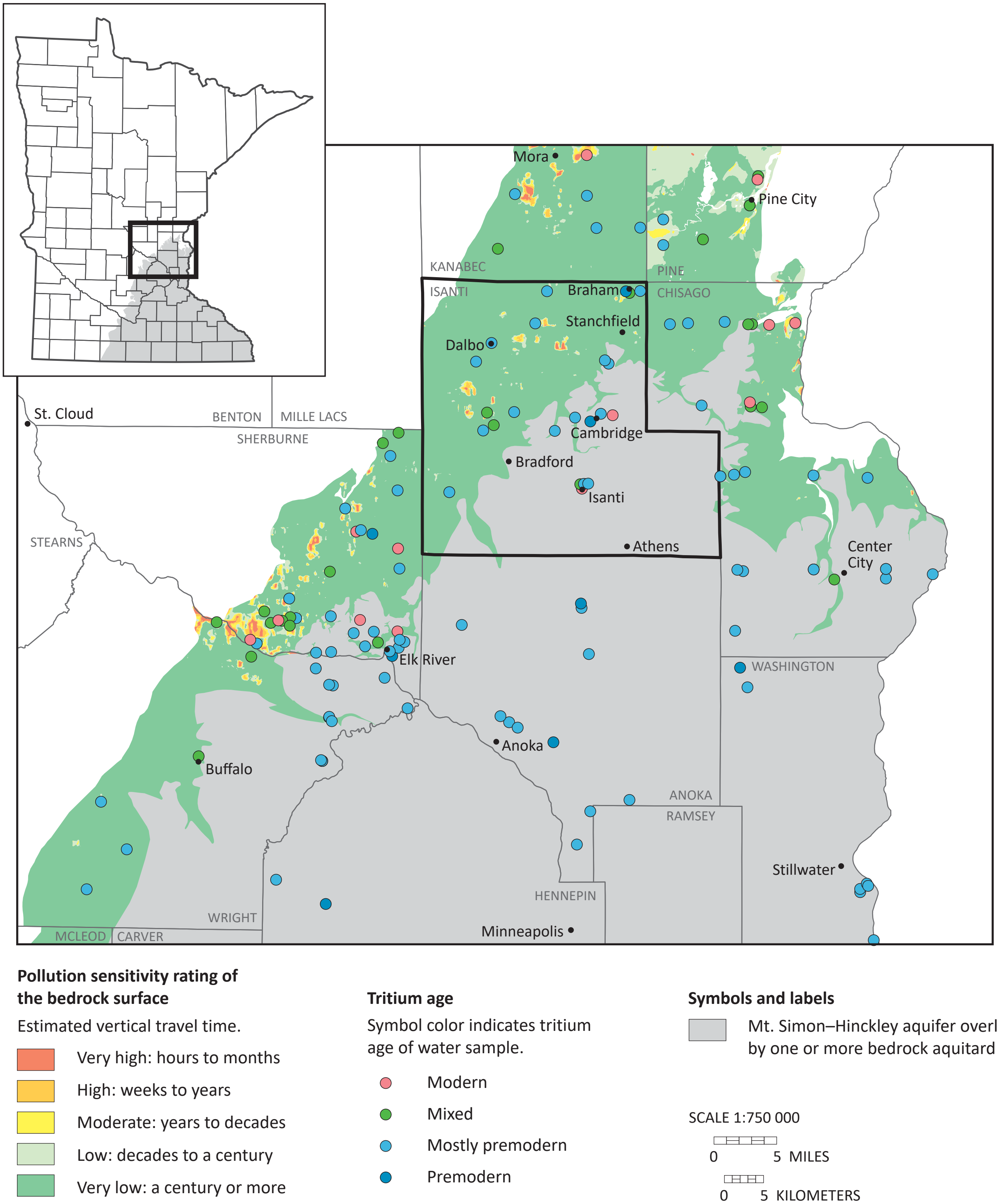


Figure 29. Pollution sensitivity and recharge of the Mt. Simon–Hinckley subcrop

The best potential for enhanced recharge is where the Mt. Simon or Hinckley subcrops beneath overlying glacial sediment. The pollution sensitivity of the bedrock surface represents the subcrop area. The gray area to the southeast illustrates the portion of the aquifer overlain by one or more bedrock aquitards. Within the subcrop area, surficial sand that is hydraulically connected to underlying buried sand aquifers creates areas of focused recharge (shown as very high to moderate sensitivity). Scattered modern and mixed tritium-age samples provide some verification that enhanced recharge is occurring in these areas.

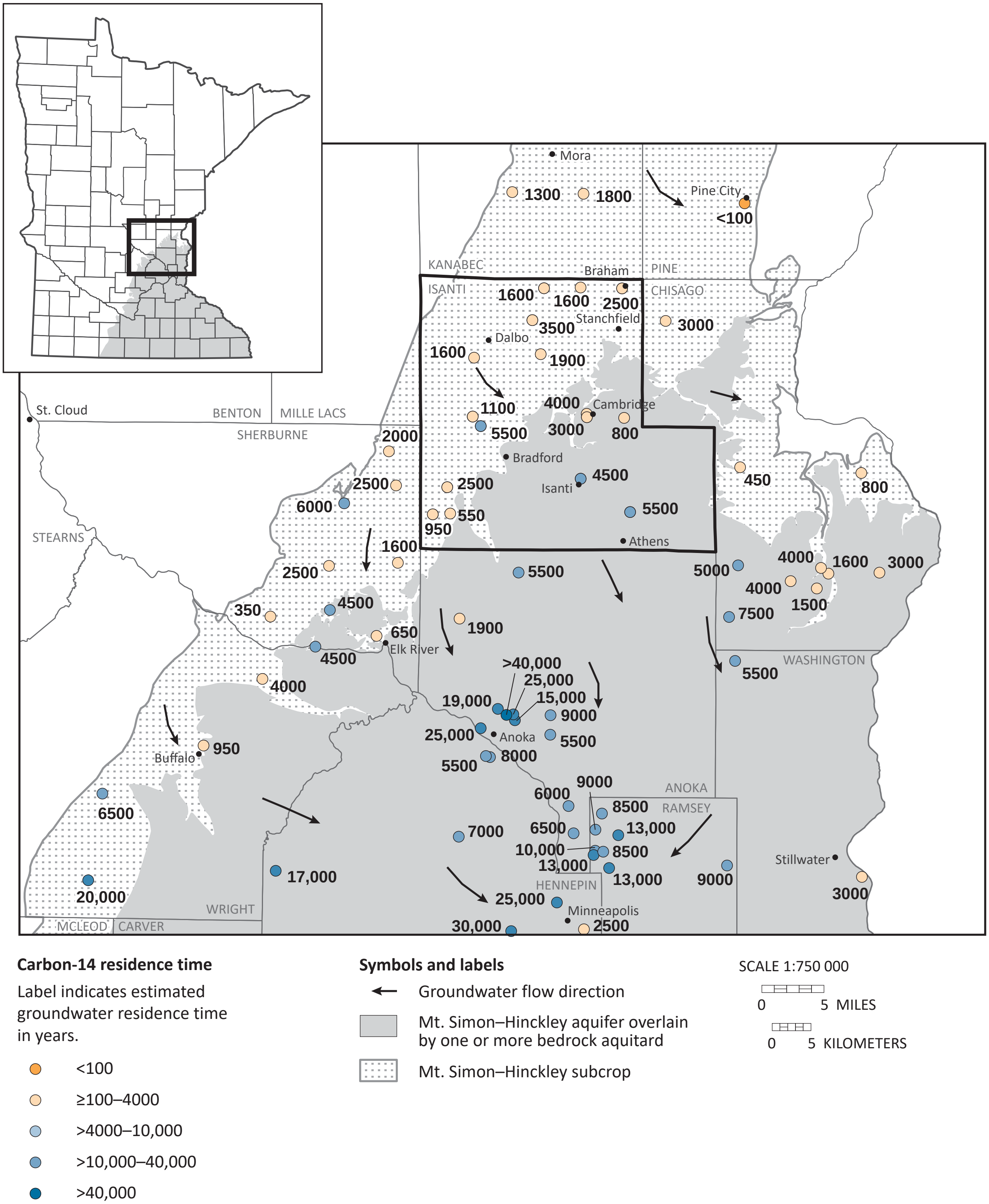


Figure 30. Carbon-14 residence time and groundwater flow of the Mt. Simon–Hinckley subcrop

Carbon-14 residence time estimates indicate that the Mt. Simon–Hinckley subcrop has the best potential for aquifer recharge. The Mt. Simon–Hinckley aquifer in the core TCMA recharged from northeastern Wright, eastern Sherburne, and northwestern Isanti counties over many millennia.

Groundwater level monitoring

The DNR maintains a statewide groundwater level monitoring program to assess groundwater resources, determine long-term trends, interpret the impacts of pumping and climate, plan for water conservation, evaluate water conflicts, and manage water resources.

Hydrographs depict groundwater levels over time. They help determine trends and provide insight into how aquifers respond to recharge events, pumping stresses, and changing climatic conditions.

Hydrographs from *well nests* are often the most useful. Well nests consist of closely spaced wells constructed at different depths. The hydraulic relationship between the different aquifers, known as vertical gradient, is needed to understand groundwater flow and the impacts of water use and other changes on the groundwater system.

Figure 31 shows the locations of the actively monitored DNR observation wells and surrounding permitted appropriations considered in this groundwater level monitoring evaluation (additional information about permitted appropriations is discussed in the groundwater use section). Much of the high-volume groundwater use is from the Mt. Simon–Hinckley aquifer near the cities of Cambridge and Isanti.

Hydrographs (Figures 32 to 34) were created for two well nests and a single well labeled on Figure 31, produced from data retrieved online from the DNR Cooperative Groundwater Monitoring Program (DNR, 2021a). Monthly gridded precipitation data were obtained through the Minnesota State Climatology Office (DNR, 2021b).

Location 1 on Figure 31 is a well nest in the southwest corner of the county that has a relatively shallow (39 feet) surficial sand well and a deeper Mt. Simon–Hinckley well (312 feet). Both hydrographs (Figure 32) show similar annual patterns primarily controlled by precipitation. Groundwater elevation response to recharge in the surficial sand aquifer is greater than the Mt. Simon–Hinckley. The surficial sand aquifer groundwater elevation over the period of record ranges approximately 9.5 feet from highs to lows, whereas the Mt. Simon–Hinckley range is approximately 4 feet. Groundwater elevations of these aquifers differ by approximately 5 feet, showing a vertical hydraulic gradient downward from the surficial sand to the Mt. Simon–Hinckley.

Location 2 on Figure 31 is a well nest east of Lory Lake that has a shallow (50 feet) buried sand aquifer well (csa) and a deeper (185 feet) Hinckley well. Both hydrographs (Figure 33) show similar annual patterns primarily controlled by precipitation, with the largest fluctuations during the growing season. Groundwater elevations of the Hinckley well are slightly above the buried sand aquifer, indicating a slight upward gradient.

Location 3 on Figure 31 is a Mt. Simon well in the Cambridge area (Figure 34) that shows groundwater elevations affected by combined groundwater use of the Mt. Simon and Hinckley aquifers. From 2005 to 2007, cumulative groundwater use in a 3-mile radius of the well increased from approximately 100 million gallons per year (mgy) to approximately 400 mgy. In 2005, when groundwater use in the 3-mile radius approximately doubled, groundwater elevations in the Mt. Simon observation well dropped approximately 6 feet and have remained near this lower level to the end of the record period in 2020.

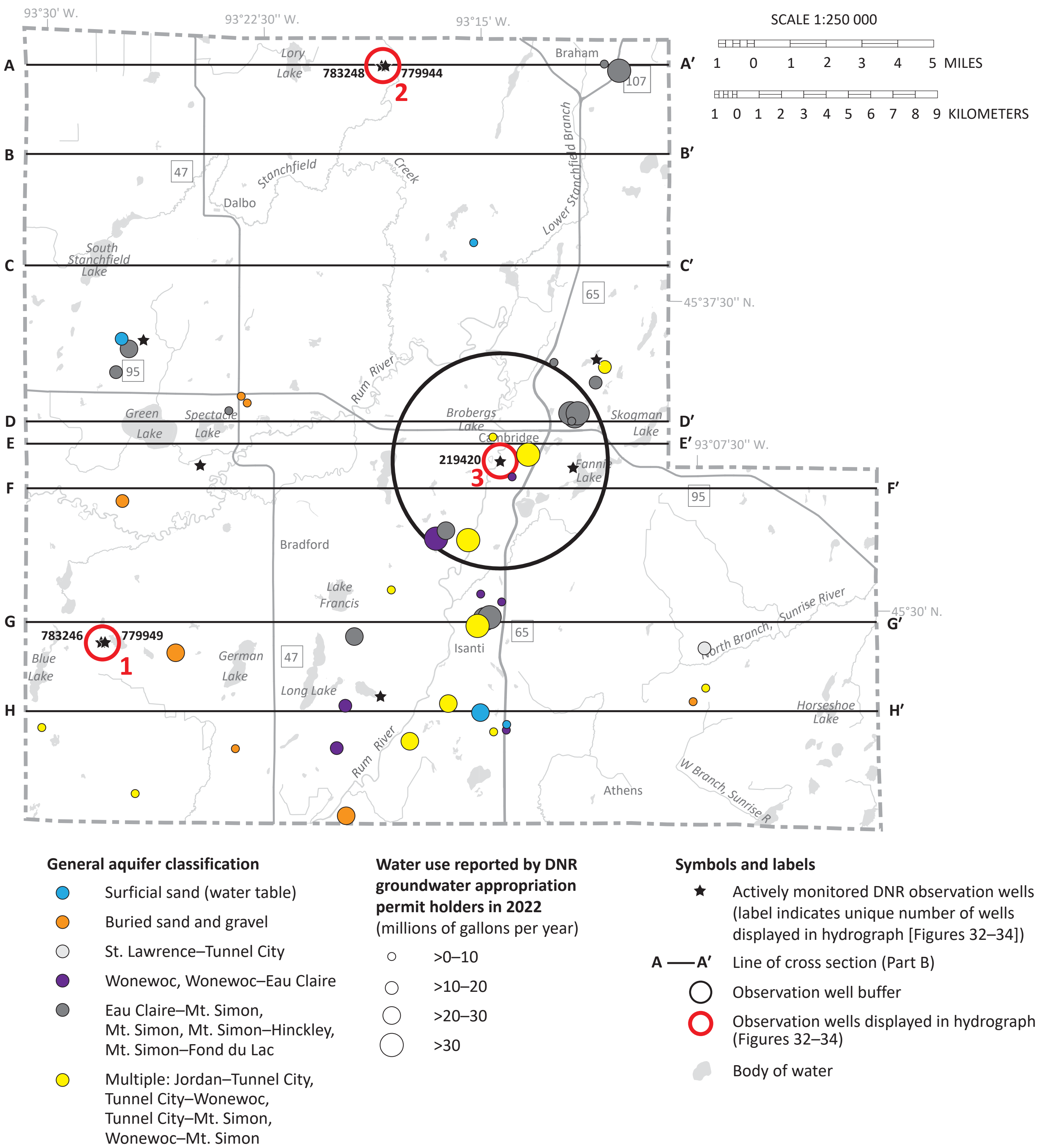


Figure 31. Groundwater appropriation permits shown by aquifer group and observation well locations

This figure shows the well nest locations and surrounding permitted appropriations considered in the groundwater level monitoring evaluation. Much of the high-volume groundwater use is from the Mt. Simon–Hinckley aquifer, near the cities of Cambridge and Isanti. The red circles denote the locations of hydrographs illustrated in Figures 32 to 34.

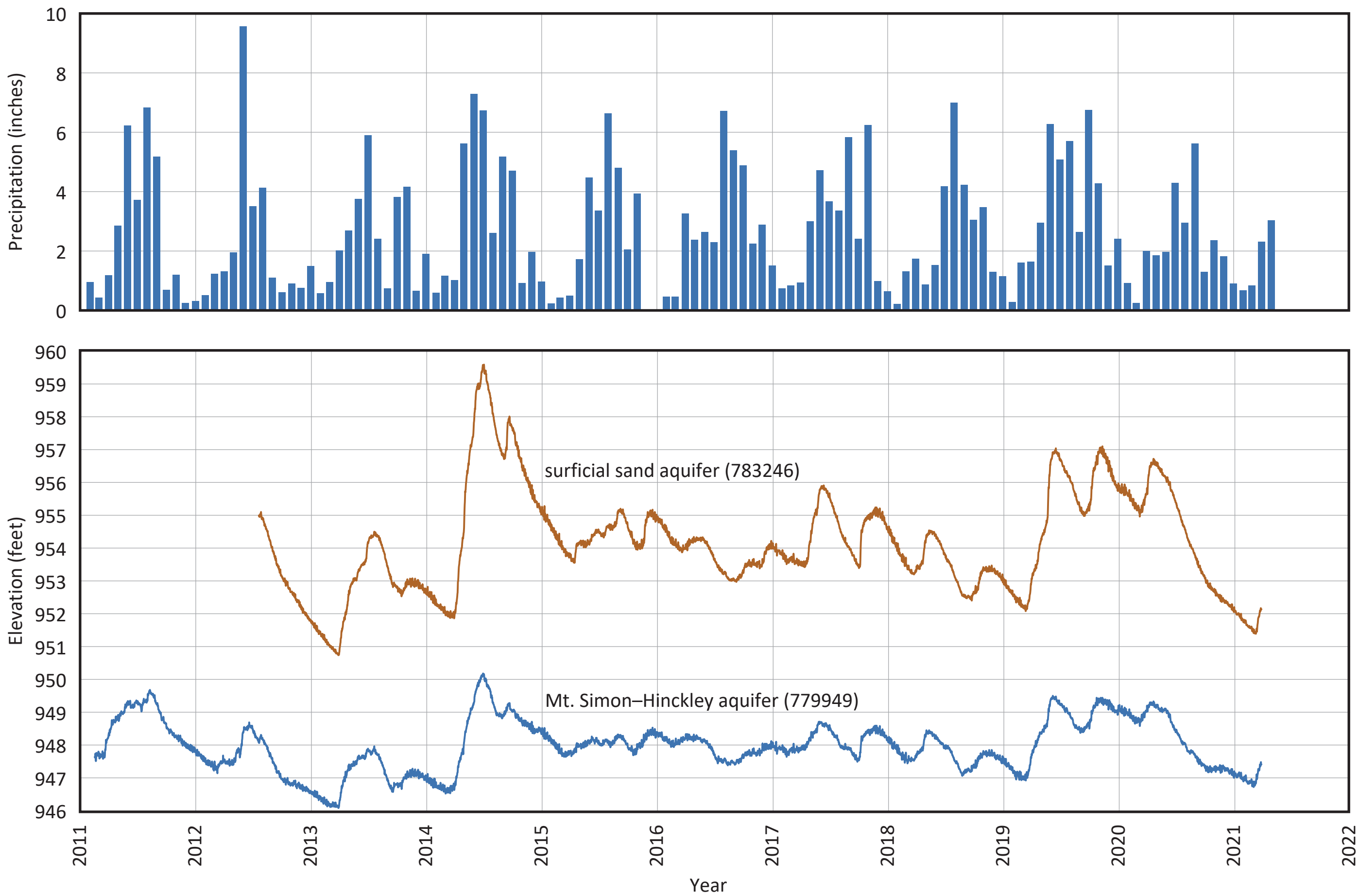


Figure 32. Hydrograph of precipitation and groundwater elevation of a well nest at location 1 in southwest Isanti County

Both hydrographs show similar annual patterns, primarily controlled by precipitation. The groundwater elevation values from the surficial sand aquifer are higher than those of the Mt. Simon–Hinckley aquifer, indicating a downward gradient and local recharge of the deeper aquifer.

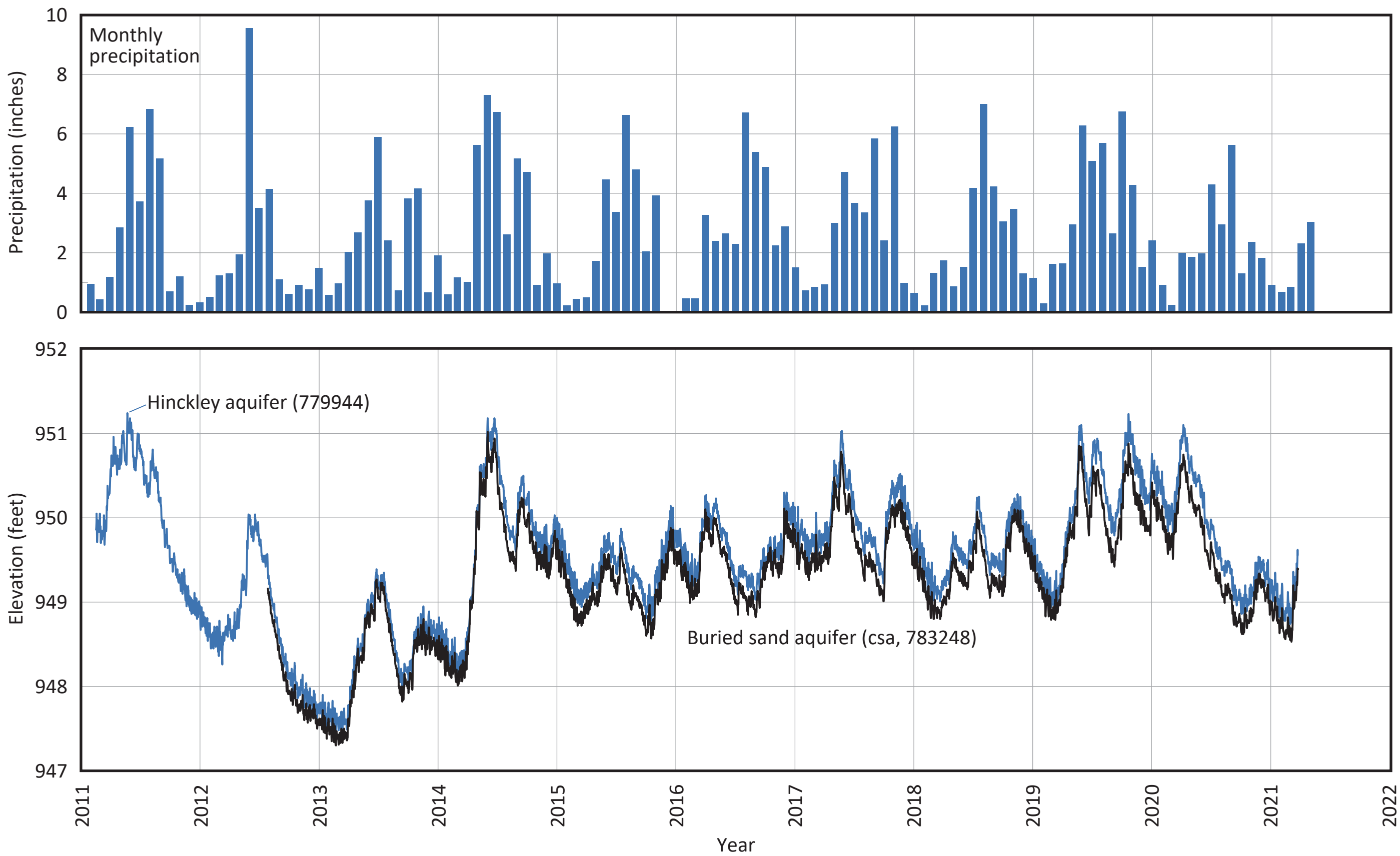


Figure 33. Hydrograph of precipitation and groundwater elevation of a well nest at location 2 in northern Isanti County

Both hydrographs show similar annual patterns, primarily controlled by precipitation. The groundwater elevations from the Hinckley well are the same as or slightly above the buried sand aquifer, indicating a slight upward gradient.

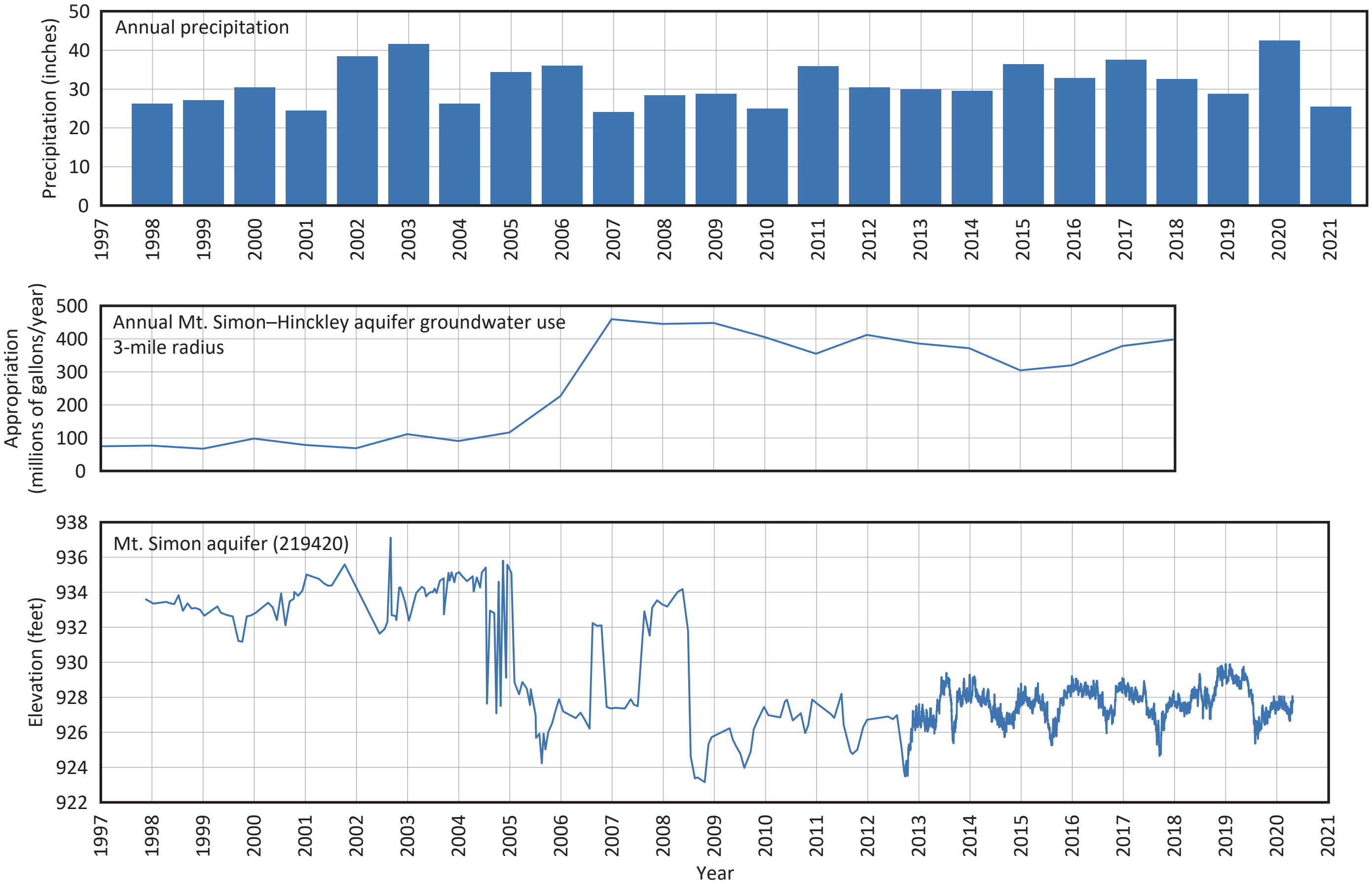


Figure 34. Hydrograph of precipitation, groundwater use, and groundwater elevation of a well at location 3 near Cambridge

The Cambridge area observation well shows elevation dropped in 2005 by approximately 6 feet and has remained at this lower level to the end of the record period in 2020. This drop could be due to the increase of cumulative groundwater use by approximately 300 mgy in nearby pumping wells from 2005 to 2007.

Groundwater use

The Minnesota CWI provides information for the 5,663 wells in Isanti County. Of the wells with identified aquifers, most were completed in the buried sand aquifers (67%), followed by bedrock aquifers (26%) and surficial sand aquifers (7%). By total number of wells, 94% are domestic, 2% are public water supply, 1% are irrigation, and less than 1% are commercial/industrial.

A water appropriation permit is required from the DNR for groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year. This allows the DNR to assess which aquifers are being used and for what purpose. Permits require annual water-use reporting. This information is recorded using the Minnesota Permitting and Reporting System (MPARS), which helps the DNR track the volume, source aquifer, and type of water use (DNR, 2024).

Permitted groundwater use is presented by water use category in Table 3 and Figure 35. Aquifers are listed in Table 3 and Figure 31 by general aquifer type. The highest volume use by general aquifer type is from combinations of the Mt. Simon–Hinckley aquifer and adjoining units, such as the Eau Claire and Fond du Lac (58%), then multiple bedrock aquifer combinations that are completed across regional aquitards (21%).

The most common water use by volume is for water supply (55%). Much of this use is in the area near the cities of Cambridge and Isanti. Agricultural irrigation (37%) is also a relatively common at locations dispersed across the southern half of the county.

Table 3. Reported 2022 water use from DNR groundwater permit holders

		Use (mgy)						
Aquifer	**No. of wells**	**Agricultural irrigation**	**Industrial processing**	**Noncrop irrigation**	**Special categories (livestock watering and power generation)**	**Water supply**	**Total (mgy)**	**Total (%)**
Unconsolidated								
Water table	2	39.4	--	--	--	--	39.4	4
Confined buried sand	9	79.3	--	--	--	4	83.3	8
Bedrock								
St. Lawrence–Tunnel City	1	13.6	--	--	--	--	13.6	1
Wonewoc, and Wonewoc–Eau Claire	7	67.1	2.1	5.4	--	9.3	83.9	8
Eau Claire–Mt. Simon, Mt. Simon, Mt. Simon–Hinckley, Mt. Simon–Fond du Lac	16	64.6	--	3.5	22	530.1	620.2	58
Multiple*: Jordan–Tunnel City, Tunnel City–Wonewoc, Tunnel City–Mt. Simon, Wonewoc–Mt. Simon	12	132.8	44.2	2.6	--	47.6	227.2	21
Total (mgy)	**N/A**	**396.8**	**46.3**	**11.5**	**22**	**591**	**1,067.6**	**N/A**
Total (%)	**N/A**	**37**	**4**	**1**	**2**	**55**	**N/A**	**N/A**

Data from MPARS; mgy, million gallons per year; dash marks (--) indicate no use; N/A indicates not applicable
Percentage might not equal 100 due to rounding.
*Wells in this category are open to multiple aquifers that cross an aquitard.

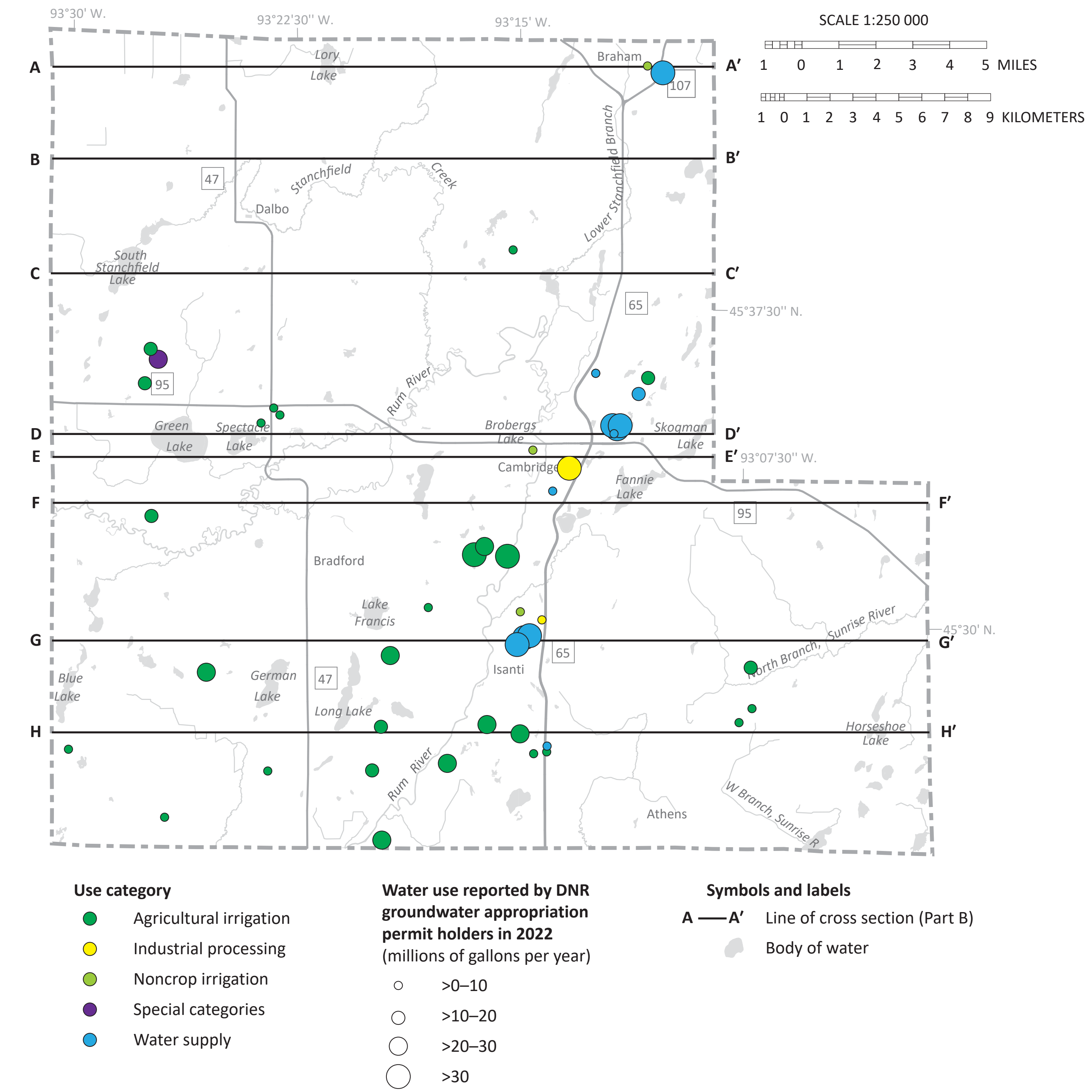


Figure 35. Groundwater appropriation permit holders by water use

The most common use by volume is for water supply (55%). Much of this use is for the cities of Cambridge and Isanti. Agricultural irrigation (37%) is also a relatively common use at locations dispersed across the southern part of the county.

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Glossary

air-lift pumping—water is pumped from a well by releasing compressed air into a discharge pipe (air line) lowered into the well. It is commonly used only for well development, not water production.

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

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

aquitard (or confining layers)—a low permeability geologic layer that slows groundwater movement between aquifers.

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

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

brine—highly saline water.

buried aquifer—a body of porous and permeable sediment separated from the land surface by low permeability layer(s).

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 less than 100 to greater than 40,000 years before the 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.

clast—an individual constituent, grain, or fragment of a sediment or rock, produced by the mechanical or chemical disintegration of a larger rock mass.

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. It 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.

denitrification—is a microbially facilitated process where nitrate (NO_3^-) is ultimately reduced to nitrogen gas (N_2). Typically, denitrification occurs in anoxic environments, where the concentration of dissolved oxygen is depleted.

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

equipotential contour—a line along which the pressure head of groundwater is the same. Groundwater flow is perpendicular to these lines in the direction of decreasing pressure.

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

fractionation—a separation process in which a mixture (solid, liquid, solute, suspension, or isotope) is divided based on the difference of a specific property of the components. Stable isotopes are fractionated by mass.

groundwater—water that collects or flows beneath the surface of the earth, 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.

hydraulic—relating to water movement.

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

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

hydrograph—a graph showing characteristics of water with respect to time. A stream hydrograph commonly shows the rate of flow. A groundwater hydrograph shows water level, head, or water-use volume.

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 a different number of neutrons.

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

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

Paleozoic—an era of geologic time from approximately 541 to 251 million years ago.

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

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

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

residence time indicators—chemical or isotope used to interpret groundwater residence time.

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

stable isotope—chemical isotopes that are not radioactive.

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

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

till—unsorted glacial sediment deposited directly by ice. It is derived from the erosion and entrainment of rock and sediment.

tritium (^3H)—a radioactive isotope of hydrogen that has a half-life of 12.32 years. The nucleus of tritium contains one proton and two neutrons. It is used to identify groundwater that entered the ground since the 1950s.

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

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

unconsolidated—sediment that is loosely arranged, where the particles are not cemented together.

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

upgradient—an area that has a higher potentiometric surface (hydraulic head) than a reference point of interest.

watershed—the area of land that drains into a specific downstream location.

well nest—two or more wells in close proximity completed at different depths.

Appendix A

Groundwater field sample collection protocol

The DNR collected groundwater samples for the project from an outside faucet or hydrant. The wells were purged before sampling to remove stagnant water from the well casing and plumbing system. Samples were collected after the following field parameters had stabilized: temperature, dissolved oxygen, conductivity, oxidation-reduction potential, and pH. Each sample was filtered and preserved according to the protocols listed below and submitted for laboratory analysis.

Samples were analyzed by DNR staff, the Minnesota Department of Agriculture (MDA), or the University of Waterloo Environmental Isotope Laboratory (Waterloo). The University of Minnesota (UMN) assisted in the collection and data analysis of carbon-14 samples.

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

Appendix Table A. Groundwater field sample collection and handling details

Parameter	Tritium (^3H)	^{18}O and Deuterium (^2H)	Nitrate/Nitrite & Total Phosphorus	Br, F, Cl, SO_4	Metals	Alkalinity	Carbon-14 (^{14}C)
Lab	**Waterloo**	**Waterloo**	**MDA**	**MDA**	**MDA**	**DNR**	**UMN**
Sample container	500 ml HDPE	60 ml HDPE	250 ml plastic	250 ml plastic	250 ml plastic	500 ml plastic	30 or 55 gallon plastic-lined drum
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
Preservation	none	none	Sulfuric acid (H_2SO_4) to pH <2, cool to ≤6°C	Cool to ≤6°C	Nitric acid (HNO_3) to pH <2***	Cool to ≤6°C, if not analyzed onsite	NH_4OH to pH 10 to precipitate carbonate
Holding time	long	long	28 days	28 days	6 months	24 to 48 hours	long
Field duplicate	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	none
Field blank	none	none	1 for every 20 samples****	1 for every 20 samples****	1 for every 20 samples****	none	none
Storage duplicate	yes	yes	no	no	no	no	no

*Rinse the bottle three times with filtered sample water before collection. Rinse means fill the bottle with sample water and then pour the contents out over the cap.

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

***Sample bottle is stored at 0 to 6°Celsius (C) for convenience. Refrigeration is not required.

****Use deionized water from designated lowboy for blanks. Attach lowboy to the inline filter with a 3/8-inch tube and purge 1 liter of water to rinse the tubing and filter. Rinse and fill the bottles through the filter with the procedures outlined above.

Appendix B

Tritium values from precipitation and surface water

Samples were analyzed for enriched tritium by the University of Waterloo Environmental Isotope Laboratory to determine atmospheric values. Samples came from two main sources:

- **Precipitation** (daily or composite) was collected at two DNR gages in Minnesota: the Minnesota DNR MNgage precipitation monitoring station MWDM5 in Maplewood (Twin Cities metropolitan area) and the DNR Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) precipitation monitoring station MN-SL-137 in Hibbing. Precipitation was collected daily, and most samples were composited for approximately 30 days.
- A **lake-water** sample was collected near the shore, where the water depth is approximately 1 meter.

For additional tritium information, contact the DNR Groundwater Atlas Program (mndnr.gov/groundwatermapping).

For additional weather station information, contact the administering program.

- MNgage (climateapps.dnr.state.mn.us/HIDENsityEdit/HIDENweb.htm)
- CoCoRaHS (cocorahs.org)

Appendix Table B: Enriched tritium results

Sample location	Sample date range	Tritium (TU)	Sample type
MNgage precipitation station (MWDM5)	05/21/2012–06/20/2012	8.7	Precipitation composite
	09/30/2012–10/30/2012	6.7	Precipitation composite
	05/09/2014–06/09/2014	7.0	Precipitation composite
	10/01/2014–10/31/2014	6.7	Precipitation composite
	05/01/2015–05/31/2015	5.3	Precipitation composite
	08/17/2016–09/16/2016	8.3	Precipitation composite
	04/01/2017–04/30/2017	8.1	Precipitation composite
	09/06/2017–10/06/2017	6.5	Precipitation composite
	10/03/2018–11/01/2018	3.7	Precipitation composite
	4/11/2019	13.4	Snow
	04/04/2019–05/04/2019 (excluding 04/11/2019)	12.1	Precipitation composite
	09/09/2019–10/03/2019	5.0	Precipitation composite
	09/01/2020–09/30/2020	7.7	Precipitation composite
CoCoRaHS precipitation station (MN-SL-137)	09/01/2020–10/01/2020	8.1	Precipitation composite
South Stanchfield Lake	08/09/2018	6.3	Littoral zone

Tritium-age methodology

The method to calculate tritium age was revised in 2020 due to decreasing tritium in the atmosphere. This changed the nomenclature for subsequent atlases.

Atlases C-1 through C-39 use the method from *Residence times of Minnesota groundwaters* (Alexander and Alexander, 1989) with the terms recent, mixed, and vintage tritium age.

Atlases from C-40 on use the method from *Tritium age classification–revised method for Minnesota, GW-05* (DNR and MDH, 2020) with the terms modern, mixed, and premodern tritium age.

The following is true for the purposes of all atlases.

- **Pre-1953** groundwater recharge is implied by both ***vintage*** and ***premodern*** tritium age.
- **Post-1953** groundwater recharge is implied by both ***recent*** and ***modern*** tritium age.

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