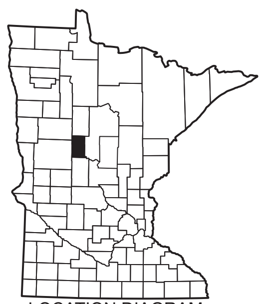
Groundwater Atlas of Wadena County, Minnesota

County Atlas Series C-40, Part B - Hydrogeology



Report

To accompany these atlas components:

Plate 6, Water Chemistry

Plate 7, Hydrogeologic Cross Sections

DEPARTMENT OF NATURAL RESOURCES

St. Paul 2024

mndnr.gov/groundwatermapping

The County Atlas Series

The Minnesota County Geologic Atlas Series has been produced since 1982. Recent atlases are produced in two parts: Part A: Geology, and Part B: Groundwater (this atlas). Note that before 2019, Part B was titled "*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 Wadena County, Minnesota, C-40, Part A* (Lusardi, 2016), published by the Minnesota Geological Survey. It contains Plate 1, Data-Base Map (Bauer and Chandler); Plate 2, Bedrock Geology (Radakovich and Chandler); Plate 3, Surficial Geology (Lusardi and Marshall); Plate 4, Quaternary Stratigraphy (Lusardi and Marshall); Plate 5, Bedrock Topography, Depth to Bedrock, and Sand-Distribution Model (Radakovich, Chandler, Lusardi, Marshall, and Hamilton). Information is available online at the Minnesota Geological Survey County Geologic Atlas page (cse.umn.edu/mgs/county-geologic-atlas).

Part B - Groundwater Atlas

This atlas was published by the Minnesota Department of Natural Resources, which expanded on the geologic information from Part A. Completed atlases and information are available online at the Minnesota Department of Natural Resources, Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

Citation for this atlas:

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Acknowledgments

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The author is grateful for the reviews provided by Melinda Erickson, United States Geological Survey; Jay Frischman and Robert Guthrie, Minnesota Department of Natural Resources; Gail Haglund, Minnesota Department of Health; Kimberly Kaiser, Minnesota Department of Agriculture; Nicole Lundeen, East Otter Tail/Wadena Soil and Water Conservation District; and Anthony Runkel, Minnesota Geological Survey. Their feedback helped greatly improve this atlas.

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 at 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 title, boundaries, or locations of improvements.

Base maps were modified from the Minnesota Geological Survey, *Geologic Atlas of Wadena County, Minnesota,* 2016. 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 x 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 Wadena County, Minnesota

by Nicholas R. Budde and Vanessa M. Baratta-Person

Executive summary

This report and the accompanying plates describe the groundwater characteristics of the county and were produced by the Minnesota Department of Natural Resources (DNR). They build on the geology described in Part A, previously published by the Minnesota Geological Survey (MGS) (Lusardi, 2016).

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. The following summarizes key elements and findings.

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

Hydrogeology and groundwater flow (pages 5 to 21) 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).

Surficial sand and gravel aquifers are found in extensive glacial outwash plains across much of the county. Buried sand and gravel aquifers consist of glacial outwash channels buried by glacial till or other sand and gravel aquifers.

Surficial and buried sand and gravel aquifers are abundant, and productive aquifers are often encountered at shallow depths. Consequently, less aquifer data is available at greater depth. Bedrock is rarely used as a water source because it is deeply buried by glacial deposits.

Groundwater flow direction of the water table is typically consistent with surface-water flow and moves from topographic highs toward lows occupied by streams, lakes, and wetlands. Groundwater flow direction of buried aquifers is broadly toward the southeast with localized flow toward rivers.

Water chemistry (pages 22 to 35, Plate 6) provides information about the following.

Groundwater recharge pathways: recharge from direct infiltration of precipitation that can be distinguished from recharge via surface water.

Groundwater is primarily recharged by direct infiltration of precipitation. However, evidence of recharge via surface water was found in the north.

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

Groundwater with tritium ages reflecting recharge after 1953 was generally found in surficial and buried sand and gravel aquifers up to 150 feet below the land surface in the north, decreasing to 60 feet below the land surface in the south.

Groundwater with tritium ages reflecting recharge before 1953 was generally found in buried sand and gravel aquifers at depths over 150 feet below the land surface in the north and at decreasing depths to 60 feet below the land surface in the south. Carbon-14 residence times for a subset of samples ranged from less than 100 to greater than 40,000 years.

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

Chloride and nitrate concentrations suggest that groundwater is affected by anthropogenic sources, primarily in areas where sand is the surficial geologic unit. Nearly all the samples influenced by anthropogenic sources were collected from shallow wells (less than 100 feet deep) where crop cultivation, developed land, or roadways were nearby land uses.

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

Naturally sourced chloride, possibly from unmapped Cretaceous bedrock, was identified in several samples collected from deeply buried aquifers.

Arsenic was detected in over three-quarters of the well water samples. Two of the 103 samples exceeded the drinking water standard of 10 parts per billion.

Manganese was detected in most well water samples; over half exceeded the health-based drinking water guideline of 100 parts per billion.

Pollution sensitivity (pages 36 to 55) is defined as the time required for a contaminant to travel vertically from the land surface to the water table, a buried sand and gravel aquifer, or the bedrock surface. Two models are used to estimate pollution sensitivity. Pollution sensitivity of the **near-surface materials** estimates travel time to the water table. Pollution sensitivity of **buried sand and gravel aquifers** and the **bedrock surface** estimates travel time to a buried aquifer or the bedrock surface.

The pollution sensitivity of **near-surface materials** ranges from high to low. High sensitivity is associated with extensive sand and gravel outwash deposits. Moderate and low sensitivity is associated with sandy till deposits, drumlins, 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. 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 very low, except at a bedrock high north of the city of Verndale.

Hydrogeologic cross sections (pages 56 and 57, Plate 7) illustrate the horizontal and vertical extent of aquifers and aquitards, the relative hydraulic conductivity of aquitards, general groundwater flow direction, and groundwater residence time.

Aquifer characteristics and groundwater use (pages 58 to 66) summarizes specific capacity tests, aquifer tests, water use records, and groundwater level monitoring data.

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 greater than 10,000 gallons per day or 1 million gallons per year.

Agricultural crop irrigation is the largest permitted user of groundwater, accounting for 95% of use in 2021. Use in 2021 was the highest for the years 2017 to 2021 across permitted use types.

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 fluctuate with wet and dry years. Water levels fluctuate rapidly in rivers and water-table aquifers following precipitation. Water takes longer to travel to deeply buried aquifer systems, so the changes are often delayed. 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 provides baseflow to streams and major river systems.

Wadena County is in north-central Minnesota (Figure 1) and had an estimated population of 14,307 on July 1, 2022 (U.S. Census Bureau, 2024). Open water covers approximately 1%, and wetlands cover about 38% of the county's 543-square-mile surface (Dewitz and USGS, 2021). The county lies entirely within the greater Mississippi River Watershed. Surface waters primarily drain to the southeast via the Crow Wing River and Redeye River watersheds, with a small portion in the south draining via the Long Prairie River watershed (Figure 1). All three watersheds join the Crow Wing River before it reaches the Mississippi River, approximately 20 miles to the southeast of the county. Land use varies between forest, pasture, hay, and crop cultivation, with these uses often bisected by wetlands (Dewitz and USGS, 2021).

Wadena County's climate is humid-continental, with warm to hot summers, cold winters, and an annual temperature range typically greater than 130° Fahrenheit (F). Based on 1991 to 2020 climate normals, the June through August average temperature is 66.6°F, with December through February averaging 12.5°F (DNR, 2024). Average annual precipitation is approximately 26.8 inches, which is on the mid-low side of the statewide range of 21 to 38 inches (DNR, 2023a). The region has pronounced wet and dry seasons, with precipitation during the summer approximately more than five times greater than during the 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 30% faster than daily maximum temperatures, and average winter temperatures have risen nearly three times faster than average summer temperatures. Annual precipitation has increased by 2.2 inches since 1895, and intense rainfall events producing daily totals over 1, 2, and 3 inches were more common since 1990 than during any other period on record (DNR, 2024).

Climate projections summarized in the 2014, 2017, 2018, and 2023 National Climate Assessments indicate that Wadena County is predicted to warm by an additional 2.5 to 5°F by 2050, while annual precipitation is predicted to increase by an additional 1 to 2 inches. Short-term variations can be expected, 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.

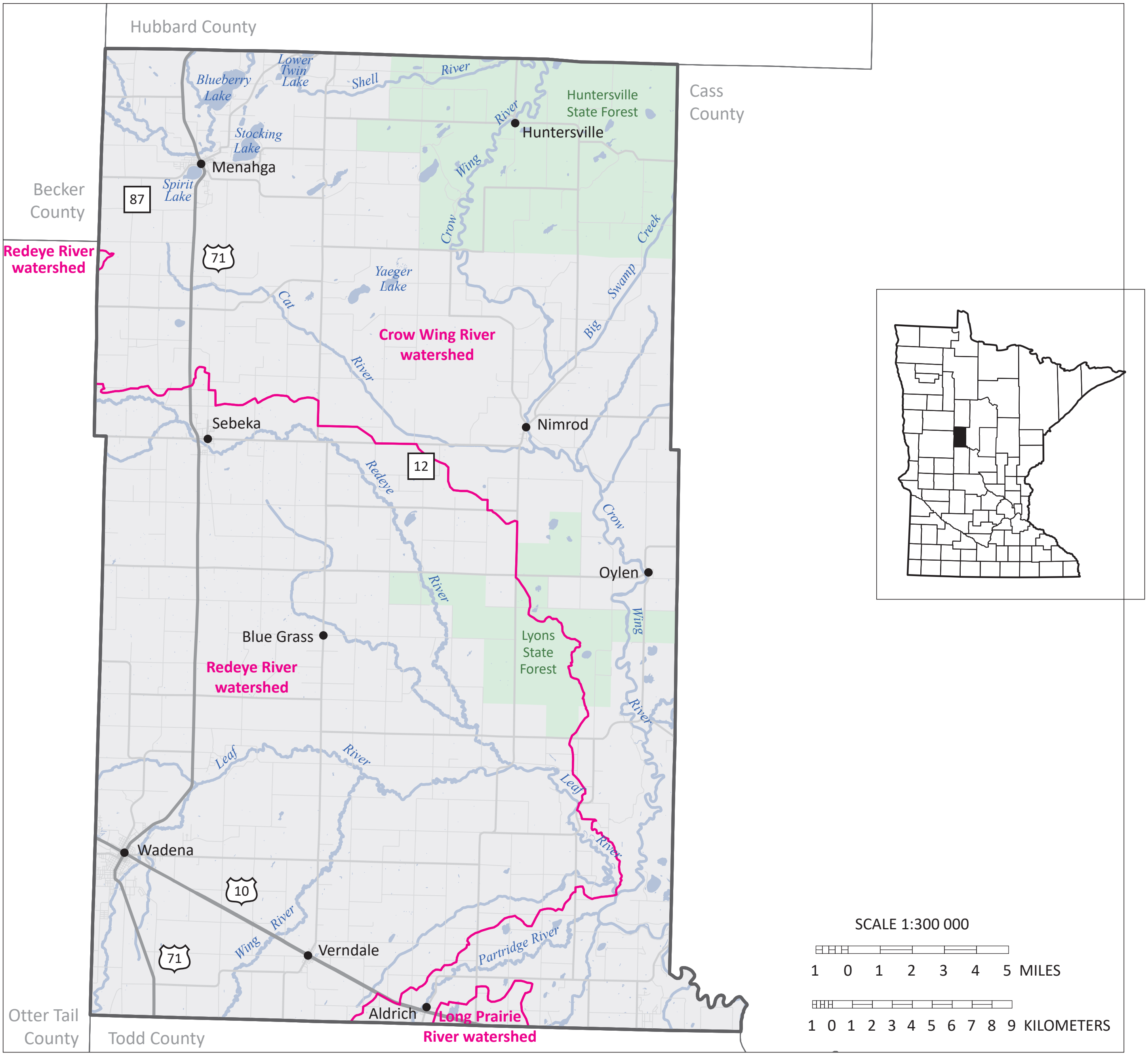


Figure 1. Wadena County, Minnesota

Hydrogeology and groundwater flow

Hydrogeology

Quaternary hydrostratigraphy

This report depicts the geologic units in the **Quaternary unconsolidated** sediment. The Quaternary is the most recent geologic period, encompassing the last 2.6 million years. In Minnesota, sediment deposited during this timeframe includes glacial and postglacial deposits. A stratigraphic column shows the vertical sequence of geologic units found in the county, with the oldest units on the bottom and the youngest on top. These units are depicted in the **hydrostratigraphic column** (Figure 2) as either 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 two textural categories.

1. Sediment mixture of sand, silt, clay, and gravel referred to as till (also diamicton).
2. Fine-grained silt and clay deposited in both ice-walled lakes and depressions.

Relative ranges of groundwater recharge can be inferred from surficial geology textural information. The textural categories described above were combined into three groups (outwash and fluvial sediment, till, and modern lake sediment) to show areas of groundwater recharge potential (Figure 3). The coarse-grained outwash and fluvial sediment readily transmit water and are where groundwater recharge potential is greatest.

Surficial sand aquifers

Sand and gravel aquifers are extensive across much of Wadena County's surface. The latest glacial advance across the county moved in a northeast-to-southwest direction, depositing sandy tills and leaving behind drumlins, which are elongated hills oriented in the direction of glacial flow sometimes buried by later-deposited sand (Part A, Plate 3). As the glaciers retreated northward, glacial meltwater deposited the extensive Park Rapids, Oshawa, and Parkers Prairie outwash plains (Figure 3) (Part A, Plate 3).

After the glacial period ended approximately 11,700 years ago, sand was deposited along modern-day streams, and organic-rich materials were deposited in low-lying areas (Part A, Plate 3). The county's numerous wetlands are often found in depressions called swales between parallel northeast-to-southwest oriented drumlins. Wind-blown sand deposits, sometimes over 20 feet thick, can also be found at the surface, particularly in the northeast (Part A, Plate 3).

Approximately 12% of wells with assigned aquifers are completed in surficial sand and gravel aquifers.

Pineland Sands

The Park Rapids and Oshawa outwash plains largely define the Pineland Sands, an area of intensely irrigated agriculture that covers portions of Becker, Hubbard, Wadena, and Cass counties (Figure 4). The area is characterized by extensive connected surficial and buried sand and gravel aquifers. The DNR identified the Straight River area, which mostly overlays the western part of the Pineland Sands and covers a small portion of northwestern Wadena County, as an area of specific concern where groundwater resources are at risk from overuse and degraded quality. Between 1988 and 2013, there was an 85% increase in water demand in the Straight River area, compared to a 35% increase statewide; agricultural irrigation was the primary driver of this growth (DNR, 2017). In 2017, the DNR established the Straight River Groundwater Management Area (GWMA) (Figure 4) and approved an action plan that sets out objectives and actions the DNR will take to ensure sustainable groundwater use in the area (DNR, 2017).

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. The naming convention for the buried sand and gravel aquifers in this atlas is based on the underlying till unit, as described in the associated Part A atlas (Figure 2).

Locally, some buried sand and gravel bodies directly underlie surficial sand units and may act as unconfined aquifers under water-table conditions. More often, confining layers (aquitards) cover the buried sand and gravel bodies. Confining layers include sediment mixtures of sand, silt, and clay deposited directly by the ice (till) and silt and clay deposited in ponds and lakes. The till units tend to be laterally extensive.

Glacial sediment in the county varies in thickness from approximately 35 to 574 feet. The greatest thickness is primarily in the northeast and north-central over a buried bedrock valley, while the least thick is in the south over several bedrock highs (Part A, Plate 5).

Textural information for the deepest glacial deposits is limited, because well drillers often find water at shallower depths. Therefore, the deepest sediment in some areas is unknown and mapped as undifferentiated sediment (ups). Areas of high uncertainty in buried glacial deposit extents, resulting from limited water well information, are mapped on atlas figures and plates as speculative areas.

Approximately 88% of wells with assigned aquifers 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

Bedrock in the county consists of Precambrian-age metamorphic crystalline rocks, intrusive crystalline rocks, and fine-grained sedimentary rocks locally overlain by much younger Cretaceous-age sandstone and shale (Part A, Plate 2). Little is known about bedrock groundwater supply potential. Only a handful of wells are completed in bedrock because there is typically sufficient water supplied by overlying surficial and buried sand aquifers. Bedrock is typically hundreds of feet below the land surface, and crystalline rocks generally have low primary porosity and limited permeability.

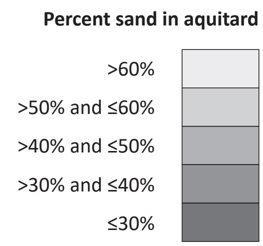
	Part A	Part B	Potentiometric surface figure	Pollution sensitivity figure
Fine-grained surface sediment	sc	sc		
Surficial sand aquifers				
Sandy surface sediment	pgs	pgs		Figure 22
Goose River Formation	gs	gs		
Undifferentiated surficial outwash	ou	ou		
New Ulm Formation	ns	ns		
Hewitt Formation, Itasca Phase	hsi	hsi		
Independence Formation	is	is		
Buried sand aquifers and associated tills				
Hewitt Formation, Alexandria Phase	hta0	hta0	Figure 7	Figure 26
	hsa1	hsa1		
	hta1	hta1		
	hsa2	hsa2	Figure 8	Figure 27
	hta2	hta2		
Unnamed Riding Mountain Formation	usrm	usrm		
	utrm	utrm		
Browerville Formation	brl	brl	Figure 9	Figure 28
	brs1	brs1		
	brt1	brt1		
	brs2	brs2	Figure 10	Figure 29
	brt2	brt2		
	brs3	brs3	Figure 11	Figure 30
	brt3	brt3		
Unknown Superior Formation	uss	uss		
	uts	uts		
Lake Henry Formation, Sauk Centre Member	scs	scs	Figure 12	Figure 31
	sct	sct		
Lake Henry Formation, Meyer Lake Member	mls	mls	Figure 13	Figure 32
	mlt	mlt		
St. Francis Formation	fl2	fl2		
	fs2	fs2		
	ft2	ft2		
Eagle Bend Formation	ebs	ebs	Figure 14	Figure 33
	ebt	ebt		
Unnamed Winnipeg Formation	usw	usw	Figure 14	Figure 34
	utw	utw		
Unnamed Rainy Formation	usr	usr *		
	utr	utr		
Undifferentiated	uns	uns	Figure 14	Figure 35
	ups	ups		

*Unit is not shown on cross sections.

Figure 2. Hydrostratigraphy of Quaternary unconsolidated sediment

This hydrostratigraphic column correlates the unconsolidated geologic units from Part A with the hydrogeologic units of Part B as follows:

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



- ***Fine-grained surficial sediment*** and ***lake clay*** units from Part A are also usually described as ***aquitards*** in Part B, shown in ***dark brown***; these units do not have listed sand contents.
- ***Undifferentiated sediment*** is shown in ***light brown***.

Areas of high uncertainty in buried glacial deposit extents, resulting from limited water well information, are mapped as ***speculative areas***.

The right two columns show the potentiometric surface and pollution sensitivity figures representing each aquifer.

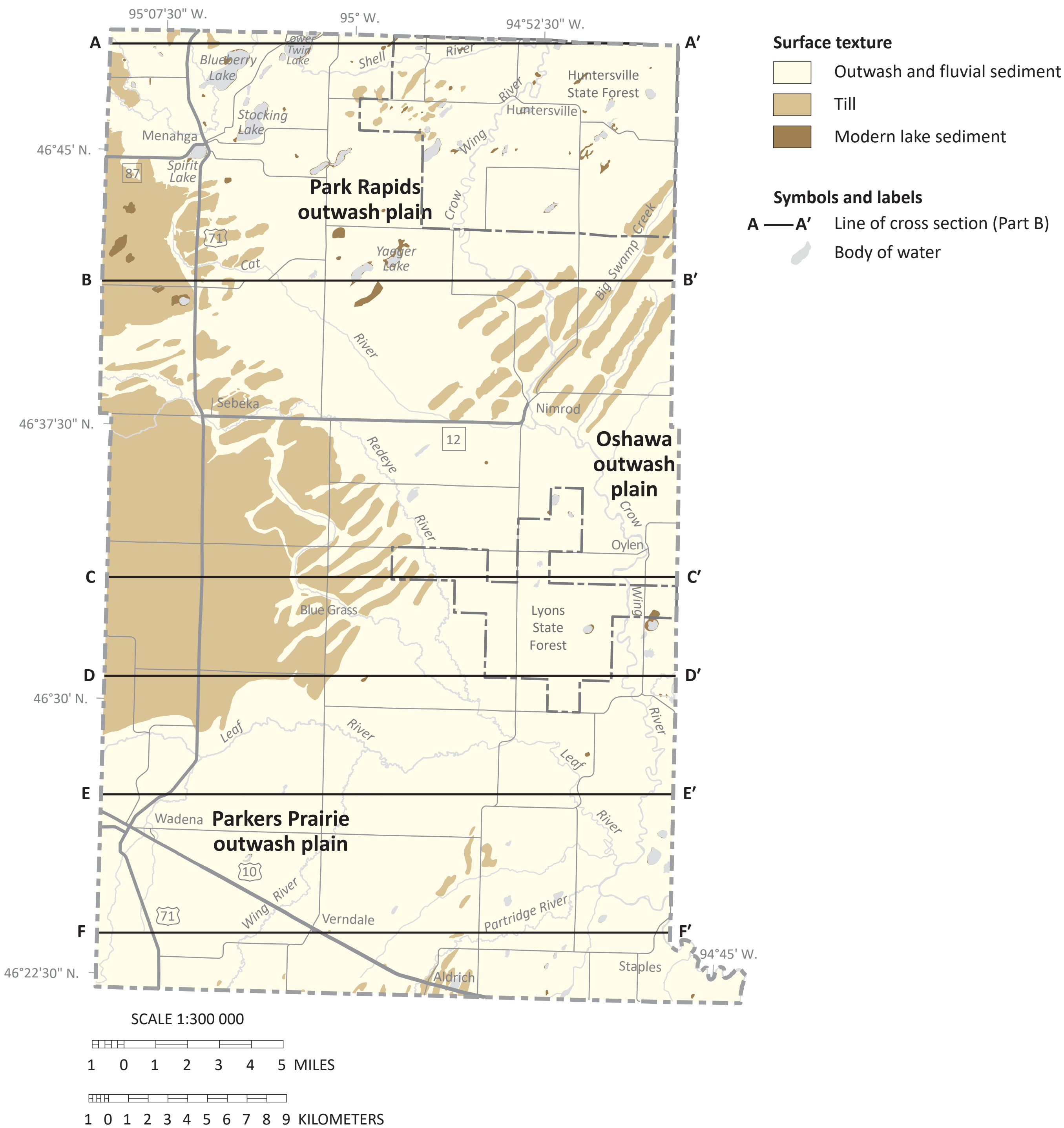


Figure 3. Surficial geologic units – generalized textural classification

Surficial geologic units are grouped by texture into three classifications: outwash and fluvial sediment (sand and gravel), till (a mixture of sand, silt, clay, and gravel), and modern lake sediment (sand, silt, and clay). Outwash and fluvial sediment have the highest permeability and groundwater recharge potential.

Figure 4. Pineland Sands and Straight River GWMA

The Pineland Sands consists of an extensive area of connected outwash sands that stretch across eastern Wadena County and surrounding counties. The mapped extent is from Helgesen (1977).
In 2017, the DNR established the *Straight River GWMA* in the western Pineland Sands as an area of concern where groundwater is at risk of overuse and degraded quality.

Groundwater flow

There are two types of maps illustrating groundwater flow in this report.

1. The **water-table** map illustrates the shallowest groundwater flow where groundwater is unconfined and at equilibrium with atmospheric pressure. Groundwater flows from higher to lower elevations.
2. The **potentiometric surface** maps describe groundwater flow for buried aquifers where groundwater is confined and hydrostatic pressure exceeds atmospheric pressure. Groundwater flows from higher to lower pressure.

Water table

The water table is the surface between the unsaturated and saturated zones where water pressure equals atmospheric pressure. Water-table elevations are contoured similar to land-surface elevations on a topographic map. The water table occurs in both aquifer and aquitard sediment across the entire county. Although it is shown in the figure as a static surface, it fluctuates over time. Surficial sand aquifers are present where there is sufficient saturated thickness and yield to install a well and pump water.

The maps guide many applications, but site-specific information is needed at local scales. The water table is a dynamic system that varies in response to changes in recharge and discharge. Some of these changes include seasonal weather conditions, land-use practices, vegetation composition and distribution, and large groundwater withdrawals.

Water-table elevation (Figure 5) was estimated from several sources of data.

- Elevation of surface-water bodies (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*

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

The water-table elevation is generally a subdued expression of surface topography with flow directions typically consistent with surface-water flow and watershed boundaries. At a county scale, flow is largely to the south and east. Local groundwater flow directions are typically from topographic highs, such as drumlins (Figure 6), to streams, lakes, and wetlands.

Depth to water table (Figure 6) was derived 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).

The water table is commonly less than 10 feet below the land surface. Greater depths to the water table are found along steep slopes in sandy materials (such as along the Leaf River), along the raised northeast-southwest axis of drumlins consisting of sandy till, and broadly in the far north and southeast.

The depth to water table may be overestimated beneath drumlins. This results from contouring data from adjacent lower elevations across localized areas of higher elevation where water-table elevation data are unavailable. Site-specific data would be needed to establish a more accurate depth to water table.

Potentiometric surface

Potentiometric surface maps show the general horizontal 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 elevations of these water levels are contoured similar to land-surface elevations on a topographic map.

The potentiometric surface of an aquifer represents the 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.

Potentiometric surface maps were created using static water-level data from the CWI and measurements made by DNR staff. The CWI records represent water levels collected under various climatic and seasonal conditions from 1942 through 2016 (MGS and MDH, 2017). This data variability creates some uncertainty in potentiometric surface elevations. High-volume pumping wells can also locally influence groundwater flow by drawing groundwater toward the well screen.

Wells associated with buried sand aquifers have a median depth to water of 15 feet below the land surface, and all have depths to water less than or equal to 45 feet below the land surface. Consequently, contouring these water levels produced potentiometric surfaces that generally correspond to surface topography. Groundwater recharges across much of the county surface, with higher rates in areas of sandy sediment. Groundwater flow is broadly toward the south and east, with localized flow toward major rivers, such as the Crow Wing, Cat, Redeye, and Leaf (Figures 7 to 14).

Potentiometric surface maps were not created for the usrm, uss, fs2, and usr aquifers since these aquifers have insufficient well numbers to create meaningful potentiometric surface maps. A combined potentiometric surface map was created for the ebs, usw, and uns aquifers (Figure 14), given the limited number of wells completed in each aquifer and their deeply buried nature.

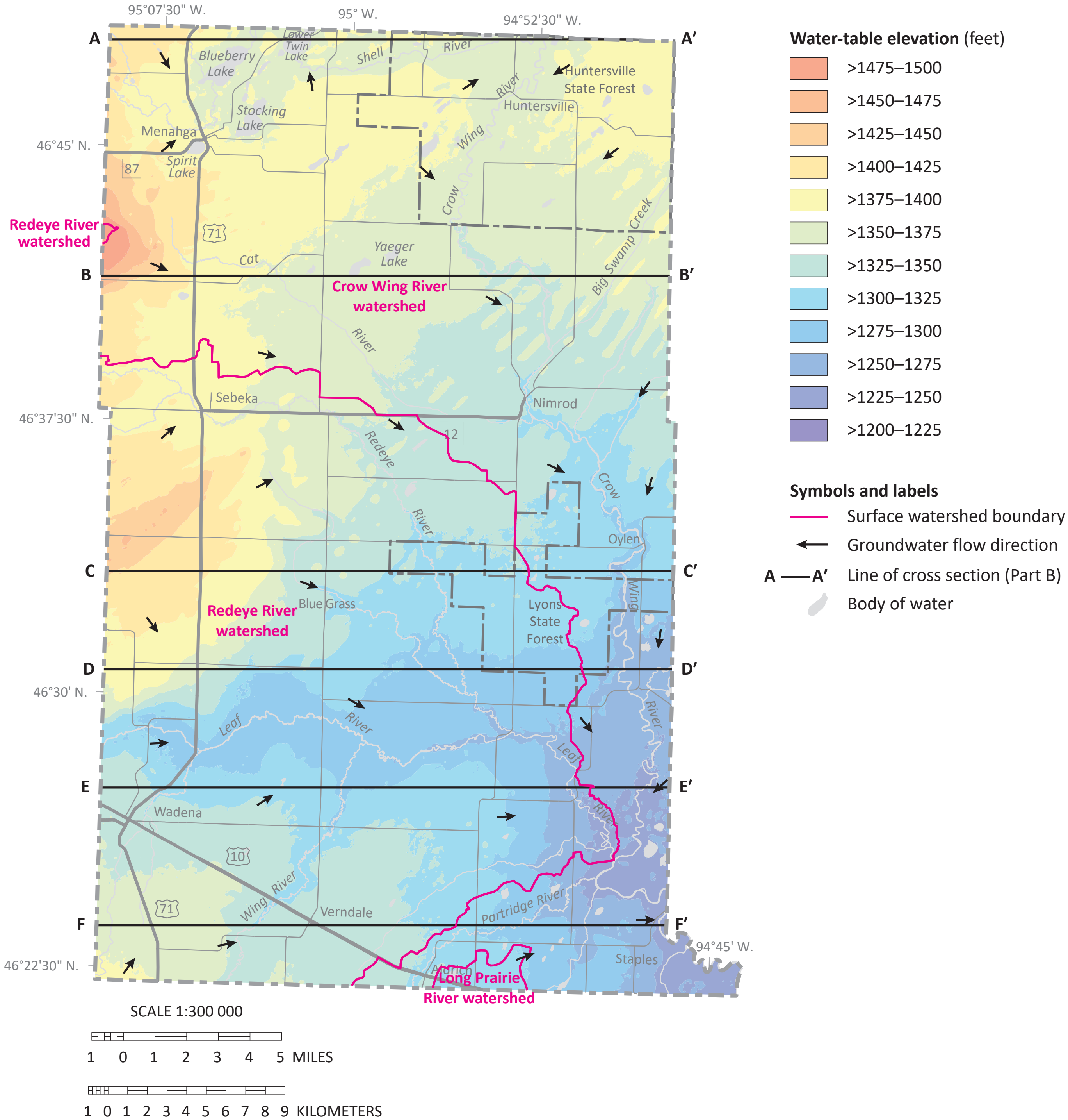


Figure 5. Water-table elevation and groundwater flow directions

Groundwater flow is primarily to the south and east. Locally, groundwater flow direction is from topographic highs to streams, lakes, and wetlands.

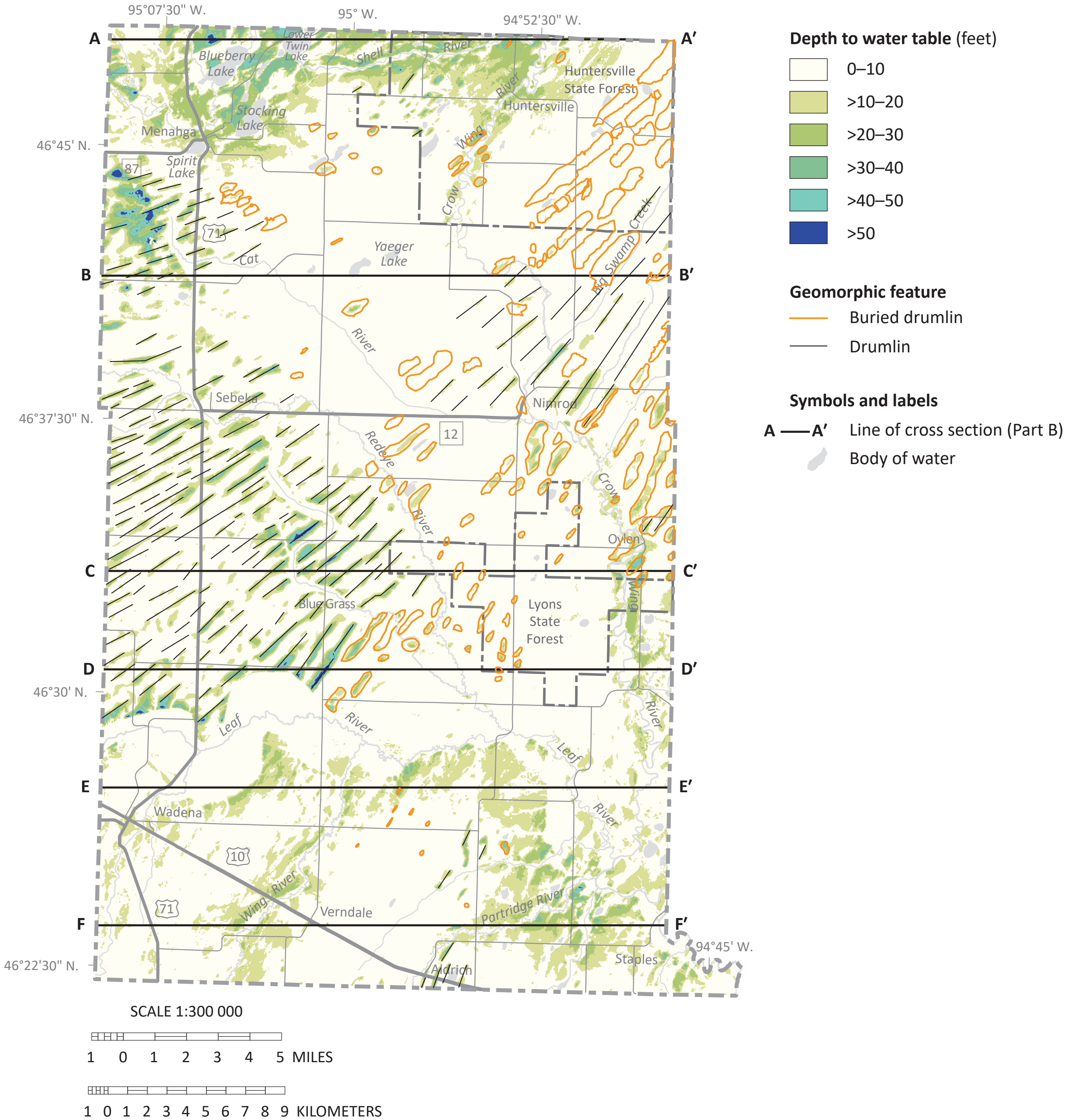


Figure 6. Depth to water table

The water table is commonly less than 10 feet below the land surface, except in areas along steep slopes in sandy materials (such as along the Leaf River), beneath drumlins, and in local areas of sandy sediment with limited water-table information.

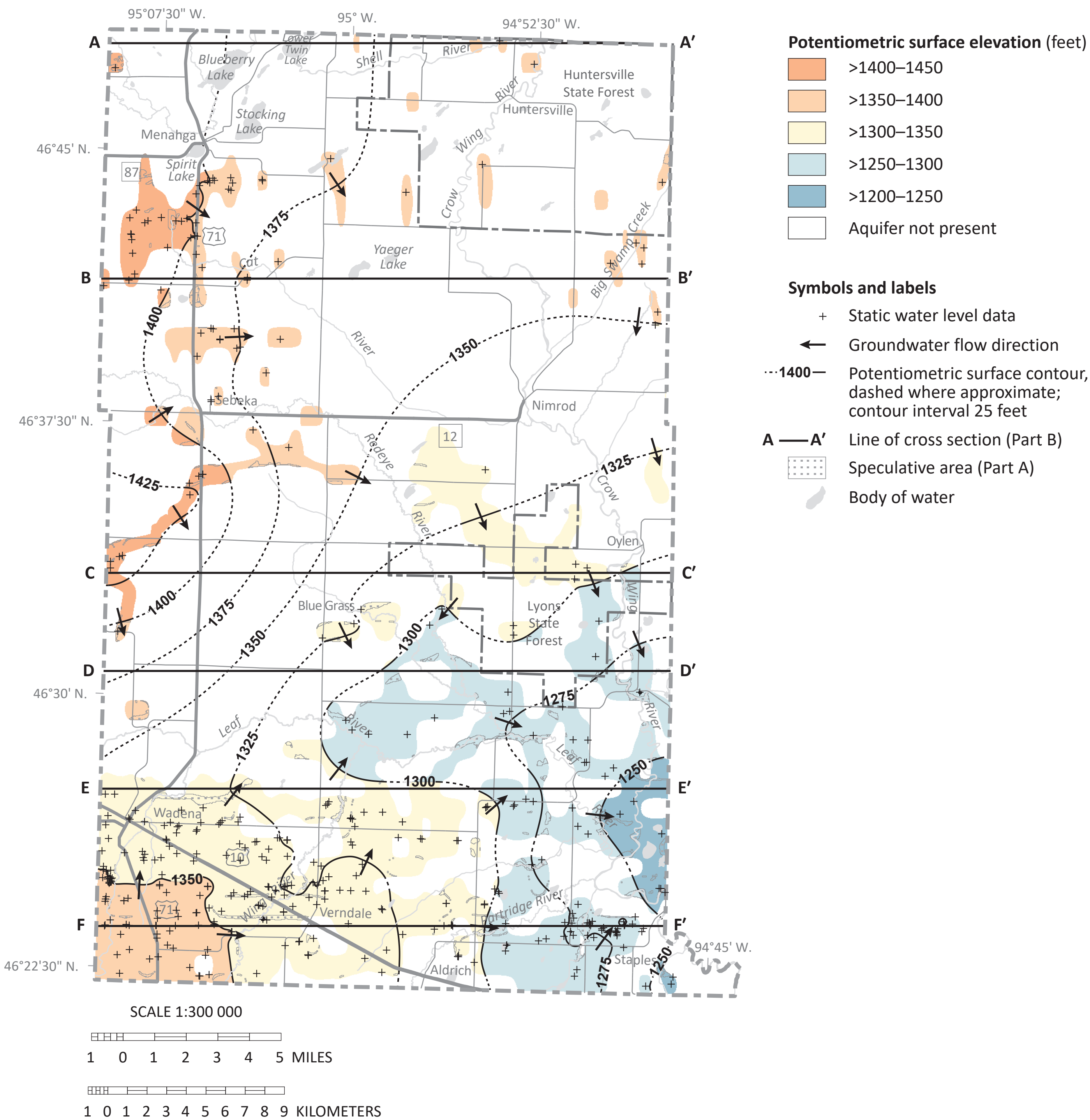


Figure 7. Potentiometric surface of the hsa1 aquifer

Groundwater generally flows toward the south and east, with local flow toward the Leaf and Crow Wing rivers and other streams. Though this aquifer is considered buried, it often is under unconfined water-table conditions.

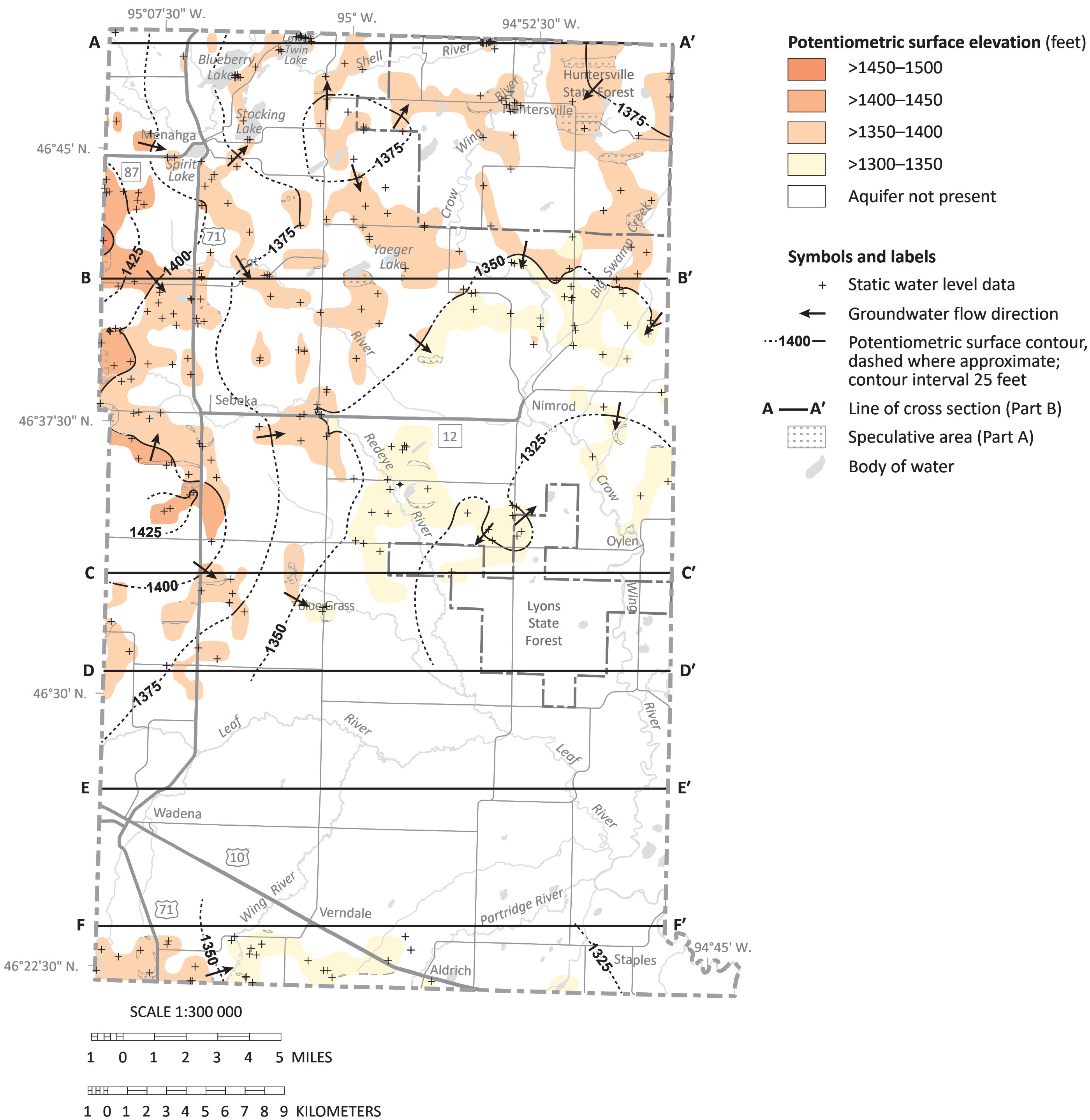


Figure 8. Potentiometric surface of the hsa2 aquifer

Groundwater generally flows toward the south and east, with local flow toward the Crow Wing River and other streams.

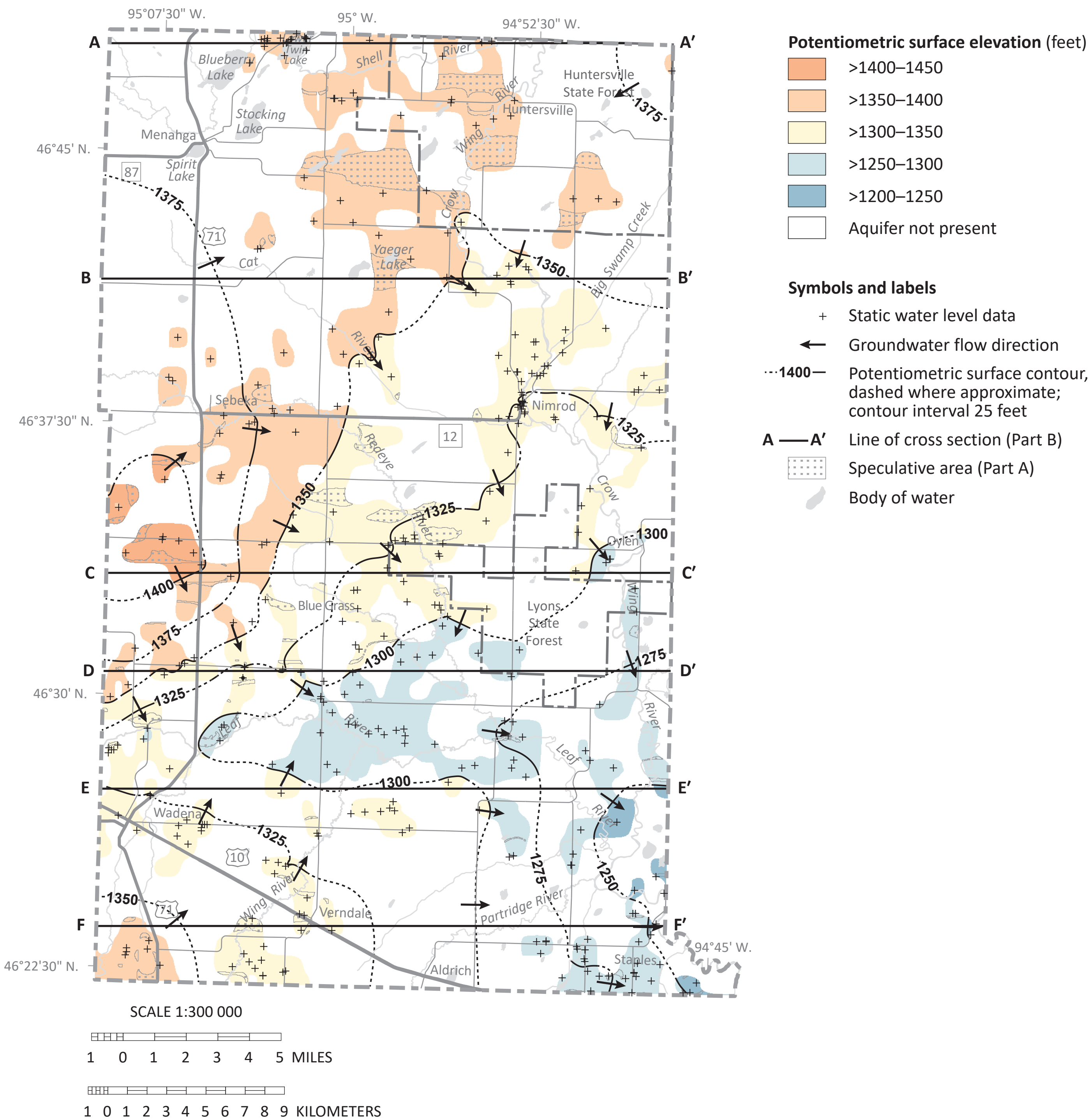


Figure 9. Potentiometric surface of the brs1 aquifer

Groundwater generally flows toward the south and east, with local flow toward the Leaf and Crow Wing rivers and other streams.

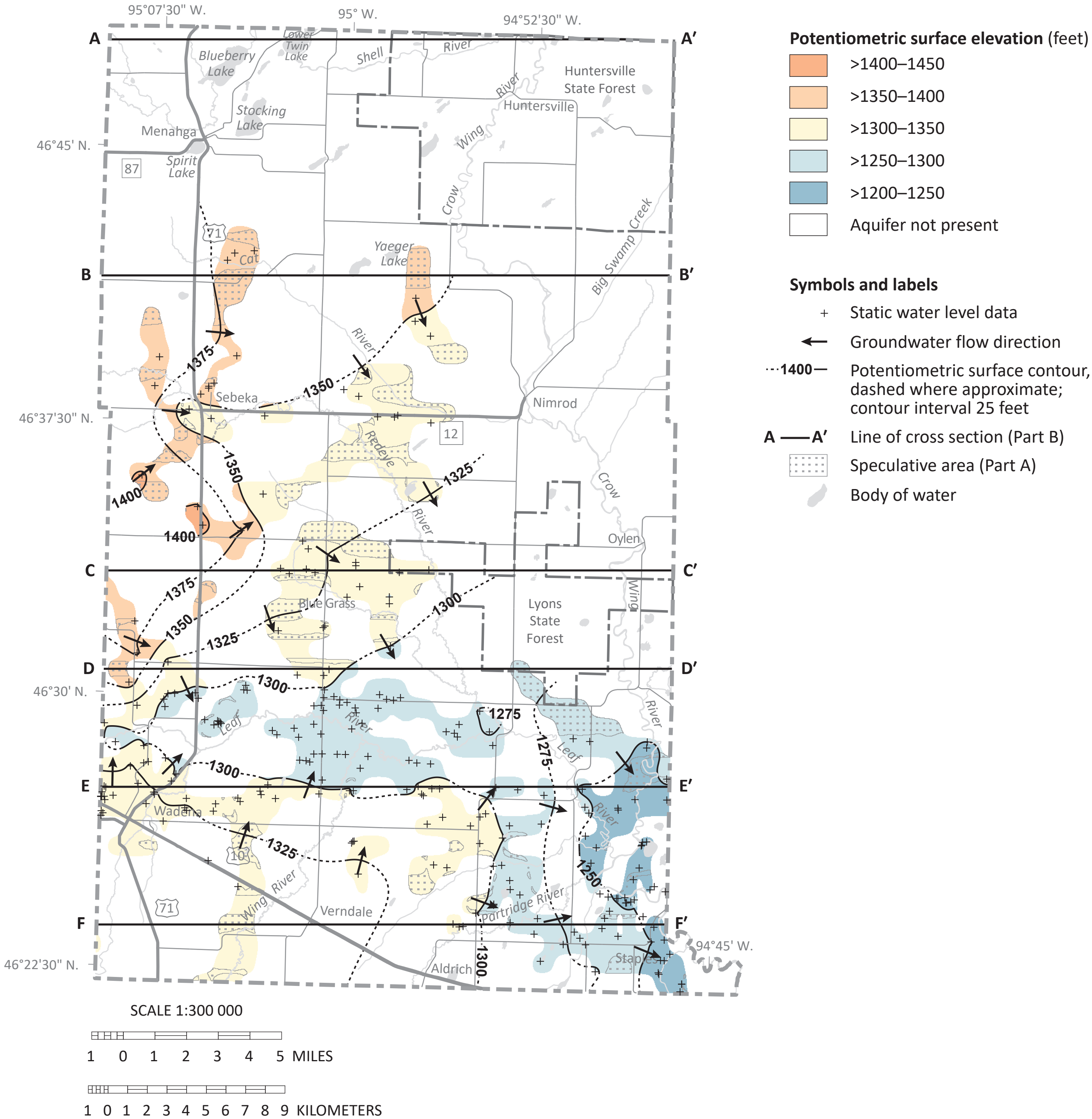


Figure 10. Potentiometric surface of the brs2 aquifer

Groundwater generally flows toward the south and east, with local flow toward the Leaf and Crow Wing rivers and other streams.

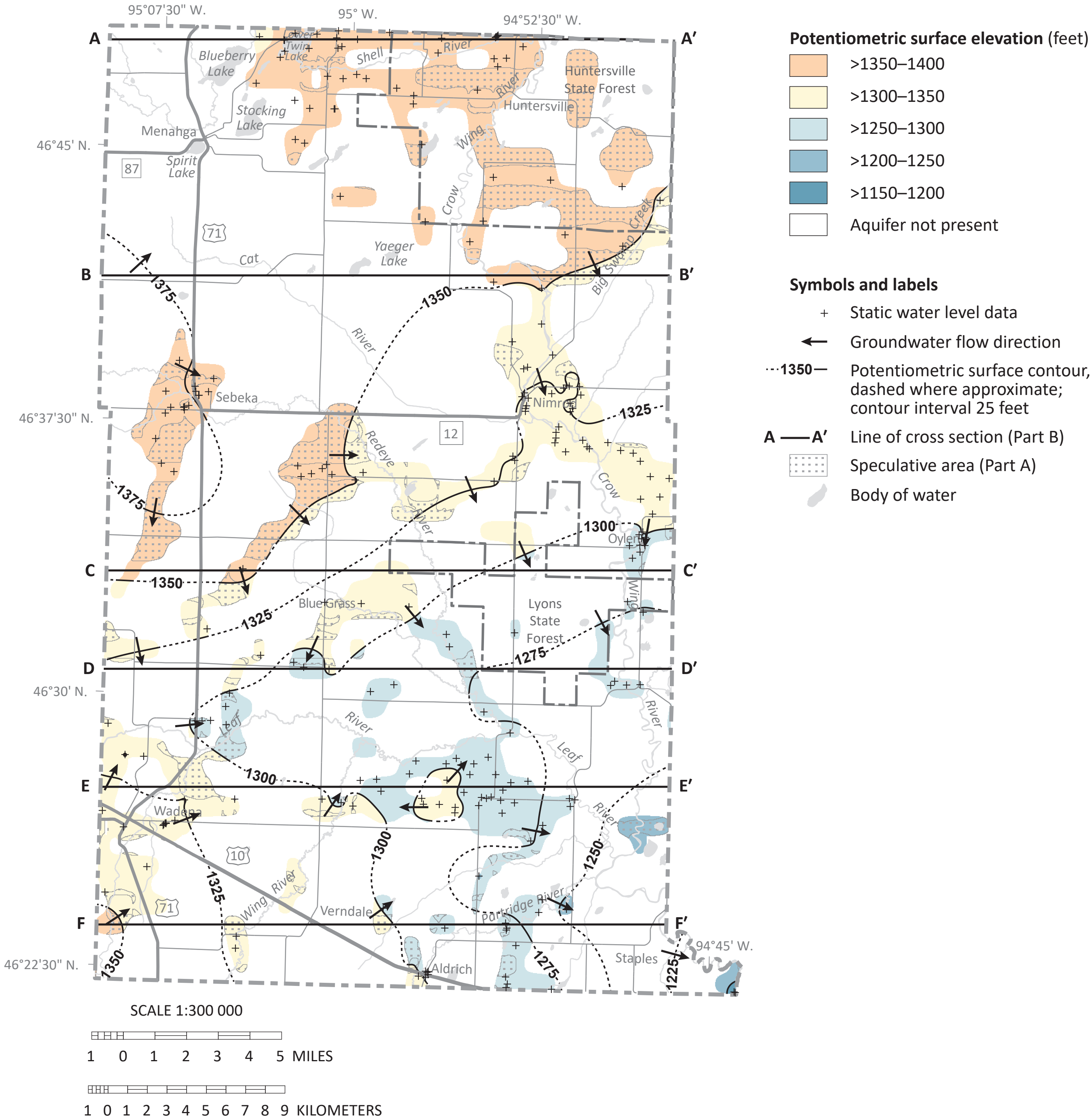


Figure 11. Potentiometric surface of the brs3 aquifer

Groundwater generally flows toward the south and east, with local flow toward the Leaf and Crow Wing rivers and other streams.

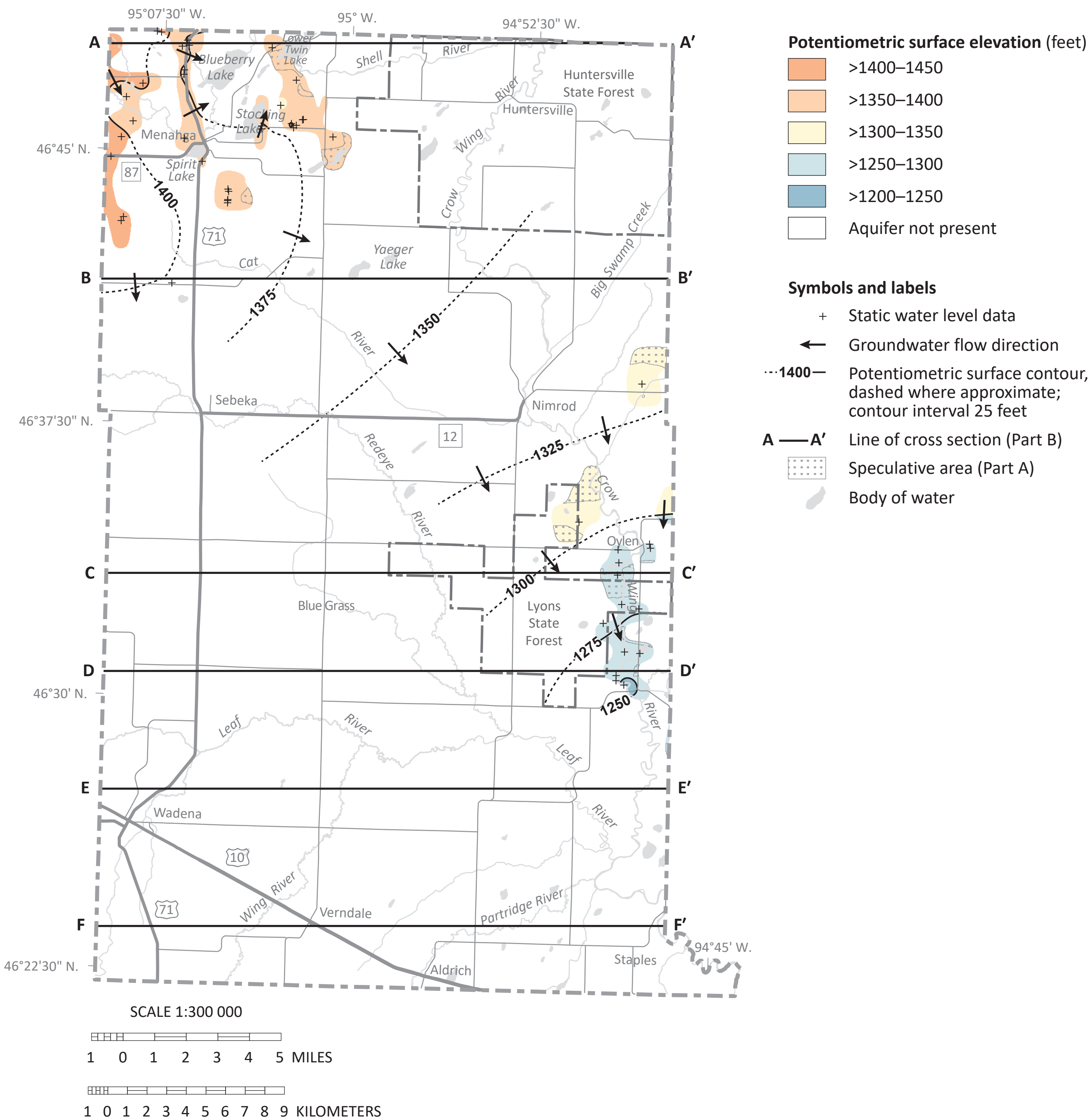


Figure 12. Potentiometric surface of the scs aquifer

Groundwater generally flows toward the south and east.

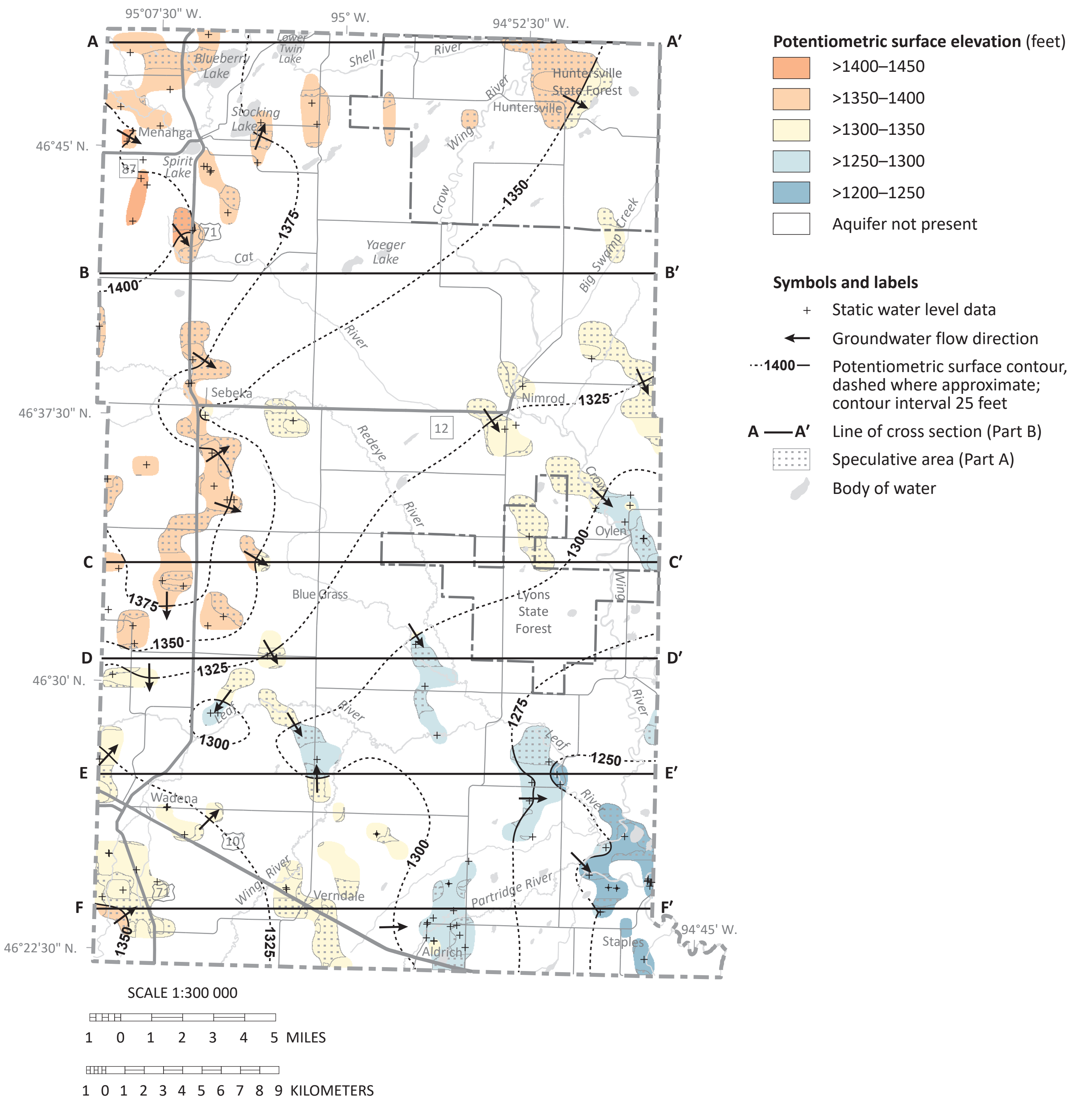


Figure 13. Potentiometric surface of the mls aquifer

Groundwater generally flows toward the south and east, with local flow toward the Leaf and Crow Wing rivers.

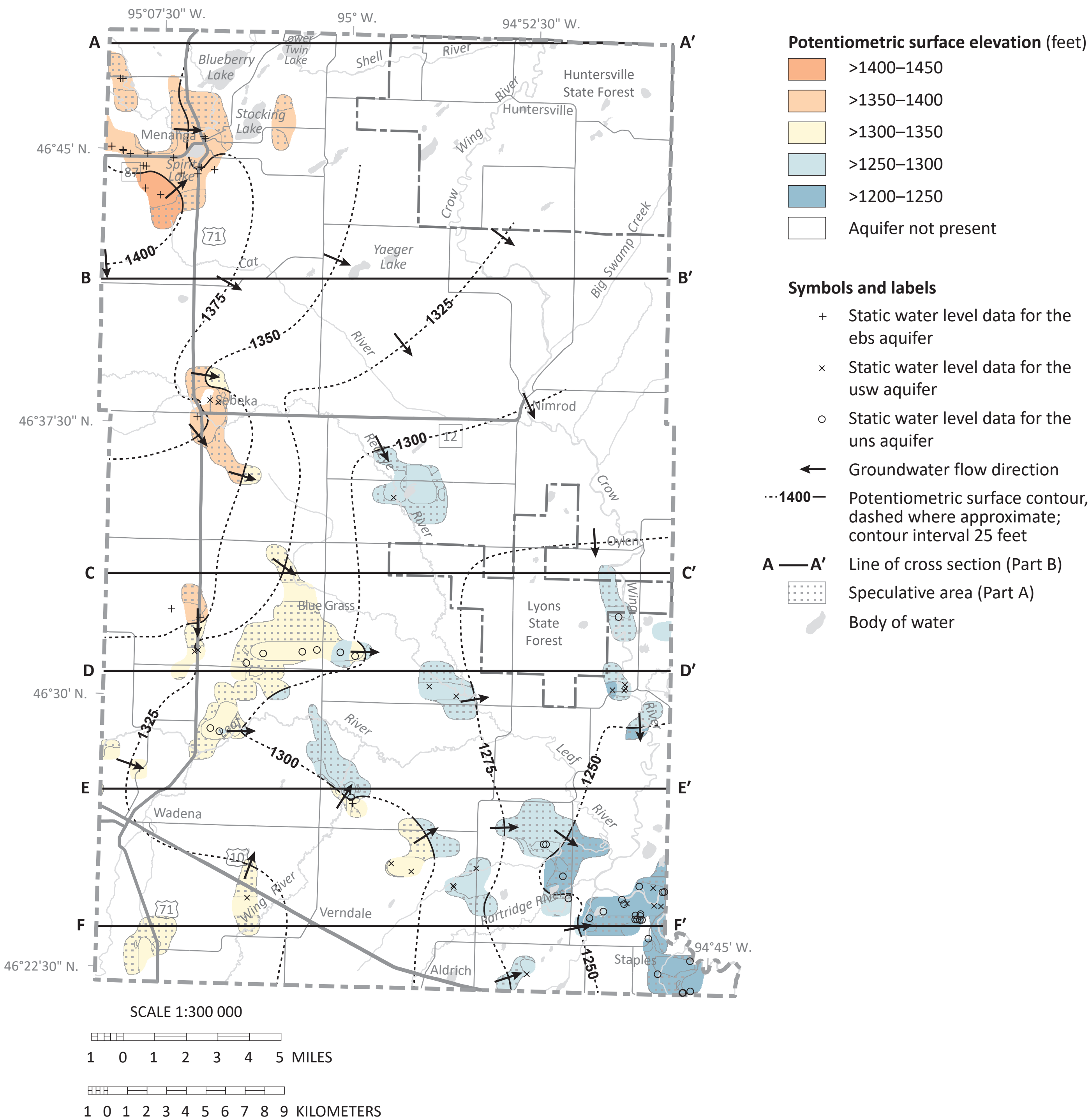


Figure 14. Potentiometric surface of the ebs, usw, and uns aquifers

Groundwater generally flows toward the south and east, with local flow toward the Leaf and Crow Wing rivers.

Water chemistry (Plate 6)

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 is used to provide information about the following:

- **Groundwater recharge pathways:** direct infiltration of precipitation can be distinguished from recharge through surface water.
- **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 introduced by human activities.

Water sampling

Samples were collected from wells in aquifers used for domestic and municipal water supply. Wells were selected based on well construction, and 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. The final network sampled depended on citizen willingness to participate. Approximately 1,000 well owners were contacted for permission to sample.

The DNR collected water samples and standard field parameters from 90 wells and 5 lakes. The results were combined with historical chemistry data, including 24 well, 2 stream, and 2 pond samples from the Minnesota Department of Health (MDH) and 5 well samples from the DNR Otter Tail Regional Hydrogeologic Assessment (DNR, 2002).

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, $^{18}O/^{16}O$ 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).

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 area to lake area ratios typically have significant groundwater input, longer lake water residence times, and more fractionation. Lakes with large watershed area to lake area ratios generally have significant surface-water inflows, shorter lake water residence times, and less fractionation (DNR, 2022).

Results

Figure 15 compares county results to the **global meteoric water line**, which was developed from precipitation around the world (Craig, 1961). Groundwater samples plot primarily along the global meteoric water line, indicating that most groundwater is recharged by precipitation directly infiltrating into the subsurface.

A portion of precipitation ends up in surface-water bodies where evaporation fractionates the stable isotopes of oxygen and hydrogen along an evaporation line below and to the right of the global meteoric water line. The evaporation line was established by sampling 5 lakes for stable isotopes and plotting their results to establish a range of lake isotopic ratios.

For practicality in the following discussion, only oxygen stable isotope values are used for reference. The lake $\delta^{18}O$ isotopic values ranged from -8.97 (Blueberry Lake) to -4.47 (Duck Lake), reflecting differences in the degree of evaporation in each lake.

There are exceptions to the normal relationship between watershed to lake area ratio and fractionation. Lakes with low watershed to lake area ratios can plot closer to the meteoric water line than expected if the water sample was collected at the upstream edge of the lake, where water may be entering the lake from an adjacent surficial sand aquifer, as at Stocking Lake. Lakes with high watershed to lake area ratios can plot with greater fractionation than expected if lake water levels are below the outlet elevation, as at Duck Lake and possibly at Yaeger Lake.

Wells in the county with $\delta^{18}O$ values greater than (plotting to the right of) -8 are considered to have an evaporative signature. Of 100 well samples analyzed for stable isotopes of oxygen and hydrogen, 5 had evaporative signatures. Groundwater samples that plot along the evaporation line have lake (or open-water wetland) 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. As samples plot closer to the meteoric water line, it becomes increasingly difficult to distinguish those that receive a portion of their recharge from a lake source.

Duck Lake is the likely source of lake water for 4 of the groundwater samples with evaporative signatures, as all were collected from wells immediately on the downgradient side of Duck Lake, between the lake and the Shell River (Figure 16). The shallowest well (54 feet deep in the hsa1 aquifer) had the highest evaporative signature, progressing to the deepest well (138 feet deep in the brs3 aquifer) with the lowest evaporative signature (see cross section A–A'). All 4 samples had more meteoric signatures than Duck Lake, suggesting increased mixing with precipitation-sourced groundwater with depth. The fifth sample with an evaporative signature was collected from a 59-foot well along the shore of a small unnamed water body.

The 4 surface-water samples from ponds and streams collected by MDH all plot along the meteoric water line, suggesting short residence times and minimal evaporation.

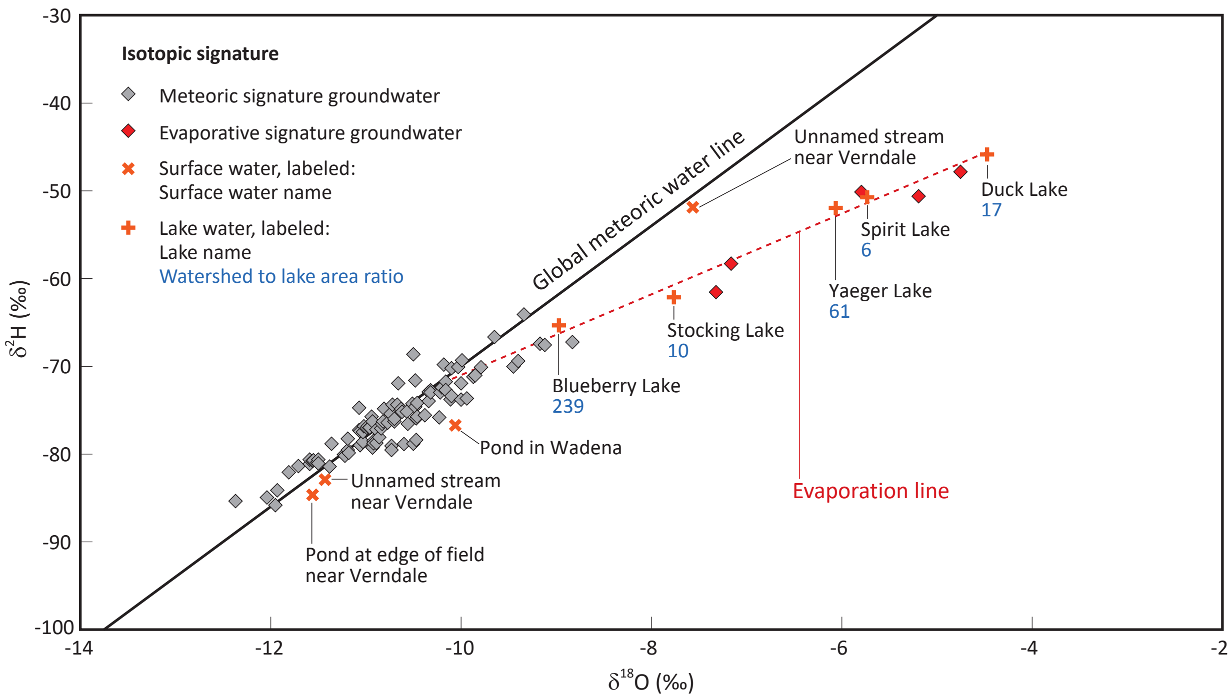


Figure 15. Stable isotope values from water samples

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 **global meteoric water line** 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, described by the equation $\delta^2H = 4.6\ \delta^{18}O - 25.0$, is calculated from 5 lake-water samples collected for this study.

Five well samples plotting along the evaporation line show evidence of lake-water recharge. The rest of the well samples show evidence of recharge primarily from precipitation.

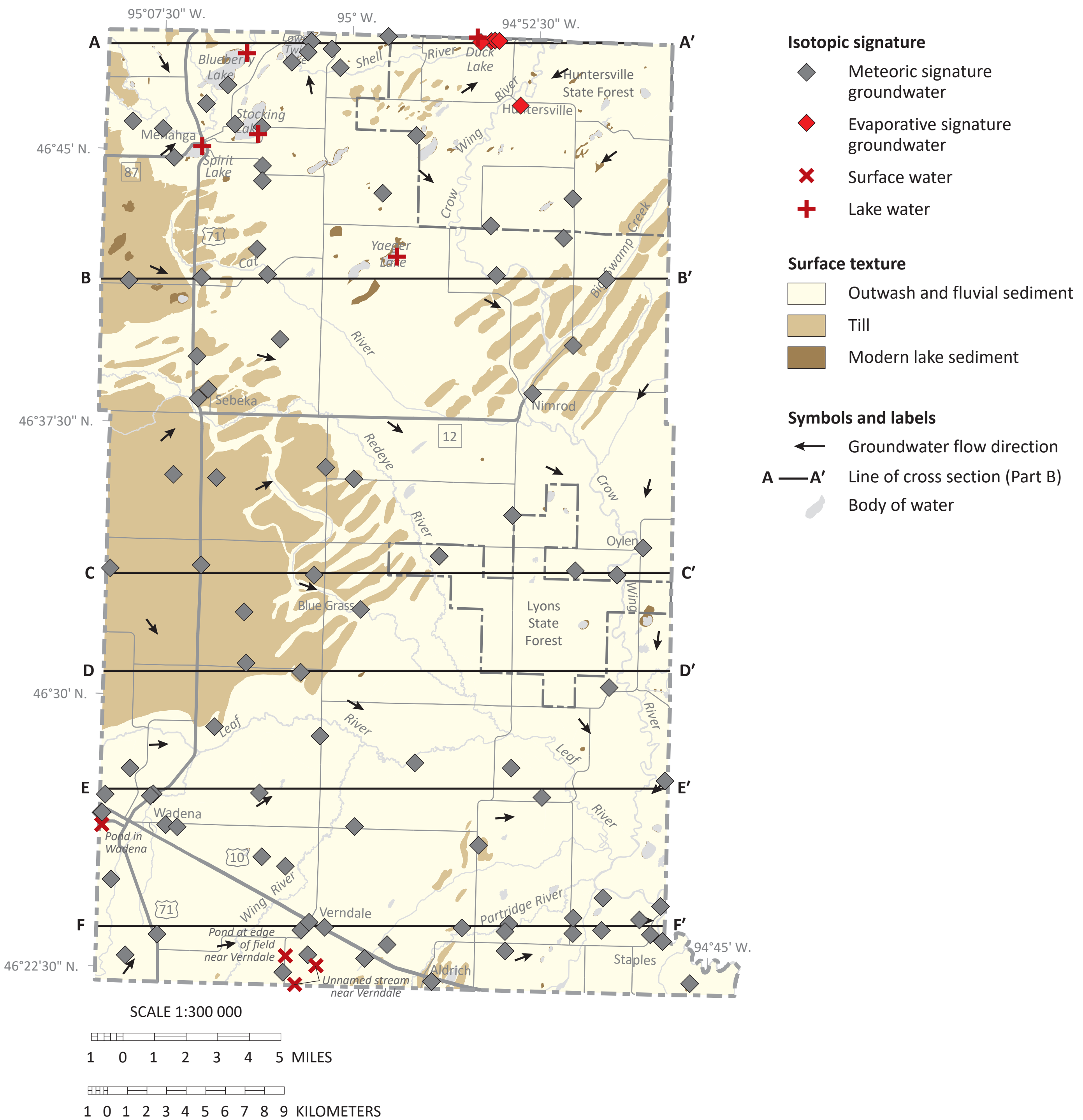


Figure 16. Stable isotope map

Groundwater partially sourced from lakes and wetlands was identified in samples from 5 wells located in areas of sandy surficial geology in northern Wadena County. Arrows represent the direction of water table groundwater flow.

Groundwater residence time

Groundwater residence time is the approximate time elapsed since water infiltrated the land surface to the time it was pumped from a well or discharged to a lake, river, wetland, or spring. 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 is used to 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. (Not present in the dataset for this county).

Tritium was analyzed in samples from 108 wells and 1 lake to assist in residence time interpretations. Of the 108 well samples analyzed for tritium, 71 were modern, 9 were mixed, and 28 were mostly premodern tritium age. The 1 lake sample was modern tritium age.

Carbon-14

Selected wells with mostly premodern or mixed 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 that form carbonic acid. This mildly acidic water dissolves calcite and dolomite present in the soil or bedrock. Plant communities present at the time of infiltration determine soil $\delta^{13}C$ ratios that are used within the model to estimate the groundwater residence time. Approximately half of the dissolved carbon in 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.

A total of 10 carbon-14 samples were collected for this study. Carbon-14 residence times ranged from less than 100 years to greater than 40,000 years. A carbon-14 residence time of 400 ears was determined for a mixed tritium-age sample with 0.9 tritium units (TU). This mixed tritium-age sample was slightly above the minimum reportable limit for the method, 0.8 TU, signifying that most of the water in the mixture is premodern tritium age on the order of hundreds of years old.

Two pairs of wells less than a mile apart were sampled for carbon-14 and highlighted increased residence time with depth. The first pair is just over a mile west of Menahga. The shallower 65-foot well in the scs aquifer had a residence time of 3,500 years, and the deeper 117-foot well in the mls aquifer had a residence time of 6,000 years. The second pair is approximately 3 miles northwest of Aldrich. The shallower 67-foot well in the brs2 aquifer had a residence time of less than 100 years, and the deeper 105-foot well in the brs3 aquifer had a residence time of 25,000 years. The oldest carbon-14 residence time, greater than 40,000 years, was from the deepest well sampled, a 329-foot well located approximately 3 miles southwest of Blue Grass in the uns aquifer.

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 may reasonably be expected to contain 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 certain levels in drinking water, while others may negatively affect the aesthetics of water.

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

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 the course of 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, 2023a)

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

Inorganic constituents of groundwater are described below, and the sample results are compared to drinking water guidelines. Major cations and anions are reported in units of parts per million (ppm). Trace elements, such as arsenic and manganese, are reported in units of parts per billion (ppb).

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 present in the atmosphere and in 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.

Sampling results

All of these constituents are common in Minnesota groundwater. There are currently no guidelines for these constituents.

Chloride

SMCL 250 ppm

Chloride can occur naturally from deep sources, such as residual brine, or from an anthropogenic source, such as road salt, water softener salt, or fertilizer (Davis and others, 1998; 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 a source using the chloride/bromide ratio as a screening tool.

- 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 112 well samples analyzed for chloride, 65 had concentrations above 5 ppm and were assigned a source (Figure 17). Of these 65 well samples, 53 had an anthropogenic source, 8 a natural source, and 4 an unknown source. The SMCL was exceeded in 1 sample with an anthropogenically sourced chloride concentration of 265 ppm. The median concentration was 8.3 ppm. The source interpretation was adjusted for 9 of 65 samples in this atlas based on other evidence, such as bromide concentration uncertainty, tritium age, nitrate presence, or geologic conditions.

- The 53 well samples with **anthropogenic** chloride were nearly all from areas of surficial sand, where crop cultivation is a major land use, or alongside developed land and roadways. Forty-eight of the 53 anthropogenic samples were from wells less than 100 feet deep. Of the remaining 5 samples, 3 were from municipal wells, where pumping may have drawn chloride deeper into the wells. One sample had its chloride source adjusted from natural to anthropogenic because it is directly adjacent to another well in the same aquifer with an anthropogenic source of chloride.
- The 8 well samples with **natural** chloride were from deeply buried aquifers. The wells ranged in depth from 117 to 329 feet, and carbon-14 residence times available for 2 of the samples were 6,000 and greater than 40,000 years. The source interpretation was changed from anthropogenic to natural for 4 samples because of their mostly premodern tritium ages, available carbon-14 residence times, and evidence of cation exchange. These 4 samples were also collected from wells screened 25 to 40 feet above crystalline bedrock. Given the uncertainties in mapping Cretaceous bedrock, a potential source of residual brine, the chloride in these 4 samples is likely from a natural source.
- One sample with an **unknown** chloride source was collected from a 37-foot well south of cross section F–F′, near the Crow Wing River in the brs2 aquifer. Though the chloride-to-bromide ratio of 120 for this sample suggests a natural source, its bromide concentration of 0.13 ppm is significantly higher than the county median of 0.0135 ppm and lowered the ratio.
- Three additional well samples with **unknown** chloride sources had their chloride interpretations adjusted from anthropogenic. The adjustment was made for 2 samples based on their mostly premodern tritium age and the presence of approximately 160 feet of clay providing protection above the aquifer. The third well was adjusted because of the estimated carbon-14 residence time of 7,500 years. Anthropogenic chloride was possibly introduced into the wells or distribution system via disinfection or construction issues rather than entering from the aquifer.

Two ponds were sampled for chloride; 1 at the edge of an agricultural field along a highway near the city of Verndale had an anthropogenic source, and 1 in the city of Wadena had a concentration below 5 ppm. One stream south of Verndale was sampled and had an anthropogenic source.

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 than or equal to 1 ppm.

Sampling results

Of the 111 well samples analyzed, nitrate was detected in 46 samples, and 22 had an anthropogenic source (Figure 18). All 22 well samples with anthropogenic nitrate were collected from wells within 1 mile of land used for crop cultivation, and 17 of the samples were collected from wells where sand is the surficial geologic texture. The deepest well with anthropogenic nitrate was 103 feet; the average well depth of samples with anthropogenic nitrate was 52 feet.

Nitrate concentrations exceeded the MCL in 7 samples (6.3%). All 7 were collected from wells within a quarter mile of land used for crop cultivation. The deepest well with an MCL exceedance was 82 feet. The highest measured concentration was 27.8 ppm in a 48-foot well. The median nitrate concentration was below the laboratory detection limit.

Two ponds were sampled for nitrate, 1 at the edge of a field near the city of Verndale with an anthropogenic concentration of 2.9 ppm and 1 in the city of Wadena, where nitrate was not detected. One stream south of Verndale was sampled and had a concentration of 14 ppm, exceeding the MCL.

The objectives of atlas sampling do not target nitrate in groundwater. A Township Testing Program study published by the Minnesota Department of Agriculture (MDA) (MDA, 2018) targeted nitrate in groundwater. Four townships in Wadena County were selected for testing because of intensive row crop agriculture and vulnerable geology defined by coarse-grained glacial sediment at the surface.

The initial MDA study included volunteers' wells where specific details about participant wells, such as aquifer, depth, and well construction, weren't always available. In the initial study, 33 of 252 wells (13.1%) had MCL exceedances. A final dataset was constructed following two rounds of sampling and processing to remove wells with construction concerns, insufficient construction information, and those near potential non-fertilizer sources of nitrate. The median depth of sampled wells in the final dataset was 71 feet. In the final dataset, 13 of 222 wells (5.9%) had MCL exceedances. Aldrich, Wadena, and Wing River townships had 8.3 to 10.3% of wells in the final dataset exceeding the MCL, while Thomastown township had only 1.1%. Similar to DNR atlas sampling results, the median nitrate concentration for the final MDA dataset was below the laboratory detection limit.

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, 2023b). 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).

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 103 well samples analyzed, arsenic was detected in 88, with 2 exceeding the MCL (Figure 19). The highest concentration was 11.3 ppb, and the median was 1.3 ppb. No discernible patterns or correlations with specific aquifers were found. The limited number of MCL exceedances is consistent with the lack of northwest-source, fine-grained sediment correlated with high arsenic (Part A, Plate 4; Erickson and Barnes, 2005a). However, detectable arsenic was commonly found.

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 cause negative secondary effects, such as poor taste, odor, and water discoloration (stained laundry and plumbing fixtures).

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) (MDH, 2012).

Sampling results

Of the 107 well samples analyzed, manganese was detected in 101, with 80 exceeding the SMCL and 61 exceeding the HBV. The highest concentration was 799 ppb, and the median concentration was 137 ppb. No discernible patterns or correlations with specific aquifers were found.

Iron

SMCL 0.3 ppm

Iron is a common naturally occurring element in Minnesota groundwater. At levels above the SMCL, iron may give water a metallic taste; cause yellow, red, or brown stains on dishes, laundry, and plumbing fixtures; and can clog wells, pumps, sprinklers, dishwashers, and other devices.

Sampling results

Of the 101 well samples analyzed, iron was detected in 86, with 72 exceeding the SMCL. The highest concentration was 13.3 ppm, and the median concentration was 1.1 ppm. No discernible patterns or correlations with specific aquifers were found.

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 91 samples analyzed, boron was detected in all, with 2 exceeding the RAA. The highest concentration was 1,980 ppb, and the median concentration was 17.8 ppb. Both samples exceeding the RAA were collected from wells 216 and 329 feet deep in the uns aquifer. Higher boron concentrations were more common in deep wells; the next-highest concentrations (each greater than 100 ppb) were from 6 wells at least 105 feet deep in the brs2, brs3, or usw aquifers.

Sulfate

SMCL 250 ppm

Sulfate is largely naturally occurring and is produced from the oxidation of sulfide minerals and the 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 can act as a laxative.

Sampling results

Of the 105 well samples analyzed, sulfate was detected in 83. A sample from a 329-foot well in the uns aquifer exceeded the SMCL with a concentration of 371 ppm, much higher than the second-highest concentration of 81.4 ppm. The median concentration was 6.8 ppm. No discernible patterns or correlations with specific aquifers were found.

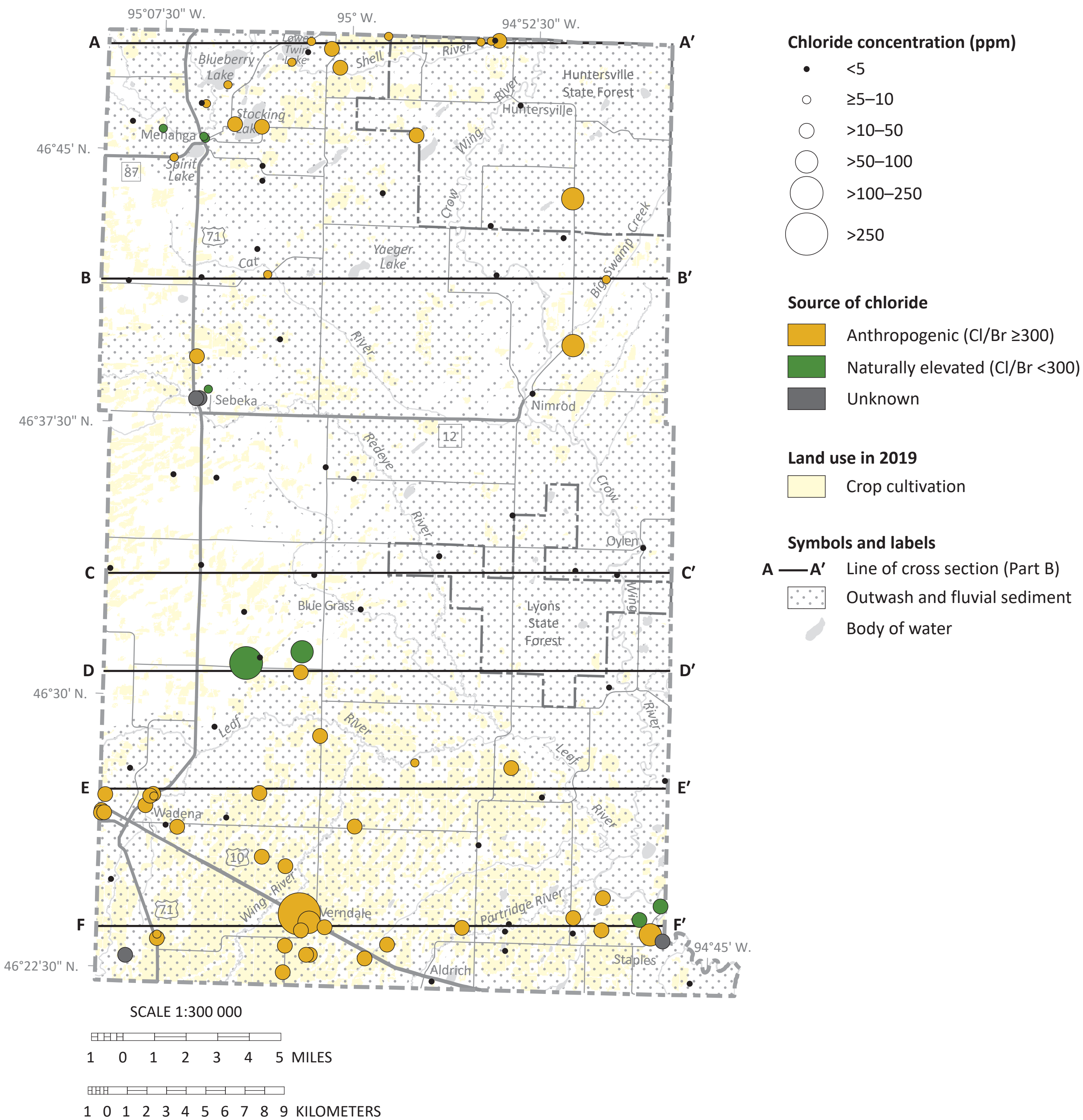


Figure 17. Chloride concentrations from groundwater samples

Anthropogenic chloride concentrations were predominantly found where sand is at the surface and near crop cultivation and developed areas. Samples with source adjustments are noted on Plate 6.

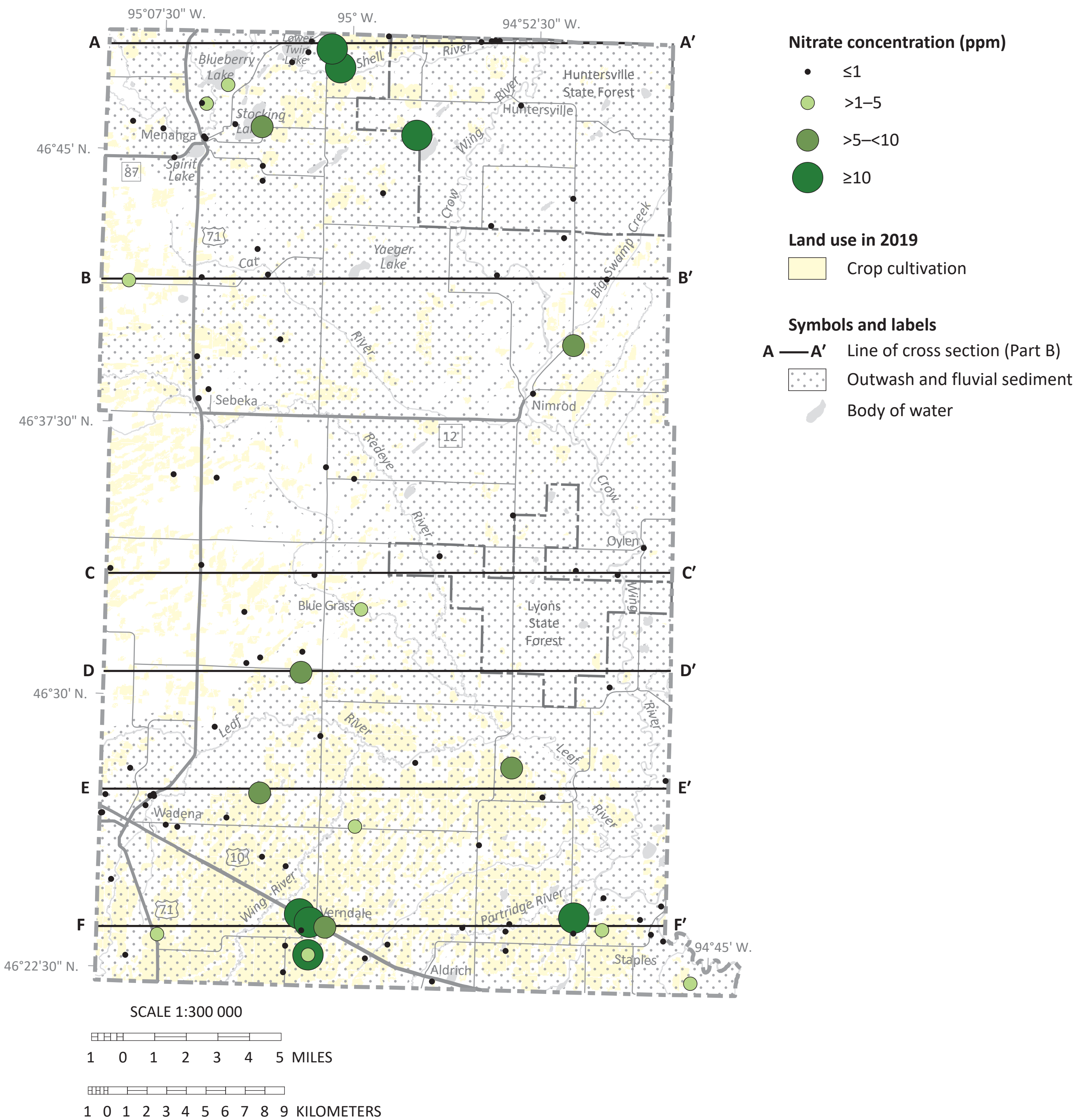


Figure 18. Nitrate concentrations from groundwater samples

Anthropogenic nitrate concentrations were predominantly found where sand is at the surface and near crop cultivation.

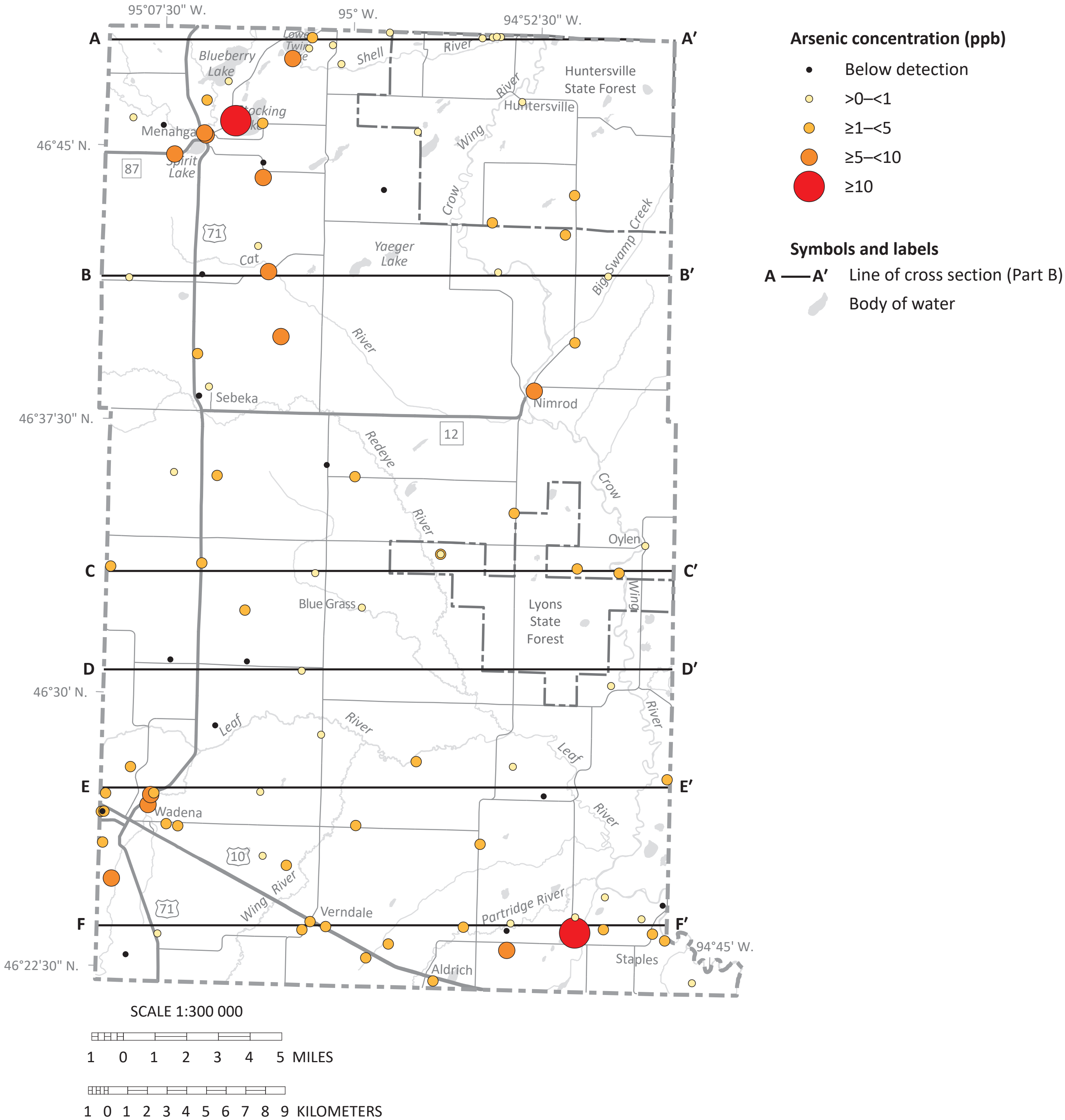


Figure 19. Arsenic concentrations from groundwater samples

Detectable arsenic was found across the county. No discernible patterns or correlations with specific aquifers were found.

Piper diagram

The Piper diagram (Figure 20) 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 most common water type in Wadena County is calcium-magnesium bicarbonate. Concentrations of other ions, including sodium, chloride, and nitrate, are proportionally higher for some samples, causing them to plot away from most samples.

On the cation triangle of Figure 20, samples typically plot in a cluster dominated by calcium and magnesium. However, there is a trend of mostly premodern tritium-age samples plotting away from the main cluster toward the sodium and potassium corner of the triangle. The increasing dominance of sodium in these samples is likely the result of calcium and magnesium in water exchanging with sodium adsorbed on fine-grained sediment along deeper flow paths (Hounslow, 1995) or of contributions of residual brine from Cretaceous bedrock.

On the anion triangle of Figure 20, samples typically plot close to the bicarbonate corner of the triangle. There is a trend of modern tritium-age samples with anthropogenic chloride or nitrate plotting with increasing proportions of chloride and nitrate. The mostly premodern tritium-age sample that plots near the center of the anion triangle is from a 329-foot well that had the highest concentrations of sulfate and natural chloride in the county. This well is completed in the uns aquifer approximately 25 feet above bedrock, a potential source of residual brine.

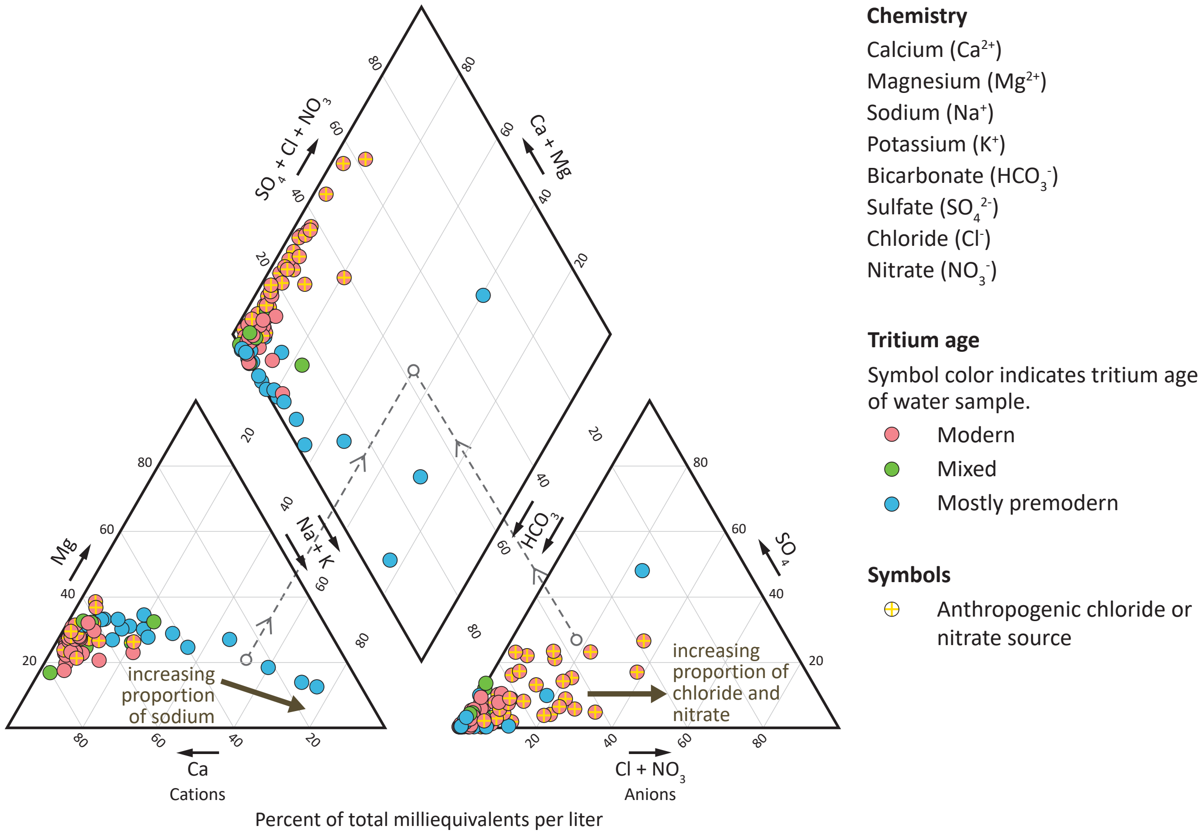


Figure 20. Piper diagram of groundwater sampled by DNR staff

The 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 dashed arrows show an example of this relationship. The sample points in the figure are color coded according to tritium age to show chemical relationships.

Calcium-magnesium bicarbonate water is the dominant water type. In the cation triangle, mostly premodern tritium-age samples plot away from the cluster of samples dominated by calcium and magnesium with increasing proportions of sodium resulting from cation exchange along deeper flow paths or contributions from bedrock. In the anion triangle, modern tritium-age samples with anthropogenic chloride or nitrate concentrations plot further from most of the samples in the bicarbonate corner with increasing proportions of chloride and nitrate. One mostly premodern tritium-age sample collected from a 329-foot well near the bedrock surface plots toward the center of the anion triangle with high sulfate and natural chloride concentrations.

Pollution sensitivity

For this report, pollution sensitivity is defined as the time it takes for a contaminant to travel from the land surface to a specific target: water table, 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 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 is an estimate of the time it takes for water to infiltrate the land surface, travel through the unsaturated zone, and reach the water table, which is assumed to be 10 feet below 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 texture. Coarse-grained materials generally have faster transmission rates than fine-grained materials. The two primary inputs used to estimate the transmission rate are the hydrologic soil group (Table 1) (Natural Resources Conservation Service, 2020) and the surficial geologic matrix texture (Part A, Plate 3). Attributes of both are used to estimate the time of travel. Travel time varies from hours to approximately a year; ratings are shown in Figure 21. For further details, see *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

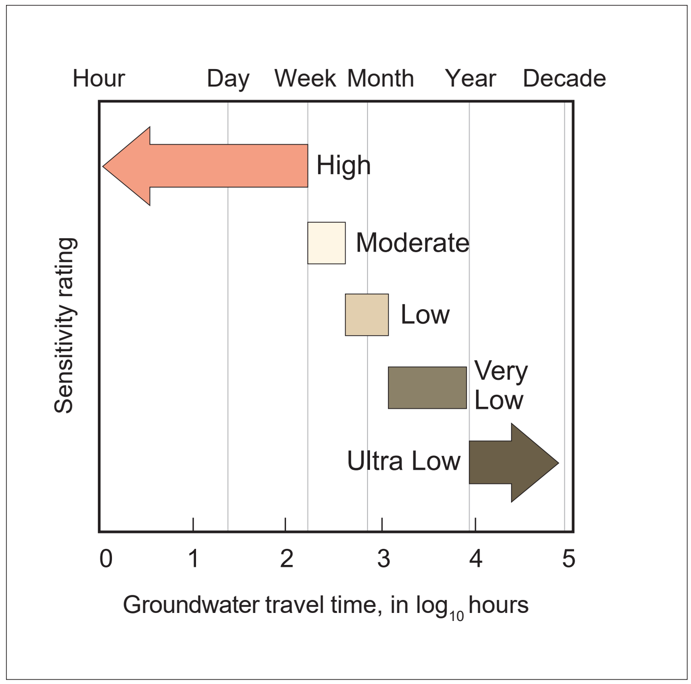


Figure 22. Pollution sensitivity rating of near-surface materials: travel time and ratings

Results

Near-surface pollution sensitivity conditions range from high to low (Figure 22). High sensitivity is found in the extensive sandy outwash plains. Areas of moderate and low sensitivity, particularly in the west-central and east-central, are largely associated with sandy tills and drumlins. Less permeable hydrologic soil groups also mark local areas of low sensitivity.

Surficial sand aquifers

Water samples were collected from 16 wells completed in the surficial ns, hsi, and is aquifers (Figure 22).

- *Extent:* Surficial sand aquifers are present across the county in areas of glacial outwash and modern fluvial sediment.
- *Depth:* Varies with the water-table elevation.
- *Thickness:* Mean thickness is 20 feet, with most areas less than 50 feet thick and only a few local areas greater than 100 feet thick (Part A, Plate 5, Figure 3).
- *Use:* Approximately 12% of wells with an assigned aquifer are completed in surficial sand aquifers.
- *Pollution sensitivity*: Wells completed in surficial sand units are highly sensitive to pollution entering from the surface because of the lack of overlying protective fine-grained sediment.
- *Residence time:* Of the 14 samples analyzed for tritium age, 12 were modern and 2 were mixed. Of these samples, 12 were collected from areas of high near-surface pollution sensitivity, and 2 modern tritium-age samples were collected from areas of low near-surface pollution sensitivity with less permeable hydrologic soil groups at the surface.
- *Anthropogenic chemical indicators:* Of the 16 samples analyzed for chloride, 14 had concentrations at or above 5 ppm and were anthropogenic. Of the 16 samples analyzed for nitrate, 10 were anthropogenic.

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	Qa, Qgo, Qho, Qio, Qno, Qo
		sand, silty sand	0.71	Not mapped in county
B, B/D	0.50	silt, loamy sand	0.50	Not mapped in county
		sandy loam, peat	0.28	Qht
C, C/D	0.075	silt loam, loam	0.075	Ql
		sandy clay loam	0.035	Not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Not mapped in county

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.

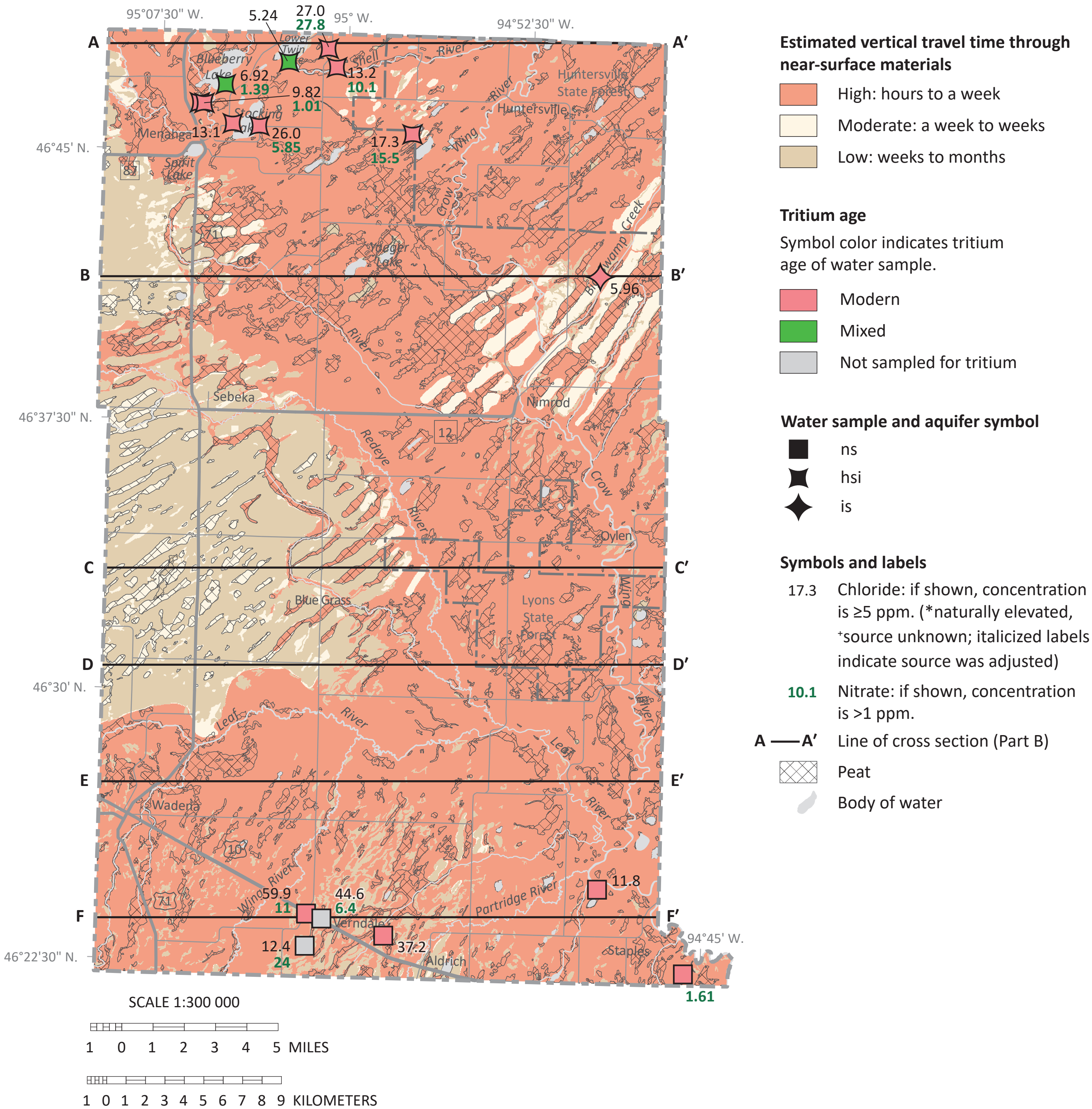


Figure 21. Pollution sensitivity rating of near-surface materials

Near-surface pollution sensitivity is rated high in areas of sandy outwash and alluvial deposits; moderate and low sensitivities are in areas of surficial till and drumlins in the west-central and east-central and locally elsewhere.

Well water samples from surficial sand aquifers had modern or mixed tritium-age water and commonly had anthropogenic chloride or nitrate.

Buried sand aquifer and bedrock surface model

Method

The pollution sensitivity of buried sand aquifers and the bedrock surface is an estimate of 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).

This 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 estimated 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 23 and 24). 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).

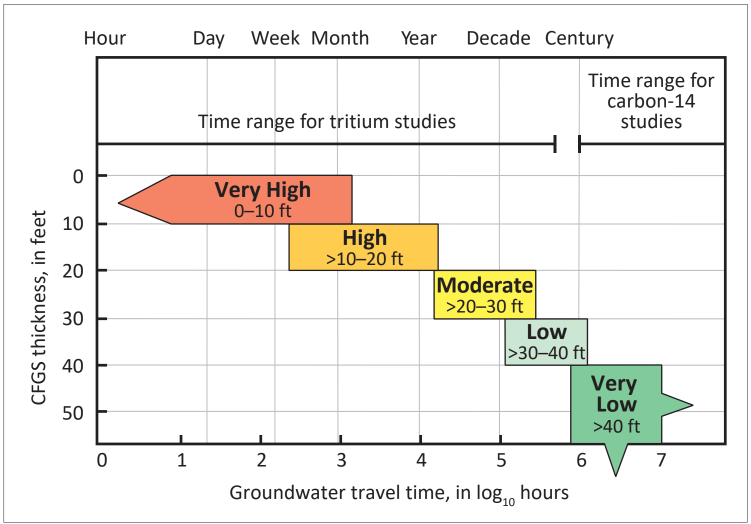


Figure 23. Pollution sensitivity rating for the buried sand aquifers and the bedrock surface

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 ratings of very high or high have relatively short estimated travel times of less than a few years. Areas rated low or very low have estimated travel times of decades or longer. Travel time varies from hours to thousands of years.

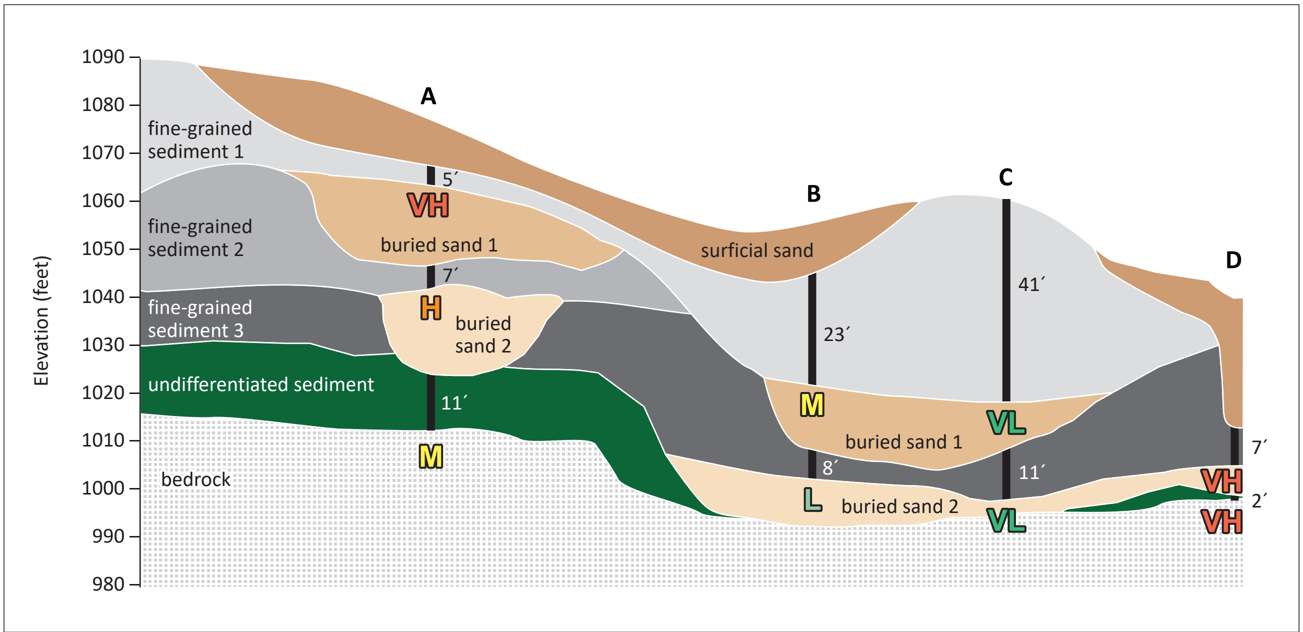


Figure 24. Cross section illustration of the pollution sensitivity model

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 are expected to have modern or mixed tritium-age water and anthropogenically sourced chemicals if a source is present.

Aquifers with very low pollution sensitivity ratings are generally expected to 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 (Figure 25).

Ⓛ **Lateral flow:** 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.

Ⓤ **Unknown:** neither the pollution sensitivity model nor groundwater conditions explained the presence of modern or mixed tritium-age water. The presence of modern or mixed tritium may be the result of a well construction issue, such as insufficient grouting or a damaged well casing.

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

Ⓓ **Discharge:** older water upwelled from deep aquifers and discharged to shallow aquifers.

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 are used to aid in identifying areas where upwelling older groundwater interacts with aquifers near the surface.

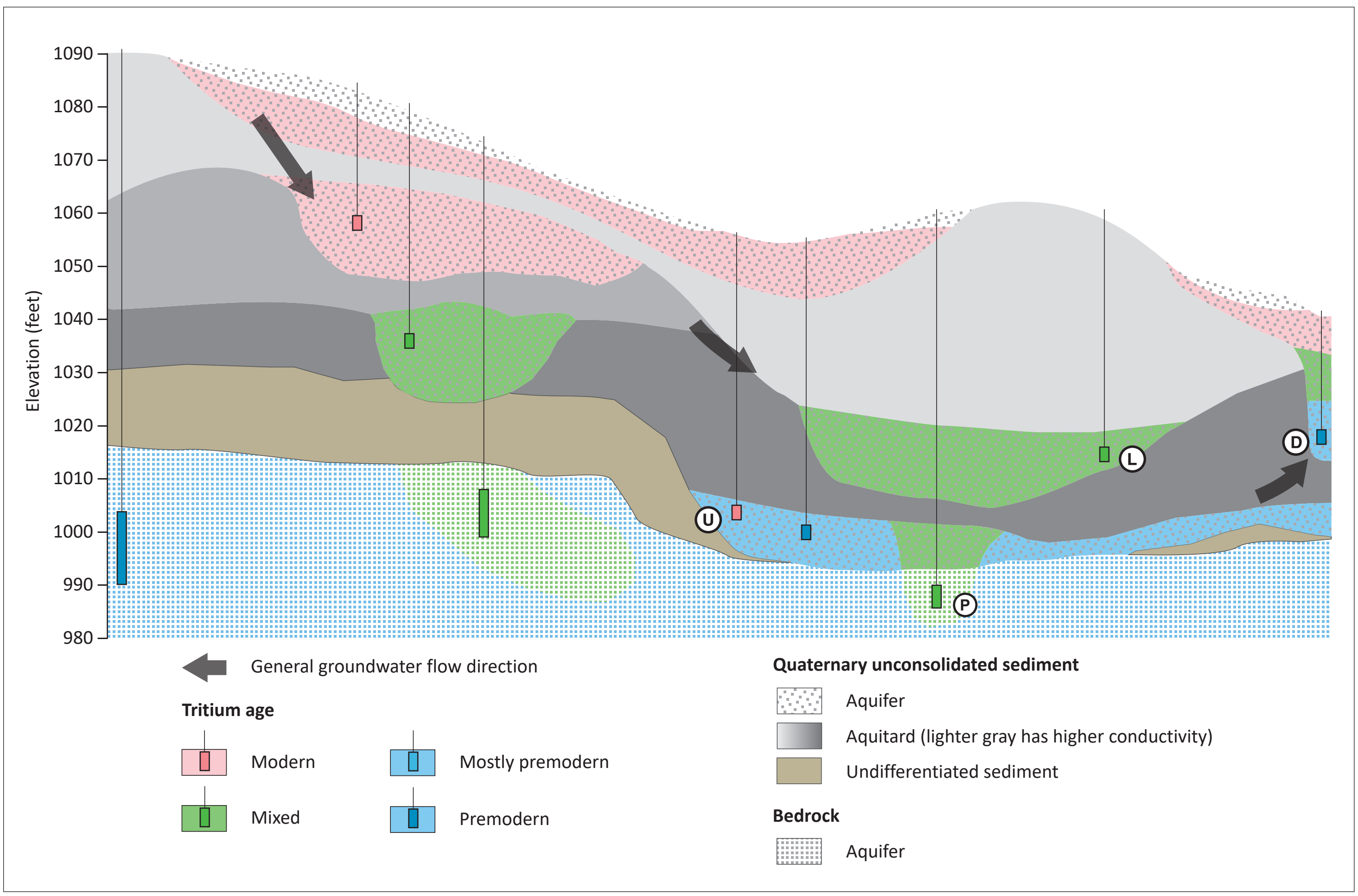


Figure 25. Cross section illustration of groundwater conditions

Buried sand and bedrock aquifers are shaded to indicate modern, mixed, or premodern tritium-age water. Wells sampled for tritium are shown for comparison. Groundwater condition labels are present where the tritium age of a water sample contradicts the pollution sensitivity rating for the aquifer where the sample was taken. This figure was developed from Figure 24.

Results

The following section provides a general characterization of the buried aquifers in stratigraphic order (Figure 2) and includes aquifer depth and spatial distribution, pollution sensitivity, and the approximate percentage of wells completed in each aquifer.

The modeled pollution sensitivity results are compared to groundwater residence times from tritium and carbon-14 and to the presence of anthropogenic chemical indicators (nitrate greater than 1 ppm or chloride greater than or equal to 5 ppm with a chloride/bromide ratio greater than or equal to 300).

Tills associated with the hsa1 and hsa2 aquifers have sand contents of approximately 60% (Figure 2). Water likely moves more readily through these high-sand-content tills, and the pollution sensitivity model overestimates the degree of protection these tills provide. This often contributes to modern and mixed tritium-age water being found deeper than expected in wells marked with the "Unknown" groundwater condition.

hsa1 aquifer (Figure 26)

- *Extent:* The aquifer is extensive in the south and the northwest, with localized pockets elsewhere.
- *Depth:* Mean depth is 18 feet, ranging from approximately 0 to 38 feet.
- *Thickness:* Mean thickness is 15 feet, with a maximum of approximately 41 feet.
- *Use:* Approximately 18% of wells with an assigned aquifer.
- *Pollution sensitivity:* Very high sensitivity is found extensively in the south, with very high to very low sensitivity elsewhere.
- *Residence time:* Of the 17 samples analyzed for tritium age, all were modern.
- *Anthropogenic chemical indicators:* Of the 20 samples analyzed for chloride, 13 had concentrations at or above 5 ppm and were anthropogenic. Of the 19 samples analyzed for nitrate, 7 were anthropogenic.
- *Summary:* Chemical and residence time indicators largely support the sensitivity model. Sandy overlying tills may provide less protection than predicted by the model, resulting in modern tritium-age water with anthropogenic nitrate in a sample from an area of very low sensitivity at the west end of B–B'. Lateral flow likely moved modern tritium-age water to an area of very low sensitivity.

hsa2 aquifer (Figure 27)

- *Extent:* The aquifer is present in the northern two-thirds of the county and along the southern border.
- *Depth:* Mean depth is 49 feet, ranging from approximately 16 to 82 feet.
- *Thickness:* Mean thickness is 15 feet, with a maximum of approximately 52 feet.
- *Use:* Approximately 15% of wells with an assigned aquifer.
- *Pollution sensitivity:* Varies widely, with areas of very high to very low sensitivity across the aquifer.
- *Residence time:* Of the 13 samples analyzed for tritium age, 11 were modern and 2 were mixed.
- *Anthropogenic chemical indicators:* Of the 13 samples analyzed for chloride, 5 had concentrations at or above 5 ppm and were anthropogenic. Of the 13 samples analyzed for nitrate, 1 was anthropogenic.
- *Summary:* Chemical and residence time indicators largely support the sensitivity model. Sandy overlying tills may provide less protection than predicted by the model, resulting in modern tritium-age water in a sample from an area of very low sensitivity south of Sebeka. Lateral flow likely moved modern and mixed tritium-age water to areas of very low sensitivity.

brs1 aquifer (Figure 28)

- *Extent:* The aquifer is present across much of the county.
- *Depth:* Mean depth is 64 feet, ranging from approximately 10 to 118 feet.
- *Thickness:* Mean thickness is 12 feet, with a maximum of approximately 29 feet.
- *Use:* Approximately 17% of wells with an assigned aquifer.
- *Pollution sensitivity:* Very high sensitivity is common in the south, and very low sensitivity is common in the north, with areas of very high to very low sensitivity throughout.
- *Residence time:* Of the 16 samples analyzed for tritium age, 11 were modern and 5 were mostly premodern. Carbon-14 residence times of less than 100 years were determined for 2 mostly premodern tritium-age samples, and 7,500 years was determined for a third mostly premodern tritium-age sample.
- *Anthropogenic chemical indicators:* Of the 18 samples analyzed for chloride, 11 had concentrations at or above 5 ppm. Of these 11 samples, 10 had an anthropogenic source and 1 had an unknown source. Of the 18 samples analyzed for nitrate, 3 were anthropogenic.

- *Summary:* Chemical and residence time indicators largely support the sensitivity model. Sandy overlying tills may provide less protection than predicted by the model for 3 samples with modern tritium-age water, 1 of which also had anthropogenic chloride. Lateral flow likely moved modern tritium-age water to areas of very low sensitivity. Two mostly premodern tritium-age samples with carbon-14 residence times of less than 100 years do not fit the estimated vertical travel time of a century or more for very low sensitivity areas; however, their mostly premodern tritium age suggests residence times of approximately 70 to 100 years. For a sample from a 108-foot well in the southwest, the model underestimated travel time. This sample had a mostly premodern tritium age and a carbon-14 residence time of 7,500 years in an area of low sensitivity. Nearly 60 feet of clay above the aquifer was noted in the driller report for the well, suggesting a locally very low sensitivity. A mostly premodern tritium-age sample from a 58-foot well in the southeast collected from an area of moderate sensitivity may have a residence time of approximately 70 to 100 years; a nearby 67-foot well in the underlying brs2 aquifer had a carbon-14 residence time of less than 100 years.

brs2 aquifer (Figure 29)

- *Extent:* The aquifer is present in the south and central.
- *Depth:* Mean depth is 77 feet, ranging from approximately 13 to 141 feet.
- *Thickness:* Mean thickness is 12 feet, with a maximum of approximately 29 feet.
- *Use:* Approximately 13% of wells with an assigned aquifer.
- *Pollution sensitivity:* Very low sensitivity is common in the central part of the county, with very high to very low sensitivity in the south.
- *Residence time:* Of the 17 samples analyzed for tritium age, 11 were modern, 1 was mixed, and 5 were mostly premodern. A carbon-14 residence time of less than 100 years was determined for 1 mostly premodern tritium-age sample.
- *Anthropogenic chemical indicators:* Of the 15 samples analyzed for chloride, 9 had concentrations at or above 5 ppm. Of these 9 samples, 7 had an anthropogenic source, 1 had a natural source, and 1 had an unknown source. Of the 15 samples analyzed for nitrate, 1 was anthropogenic.
- *Summary:* Chemical and residence time indicators largely support the sensitivity model. Lateral flow likely moved modern tritium-age water to areas of very low sensitivity. Two samples in the southeast with premodern tritium ages were collected from areas of moderate sensitivity; 1 of these samples had a carbon-14 residence time of less than 100 years. Residence times of 70 to 100 years are likely for these 2 samples.

brs3 aquifer (Figure 30)

- *Extent:* The aquifer is present across much of the county.
- *Depth:* Mean depth is 112 feet, ranging from approximately 43 to 181 feet.
- *Thickness:* Mean thickness is 15 feet, with a maximum of approximately 41 feet.
- *Use:* Approximately 12% of wells with an assigned aquifer.
- *Pollution sensitivity:* Very low sensitivity is common, with areas of very high to low sensitivity.
- *Residence time:* Of the 16 samples analyzed for tritium age, 7 were modern, 2 were mixed, and 7 were mostly premodern. Carbon-14 residence times of less than 100 years and 25,000 years were determined for 2 mostly premodern tritium-age samples.
- *Anthropogenic chemical indicators:* Of the 15 samples analyzed for chloride, 5 had concentrations at or above 5 ppm. Of these 5 samples, 3 had an anthropogenic source and 2 had an unknown source. Of the 15 samples analyzed for nitrate, none were anthropogenic.
- *Summary:* Chemical and residence time indicators largely support the sensitivity model. Lateral flow likely moved mixed tritium-age water to areas of very low sensitivity. High-capacity pumping, in conjunction with the high sand content of some overlying tills, likely allowed modern tritium-age water to reach 3 wells in very low sensitivity areas along A–A'; 1 of these wells also had anthropogenic chloride. The mostly premodern tritium-age sample with a carbon-14 residence time of less than 100 years in the northeast does not fit the estimated vertical travel time of a century or more for very low sensitivity areas; however, the mostly premodern tritium age suggests a residence time of approximately 70 to 100 years. Mostly premodern tritium-age water with a carbon-14 residence time of 25,000 years found in a 105-foot well in an area of low sensitivity along F–F' near the Partridge River may be a result of increased residence time from horizontal flow paths and a low vertical gradient.

scs aquifer (Figure 31)

- *Extent:* The aquifer is locally present in the northwest and east-central.
- *Depth:* Mean depth is 103 feet, ranging from approximately 36 to 171 feet.
- *Thickness:* Mean thickness is 11 feet, with a maximum of approximately 27 feet.
- *Use:* Approximately 3% of wells with an assigned aquifer.
- *Pollution sensitivity:* Very low sensitivity is common, with localized areas of very high to low sensitivity.
- *Residence time:* Of the 2 samples analyzed for tritium age, 1 was modern and 1 was mostly premodern. A carbon-14 residence time of 3,500 years was determined for the mostly premodern tritium-age sample.
- *Anthropogenic chemical indicators:* Of the 2 samples analyzed for chloride, both had concentrations below 5 ppm. Of the 2 samples analyzed for nitrate, none were anthropogenic.
- *Summary:* Modern tritium-age water with 13 TU from a well within an area of very low sensitivity along C–C′ near the Crow Wing River is likely a remnant of Cold War-era (late 1950s to 1960s) recharge (DNR and MDH, 2020). The sensitivity model underestimated travel time for a mostly premodern tritium-age sample with a carbon-14 residence time of 3,500 years from a 65-foot well in an area of high sensitivity west of Menahga. This longer residence time may be a result of long flow paths from recharge areas to the west.

mls aquifer (Figure 32)

- *Extent:* The aquifer is locally present across the county.
- *Depth:* Mean depth is 154 feet, ranging from approximately 60 to 255 feet.
- *Thickness:* Mean thickness is 10 feet, with a maximum of approximately 26 feet.
- *Use:* Approximately 6% of wells with an assigned aquifer.
- *Pollution sensitivity:* Very low sensitivity is common, with very small areas of moderate to low sensitivity.
- *Residence time:* Of the 6 samples analyzed for tritium age, 1 was modern, 2 were mixed, and 3 were mostly premodern. A carbon-14 residence time of 400 years was determined for 1 mixed tritium-age sample, and a carbon-14 residence time of 6,000 years was determined for 1 mostly premodern tritium-age sample.
- *Anthropogenic chemical indicators:* Of the 6 samples analyzed for chloride, 2 had concentrations at or above 5 ppm. Of these 2 samples, 1 had an anthropogenic source and 1 had a natural source. Of the 6 samples analyzed for nitrate, none were anthropogenic.
- *Summary:* Chemical and residence time indicators largely support the sensitivity model. Lateral flow likely moved mixed tritium-age water to an area of very low sensitivity. High-capacity pumping likely drew modern tritium-age water with anthropogenic chloride to an area of very low sensitivity near Wadena. Although a sample from an area of very low sensitivity near Nimrod had a mixed tritium age, the carbon-14 residence time of 400 years supports the pollution sensitivity model. A sample with a carbon-14 residence time of 6,000 years and natural chloride near Menahga supports the sensitivity model.

ebs aquifer (Figure 33)

- *Extent:* The aquifer is locally present in the west.
- *Depth:* Mean depth is 178 feet, ranging from approximately 86 to 282 feet.
- *Thickness:* Mean thickness is 15 feet, with a maximum of approximately 44 feet.
- *Use:* Approximately 1% of wells with an assigned aquifer.
- *Pollution sensitivity:* Very low sensitivity is common, with 1 small area of low sensitivity.
- *Residence time:* Of the 2 samples analyzed for tritium age, both were mostly premodern.
- *Anthropogenic chemical indicators:* Of the 2 samples analyzed for chloride, both had concentrations at or above 5 ppm and had a natural source. Of the 2 samples analyzed for nitrate, none were anthropogenic.
- *Summary:* The natural chloride source and mostly premodern tritium ages of both samples from areas of very low sensitivity support the sensitivity model.

usw aquifer (Figure 34)

- *Extent:* The aquifer is locally present in the south and central.
- *Depth:* Mean depth is 177 feet, ranging from approximately 97 to 305 feet.
- *Thickness:* Mean thickness is 9 feet, with a maximum of approximately 29 feet.
- *Use:* Approximately 1% of wells with an assigned aquifer.
- *Pollution sensitivity:* Sensitivity is very low.
- *Residence time:* The 1 sample analyzed for tritium age was mostly premodern.

- *Anthropogenic chemical indicators:* The 1 sample analyzed for chloride had a concentration at or above 5 ppm and had a natural source. The 1 sample analyzed for nitrate was not anthropogenic.
- *Summary:* The natural chloride source and mostly premodern tritium age of the sample from an area of very low sensitivity supports the sensitivity model.

uns aquifer (Figure 35)

- *Extent:* The aquifer is locally present in the south.
- *Depth:* Mean depth is 217 feet, ranging from approximately 109 to 338 feet.
- *Thickness:* Mean thickness is 14 feet, with a maximum of approximately 39 feet.
- *Use:* Approximately 2% of wells with an assigned aquifer.
- *Pollution sensitivity:* Sensitivity is very low.
- *Residence time:* Of the 3 samples analyzed for tritium age, all were mostly premodern. A carbon-14 residence time of greater than 40,000 years was determined for 1 mostly premodern tritium-age sample.
- *Anthropogenic chemical indicators:* Of the 3 samples analyzed for chloride, all had concentrations at or above 5 ppm and had a natural source. Of the 3 samples analyzed for nitrate, none were anthropogenic.
- *Summary:* The natural chloride source and mostly premodern tritium ages of samples from areas of very low sensitivity support the sensitivity model, as does the carbon-14 residence time of greater than 40,000 years of 1 sample.

Bedrock surface (Figure 36)

- *Depth:* Ranges from approximately 35 to 574 feet below the surface (Part A, Plate 5).
- *Use:* The bedrock is rarely used as a water source; it is used by only approximately 0.2% of wells with an assigned aquifer.
- *Pollution sensitivity:* Sensitivity is very low except at a localized bedrock high north of the city of Verndale (Part A, Plate 5), where the sensitivity increases to very high.
- No water samples were collected from the bedrock.

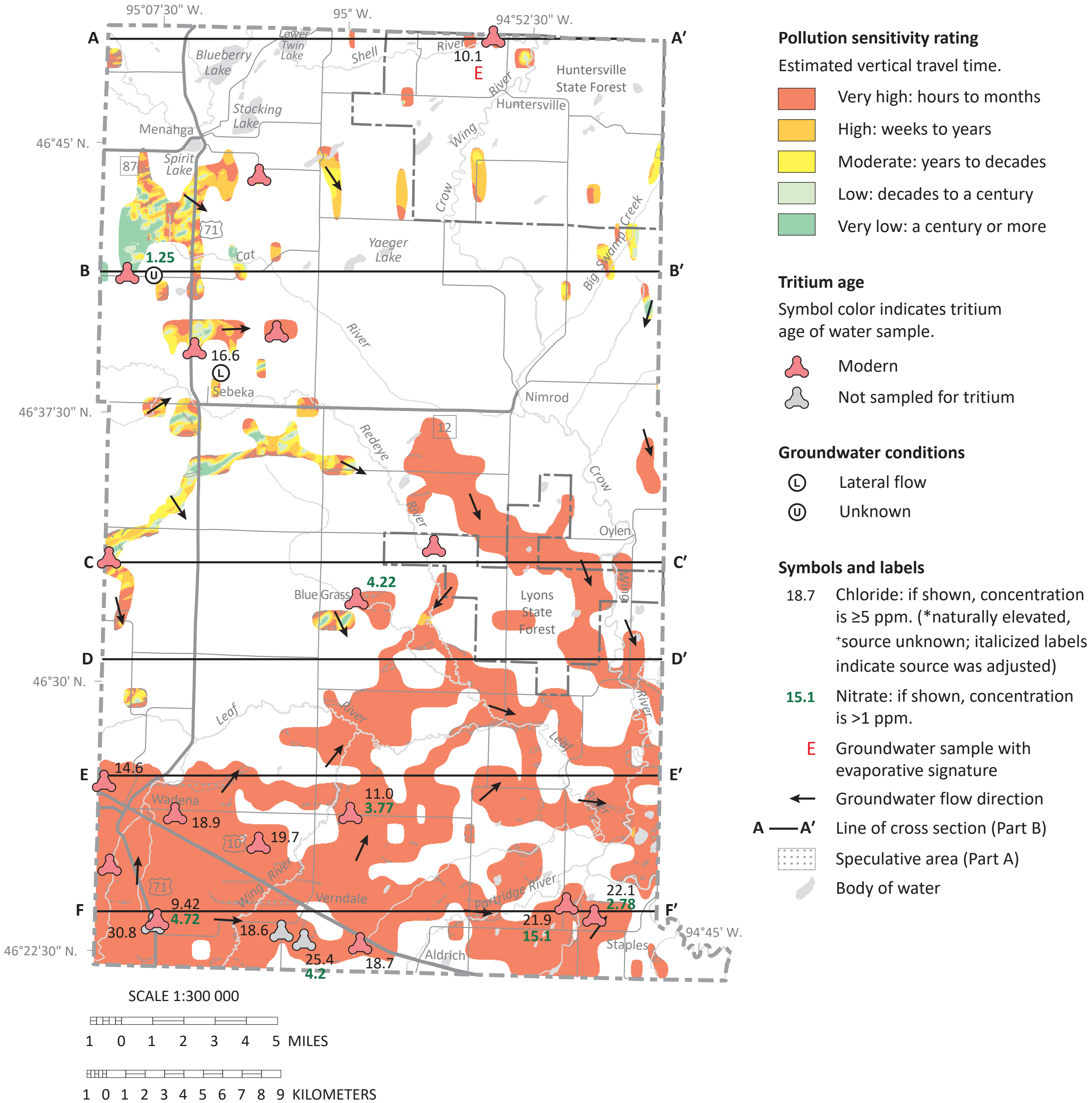


Figure 26. Pollution sensitivity of the hsa1 aquifer and groundwater flow directions

Aquifer sensitivity ranges from very high to very low, with large areas of very high sensitivity in the south. Chemical and residence time indicators largely support the sensitivity model, but sandy tills may provide less protection than predicted by the model.

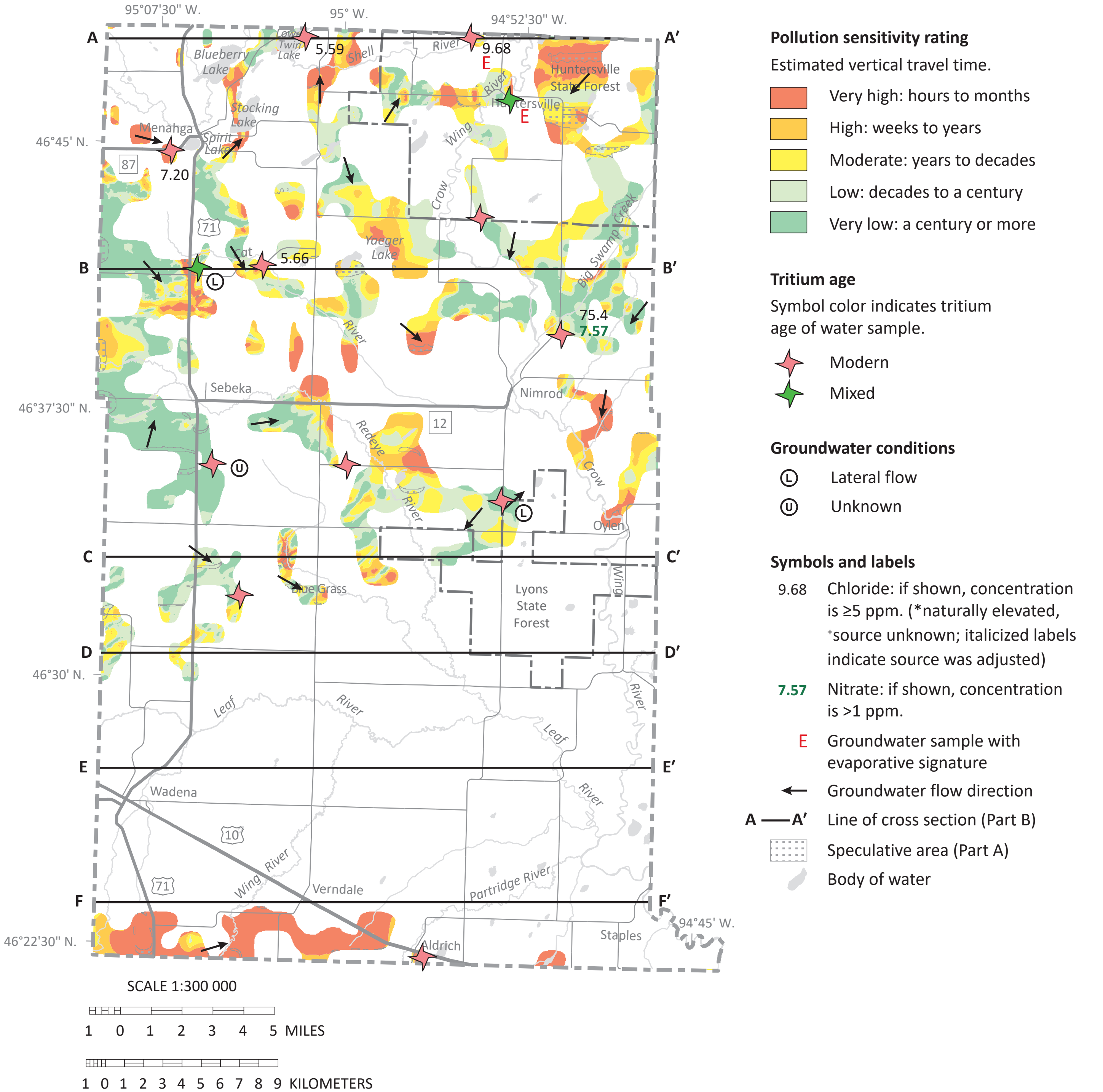


Figure 27. Pollution sensitivity of the hsa2 aquifer and groundwater flow directions

Aquifer sensitivity ranges from very high to very low. Chemical and residence time indicators largely support the sensitivity model, but sandy tills may provide less protection than predicted by the model.

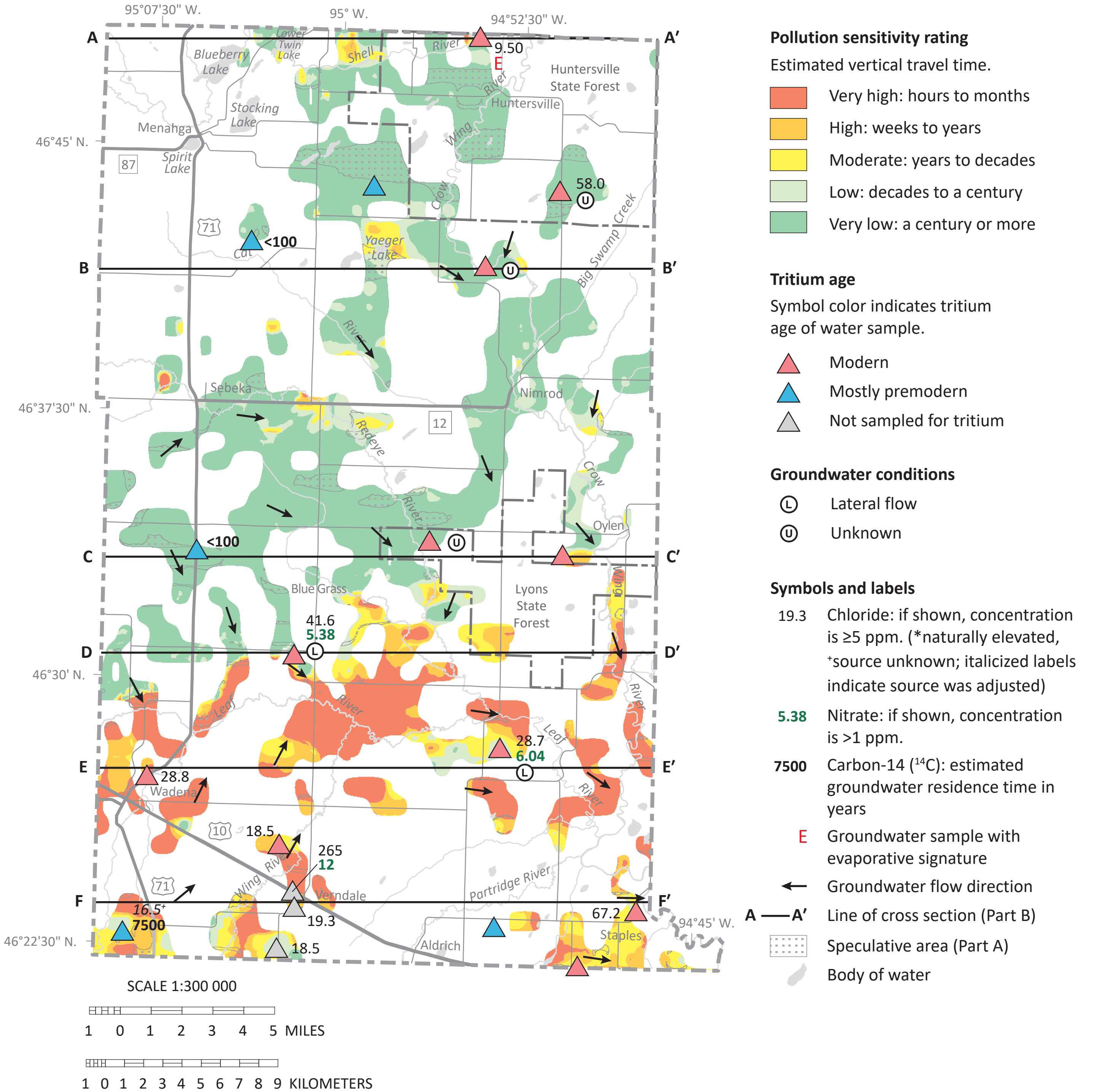


Figure 28. Pollution sensitivity of the brs1 aquifer and groundwater flow directions

Aquifer sensitivity ranges from very high to very low, with large areas of very high sensitivity in the south and very low sensitivity in the north. Chemical and residence time indicators largely support the sensitivity model, but sandy tills may provide less protection than predicted by the model. The model underestimated travel time for a sample from an area of low sensitivity in the southwest with a carbon-14 residence time of 7,500 years.

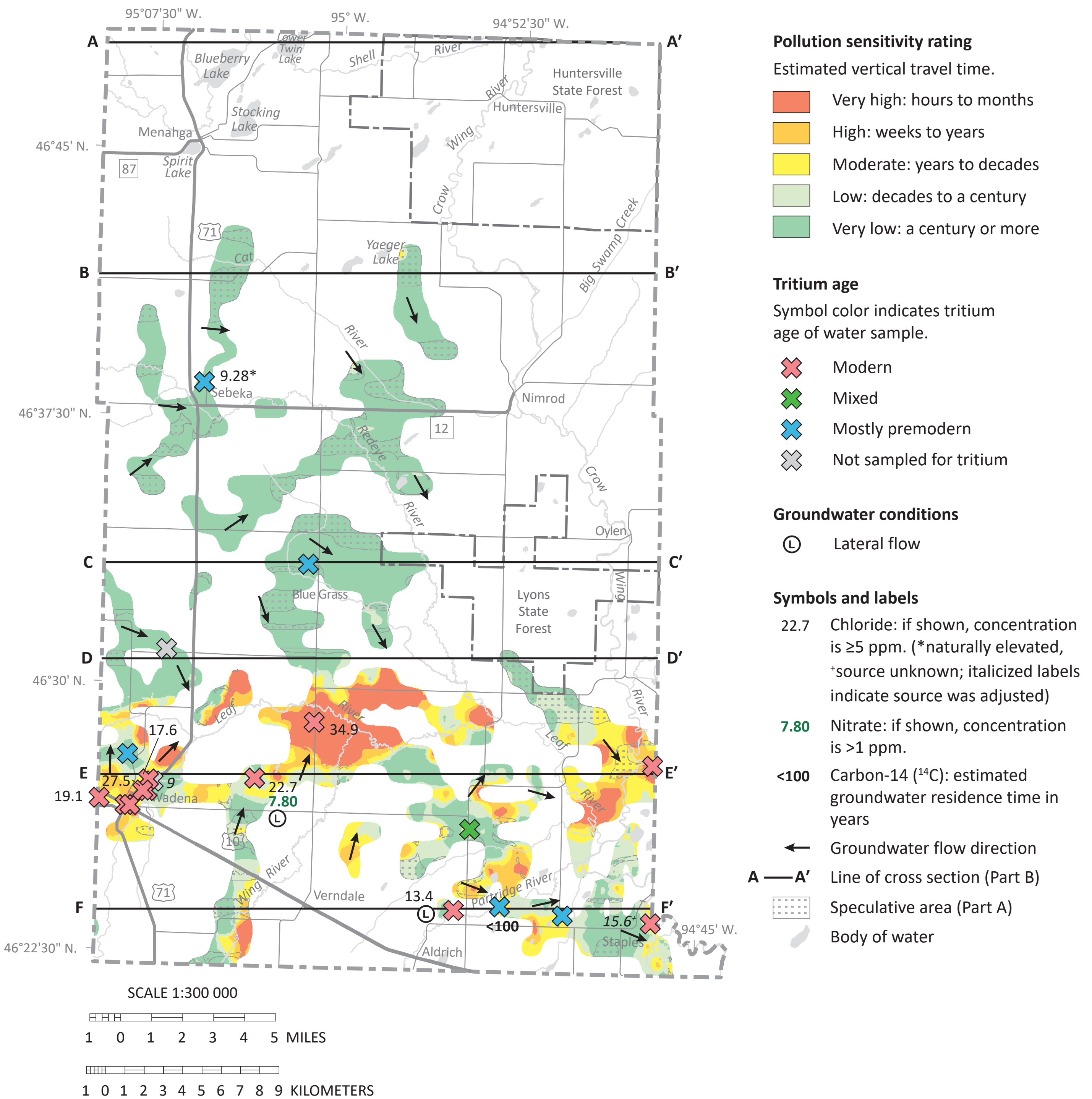


Figure 29. Pollution sensitivity of the brs2 aquifer and groundwater flow directions

Aquifer sensitivity ranges from very high to very low, with very low sensitivity common in the central part of the county. Chemical and residence time indicators largely support the sensitivity model.

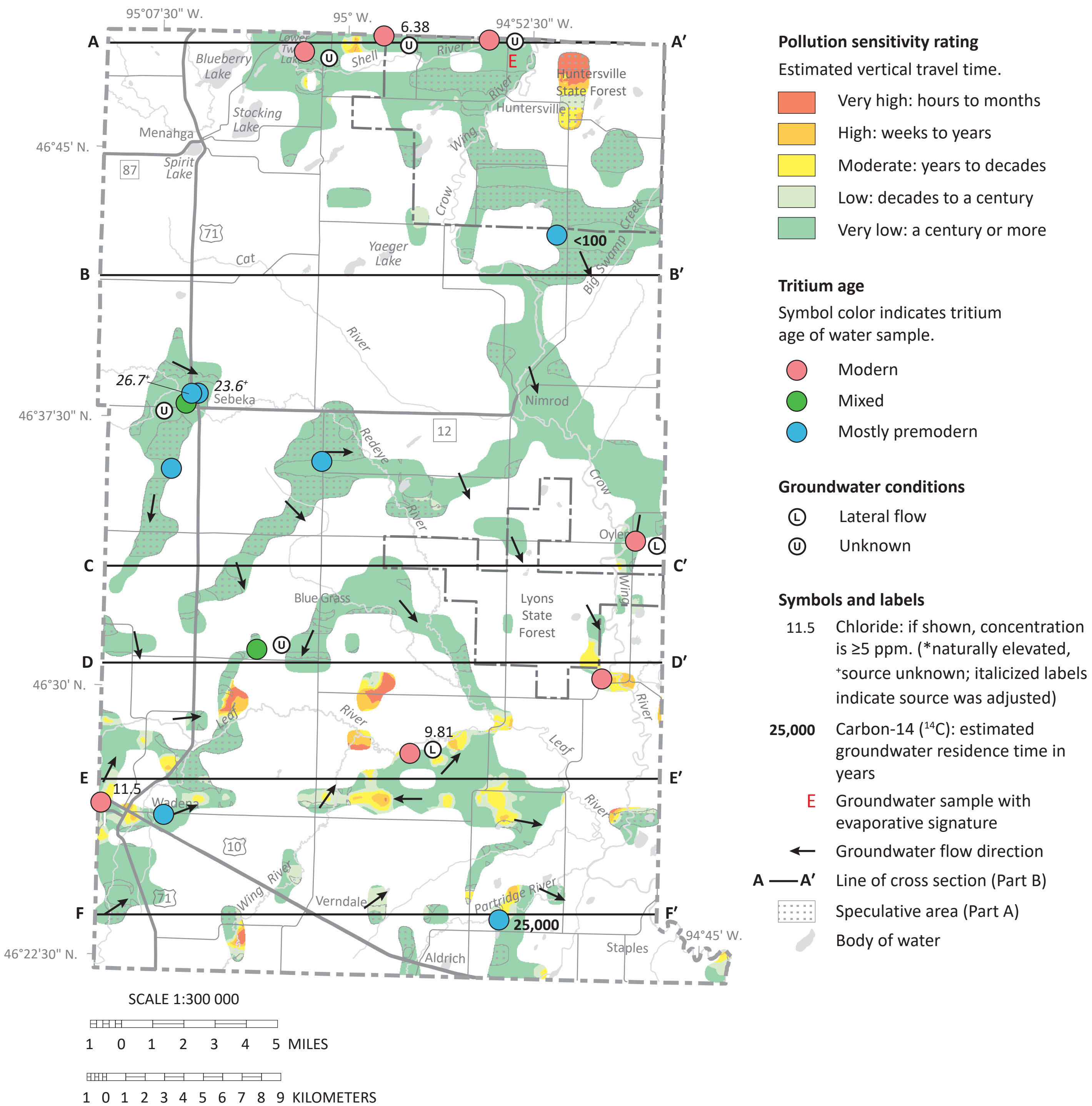


Figure 30. Pollution sensitivity of the brs3 aquifer and groundwater flow directions

Aquifer sensitivity is primarily very low, with areas of higher sensitivities. Chemical and residence time indicators largely support the sensitivity model. High-capacity pumping, in conjunction with the high sand content of some overlying tills, allowed modern tritium-age water to reach areas of very low sensitivity along A–A′. A carbon-14 residence time of 25,000 years was established for a sample from a low sensitivity area in the southeast and is likely a result of horizontal flow paths and a low vertical gradient.

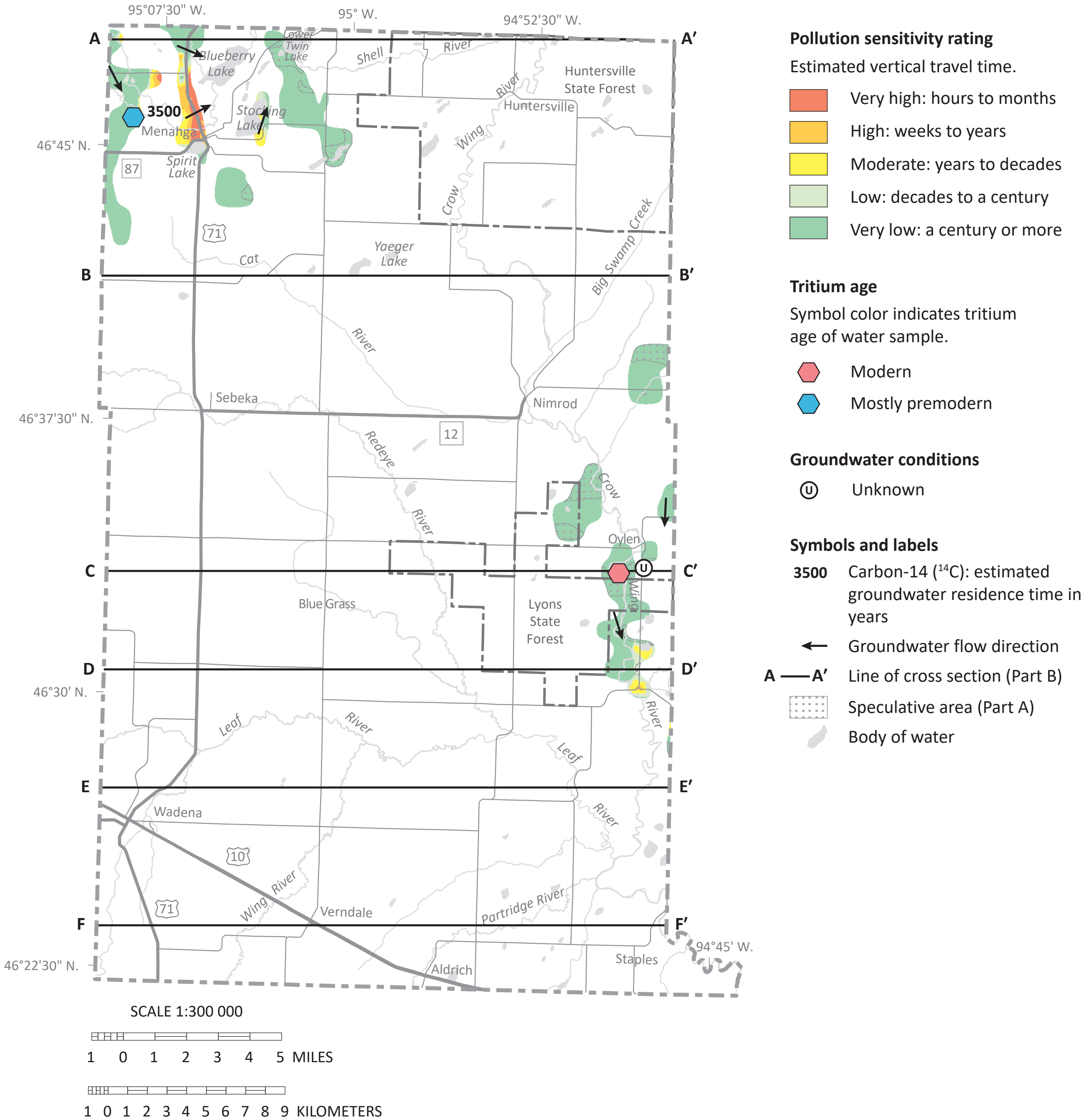


Figure 31. Pollution sensitivity of the scs aquifer and groundwater flow directions

Aquifer sensitivity is primarily very low, with areas of higher sensitivities. Modern tritium-age water from a well in an area of very low sensitivity along C–C′ near the Crow Wing River is likely a remnant of Cold War-era (late 1950s to 1960s) recharge. Mostly premodern tritium-age water found in a well within an area of high sensitivity west of Menahga may be a result of increased residence time along long flow paths from recharge areas to the west.

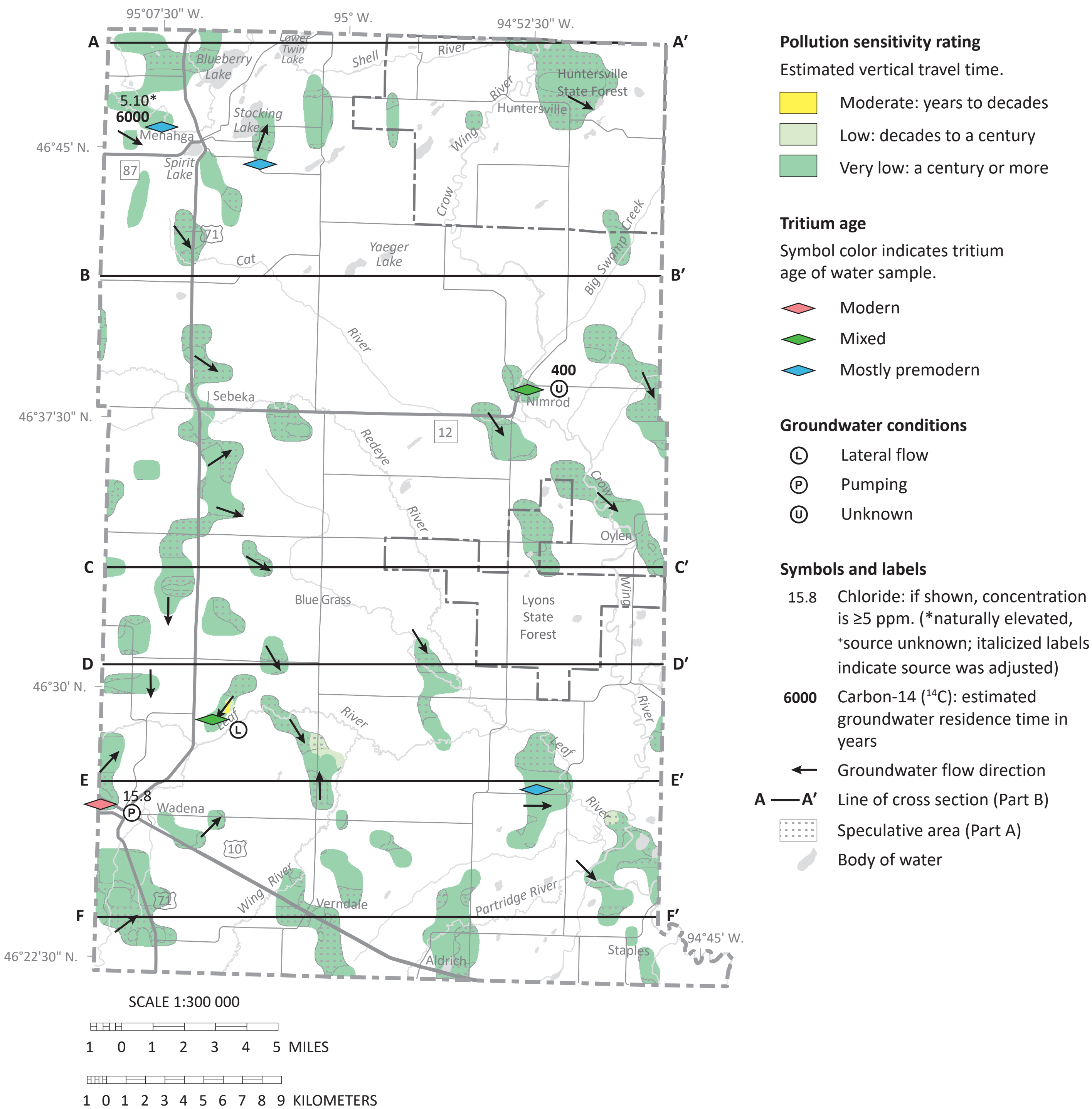


Figure 32. Pollution sensitivity of the mls aquifer and groundwater flow directions

Aquifer sensitivity is primarily very low, with isolated areas of moderate and low sensitivity. Chemical and residence time indicators largely support the sensitivity model. High-capacity pumping likely drew modern tritium-age water with anthropogenic chloride into a well in an area of very low sensitivity near Wadena.

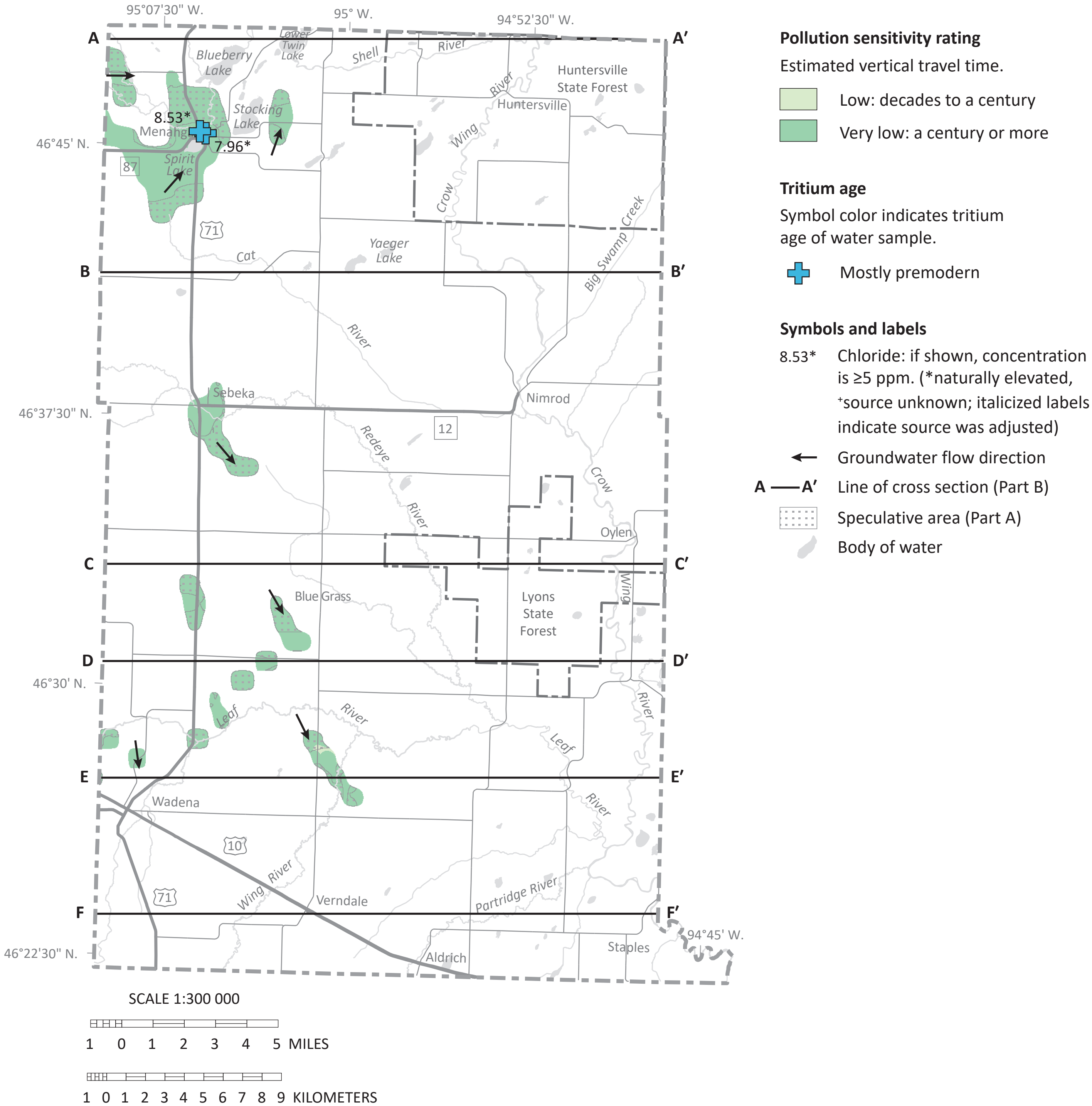


Figure 33. Pollution sensitivity of the ebs aquifer and groundwater flow directions

Aquifer sensitivity is primarily very low, with an isolated area of low sensitivity. Chemical and residence time indicators support the sensitivity model.

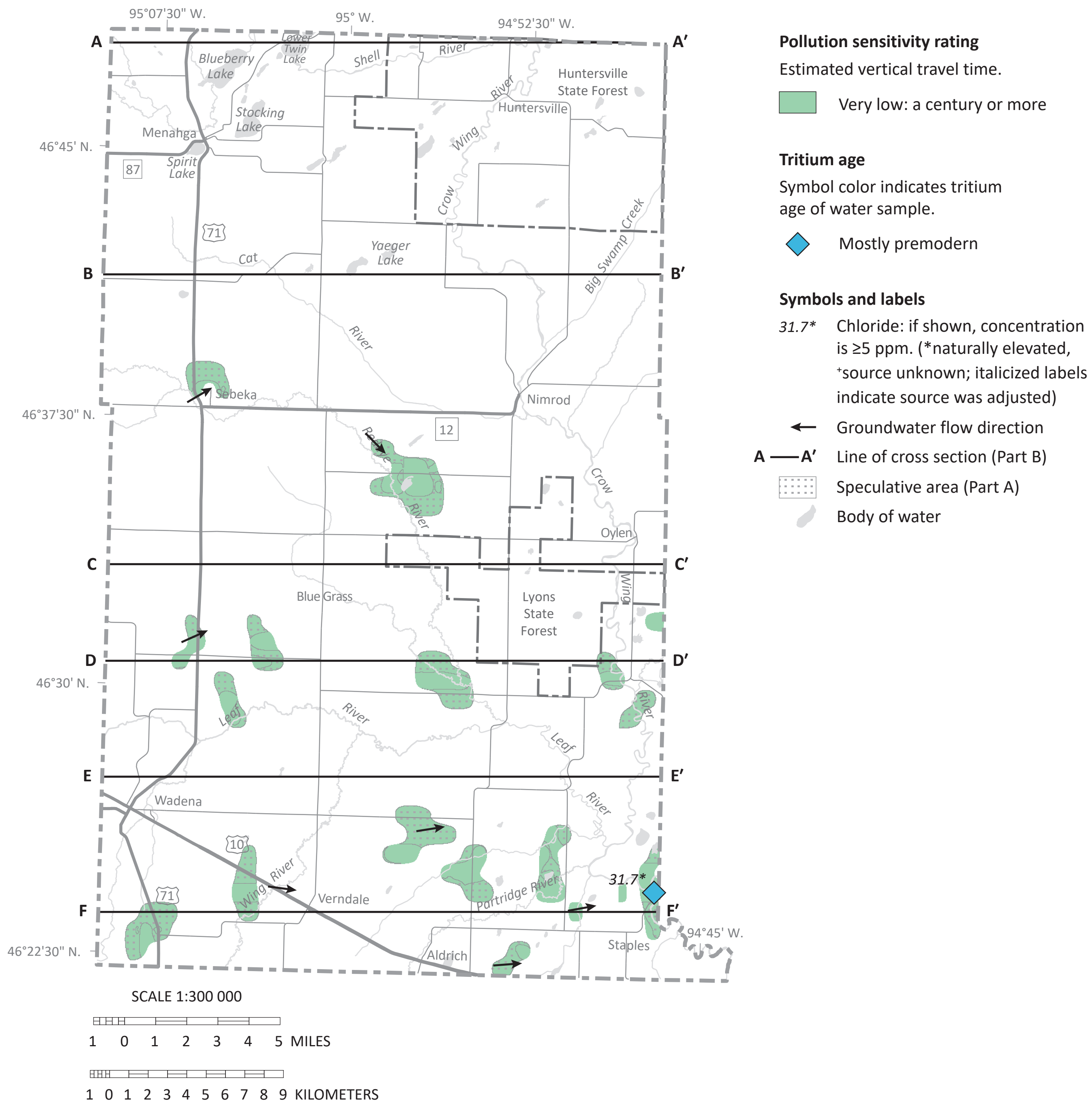


Figure 34. Pollution sensitivity of the usw aquifer and groundwater flow directions

Aquifer sensitivity is very low. Chemical and residence time indicators support the sensitivity model.

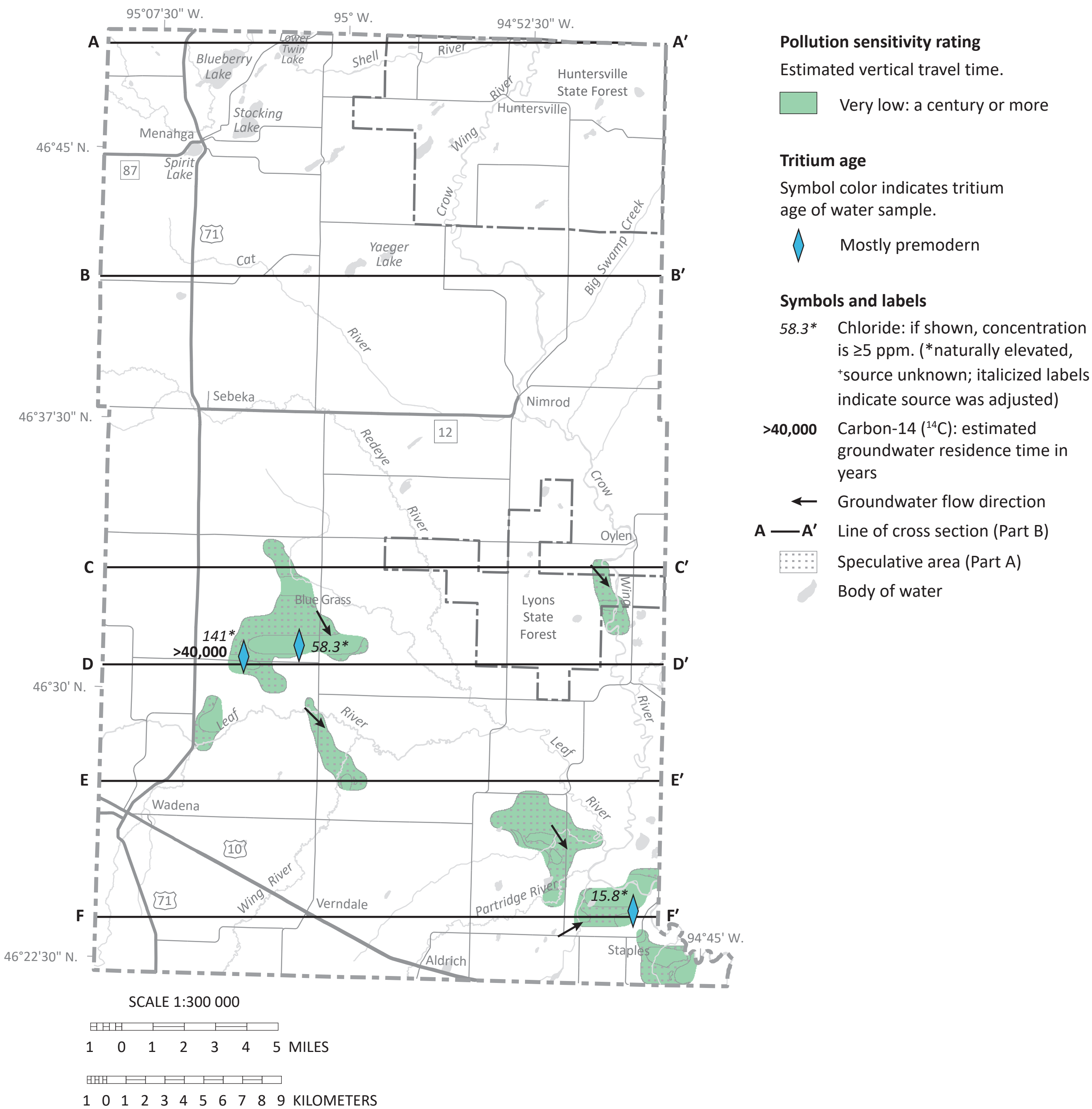


Figure 35. Pollution sensitivity of the uns aquifer and groundwater flow directions

Aquifer sensitivity is very low. Chemical and residence time indicators support the sensitivity model.

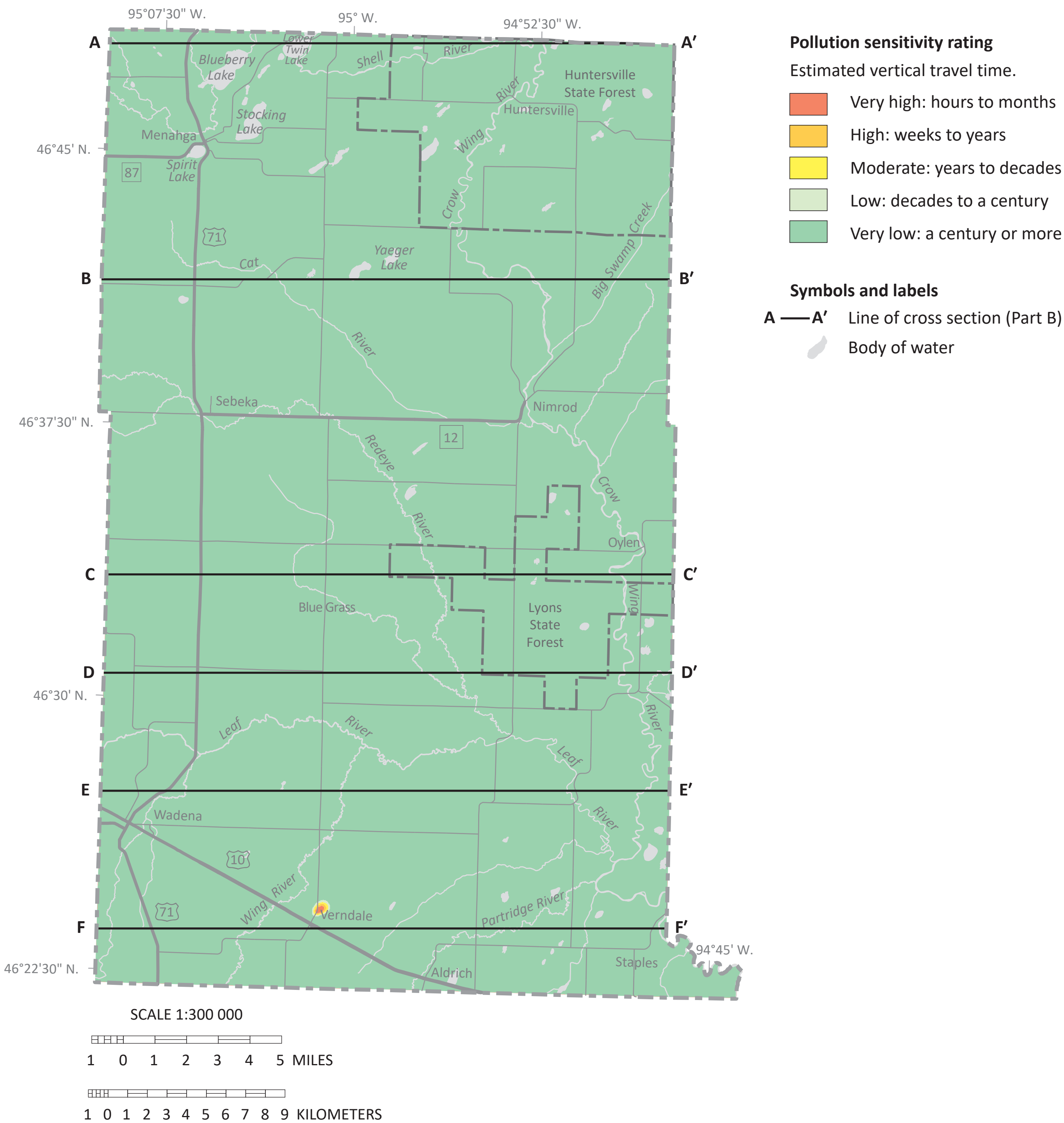


Figure 36. Pollution sensitivity of the bedrock surface

The bedrock surface is primarily very low sensitivity except at an area associated with a bedrock high near the city of Verndale, where it increases to very high sensitivity. No water samples were collected from the bedrock.

Hydrogeologic cross sections (Plate 7)

The six 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 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 one-half a kilometer.

Relative hydraulic conductivity of aquitards

Hydraulic conductivity represents the relative ease of water movement through sediment or bedrock. It is affected by the porosity and permeability.

Groundwater is found in voids (porosity) between sediment grains and within fractures in both unconsolidated sediment and 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 in shades of gray based on its assumed ability to transmit water. Hydraulic conductivity values are not available for the aquitards; therefore, the percent sand content of each aquitard 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).

The tills (aquitards) closer to the land surface have higher sand content (around 60%) and are likely more fractured in the upper 50 feet (Tipping and others, 2010), making them less competent confining layers and allowing more interconnection between aquifers. Deeper tills primarily have lower sand content (less than 45%) and are more clay- and silt-rich, making them more competent aquitards that better protect aquifers confined by these tills.

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 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'

Groundwater flows from slight topographic highs at the western and eastern edges toward the Crow Wing River. Modern tritium-age water has moved downward through the abundant vertically connected surficial and buried aquifers to 150 feet below the land surface. Modern tritium-age water was sampled in 3 wells, ranging from 126 to 144 feet deep between Lower Twin Lake and the Crow Wing River in the brs3 aquifer. High-capacity pumping, in conjunction with the high sand content of some overlying tills, allows modern water to reach deeper aquifers. Pumping may also be responsible for the evaporative lake water signatures below Duck Lake in the hsa1, hsa2, brs1, and brs3 aquifers. Anthropogenic chloride was identified in all modern tritium-age samples along the cross section, except for 2 from the brs3 aquifer below Lower Twin Lake and the Shell River. Anthropogenic nitrate was detected east of Lower Twin Lake in a sample from the surficial hsi aquifer. Mostly premodern tritium-age water is generally found greater than 150 feet below the land surface in aquifers protected by lower-sand-content tills.

B–B'

Groundwater flows from a slight topographic high in the west toward the Crow Wing River in the east, where there is a flow component out of the page toward the south. Modern and mixed tritium-age water has moved downward from surficial aquifers to aquifers approximately 100 feet below the land surface buried by high-sand-content tills. Anthropogenic chloride was identified in 2 wells with modern tritium-age water near the Cat River and Big Swamp Creek. Anthropogenic nitrate was detected in a sample on the west edge of the cross section from the hsa1 aquifer. Mostly premodern tritium-age water is generally found greater than 100 feet below the land surface.

C–C'

Groundwater flows from a topographic high in the west toward the Crow Wing River in the east. Modern tritium-age water has moved downward from surficial aquifers and till to buried aquifers approximately 100 feet below the surface. In a sample collected near the Crow Wing River from the scs aquifer, modern tritium-age water was measured at 13 TU. The elevated tritium concentration in this till-protected aquifer is likely a remnant of Cold War-era recharge. Mostly premodern tritium-age groundwater is generally found greater than 100 feet below the land surface. However, near US Highway 71, a sample from a 68-foot well in the brs1 aquifer had a mostly premodern tritium age and a carbon-14 residence time of less than 100 years. The water likely recharged in the decades just before the beginning of nuclear weapon testing in 1953.

D–D'

Groundwater flows from topographic highs in the west toward the Crow Wing River in the east. Modern tritium-age water has moved downward from surficial aquifers and till to buried aquifers approximately 100 feet below the surface. Anthropogenic chloride and nitrate were detected in a modern tritium-age sample collected near County Road 23 in the brs1 aquifer. Mostly premodern tritium-age groundwater is generally found greater than 100 feet below the land surface and was identified in a well near County Road 109 in the uns aquifer. The chloride in this same sample is interpreted to have a natural source, likely Cretaceous bedrock. The sample also had a carbon-14 residence time of greater than 40,000 years.

E–E'

Groundwater flows from topographic highs in the west and center of the cross section toward the east. Additionally, there is a flow component into the page along much of the western half of the cross section, where groundwater is flowing north toward the Leaf River. Modern tritium-age water has moved downward from surficial aquifers to buried aquifers approximately 100 feet below the surface. Anthropogenic chloride was identified in 4 of 5 modern tritium-age samples and 1 sample without tritium data. The 1 modern tritium-age sample that did not have anthropogenic chloride was collected at the east edge of the cross section in the brs2 aquifer. Anthropogenic nitrate was detected in a modern tritium-age sample from a well near County Road 109 in the brs2 aquifer. Mostly premodern tritium-age water is generally found greater than 100 feet below the land surface and was identified in a well west of the Leaf River in the mls aquifer.

F–F'

Groundwater flows from a slight topographic high in the west toward the Crow Wing River in the east. Modern tritium-age water has moved downward from surficial aquifers and till to buried aquifers approximately 60 feet below the surface. Anthropogenic chloride was identified in all modern tritium-age samples and 2 other wells less than 55 feet deep without tritium data. Anthropogenic nitrate was also identified in 5 of these under-60-foot-deep wells. Lower-sand-content tills better protect buried aquifers at shallower depths below the land surface compared to cross sections in the north. Mostly premodern tritium-age water was found at depths greater than 60 feet below the land surface. Carbon-14 residence times of less than 100 years and 25,000 years were determined near the Partridge River for samples from the vertically connected brs2 and brs3 aquifers, respectively. The large difference in carbon-14 residence times for these aquifers highlights the low vertical gradient and dominance of horizontal flow paths. Chloride in a sample from near County Road 30 in the uns aquifer is interpreted to have a natural source. The natural source is possibly nearby, unmapped Cretaceous bedrock; adjacent undifferentiated sediment (ups) is speculatively mapped.

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

Specific capacity describes how efficiently a well transmits water, and transmissivity describes how easily water moves through an aquifer. Larger values indicate more productive wells and aquifers.

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

To ensure that the specific-capacity values reflect actual pumping (not air-lift pumping), the pumping-test data were obtained from 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.

Specific capacity was determined for 104 wells with assigned aquifers (Table 2 and Figure 37). The wells are primarily located in the northern and southern thirds of the county, and 96 of the 104 wells are for irrigation use, with the remaining being public water supply or domestic use. Values were determined for 8 wells in the surficial sand hsi aquifer, with a mean value of 19.5 gpm/ft. The rest were determined for wells completed in buried sand aquifers. Mean specific capacity values consistently ranged from 29.8 to 36.6 gpm/ft for the hsa1 through brs3 aquifers. The highest mean value was measured in a test of a well screened in both the hsa2 and brs1 aquifers at 73.2 gpm/ft. The lowest mean value was measured in the scs aquifer at 6.7 gpm/ft.

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).

Transmissivity values were compiled from aquifer tests conducted at 5 wells (Table 2 and Figure 37). For the test in the surficial sand ns aquifer, transmissivity was determined to range from 3,140 to 21,000 ft^2/day. For buried sand aquifers, the brs2 and brs3 aquifers had wide ranges of calculated transmissivity values, while the hsa2 and ebs aquifers had lower ranges between the minimum and maximum values. The brs2 aquifer had the lowest value determined at 444 ft^2/day, and the brs3 aquifer had the highest value determined at 115,000 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.)	Min	Max	No. of tests
Surficial sand									
ns	-	-	-	-	-	6	3,140	21,000	1⁺
hsi	8 to 12	19.5	7.7	39.1	8	-	-	-	-
Buried sand									
hsa1	8 to 24	33.2	5.2	100	33	-	-	-	-
hsa2	8 to 16	29.8	5.8	62.5	5	16	2,470	5,060	1⁺
brs1	8 to 18	36.6	7.9	125	14	-	-	-	-
brs2	12 to 16	29.8	6	75	12	12	444	108,000	1⁺
brs3	8 to 16	31.2	3.9	350	24	12	1,020	115,000	1⁺
scs	12	6.7	6.2	7.1	2	-	-	-	-
mls	12	20	11.6	35.7	3	-	-	-	-
ebs	12	39.2	-	-	1	12	11,600	21,800	1⁺
usw	12	18.7	-	-	1	-	-	-	-
Multiple (hsa2 and brs1)	16	73.2	-	-	1	-	-	-	-

Specific capacity data adapted from the CWI.

Transmissivity data are from aquifer properties data (DNR, 2023b).

Dash means no data.

⁺For a single aquifer test, multiple transmissivity values may be calculated using different models.

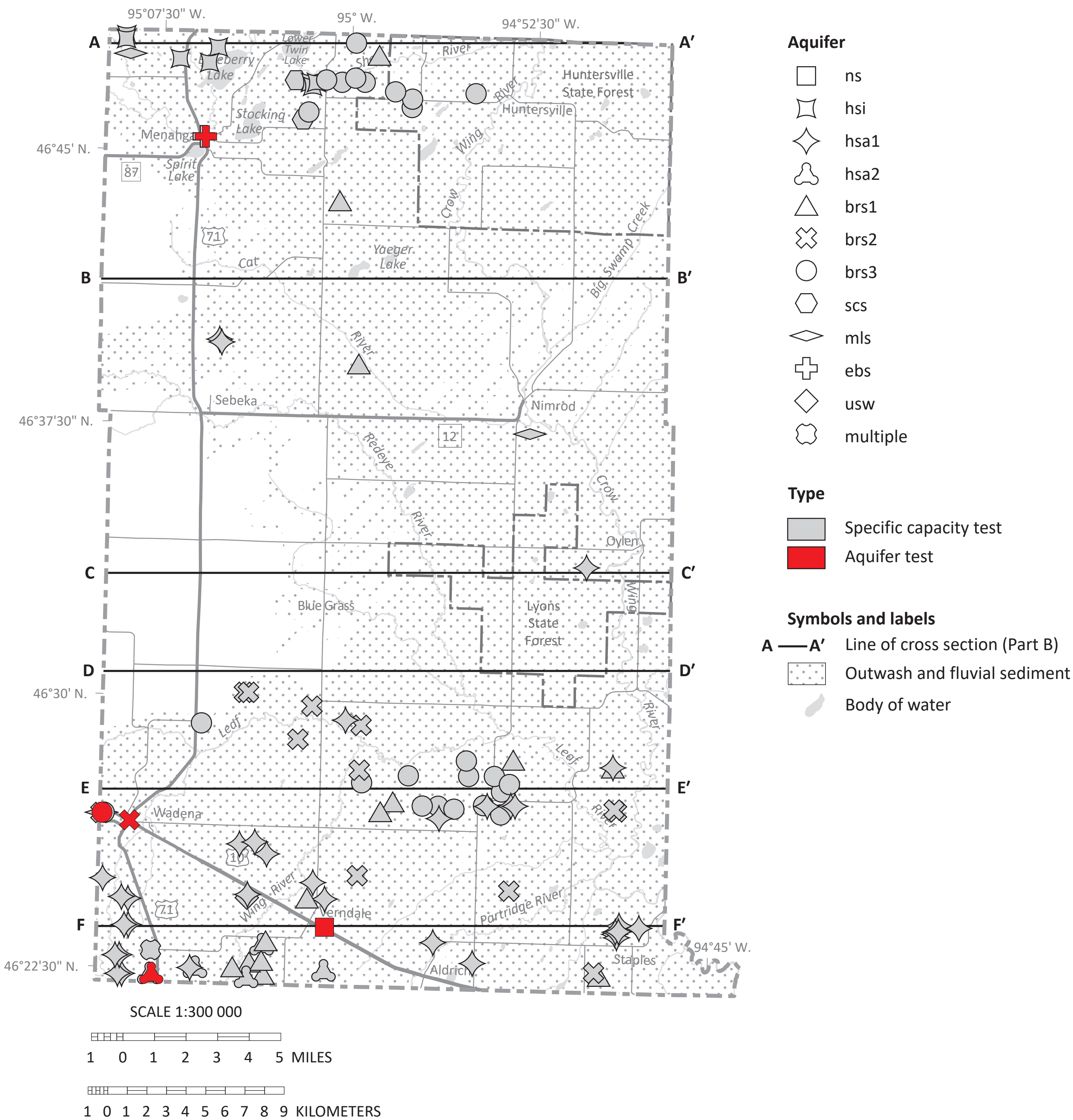


Figure 37. Well locations for specific capacity and aquifer tests

Specific capacity was determined for 104 wells, and transmissivity was compiled from aquifer tests of 5 wells (Table 2). Most wells are located in the northern and southern thirds of the county.

Groundwater level monitoring

The DNR maintains a statewide groundwater level monitoring program for assessing groundwater resources, determining long-term trends, interpreting impacts of pumping and climate, planning for water conservation, evaluating water conflicts, and managing water resources.

Hydrographs depict groundwater levels over time. They are useful for determining 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 that are completed in different aquifers. 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.

Groundwater level monitoring in the county currently occurs in 20 surficial and shallowly-buried sand aquifers under unconfined water-table conditions and in 8 confined buried sand aquifers (Figure 38). Observation wells are primarily located where surficial sand and agricultural irrigation are common (see Groundwater Use section).

Two sets of wells are described below to illustrate responses to recharge and pumping. Hydrograph data were retrieved from the DNR Cooperative Groundwater Monitoring Program (DNR, 2023c). Monthly gridded precipitation data were obtained through the Minnesota State Climatology Office (DNR, 2023d). Palmer Drought Severity Index data were obtained from the Midwestern Regional Climate Center’s cli-MATE database (MRCC, 2024).

Water-level records for other observation wells spanning back over five decades not presented in this report are available from the DNR Cooperative Groundwater Monitoring Program (DNR, 2023c).

Aldrich wells (Figure 39)

Two wells, approximately 1 mile north of the city of Aldrich (Figure 38), were selected to illustrate the effects of agricultural irrigation and seasonality on water levels from 2016 to 2021 (Figure 39). The 2 selected wells north of Aldrich are located 0.75 miles apart. Well 809293 is 23 feet deep and completed in the surficial sand ns aquifer under water-table conditions. Well 792507 is 124 feet deep and completed in the buried sand mls aquifer under confined conditions. An agricultural irrigation well located 0.3 miles south of the shallower well in the same ns aquifer averaged 7.4 million gallons per year of pumping during the hydrograph period of 2016 to 2021 (DNR, 2023e). Four agricultural irrigation wells are located within 1.5 miles of the deeper well in the same mls aquifer and averaged 47 million gallons per year of pumping during the same period (DNR, 2023e). For the drier year of 2021, use in these wells was up to three times greater than the previous year.

Water level in the shallow well generally increased in the late spring as snowmelt and rainfall recharged the aquifer before often falling slightly through the summer and fall, except during months of above-normal precipitation. Water level also dropped slightly during the frozen winter months when less recharge was able to reach the aquifer as a result of frozen soils. Water level reached its lowest point during the summer of 2021, after a period with several months of below-normal precipitation.

The deep observation well showed sharp water level declines of up to 30 to 50 feet, followed by rapid recoveries during the irrigation season as a result of nearby irrigation wells in the same aquifer cycling on and off. Over the late fall to spring months, when the pumps were idle, water level returned to pre-irrigation-season levels; this suggests current sustainable groundwater use in the aquifer. Below-normal monthly precipitation and increased pumping in 2021 resulted in a drawdown nearly twice as large as in previous years during the irrigation season. There was minimal short-term water level increase following precipitation events.

Groundwater elevations depict a downward gradient between these wells. The lack of a notable pumping signal in the shallow well likely highlights the protective and confining capabilities of tills overlying the mls aquifer, where the deeper well showed a significant pumping signal and minimal short-term reaction to precipitation events.

Menahga wells (Figure 40)

Two wells, approximately 5 miles east of the city of Menahga (Figure 38), were selected to illustrate long-term trends in water levels over several decades (Figure 40). The wells are 1.4 miles apart and are not a conventional well nest. Well 244582 is 15 feet deep and completed in the surficial sand hsi aquifer under water-table conditions. Well 516180 is 112 feet deep and completed in the buried sand brs1 aquifer under confined conditions. Up to 5 high-capacity pumping wells within 1.5 miles of the deeper well have been active in the brs1 or closely underlying brs3 aquifer since 1988, often withdrawing tens of millions of gallons of groundwater per year (DNR, 2023e).

Starting in 1974, water level in the shallow well was measured manually, monthly or less, with automated hourly measurements starting in 2015. Water level remained stable with short-term responses to precipitation events from 1974 to 2019. Water level rebounded from long-term drought events (defined by 6 or more months with a Palmer Drought Severity Index value of less than or equal to -3) in 1976 and 1977 and 1987 to 1990.

Water level in the deep well was measured manually, monthly or less, starting in 1992, with automated hourly measurements starting in 2012. Water level remained relatively stable from 1992 to 2019. Sharp drops in water level associated with high-capacity pumping during the irrigation season have been observed over the entire period; however, the water levels broadly recovered to within a foot of pre-pumping level. In some years, the water level recovered higher than the pre-pumping level.

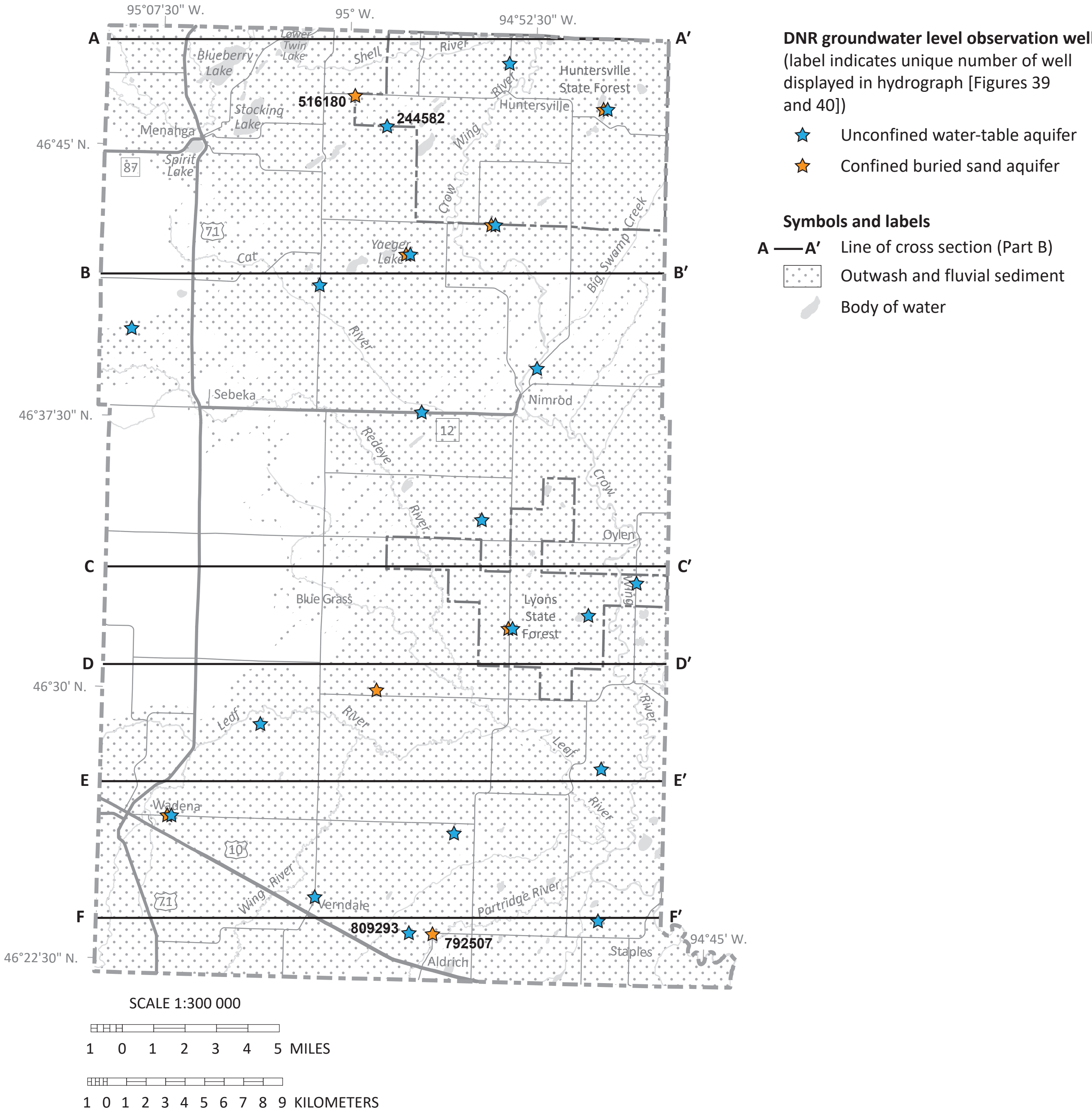


Figure 38. Actively monitored DNR observation wells

The largest concentration of actively monitored observation wells is in areas of surficial sand and where agricultural irrigation is common. Well locations for hydrographs shown in Figures 39 and 40 are labeled.

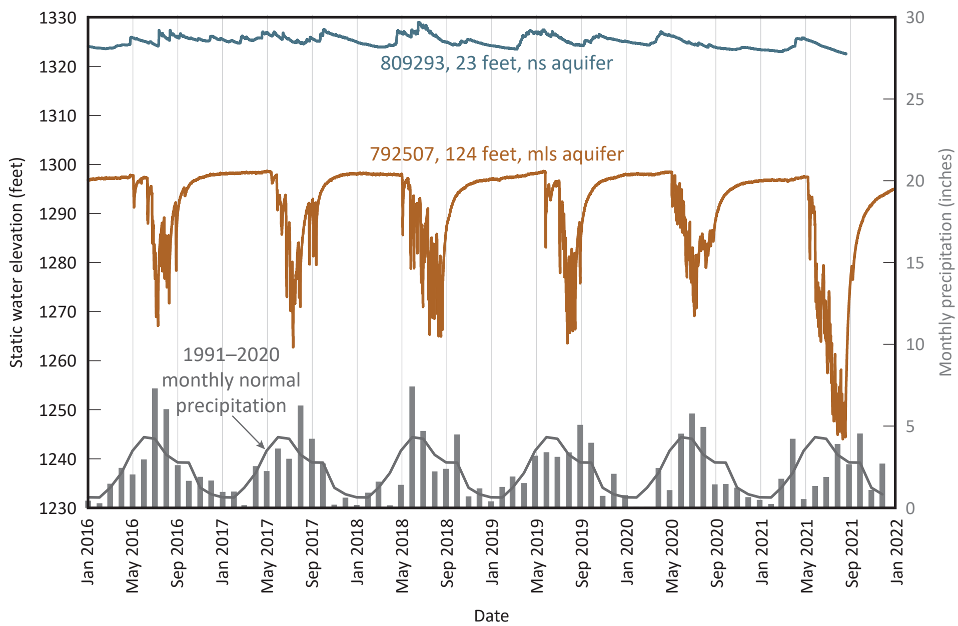


Figure 39. Groundwater hydrographs near Aldrich 2016 to 2021

Water level in the shallower observation well in the ns aquifer generally tracked with precipitation. The deeper observation well in the mls aquifer showed sharp drops and recoveries in water levels during the irrigation season from nearby irrigation wells cycling on and off and an increased drop in water level from greater water use and below-normal precipitation in 2021. Groundwater elevations show the downward movement of groundwater from the water table to buried aquifers and highlight the protective nature of tills between the 2 monitored aquifers.

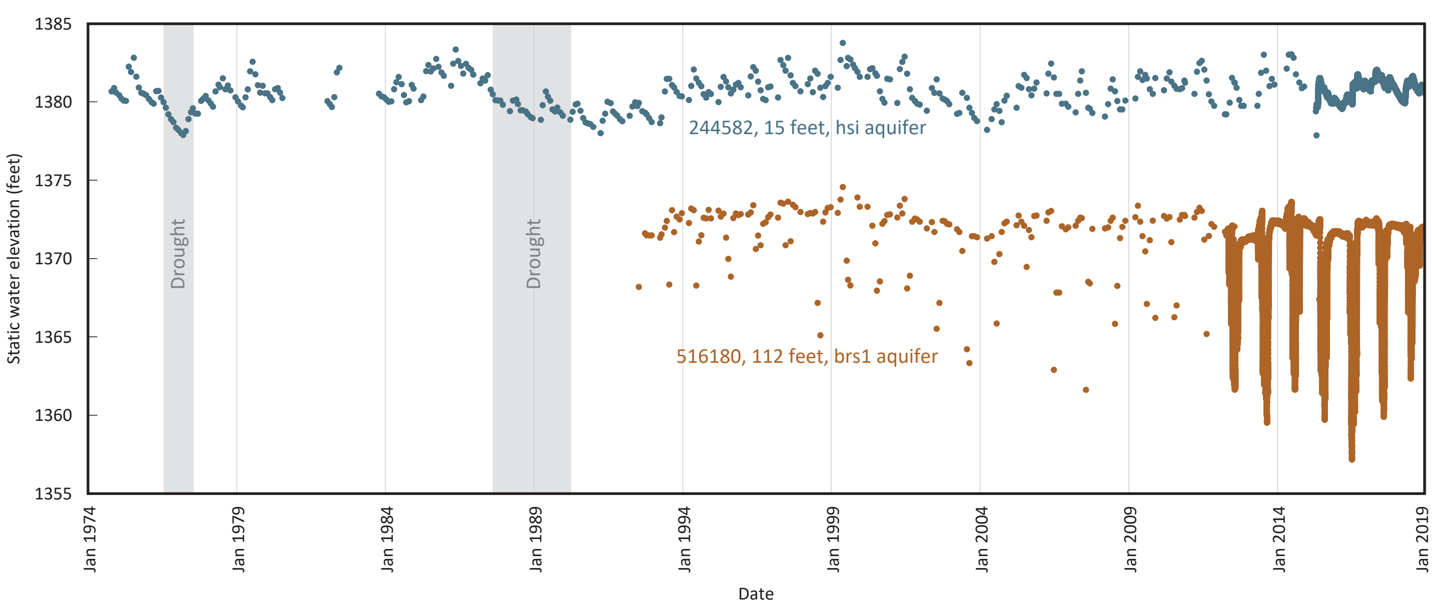


Figure 40. Long-term groundwater hydrographs near Menahga

Hydrographs for observation wells in both the shallow hsi aquifer and deeper brs1 aquifer span several decades. Water level in the shallow hsi aquifer was broadly stable, with small-scale responses to precipitation events and rebound from drought events. Water level in the deeper brs1 aquifer showed sharp drops associated with high-capacity pumping and recoveries to within a foot of pre-pumping level.

Groundwater use

CWI provides information for 2,230 verified wells in Wadena County. The majority of wells were for domestic use (70%), followed by irrigation (18%), monitoring or observation wells (7%), and all other uses (5%).

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 provides the DNR with the ability 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.

Water use for DNR permit holders in 2021 is shown in Figure 41 by water use type and in Figure 42 by general Quaternary aquifer classification (DNR, 2023e). Table 3 uses data for 304 permitted wells with appropriations in 2021 and the highest annual use in each use type for the period from 2017 to 2021.

Agricultural crop irrigation is the largest permitted use of groundwater, accounting for 95.1% of use in 2021. Agricultural crop irrigation was concentrated in the Pineland Sands and in the extensive surficial sand outwash plain in the south (Figure 41). Municipal/public water supply (3.2% of use) and golf course irrigation (1.1% of use) were the next largest uses. Water use was highest in 2021 for all use types during the 2017 to 2021 timeframe.

Table 3. Reported 2021 water use from DNR groundwater permit holders and highest and median annual use 2017 to 2021

		Use (mgy)					
Quaternary aquifer	**No. of wells**	**Agricultural crop irrigation**	**Municipal/ public water supply**	**Golf course irrigation**	**Other[+]**	**Total (mgy)**	**Total (%)**
Unconfined water table (QWTA)*	163	4,300.6	233.1	76.2	16.2	4,626.1	51.3
Confined buried sand (QBAA)	129	3,912.2	57.3	26	33	4,028.5	44.7
Unknown or unassigned	12	362.1	--	--	--	362.1	4.0
Total (mgy)	**N/A**	**8,574.9**	**290.4**	**102.2**	**49.2**	**9,016.7**	**N/A**
Total (%)	**N/A**	**95.1**	**3.2**	**1.1**	**0.6**	**N/A**	**100**
Highest annual use 2017 to 2021	N/A	8,574.9	290.4	102.2	49.2	N/A	N/A
Median annual use 2017 to 2021	N/A	4,579.4	251.8	71.7	27.9	N/A	N/A

*Surficial sand aquifers and buried sand aquifers under water-table conditions
Data from MPARS; mgy, million gallons per year; dash marks (--) indicate no use; N/A indicates not applicable
[+]Other use types in 2021 include sod farm irrigation, landscaping/athletic field irrigation, livestock watering, private water supply, pipeline and tank testing, and construction dewatering.

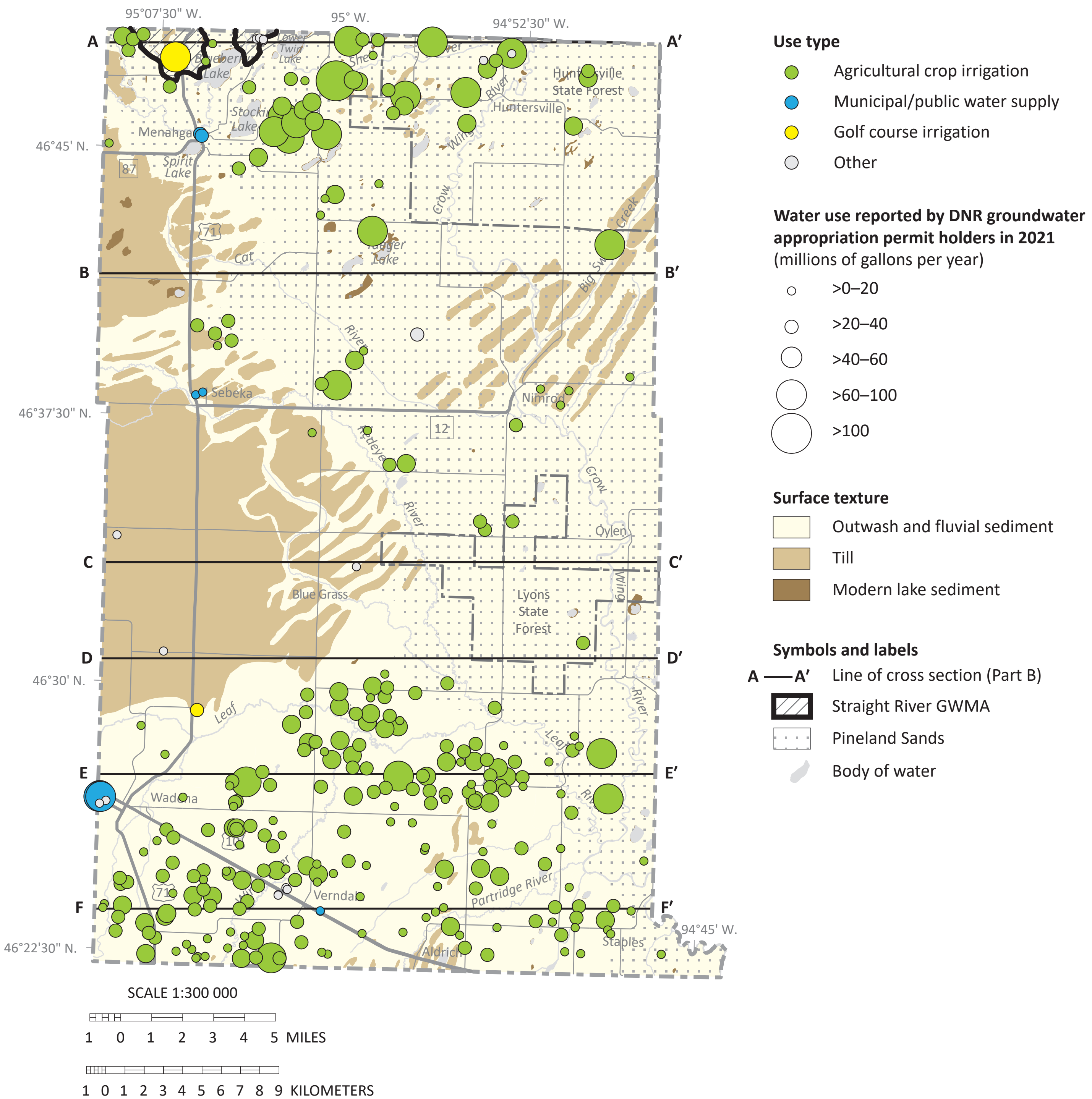


Figure 41. Distribution of groundwater permits by volume and use type

Agricultural crop irrigation is the largest permitted use of groundwater. Permitted water use is concentrated in the Pineland Sands and the surficial sand outwash plain in the south. The DNR established the Straight River GWMA in an effort to sustainably manage groundwater resources in the northwest and neighboring counties (DNR, 2017).

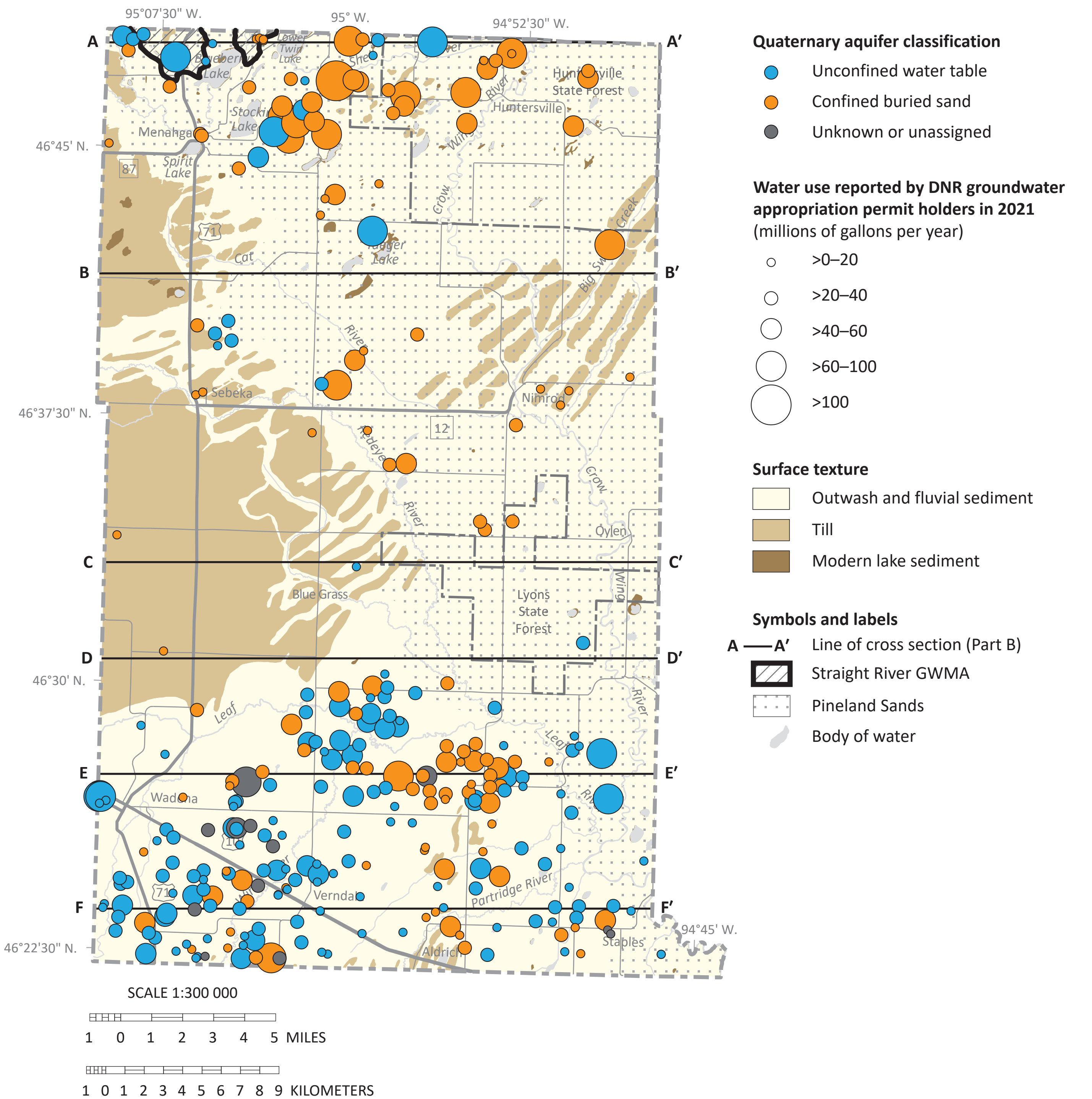


Figure 42. Distribution of groundwater permits by general aquifer classification

Groundwater use was slightly greater for wells completed in unconfined aquifers under water-table conditions than those in confined buried sand aquifers. A larger proportion of wells with permitted use from aquifers under water-table conditions are in the south.

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Glossary

adsorb—individual molecules, atoms, or ions gathering on surfaces.

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.

alluvial—relating to or derived from sediment deposited by rivers or streams.

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 layer)—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.

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

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

carbon-14 (^{14}C)—a radioactive isotope of carbon with 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 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. Information includes location, depth, static water level, construction, and geological information. The database and other features are available through the **Minnesota Well Index** online mapping application.

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.

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

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

drumlin—an elongated mound or ridge of glacial till built under the margin of glacial ice and shaped by its flow. Its longer axis is parallel to the direction of movement of the ice. It usually has a blunt nose pointing in the direction from which the ice approached and a gentler slope tapering in the other direction.

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.

flowpath—the direction of movement of water. The subsurface course that a water molecule follows.

fluvial—relating to or formed by rivers and streams.

formation—a fundamental unit of lithostratigraphy. A formation consists of a number of rock strata that have a 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 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 have the same number of protons but a different number of neutrons.

lacustrine—relating to or formed in a lake.

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).

potential energy—energy (in groundwater) held by water because of differences in elevation or pressure.

proton—a subatomic particle contained in the atomic nucleus. It has a positive electrical charge and an atomic mass of 1.

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 indicator—chemical and/or isotope used to interpret groundwater residence time.

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

stable isotope—chemical isotope that is 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 which 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.

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

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

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

watershed—the area of land 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

Groundwater samples collected by the DNR for the project were collected from an outside faucet or hydrant. The wells were purged prior to 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 to laboratories for analysis.

Samples were analyzed by DNR staff, the 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 prior to 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 prior to 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 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 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 for determining 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 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 page (mndnr.gov/groundwatermapping)

For additional weather station information, contact the administering program.

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

Appendix Table B: Enriched tritium results

Sample location	Sample date range	Tritium (TU)	Sample type
MNgage precipitation station (MWDM5)	05/21/2012 to 06/20/2012	8.7	Precipitation composite
	09/30/2012 to 10/30/2012	6.7	Precipitation composite
	05/09/2014 to 06/09/2014	7.0	Precipitation composite
	10/01/2014 to 10/31/2014	6.7	Precipitation composite
	05/01/2015 to 05/31/2015	5.3	Precipitation composite
	08/17/2016 to 09/16/2016	8.3	Precipitation composite
	04/01/2017 to 04/30/2017	8.1	Precipitation composite
	09/06/2017 to 10/06/2017	6.5	Precipitation composite
	10/03/2018 to 11/01/2018	3.7	Precipitation composite
	4/11/2019	13.4	Snow
	04/04/2019 to 05/04/2019 (excluding 04/11/2019)	12.1	Precipitation composite
	09/09/2019 to 10/03/2019	5.0	Precipitation composite
	09/01/2020 to 09/30/2020	7.7	Precipitation composite
CoCoRaHS precipitation station (MN-SL-137)	09/01/2020 to 10/01/2020	8.1	Precipitation composite
Lake-water sample (Blueberry Lake)	6/14/2018	7.9	Limnetic 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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CLEAN WATER LAND & LEGACY AMENDMENT