Groundwater Atlas of Hubbard County, Minnesota

County Atlas Series C-41, Part B - Hydrogeology

Report

To accompany these atlas components:

Plate 7, Water Chemistry

Plate 8, Hydrogeologic Cross Sections

Plate 9, 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 Hubbard County, Minnesota, C-41, Part A* (Lusardi, 2018), published by the Minnesota Geological Survey. It contains Plate 1, Data-Base Map (Bloomgren and Chandler); Plate 2, Bedrock Geology (Chandler and Radakovich); Plate 3, Surficial Geology (Knaeble and Hougardy); Plate 4, Quaternary Stratigraphy (Knaeble); Plate 5, Sand-Distribution Model (Knaeble and Hamilton); Plate 6, Bedrock Topography and Depth to Bedrock (Radakovich and Chandler). Information is available on 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 on the Minnesota Department of Natural Resources, Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

Citation for this atlas:
Budde, N.R., 2024, Groundwater atlas of Hubbard County, Minnesota: Minnesota Department of Natural Resources, County Atlas Series C-41, Part B, report, 3 pls., GIS files.

Acknowledgments

Author Nicholas R. Budde, GIS/Cartography Nicholas R. Budde and Holly Johnson, Editors Holly Johnson and Susan Montgomery.

The author would like to thank the following people from the Groundwater Atlas Program for their contributions and suggestions: Vanessa Baratta-Person, John Barry, Randy Bradt, Dan Cronquist, Rachel Lindgren, and J. Wes Rutelonis. The author would also like to thank Kenneth Blumenfeld of the Minnesota DNR State Climatology Office for preparing the climate summary for this atlas.

The author is grateful for the reviews of this atlas provided by Eric Bunge, Robert Guthrie, Gail Haglund, Kimberly Kaiser, Kal Larson, and Barbara Lusardi. Comments received from contributors and reviewers 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 page.

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 Hubbard County, Minnesota, Part A*, 2018. Universal Transverse Mercator projection, Zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion factors

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

Groundwater Atlas of Hubbard County, Minnesota

by Nicholas R. Budde

Executive summary

This report and the accompanying plates describe the groundwater characteristics of Hubbard 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, 2018).

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. Key elements and findings are summarized below.

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

Hydrogeology and groundwater flow (pages 5–15) 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 in the south, in localized glacial outwash channels in the north, and along modern-day streams. Buried sand and gravel aquifers consist of glacial outwash channels buried by glacial till or other sand and gravel aquifers. Sand and gravel aquifers are broken into two broad systems in this atlas:

1. An upper system of aquifers within a relatively sand-rich glacial till (approximately 60 percent sand content).
2. A lower system of aquifers within less permeable till (sand contents below 45 percent).

Groundwater flow at the water table and in the upper system of aquifers usually follows surface-water flow, with recharge in uplands and flow from higher elevations to areas of lower elevation occupied by streams, lakes, and wetlands. Groundwater flow in the lower system of aquifers is more generalized, with a regional west-to-east flow pattern present.

The upper system of aquifers provides water for 93 percent of well owners. Consequently, less aquifer data is available at greater depths in the lower system of aquifers. Bedrock is not used as a water source because it is deeply buried by glacial deposits.

Water chemistry (pages 16–28, Plate 7) provides information about the following:

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

Groundwater is primarily recharged by direct infiltration of precipitation. Evidence of recharge via surface water was found downgradient of some lakes.

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

Groundwater with tritium ages reflecting recharge after 1953 was found in surficial and buried sand and gravel aquifers generally to 100–150 feet below the land surface.

Groundwater with tritium ages reflecting recharge prior to 1953 was found in buried sand and gravel aquifers predominately greater than 100 feet below the land surface. Carbon-14 residence times for a subset of these samples ranged from 400–4,500 years.

Inorganic chemistry:

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

Chloride and nitrate concentrations suggest that groundwater is impacted by anthropogenic sources, primarily in areas where sand is the surficial geologic unit. A majority of the samples impacted by anthropogenic sources were collected from shallow wells (less than 100 feet deep) located in the southern part of the county, where crop cultivation is a common land use.

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

Arsenic was detected in over half of the well water samples. Three of the 114 samples exceeded the drinking water standard of 10 parts per billion.

Manganese was detected in approximately three-quarters of the well water samples, and just over half of the well water samples exceeded the health-based drinking water guideline of 100 parts per billion.

Pollution sensitivity (pages 29–46) 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 very low. High sensitivity is associated with the outwash plain sand and gravel deposits in the south and channel outwash deposits in the north. Moderate and low sensitivity is associated with sandy loam tills found across much of the remaining area.

The pollution sensitivity of **buried sand and gravel aquifers** ranges from very high to very low depending on the thickness of fine-grained sediment above the aquifer. Aquifers closest to the land surface have higher pollution sensitivity, as do deeper aquifers that are overlain by sand and gravel. In the south, aquifers are often connected with no intervening fine-grained sediment. Deep buried sand and gravel aquifers are typically less sensitive to pollution. However, relatively young (post-1953) water was found in some deeply buried aquifers, likely as a result of the sandy and transmissive nature of the upper tills.

Hydrogeologic cross sections (pages 47–49, Plates 8 and 9) 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 50–60) 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 rarely require a use permit. Permits are required for wells that withdraw greater than 10,000 gallons per day or 1 million gallons per year.

Agricultural crop irrigation was the largest permitted user of groundwater in 2020, accounting for 85.7 percent of use. Agricultural/food processing (8.9 percent) and municipal/public water supply (3.9 percent) were the next-largest users. Permitted groundwater use is concentrated in the south.

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.

Hubbard County is in north-central Minnesota (Figure 1) and had an estimated population of 21,960 on July 1, 2022 (U.S. Census Bureau, 2023). Open water covers approximately 7 percent and wetlands cover approximately 15 percent of the county's 999-square-mile surface area (Dewitz and USGS, 2021). While the entire county lies within the uppermost reaches of the greater Mississippi River watershed, a local east-west watershed divide bisects the county center. In the north, water flows north as a part of the Mississippi River–Headwaters watershed and east as part of the Leech Lake River watershed (Figure 1). South of the divide, water primarily flows south as part of the Crow Wing River watershed, with small areas in the southeast flowing to the east as parts of the Leech Lake River and Pine River watersheds. Land use varies with forests covering the hilly northern and central portions, transitioning to mixed forest and agriculture in the south (Dewitz and USGS, 2021).

The climate is humid-continental, with warm to hot summers, cold winters, and an annual temperature range typically greater than 130° Fahrenheit (F). Based on 1991–2020 climate normals, the June through August average temperature is 65.7°F, with December through February averaging 11.6°F (DNR, 2023a). Average annual precipitation is approximately 26 inches, placing Hubbard County on the mid-low side of the statewide range of 21–38 inches (DNR, 2023b). The region has pronounced wet and dry seasons, with precipitation during the summer being approximately five times greater than during the winter.

From 1895 through 2022, average annual temperatures increased by 2.8°F, which is near the statewide average temperature increase of 2.9°F. The increases were fastest during winter, at night, and especially in the period since 1970, when daily minimum temperatures have risen more than 40 percent faster than daily maximum temperatures; average winter temperatures have risen more than two times faster than average summer temperatures. Annual precipitation shows no trend or a very slight decline since 1895, although intense rainfall events producing daily totals over 1–3 inches were more common since 1990 than during any other period on record (DNR, 2023a).

Climate projections summarized in the 2014, 2017, and 2018 National Climate Assessments and others available for the state of Minnesota indicate that Hubbard County is predicted to warm by an additional 2–4°F by 2050, while annual precipitation is predicted to increase by an additional 1–3 inches. Short-term variations are 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).

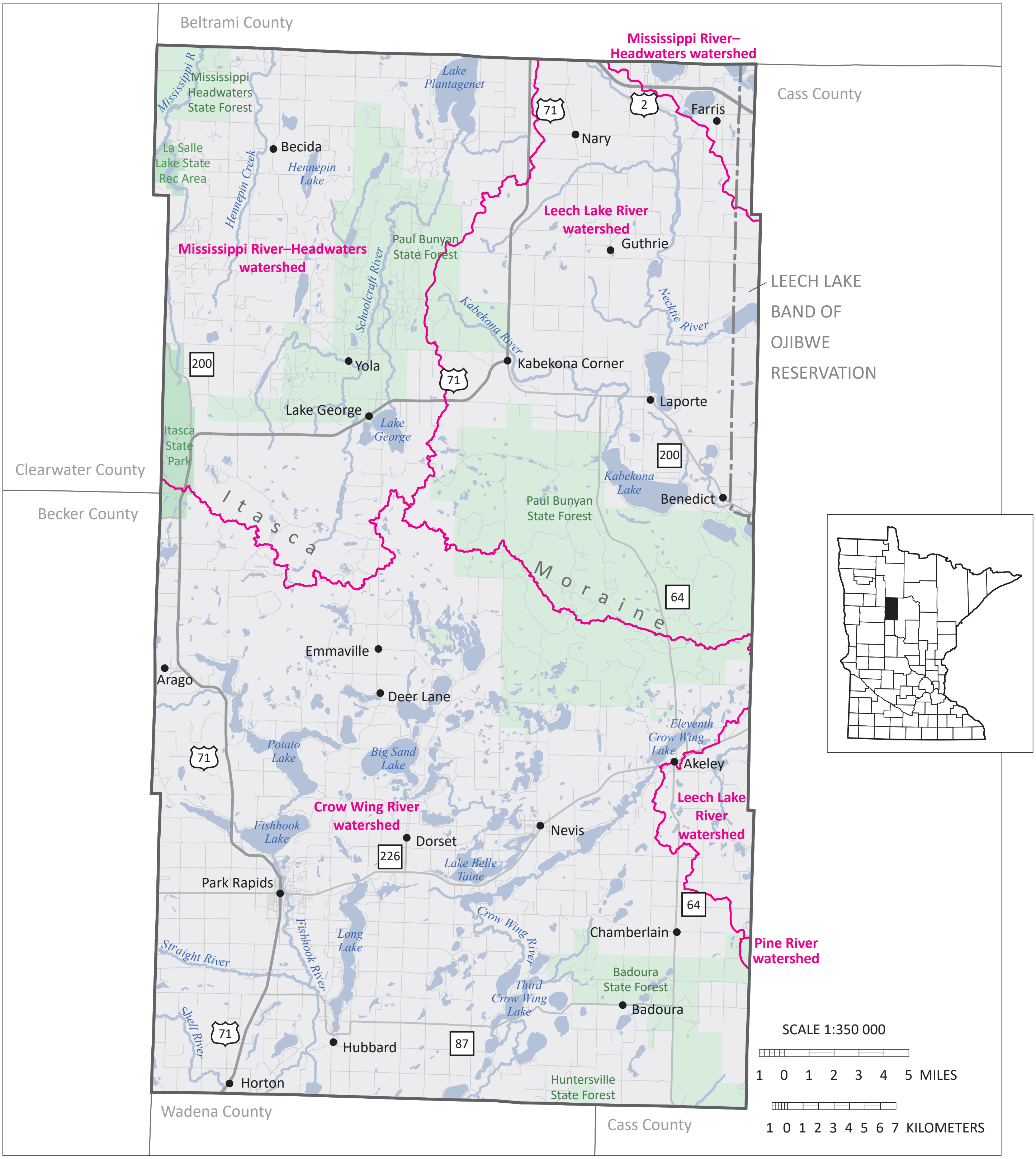


Figure 1. Hubbard County, Minnesota

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 is used to describe 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 typically 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 to show areas of groundwater recharge potential (Figure 3). The coarse-grained outwash and fluvial sediment readily transmit water and are likely where groundwater recharge is greatest.

Surficial sand aquifers

The most extensive surficial sand and gravel aquifers are in southern Hubbard County and consist of the Park Rapids and Oshawa outwash plains (Part A, Plate 3). The Itasca moraine, a large, east-west ridge of sandy clay glacial till, eventually blocked outwash from retreating glaciers from reaching south of the moraine. Sand and gravel outwash was deposited in localized channels north of the moraine (Part A, Plate 3). Additional sand and gravel deposits are associated with modern streams.

Pineland Sands

The Park Rapids and Oshawa outwash plains largely define the surficial extent of 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 portion of southwestern Hubbard County, as an area of specific concern where groundwater resources are at risk as a result of overuse and degraded quality. Between 1988–2013, there was an 85 percent increase in water demands in the Straight River area, compared to a 35 percent 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).

Buried sand and gravel bodies may locally underlie surficial sand units 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.

The glacial sediment in Hubbard County varies in thickness from 150 to 1,025 feet. The thickest sediment corresponds with deep bedrock valleys in the north-central and east, as well as under the Itasca moraine across the central region (Part A, Plate 6).

The sand content of tills in Hubbard County varies with depth, with sandy tills closer to the surface and fine-grained tills at depth. Aquifers were broken into two systems using the sand content of intervening tills (Figure 2):

1. An **upper system** of aquifers that are surficial, connected to an overlying buried aquifer, or are

overlain by tills with sand contents of at least 58 percent. The hsi1 aquifer is only buried in the northeast, near Akeley, and where overlain by modern alluvial sediment. The inclusion of both surficial and buried sand aquifers is a result of the strong hydraulic connection between aquifers in this system and groundwater flow acting similarly across aquifers (see Groundwater Flow section). Approximately 93 percent of wells with assigned aquifers are completed in this system.

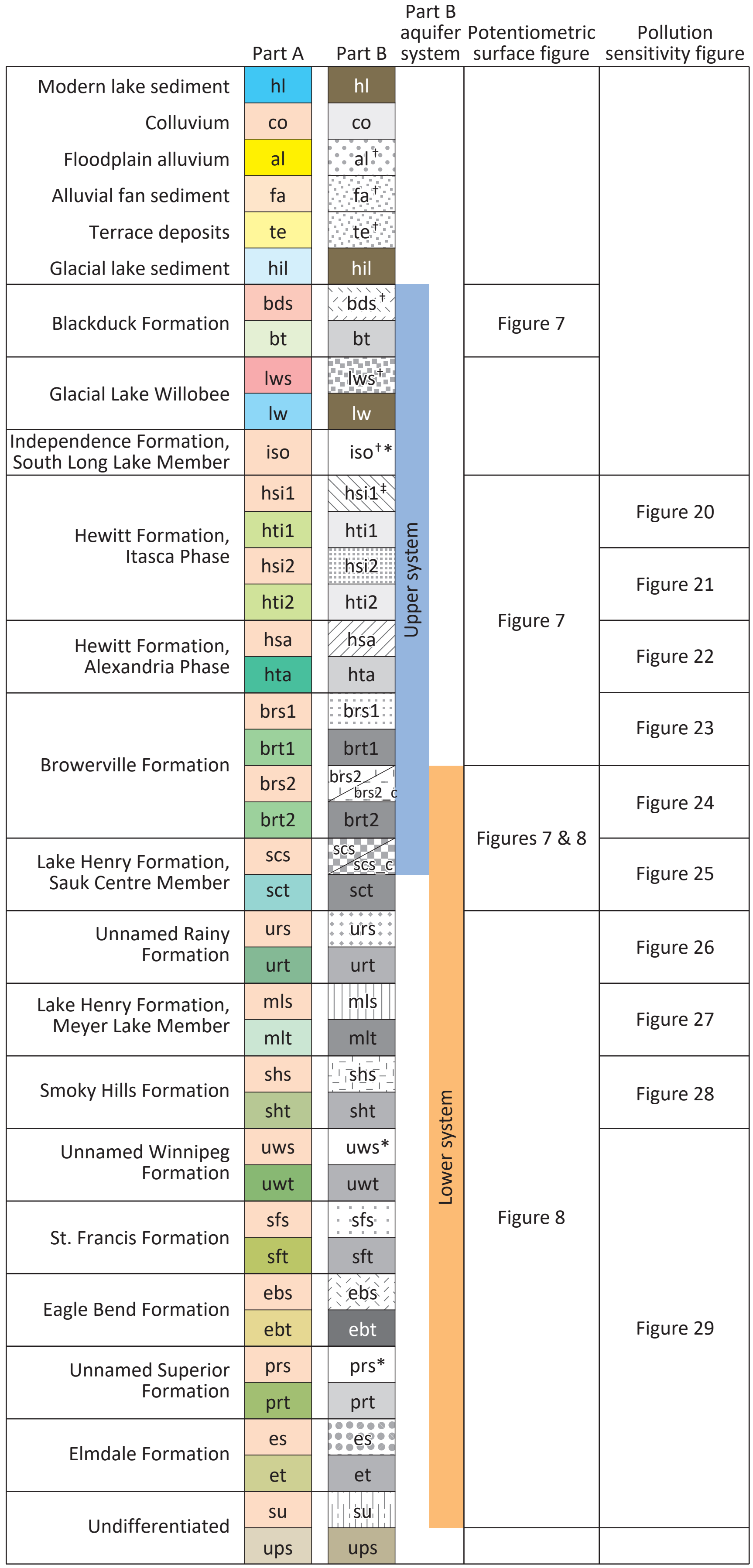
2. A **lower system** of aquifers that are confined by till units with sand contents less than 45 percent. Approximately 7 percent of wells with assigned aquifers are completed in this system.

Textural information for the deepest glacial deposits is limited, as well drillers often find water at shallower depths. Therefore, the deepest sediment in some areas is unknown and mapped as undifferentiated sediment (ups).

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

Bedrock aquifers

Bedrock in Hubbard 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). Very little is known about bedrock water supply potential. No wells use the bedrock as a water source as there is sufficient water supplied by surficial and buried sand aquifers. Bedrock is typically hundreds of feet below the land surface, and crystalline rocks usually have low primary porosity and limited permeability.



†Surficial sand
‡Unit is a surficial aquifer except where buried in the northeast, near Akeley, or overlain by modern alluvial sediment.
*Unit is not shown on cross sections.

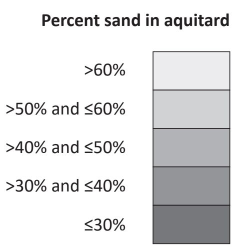
Figure 2. Hydrostratigraphy of Quaternary unconsolidated sediment

Image at right; full caption on page 7.

Figure 2. Hydrostratigraphy of Quaternary unconsolidated sediment

The hydrostratigraphic column on page 6 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 (portion that is less than 2-millimeter grain size). Lighter shades represent units with more sand, implying a higher hydraulic conductivity.
- ***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***.



The right three columns show the groupings of aquifers into the upper and lower systems and the potentiometric surface and buried pollution sensitivity figures representing each aquifer. The upper system is poorly confined and is under water-table conditions in portions of the county.

The brs2 and scs aquifers were each split into two separate units to distinguish the portions of those aquifers that are in the upper system (brs2 and scs) and those confined by the brt1 and brt2 tills in the lower system (brs2_c and scs_c).

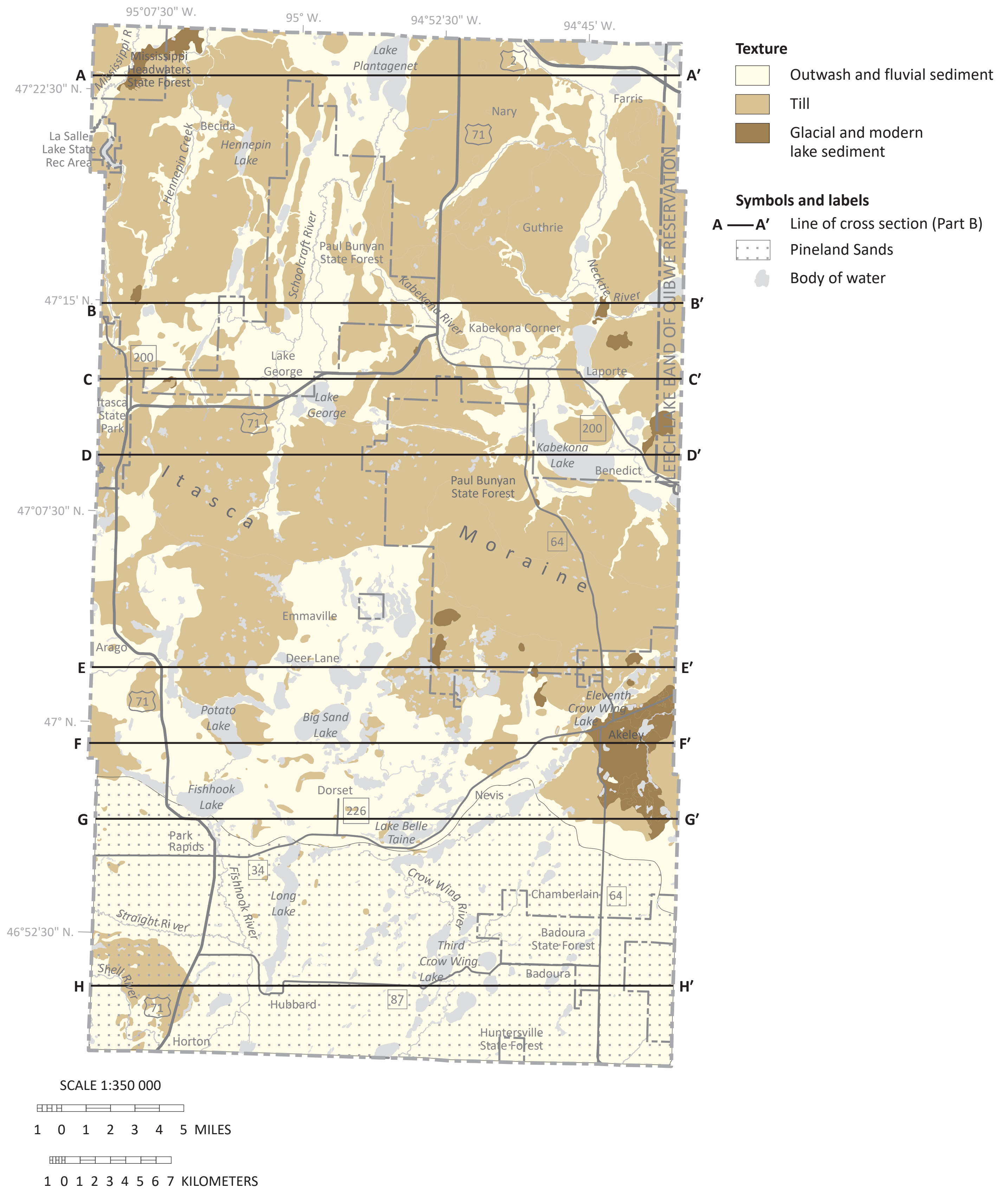


Figure 3. Surficial geologic units-generalized textural classification

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 glacial and modern lake sediment (silt and clay). Outwash has the highest permeability and groundwater recharge potential.

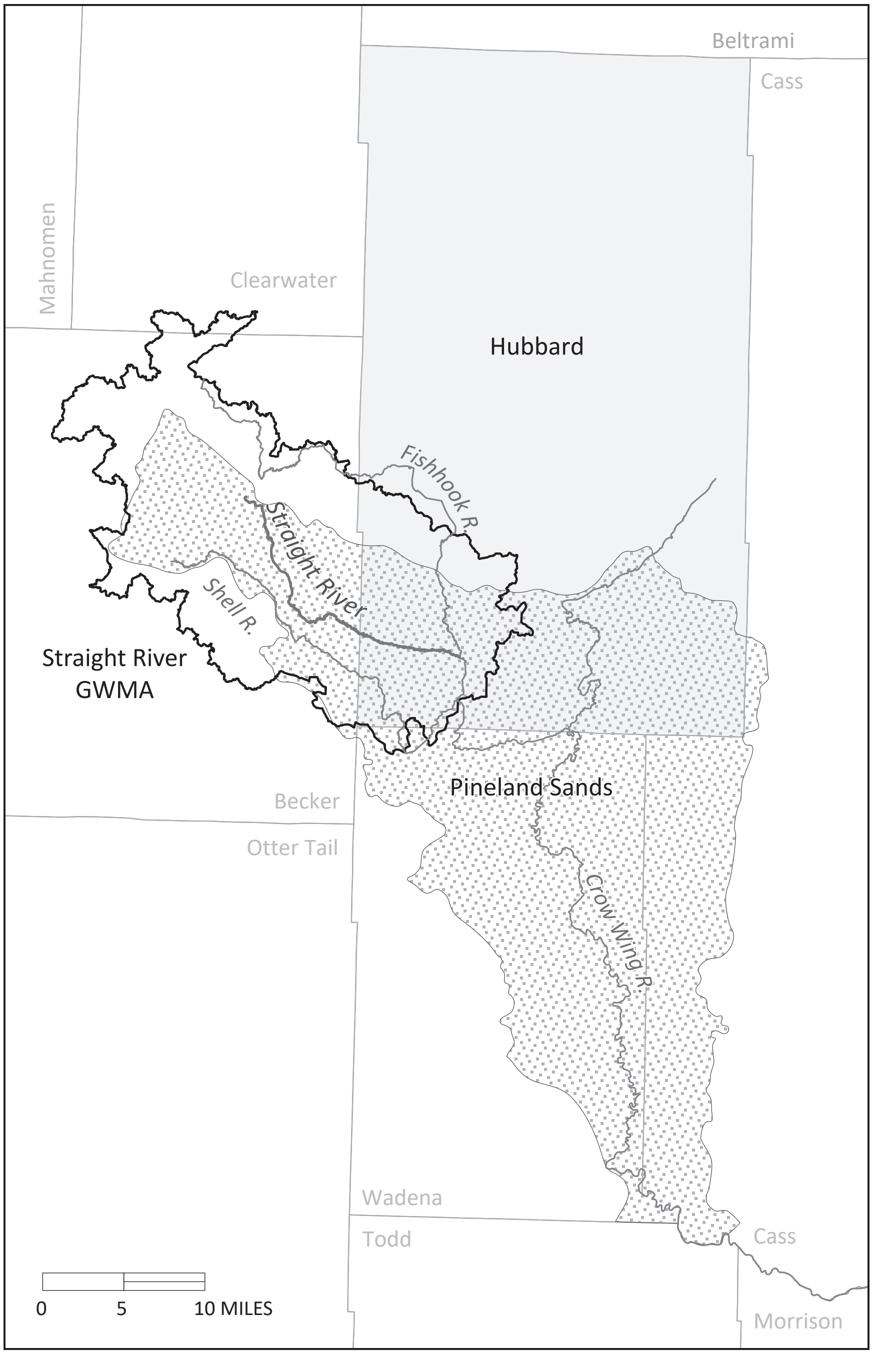


Figure 4. Pineland Sands and Straight River GWMA

The Pineland Sands consists of an extensive area of connected outwash sands that stretches across southern Hubbard 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. **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 provide guidance for 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 (i.e., 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. Locally, flow direction is from topographic highs to streams, lakes, and wetlands.

The Itasca moraine traverses the county from west to east across its center and acts as a major watershed divide. Groundwater under water-table conditions in the north generally flows north and east as parts of the Mississippi River–Headwaters and Leech Lake River watersheds. In the south, groundwater under water-table conditions primarily flows to the south as part of the Crow Wing River watershed, with a small area in the southeast flowing east as parts of the Leech Lake River and Pine River watersheds.

Approximately 39 percent of wells with assigned aquifers are completed in unconfined aquifers under water-table conditions.

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. Extensive areas with greater than 10 feet of depth to the water table are present in the south of the county. Greater depths are also found where glacial sediment such as drumlins and push moraine ridges form localized areas of higher elevation, along steep slopes, and where surficial sand deposits are at higher elevations and adjacent to low areas on the landscape (Part A, Plate 3).

The depth to water table may be overestimated where local high-elevation features are composed of fine-grained sediment and no corresponding water-level data are available. This results from contouring data from adjacent lower elevations across localized areas of higher elevation. Site-specific data would be needed to establish a more accurate depth to water table. Large tracts of sparsely-visited state and private forestland locally limit the availability of groundwater level data.

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 similarly 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 CWI and measurements made by DNR staff. The CWI records represent water levels collected under various climatic and seasonal conditions from 1906 through 2017 (MGS and MDH, 2018). 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 or open hole.

Two potentiometric surface maps were created for Hubbard County based on their position relative to sandy tills in the upper subsurface (Figure 2).

1. The first represents the upper system of aquifers (Figure 7), which includes surficial aquifers and buried sand aquifers overlain by tills with sand contents of at least 58 percent or by adjacent aquifers. Consequently, this system includes wells under both water-table and confined conditions. Wells under water-table conditions are common in the south. Groundwater flow directions in the upper system are similar to the water table as a result of the high sand content of the tills and the prevalence of adjacent aquifers.
2. The second represents the lower system (Figure 8), consisting of all buried sand aquifers separated from the upper system by tills with sand contents below 45 percent that act as more competent aquitards. The potentiometric surface for each component aquifer is predominantly within 20 feet of the combined potentiometric surface presented in Figure 8. Groundwater in these aquifers follows flow paths that are a muted expression of the surficial system, with a regional west-to-east flow pattern more prominent.

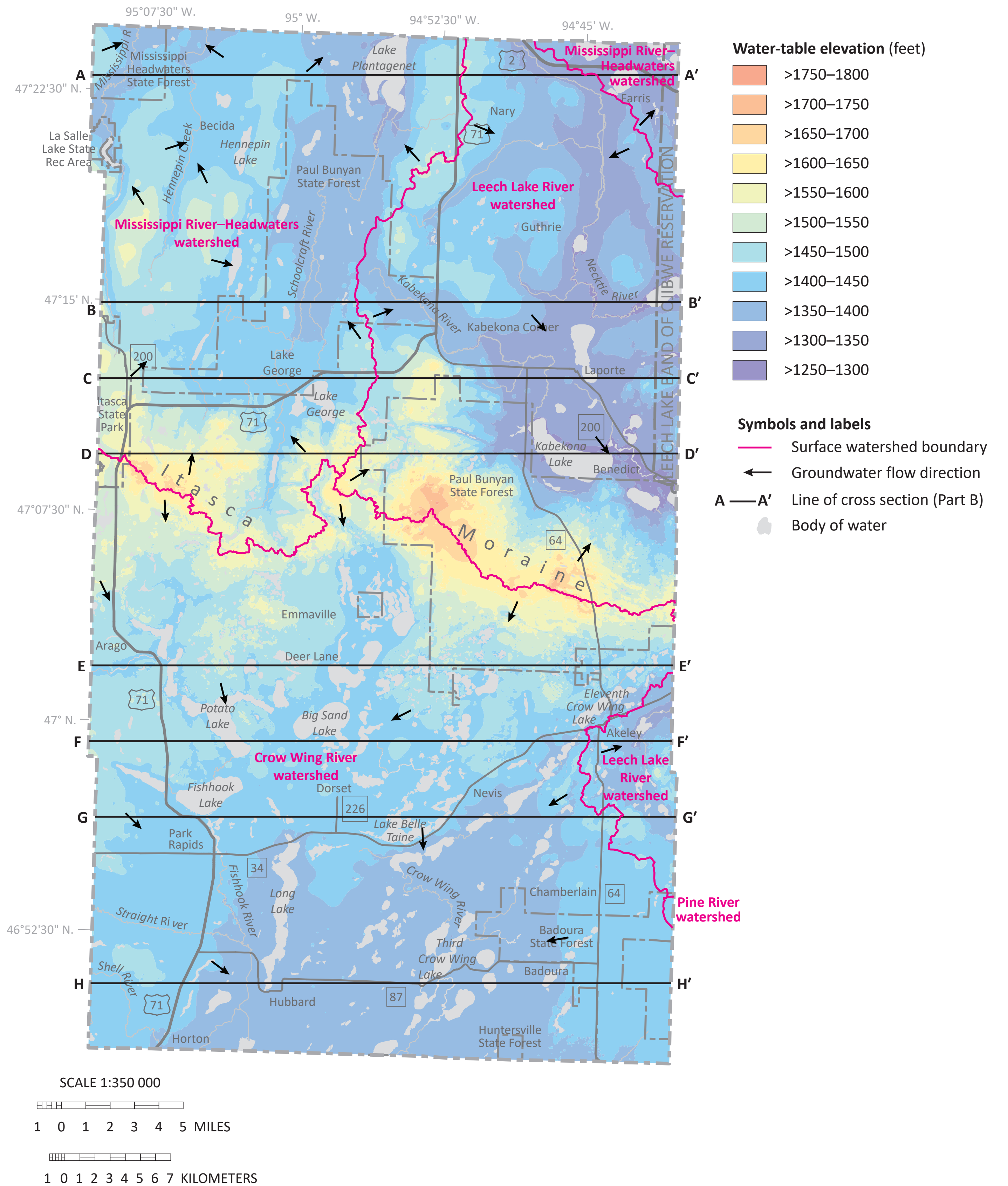


Figure 5. Water-table elevation and groundwater flow directions

The water-table elevation is generally a subdued expression of the surface topography. Flow directions are typically consistent with surface-water flow from topographic highs at watershed boundaries toward streams, lakes, and wetlands.

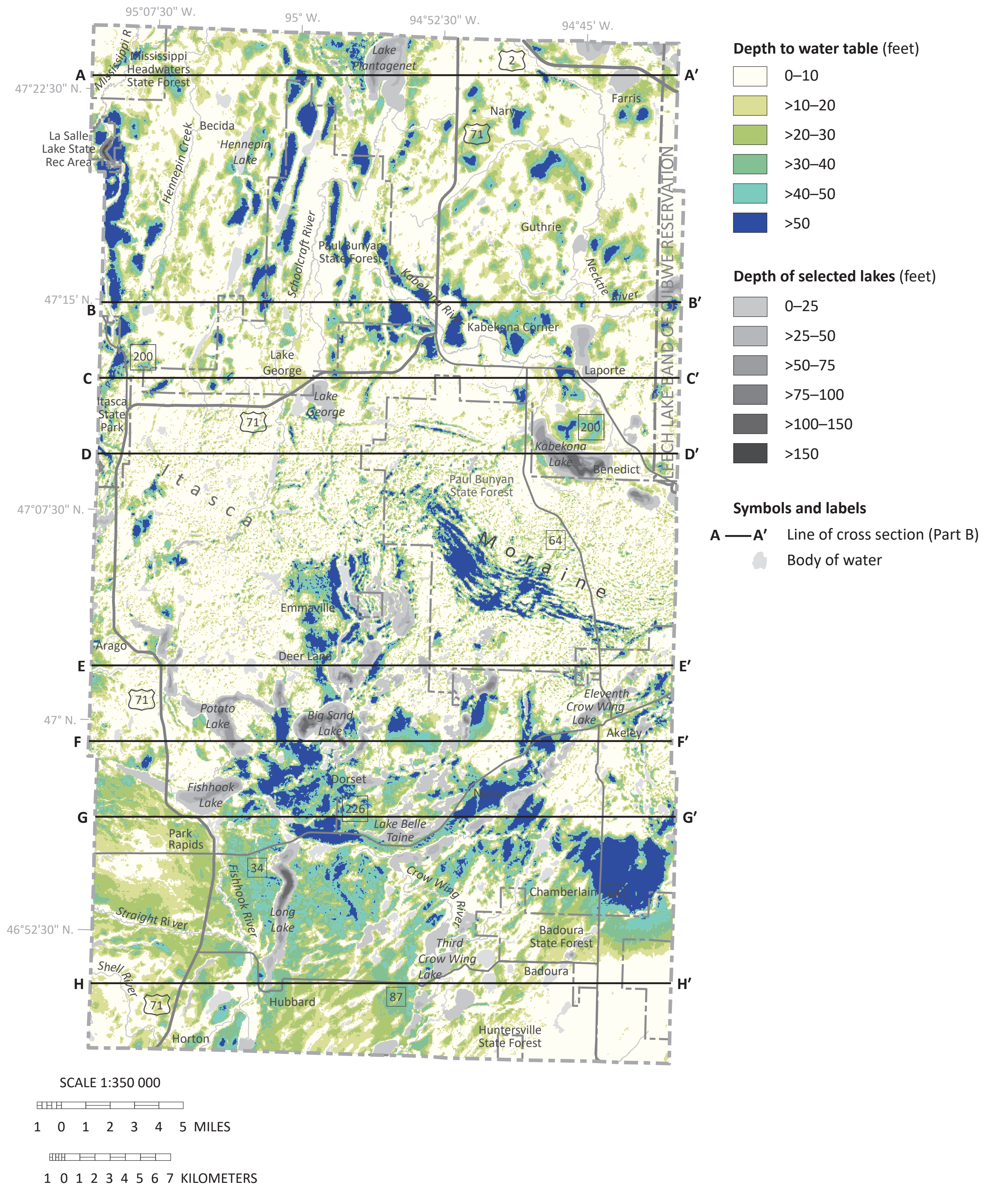


Figure 6. Depth to water table

The water table is commonly less than 10 feet below the land surface except in the south and in locally sandy areas of high elevation or steep slopes. Locally, high-elevation areas of fine-grained sediment with sparse water-table elevation data may have an overestimated depth to water table.

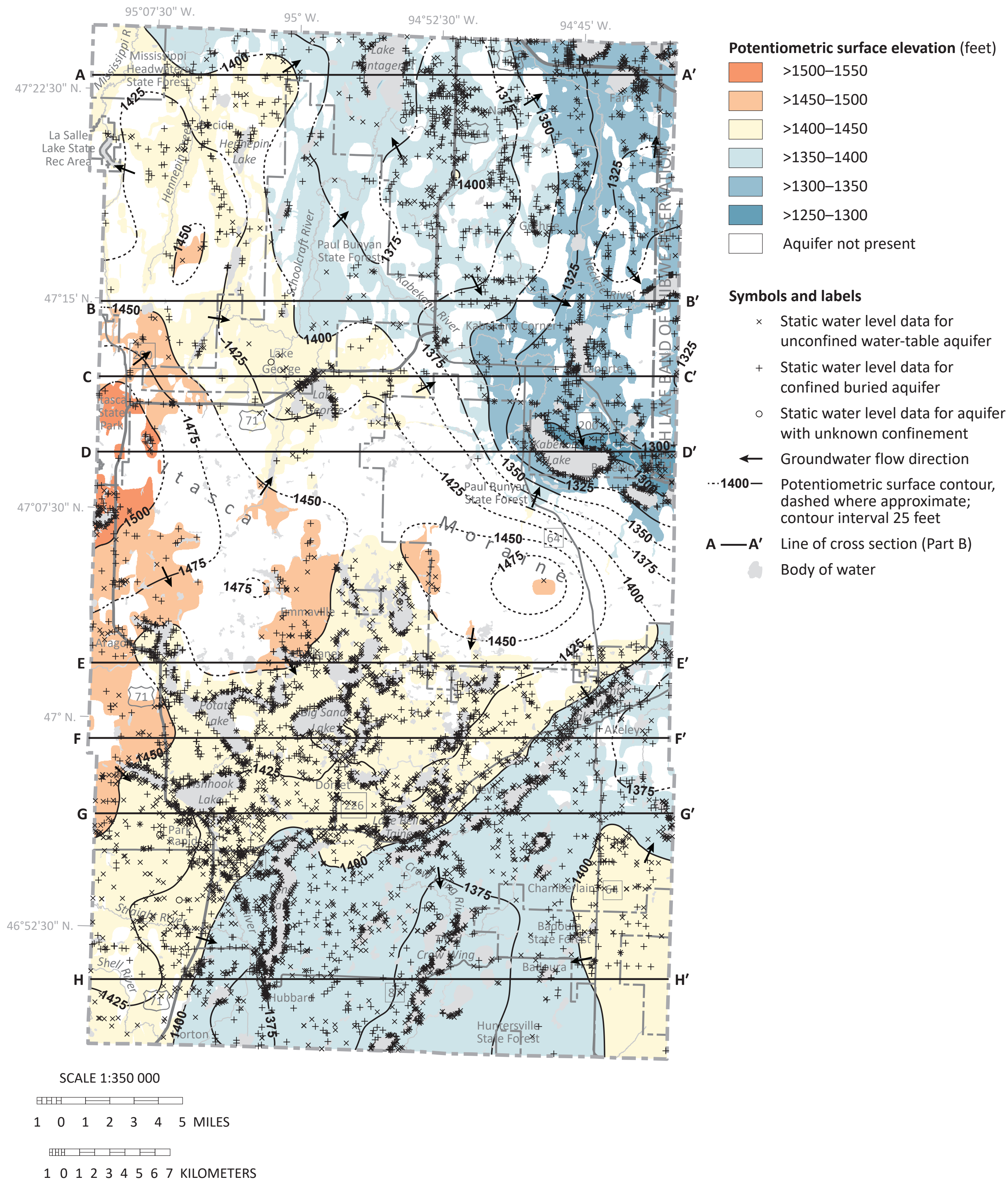


Figure 7. Potentiometric surface of the upper system aquifers

The upper system of aquifers consists of the bds, hsi1, hsi2, hsa, brs1, brs2, and scs aquifers (Figure 2). Groundwater generally follows water-table and surface-water flow directions.

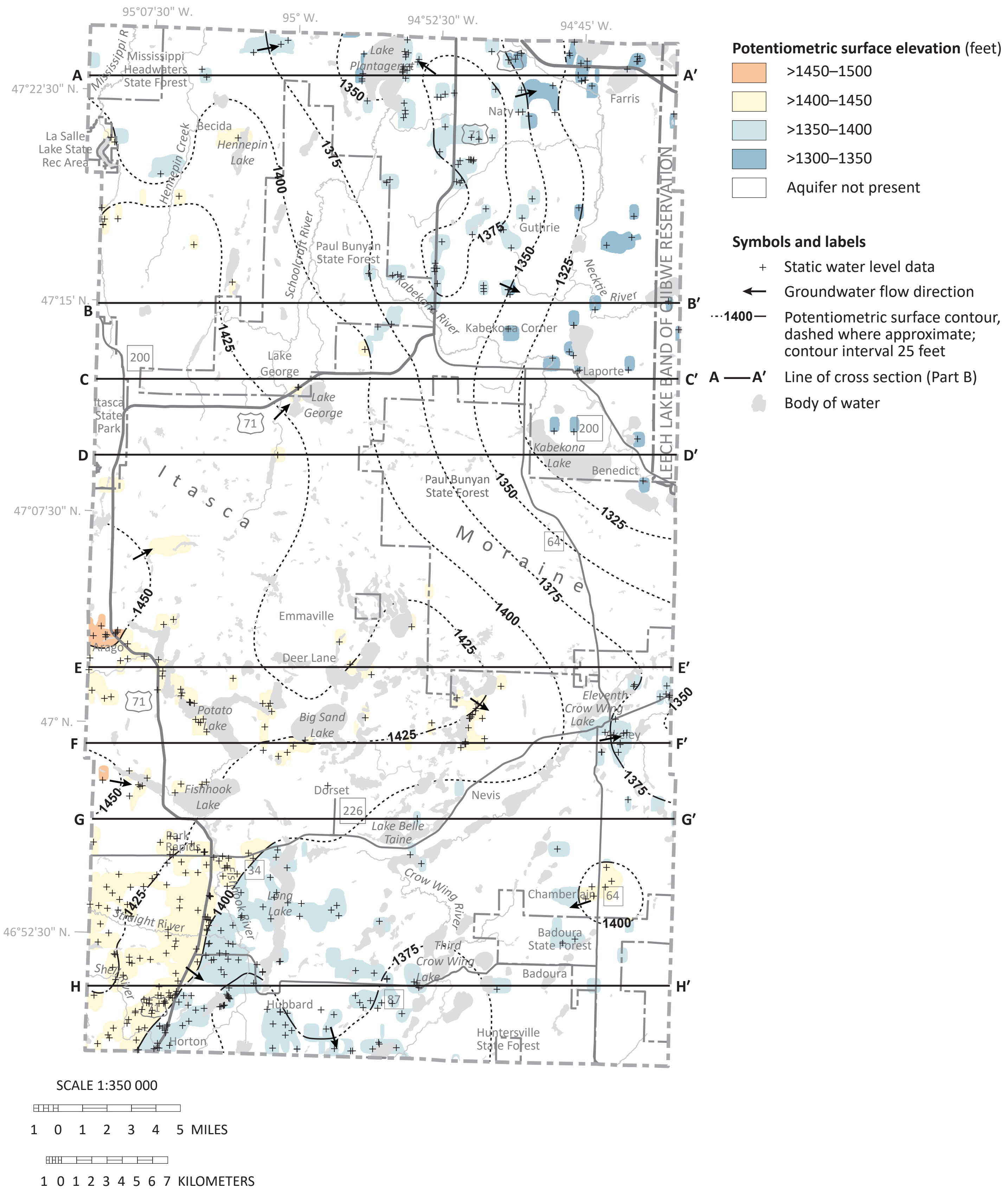


Figure 8. Potentiometric surface of the lower system aquifers

The lower system of aquifers consists of the brs2_c, scs_c, urs, mls, shs, uws, sfs, ebs, prs, es, and su aquifers (Figure 2). Groundwater flow is a muted version of the upper system flow, with a more dominant regional west-to-east pattern.

Water chemistry (Plate 7)

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

Water chemistry 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 that have been introduced by human activities.

Water sampling

Samples were collected from wells in aquifers used for domestic and municipal water supply. Wells were selected to get an even distribution across the county, include populated areas, and target surface-water and groundwater interaction around lakes and larger rivers. Groundwater samples were collected according to the protocols outlined in Appendix A. 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 11 lakes. The results were combined with historical chemistry data, including 56 well and 3 lake samples from the Minnesota Department of Health (MDH) and 4 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 compositions are reported as δ values:
$\delta\ (^{0}/_{00}) = (R_x / R_s - 1) * 1000$.

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

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

Watershed to lake area ratio is a screening tool that can indicate the relative importance of groundwater flow to the water balance of a lake. Lakes with small watershed to lake area ratios typically have significant groundwater input, longer lake water residence times, and more fractionation. Lakes with large watershed to lake area ratios generally have significant surface-water inflows, shorter lake water residence times, and less fractionation (DNR, 2022).

Results

Figure 9 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 of the 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 14 lakes for stable isotopes and plotting their results to establish a range of lake isotopic ratios for comparison against groundwater samples.

For practicality in the following discussion, only oxygen stable isotope values are used for reference. The lake $\delta^{18}O$ isotopic values ranged from -10.13 (Third Crow Wing Lake) to -4.47 (Duck Lake), reflecting differences in the degree of evaporation in each lake, and are often related to the lake's watershed to lake area ratio.

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. Water collected at the upstream edge may have a higher proportion of meteoric surface water or groundwater from adjacent sand aquifers entering the lake. In Hubbard County, this phenomena can be observed at Lake Plantagenet, Kabekona Lake, Long Lake, and Lake George. 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 is the case at Duck Lake. Greater fractionation than expected can also occur if the lake does not have a natural outlet, as is the case at Lake Belle Taine.

Of the 101 well samples analyzed for stable isotopes of oxygen and hydrogen, 19 had evaporative signatures, consistent with the prevalence of lakes. Groundwater samples that plot along the evaporation line have lake water as a portion of their recharge. Each sample's position is based on the initial $\delta^{18}O$ value of the lake source and the proportion of lake water and precipitation that recharged the aquifer. Wells with $\delta^{18}O$ values greater than (plotting to the right of) -10 are considered to have an evaporative signature. 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.

Wells with evaporative signatures are downgradient of lakes and often located in areas with sand at the surface (Figure 10). The majority of wells (12 of 19) with evaporative signatures are less than or equal to 100 feet deep, with the deepest well being 265 feet deep.

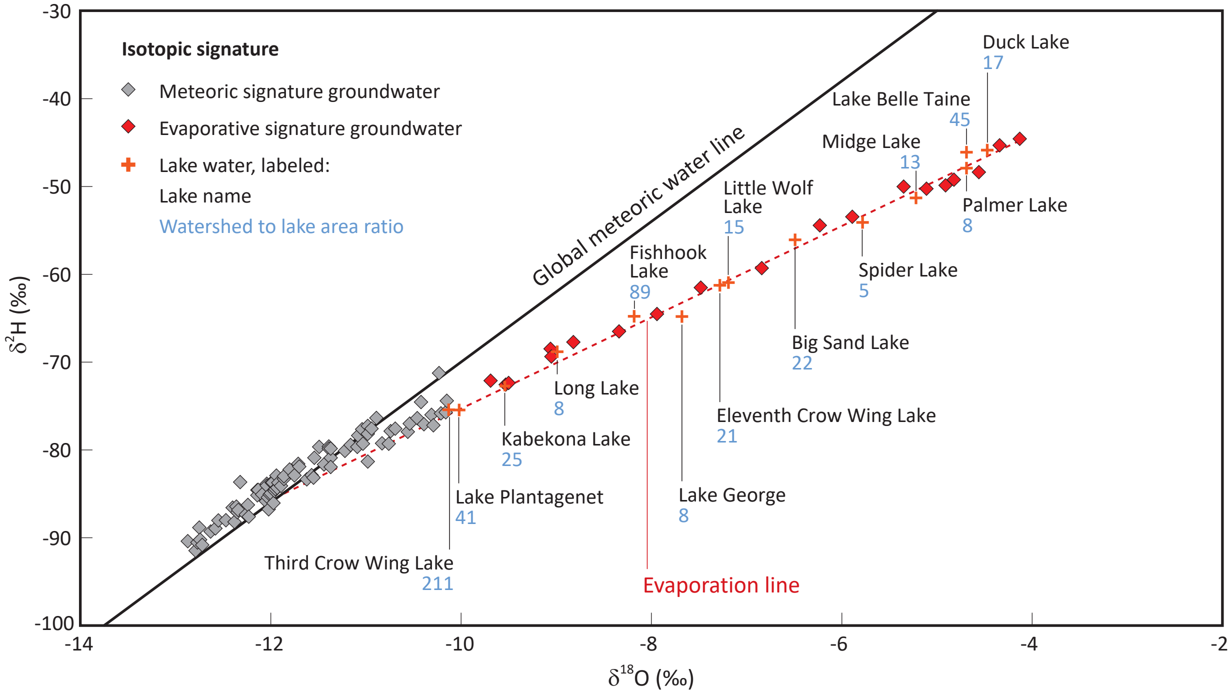


Figure 9. Stable isotope values from water samples

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 that has been fractionated by evaporation. Groundwater that plots on the evaporation line indicates recharge through surface water. The local evaporation line is described by the equation $\delta^2H = 5.2\ \delta^{18}O - 23.3$, calculated from 11 lake-water samples collected for this study and 3 lake-water samples collected by the MDH.

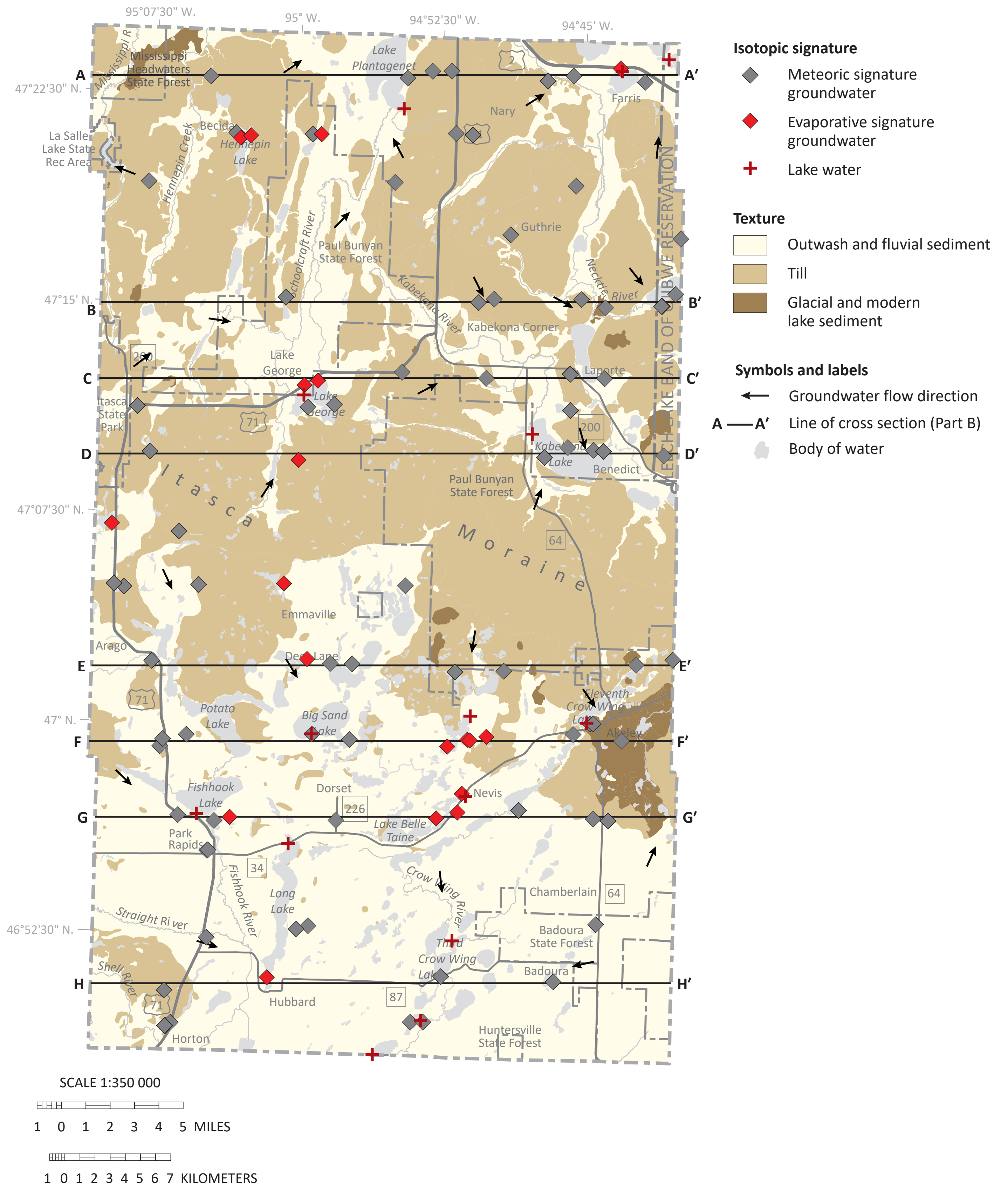


Figure 10. Stable isotope map

Groundwater that is partially sourced from lakes and wetlands is common. The 19 wells identified as having evaporative signatures are primarily located downgradient of lakes in areas of surficial sand.

Groundwater residence time

Groundwater residence time is the approximate time that has elapsed since water infiltrated the land surface to the time it was pumped from a well or discharged to a lake, river, wetland, or spring. Short residence time normally suggests short travel paths and/or high recharge rates; long residence time suggests long travel paths and/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 were 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 by 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 described 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 likely entered the ground before 1953 but may contain a small amount of modern water.
- **Premodern:** water entered the ground before 1953.

> For hydrogeologic interpretation *premodern* includes *mostly premodern*.
>
> Data shown on figures and plates uses both *premodern* and *mostly premodern*.

Tritium was analyzed in samples from 124 wells and 1 lake to assist in residence time interpretations. Of the 124 well samples analyzed for tritium, 83 were modern, 21 were mixed, and 20 were premodern tritium age. The lake sample was modern tritium age.

Carbon-14

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

When precipitation infiltrates the unsaturated zone — the layer between the land surface and the top of the water table — it absorbs carbon dioxide, including carbon-14, from biospheric soil gases forming 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 9 carbon-14 samples were collected for this study. Carbon-14 residence times ranged from 400 to 4,500 years for 8 of the samples. A carbon-14 residence time could not be modeled for the ninth sample.

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 dissolution of naturally occurring geologic material. For a select group of dissolved contaminants, this atlas uses the following guidelines.

Drinking Water Guidelines

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

Maximum Contaminant Level (MCL): legally enforceable federal standards that apply to public water systems to limit 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.

Chloride
SMCL 250 ppm

Chloride can occur naturally from deep sources, such as residual brine, or it can come 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 110 well samples analyzed for chloride, 39 had concentrations above 5 ppm and could be assigned a source (Figure 11). Of those 39 well samples, 37 were assigned an anthropogenic source, 1 was assigned a natural source, and 1 was assigned an unknown source. Of the 3 lake samples analyzed for chloride (Lake Belle Taine, Eleventh Crow Wing Lake, and Little Wolf Lake), 1 (Little Wolf Lake) had a concentration above 5 ppm (10.5 ppm) and was assigned an anthropogenic source.

The source interpretation was adjusted for 9 samples in this atlas based on other evidence, such as bromide concentration uncertainty, tritium age, nitrate presence, or geologic conditions.

- The 37 well samples with anthropogenic chloride were nearly all from areas where sand is the surficial geologic unit. Three-quarters of wells with anthropogenic chloride were in the southern half of the county, where crop cultivation is a common land use. Anthropogenic chloride was also found in wells along major highways where the source of chloride may be road salt. Of the anthropogenic samples, 32 were from wells less than 100 feet deep. The source interpretation for 6 samples was changed from a natural source to an anthropogenic source. Their modern tritium age, well depths of less than 80 feet, and in some cases, the presence of anthropogenic nitrate or bromide concentration uncertainty suggest a likely anthropogenic source. The source interpretation was also made for one sample where bromide was not determined. The sample had a chloride concentration of 109 ppm and a nitrate concentration of 3 ppm, suggesting a likely anthropogenic source.
- The sample with natural chloride was from a 403-foot well on the southwestern edge of the county that is screened approximately 30 feet above the Cretaceous bedrock. Though the chloride/bromide ratio for this sample is 430, which indicates an anthropogenic source, the aquifer is well protected, as evidenced by the premodern tritium age, and is likely receiving water from the nearby Cretaceous bedrock. Residual brines associated with Cretaceous bedrock can be a natural chloride source.
- The sample with an unknown chloride source was from a now-sealed 287-foot public supply well in the confined es aquifer with premodern tritium-age water. The source interpretation for this sample was originally anthropogenic but changed to unknown based on the depth and well-protected nature of the aquifer. Anthropogenic chloride was possibly introduced into the well or distribution system via disinfection or construction issues rather than coming from the aquifer.
- None of the samples equaled or exceeded the SMCL. The highest concentration was 132 ppm and the median was 1.8 ppm.

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 119 wells analyzed, nitrate was detected in 71 samples and 21 had an anthropogenic source (Figure 12). The median concentration was 0.03 ppm. Nitrate was not detected in either of the two lake samples collected by MDH (Lake Belle Taine and Eleventh Crow Wing Lake).

- Of the 21 well samples with anthropogenic concentrations, 19 were from the southern half of the county where crop cultivation is a common land use. All anthropogenic samples were from wells screened in the upper system of aquifers.
- Of the 21 well samples with anthropogenic concentrations, 20 were from wells less than 100 feet deep. The one well greater than 100 feet deep had a measured nitrate concentration of 1.08 ppm, barely greater than the anthropogenic threshold. The average well depth with measured anthropogenic nitrate concentrations was 64 feet.
- Six samples (5 percent) equaled or exceeded the MCL. The highest concentration measured was 28 ppm. All samples were from wells in the southern half of the county in the Pineland Sands and from wells less than or equal to 75 feet deep.

The objectives of atlas sampling do not target nitrate in groundwater. A Township Testing Program study published by the Minnesota Department of Agriculture (MDA, 2018) targeted nitrate in groundwater. Six townships in the Pineland Sands region were selected 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, 116 of 1,106 wells (10.5 percent) 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 54 feet. In the final dataset, 80 of 1,048 wells (7.6 percent) had MCL exceedances. Township nitrate MCL exceedances ranged from 2.4–15.2 percent of the wells sampled in the final dataset, with Hubbard and Badoura townships each having greater than 10 percent of wells with MCL exceedances. Similar to the DNR atlas sampling, the median nitrate concentration for both the initial and final datasets were below the laboratory detection limit of 0.03 ppm.

Arsenic

MCL 10 ppb; MCLG 0

Arsenic is a naturally occurring element that has been 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 that have short-screened sections near the boundary of an aquifer and aquitard (Erickson and Barnes, 2005b; Erickson and others, 2018).

Sampling results

Of the 114 samples analyzed, arsenic was detected in 77, with 3 equaling or exceeding the MCL (Figure 13). The highest concentration was 18.7 ppb and the median concentration was 0.25 ppb. The detections and exceedances were spread throughout the county. The low number of MCL exceedances is consistent with the limited extent of northwest-source, fine-grained glacial sediment correlated with high arsenic (Erickson and Barnes, 2005a).

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 104 samples analyzed, manganese was detected in 77, with 64 equaling or exceeding the SMCL and 55 equaling or exceeding the HBV. The highest concentration was 655 ppb and the median concentration was 117 ppb. No discernable patterns or correlations with specific aquifers were found.

Boron

RAA 500 ppb

Boron is a naturally occurring element that has been 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 89, with none equaling or exceeding the RAA. The highest concentration was 113 ppb and the median concentration was 11.7 ppb. No discernable 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 water-using devices.

Sampling results

Of the 105 samples analyzed, iron was detected in 68, with 56 equaling or exceeding the SMCL. The highest concentration was 67.5 ppm and the median concentration was 0.57 ppm. No discernable patterns or correlations with specific aquifers were found.

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 samples analyzed, sulfate was detected in 89, with none equaling or exceeding the SMCL. The highest concentration was 39.3 ppm and the median concentration was 6.3 ppm. No discernable patterns or correlations with specific aquifers were found.

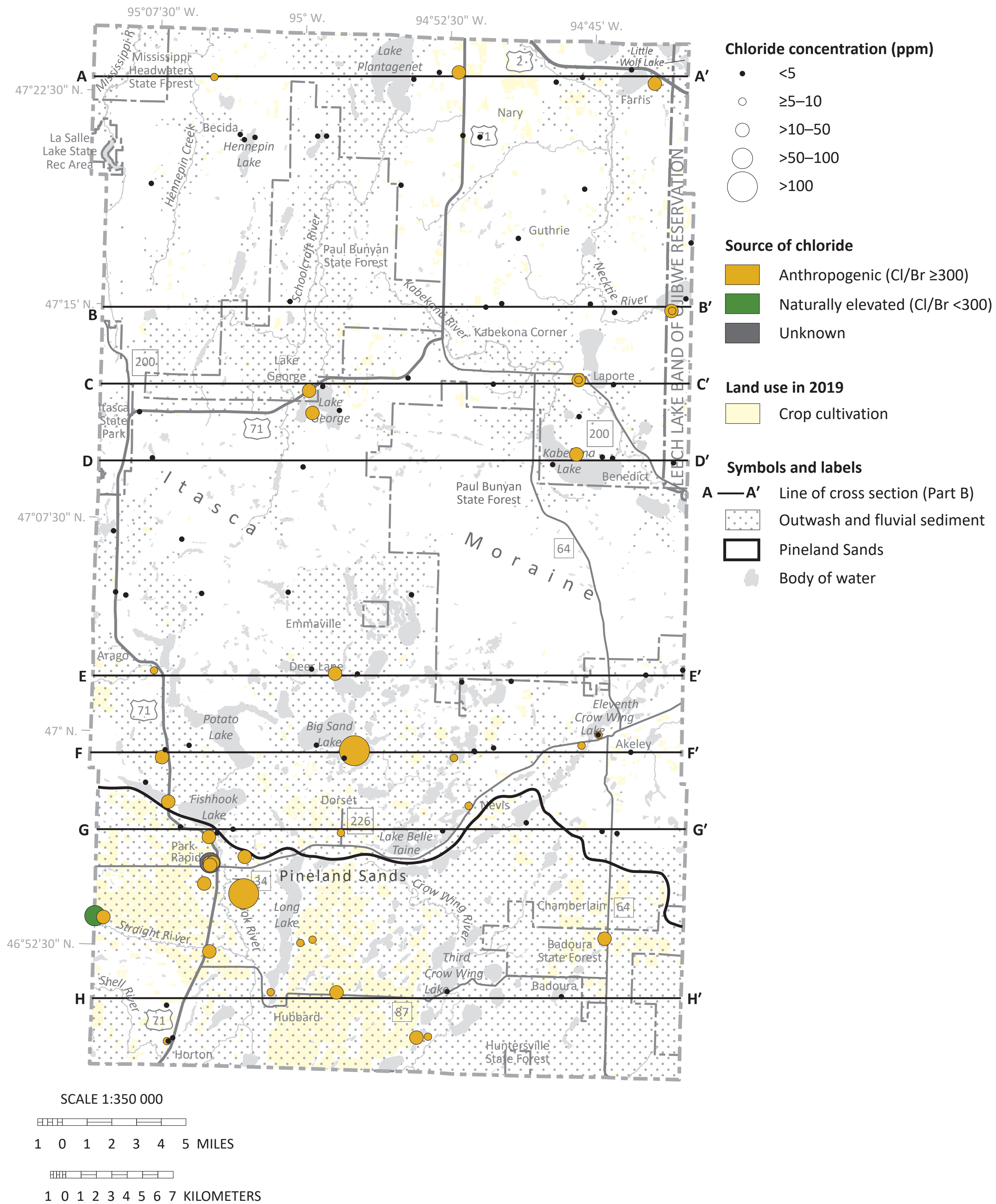


Figure 11. Chloride concentrations from groundwater samples

Anthropogenic chloride concentrations were more common in the south, where sand is at the surface.

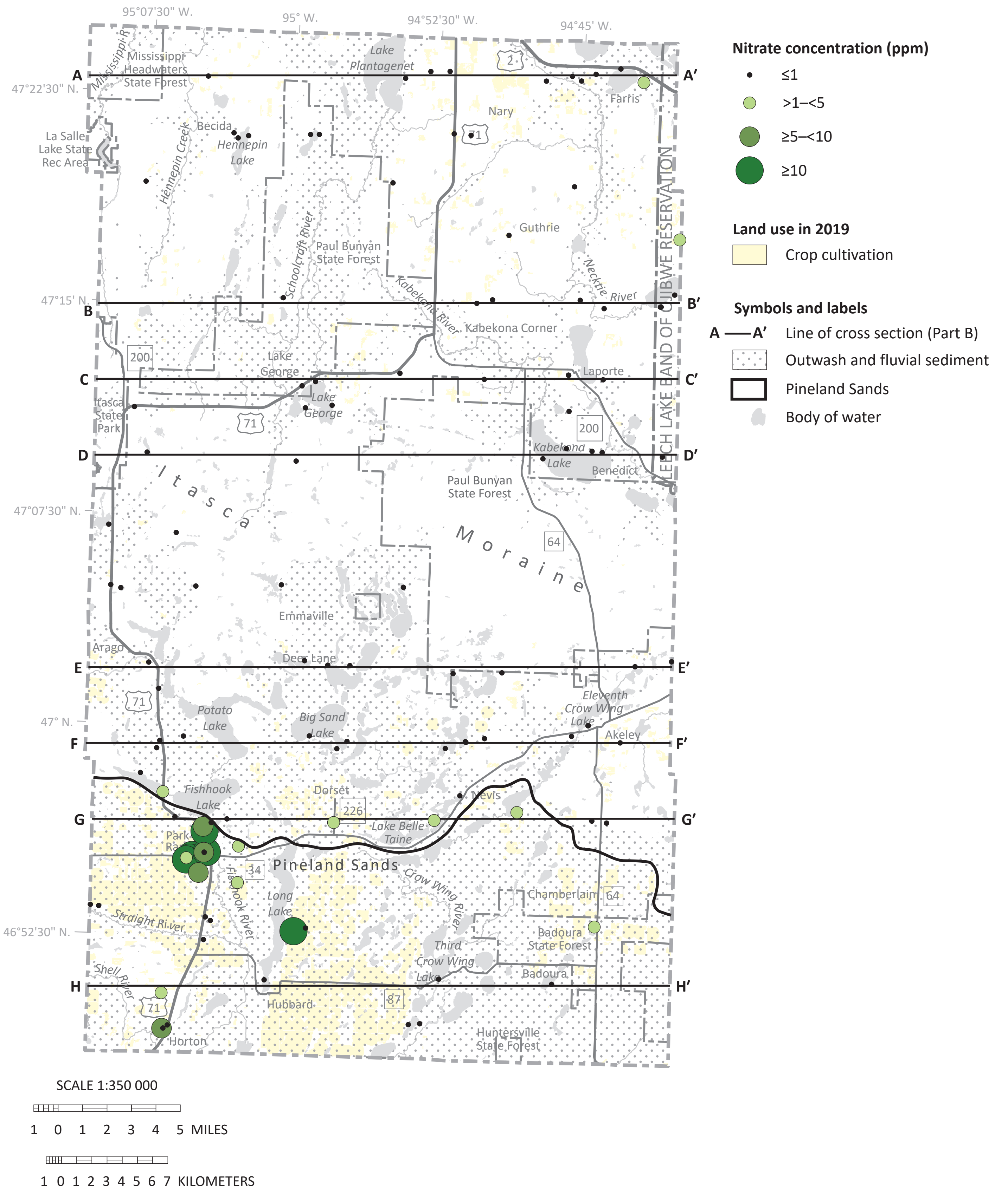


Figure 12. Nitrate concentrations from groundwater samples

Anthropogenic nitrate concentrations were common where crop cultivation is a dominant land use, particularly in the south where sand is at the surface.

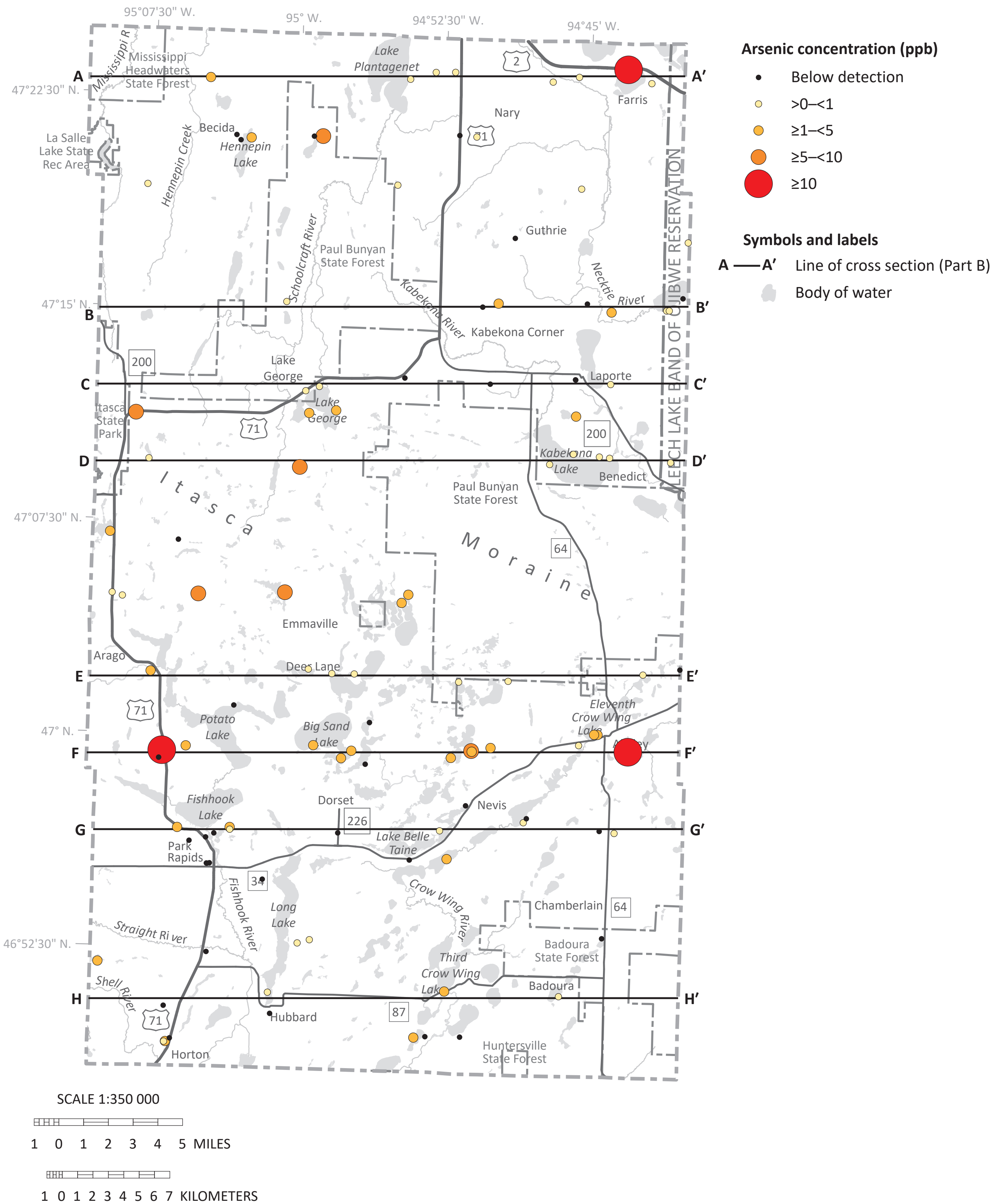


Figure 13. Arsenic concentrations from groundwater samples

The relatively low concentrations of arsenic measured in wells are consistent with the lack of extensive northwest-source, fine-grained tills correlated with high arsenic (Erickson and Barnes, 2005a).

Piper diagram

The Piper diagram (Figure 14) 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 Hubbard 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 the majority of samples.

On the cation triangle, most samples plot in a cluster dominated by calcium and magnesium. There is one notable exception that plots with an increased proportion of sodium. The premodern tritium-age sample (circled and labeled as 1) was collected from a 403-foot well completed approximately 30 feet above the top of Cretaceous bedrock. This was the deepest well sampled, with the next deepest being 300 feet deep. The dominance of sodium in this sample 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 from residual brines in the nearby Cretaceous bedrock.

On the anion triangle, most samples plot in the lower left corner, marked by a dominance of bicarbonate. A subset of samples plot to the right along a trend toward the chloride plus nitrate corner. With one notable exception, these samples have a modern or mixed tritium age and anthropogenic chloride or nitrate concentrations. The one premodern tritium-age sample from a 403-foot well (circled and labeled as 2) has a higher proportion of chloride, likely from a natural Cretaceous bedrock source.

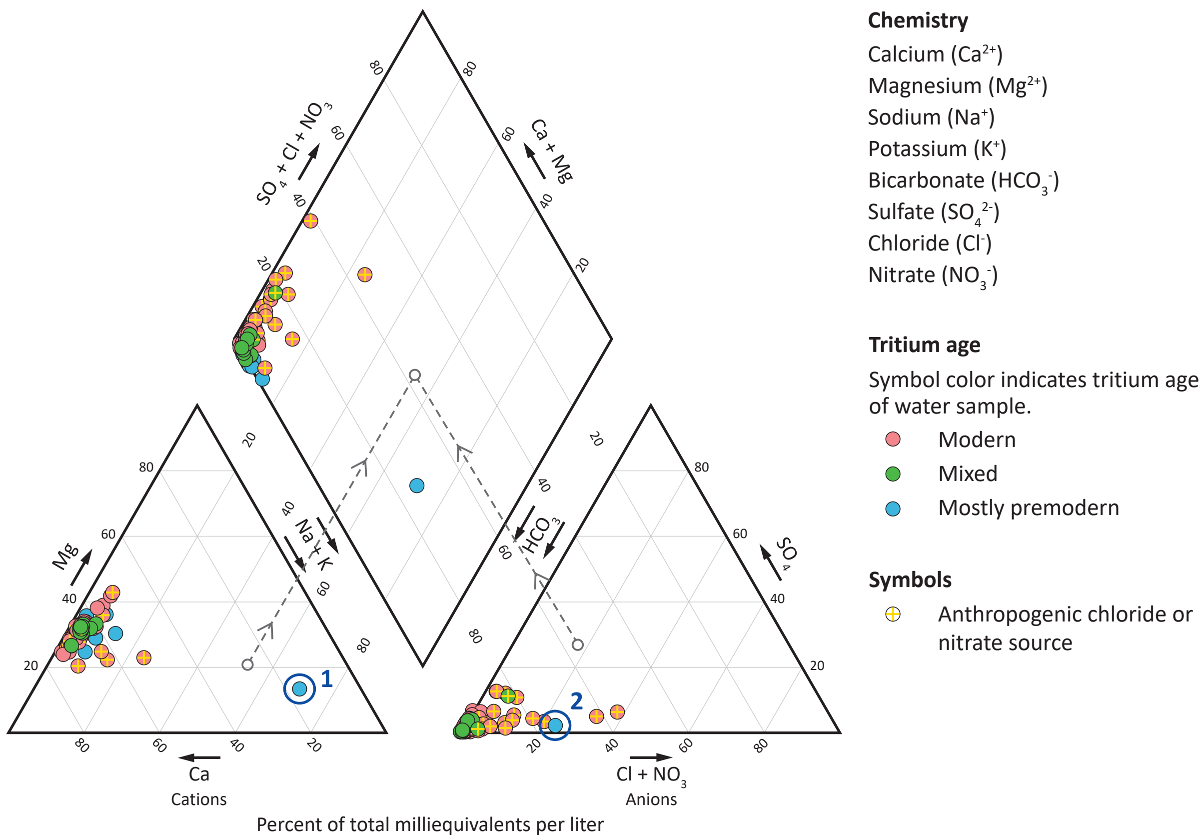


Figure 14. Piper diagram of groundwater sampled by DNR staff

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 is the dominant water type. The cation diagram shows most of the samples clustered in an area between the calcium and magnesium-dominated corners.

One premodern tritium-age sample (labeled 1) has a notably higher proportion of sodium plus potassium, reflecting the exchange of calcium and magnesium in water with sodium adsorbed to fine-grained sediment or sodium contribution from brine associated with nearby Cretaceous bedrock. On the anion triangle, several modern and mixed tritium-age samples with anthropogenic chloride or nitrate plot along a trend toward the chloride plus nitrate corner away from the cluster of the samples in the bicarbonate corner. The premodern tritium-age sample (labeled 2) has naturally sourced chloride likely from nearby Cretaceous bedrock.

Pollution sensitivity

For this report, pollution sensitivity is defined as the time 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 transmission rate are the hydrologic soil group (Table 1) (Natural Resources Conservation Service, 2022) 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 15. For further details, see *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

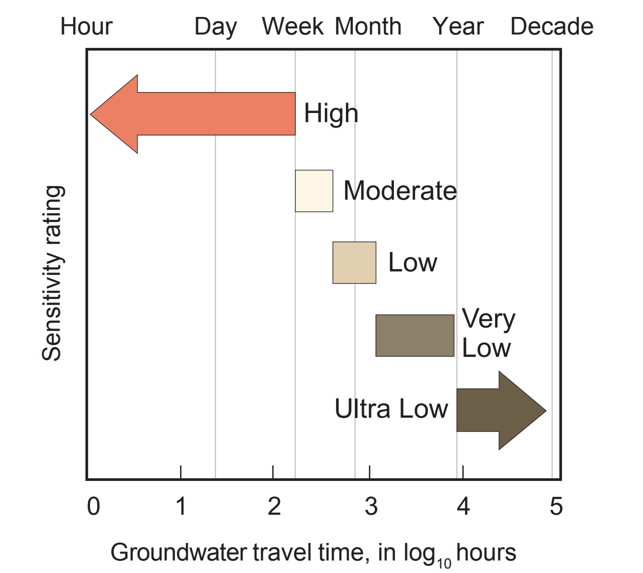


Figure 15. Pollution sensitivity rating of near-surface materials: travel time and ratings

Results

Near-surface pollution sensitivity conditions range from high to very low (Figure 16). High sensitivity is found throughout the large outwash plain south of the Itasca moraine (Pineland Sands) and in outwash and stream channel deposits in the northern half of the county. Moderate and low sensitivity areas are found across much of the remaining area and are associated with sandy loam tills. Differences in hydrologic soil groups delineate the moderate and low sensitivity areas in the tills. An area of very low sensitivity is located south and east of Akeley and is associated with lacustrine silt and clay sediment left behind by glacial Lake Willobee (Part A, Plate 3).

Table 1. Transmission rates through unsaturated materials

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

Hydrologic Soil Group (0–3 feet)		Surficial Geologic Texture (3–10 feet)		
Group*	**Transmission rate (in/hr)**	**Classification**	**Transmission rate (in/hr)**	**Surficial geology map unit (Part A, Plate 3)**
A, A/D	1	gravel, sandy gravel, silty gravel	1	bii, bio, hii, hio, hst, iso, te
		sand, silty sand	0.71	lws
B, B/D	0.50	silt, loamy sand	0.50	fa
		sandy loam, peat	0.28	bt, co, hta, hti, htm, htt, htw
C, C/D	0.075	silt loam, loam	0.075	hil
		sandy clay loam	0.035	not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	lw

Note that peat is used as an overlay on the map due to variable and typically unknown thicknesses.
*The Natural Resources Conservation Service (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 percent sand and gravel.
Group B: soils are less permeable but water transmission is still unimpeded.
Group C: water transmission is somewhat restricted.
Group D: water movement is restricted or very restricted.

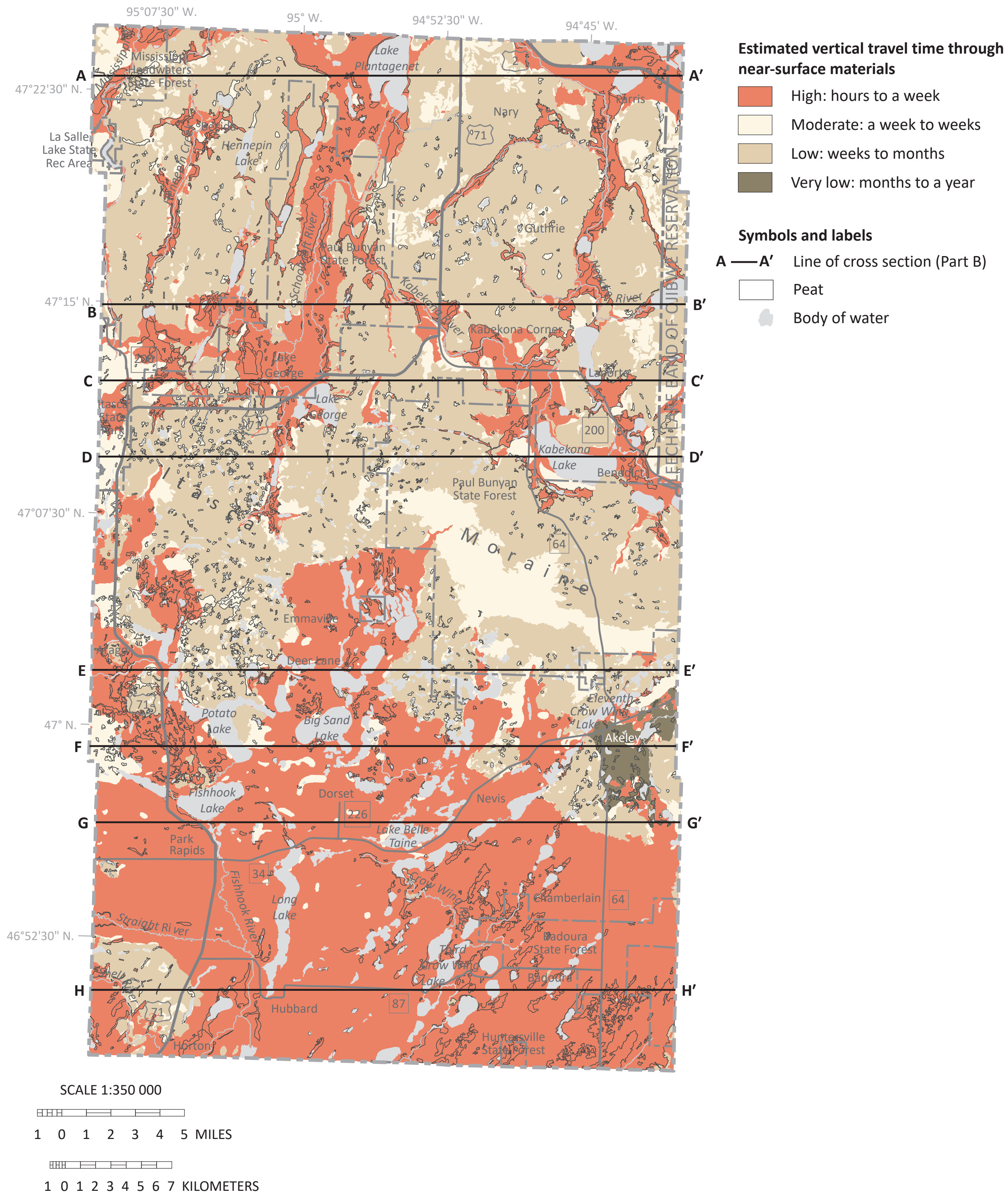


Figure 16. Pollution sensitivity of near-surface materials

Pollution sensitivity of near-surface materials is primarily rated high in areas of sandy outwash and fluvial deposits and moderate or low in areas with sandy loam till at the surface. A small area south and east of Akeley, rated very low, is associated with silt and clay glacial Lake Willobee deposits.

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 estimate of travel time is assumed to be proportional to the cumulative fine-grained sediment (CFGS) thickness overlying a buried sand aquifer or the bedrock surface (Figures 17 and 18). 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).

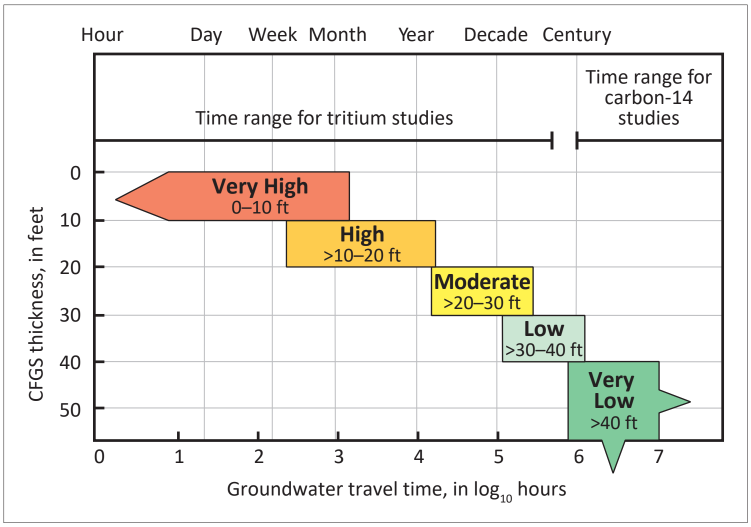


Figure 17. Pollution sensitivity rating for the buried sand aquifers and the bedrock surface

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 high or very 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.

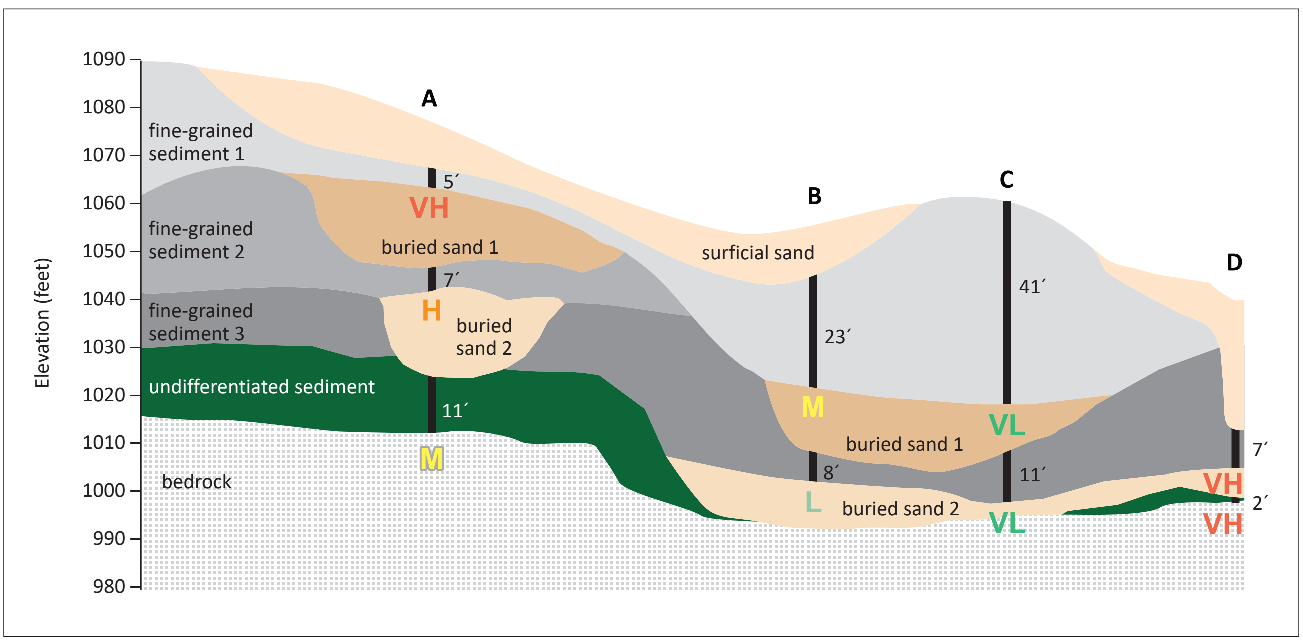


Figure 18. Cross section illustration of the pollution sensitivity model

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 mixed or modern 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 mixed or modern tritium-age water has traveled to an aquifer (Figure 19).

Ⓛ **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 mixed or modern tritium-age water.

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

Ⓓ **Discharge:** older water upwelled from deep aquifers 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.

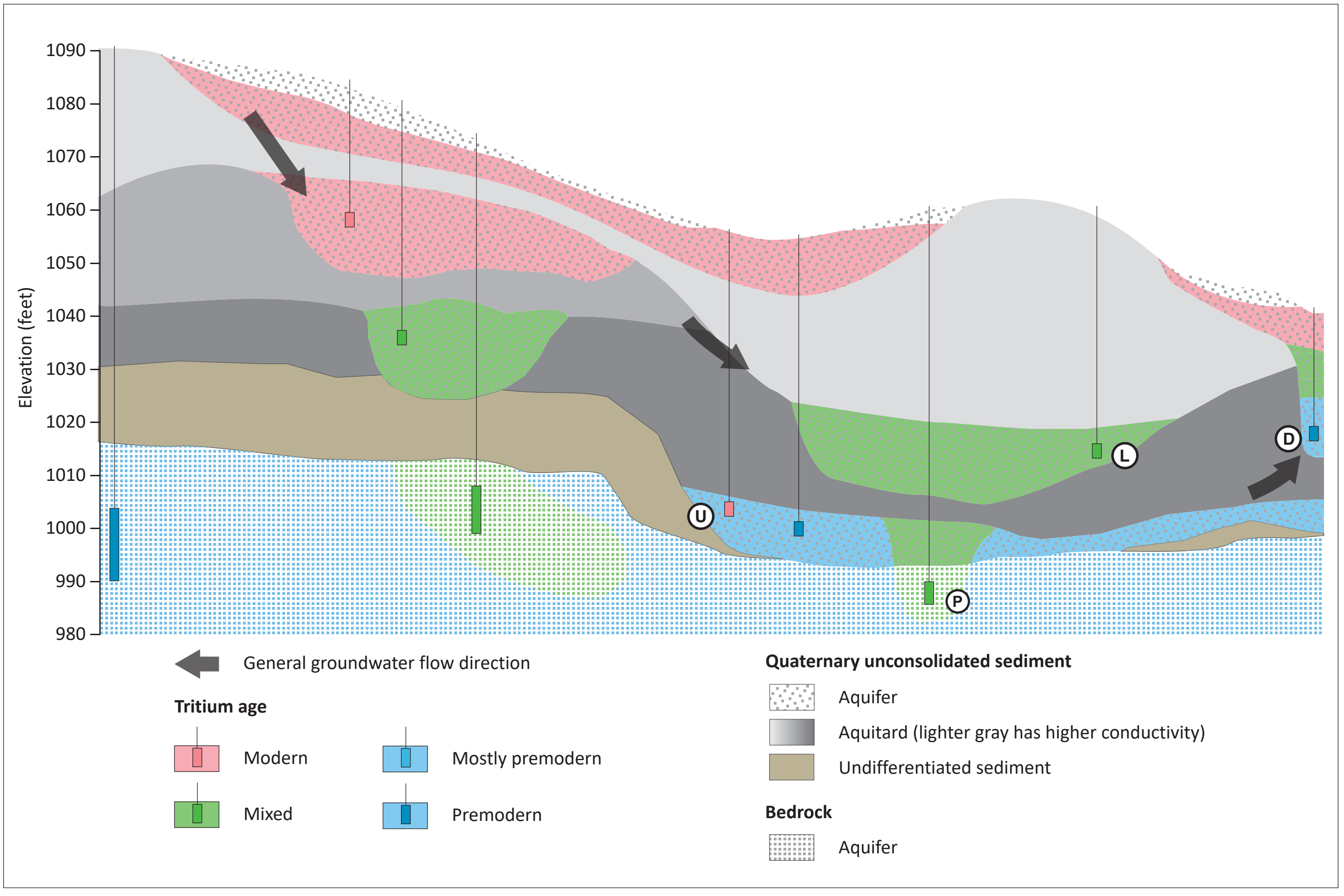


Figure 19. Cross section illustration of groundwater conditions

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 18.

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 samples 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).

The tills separating aquifers of the upper system (Figure 2) have sand contents of approximately 60 percent. It is likely that water moves more readily through these high-sand-content tills, and the pollution sensitivity model overestimates the degree of protection these tills provide. In most cases, this explains modern and mixed tritium-age water found in wells marked with the "Unknown" groundwater condition.

The bedrock surface has very low sensitivity throughout the entire county.

hsi1 aquifer (Figure 20)

- *Aquifer system:* upper system.
- *Extent*: the aquifer is a widely distributed surficial sand aquifer, except where buried in the northeast, near Akeley, or where it is overlain by modern alluvial sediments. The unit is extensive in the south and may be locally unsaturated. In the north, the unit follows glacial outwash channels often occupied by modern streams.
- *Depth*: mean depth is 2 feet, ranging from approximately 0–16 feet.
- *Thickness*: mean thickness is 27 feet, with a maximum of approximately 66 feet.
- *Use*: approximately 6 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: very high sensitivity is found throughout the aquifer, with localized areas of high to very low sensitivity in the northeast and near Akeley.
- *Residence time*: of the 10 samples analyzed for tritium age, 8 were modern and 2 were mixed.
- *Anthropogenic chemical indicators*: of the 9 samples analyzed for chloride, 6 had concentrations at or above 5 ppm and are anthropogenic. Of the 8 samples analyzed for nitrate, 3 are anthropogenic.

hsi2 aquifer (Figure 21)

- *Aquifer system:* upper system.
- *Extent*: the aquifer is present across most of the county. It is laterally extensive in the south and may be locally unsaturated.
- *Depth*: mean depth is 34 feet, ranging from approximately 0–79 feet.
- *Thickness*: mean thickness is 21 feet, with a maximum of approximately 51 feet.
- *Use*: approximately 30 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: very high sensitivity is found extensively in the south and sporadically in the north, with localized areas of high to very low sensitivity elsewhere.
- *Residence time*: of the 31 samples analyzed for tritium age, 27 were modern and 4 were mixed.
- *Anthropogenic chemical indicators*: of the 30 samples analyzed for chloride, 9 had concentrations at or above 5 ppm and are anthropogenic. Of the 33 samples analyzed for nitrate, 4 are anthropogenic.

hsa aquifer (Figure 22)

- *Aquifer system:* upper system.
- *Extent*: the aquifer is present across most of the county. It is laterally extensive in the south and may be locally unsaturated.
- *Depth*: mean depth is 64 feet, ranging from approximately 0–130 feet.
- *Thickness*: mean thickness is 16 feet, with a maximum of approximately 41 feet.
- *Use*: approximately 41 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: very high to moderate sensitivities are found extensively in the south and sporadically in the central and north, with areas of low to very low sensitivity elsewhere.
- *Residence time*: of the 47 samples analyzed for tritium age, 33 were modern, 9 were mixed, and 5 were premodern. Carbon-14 residence times of 1,200 years, 1,500 years, and 4,500 years were determined for three premodern tritium-age samples.
- *Anthropogenic chemical indicators*: of the 45 samples analyzed for chloride, 17 had concentrations at or above 5 ppm and are anthropogenic. Of the 49 samples analyzed for nitrate, 12 are anthropogenic.

brs1 aquifer (Figure 23)

- *Aquifer system:* upper system.
- *Extent*: the aquifer is present in the north.
- *Depth*: mean depth is 119 feet, ranging from approximately 36–202 feet.
- *Thickness*: mean thickness is 10 feet, with a maximum of approximately 32 feet.
- *Use*: approximately 5 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: very low sensitivity is common, with localized pockets of very high to low sensitivity.
- *Residence time*: of the 4 samples analyzed for tritium age, 2 were modern and 2 were premodern. Carbon-14 residence times of 400 years and 850 years were determined for two premodern tritium-age samples.
- *Anthropogenic chemical indicators*: of the 4 samples analyzed for chloride, none had concentrations at or above 5 ppm. Of the 4 samples analyzed for nitrate, none are anthropogenic.

brs2/brs2_c aquifer (Figure 24)

- *Aquifer system:* upper system for brs2 and lower system for brs2_c.
- *Extent*: the aquifer is present locally in the north and southeast. Much of the northern extent of the aquifer is overlain by the brt1 clay loam till; the aquifer is designated as brs2_c in those areas.
- *Depth*: mean depth is 145 feet, ranging from approximately 47–242 feet.
- *Thickness*: mean thickness is 12 feet, with a maximum of approximately 39 feet.
- *Use*: approximately 3 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: very low sensitivity is common, with localized pockets of very high to low sensitivity, particularly in the southeast.
- *Residence time*: of the 5 samples analyzed for tritium age, 1 was modern, 1 was mixed, and 3 were premodern. A carbon-14 residence time of 1,800 years was determined for one premodern tritium-age sample.
- *Anthropogenic chemical indicators*: of the 3 samples analyzed for chloride, none had concentrations at or above 5 ppm. Of the 3 samples analyzed for nitrate, none are anthropogenic.

scs/scs_c aquifer (Figure 25)

- *Aquifer system:* upper system for scs and lower system for scs_c.
- *Extent*: the aquifer is present primarily in the southwest, with localized pockets elsewhere. Northern and eastern pockets of the aquifer are overlain by brt1 and brt2 clay loam tills; the aquifer is designated as scs_c in those areas.
- *Depth*: mean depth is 106 feet, ranging from approximately 0–222 feet.
- *Thickness*: mean thickness is 14 feet, with a maximum of approximately 37 feet.
- *Use*: approximately 9 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: very high to very low sensitivity is found in the scs part of the aquifer in the southwest, with very low sensitivity in the scs_c part of the aquifer where it is overlain by the brt1 and brt2 clay loam tills.
- *Residence time*: of the 9 samples analyzed for tritium age, 4 were modern, 2 were mixed, and 3 were premodern.
- *Anthropogenic chemical indicators*: of the 10 samples analyzed for chloride, 3 had concentrations at or above 5 ppm and are anthropogenic. Of the 10 samples analyzed for nitrate, 2 are anthropogenic.

urs aquifer (Figure 26)

- *Aquifer system:* lower system.
- *Extent*: the aquifer is present in the southwest.
- *Depth*: mean depth is 97 feet, ranging from approximately 54–140 feet.
- *Thickness*: mean thickness is 12 feet, with a maximum of approximately 29 feet.
- *Use*: less than 1 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: sensitivity varies from very high to very low.
- *Residence time*: of the 3 samples analyzed for tritium age, all were modern.
- *Anthropogenic chemical indicators*: no samples were analyzed for chloride. Of the 2 samples analyzed for nitrate, none are anthropogenic.

mls aquifer (Figure 27)

- *Aquifer system:* lower system.
- *Extent*: the aquifer is present primarily in the southwest, with localized pockets elsewhere.
- *Depth*: mean depth is 149 feet, ranging from approximately 19–279 feet.
- *Thickness*: mean thickness is 13 feet, with a maximum of approximately 37 feet.
- *Use*: approximately 3 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: very low sensitivity is common, with localized pockets of very high to low sensitivity in the southwest.
- *Residence time*: of the 10 samples analyzed for tritium age, 4 were modern, 3 were mixed, and 3 were premodern. A carbon-14 residence time of 3,000 years was determined for one premodern tritium-age sample.
- *Anthropogenic chemical indicators:* of the 5 samples analyzed for chloride, 2 had concentrations at or above 5 ppm and both are anthropogenic. Of the 6 samples analyzed for nitrate, none are anthropogenic.

shs aquifer (Figure 28)

- *Aquifer system:* lower system.
- *Extent:* the aquifer is present in the southwest.
- *Depth*: mean depth is 164 feet, ranging from approximately 105–223 feet.
- *Thickness:* mean thickness is 13 feet, with a maximum of approximately 41 feet.
- *Use*: approximately 1 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: sensitivity is primarily very low, with localized pockets of high to low sensitivity.
- *Residence time*: of the 2 samples analyzed for tritium, 1 was modern and 1 was premodern.
- *Anthropogenic chemical indicators*: the 1 sample analyzed for chloride had a concentration below 5 ppm. The 1 sample analyzed for nitrate does not indicate an anthropogenic source.

uws, sfs, ebs, prs, es, and su aquifers (Figure 29)

- *Aquifer system:* lower system.
- *Extent*: these aquifers are present in isolated pockets throughout the county and were combined because of their limited extents and very low sensitivities.
- *Depth*: mean depths range from 252–453 feet.
- *Thickness*: mean thicknesses range from 5–24 feet.
- *Use*: combine to less than 1 percent of wells with an assigned aquifer.
- *Pollution sensitivity*: sensitivity is very low for all these aquifers.
- *Residence time*: of the 3 samples analyzed for tritium (from the ebs and es aquifers), all were premodern. A carbon-14 residence time of 1,400 years was determined for a premodern tritium-age sample from the ebs aquifer.
- *Anthropogenic chemical indicators*: of the 3 samples analyzed for chloride, 2 had concentrations at or above 5 ppm. Of these 2 samples, 1 has a natural source and 1 has an unknown source. Of the 3 samples analyzed for nitrate, none are anthropogenic.

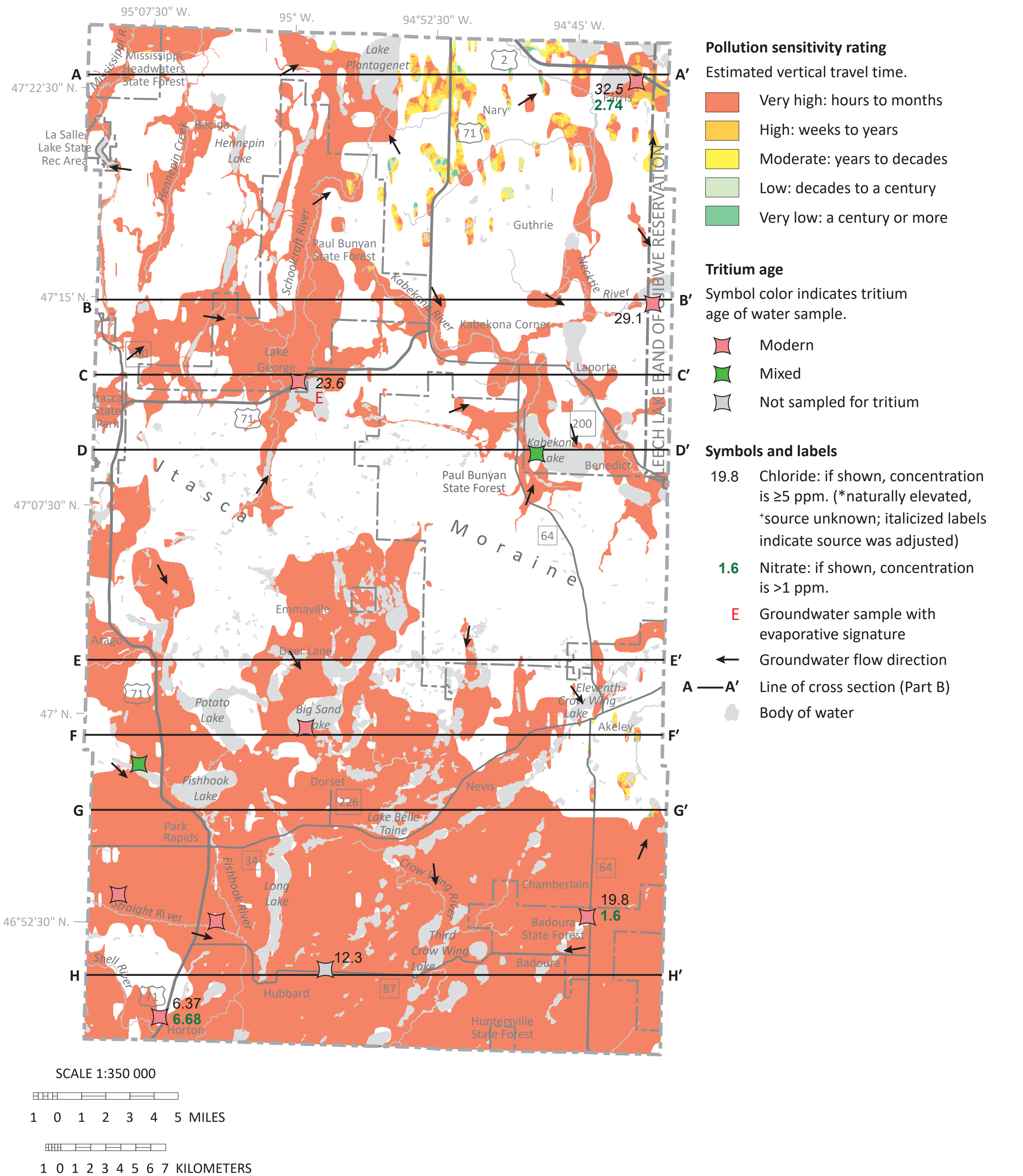


Figure 20. Pollution sensitivity of the hsi1 aquifer and groundwater flow directions

Aquifer sensitivity is primarily very high, with pockets of lower sensitivity in the northeast and near Akeley. Chemical and residence time indicators support the sensitivity model.

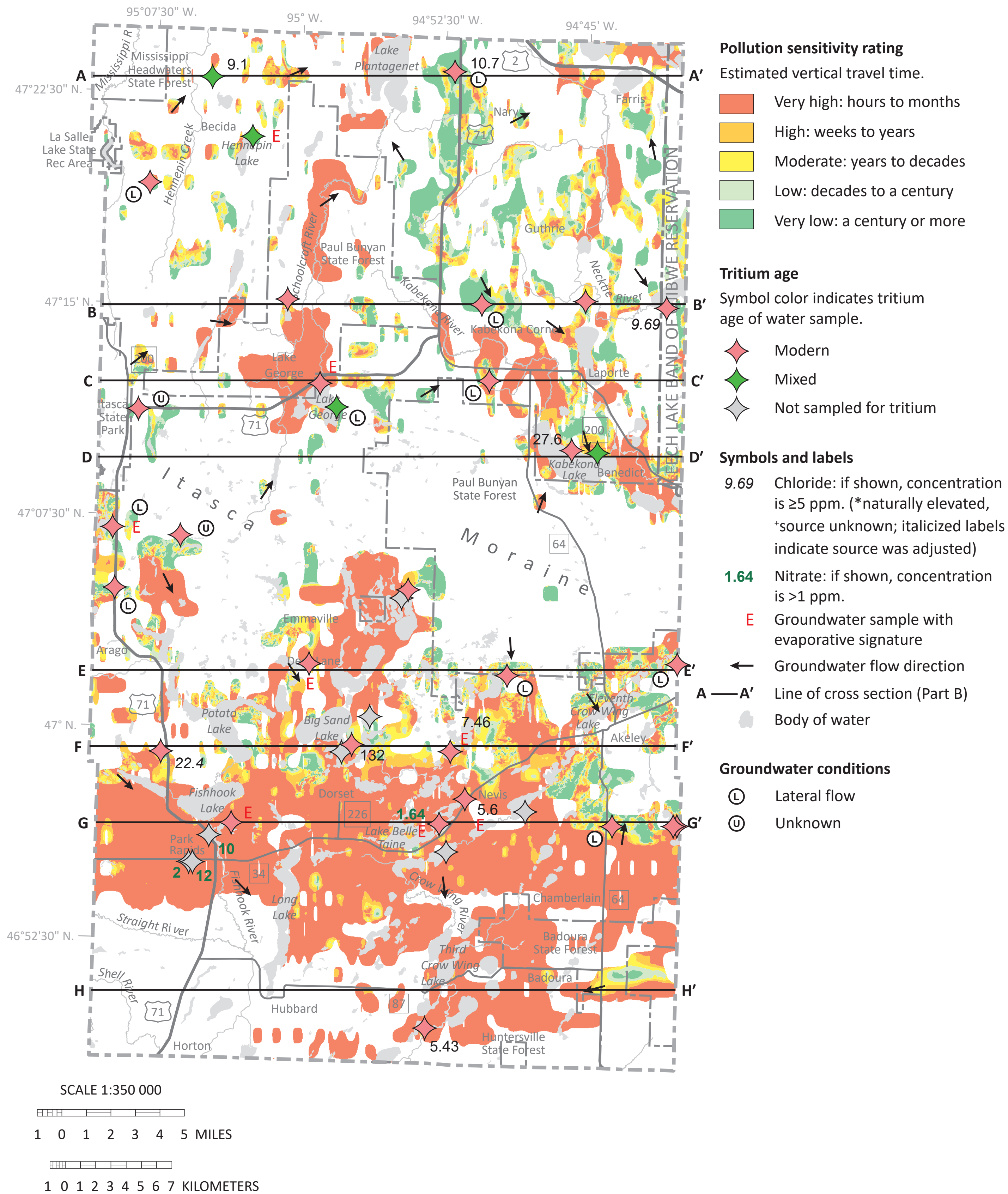


Figure 21. Pollution sensitivity of the hsi2 aquifer and groundwater flow directions

Aquifer sensitivity is primarily very high to moderate, with pockets of lower sensitivity. Chemical and residence time indicators largely support the sensitivity model, but sandy tills may provide less protection than predicted. Lateral flow also moves modern and mixed tritium-age water to very low sensitivity areas.

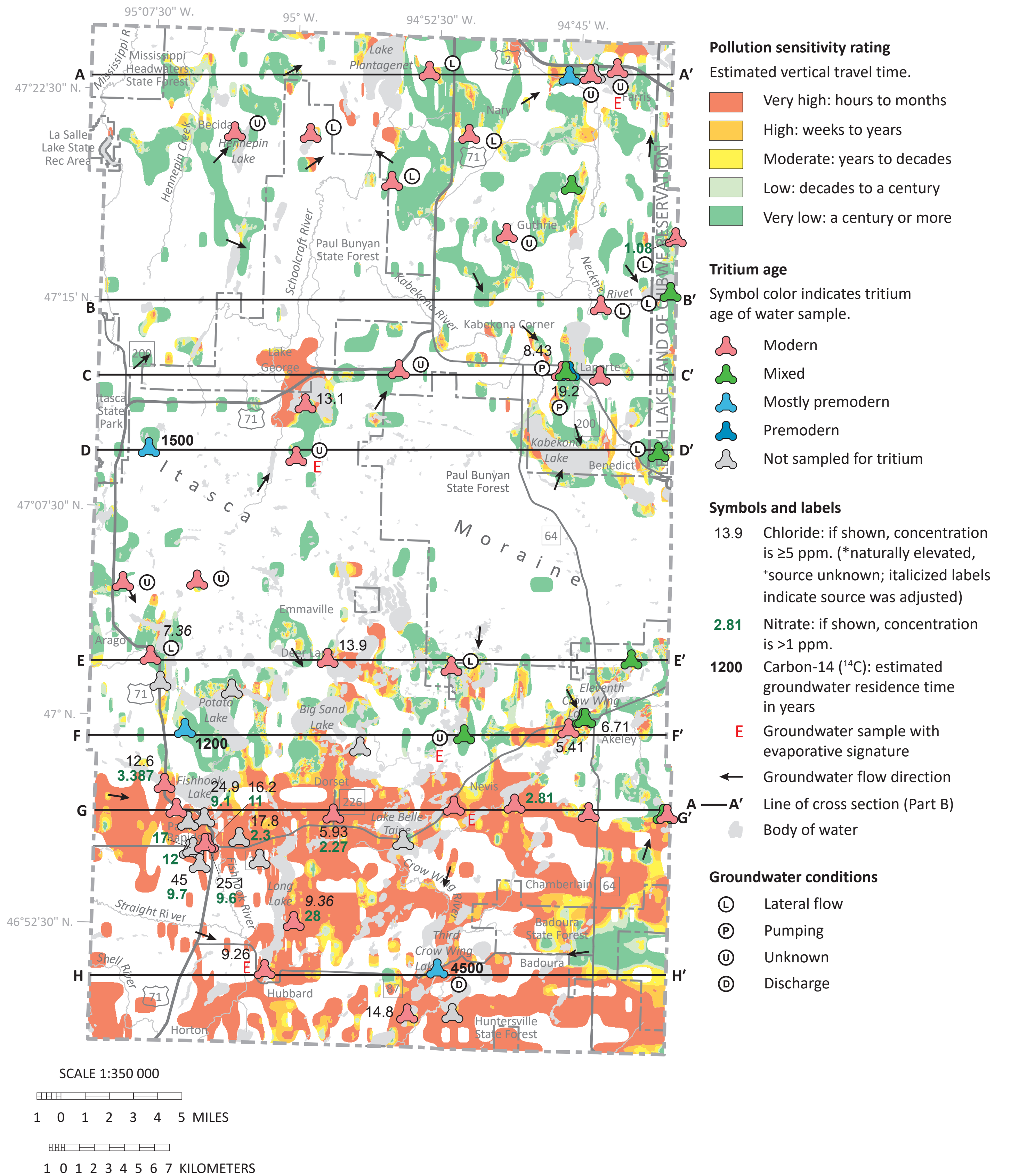


Figure 22. Pollution sensitivity of the hsa aquifer and groundwater flow directions

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. High-capacity pumping and lateral flow also move modern and mixed tritium-age water to very low sensitivity areas. A long groundwater flow path from a high-elevation area to the west likely brought premodern tritium-age water to a sample from an area of moderate sensitivity along A–A′ near the Necktie River. Upwelling to the Crow Wing River along H–H′ likely contributes to the premodern tritium age and carbon-14 residence time of 4,500 years in a sample collected in an area of high sensitivity.

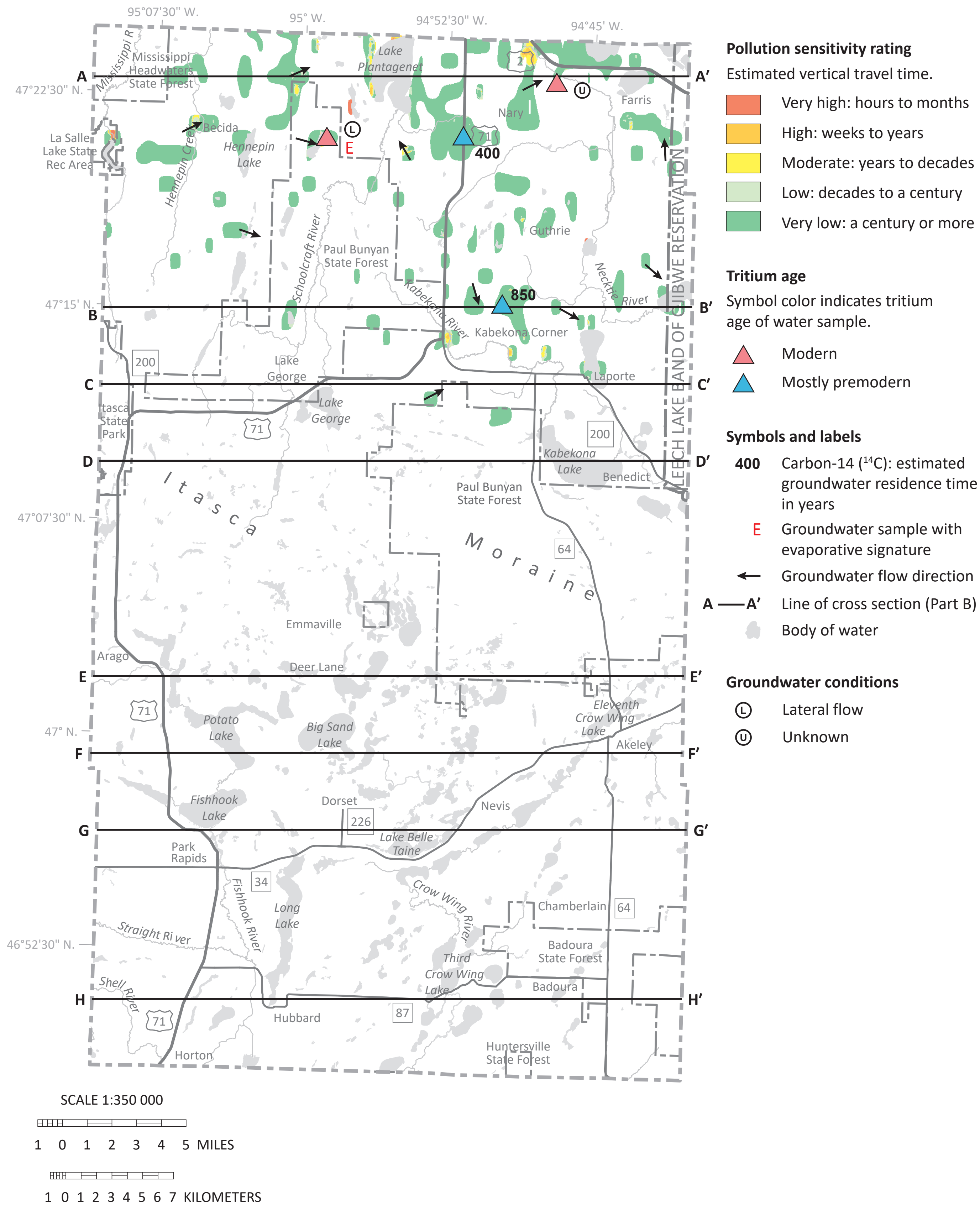


Figure 23. Pollution sensitivity of the brs1 aquifer and groundwater flow directions

Aquifer sensitivity is primarily very low, with pockets of higher sensitivity. Chemical and residence time indicators largely support the sensitivity model, but sandy tills may provide less protection than predicted. Lateral flow also moves modern tritium-age water to lower sensitivity areas.

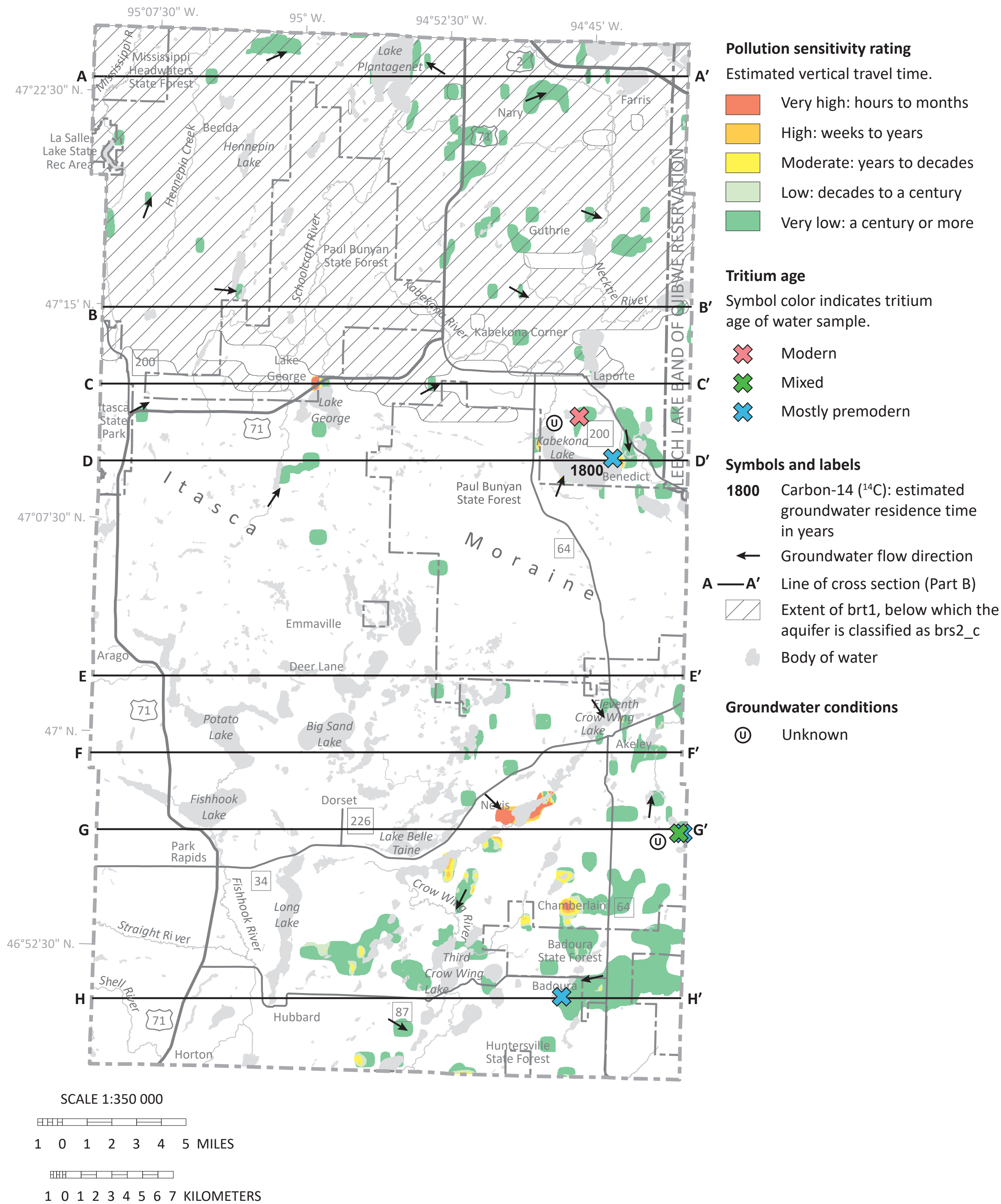


Figure 24. Pollution sensitivity of the brs2/brs2_c aquifers and groundwater flow directions

Aquifer sensitivity is primarily very low, with pockets of higher sensitivity. Wells in the hatched area are within the brs2_c part of the aquifer overlain by the brt1 clay loam till. Chemical and residence time indicators largely support the sensitivity model, but sandy tills may provide less protection than predicted.

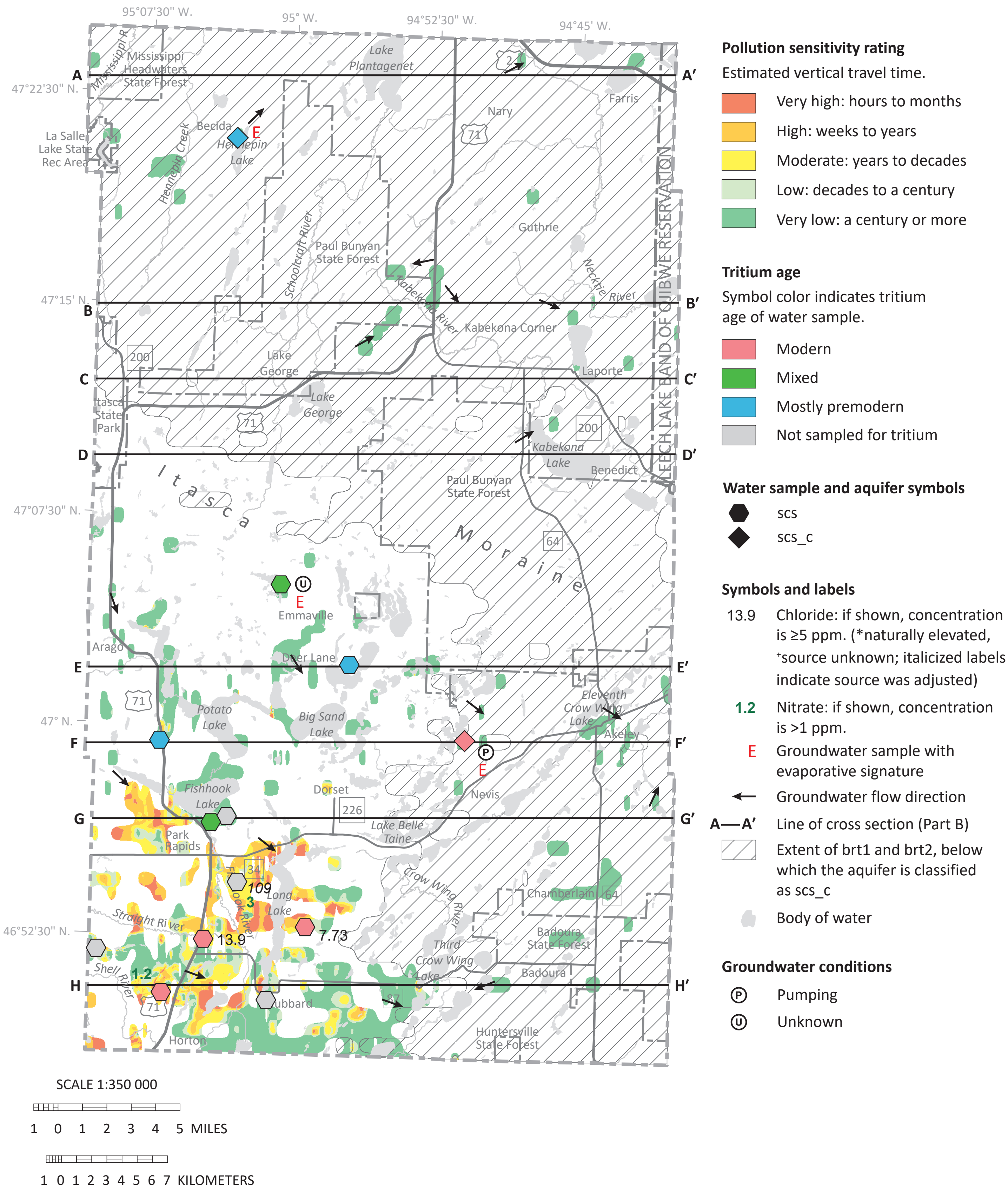


Figure 25. Pollution sensitivity of the scs/scs_c aquifers and groundwater flow directions

Aquifer sensitivity is primarily very low, with higher sensitivities in the southwest. Wells in the hatched area are within the scs_c part of the aquifer overlain by the brt1 and brt2 clay loam tills. Chemical and residence time indicators largely support the sensitivity model, but sandy tills may provide less protection than predicted. High-capacity pumping also moves modern tritium-age water to very low sensitivity areas. A long groundwater flow path from the high-elevation Itasca moraine to the north likely brought premodern tritium-age water to a sample from a high sensitivity area along E–E′ east of Deer Lane and Lower Bottle Lake.

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

Aquifer sensitivity ranges from very high to very low. Chemical and residence time indicators largely support the sensitivity model. Lateral flow moves modern tritium-age water to areas of very low sensitivity.

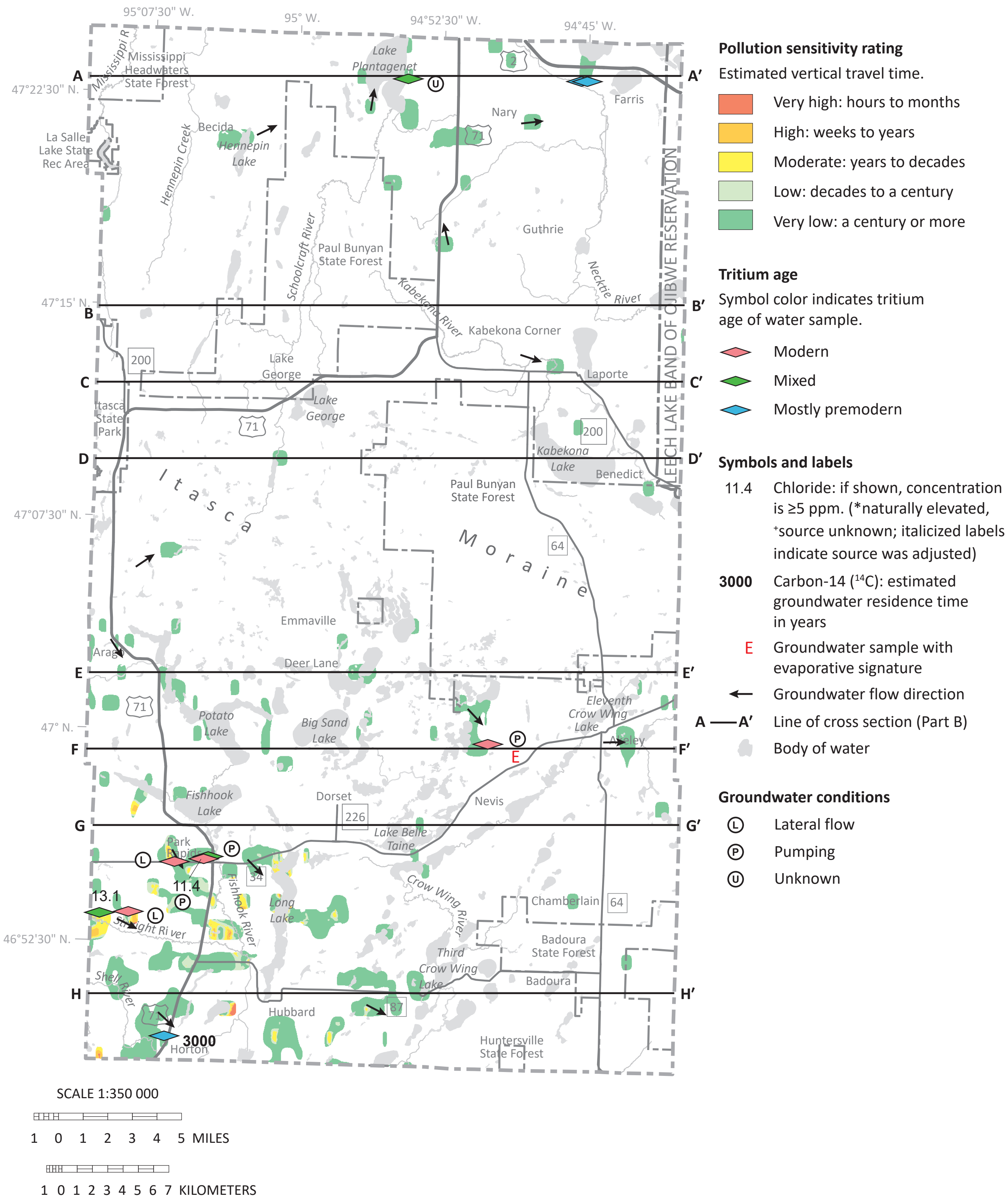


Figure 27. Pollution sensitivity of the mls aquifer and groundwater flow directions

Aquifer sensitivity is primarily very low, with pockets of higher sensitivities in the southwest. Chemical and residence time indicators largely support the sensitivity model. High-capacity pumping and lateral flow also move modern and mixed tritium-age water to very low sensitivity areas. Mixed tritium-age water found in an area of very low sensitivity along A–A′ east of Lake Plantagenet may be a result of a well construction issue.

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

Aquifer sensitivity is primarily very low, with a few isolated pockets of high to low sensitivity. Chemical and residence time indicators largely support the sensitivity model. High-capacity pumping may move modern tritium-age water to very low sensitivity areas.

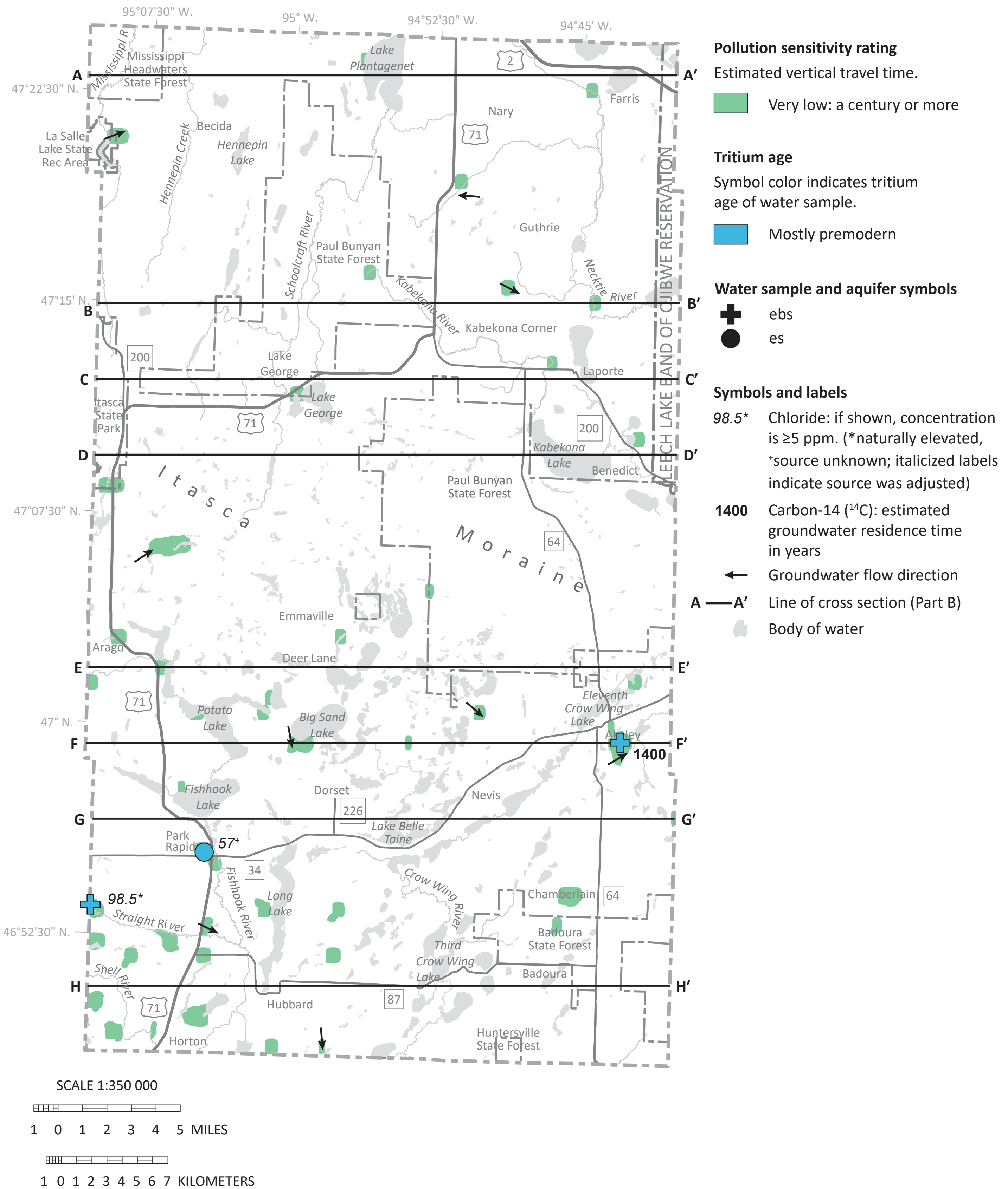


Figure 29. Pollution sensitivity of the uws, sfs, ebs, prs, es, and su aquifers and groundwater flow directions

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

Hydrogeologic cross sections (Plates 8 and 9)

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

Eight 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 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 in both unconsolidated sediment and bedrock or in fractures or dissolution channels in bedrock. The relative ease of water movement through sediment or bedrock is a function of the connectedness of these pores (permeability).

Sediment that makes up the Quaternary aquitards (typically till) is shown on the cross sections 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 percent), making them less competent and allowing for more interconnection between aquifers. Deeper aquitards typically have lower sand content (less than 45 percent) and are more clay-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 topographic highs at County Road 10 and US Highway 71 toward streams, such as Hennepin Creek and lakes such as Lake Plantagenet. Modern tritium-age water has moved downward through surficial aquifers and high sand-content tills to buried aquifers 100–150 feet below the land surface. Anthropogenic chloride and nitrate were found in areas with modern tritium-age water, particularly near Midge Lake. Lake water also has recharged aquifers, evidenced by an evaporative signature in a well by Midge Lake. Premodern tritium-age water was found in aquifers generally greater than 100 feet below the land surface. Near the Necktie River in the hsa aquifer, a longer horizontal flow path from the topographic high to the west brought premodern tritium-age water to a shallower depth of 90 feet below the land surface. Premodern tritium-age water would be expected in the mls aquifer below the east end of Lake Plantagenet, considering the upward movement of groundwater toward the lake. The mixed tritium age of this sample is possibly a result of a well construction issue.

B–B’

Groundwater flow is broadly downward and from west to east. Modern tritium-age water has moved downward through surficial aquifers and shallow aquifers buried by high-sand-content till up to 100 feet below the land surface. Anthropogenic chloride was found in these aquifers near Steamboat Lake. Premodern tritium-age water was found in aquifers at the base of the sand-rich hta till and in aquifers buried by tills with low sand contents at depths generally greater than 100 feet below the land surface. A carbon-14 residence time of 850 years was determined for a sample from the brs1 aquifer below County Road 36. Sparse well logs in the western half of the cross section limit the ability to provide information about groundwater flow and the presence of aquifers in that area.

C–C′

Groundwater flows from topographic highs near State Highway 200 and County Road 91 toward streams including the Schoolcraft and Kabekona rivers. Modern tritium-age water has moved downward through the upper system of aquifers and high-sand-content tills to 140 feet below the land surface. Anthropogenic chloride was found in aquifers with modern tritium-age water near US Highway 71 and the city of Laporte. Lake-water recharge was identified in vertically connected aquifers with modern tritium-age water near US Highway 71. Near the city of Laporte, high-capacity pumping has pulled progressively younger water into the hsa aquifer over its sampling history. A sample taken in 1995 contained premodern tritium-age water. In 2002, a sample contained mixed tritium-age water. A sample taken in 2015 had modern tritium-age water.

D–D′

Groundwater flows from the high-elevation Itasca moraine west of State Highway 64 toward Kabekona Lake in the east, with localized flow toward the Schoolcraft River. Modern tritium-age water has moved downward into surficial aquifers and aquifers buried by high-sand-content tills to 100 feet below the land surface. Evidence of lake-water recharge was identified in a well near the Schoolcraft River. A limited quantity of aquifers have been identified in the Itasca moraine owing to the limited availability of well logs in the area. Longer groundwater flow paths through the till discharge to Kabekona Lake, resulting in mixed-tritium age water in a 70-foot well on the west side of the lake. A mixed tritium-age sample and a premodern tritium-age sample with a carbon-14 residence time of approximately 1,800 years collected on the east side of Kabekona Lake from wells less than 100 feet deep also highlight groundwater discharging to the lake. Weak vertical gradients in sand-rich upper tills increase residence time, evidenced by a premodern tritium-age sample from a 126-foot well east of US Highway 71 in the hsa aquifer, which had a carbon-14 residence time of 1,500 years.

E–E′

Groundwater flow is primarily downward, with west-to-east flow at the eastern end. Modern and mixed tritium-age water has moved downward to the surficial aquifers and aquifers buried by high-sand-content tills to 100 feet below the land surface. Anthropogenic chloride was identified in two wells near Eagle and Lower Bottle lakes with modern tritium-age water. Lake water provided a portion of recharge for a well with an evaporative signature east of Pickerel Lake in the hsi2 aquifer. Between Upper Bottle and Lower Bottle lakes, a well with premodern tritium-age water in the scs aquifer with limited till protection may indicate the presence of water with a long southward flow path entering the aquifer from the high-elevation Itasca moraine to the north. Premodern tritium-age water is found greater than 100 feet below the land surface.

F–F′

Groundwater flows from west to east and locally toward lakes, such as Big Sand and Little Sand lakes. Modern tritium-age water has moved downward through abundant surficial aquifers and into aquifers shallowly buried by high-sand-content tills to 100 feet below the land surface. Upgradient high-capacity pumping near County Road 2 also may have drawn modern tritium-age water into the more deeply buried scs_c and mls aquifers. Three high-capacity pumping wells pulling approximately 20–40 million gallons of water per year were identified up to 2 miles upgradient of these wells in the same aquifers. As a result of limited well log information, there may be better connection between these aquifers than indicated along the cross section. Mixed tritium-age water found in the overlying hsa aquifer could be a perched pocket of slightly older water because there was no nearby high-capacity pumping in the hsa aquifer. Evidence of lake-water recharge was identified in these samples and one other near Spider Lake. Premodern-tritium age water was found in aquifers greater than 100 feet below the land surface. A premodern tritium-age sample from east of US Highway 71 in the hsa aquifer had a carbon-14 residence time of 1,200 years. Another premodern tritium-age sample from near County Road 12 in the ebs aquifer highlights the interconnectedness of the overlying aquifers as water with a carbon-14 residence time of 1,400 years made it to this 300-foot well.

G–G'

Groundwater flows from topographic highs toward streams and lakes, such as the Crow Wing River and Fish Hook River Dam Lake. Modern tritium-age water has moved downward through the abundant vertically connected surficial and buried aquifers, up to 100 feet below the land surface. Anthropogenic nitrate was detected in samples from these connected shallow aquifers near State Highway 226, Lake Belle Taine, and east of County Road 119. Anthropogenic chloride was also detected in the sample from near State Highway 226. Evidence of lake-water recharge was identified in 3 wells. Abundant water at shallow depths limits the need for deeper wells associated with premodern tritium-age water along the cross section. A series of progressively deeper wells near Williams Lake show the progression of modern to mixed to premodern tritium-age water with increasing depth to 225 feet below the land surface.

H–H'

Groundwater flows from topographic highs at the western and eastern edges of the county toward the Fishhook and Crow Wing rivers. Modern tritium-age water has moved downward through the abundant vertically connected surficial and buried aquifers, generally up to 100 feet below the land surface. Anthropogenic nitrate was detected in a sample from a well near County Road 115 from the shallowly buried scs aquifer. Evidence of lake-water recharge was identified in a well near Long Lake completed in the near-surface connected sand units. Premodern tritium-age water was found in aquifers greater than 100 feet below the land surface where groundwater flow takes longer to travel through overlying till; an example is seen in a sample near County Road 110 from the brs2 aquifer. The carbon-14 residence time of 4,500 years for a premodern tritium-age sample collected near Third Crow Wing Lake from the hsa aquifer likely highlights groundwater upwelling to the Crow Wing River, which flows through Third Crow Wing Lake.

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

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

Specific capacity is 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 or open hole.

Specific capacity was determined for 75 wells with assigned aquifers (Table 2 and Figure 30). The wells are primarily located in the south within the Pineland Sands and are mostly irrigation wells, with a few public supply and other use wells. Tests were also available for several public supply wells located in the northeastern corner of the county. The highest mean specific capacity values were measured in the brs2 (49.2 gpm/ft) and hsi2 (45.1 gpm/ft) aquifers in the upper system and the scs_c aquifer (36.9 gpm/ft) in the lower system. The lowest mean value was measured in a single test of the ebs aquifer (2.7 gpm/ft) in the lower system.

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 8 wells (Table 2 and Figure 30). All but 1 are in the Pineland Sands. A wide range of transmissivities was determined across all aquifers. The hsa aquifer had both the lowest (253 ft^2/day) and highest (41,500 ft^2/day) transmissivity values.

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
Upper system aquifers									
hsi1*	12	31.5	20.7	44.6	3	--	--	--	--
hsi2	8–12	45.1	5.3	100	3	--	--	--	--
hsa	8–18	24.4	4.9	62.5	18	4–16	253	41,500	2
brs2	8–12	49.2	6	350	9	12	2,010	4,870	2
scs	8–12	17.8	9.5	27.6	16	--	--	--	--
Lower system aquifers									
scs_c	8–12	36.9	16.7	57.1	2	--	--	--	--
urs	--	--	--	--	--	12	8,820	12,200	1⁺
mls	12–18	22.8	6	53.6	19	12	7,520	32,000	1⁺
shs	12	19.7	8.9	26.7	4	4–12	444	6,920	2
ebs	8	2.7	--	--	1	--	--	--	--

*hsi1 is a surficial aquifer except where buried in the northeast, near Akeley, or overlain by modern alluvial sediment.
⁺For a single aquifer test, multiple transmissivity values may be calculated using different models.
Specific capacity data adapted from the CWI. Transmissivity data are from aquifer properties data (DNR, 2023c).
Dash marks (--) indicate no data

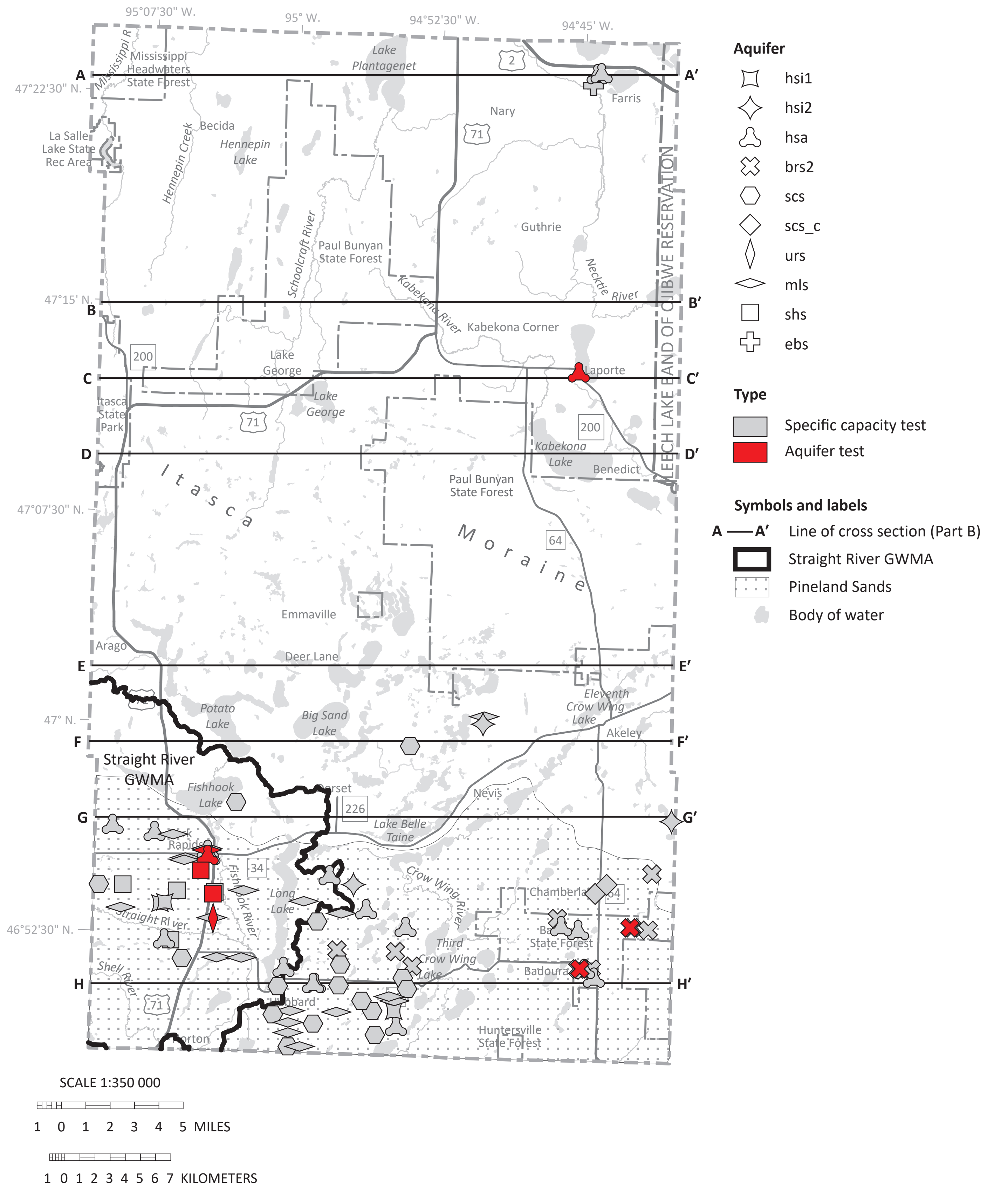


Figure 30. Well locations for specific capacity and aquifer tests

Specific capacity was determined for 75 wells and transmissivity was compiled from aquifer tests of 8 wells (Table 2). Nearly all wells with data available are in the Pineland Sands.

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 constructed 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 occurs in aquifers of both the upper system and the lower system (Figure 31). The largest concentration of observation wells is in the Pineland Sands, where agricultural irrigation wells are common. The Straight River flows through the Pineland Sands and is reliant on cool, consistent temperature groundwater input to sustain its trout population.

Two well nests within the Pineland Sands (Figures 31 and 32) were selected to illustrate the effects of agricultural irrigation and seasonality on water levels in wells and the Straight River for the years 2016–2019 using hydrographs (Figures 33 and 34). Average annual permitted groundwater use within 1.5 miles of each well nest for the same period is displayed in Figure 32 (DNR, 2023d). Hydrograph data were retrieved from the DNR Cooperative Groundwater Monitoring Program (DNR, 2023e) and the United States Geological Survey (USGS) (USGS, 2023). Monthly gridded precipitation data were obtained through the Minnesota State Climatology Office (DNR, 2023f).

Water level records for over 70 observation wells spanning up to five decades not presented in this report are available from the DNR Cooperative Groundwater Monitoring Program (DNR, 2023e).

West nest (Figure 33)

The west nest is located in the uplands 1 mile north of the Straight River and includes two wells (Figure 32). Well 243371 is 34 feet deep and completed in the hsi1 aquifer, part of the upper system. Well 243874 is 145 feet deep and completed in the shs aquifer, part of the lower system. Average annual water use within a 1.5-mile radius of the well nest from 2016–2019 was 352 million gallons per year (Figure 32). The nest is located just over 200 feet from an irrigation well in the shs aquifer of the lower system, which had an average annual water use of 24.7 million gallons per year during 2016–2019.

Water level in the shallow observation well in the hsi1 aquifer primarily tracked with precipitation. There was a slight drop in water level during the winter months when frozen soils prevented recharge to the aquifer. A spring rise in water level associated with snowmelt and precipitation recharge was followed by a general drop in water level during the irrigation season from late spring through late summer, matching the trend followed by the irrigation-impacted deeper well. Following the irrigation season, water level in the shallow well recovered in sync with the deeper well. Above-normal precipitation in late 2019 contributed to a larger rise in late-year water level compared to previous years.

The deep observation well in the shs aquifer showed sharp water level declines of up to 10 feet, followed by rapid recoveries during the irrigation season as a result of nearby irrigation wells in the same aquifer cycling on and off. During this time, water level recovered to within 2–3 feet of the level at the start of the season. Over the late fall and spring months, when the pumps were idle, water level returned to the preirrigation season level. Water level also tracked with overall precipitation like the shallow well in response to less recharge being able to enter aquifers in winter months and above-normal precipitation in late 2019. There was a downward gradient from the shallow well to the deeper well, typical of groundwater flow directions in upland areas away from streams.

East nest (Figure 34)

The east nest is located approximately 100 feet south of the Straight River in a groundwater discharge area and includes 3 wells (Figure 32). Straight River water level is recorded at a USGS stream gage within a few hundred feet of the well nest (USGS, 2023). Well 243392 is 12 feet deep and completed in the hsi1 aquifer. Well 272084 is 26 feet deep and also completed in the hsi1 aquifer. Well 243870 is 75 feet deep and completed in the scs aquifer. All wells are completed in the upper system of aquifers. Average annual water use within a 1.5-mile radius of the well nest from 2016–2019 was 268 million gallons per year (Figure 32). This well nest is much further from pumping wells compared to the west nest (described previously), with the closest permitted irrigation wells in the upper system over 5,000 feet away.

Water levels in the two shallow hsi1 aquifer wells closely tracked with those in the Straight River and fluctuated in response to precipitation events and spring snowmelt recharge. There was a small decreasing trend in water levels during the irrigation season from late spring through late summer, followed by a recovery during the irrigation off-season.

Water level in the deep scs aquifer well showed sharp declines followed by rapid recoveries during the irrigation season. The largest water level decline during the irrigation season was approximately 1.5 feet compared to 10 feet at the west nest. The difference in water level decline at the nests is likely a function of their proximity to high-capacity irrigation wells. Water level in the deep aquifer well at the east nest recovered to preirrigation season level during the irrigation off-season and responded to above-normal precipitation, particularly in summer 2016 and late 2019.

Water levels were generally highest in the deepest well and decreased to the shallowest well, showing an upward gradient and groundwater discharge to the Straight River in this locale. During three irrigation seasons, water levels in the 75-foot-deep scs well decreased below those in the 26-foot hsi1 well, reversing the gradient and causing downward flow toward the deeper aquifer.

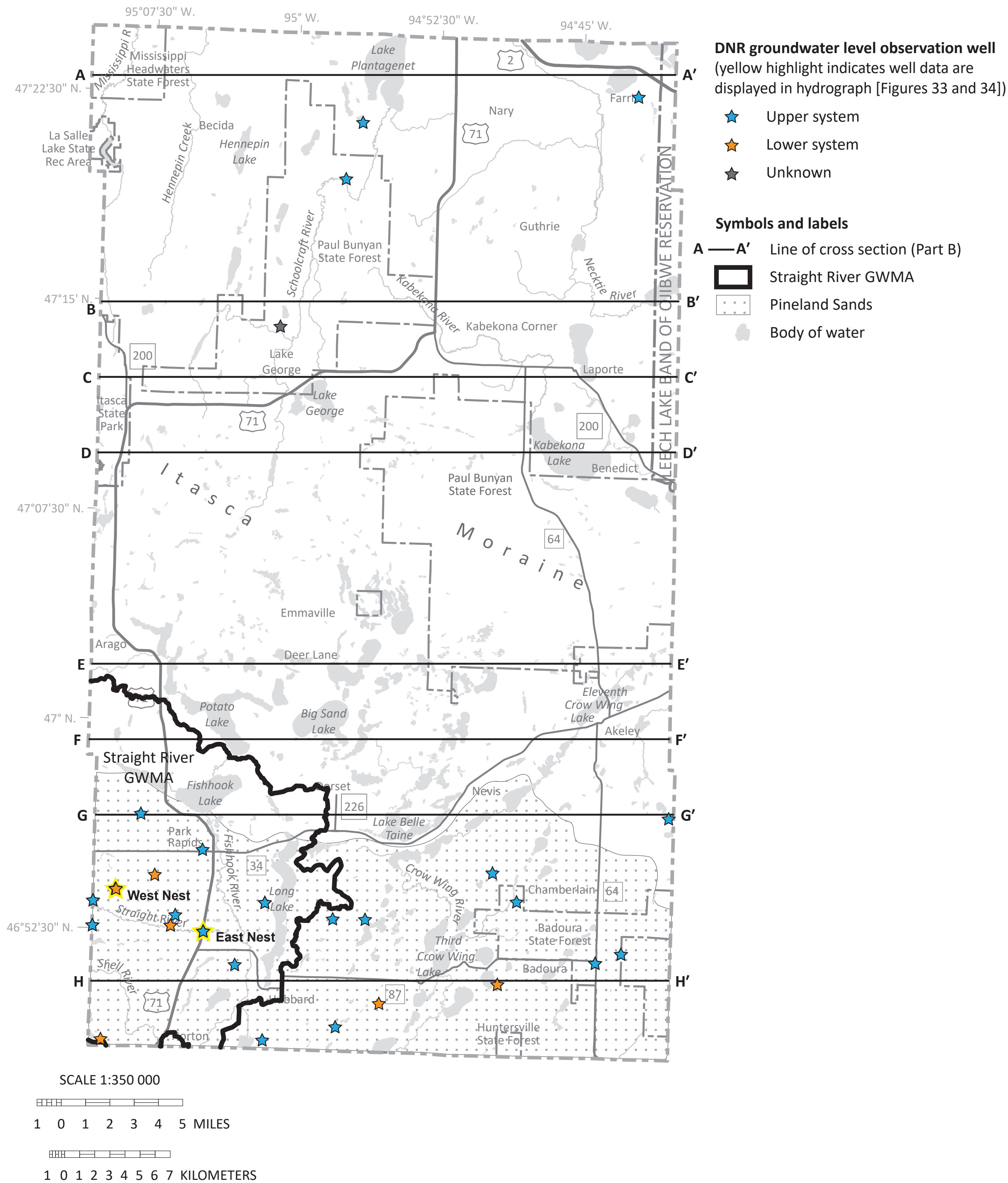


Figure 31. Actively monitored DNR observation wells

The largest concentration of actively monitored observation wells is in the Pineland Sands. Well nest locations for hydrographs shown in Figures 33 and 34 are highlighted.

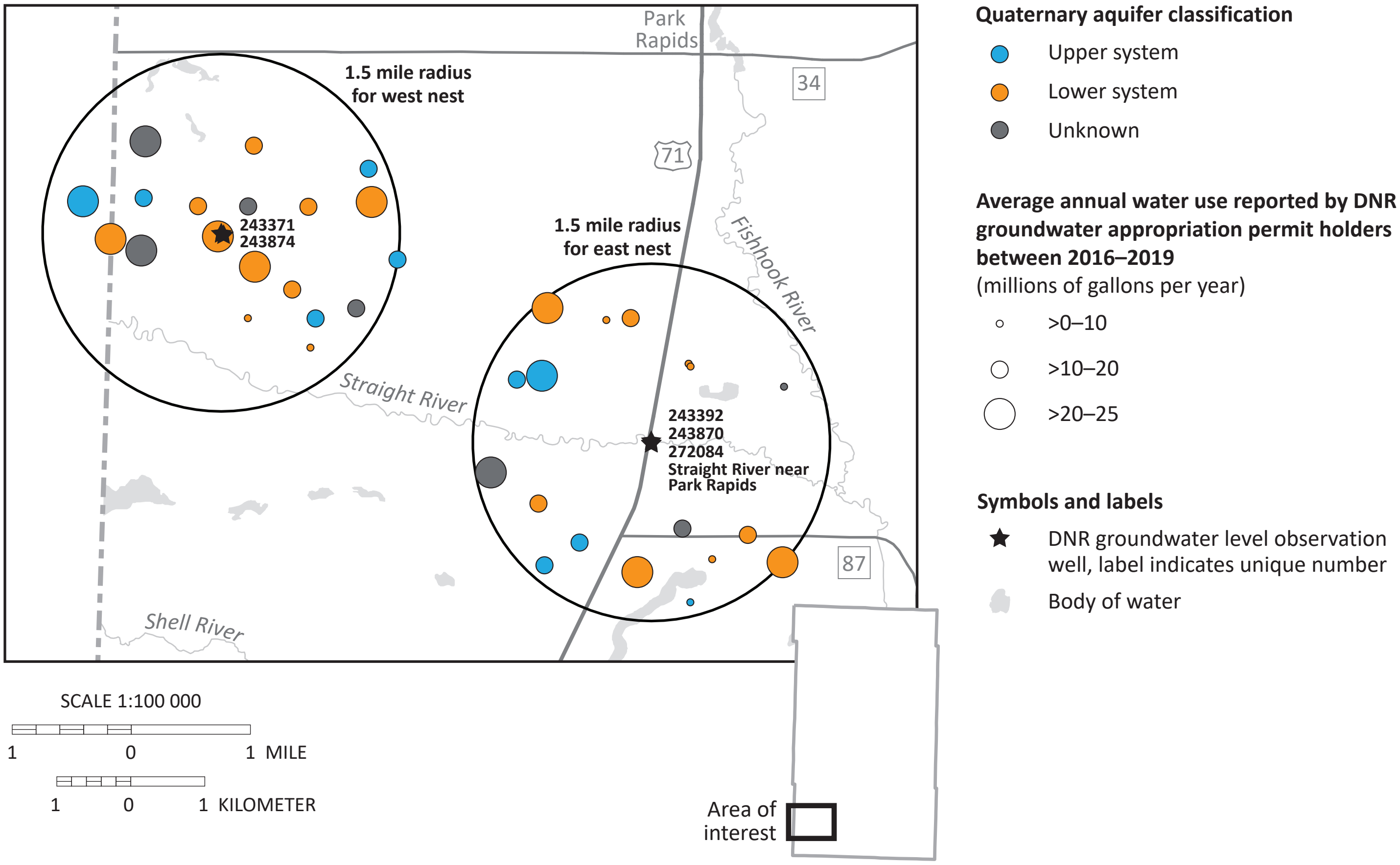


Figure 32. Average annual permitted groundwater use 2016–2019 within 1.5-mile radius of well nests

Between 2016 and 2019, permitted water use averaged 352 million gallons per year within 1.5 miles of the west nest and 268 million gallons per year within 1.5 miles of the east nest. Permitted irrigation wells are located closer to the west nest than the east nest.

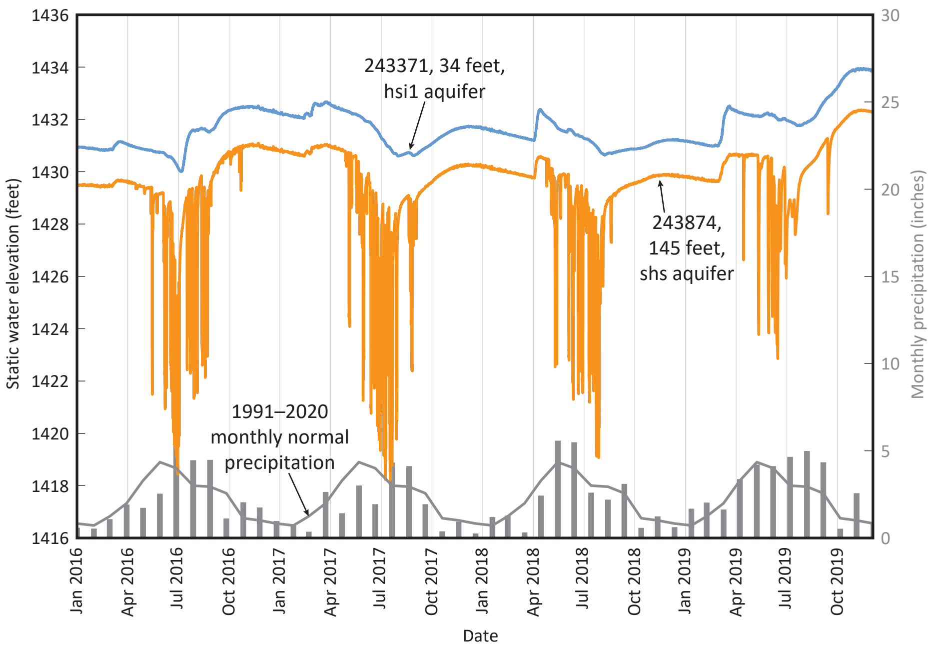


Figure 33. West well nest groundwater hydrographs

Hydrographs show the downward movement of groundwater typical of upland areas. The shallower hsi1 aquifer well showed a general decrease in water level during the irrigation season, followed by a recovery in the irrigation off-season. The deeper observation well in the shs aquifer showed sharp drops and recoveries in water levels during the irrigation season as a result of nearby irrigation wells cycling on and off. Both wells responded to precipitation events.

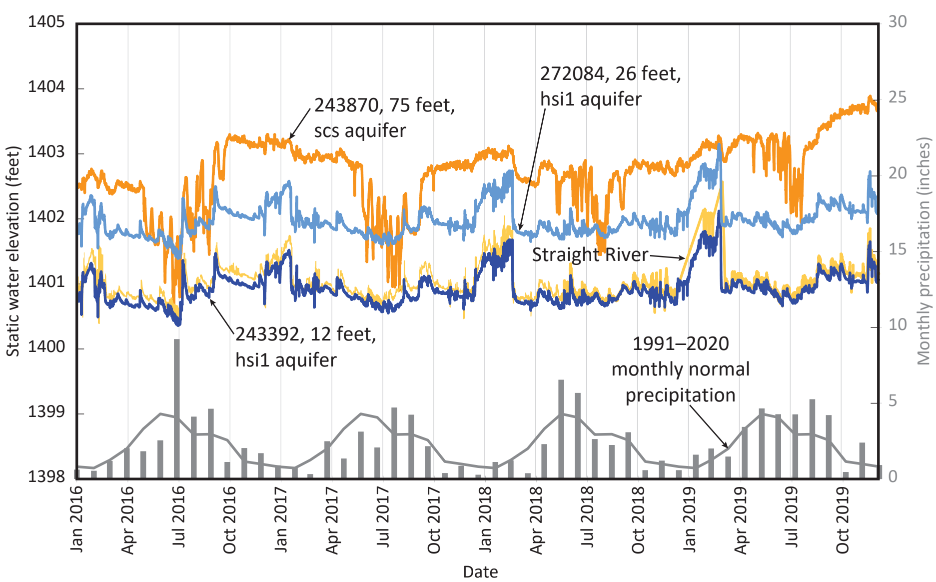


Figure 34. East well nest and Straight River hydrographs

Hydrographs show the upward movement of groundwater from the deeper scs aquifer to the shallower hsi1 aquifer and Straight River, typical of groundwater discharge to streams. High-capacity pumping from wells at greater distance than at the west nest reverse groundwater flow during the irrigation season. All wells and the river responded to precipitation events.

Groundwater use

CWI provides information for 7,623 verified wells in Hubbard County. The majority of wells were for domestic use (88 percent), followed by irrigation (4 percent), public supply (4 percent), and other (4 percent).

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 2020 is shown in Figure 35 by water use type and in Figure 36 by aquifer system (Figure 2) classification (DNR, 2023d). Table 3 uses data from 248 permitted wells with appropriations in 2020 and the highest annual use in each use type for the period from 2016–2020 to account for annual variations in water use. Water use in 2020 was similar for the upper system of aquifers (45.8 percent of use) and the lower system (42.2 percent of use), even though approximately 93 percent of wells use upper system aquifers and only 7 percent of wells use lower system aquifers.

Agricultural crop irrigation was the largest permitted use of groundwater, accounting for 85.7 percent of use in 2020. Irrigation use was largely concentrated in the Pineland Sands (Figure 35). Agricultural/food processing (8.9 percent) and municipal/public water supply (3.9 percent) were the next largest users and are concentrated in the Park Rapids area (Figure 35).

Intensive groundwater irrigation and degraded water quality in the Pineland Sands led to the development of the Straight River GWMA, established by the DNR in 2017. There continues to be a large groundwater demand in the Pineland Sands, even outside of the GWMA, with a large number of agricultural irrigation permits to the east (Figure 35).

Table 3. Reported 2020 water use and highest annual use 2016–2020 from DNR groundwater permit holders

Aquifer	No. of wells	Use (mgy)							
		Agricultural crop irrigation	Agricultural/ food processing	Municipal/ public water supply	Nursery irrigation	Golf course irrigation	Other⁺	Total (mgy)	Total (percent)
Upper system aquifers									
hsi1*	8	126.8	--	--	--	--	--	126.8	2.2
hsi2	7	80.8	--	--	7.3	--	--	88.1	1.5
hsa	49	780.2	--	26	13	7.4	2	828.6	14.4
brs2	24	451.4	--	--	16.7	--	--	468.1	8.1
scs	51	1,108.3	--	--	--	15.5	4.2	1,128	19.6
Total in category	*139*	*2,547.5*	*0*	*26*	*37*	*22.9*	*6.2*	*2,639.6*	*45.8*
Lower system aquifers									
scs_c	11	218	--	--	--	--	--	218	3.8
urs	2	--	--	--	--	--	5.9	5.9	0.1
mls	48	1,115.4	--	197.3	--	4.4	8.8	1,325.9	23.1
shs	18	341.9	511.3	--	--	--	--	853.2	14.8
uws	1	22.3	--	--	--	--	--	22.3	0.4
Total in category	*80*	*1,697.6*	*511.3*	*197.3*	*0*	*4.4*	*14.7*	*2,425.3*	*42.2*
Unknown/unassigned aquifer									
Unknown/unassigned	29	685.6	--	--	--	--	1	686.6	11.9
Grand totals									
Total (mgy)	N/A	4,930.7	511.3	223.3	37	27.3	21.9	5,751.5	N/A
Total (percent)	N/A	85.7	8.9	3.9	0.6	0.5	0.4	N/A	100
Highest annual use 2016–2020	N/A	4,930.7	595.6	254	37	38.7	31.2	N/A	N/A

*hsi1 is a surficial aquifer except where buried in the northeast, near Akeley, or overlain by modern alluvial sediment.
⁺Other use types in 2020 include nonmetallic processing, landscaping/athletic field irrigation, livestock watering, campground/wayside/highway rest area water supply, fire protection water supply, and sand and gravel washing.
Data from MPARS; mgy, million gallons per year; dash marks (--) indicate no use; N/A indicates not applicable
Percentage might not equal 100 due to rounding.

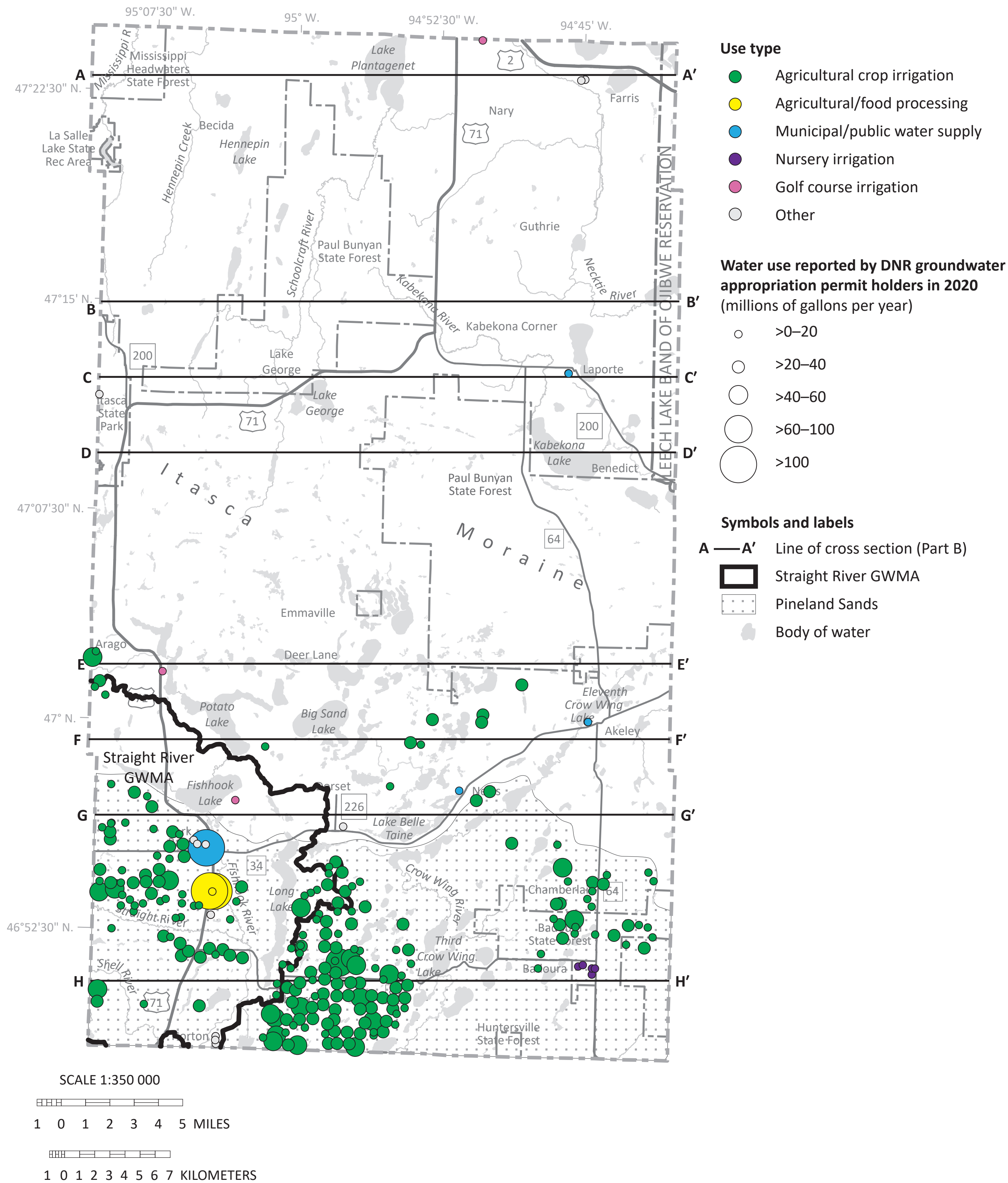


Figure 35. Distribution of groundwater permits by volume and use type

Agricultural crop irrigation is the largest permitted use of groundwater. Permitted water use is concentrated in the south, particularly in the Pineland Sands. The DNR established the Straight River GWMA in an effort to sustainably manage groundwater resources in the area (DNR, 2017).

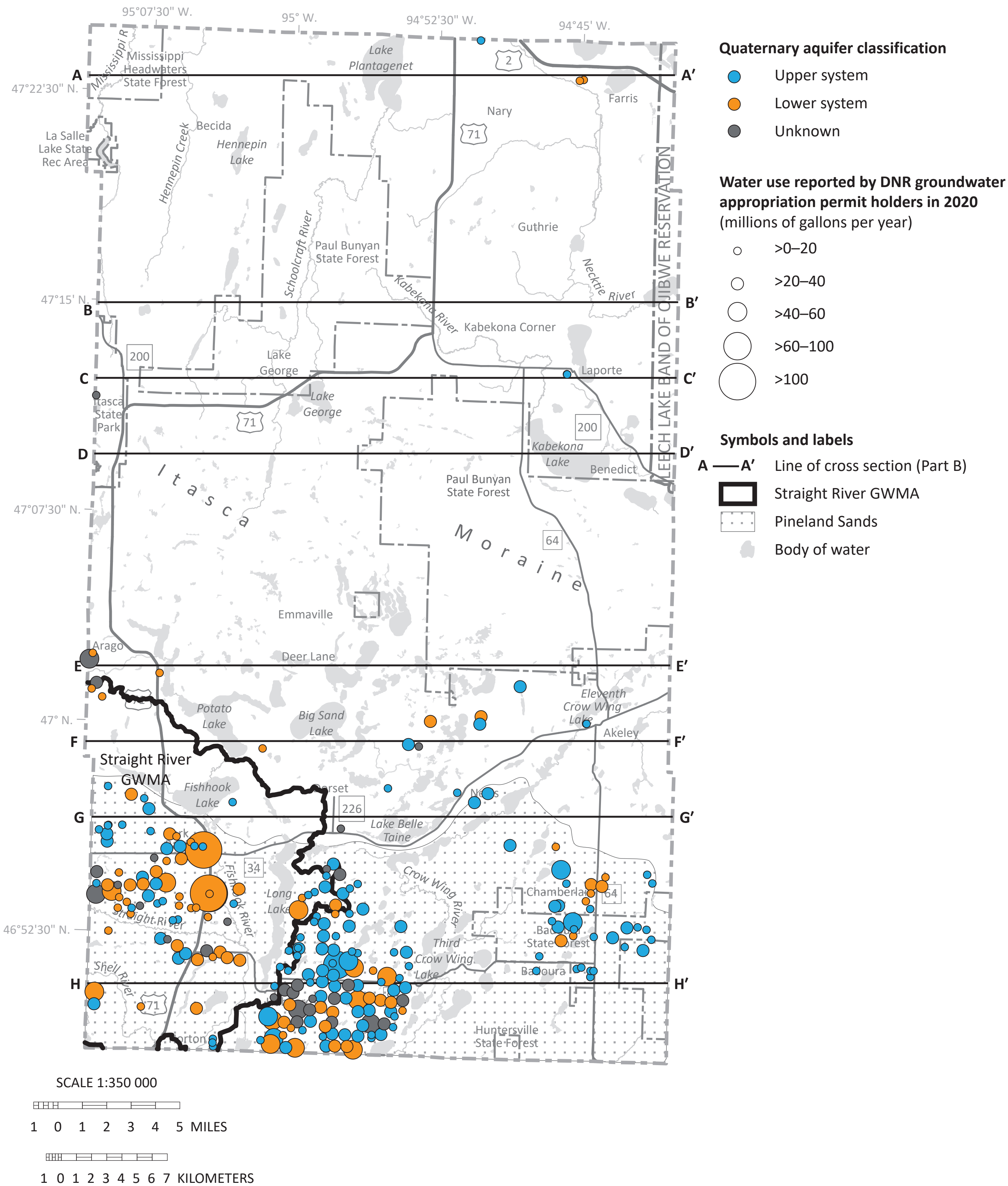


Figure 36. Distribution of groundwater permits by aquifer system classification

Groundwater appropriations are distributed relatively equally between the upper system aquifers and the lower system aquifers.

References

Alexander, S.C., and Alexander, E.C., Jr., 1989, Residence times of Minnesota groundwaters: Minnesota Academy of Sciences Journal, v. 55, no. 1, p. 48–52.

Alexander, S.C., and Alexander, E.C., Jr., 2018, Carbon-14 age dating calculations for Minnesota groundwaters: Retrieved from the University of Minnesota Digital Conservancy.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702–1703.

Crawford, K., and Lee, T., 2015, Using nitrate, chloride, sodium, and sulfate to calculate groundwater age: Proceedings of the 14th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, p. 43–52.

Davis, S.N., Whittemore, D.O., and Fabrryka-Martin, J., 1998, Uses of chloride/bromide ratios in studies of potable water: Ground Water, March–April, v. 36, no. 2, p. 338–350.

Dewitz, J. and USGS, 2021, National Land Cover Database 2019 Products (ver. 2.0, June 2021): United States Geological Survey.

DNR, 2002, Regional hydrogeologic assessment of Otter Tail area, west-central Minnesota: Minnesota Department of Natural Resources, RHA-5, Part B, 2 pls., appendix, GIS files.

DNR, 2016a, Methods for estimating water-table elevation and depth to water table: Minnesota Department of Natural Resources, GW-04.

DNR, 2016b, Methods to estimate near-surface pollution sensitivity: Minnesota Department of Natural Resources, GW-03.

DNR, 2016c, Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment (CFGS) thickness: Minnesota Department of Natural Resources, GW-02.

DNR, 2017, Straight River Groundwater Management Area Plan: Minnesota Department of Natural Resources, March 2017.

DNR, 2022, Groundwater dominated lakes GIS dataset: Minnesota Department of Natural Resources.

DNR, 2023a, Minnesota Climate Explorer: Minnesota Department of Natural Resources, data for Hubbard County, accessed October 2023.

DNR, 2023b, Minnesota annual precipitation normal–1991-2020 and the change from 1981-2020: Minnesota Department of Natural Resources.

DNR, 2023c, Minnesota aquifer properties database: Minnesota Department of Natural Resources, statewide dataset of aquifer tests, accessed October 2023, available upon request.

DNR, 2023d, Minnesota Permitting and Reporting System (MPARS): Minnesota Department of Natural Resources, data for 2016–2020, accessed October 2023.

DNR, 2023e, Cooperative Groundwater Monitoring database: Minnesota Department of Natural Resources, data for Hubbard County wells, accessed October 2023.

DNR, 2023f, Precipitation data retrieval from a gridded database: Minnesota State Climatology Office, Minnesota Department of Natural Resources, accessed October 2023.

DNR and MDH, 2020, Tritium age classification–revised method for Minnesota: Minnesota Department of Natural Resources and the Minnesota Department of Health, DNR Groundwater Atlas Program, GW-05.

Easterling, D.R., Kunkel, K.E., Arnold, J.R., Knutson, T., LeGrande, A.N., Leung, L.R., Vose, R.S., Waliser, D.E., and Wehner, M.F., 2017, Precipitation change in the United States–chapter 7, *in* Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Dokken, D.J., Stewart, B.C., and Maycock, T.K., eds., Climate science special report–fourth national climate assessment: U.S. Global Change Research Program, v. 1, p. 207–230.

EPA, 2023 January, National primary drinking water regulations–inorganic chemicals: U.S. Environmental Protection Agency website.

EPA, 2023 February, Secondary drinking water standards–guidance for nuisance chemicals: U.S. Environmental Protection Agency website.

Erickson, M.L., and Barnes, R.J., 2005a, Glacial sediment causing regional-scale elevated arsenic in drinking water: Ground Water, November–December, v. 43, no. 6, p. 796–805.

Erickson, M.L., and Barnes, R.J., 2005b, Well characteristics influencing arsenic concentrations in ground water: Water Research, v. 39, p. 4029–4039.

Erickson, M.L., Elliott, S.M., Christenson, C.A., and Krall, A.L., 2018, Predicting geogenic arsenic in drinking water wells in glacial aquifers, north-central USA–accounting for depth-dependent features: Water Resources Research, v. 54, issue 12, p. 10172–10187.

Geologic Sensitivity Workgroup, 1991, Criteria and guidelines for assessing geologic sensitivity of ground water resources in Minnesota: Minnesota Department of Natural Resources, 122 p.

Helgesen, J.O., 1977, Ground-Water Appraisal of the Pineland Sands Area, Central Minnesota: U.S. Geological Survey, Water Resources Investigations 77-102, 49 p., 3 pls.

Hem, J.D., 1985 [1986, 1989], Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey, Water-Supply Paper 2254, 272 p. [U.S. Government Printing Office 1985, reprinted in 1986 and 1989, ISBN 85-600603].

Hounslow, A.W., 1995, Water quality data–analysis and interpretation: CRC Press, p. 71–128.

Jay, A., Reidmiller, D.R., Avery, C.W., Barrie, D., DeAngelo, B.J., Dave, A., Dzaugis, M., Kolian, M., Lewis, K.L.M., Reeves, K., and Winner, D., 2018, Overview–chapter 1, *in* Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., and Stewart, B.C., eds., Impacts, risks, and adaptation in the United States–fourth national climate assessment: U.S. Global Change Research Program, v. II, p. 33–71.

Kendall, C., and Doctor, D., 2003, Stable isotope applications in hydrologic studies, *in* Holland, H.D., and Turekian, K.K., eds., Surface and ground water, weathering, and soils: Amsterdam, The Netherlands, Elsevier, Inc., Treatise on Geochemistry, 1st edition, v. 5.11, p. 319–364, ISBN 978-0-08-043751-4.

Lucas, L.L., and Unterweger, M.P., 2000, Comprehensive review and critical evaluation of the half-life of tritium: Journal of Research of the National Institute of Standards and Technology, v. 105, p. 541–549.

Lusardi, B.A., 2018, Geologic atlas of Hubbard County, Minnesota: Minnesota Geological Survey, County Atlas Series C-41, Part A, 6 pls.

MDA, 2018, Final township testing nitrate report–Hubbard County 2016-2017: Minnesota Department of Agriculture, Pesticide and Fertilizer Management Division, 58 p.

MDH, 1998, Guidance for mapping nitrates in Minnesota groundwater: Minnesota Department of Health, revised January 10, 2003 [available upon request from the DNR Groundwater Atlas Program].

MDH, 2012, Initial assessment of manganese in Minnesota groundwater: Minnesota Department of Health, Internal Memorandum, September 5, 2012.

MDH, 2017, Boron and drinking water: Minnesota Department of Health, Human Health-Based Water Guidance Table website.

MDH, 2021, Manganese in drinking water: Minnesota Department of Health, Fact Sheet March 25, 2021.

MDH, 2023a, Human health-based water guidance table: Minnesota Department of Health website under Environmental Health.

MDH, 2023b, Arsenic in drinking water: Minnesota Department of Health, Fact Sheet 08/29/2023R.

MGS and MDH, 2018, County Well Index: Database created and maintained by the Minnesota Geological Survey, a department of the University of Minnesota; with the assistance of the Minnesota Department of Health. Accessible through the MDH Minnesota Well Index mapping application, accessed July 2018.

Minnesota Legislature 2008, Minnesota Administrative Rule 4725.5650, Water quality samples from newly constructed potable water-supply well: State of Minnesota, Office of the Revisor of Statutes.

Natural Resources Conservation Service, 2009, Hydrologic soil groups: U.S. Department of Agriculture, National Engineering Handbook, Chapter 7, Part 630, Hydrology.

Natural Resources Conservation Service, 2022, Web soil survey: U.S. Department of Agriculture, data for Hubbard County, Minnesota, accessed September 2022.

Panno, S.V., Hackley, K.C., Hwang, H.H., Greenberg, S.E., Krapac, I.G., Landsberger, S., and O'Kelly, D.J., 2006, Characterization and identification of Na-Cl sources in ground water: Ground Water, March–April, v. 44, no. 2, p. 176–187.

Pryor, S.C., Scavia, D., Downer, C., Gaden, M., Iverson, L., Nordstrom, R., Patz, J., and Robertson, G.P., 2014, Midwest–chapter 18, *in* Melillo, J.M., Richmond, T.C., and Yohe, G.W., eds., Climate change impacts in the United States–third national climate assessment: U.S. Global Change Research Program, p. 418–440, ISBN 9780160924026.

Smith, E.A., and Westenbroek, S.M., 2015, Potential groundwater recharge for the state of Minnesota using the soil-water-balance model, 1996–2010: U.S. Geological Survey, Scientific Investigations Report 2015-5038, 85 p.

SDWA, et seq., 1974, Safe Drinking Water Act: U.S. Environmental Protection Agency, Public Law 104–182, 42 U.S. Code § 300f – Definitions.

U.S. Census Bureau, 2023, QuickFacts: data for Hubbard County, accessed October 2023.

USGS, 2023, Water Data for the Nation: United States Geological Survey, data for Straight River Near Park Rapids, MN–05243725, accessed October 2023.

Vose, R.S., Easterling, D.R., Kunkel, K.E., LeGrande, A.N., and Wehner, M.F., 2017, Temperature changes in the United States–chapter 6, *in* Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Dokken, D.J., Stewart, B.C., and Maycock, T.K., eds., Climate science special report–fourth national climate assessment: U.S. Global Change Research Program, v. 1, p. 185–206.

Wilson, J.T., 2012, Water-quality assessment of the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Scientific Investigations Report 2011-5229, 154 p.

Glossary

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. Natural arsenic contamination of groundwater is a problem that affects millions of people across the world, including over 100,000 people served by domestic wells in Minnesota.

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

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

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

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

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

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.

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

fluvial—relating to or formed by rivers and streams.

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).

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.

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 protocols listed below and submitted to laboratories for analysis.

Samples were analyzed by DNR staff, the Minnesota Department of Agriculture (MDA), or the University of Waterloo Environmental Isotope Laboratory (Waterloo). The University of Minnesota (UMN) assisted in 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	24–48 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 bottle submerged with cap in hand. Seal bottle submerged ensuring no remnant bubbles.

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

****Use deionized water from designated lowboy for blanks. Attach lowboy to the inline filter with a 3/8-inch tube and purge 1 liter of water to rinse tubing and filter. Rinse and fill bottles through 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 Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) precipitation monitoring station MN-SL-137 in Hibbing. Precipitation was collected daily and most samples were composited for approximately 30 days.
- A **lake-water** sample was collected near the shore where the water depth is approximately 1 meter.

For additional tritium information, contact the DNR Groundwater Atlas Program 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)	05/21/2012–06/20/2012	8.7	Precipitation composite
	09/30/2012–10/30/2012	6.7	Precipitation composite
	05/09/2014–06/09/2014	7.0	Precipitation composite
	10/01/2014–10/31/2014	6.7	Precipitation composite
	05/01/2015–05/31/2015	5.3	Precipitation composite
	08/17/2016–09/16/2016	8.3	Precipitation composite
	04/01/2017–04/30/2017	8.1	Precipitation composite
	09/06/2017–10/06/2017	6.5	Precipitation composite
	10/03/2018–11/01/2018	3.7	Precipitation composite
	4/11/2019	13.4	Snow
	04/04/2019–05/04/2019 (excluding 04/11/2019)	12.1	Precipitation composite
	09/09/2019–10/03/2019	5.0	Precipitation composite
	09/01/2020–09/30/2020	7.7	Precipitation composite
CoCoRaHS precipitation station (MN-SL-137)	09/01/2020–10/01/2020	8.1	Precipitation composite
Lake-water sample (Long Lake)	05/28/2019	6.0	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.

DEPARTMENT OF NATURAL RESOURCES

500 Lafayette Road
St. Paul, MN 55155-4040
888-646-6367 or 651-296-6157
mndnr.gov

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

Funding for this project was provided by the following:

The Minnesota Environment and Natural Resources Trust Fund, as recommended by the Legislative Citizen Commission on Minnesota Resources (LCCMR).

The Clean Water Fund, which receives 33 percent of the sales tax revenue from the Clean Water, Land and Legacy Amendment, approved by voters in November 2008.

CLEAN WATER LAND & LEGACY AMENDMENT