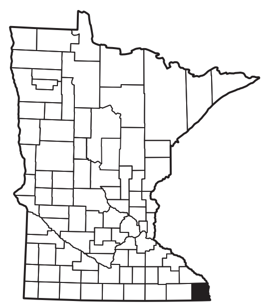
Groundwater Atlas of Houston County, Minnesota

County Atlas Series C-33, Part B - Hydrogeology



Report

To accompany these atlas components:

Plate 5, Water Chemistry

Plate 6, Hydrogeologic Cross Sections

DEPARTMENT OF NATURAL RESOURCES

St. Paul 2025

mndnr.gov/groundwatermapping

The County Atlas Series

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

Part A - Geologic Atlas

The precursor to this atlas is the *Geologic Atlas of Houston County, Minnesota*, C-33, Part A (Setterholm, 2014), published by the Minnesota Geological Survey (MGS). It contains Plate 1, Data-Base Map (Bauer and Chandler); Plate 2, Bedrock Geology (Steenberg); Plate 3, Surficial Geology (Lusardi, Adams, and Hobbs); Plate 4, Bedrock Topography and Depth to Bedrock (Steenberg).

Information is available on the MGS webpage (cse.umn.edu/mgs/county-geologic-atlas).

Part B - Groundwater Atlas

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

Citation for this atlas:

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Acknowledgments

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A 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 on the Minnesota Department of Natural Resources Groundwater Atlas Program webpage (mndnr.gov/groundwatermapping).

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

Base maps were modified from the Minnesota Geological Survey, *Geologic Atlas of Houston County, Minnesota*, 2014. 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 Houston County, Minnesota

by John D. Barry

Executive summary

This report and the accompanying plates describe the groundwater characteristics of Houston County and were produced by the Minnesota Department of Natural Resources (DNR). Groundwater is a mixture of water of various chemical compositions and ages that exists underground, filling the pores and fractures of geologic materials beneath the land surface.

This report builds on the geology described in Part A, previously published by the Minnesota Geological Survey (MGS) (Setterholm, 2014), illustrating the hydrogeologic setting using maps, plates, figures, tables, and text. Principal products include groundwater flow maps, illustrations summarizing the results of select water chemistry, aquifer pollution sensitivity maps, and hydrogeologic cross sections. Key elements and findings are summarized in this section.

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

Houston County is in southeastern Minnesota with land use that is a mix of agricultural cropland, forest, and small towns. The county lies within four surface watersheds: the Root River, Mississippi River–Reno, Mississippi River–La Crescent, and Upper Iowa River. It has a cool subhumid climate with average temperatures of 69.6 degrees Fahrenheit (°F) in the summer and 20°F in the winter. Average annual precipitation is approximately 37 inches, making it one of the wettest counties within the statewide range of 21 to 38 inches.

Physical geology and hydrogeology (pages 6 to 20) describes the aquifers and aquitards and identifies their hydrostratigraphic characteristics and corresponding geologic units from Part A. Groundwater-elevation maps broadly illustrate the direction of groundwater flow in unconfined conditions (water-table elevation) and confined conditions (potentiometric-surface contours).

The county is underlain by a thick sequence of Paleozoic sedimentary bedrock layers. Bedrock is generally within 50 feet of the land surface and is covered by a veneer of unconsolidated sediment, such as loess, sand, and colluvium. Thick layers of unconsolidated sediment generally only exist in valley bottoms, making bedrock aquifers the primary source of drinking water and groundwater discharge to streams.

Much of the county is a karst terrain formed by precipitation and groundwater dissolving the underlying carbonate sedimentary rock. Karst provides rapid water movement between the land surface and underlying aquifers and may be characterized on the surface by sinkholes, caves, and springs. Even where surficial evidence of karst features is absent, there can still be connections for rapid water movement between the land surface and aquifers (higher pollution sensitivity).

Groundwater flow directions in the water table are regionally toward the Mississippi River and locally toward streams and creeks. Water-table depth is shallow (0 to 20 feet) in valley bottoms. Elsewhere, it can be very deep and difficult to determine because of the karst setting, unsaturated soils, and few shallow bedrock wells. In sporadic areas, soil moisture suggests there is a perched water table. Bedrock aquifers show groundwater flow patterns similar to the water table, regionally toward the Mississippi River and locally toward streams and creeks. Rapid recharge can occur in aquifers above the St. Lawrence aquitard or where aquitards are not present.

Water chemistry (pages 21 to 32, Plate 5) provides information about the groundwater sources, flow paths, and travel times. Water chemistry can indicate high pollution sensitivity or problems with naturally occurring geologic (geogenic) contaminants. Human-caused (anthropogenic) occurrences of chloride and nitrate-nitrogen (nitrate) are relatively widespread in the water-table aquifer. The water-table aquifer comprises the Prairie du Chien and Jordan aquifers in upland settings and the sand and gravel aquifer in lowland settings. Elevated levels of chloride and nitrate most commonly occur in wells completed in aquifers located above the first regionally competent aquitard, the St. Lawrence aquitard, or in valley bottoms where overlying aquitards are not present. Springs commonly have elevated levels of both chloride and nitrate, as even springs emanating beneath aquitards include a component of recent water susceptible to contamination.

Arsenic and manganese are geogenic contaminants that generally have low concentrations in the county. The Minnesota Department of Health (MDH) recommends water treatment if any arsenic is present.

Pollution sensitivity (pages 33 to 47) of an aquifer is estimated based on the time it takes water to flow from the land surface through various types and thicknesses of soils and geologic materials. Pollutants are assumed to travel with water at the same rate. Sensitivity is modeled with different methods for the near-surface materials and bedrock aquifers. The model results are evaluated by comparing select chemistry from sampled wells and springs. Rapid recharge is associated with high pollution sensitivities.

Near-surface sensitivity ratings can be broadly grouped into two types:

1. Very high sensitivity in the area prone to karst feature development, which covers most of the county.
2. High to moderate sensitivity areas that occur along the Mississippi River Valley and in valley bottoms with coarse-grained deposits.

Sensitivity ratings for bedrock aquifers were developed using chemical constituents, such as tritium and carbon-14 data, for residence time, and select inorganic chemicals, such as chloride and nitrate, for contamination. Groundwater residence times range from less than 100 to 30,000 years. Anthropogenic chloride and nitrate are relatively widespread in shallow aquifers, especially where wells are completed in aquifers above the St. Lawrence aquitard. Below the St. Lawrence aquitard, groundwater has longer residence times and less contamination. Wells completed in aquifers below the St. Lawrence can generally provide groundwater that is typically unimpacted by human activities, if properly installed according to the Minnesota Well Code. Springs commonly have elevated levels of both chloride and nitrate, even if located below the St. Lawrence aquitard. A portion of the water emanating from these springs is anthropogenically impacted water that flows vertically downward through conduits and fractures in valley settings.

Hydrogeologic cross sections (pages 48 and 49, Plate 6) illustrate groundwater flow, residence time, and distribution of chemical indicators. Cross sections help define areas of interest, such as locations of important groundwater recharge, discharge, and sensitivity to pollution.

Aquifer characteristics and groundwater use (pages 50 to 55) summarizes specific capacity tests, aquifer tests, water use records, and groundwater level monitoring data. These data can be used to characterize aquifer recharge in the county and plan for new well installations. The majority of permitted water use is for municipal and public water supply, which is primarily from the Mt. Simon aquifer. High-volume use is generally centered in the city of La Crescent, but is also near the cities of Caledonia, Spring Grove, and Houston. The next most common use categories are pollution containment and livestock watering.

Physical setting and climate

Houston County is located in the southeastern corner of Minnesota (Figure 1). Its landscape is characterized by broad plateaus intersected with deeply incised valleys. Elevation changes from ridgetops to valleys can be greater than 500 feet. The modern landscape was primarily shaped by erosion from river systems.

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, with water levels fluctuating rapidly in rivers and water-table aquifers following precipitation. Water takes longer to travel to deeply buried aquifers, so the changes are often delayed or subdued. 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 (Figure 1). Groundwater provides baseflow to streams and major river systems.

The county is located on a portion of the western edge of the upper Mississippi River Valley commonly referred to as the Driftless Area. The term driftless implies the area was never glaciated; however, this is not accurate in Houston County. Glacial till of pre-Illinoian age is found in the western portion of the county, and scattered glacial material can be found in the east (Part A, Plate 3). Since Houston County was not covered by sediment during recent glaciations, its landscape represents a mature and heavily eroded ancient surface. Surface-water flow in the county is controlled by elevation and landform and drains toward four separate surface watersheds (Figure 1), all of which ultimately flow into the Mississippi River. Surface-water features (lakes and wetlands) in upland areas are limited due to fracture and conduit networks that prevent water from ponding at the surface. Surface-water features are mostly streams in valleys, many of which are cold-water trout streams with springs in their headwaters. Groundwater discharge provides critical baseflow to these cold-water resources.

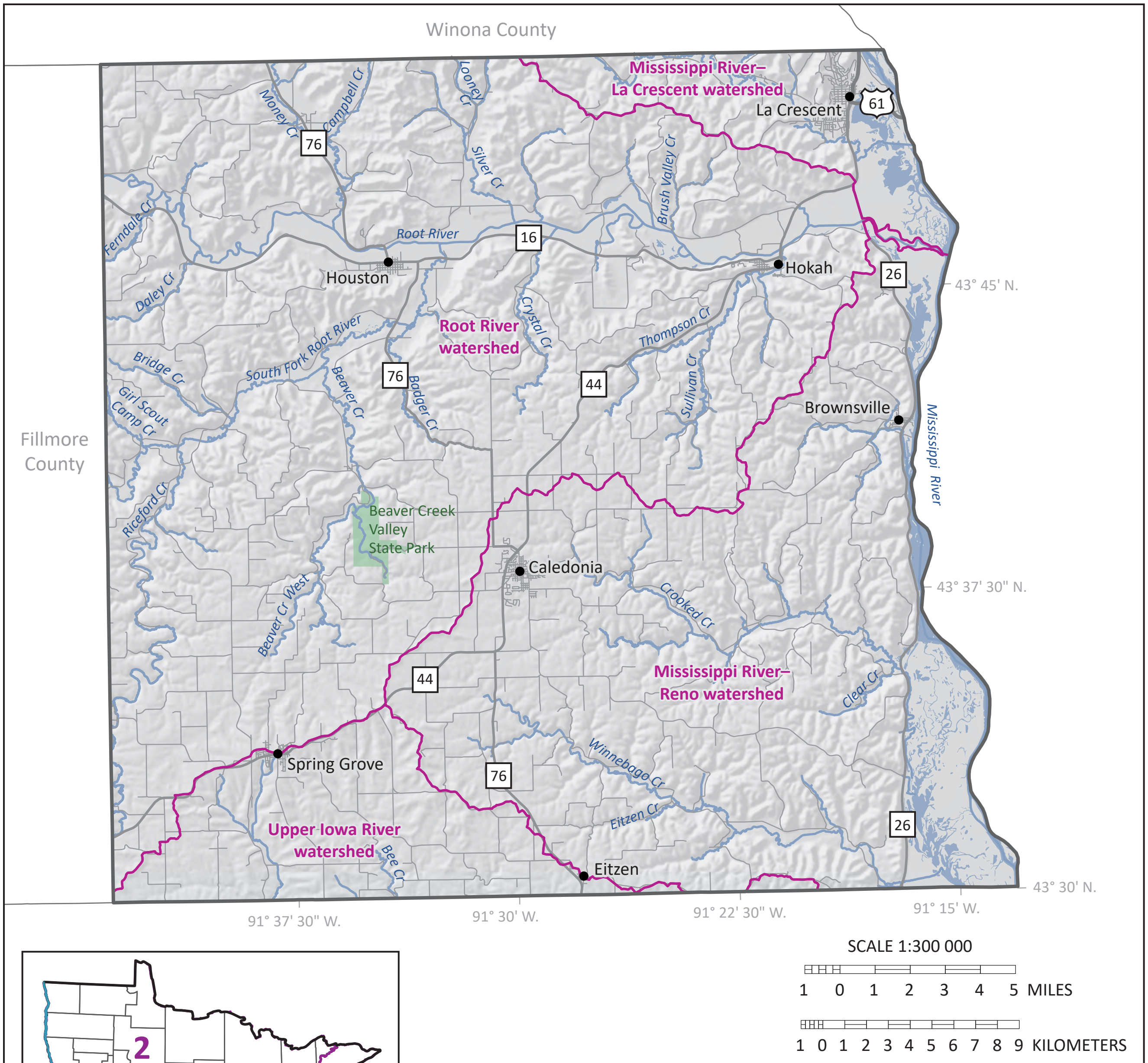
The Mississippi River forms the entire eastern border of the county, and the Root River prominently crosses the northern portion. Smaller streams flow in valleys east to the Mississippi, to the Root River, or south to the Iowa River.

The climate is humid continental with warm to hot summers, cold winters, and an annual temperature range typically greater than 110°F. Based on 1991 to 2020 climate normals, the June through August average temperature is 69.6°F (DNR, 2023a). The typical growing season is from April to October, when average monthly air temperatures are over 45°F (Figure 2). Evaporation increases dramatically during the growing season through plant uptake and transpiration, reducing the amount of precipitation that ultimately becomes groundwater. Winter temperatures are cold, with December through February averaging 20°F (DNR, 2023a). The soil frost depth can reach from 3 to more than 5 feet below ground, limiting precipitation that can infiltrate and become groundwater. Although diffuse recharge is limited in the winter, focused recharge to sinkholes and stream sinks can still occur.

Average annual precipitation is approximately 37 inches, placing Houston County at the high end of the statewide range of 21 to 38 inches (DNR, 2023b). The region has pronounced wet and dry seasons, with precipitation during the summer nearly four times greater than during the winter. Historically, most annual precipitation (approximately 23 inches) occurs from April to August (Figure 2). Only a small fraction of this eventually becomes groundwater because of evaporation, transpiration, and overland runoff to streams. Most groundwater recharge occurs in the spring, when snowmelt and precipitation infiltrate the land surface prior to the growing season.

From 1895 through 2023, average annual temperatures increased by 1.4°F, which is below the statewide average temperature increase of 3.1°F. The increases were fastest during winter, at night, and especially in the period since 1970, when daily minimum temperatures have risen nearly 70% faster than daily maximum temperatures, and average winter temperatures have risen three to four times faster than average summer temperatures.

Annual precipitation has increased by 6.2 inches since 1895, with virtually all of that change occurring since 1970. Houston County's precipitation has increased four times faster than the statewide average since 1970. Intense rainfall events producing daily totals in excess of 1, 2, and 3 inches have been more common since 1990 than during any other period on record.



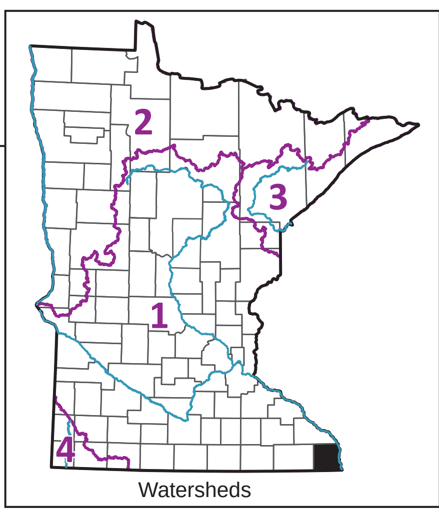


Figure 1. Houston County, Minnesota

Houston County is in southeastern Minnesota, within the surface watershed (labeled 1 on the statewide map) of the southeast-flowing Mississippi River. Statewide, additional surface watersheds are drained by networks of rivers that (2) flow north to the Red River basin, (3) east to the Great Lakes basin, or (4) southwest to the Missouri River basin.

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

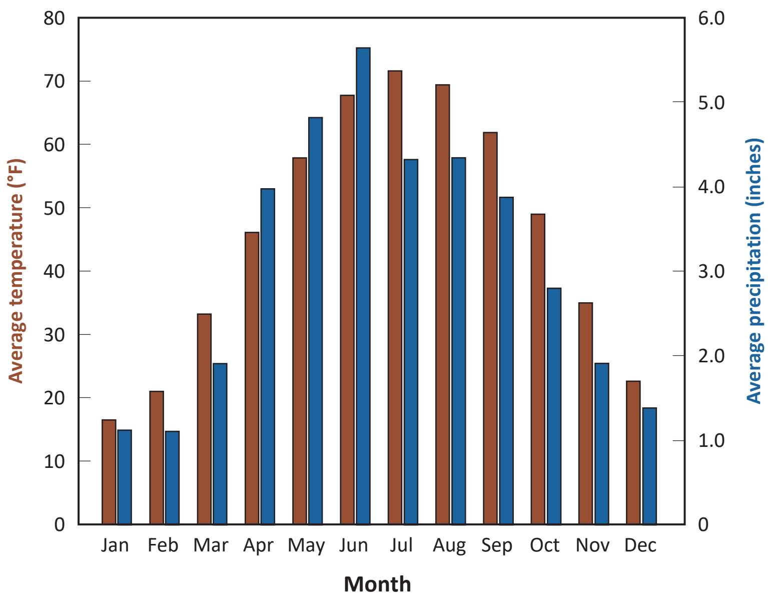


Figure 2. Average monthly temperature and precipitation for Houston County, Minnesota

Data from Minnesota Climate Trends (1991 to 2020, 30-year record; DNR, 2023a; DNR, 2023b).

Physical geology and hydrogeology

Bedrock dominates the geology of Houston County. It is generally within 50 feet of the land surface and covered by a veneer of unconsolidated sediment, such as loess, sand, and colluvium (Part A, Plates 3 and 4). Thick layers of saturated unconsolidated sediment generally only exist in valley bottoms, making bedrock aquifers the primary source of drinking water and groundwater discharge to springs and streams.

Bedrock aquifers and aquitards

In general, the bedrock geologic units in Houston County are composed of carbonate (limestone and dolostone), sandstone, or siltstone. The rock composition, presence of fractures, and degree of karstification ultimately govern whether they behave hydraulically as an aquifer or aquitard.

Aquifers are water-bearing, permeable rock from which groundwater can be extracted via a well. Many of the aquifers in the county also provide continual cold-water discharge to springs and streams. Aquitards are layers of material with low permeability, such as siltstone and shale, that impede the vertical movement of water. However, some aquitards contain high-permeability fractures and bedding plane openings that can yield large quantities of groundwater to springs or wells. For instance, many springs emerge from near the base of the St. Lawrence aquitard (Figure 3).

The depth from the land surface partially controls the ease with which an aquifer or aquitard transmits groundwater. Hydrologists can broadly describe hydrogeologic behavior using the relative terms of shallow bedrock conditions and deep bedrock conditions. The boundary between these conditions is not consistent throughout the state; it is estimated to be 50 feet below the bedrock surface in Houston County and most of southeastern Minnesota. Shallow bedrock conditions (the first 50 feet in the uppermost bedrock units) have a zone of enhanced permeability from fractures that developed when the bedrock was originally exposed and weathered at the land surface. As groundwater flows through these fractures, carbonic acid continues to slowly dissolve carbonate bedrock, which increases the aquifer's permeability over time through the progressive development of conduits and voids. The enhanced permeability zone can increase the ability of an aquifer to transmit water, but can also degrade the ability of aquitards to provide protection to underlying aquifers. In deep bedrock conditions, there is typically lower permeability, as there are fewer interconnected fractures and dissolution networks at deeper depths (Runkel and others, 2006; Barry and others, 2023b).

Geomorphology

The Spring Grove region of southwestern Houston County forms a plateau capped by the erosion-resistant limestone of the Cummingsville Formation (Part A, Plate 2). Underlying the Cummingsville is the Decorah Shale through the St. Peter Sandstone. This local sequence of rock overlies a prominent regional plateau, the Prairie du Chien Plateau, that is present over most of the county and extends to the edge of the Mississippi River Valley. These plateaus exist because of the erosion-resistant properties of carbonate.

Underlying the Prairie du Chien Group is a sequence of sedimentary bedrock layers that are more easily eroded. Numerous deeply incised valleys truncate the overlying Prairie du Chien Plateau, exposing the Jordan Sandstone, St. Lawrence Formation, Lone Rock Formation, Wonewoc Sandstone, and Eau Claire Formation. The Mt. Simon Sandstone is present as uppermost bedrock in the deepest parts of these valleys, but is not exposed at the land surface (Figure 3). These units predominantly consist of sandstones, siltstones, and shales and are exposed within the Root River valley and its tributaries, and also along and within narrow valleys of the Mississippi River. The deeply incised valleys have an influence on groundwater, as they penetrate both aquifers and aquitards.

Karst

Much of Houston County is covered by karst (Figure 4). The term karst is typically used to describe unique landforms and hydrology formed by precipitation and groundwater dissolving carbonate rock. In Minnesota, St. Peter Sandstone can also exhibit karst characteristics (DNR, 2016b; Broberg, 2015). Karst is often characterized on the surface by the presence of sinkholes, sinking streams, caves, and springs, but where these features are absent, there can still be rapid connections between the land surface and underlying aquifers. Rapid water movement can also occur within the county's carbonate aquifers because they have been subjected to karst dissolution in the past (Alexander and others, 2013).

In karst areas, there is a close relationship between the land surface and the bedrock below. Connections to enlarged underground pathways allow for rapid transport of water, creating unpredictable groundwater travel times and flow directions. This makes karst aquifers particularly vulnerable to human activities and complicates remediation efforts for issues like spills or surface applications of chemicals. Classification of the karst landscape helps identify the groundwater characteristics beneath it. A companion report identifies these landscapes through analysis of karst feature position, geologic setting, and landscape position: *Karst Landscape Units of Houston and Winona Counties* (Green and Barry, 2021).

In Houston County, over 98% of mapped sinkholes and stream sinks occur where there is 50 feet or less of unconsolidated sediment overlying bedrock (Figure 5), which is consistent with other areas of karst in southeastern Minnesota (Alexander and Maki, 1988). Sinkhole and sinking stream locations are from the Karst Feature Inventory (DNR, 2020a); depth to bedrock GIS files are from Part A, Plate 4. Approximately 82% of the mapped sinkholes and stream sinks in Houston County occur where the Prairie du Chien Group is the first bedrock unit below the land surface (bedrock geology GIS files from Part A, Plate 2).

The Prairie du Chien Group contains fracture networks and solution-enhanced conduits. It is one of four prominent karst systems described for southeastern Minnesota (Runkel and others, 2003, 2014a). Much of the karstification occurred roughly 460 to 490 million years ago when the tops of the Shakopee Formation and Oneota Dolomite were at the land surface over different periods and were subjected to chemical weathering (Alexander and others, 2013). These weathered formations were subsequently buried by younger rocks and are referred to as paleokarst.

A significant zone of high permeability is found regionally throughout southeastern Minnesota at the contact of the Shakopee and Oneota formations and is a result of karstification of the Oneota Dolomite (Dalgleish and Alexander, 1984; Runkel and others, 2003; Tipping and others, 2006). Sinkhole frequency is greatest near this geological contact, but is also elevated near the contact of the St. Peter Sandstone and Shakopee Formation (Figure 3). There have been at least four catastrophic failures of sewage treatment ponds in neighboring counties in southeastern Minnesota where this zone of high permeability is close to the land surface, including failures in the cities of Altura, Lewiston, and Bellechester (Book and Alexander, 1984; Jannik and others, 1991; Alexander and others, 1993; Runkel and others, 2003; Alexander and others, 2013). Additional collapses of stormwater ponds and water retention structures have occurred where pond bottoms were close to the St. Peter Sandstone and Shakopee Formation contact (Barr and Alexander, 2012; E.C. Alexander Jr., University of Minnesota Department of Earth and Environmental Sciences, personal communication, 2018).

In incised valleys, rapid groundwater flow has been documented through siliciclastic units: sandstone, siltstone, and shale (Green and others, 2008, 2012; Barry and others, 2015). These units are classified as pseudokarst because they mimic the rapid groundwater flow of karst but were formed by processes other than dissolution (Barry and others, 2018). At these locations, surface water in valley streams frequently sinks underground and rapidly resurges at springs located farther down the valley (DNR, 2020c).

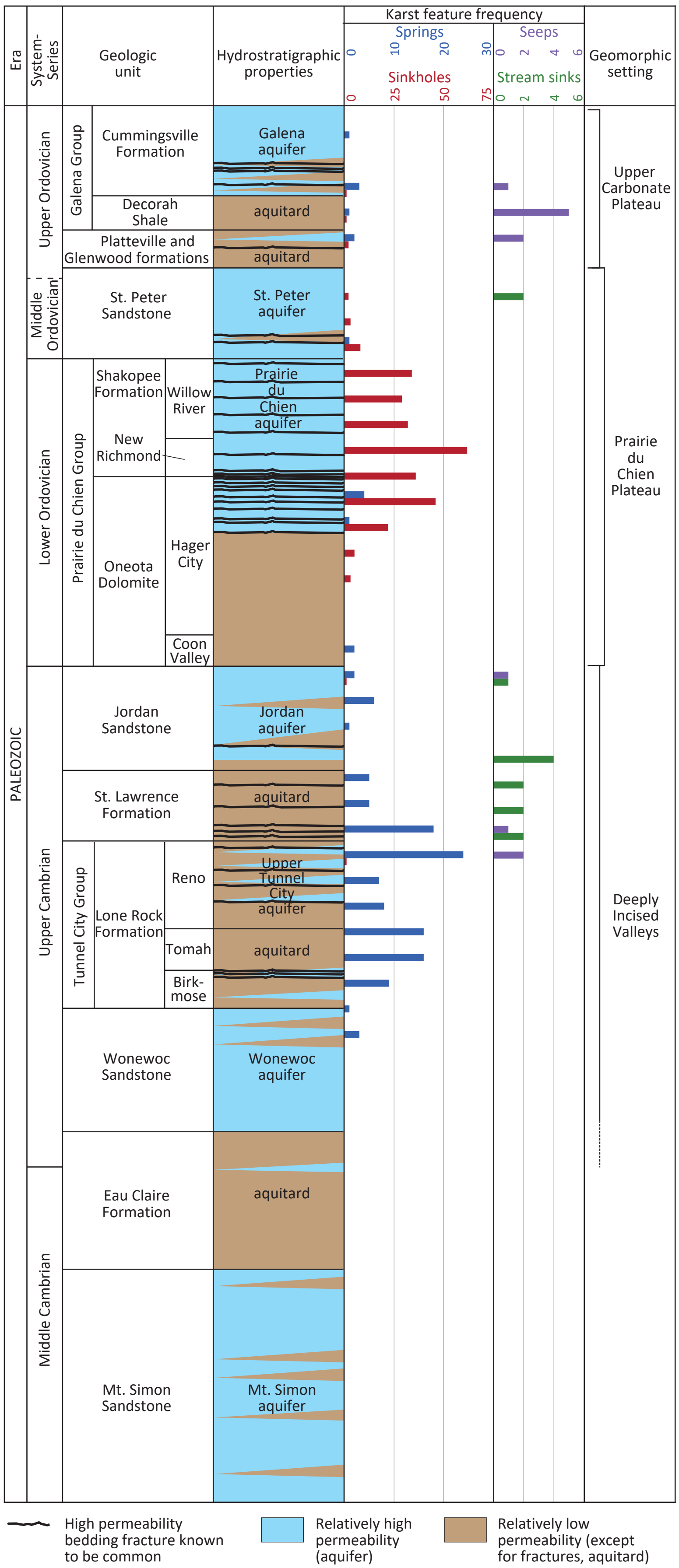


Figure 3. Bedrock stratigraphy, hydrostratigraphy, approximate distribution of karst features, and geomorphic setting

Geologic stratigraphic units (formations or groups) do not always correspond to hydrogeologic units (aquifers and aquitards). The distribution of sinkholes, stream sinks, springs, and seeps is partially controlled by bedrock stratigraphy, hydrostratigraphy, and geologic structure. Karst distribution frequency was estimated using modified techniques from Tipping and others, 2001, and Steenberg and others, 2014. Column modified from Part A, Plate 2, Figure 1.

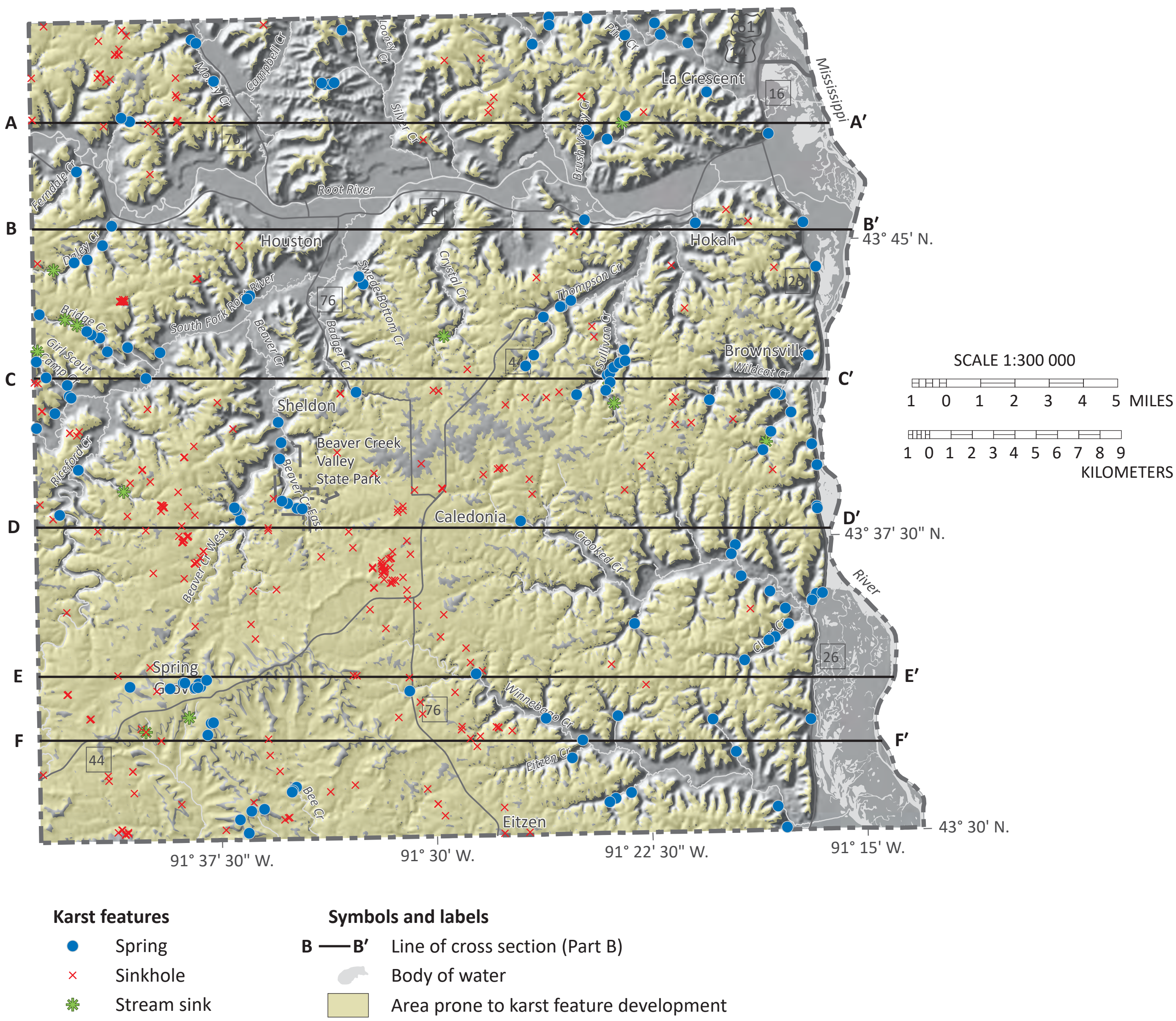


Figure 4. Area prone to karst feature development and distribution of karst features

The area prone to karst feature development is shown draped on a hillshade model of the county landform. The area was created by identifying regions with less than 50 feet of sediment underlain by carbonate bedrock, as described in DNR, 2016b. Most of the area prone to karst feature development occurs in upland settings. Sinkholes primarily occur on the plateaus, while springs and stream sinks occur within valleys. Sinkholes and stream sink locations are from the Karst Feature Inventory (DNR, 2020a). Spring locations are from the Minnesota Spring Inventory (DNR, 2020b).

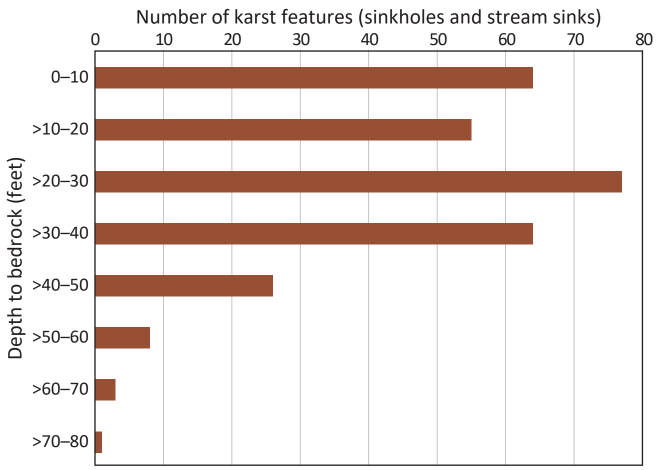


Figure 5. Sinkhole and stream sink occurrence versus depth to bedrock

Over 98% of mapped sinkholes and stream sinks occur where there is 50 feet or less of unconsolidated sediment overlying bedrock. Data used to generate this figure are from the Karst Feature Inventory (DNR, 2020a) and Depth to bedrock GIS files from Part A, Plate 4.

Surficial aquifers

The bedrock plateaus across much of Houston County are capped by surficial unconsolidated geologic deposits that are generally less than 25 feet thick and covered by a veneer of loess that generally thins eastward (Part A, Plate 3). The sediment in these uplands is generally not fully saturated and cannot provide sufficient quantities of water to supply a user economically.

Coarse-grained terrace deposits occur along the modern-day Mississippi River and within the main valley of the Root River and smaller tributaries (Part A, Plate 3). Where saturated, this coarse-grained sediment makes up the surficial sand and gravel aquifer (Figure 6).

The texture of surficial deposits influences the rate and amount of precipitation that infiltrates the surface and eventually becomes groundwater (DNR, 2016a). A detailed explanation of the county's glacial history and how it relates to present-day surficial geologic deposits is presented in Part A, Plate 3.

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

Geologic units

The following section describes the distribution and hydrologic properties of the bedrock aquifers and aquitards in the county. The units are described from the top down to match the stratigraphic column (Figure 3). Units are grouped into three geomorphic settings: Upper Carbonate Plateau, Prairie du Chien Plateau, and deeply incised valleys.

Much of the hydrologic descriptions come from Runkel and others, 2003. Detailed lithologic descriptions of each unit are available in Part A, Plate 2. Mapped karst features are shown in Figure 4, totaling 146 springs, 286 sinkholes, and 12 stream sinks. These numbers represent lower limits of potential karst features because mapping is incomplete, and sinkholes develop and are filled regularly.

Upper Carbonate Plateau

- **Cummingsville Formation (aquifer)**

  The Cummingsville is a carbonate formation that commonly forms a karst aquifer in southeastern Minnesota. In Houston County, it is only present in the southwest near Spring Grove. The aquifer is not used for water wells because it is near the land surface and has a limited extent.

  Laterally continuous shale beds in the lower Cummingsville can act as an aquitard and cause groundwater to emerge as small springs and seeps. Mapped karst features include 8 springs and 1 sinkhole.

- **Decorah Shale (aquitard)**

  The Decorah Shale serves as a regional aquitard across much of southeastern Minnesota, but it is only present in Houston County in the southwest near Spring Grove. It is primarily composed of shale that restricts the downward movement of water.

  Mapped karst features include 5 springs. Seeps are common, but not all are mapped.

- **Platteville and Glenwood formations (aquitards)**

  The Platteville and Glenwood are present in southwestern Houston County in the Spring Grove area. The Platteville is presented as an aquitard, but internal layers can be connected vertically and exhibit a secondary porosity from fractures and karst dissolution.

  The Glenwood shale exhibits low hydraulic conductivity in shallow bedrock conditions, creating numerous groundwater seeps that frequently occur near the top of the Glenwood. It generally behaves as an aquitard, but it can be thin with vertical fractures that can connect the overlying Platteville Formation to the underlying St. Peter Sandstone.

  Mapped karst features include 2 springs and 3 sinkholes.

Prairie du Chien Plateau

- **St. Peter Sandstone (aquifer)**

  The St. Peter is primarily composed of medium to coarse sandstone across much of southeastern Minnesota, but extensive fine-grained beds may be found at its base. This aquifer is present in southwestern Houston County near Spring Grove. Although several characteristics make it a good aquifer, it contains few wells because it is near the land surface and limited in saturated areal extent.

  The St. Peter commonly contains voids and fractures in shallow bedrock settings; for this reason, it is included as an area prone to karst feature development (Figure 4). Voids are relatively common in the Rochester area of nearby Olmsted County, where they have periodically required remediation using geoengineered solutions (Broberg, 2015; E.C. Alexander Jr., University of Minnesota Department of Earth and Environmental Sciences, personal communication, 2018).

  Mapped karst features include 1 spring, 37 sinkholes, and 2 stream sinks. Many of the sinkholes appear at the bottom of slopes or near the contact with the underlying Shakopee Formation of the Prairie du Chien Group.

- **Prairie du Chien Group (aquifer/aquitard)**

  The Prairie du Chien forms an extensive and prominent plateau across the county. It is composed of two formations, the upper Shakopee Formation and the lower Oneota Dolomite (Figure 3). Although this group is primarily composed of carbonate rock, the lower portions of both formations have coarse sandstone components referred to as the New Richmond Member and the Coon Valley Member, respectively. The New Richmond Member is regionally distributed as a substantially thick sandstone interval with high intergranular permeability. Karst horizons exist at the top of the Shakopee Formation and near the contact of the Shakopee and Oneota formations (Alexander and others, 2013). Both the Shakopee and Oneota are highly fractured under shallow bedrock conditions, allowing for rapid groundwater transport through fractures and voids.

  Dye-trace investigations in the Prairie du Chien in nearby Olmsted County determined a horizontal groundwater velocity of 800 feet per day (Alexander and others, 1991). Dye traces in nearby Fillmore County found shallow horizontal velocities ranging from approximately 1 to 10 miles per day (Wheeler, 2017; Barry and others, 2023a). The Prairie du Chien has low vertical permeability, with horizontal permeability as much as 10 times greater.

  Rapid vertical migration of water is limited in deep bedrock conditions in the Prairie du Chien, where the lower part of the Oneota behaves as an aquitard. Despite this, sufficient water can be extracted for low-yield uses, such as residential wells.

  Mapped karst features include 8 springs in the Oneota, 115 sinkholes in the Shakopee, and 130 in the Oneota. Sinkholes prominently occur near the geologic contact between the Shakopee and Oneota (Figure 3).

Deeply incised valleys

- **Jordan Sandstone (aquifer)**

  The Jordan is a regional aquifer across much of southeastern Minnesota. The upper portion is primarily composed of coarse sandstone, making it a productive aquifer. The lower portion is finer grained but can yield productive wells because bedding fractures are common. Fine grained layers in the lower portion can serve as internal aquitards that isolate old water. Fractures in shallow bedrock conditions are particularly abundant and can allow surface waters in valley settings to rapidly sink into the aquifer.

  Mapped karst features include 6 springs and 2 stream sinks.

- **St. Lawrence Formation (aquitard)**

  The St. Lawrence is an important aquitard in southeastern Minnesota. In deep bedrock conditions, it is a competent and regionally significant aquitard. It is primarily composed of very fine-grained sandstone and siltstone in its upper part and carbonate rock in its lower part. The unit has low vertical permeability, which restricts downward flow.

The Minnesota Well Rule handbook specifically states that “a stratum at least 10 feet in vertical thickness of the St. Lawrence” is a confining layer (MDH, 2011). However, the aquitard loses its protective characteristics in shallow bedrock conditions or where it is dissected by deeply incised valleys. In these settings, water can flow rapidly through the St. Lawrence, both vertically and horizontally. Vertical hydraulic conductivity increases with fractures near bedrock valleys (Runkel and others, 2014b, 2018). Dye tracing in St. Lawrence pseudokarst in Winona and Houston counties has revealed groundwater velocities of 150 to 890 feet per day (Green and others, 2008; Barry and others, 2018).

Mapped karst features include 12 springs and 6 stream sinks.

- **Tunnel City Group–Lone Rock Formation (aquifer/aquitard)**

  The Lone Rock is an important regional aquifer in southeastern Minnesota. It was formerly known as the Franconia Formation but was renamed to be consistent with the nomenclature used in surrounding states (Mossler, 2008). Many older well logs and reports still use the Franconia nomenclature.

  The Lone Rock is primarily composed of very fine-grained sandstone and siltstone in its upper portion, with progressively increasing carbonate rock in its lower portion. The lower portion also has very fine-grained sandstone, siltstone, and shale (Tomah Member), which limits the vertical hydraulic conductivity (Runkel and others, 2006). The Lone Rock can be highly fractured in shallow bedrock conditions. Dye tracing in Lone Rock pseudokarst has revealed groundwater velocities of tens to hundreds of feet per day (Barry and others, 2015, 2018). Groundwater freely moves laterally through the upper Lone Rock. It contains the highest number of springs, many of which form the headwaters of trout streams.

  Mapped karst features include 81 springs and 2 stream sinks.

- **Wonewoc Sandstone (aquifer)**

  The Wonewoc is a regional aquifer across much of southeastern Minnesota and is present across all of Houston County. This sandstone-rich aquifer system was formerly known as the Ironton and Galesville formations. These two formations were combined and renamed to Wonewoc to be consistent with the nomenclature used in surrounding states (Mossler, 2008). Groundwater flow is primarily intragranular, although fracture flow has been documented in both shallow and deep bedrock conditions (A. Runkel, Minnesota Geological Survey, personal communication, 2018). Although primarily composed of sandstone, the upper half also contains silt and shale with lower permeability.

  Mapped karst features include 22 springs.

- **Eau Claire Formation (aquitard)**

  The Eau Claire is an important regional aquitard in southeastern Minnesota. It is primarily composed of shale and siltstone, which limit vertical flow. In Winona, Houston, and Wabasha counties, it contains very fine sandstone in the upper portion that can be used for water supply.

  Mapped karst features include 1 spring.

- **Mt. Simon Sandstone (aquifer)**

  The Mt. Simon is an important regional aquifer in southeastern Minnesota. It can be broadly described in two parts. The upper portion consists of stacked layers of coarse-grained sandstone and fine-grained siltstone with differing permeabilities. The lower portion is primarily coarse-grained sandstone with relatively higher permeability. The aquifer is primarily used in the Root River valley and in eastern portions of the county, where its depth is shallower than in other areas of the county. The Mt. Simon aquifer is used for municipal and public water supply in the cities of Houston, Hokah, and La Crescent.

  No mapped karst features.

Groundwater flow

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

1. The water-table map illustrates the shallowest groundwater, where groundwater is unconfined and at equilibrium with atmospheric pressure. The water table flows from higher to lower elevations.
2. Potentiometric surface maps illustrate groundwater flow in confined aquifers where hydrostatic pressure exceeds atmospheric pressure. Confined groundwater flows from higher to lower pressure.

Water table

The water table (Figure 6) is the surface between the unsaturated and saturated zones, where water pressure equals atmospheric pressure. Water-table elevations are contoured similarly to land-surface elevations on a topographic map. In Houston County, the water table occurs in both the surficial sand aquifer present in valley bottoms and in multiple bedrock aquifers that are under unconfined conditions. Although it is shown in the figure as a static surface, it fluctuates over time.

The water table in the uplands and plateaus is influenced by karst and is best represented by the groundwater elevation contours of unconfined portions of the Prairie du Chien and Jordan aquifers (Figures 7, 8, and 9).

Figure 6 provides 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 was estimated from several sources of data.

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

[*]Data were converted to elevations using a digital elevation model derived from Light Detection and Ranging (LiDAR) technology. More details can be found in *Methods for estimating water table elevation and depth to water table* (DNR, 2016a).

Potentiometric surface

In confined aquifers, hydrostatic pressure greater than atmospheric pressure causes the water level in a tightly cased well to rise above the top of the aquifer. These water-level elevations are measured, mapped, and contoured to create potentiometric surface maps similar to how topographic maps show land-surface elevations. Potentiometric surface maps show the direction of groundwater flow.

The potentiometric surface of an aquifer represents the potential energy that is available to move groundwater. As groundwater moves from higher to lower potentiometric elevations, it flows perpendicular to the potentiometric elevation contours. Flow directions are shown on the maps with arrows.

Groundwater flows from recharge areas to discharge locations within a wide continuum of depth, distance, and time. Flow into, through, and out of shallow aquifers can take hours to years to travel distances of up to a mile. Flow in deeper aquifers can take centuries to millennia to travel dozens of miles. High elevation areas of the potentiometric surface can indicate important recharge areas. River valleys are typical examples of low-elevation groundwater discharge areas.

Potentiometric surface maps were created using confined aquifer static water-level data from the CWI, measurements made by DNR staff, and surface water elevation points along major rivers and streams where perennial groundwater discharge is likely. The CWI records represent groundwater conditions collected under various climatic and seasonal conditions spanning more than eight decades. This data variability creates some uncertainty in potentiometric surface elevations.

The hydrology of Houston County is heavily influenced by surface topography and enhanced permeability in karst and pseudokarst. Groundwater elevations of the deepest aquifers are subdued replicas of surface topography, evident in the contour spacing of the potentiometric surface maps (Figures 10, 11, and 12).

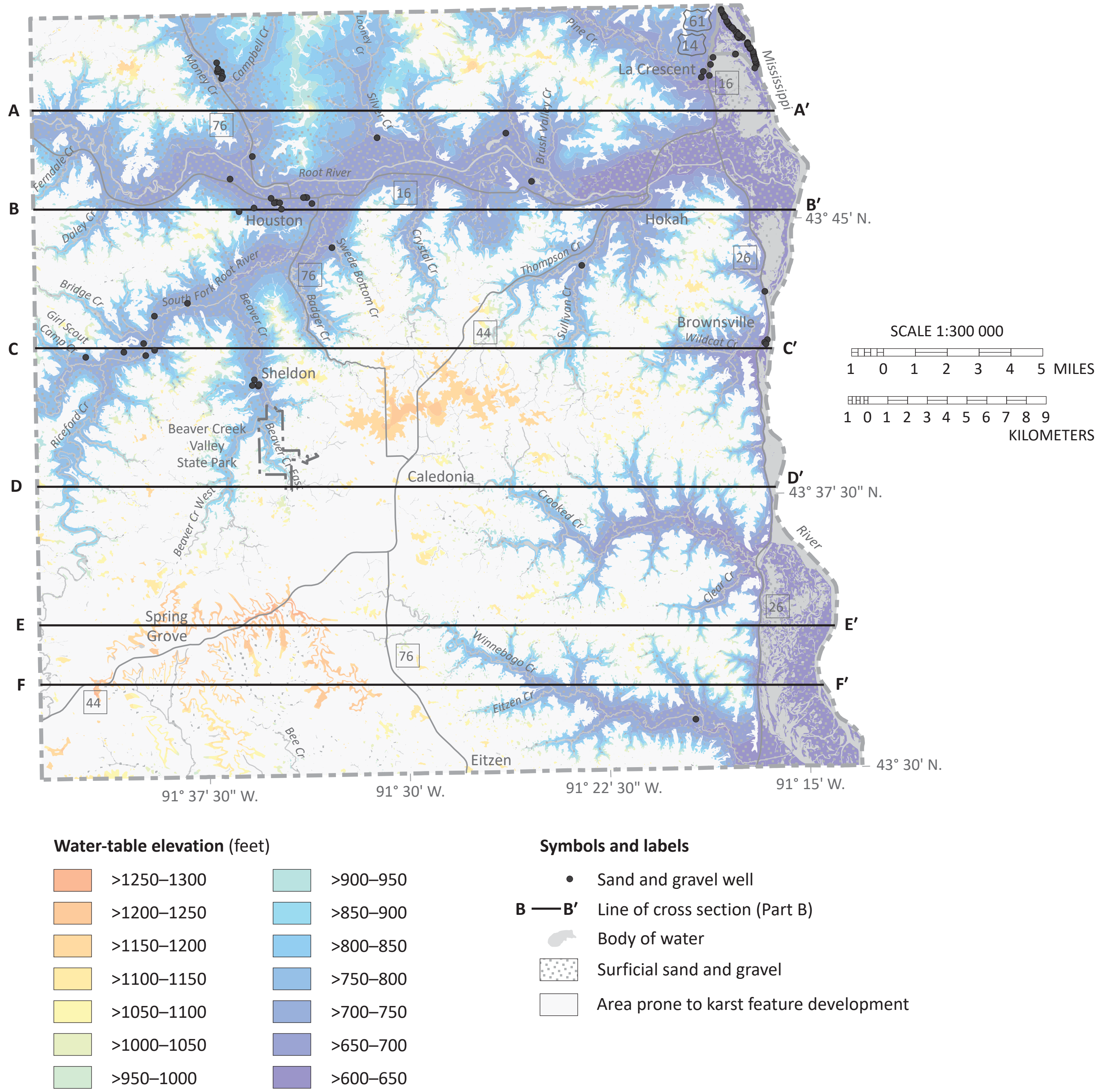


Figure 6. Water-table elevation and sand and gravel wells

Water-table elevation is poorly defined in the areas prone to karst feature development. Within the karst area, the water table often exceeds 100 feet deep and is best approximated by the groundwater elevation of the Prairie du Chien and Jordan aquifers. In valley bottoms and along the Mississippi River, the water table is estimated from wells completed in the surficial sand aquifer, the elevation of surface waters, and soil moisture. Soil moisture in unconsolidated deposits suggests there is a perched water table in the central area of the county near Caledonia and that perched water conditions may exist sporadically in other areas as well. Water-table flow is generally toward the Root River and its tributaries in the north and northwest, and the Mississippi River Valley and tributaries in the east.

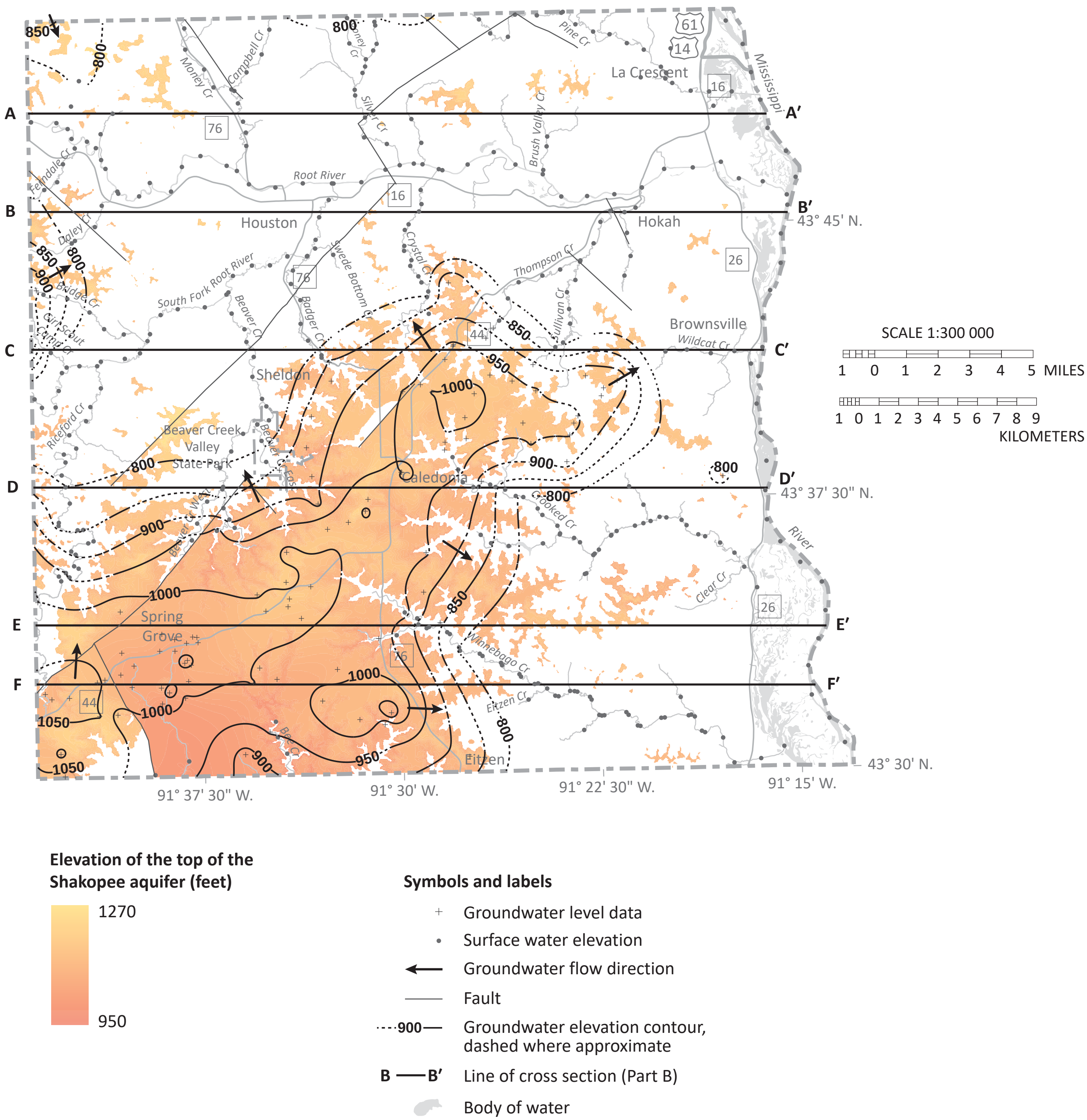


Figure 7. Water-table elevation contours of the Shakopee aquifer

Due to sparse data, groundwater elevation contours were developed using combined Shakopee, Oneota, and Jordan aquifer wells. In large areas of the county, the Prairie du Chien and Jordan aquifers are unconfined and make up the water-table system. Groundwater flow is generally toward the Root River and its tributaries in the north and northwest, and toward the Mississippi River Valley and its tributaries in the east. Potentiometric surfaces do not extend outside the area of the aquifer but are shown as dashed contours to assist in conveying groundwater flow directions. Top of aquifer elevations are from Part A, Plate 4, GIS files.

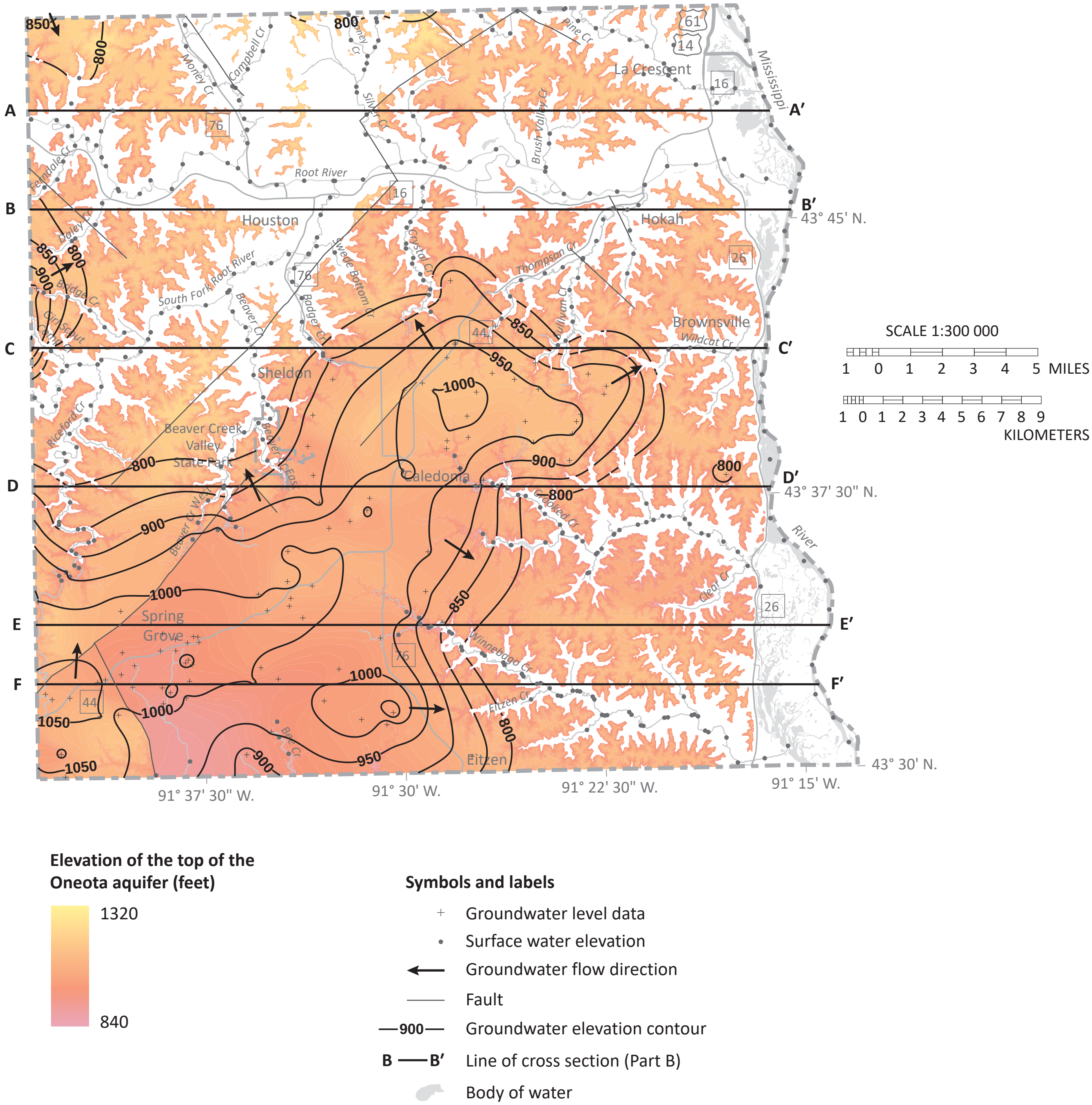
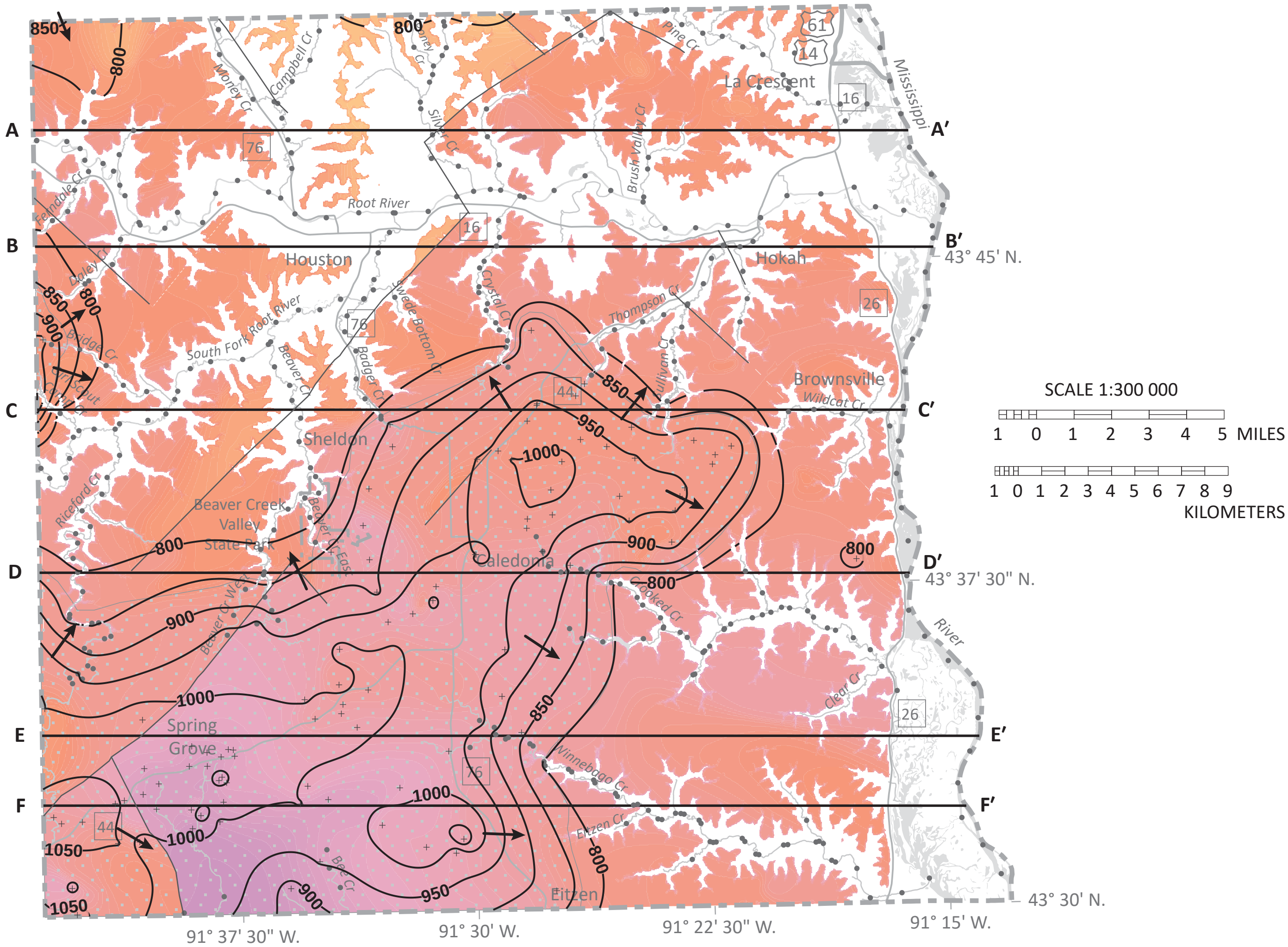


Figure 8. Water-table elevation contours of the Oneota aquifer

Due to sparse data, contours were developed using combined Shakopee, Oneota, and Jordan aquifer wells. In large areas of the county, the Prairie du Chien and Jordan aquifers are unconfined and make up the water-table system. On a regional scale, the Oneota Formation has characteristics of an aquitard, but at a local scale, it can frequently supply sufficient water for residential well use. Groundwater flow is generally toward the Root River and its tributaries in the north and northwest, and toward the Mississippi River Valley and its tributaries in the east. Top of aquifer elevations are from Part A, Plate 4, GIS files.



Elevation of the top of the Jordan aquifer (feet)

1170

720

Symbols and labels

- Groundwater level data
- Surface water elevation
- Groundwater flow direction
- Fault
- 900 Groundwater elevation contour
- B —— B′ Line of cross section (Part B)
- Confined portion of aquifer (no pattern indicates unconfined portion)
- Body of water

Figure 9. Water-table elevation and potentiometric surface contours of the Jordan aquifer

Due to sparse data, contours were developed using combined Shakopee, Oneota, and Jordan aquifer wells. Confined areas of the Jordan are indicated with a stippled pattern representing the potentiometric surface. Unconfined areas of the aquifer are indicated with no pattern and represent the water-table system. Groundwater flow is generally toward the Root River and its tributaries in the north and northwest, and toward the Mississippi River Valley and its tributaries in the east. Top of aquifer elevations are from Part A, Plate 4, GIS files.

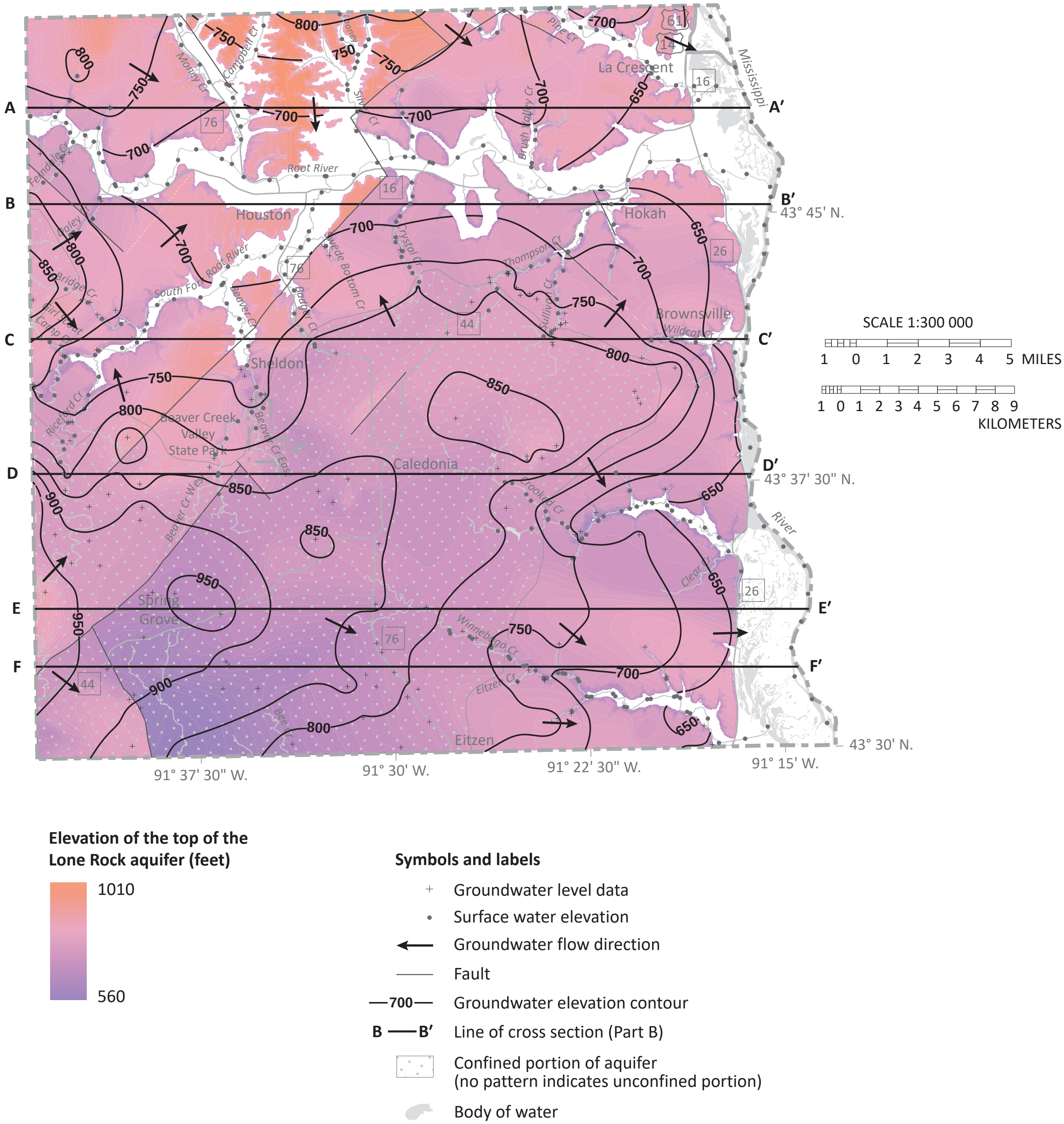


Figure 10. Potentiometric surface contours of the Lone Rock aquifer

The Lone Rock aquifer is confined over the south-central portion of the county, indicated with a stippled pattern. Unconfined areas are indicated with no pattern. Groundwater flow is generally toward the Root River and its tributaries in the north and northwest, and toward the Mississippi River Valley and its tributaries in the east. Top of aquifer elevations are from Part A, Plate 4, GIS files.

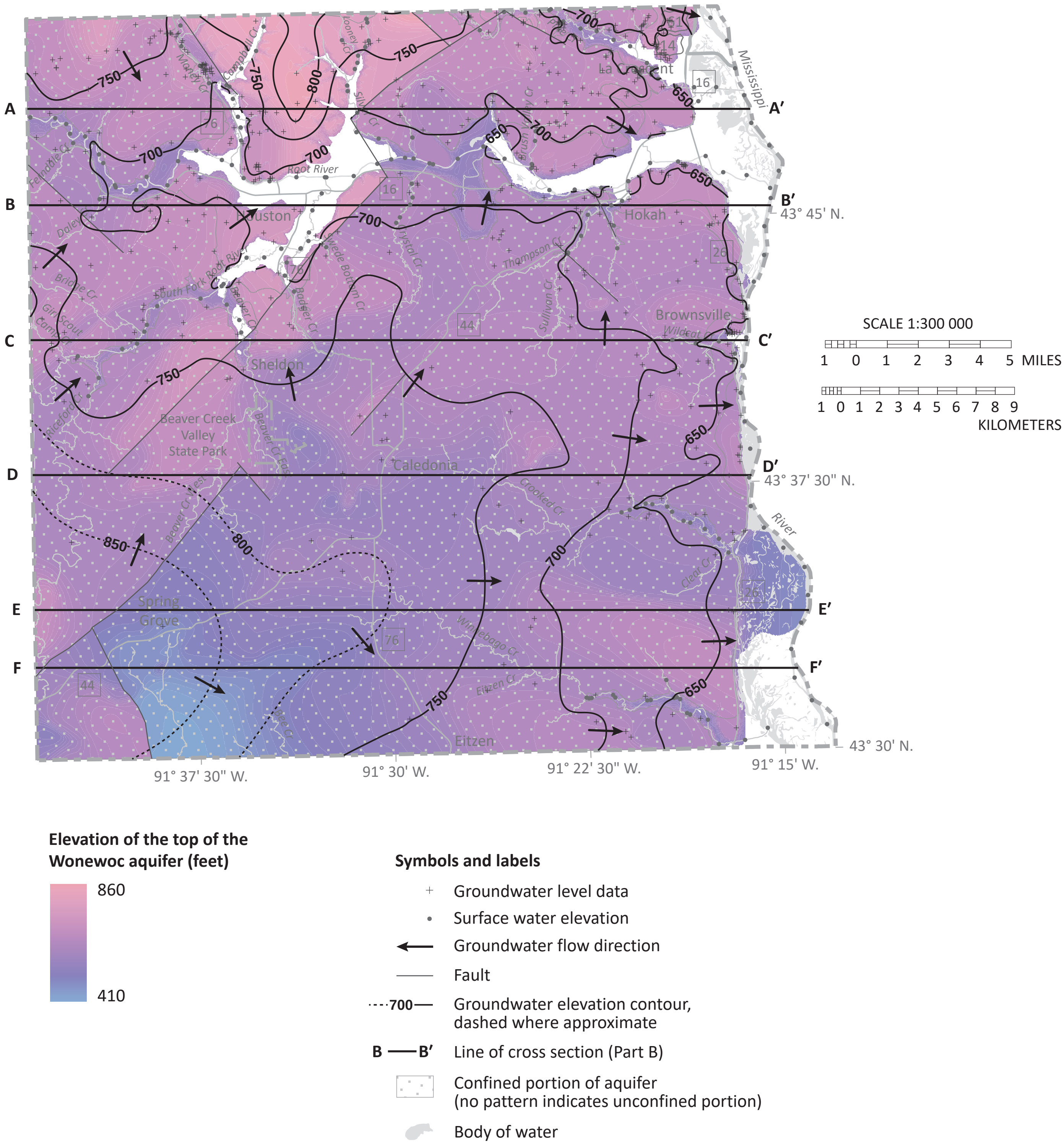


Figure 11. Potentiometric surface contours of the Wonewoc aquifer

The Wonewoc aquifer is confined over most of the county, indicated with a stippled pattern. Unconfined areas are indicated with no pattern. Few wells are completed in the aquifer in the southwestern portions of the county. Dashed lines show areas of the aquifer where potentiometric surface contours are poorly constrained. Groundwater flow is generally toward the Root River and its tributaries in the north and northwest, and toward the Mississippi River Valley and its tributaries in the east. Top of aquifer elevations are from Part A, Plate 4, GIS files.

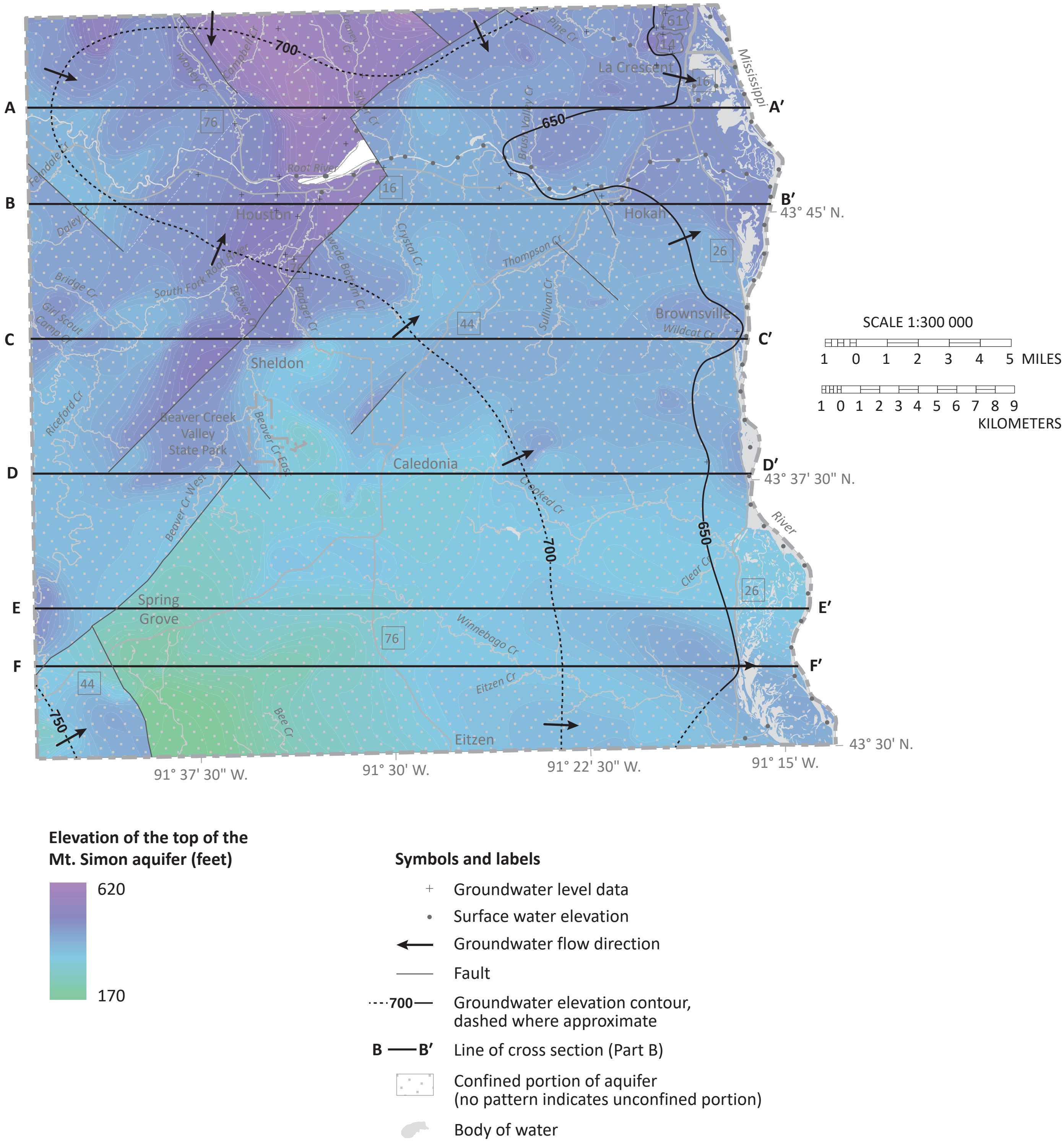


Figure 12. Potentiometric surface contours of the Mt. Simon aquifer

The Mt. Simon aquifer is confined over most of the county, indicated by a stippled pattern. Unconfined portions exist within the Mississippi River Valley where overlying strata have been eroded away, indicated with no pattern. Well data in the central and western portions of the county are limited. Dashed lines indicate areas of the aquifer where elevation contours are poorly constrained. Dashed contours are from a regional dataset developed by the MDH (J. Blum, MDH, written communication, 2014). Groundwater flow is generally toward the Root River and its tributaries in the north and northwest and toward the Mississippi River Valley and its tributaries in the east. Top of aquifer elevations are from Part A, Plate 4, GIS files.

Water chemistry (Plate 5)

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

- Groundwater **recharge** from surface water can be identified from the effect of evaporation on the isotopes of hydrogen and oxygen.
- Groundwater **residence time** is estimated from tritium and carbon-14 isotopes. Tritium is used to identify water that moved into the subsurface since the 1950s. Carbon-14 is used to determine groundwater residence times of centuries to millennia.
- The distribution of select chemicals can indicate areas of high pollution sensitivity or where groundwater consumption is a potential concern to human health.

Water sampling

Samples were collected from wells in aquifers most frequently used for domestic water supply and from springs that supply perennial flow to many of the county's cold-water trout streams. Wells were selected based on their aquifer characteristics and distribution. Samples were collected according to the protocols outlined in Appendix A. Chemical data from well and spring samples were used along with physical measurements (temperature, specific conductivity, dissolved oxygen, etc.) to understand water movement.

An ideal well-sampling network is evenly distributed across the county, includes populated areas, targets surface-water and groundwater interaction, and contains wells constructed to meet MDH standards with construction documentation. The final network sampled for an atlas depends on the willingness of citizens to participate. Approximately 1,000 well owners were contacted for permission to sample, and approximately 90 were selected for groundwater sampling. Eighty percent of the wells sampled by the DNR had adequate construction documentation (grouting, depth, open hole length, etc.). The remaining 20% lacked construction information and were spread across the aquifers sampled.

For this atlas, the DNR collected 87 well, 26 spring, and 3 river samples. These data were combined with 6 historic well samples for carbon-14 residence time investigations, 27 well samples collected by the MDH, 8 historic or special project spring samples, and 1 spring sample collected by the Minnesota Department of Agriculture (MDA). Data from the MDH are from two separate sources: the Minnesota Drinking Water Information System, a compliance-monitoring database that emphasizes treated water; and the Water Chemistry Database, a nonregulatory investigatory chemistry database.

Groundwater recharge pathways

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

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

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

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

Definition of delta (δ)

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

- 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).

Recharge results

County results were compared to the global meteoric water line (GMWL), which was developed from precipitation data from around the world (Craig, 1961). Groundwater samples plot parallel to the GMWL (Figure 13), indicating that most groundwater is recharged by precipitation directly infiltrating into the subsurface, consistent with groundwater recharge in karst and the lack of lakes and wetlands in southeastern Minnesota. Groundwater samples that plot above the GMWL differ from samples from many other counties in Minnesota sampled by the Groundwater Atlas Program, where samples plot along and on either side of the GMWL. However, groundwater samples plotting above the GMWL is common for southeastern Minnesota and was also observed in Winona, Olmsted, and Dodge counties (Barry, 2021; Barry, in preparation; Bradt and Barry, 2024).

The y-intercept value of +10 in the GMWL equation ($\delta^2H = 8.0\ \delta^{18}O + 10.0$) is called the deuterium excess value. The median deuterium excess for groundwater in Houston County is +12.7. The deuterium excess values found in southeastern Minnesota are consistent with deuterium excess values shown in Figure 9 of Kendall and Coplen (2001) and may be an indication that more evaporated moisture is contributing to air masses sourcing precipitation in this part of the state.

Houston County groundwater samples mostly fall above the meteoric water line; two samples trend along an evaporation line (Figure 13). Partial evaporative signatures are from a water-table well and a buried sand aquifer well east of the city of La Crescent (Figure 14). The source of evaporative water to the wells is uncertain but may be Blue Lake, the open water wetlands that are to the west and upgradient of the wells, or the Mississippi River (Figure 14 inset).

Two surface-water samples, collected from the Root River, plot along the deuterium excess line, consistent with a karstic watershed with no lakes and limited open water wetlands (limited surface waters subjected to significant fractionation) (Figure 13). The third surface-water sample, collected from the Mississippi River, shows minor evidence of fractionation, likely from the many opportunities for fractionation in the lakes and wetlands that contribute to the Mississippi River upstream of Houston County.

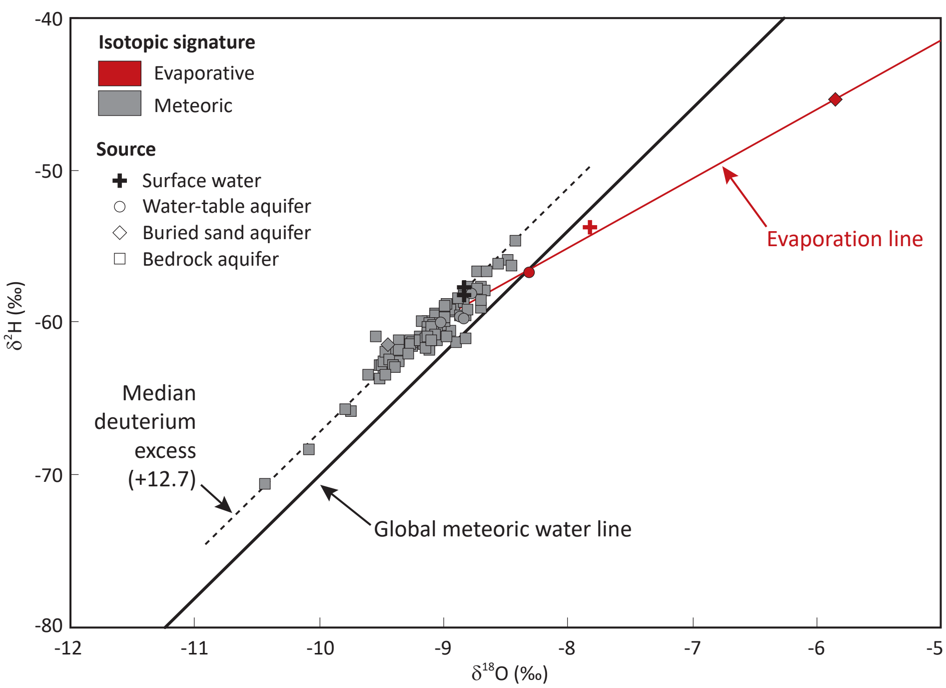


Figure 13. Stable isotope values from water samples

The meteoric water line represents precipitation values from direct infiltration. The GMWL was developed using precipitation samples from around the world and is described by the following equation: $\delta^2H = 8.0\ \delta^{18}O + 10.0$ (Craig, 1961). Most samples in Houston County have deuterium excess and plot above the GMWL, consistent with deuterium excess values found elsewhere in southeastern Minnesota.

The evaporation line represents groundwater recharge that came partially from surface-water sources. Since there aren't lake samples available for Houston County, the evaporation line is from a regression of the two evaporative signature trend well samples and is described by the following equation: $\delta^2H = 4.5\ \delta^{18}O - 18.8$. Two groundwater samples showed evidence of evaporative signatures and are shown as red symbols.

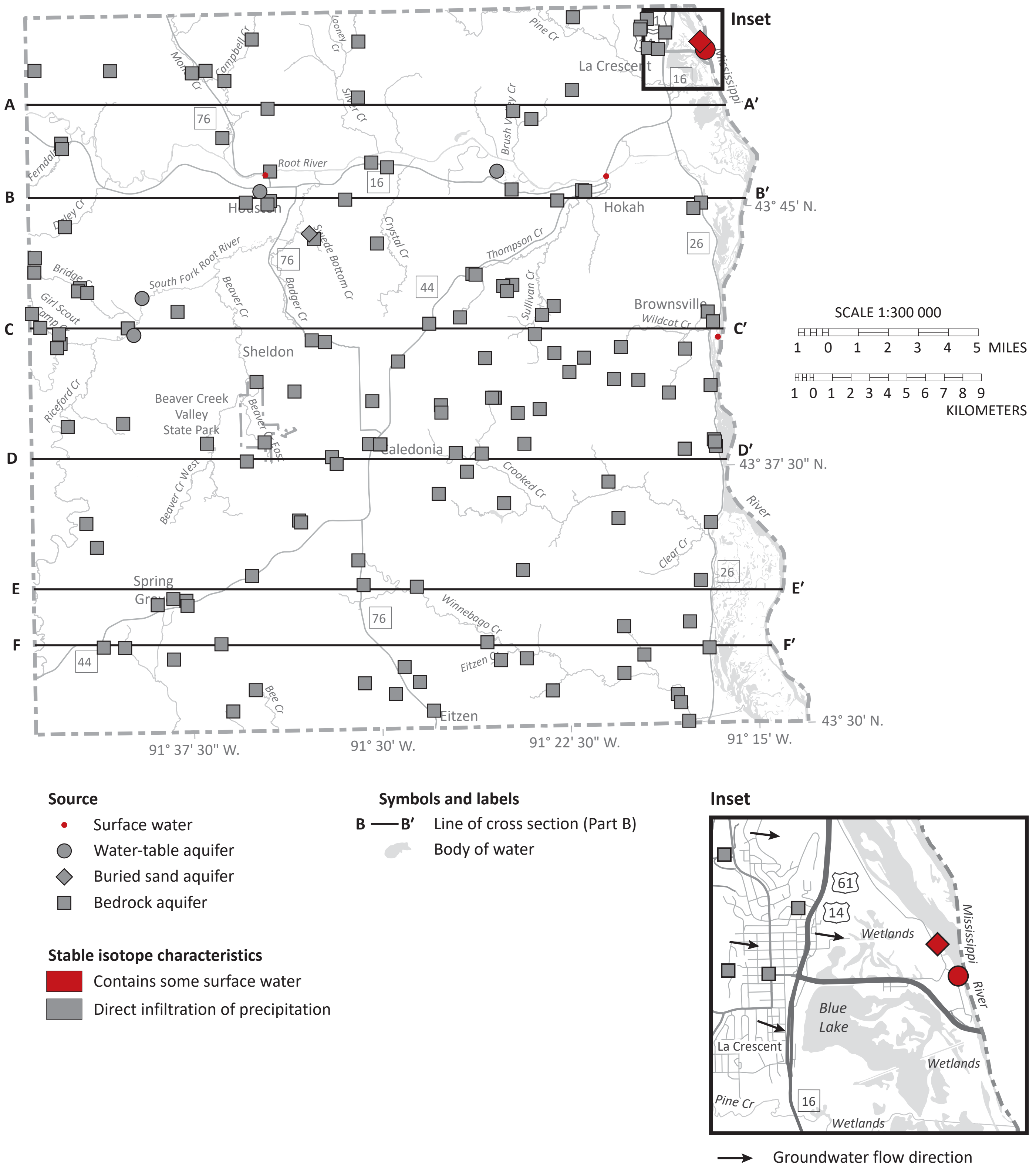


Figure 14. Stable isotope characteristics of groundwater samples

Most groundwater samples originated as direct infiltration of precipitation and are symbolized in gray, representing meteoric signatures. The red symbols represent partial evaporative signatures. The inset shows possible evaporative surface-water sources (Blue Lake, open-water wetlands, and the Mississippi River) for the two wells with partial evaporative signatures.

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 surface water body (spring, creek, or river). Short residence time generally suggests short travel paths or high recharge rates; long residence time suggests long travel paths or low recharge rates. Since groundwaters are mixtures, groundwater residence time estimates are averages of the multiple differing groundwater flow paths represented in a single sample. For instance, a groundwater sample from a karst aquifer may contain some water from open conduit flow paths that are hours to days old, combined with water that flows much more slowly through the rock matrix itself.

The residence time of groundwater was estimated for this atlas using isotopic analysis of the radioactive elements tritium and carbon-14. Groundwater residence time results are shown on Plates 5 (Water Chemistry) and 6 (Hydrogeologic Cross Sections), and Figures 19 (Piper diagram), 21, and 24 to 30 (Pollution sensitivity).

Tritium

Groundwater residence time was interpreted from the concentration of tritium. 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 concentrations were used to estimate groundwater residence time using the known half-life of 12.32 years (Lucas and Unterweger, 2000). The concentrations are presented in tritium units (TU) and are referred to as tritium age in the following categories.

- **Recent**: water entered the ground since about 1953 (greater than or equal to 8 TU).
- **Mixed**: water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- **Vintage**: water entered the ground before 1953 (less than or equal to 1 TU).

Historical data (sample dates from 1987 to 2017) are used in the residence time interpretations of this report and are classified according to Table B-2 in Appendix B.

Tritium was collected from 100 wells and 26 springs to assist in residence-time interpretations. Of the 126 samples analyzed for tritium, 62 were vintage, 57 were mixed, and 7 were recent.

Carbon-14

Select wells with vintage and mixed tritium-age results were further sampled for carbon-14 (^{14}C) to estimate longer residence times. This naturally occurring isotope has a half-life of 5,730 years and is used to estimate groundwater residence time ranging from less than 100 to greater than 40,000 years.

Carbon-14 sample collection, analysis, and modeling is described in Alexander and Alexander, 2018. In general, when precipitation infiltrates the unsaturated zone it adsorbs carbon dioxide, including carbon-14, 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 the groundwater comes from atmospheric carbon in the soil zone during infiltration and half comes from very old bedrock sources where carbon-14 has decayed completely.

Residence times from 17 sampled wells varied from less than 100 years to 30,000 years. The oldest carbon-14 residence times are in the Mt. Simon aquifer. Carbon-14 residence time generally increases with depth from land surface.

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 it moves along flow paths.

Groundwater contamination can come from human (anthropogenic) pollution or the dissolution of naturally occurring geologic (geogenic) sources. Elevated concentrations of particular chemicals can indicate short groundwater residence time, high sensitivity, or where groundwater consumption is a potential concern to human health.

Anthropogenic sources can be identified by comparing concentrations to naturally occurring background levels. Water quality evaluations describe contaminants that are potentially harmful (either geogenic or anthropogenic) or that affect aesthetics. This atlas uses the following guidelines.

Drinking water guidelines

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

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

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

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

Minnesota Department of Health (MDH, 2023)

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

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

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

Chemical descriptions and results

The following chemicals are naturally occurring, but some can be elevated by anthropogenic activities. Water quality guidelines and sampled results are presented for inorganic chemistry and include the following.

- The major cations and major anions are reported in units of parts per million (ppm)
- Trace elements, such as arsenic, manganese, and boron, are reported in units of parts per billion (ppb)

Organic chemicals were not studied as they are out of the scope of this project, but can be found in reports from other state agencies (for example, pesticides and their breakdown products, solvents, and degreasers). Geogenic, naturally occurring radionuclides, such as radium and radon, were additionally out of scope for this project, but can be elevated in the Mt. Simon aquifer (Lively and others, 1992). Radium is commonly found in southeastern Minnesota's Paleozoic aquifers (Lundy, 2010). Two municipal drinking water systems, Houston and La Crescent, require treatment for radium removal (J. Woodside, MDH, written communication, 2025).

Chloride

SMCL 250 ppm, elevated ≥5 ppm, anthropogenic: chloride/bromide ratio >300

Chloride can occur naturally from deep sources, such as groundwater basin brines, or it can come from anthropogenic sources, such as road salt, water softener salt, or fertilizer. The chloride concentration of atmospheric deposition in southeastern Minnesota is less than 1 ppm (NADP, 2025).

Chloride to bromide (Cl/Br) ratios are commonly used in hydrologic investigations to identify sources of chloride in groundwater (Whittemore, 1988; Davis and others, 1998; Thomas, 2000; Jagucki and Darner, 2001; Panno and others, 2006; Mullaney and others, 2009).

Chloride sources have different Cl/Br ratios that fall along unique mixing trends. Figure 15 shows Cl/Br ratios of Houston County samples plotted with groundwater mixing trends from Wilson (2012). Many samples plot along binary mixing curves 1 to 4, suggesting that elevated chloride in these waters is from anthropogenic sources.

The binary mixing curve from dilute groundwater/basin brines (curve 5) differs from the line shown in Wilson (2012) and was developed for Minnesota using a subset of Mt. Simon aquifer well chemistry from the MDH (MDH, 2025). The Minnesota-specific brine mixing curve is slightly different, which may reflect subtle differences between the brine of the Hollandale Embayment and those of the Illinois Basin shown in Wilson (2012). Basins are broad structural depressions of bedrock layers. The Hollandale Embayment is a basin that underlies southeastern Minnesota; the Illinois Basin includes parts of the states of Illinois, Indiana, Kentucky, Tennessee, and Missouri. Groundwater found in deep geologic basins often has naturally elevated chloride.

For this study, samples with Cl/Br mass ratios above 300 and chloride concentrations above 5 ppm likely indicate anthropogenic sources of chloride (Figure 15). The 300-break point was determined using a combination of chloride and nitrate concentrations, tritium ages, carbon-14 residence time estimates, and results from the research referenced above.

Sampling results (Figure 16)

- Of the 143 samples analyzed for chloride, 33 were elevated from anthropogenic influences. Anthropogenically elevated samples were collected from 17 springs and 16 wells; none equaled or exceeded the SMCL. Anthropogenically elevated occurrences were primarily from wells and springs in aquifers above the St. Lawrence aquitard or in valley bottoms where overlying aquitards are absent or have diminished protective characteristics.

Nitrate

MCL and HRL 10 ppm, elevated ≥1 ppm

Nitrate can occur naturally at low concentrations, but elevated concentrations indicate impacts from fertilizer and animal or human waste (Dubrovsky and others, 2010; Wilson, 2012; Kroening and Vaughan, 2019). The majority of nitrate that impacts the state's waters, including groundwater, is from agricultural activities (MPCA, 2013). Nitrate concentrations may lessen with time (denitrification) in deep and confined aquifers where 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 commonly elevated in southeastern Minnesota, in the root zone underlying row-crop agriculture. A 5-year study collected nitrate concentrations in soil water from lysimeters in cultivated row crop settings of Minnesota. Results were highly variable, averaging 22.3 ppm with a typical range of 8 to 28 ppm (Kuehner and others, 2020). Nonagricultural nitrate concentrations from lysimeters installed in prairie and forest settings had average concentrations less than 0.5 ppm.

Elevated levels of nitrate may indicate that other surface contaminants have the potential to reach an aquifer. Pesticides were not sampled as part of this study, but frequently co-occur with nitrate. The MDA has found that the likelihood of detecting at least one pesticide compound increases as the concentration of nitrate increases (MDA, 2019). In Houston County, 98% (100 of 102) of wells with a nitrate concentration greater than or equal to 3 ppm contained pesticides or pesticide metabolites (B. Schaefer, MDA, written communication, 2025). The Houston County findings are similar to the results from an investigation in Dakota County that found a median of 15 different herbicide compounds in study wells with a median nitrate concentration greater than 3 ppm (Demuth and Scott, 2020).

Sampling results (Figures 17 and 18)

- Of the 144 samples analyzed for nitrate, 53 were elevated. Elevated samples were collected from 29 springs and 24 wells; 2 well samples exceeded the MCL.
- Elevated occurrences were primarily from the Prairie du Chien and Jordan aquifers or in wells completed in valley bottoms where overlying bedrock aquitards are absent.
- Springs with elevated nitrate are common and are primarily at the edge of valleys where overlying aquitards have diminished protective characteristics.

This report's findings are consistent with the results from the MDA Township Testing Program, which found areas with a high percentage of row crop agriculture and karst vulnerability to be at risk for nitrate contamination (MDA, 2020). The MDA program consists of two assessments. The initial MDA assessment included wells where specific details about participant wells, such as aquifer, depth, and well construction, weren't always available.

The initial assessment found nitrate concentrations greater than the MCL in 10% or more of the samples collected in the following townships: Black Hammer, Caledonia, Mayville, Spring Grove, Wilmington, and Winnebago. Townships are shown on Plate 5. For the second assessment, the MDA did follow-up tests in these same townships and found nitrate concentrations consistent with the initial testing. Following the second round of testing, the MDA removed the results of wells that had insufficient documentation describing the well's depth, aquifer, or construction details, or wells that could be influenced by point sources of nitrogen. The final well assessment found nitrate concentrations greater than the MCL (10 ppm) in more than 10% of wells in Black Hammer, Caledonia, Mayville, Spring Grove, and Wilmington townships.

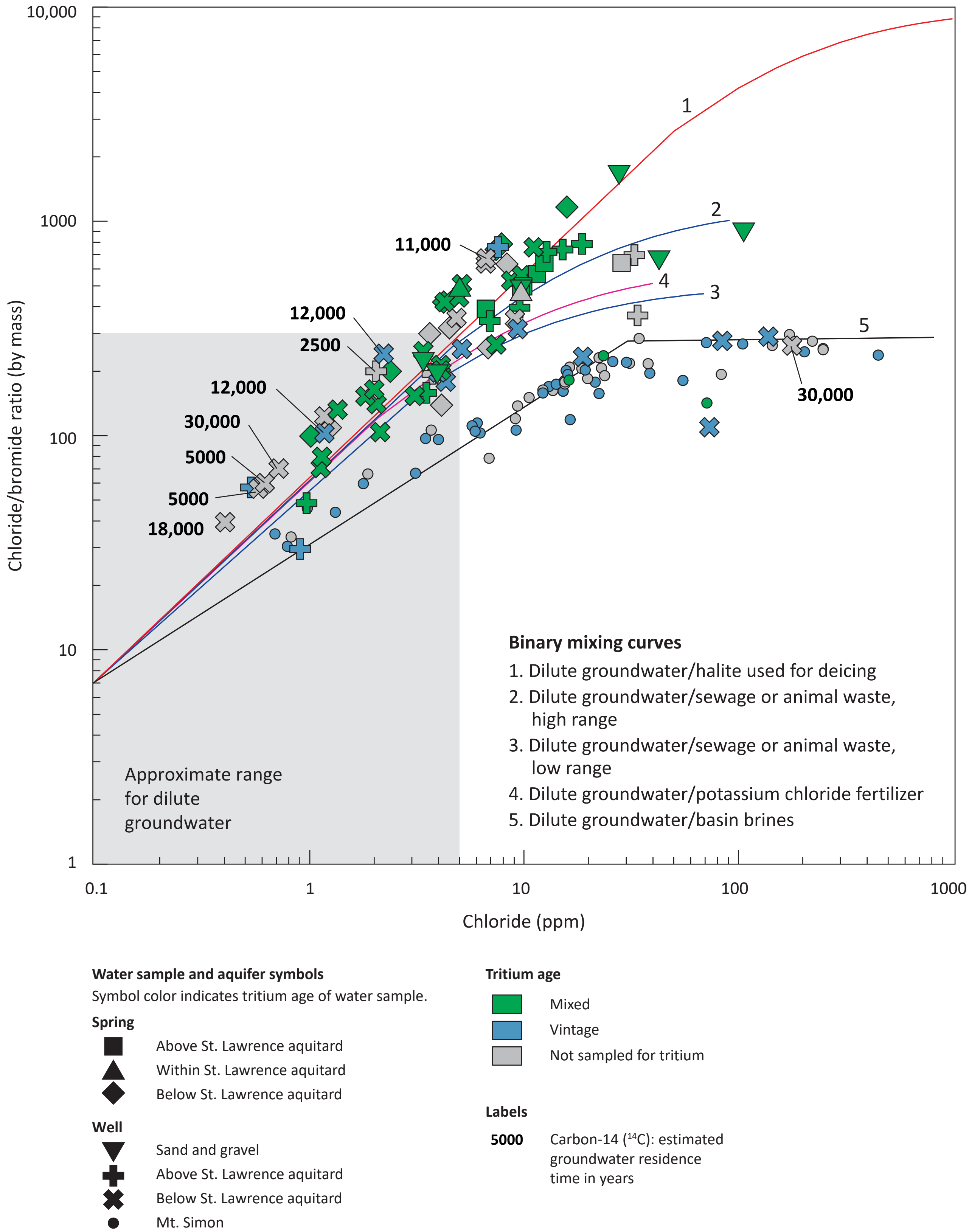


Figure 15. Chloride/bromide ratios to chloride concentration

All groundwaters are mixtures. Binary mixing curves are used to visualize the mixing of waters from two distinct waters (such as pristine groundwater and groundwater impacted by road salt or potassium chloride fertilizers). Houston County water samples are shown projected on mixing curves from Wilson (2012). Binary mixing curve number 5, dilute groundwater/basin brines, differs from the line shown in Wilson (2012) and was developed for Minnesota using a subset of Mt. Simon aquifer well chemistry from the MDH (MDH, 2025).

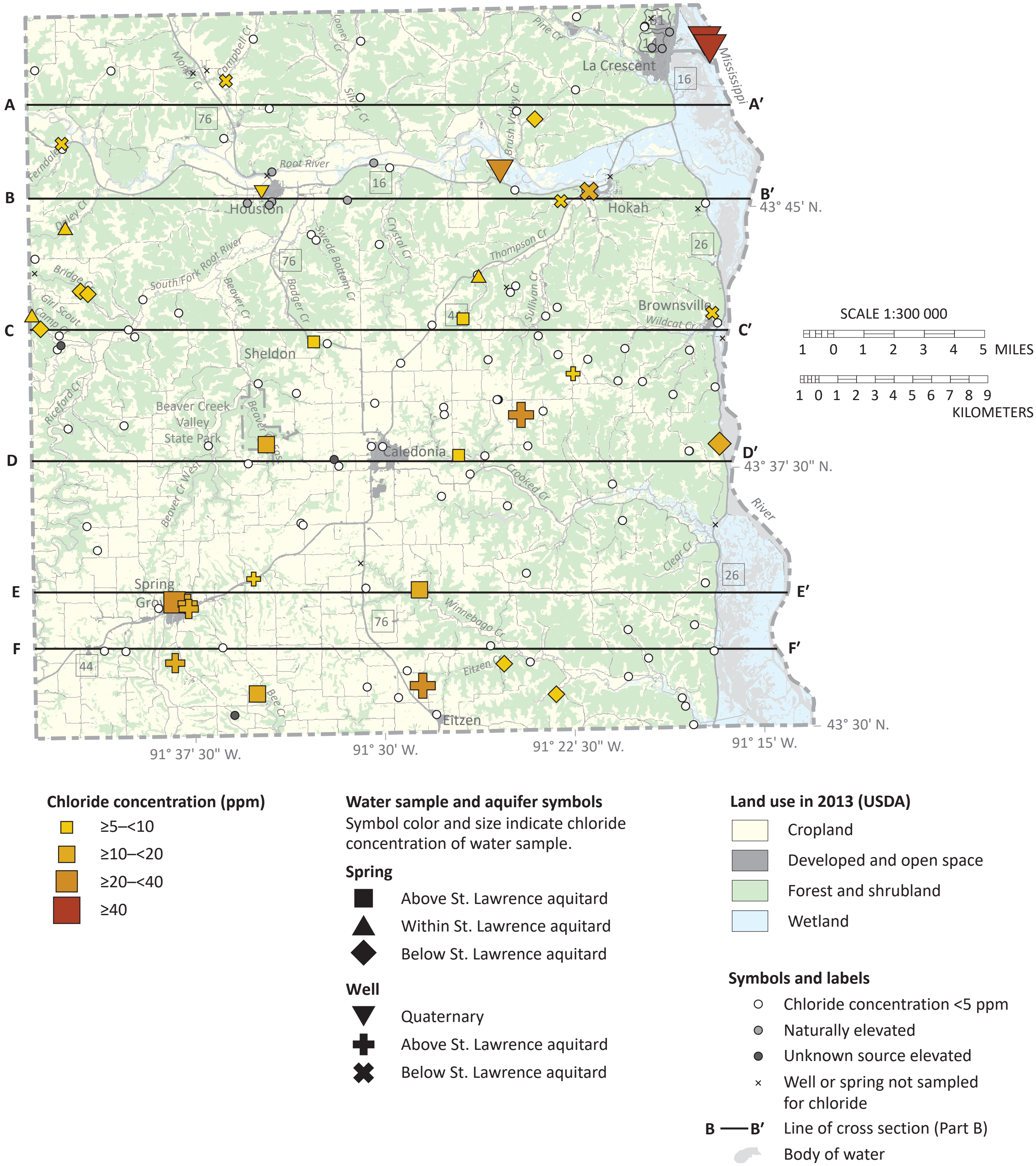
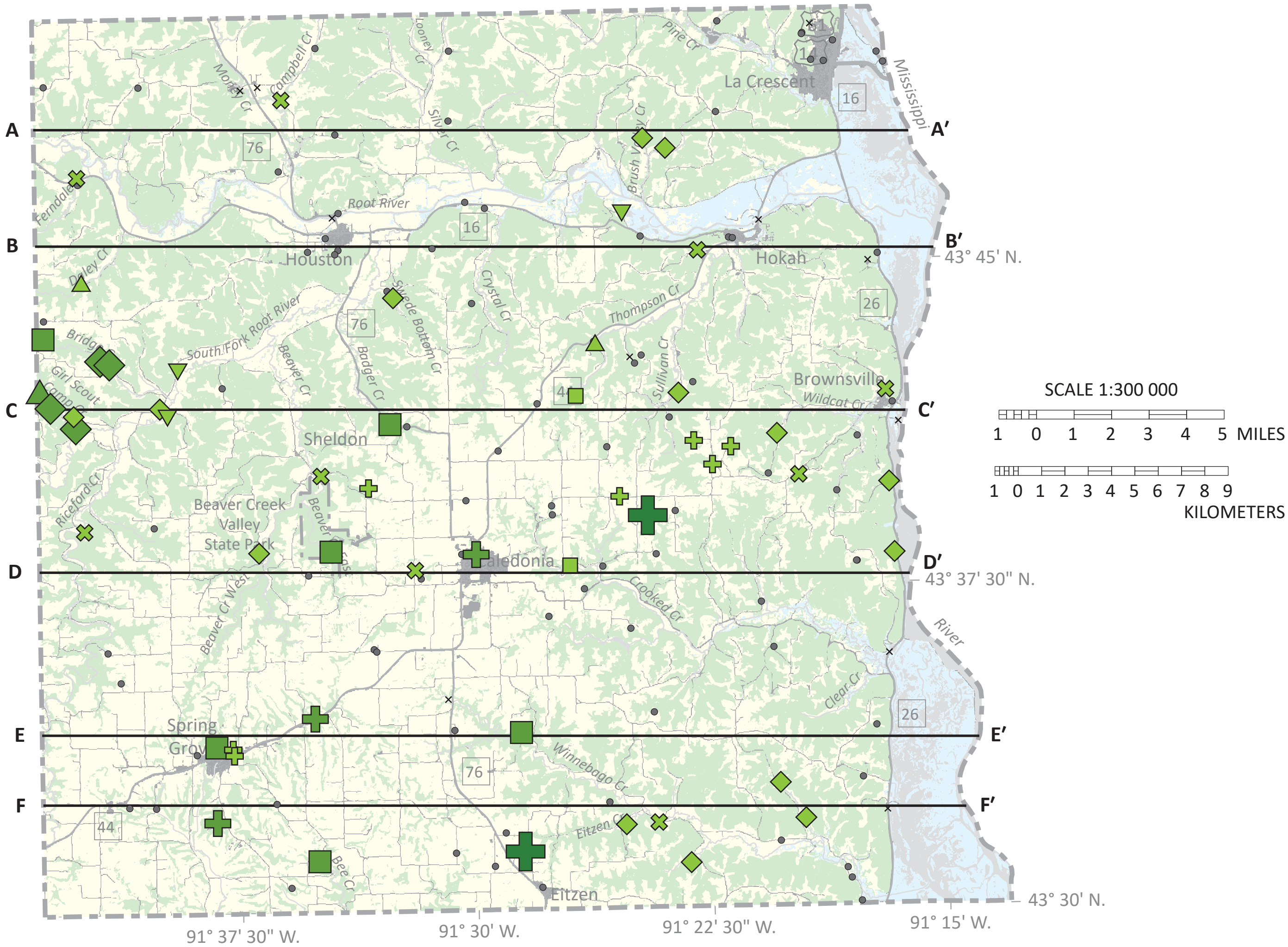


Figure 16. Elevated chloride concentrations from groundwater samples

Anthropogenically elevated chloride exceeding 5 ppm was found in 33 of 143 groundwater samples. The two highest chloride samples came from sand and gravel wells in La Crescent. Naturally elevated chloride was determined using Cl/Br ratios of less than 300 and was encountered most in wells completed in the Mt. Simon aquifer.



Nitrate concentration (ppm)

- ≥1–<5
- ≥5–<10
- ≥10

Water sample and aquifer symbols

Symbol color and size indicate nitrate concentration of water sample.

Spring

- Above St. Lawrence aquitard
- Within St. Lawrence aquitard
- Below St. Lawrence aquitard

Well

- Quaternary
- Above St. Lawrence aquitard
- Below St. Lawrence aquitard

Land use in 2013 (USDA)

- Cropland
- Developed and open space
- Forest and shrubland
- Wetland

Symbols and labels

- Nitrate concentration <1 ppm
- Well or spring not sampled for nitrate
- B —— B′ Line of cross section (Part B)
- Body of water

Figure 17. Distribution of nitrate concentrations from groundwater samples

Elevated nitrate is common in Houston County, with 53 of 144 groundwater samples equal to or exceeding 1 ppm, and 2 samples exceeding the MCL. Springs commonly have elevated nitrate. Elevated nitrate primarily occurs in wells completed in aquifers located above the St. Lawrence aquitard or in wells in valley bottoms where overlying aquitards are absent.

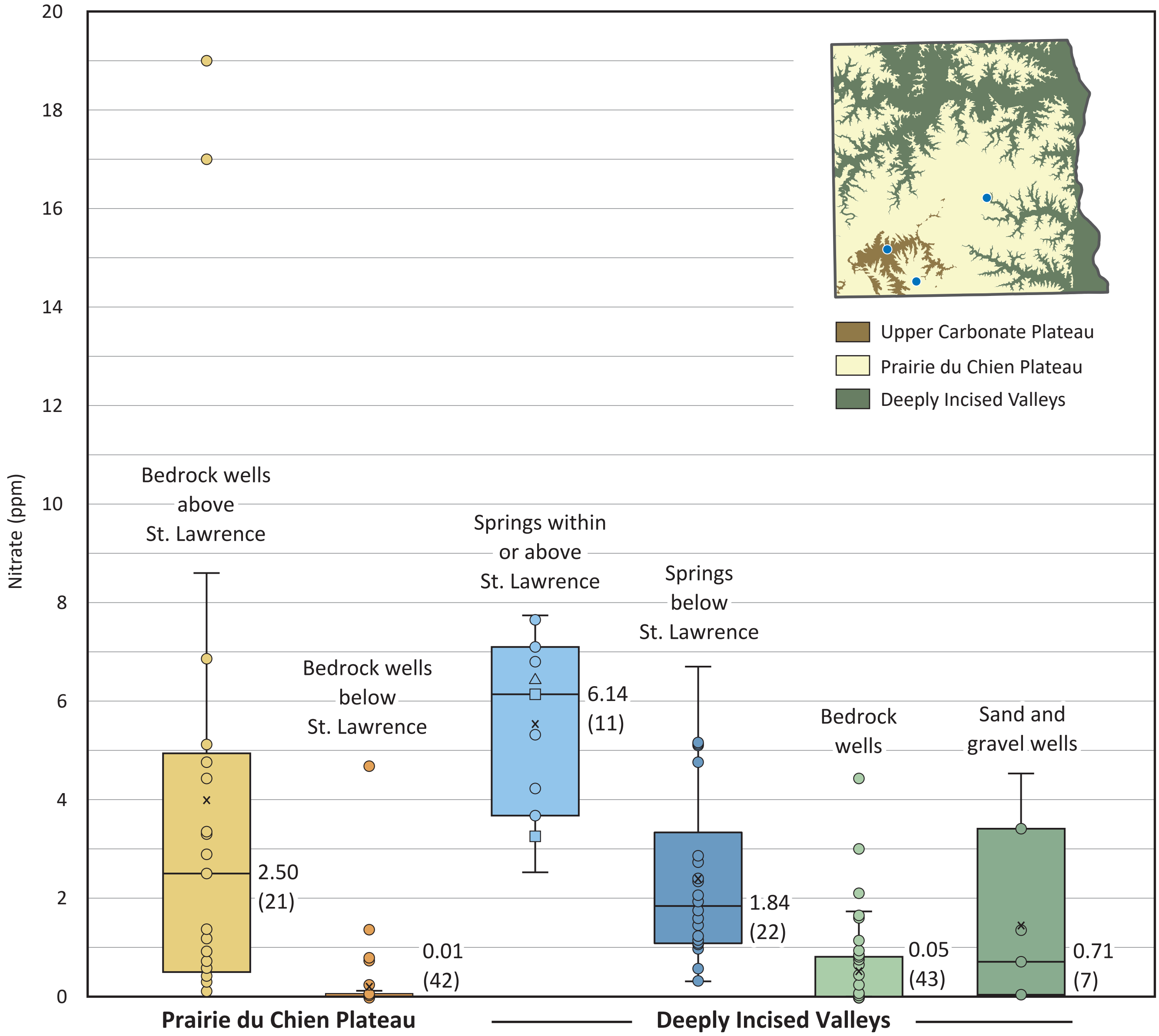


Figure 18. Nitrate box plots of groundwater samples

Nitrate concentration box plots help illustrate nitrate concentration differences, depending on the well's geomorphic setting and aquifer position above or below the St. Lawrence aquitard. Three springs included in the "Springs within or above the St. Lawrence" box plot emerged from plateaus (inset figure); the triangle symbol represents a spring from the Upper Carbonate Plateau, and the two squares represent springs of the Prairie du Chien Plateau.

Numbers to the right of each box plot represent the median nitrate concentrations; numbers within parentheses represent the number of samples within each category. Horizontal lines within each box represent median concentrations, the X represents the average value, and the whiskers represent the ranges for the top and bottom 25% (excluding outliers).

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, 2023). Current science cannot predict which wells will have high arsenic concentrations; therefore, all newly constructed drinking-water wells are analyzed for arsenic (Minnesota Administrative Rules 4725.5650, 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). Arsenic is most likely to be present in glacial drift and shallow bedrock wells that lie within the footprint of the most recent glaciation that originated from the Riding Mountain provenance (northwest). This glaciation never reached Houston County, likely influencing the relatively low number of arsenic detections.

Nicholas and others (2017) found that changes in redox conditions are largely responsible for releasing solid phase arsenic into groundwater by one of three mechanisms: desorption, reductive dissolution, or oxidative dissolution, and that the aquitard-aquifer interface is very geochemically active. 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).

Sampling results

- Of the 127 samples analyzed for arsenic, arsenic was present in 28, 1 of those exceeded 1 ppb, and none exceeded the MCL.

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).

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

Sampling results

- Of the 106 samples analyzed for manganese, 6 were greater than the SMCL and 5 were greater than the HBV.

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 52 samples analyzed for boron, none were greater than the RAA.

Sulfate

SMCL 250 ppm

Sulfate is largely naturally occurring. Common sources are 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 135 samples analyzed for sulfate, all were less than the SMCL.

Major cations and anions

Calcium, magnesium, and sodium cations, as well as bicarbonate anions, are dissolved out of glacial sediment and bedrock by groundwater. The constituents are derived from limestone and dolomite bedrock and are also common in unconsolidated aquifers (Hem, 1985). 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, fertilizer provides an additional source of potassium.

Water is considered hard or soft by its concentrations of calcium, magnesium, and bicarbonate. Hard water contains higher levels of calcium and magnesium. Most bedrock aquifers in Houston County produce hard water. Though not required, most residents typically soften their water to improve the taste and smell, and to limit the build-up of minerals (scale) on plumbing fixtures, the insides of pipes, and hot water heaters.

The Piper diagram (Figure 19) graphically represents each water sample for the most common ionic constituents in natural waters: calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and nitrate.

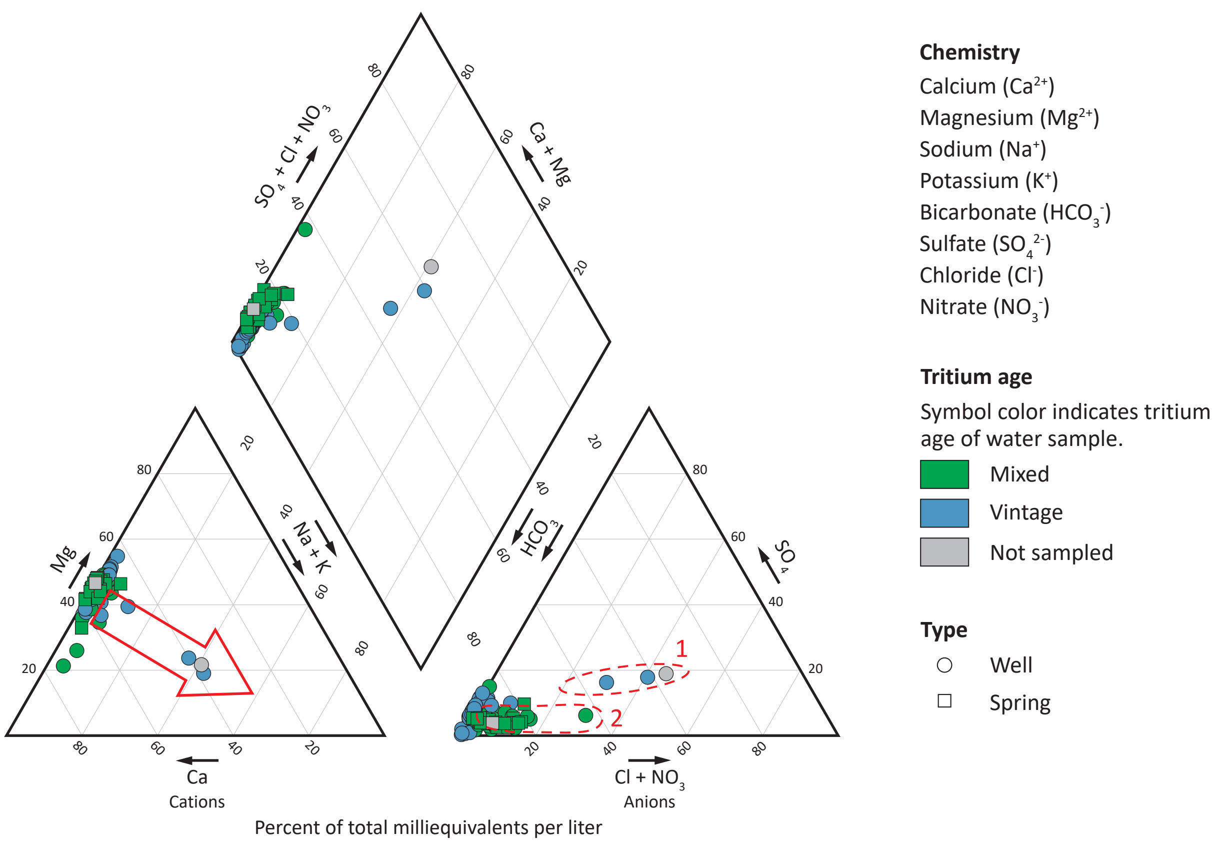


Figure 19. Groundwater Piper diagram

This diagram compares the relative proportions of cations and anions in groundwater samples. The most common water type is calcium+magnesium bicarbonate, which is typical for southeastern Minnesota.

Groundwater residence time generally increases along the path of the red arrow. Waters that plot along this path evolve from calcium bicarbonate waters to sodium+potassium bicarbonate waters. Waters within the ellipses of the anion triangle have unique geochemical signatures and trends similar to those found in Winona County (Barry, 2021).

- Ellipse 1 has two samples with vintage tritium ages and one with an estimated carbon-14 residence time of 30,000 years. Each is from the Mt. Simon aquifer. The three samples within this ellipse have naturally elevated chloride that shifts their plots along the chloride+nitrate (lower right) axis on the anion diagram.
- Ellipse 2 samples have mixed tritium ages, anthropogenically elevated chloride and nitrate, and are from all aquifers sampled except the Mt. Simon.

Pollution sensitivity

Pollution sensitivity is defined as the potential for groundwater to be contaminated by land surface activities because of the properties of the geologic material. Dissolved contaminants migrate with water through sediment and are typically affected by complex processes, such as biological degradation and oxidizing or reducing conditions. The methods used to interpret pollution sensitivity include the following general assumptions:

- Flow paths are vertical and downward from the land surface through the soil and underlying sediment to the saturated zone.
- Contaminants travel at the same rate as water.
- Dissolved contaminants move with water from the surface and are not chemically or physically altered over time.

River valleys can be important groundwater discharge areas where local groundwater movement is upward, and the actual pollution sensitivity can be lower than rated.

Two methods were used to estimate pollution sensitivity. The central concept for both models is the relative rate of water movement. This is described as infiltration in the unsaturated zone and recharge in the saturated zone.

The following describes the two methods:

- **Near-surface materials:** unsaturated flow to a depth of 10 feet (the assumed depth of the water table); the primary properties used to estimate sensitivity are texture and distance. This method is used in valleys and along the Mississippi River.

In large portions of the county, the near-surface materials are underlain by shallowly buried karst bedrock. These areas are mapped as ***prone to karst feature development***, and near-surface sensitivity is very high.

Areas of high sensitivity can be areas of high recharge. In addition to soil properties, land cover affects potential recharge (Smith and Westenbroek, 2015).

- **Bedrock aquifers**: aquifer chemistry and residence time are combined with depth from the land surface and the presence or absence of karst features and overlying aquitards. These data are used to estimate bedrock pollution sensitivity, in conjunction with the findings of historical investigations that describe the hydrologic properties of Minnesota's Paleozoic bedrock aquifers and aquitards.

Near-surface materials model

Method

The method used to estimate infiltration rates through soil and shallow geologic materials is applied successfully to large portions of Minnesota and is valid in valleys in southeastern Minnesota with thick sequences of unconsolidated deposits. The pollution sensitivity ratings of the near-surface materials model are superseded where certain geologic conditions are present. These include areas where karst is present, where bedrock is at or near the land surface, or near disturbed lands (DNR, 2016c). In Houston County and large portions of southeastern Minnesota, karst conditions supersede the near-surface pollution sensitivity method. In areas mapped as karst, the potential for extremely rapid contaminant travel is assumed.

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

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 and the surficial geologic matrix texture. Attributes of both are used to estimate the time of travel (Table 1) (Natural Resources Conservation Service, 2020; Part A, Plate 3).

The time of travel through near-surface sediment varies from hours to approximately a year (Figure 20).

- Areas with a short travel time (hours to a week) are rated high sensitivity.
- Areas with a longer travel time (weeks to a year) are rated low or very low.
- Areas with travel times of more than a year are rated ultra low. There are no ultra-low areas in this county.

For further details, see *Methods to estimate near-surface pollution sensitivity* (DNR, 2016c).

Results are depicted in Figure 21.

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	Qb
		sand, silty sand	0.71	Qa, Qat
B, B/D	0.50	silt, loamy sand	0.50	Qr**
		sandy loam, peat	0.28	Not mapped in county
C, C/D	0.075	silt loam, loam	0.075	Qc
		sandy clay loam	0.035	Not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Not mapped in county

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

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

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

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

Group C: water transmission is somewhat restricted.

Group D: water movement is restricted or very restricted.

**Residuum transmission rate was modified per discussion with the MGS.

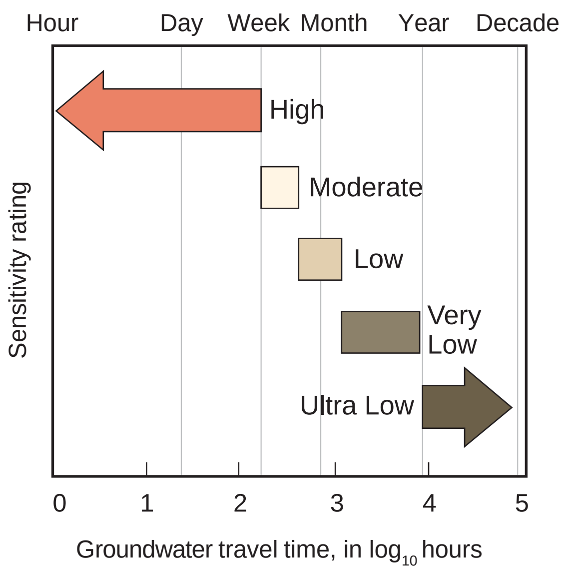
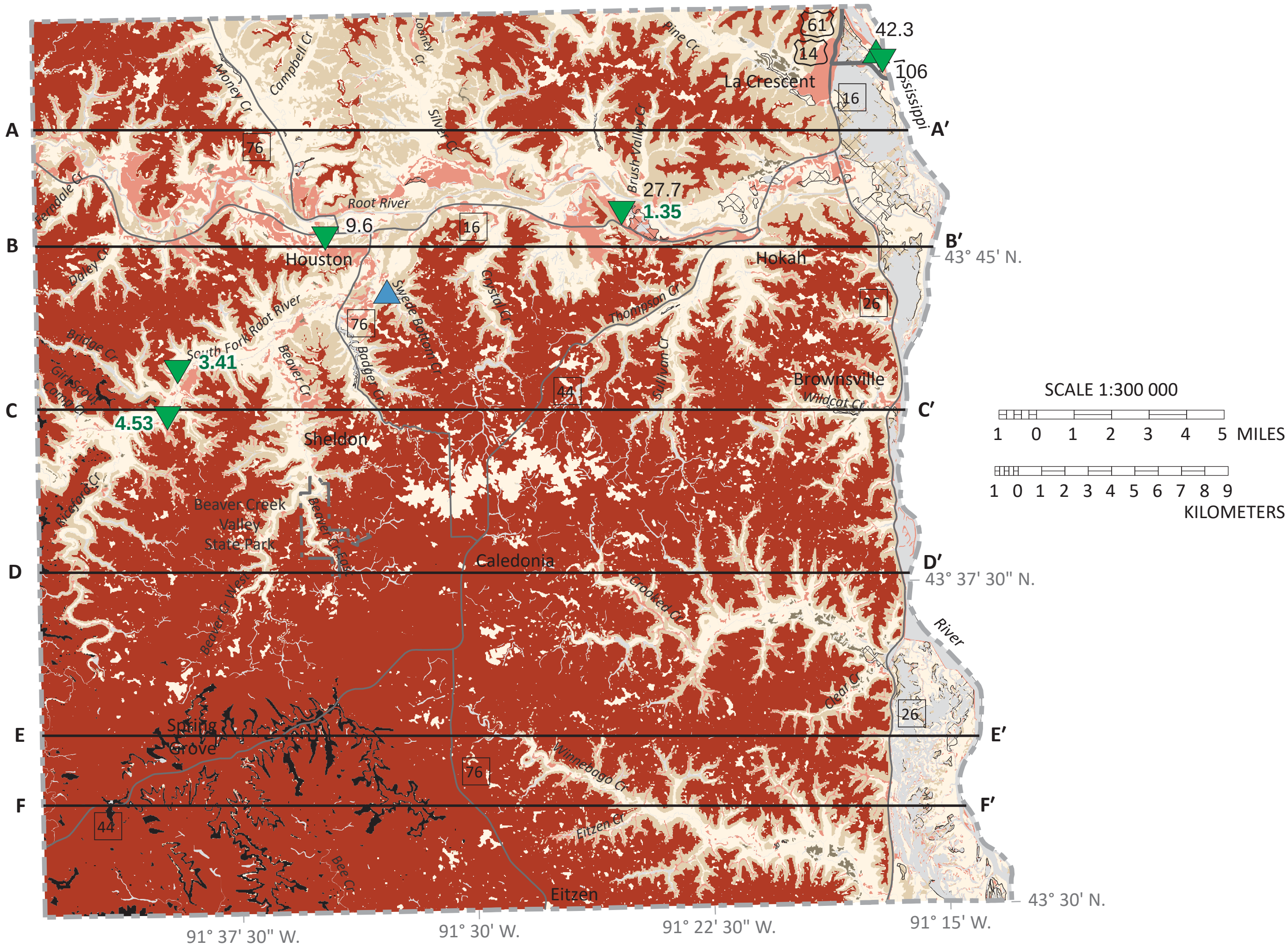


Figure 20. Geologic sensitivity ratings for near-surface materials



Estimated vertical travel time through near-surface materials

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

Special conditions

- Area prone to karst feature development
- Bedrock at or near surface

Water sample and aquifer symbols

Symbol color indicates tritium age of water sample.

- Water table
- Buried sand

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage

Symbols and labels

- 27.7 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)
- 3.41 Nitrate: if shown, concentration is ≥1 ppm.
- B —— B′ Line of cross section (Part B)
- Body of water
- Peat

Figure 21. Pollution sensitivity rating of near-surface materials

Most of the county has bedrock near the land surface that is prone to karst feature development and is a unique, very high-sensitivity area (DNR, 2016b). Elsewhere, the estimated sensitivity predominantly ranges from high to moderate in the sandy unconsolidated deposits in valley bottoms and along the Mississippi River. The surficial sand aquifer is used by approximately 6% of county wells with known construction information.

Samples were collected from 5 wells in unconfined surficial (water-table) aquifers and 2 wells in confined buried sand aquifers; each was analyzed for tritium. The water-table wells had a mixed tritium age, and the buried sand aquifers resulted in 1 mixed and 1 vintage. The vintage sample is likely Mt. Simon water that upwells into the water-table system along the edges of the South Fork Root River. Of the 7 samples analyzed for nitrate, 3 were elevated, each in the water-table aquifer. Of the 7 samples analyzed for chloride, 4 were elevated from anthropogenic sources: 3 from the water-table aquifer and the other from a buried sand aquifer.

Bedrock aquifer model

Method

The pollution sensitivity ratings for bedrock aquifers are based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with very high or high ratings have relatively short travel times of less than a few years; areas rated low or very low have estimated travel times of decades or longer (Figure 22).

The ratings are based on estimated vertical travel times inferred from tritium analysis, carbon-14 age dating, the presence or absence of anthropogenic indicators, dye trace investigations (DNR, 2020c), the presence or absence of sinkholes and stream sinks, and the findings from many previous investigations (Tipping, 1994; Tipping and others, 2006; Runkel and others, 2003, 2006, 2014a, 2014b, 2018; Kuehner and others, 2025).

Sensitivity ratings were assigned to delineate areas of the aquifers using GIS analysis of the data listed above.

Groundwater systems

Groundwater collected from aquifers located stratigraphically above the St. Lawrence aquitard often shows anthropogenic influences: elevated nitrate and chloride, or recent and mixed tritium ages (residence times of less than 70 years). Groundwater from these aquifers also frequently has measurable dissolved oxygen. Oxygenated groundwater likely reflects aeration within conduit networks that allow for rapid vertical recharge from the land surface to deeper aquifers.

Wells and springs located within or near incised valleys generally have elevated nitrate, chloride, tritium, and detectable dissolved oxygen. In valleys, the St. Lawrence aquitard is typically thinner, compromised by fractures, or absent. In shallow bedrock conditions of valleys, the St. Lawrence transitions from an aquitard to a pseudokarst aquifer (Figure 23). This finding is based on the numerous locations documented in southeastern Minnesota where streams sink into the St. Lawrence aquitard. At several of these locations, water has been documented to travel rapidly to downgradient springs and wells (Green and others, 2008, 2012; Barry and others, 2015, 2018).

Springs are highly susceptible to human impact and contamination (Barry and others, 2018; Goedjen and others, 2024; Kuehner and others, 2025). Of the 35 spring samples collected, 26 were analyzed for tritium with the following results: 3 recent and 23 mixed. Of the 33 spring samples analyzed for nitrate, 29 were elevated. Of the 32 spring samples analyzed for chloride, 18 were elevated from anthropogenic sources.

Wells located away from incised valleys in southeastern Minnesota and in aquifers below the St. Lawrence typically have low nitrate, low anthropogenic chloride, nondetectable tritium, and no detectable dissolved oxygen (Barry and others, 2018; Barry, 2021).

Pollution sensitivity ratings were compared with the tritium age of groundwater and the presence or absence of other anthropogenic chemical indicators (nitrate and chloride). Higher sensitivity is associated with the following:

- Tritium age is recent or mixed.
- Nitrate is elevated and anthropogenic if concentrations are greater than or equal to 1 ppm.
- Chloride is elevated if concentrations are greater than or equal to 5 ppm. It is anthropogenic if Cl/Br ratios are greater than 300.

The tritium dataset is a combination of sampling efforts by the DNR and MDH for projects since 1992, with most samples collected in 2015 and 2016. Groundwater chemistry was qualitatively compared to the results of the modeled pollution sensitivity. Tritium detections from aquifers in areas mapped as very low sensitivity should rarely occur, assuming that flow of groundwater to the aquifer is vertical and not altered by nearby pumping or compromised well integrity.

The following section describes and illustrates the results of the bedrock aquifers in stratigraphic order (Figure 3). It includes the extent, depth, thickness, use, mapped karst features, pollution sensitivity, residence time, and chemistry.

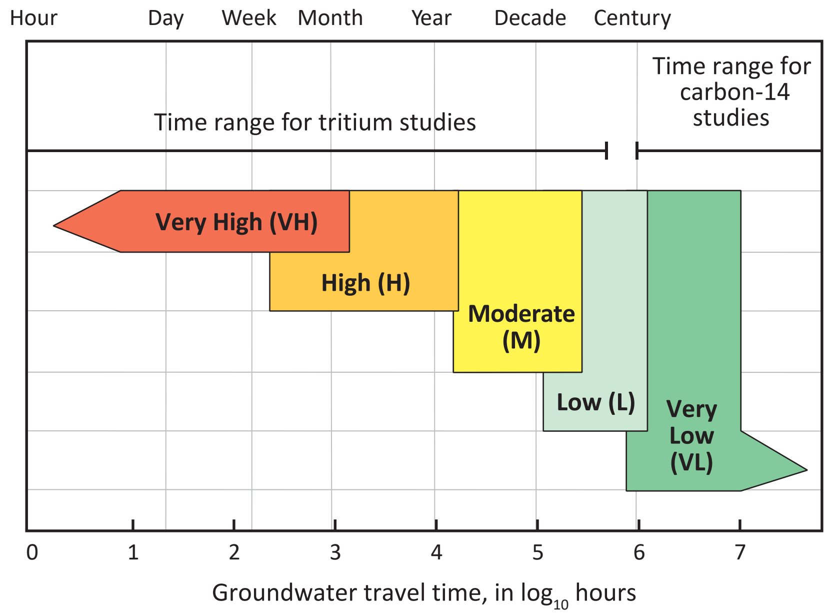


Figure 22. Pollution sensitivity ratings for bedrock aquifers

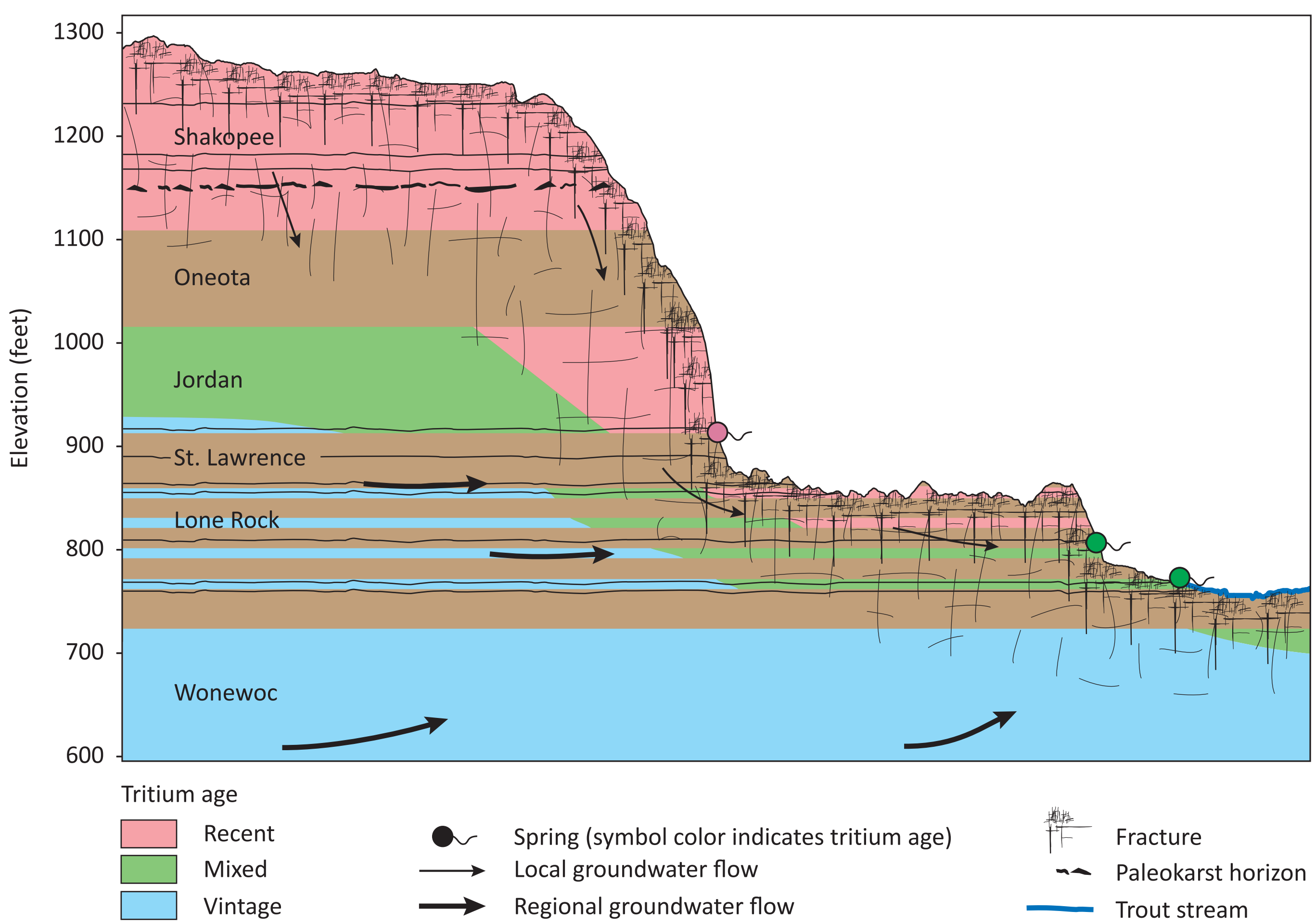


Figure 23. Generalized hydrogeologic cross section illustrating the groundwater system and springs

Springs in valleys are a mixture of younger local impacted water and older regional groundwater; springs that emanate above the St. Lawrence aquitard are especially susceptible to contamination. Tritium-age color is based on chemical results from spring and well samples collected from aquifers ranging from the Prairie du Chien to the Wonewoc. Aquitard units are represented with brown hues.

Results

Cummingsville through St. Peter aquifers (Figure 24)

- *Extent*: Present in the southwest and includes the intervening Decorah–Platteville–Glenwood aquitard units.
- *Depth*: 0 to 270 feet.
- *Thickness*: The Cummingsville ranges from 0 to 75 feet; the St. Peter ranges from 0 to 90 feet.
- *Use*: No county wells with known construction information. Because these aquifers are near the land surface, they are sensitive to pollution and are generally not used for potable water supply.
- *Mapped karst features/springs*: 41 sinkholes, 2 stream sinks, and 16 springs/seeps. Springs and seeps most commonly occur near the Decorah.
- *Pollution sensitivity*: Very high, due to proximity to land surface, mapped karst features, and the presence of anthropogenic influences in groundwater chemistry.
- *Residence time*: No residence time samples collected.
- *Anthropogenic chemistry*: A spring in Spring Grove had elevated nitrate and chloride.

Prairie du Chien aquifer (Figure 25)

- *Extent*: Present over most of the county as the first bedrock unit beneath the land surface.
- *Depth*: 0 to 550 feet. Its greatest depth occurs in the southwestern area of the county, where it is deeply buried under overlying bedrock.
- *Thickness*: 0 to 320 feet.
- *Use*: Less than 1% of county wells with known construction information. The aquifer is made up of two geologic formations with different hydrologic properties: the Shakopee and the Oneota. The Shakopee is more productive than the Oneota, which has properties of an aquitard on a regional scale. The Prairie du Chien aquifer is saturated over the southwestern and central portions of the county. In the narrow ridges of the northern and eastern portions, it is frequently dewatered.
- *Mapped karst features/springs*: 245 sinkholes, no stream sinks, and 8 springs. Sinkholes most frequently occur near the Shakopee–Oneota geologic contact; springs emanate from the Oneota.
- *Pollution sensitivity*: Very high due to its proximity to the land surface over much of the county, karst features, and the presence of anthropogenic influences on groundwater chemistry.
- *Residence time*: Samples were collected from 4 springs and 1 well from the Shakopee and Oneota combined; each was analyzed for tritium age and had a mixed tritium age. A recent investigation focused on nitrate and pesticide concentration trends in southeastern Minnesota determined average residence times for Prairie du Chien springs to be approximately two to three decades (Kuehner and others, 2025). Longer residence times corresponded to wells and springs emanating from the deepest stratigraphy.
- *Anthropogenic chemistry*: Of the 5 samples analyzed for nitrate, all were elevated. Of the 5 samples analyzed for chloride, all were elevated from anthropogenic sources.

Jordan aquifer (Figure 26)

- *Extent*: Present over most of the county.
- *Depth*: 0 to 645 feet. The greatest depth occurs in the southwestern area of the county, where it is deeply buried under overlying bedrock.
- *Thickness*: 0 to 100 feet. The aquifer is fully saturated in the western portions of the county, generally where it is confined. However, in the narrow ridges of the northern and eastern portions, it may be substantially dewatered.
- *Use*: Less than 1% of county wells with known construction information.
- *Mapped karst features/springs*: No sinkholes, 2 stream sinks, and 6 springs. Stream sinks occur in valleys where overlying units have eroded away.
- *Pollution sensitivity*: Ranges from very high to moderate. Wells cased near the top of the Jordan can extract water that is geochemically different from wells cased near the bottom, possibly from internal aquitards within the lower Jordan.

  Very high sensitivity occurs where the Jordan aquifer has no overlying bedrock units. In this setting, surface water can disappear into stream sinks and travel rapidly to springs farther down the valley.

  High sensitivity occurs where the Oneota is the first bedrock unit or where there is the entire thickness of the Oneota, and the thickness of the Shakopee Formation is less than 30 feet.

  Moderate sensitivity occurs where there is complete thickness of the Oneota and greater than a 30-foot thickness of the Shakopee Formation. This condition generally occurs where the Jordan is confined, an area covering the southwestern portion of the county, extending northeast from Spring Grove past Caledonia. The area mapped as moderate exhibits a range of residence time and connectivity to overlying aquifers, with some well samples showing vintage tritium age and carbon-14 residence times that are several thousand years old, and others showing mixed tritium age and elevated nitrate and chloride.

- *Residence time*: Samples were collected from 3 springs and 15 wells. Of these 18 samples, 16 were analyzed for tritium age with the following results: 7 mixed and 9 vintage. Two samples had carbon-14 residence times of 2,000 and 2,500 years. A recent investigation focused on nitrate and pesticide concentration trends in southeastern Minnesota determined average residence times of Jordan aquifer springs to be approximately two to three decades (Kuehner and others, 2025). Longer residence times corresponded to springs emanating from the deepest stratigraphy. Residence time for wells was similar to springs, with the longer residence times from deeper wells.
- *Anthropogenic chemistry*: Of the 18 samples analyzed for nitrate, 10 were elevated. Of the 17 samples analyzed for chloride, 5 were elevated from anthropogenic sources and 1 was from an unknown source.

Lone Rock aquifer (Figure 27)

- *Extent*: Present over most of the county.
- *Depth*: 0 to 860 feet. Its greatest depth occurs in the southwestern area of the county, where it is deeply buried under overlying bedrock.
- *Thickness*: 0 to 150 feet. The aquifer is confined in the south-central portion of the county.
- *Use*: Approximately 9% of wells with known construction information.
- *Mapped karst features/springs*: No sinkholes, 2 stream sinks, and 81 springs. Stream sinks occur in the eastern portion of the county.
- *Pollution sensitivity*: Ranges from very high near valley edges, where the St. Lawrence aquitard is thin or absent, to very low over most of the rest of the county.

  Very high sensitivity occurs where the Lone Rock has no overlying bedrock units.

  High sensitivity occurs where the St. Lawrence aquitard is the only bedrock unit above the Lone Rock.

  Very low sensitivity occurs where the Lone Rock is buried deeply and underlies the St. Lawrence aquitard.
- *Residence time*: Samples were collected from 24 springs and 22 wells. Of these 46 samples, 39 were analyzed for tritium age with the following results: 4 recent, 19 mixed, and 16 vintage. No spring samples had a vintage tritium age. Carbon-14 residence times of well samples range between 4,000 and 16,000 years. A recent investigation focused on nitrate and pesticide concentration trends in southeastern Minnesota determined the average residence time of St. Lawrence aquitard and Lone Rock aquifer springs to be approximately three to four decades (Kuehner and others, 2025).
- *Anthropogenic chemistry*: Of the 43 samples analyzed for nitrate, 21 were elevated, consisting of 18 springs and 3 wells. Of the 43 samples analyzed for chloride, 7 were elevated from anthropogenic sources, all of which were springs. Elevated samples occurred near valley edges, where the overlying St. Lawrence aquitard loses its protective characteristics.

Wonewoc aquifer (Figure 28)

- *Extent*: Present over most of the county.
- *Depth*: 0 to 975 feet. The greatest depth occurs in the southwestern area of the county, where it is deeply buried under overlying bedrock.
- *Thickness*: 0 to 130 feet. The aquifer is confined in the south-central portion of the county.
- *Mapped karst features/springs*: No sinkholes or stream sinks and 22 springs.
- *Use*: Approximately 46% of wells with known construction information.
- *Pollution sensitivity*: Ranges from high to very low.

  High sensitivity occurs where the Wonewoc aquifer has no overlying bedrock units.

  Moderate sensitivity occurs where the Lone Rock aquifer is the only bedrock unit above the Wonewoc.

  Very low sensitivity occurs across most of the aquifer because of its position below the St. Lawrence aquitard and its distance from the land surface.
- *Residence time*: Samples were collected from 42 wells. Of the 42 total samples, 35 were analyzed for tritium age with the following results: 1 recent, 13 mixed, and 21 vintage. Carbon-14 residence times ranged between less than 100 and 5,000 years.
- *Anthropogenic chemistry*: Of the 40 samples analyzed for nitrate, 4 were elevated. Of the 40 samples analyzed for chloride, 2 were elevated from anthropogenic sources. Almost all samples with recent or mixed tritium or elevated nitrate or chloride occurred in valleys or near valley edges, where pollution sensitivity is elevated.

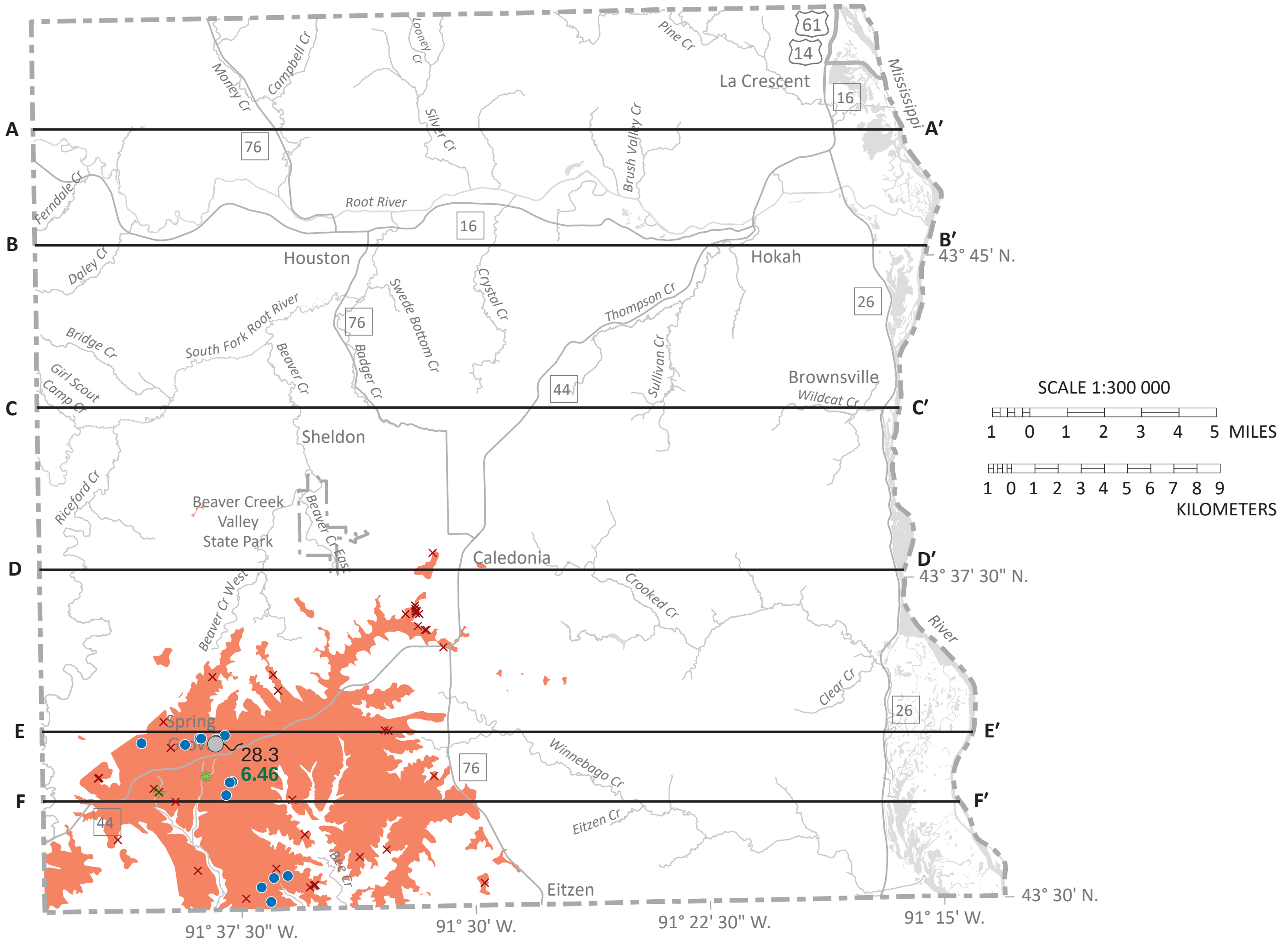
Mt. Simon aquifer (Figure 29)

- *Extent*: Present throughout the entire county.
- *Depth*: Ranges from approximately 100 feet along the Mississippi River to 1,450 feet in the west. The greatest depth occurs in the southwest, where it is deeply buried under overlying bedrock.
- *Thickness*: 300 to 350 feet. It is fully saturated and confined everywhere except in valleys, where the overlying Eau Claire aquitard is thin or absent.
- *Use*: Approximately 2% of wells with known construction information.
- *Mapped karst features/springs*: No sinkholes, stream sinks, or springs are mapped; however, along the Mississippi River, the aquifer provides continuous discharge that serves as baseflow, and artesian pressure can create flowing well conditions.
- *Pollution sensitivity*: Ranges from moderate in valleys and along the Mississippi River, where the overlying Eau Claire aquitard is absent, to very low over the majority of the rest of the county.
- *Residence time*: All 11 samples were from wells; 7 were analyzed for tritium age with the following results: 1 mixed and 6 vintage. Carbon-14 residence time from 5 well samples ranged between 12,000 and 30,000 years.
- *Anthropogenic chemistry*: Of the 11 samples analyzed for nitrate, none were elevated. Of the 11 samples analyzed for chloride, 5 were naturally elevated by ancient brine. Elevated natural chloride in the Mt. Simon is common in nearby Winona County and elsewhere in Minnesota.

Multiple-aquifer wells (Figure 30)

Multiple-aquifer wells intersect more than one aquifer. Since 2008, the Minnesota Well Code prevents new wells from interconnecting aquifers separated by a confining layer, because they can become conduits for contamination (Minnesota Administrative Rules, 4725.2020, Subpart 1).

- *Residence time*: Of the 17 samples collected, 12 were analyzed for tritium age with the following results: 2 recent, 3 mixed, and 7 vintage. One Eau Claire–Mt. Simon aquifer well had an estimated carbon-14 residence time of 11,000 years.
- *Anthropogenic chemistry*: Of the 13 samples analyzed for nitrate, 5 were elevated; 4 of these occurred above the St. Lawrence aquitard, and 1 occurred in a combined Tunnel City–Wonewoc well in a valley, where the overlying St. Lawrence aquitard is eroded away. Of the 13 samples analyzed for chloride, 5 were elevated from anthropogenic sources; 3 were naturally elevated by ancient brine.



Pollution sensitivity rating

Estimated vertical travel time.

Very high: hours to months

Water sample and aquifer symbols

Symbol color indicates tritium age of water sample.

Spring

Karst features

- Spring
- Sinkhole
- Stream sink

Tritium age

Symbol color indicates tritium age of water sample.

Not sampled for tritium

Symbols and labels

28.3 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)

6.46 Nitrate: if shown, concentration is ≥1 ppm.

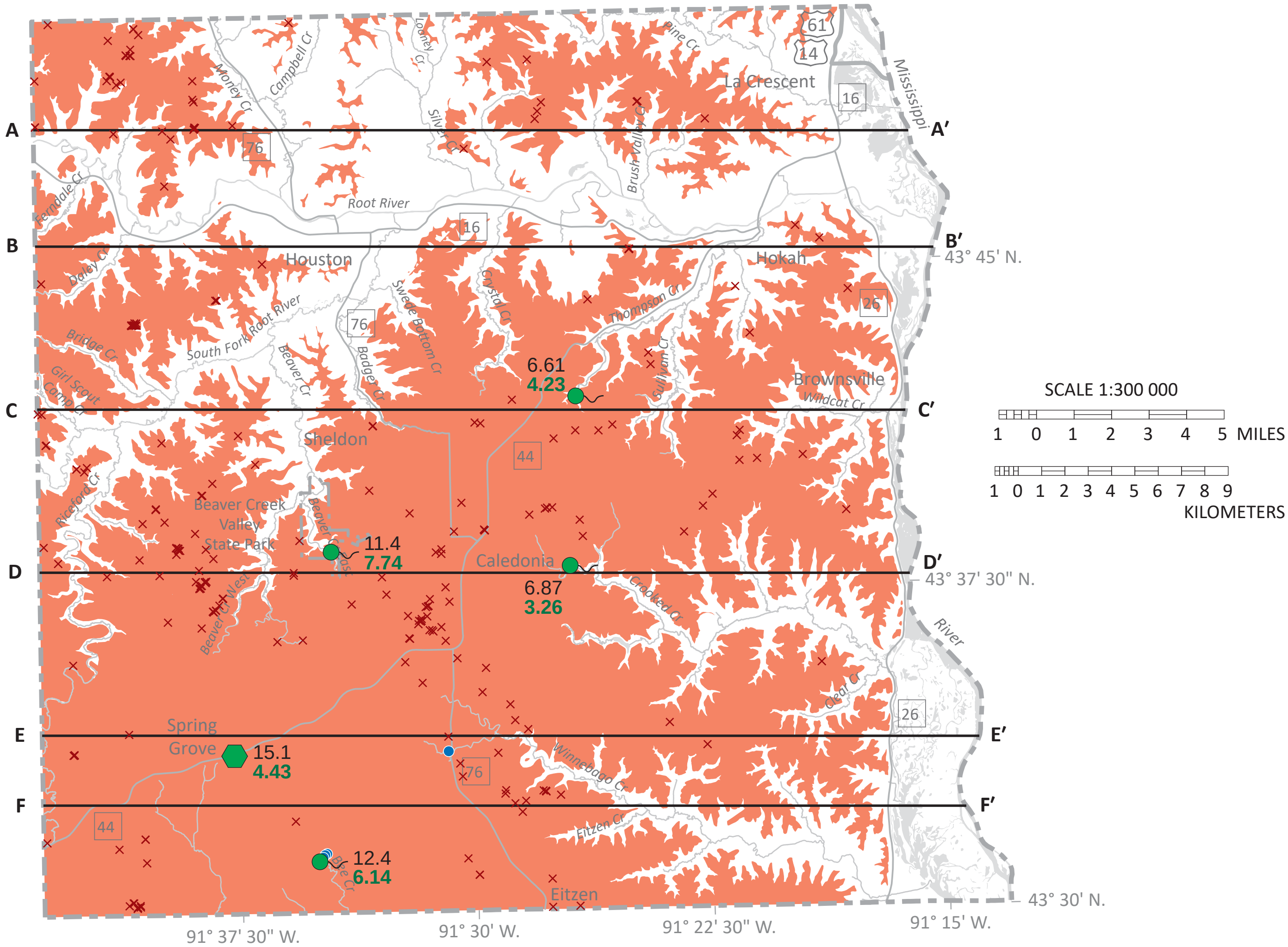
B —— B′ Line of cross section (Part B)

Body of water

View hydrostratigraphy

Figure 24. Pollution sensitivity of the Cummingsville through St. Peter aquifers

The sensitivity of each aquifer is very high due to proximity to the land surface, mapped karst features, and the presence of anthropogenic influences on groundwater chemistry.



Pollution sensitivity rating

Estimated vertical travel time.

Very high: hours to months

Tritium age

Symbol color indicates tritium age of water sample.

Mixed

Water sample and aquifer symbols

Symbol color indicates tritium age of water sample.

Well

Spring

Symbols and labels

11.4 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)

4.23 Nitrate: if shown, concentration is ≥1 ppm.

B —— B′ Line of cross section (Part B)

Body of water

Karst features

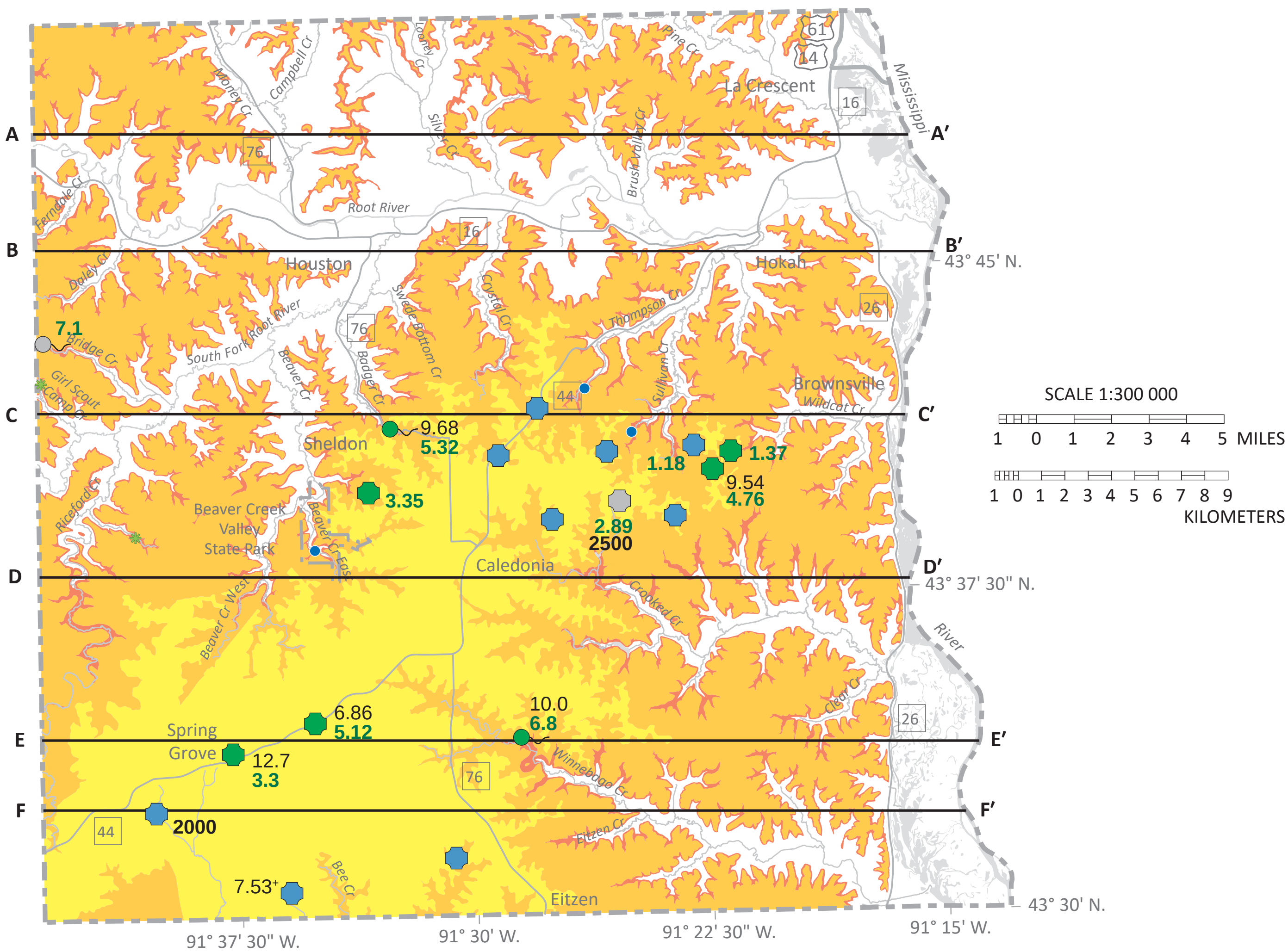
Spring

Sinkhole

View hydrostratigraphy

Figure 25. Pollution sensitivity of the Prairie du Chien aquifer

Sensitivity is very high due to proximity to the land surface over much of the county, mapped karst features, and the presence of anthropogenic influences on groundwater chemistry.



Pollution sensitivity rating

Estimated vertical travel time.

- Very high: hours to months
- High: weeks to years
- Moderate: years to decades

Water sample and aquifer symbols

Symbol color indicates tritium age of water sample.

- Well
- Spring

Karst features

- Spring
- Stream sink

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage
- Not sampled for tritium

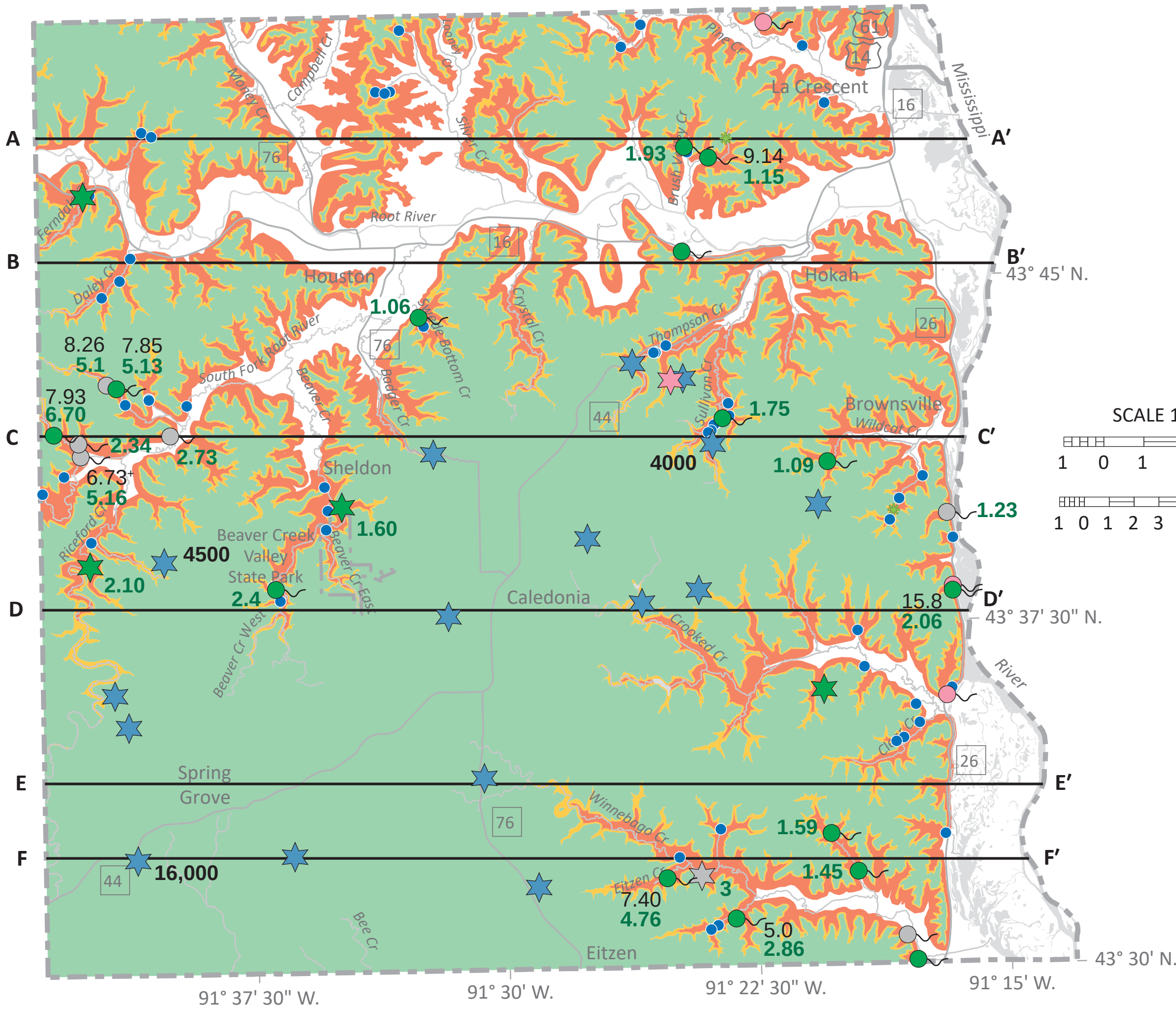
Symbols and labels

- 9.54 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)
- **3.3** Nitrate: if shown, concentration is ≥1 ppm.
- **2000** Carbon-14 (^{14}C): estimated groundwater residence time in years
- B —— B′ Line of cross section (Part B)
- Body of water

View hydrostratigraphy

Figure 26. Pollution sensitivity of the Jordan aquifer

Moderate sensitivity occurs where there is the entire thickness of the overlying Oneota Dolomite and at least 30 feet of the Shakopee Formation. High sensitivity is found in areas where the overlying Prairie du Chien is thinner than the criteria set for moderate sensitivity. Very high sensitivity occurs in valleys where the Jordan is the first unit below the ground surface. In this setting, surface water can disappear into stream sinks and travel rapidly to springs farther down the valley.



Pollution sensitivity rating

Estimated vertical travel time.

- Very high: hours to months
- High: weeks to years
- Very low: a century or more

Water sample and aquifer symbols

Symbol color indicates tritium age of water sample.

- Well
- Spring

Karst features

- Spring
- Stream sink

Tritium age

Symbol color indicates tritium age of water sample.

- Recent
- Mixed
- Vintage
- Not sampled for tritium

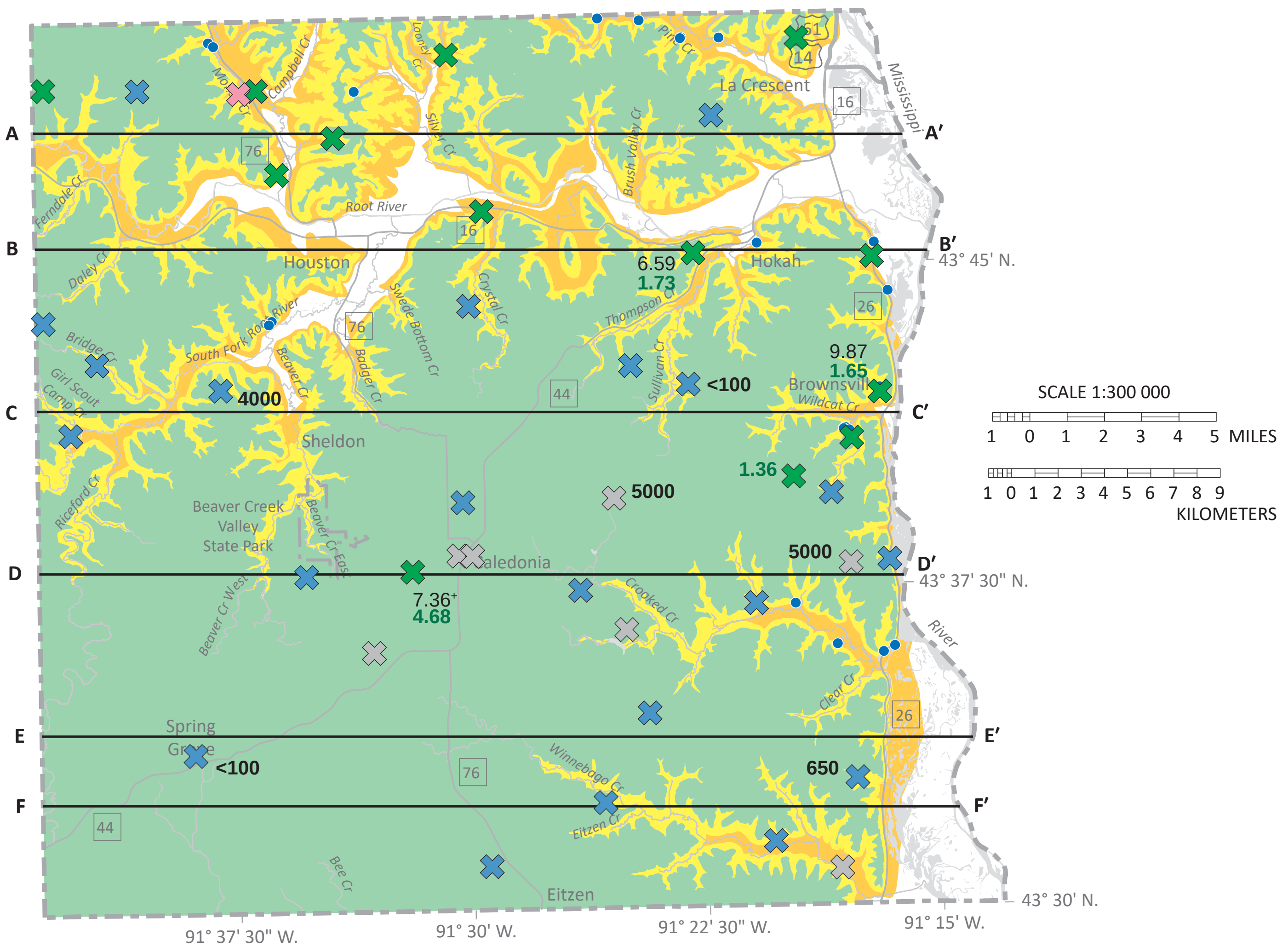
Symbols and labels

8.26	Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)
5.13	Nitrate: if shown, concentration is ≥1 ppm.
4500	Carbon-14 (^{14}C): estimated groundwater residence time in years
B —— B′	Line of cross section (Part B)
	Body of water

View hydrostratigraphy

Figure 27. Pollution sensitivity of the Lone Rock aquifer

Sensitivity is very low over much of the county but increases to high and very high near valley edges where the St. Lawrence aquitard is thin or absent. High sensitivity is delineated where the St. Lawrence aquitard is the only bedrock unit above the Lone Rock. Very high sensitivity is delineated where there are no overlying bedrock units.



Pollution sensitivity rating

Estimated vertical travel time.

- High: weeks to years
- Moderate: years to decades
- Very low: a century or more

Water sample and aquifer symbols

Symbol color indicates tritium age of water sample.

- ✖ Well

Karst features

- • Spring

Tritium age

Symbol color indicates tritium age of water sample.

- Recent
- Mixed
- Vintage
- Not sampled for tritium

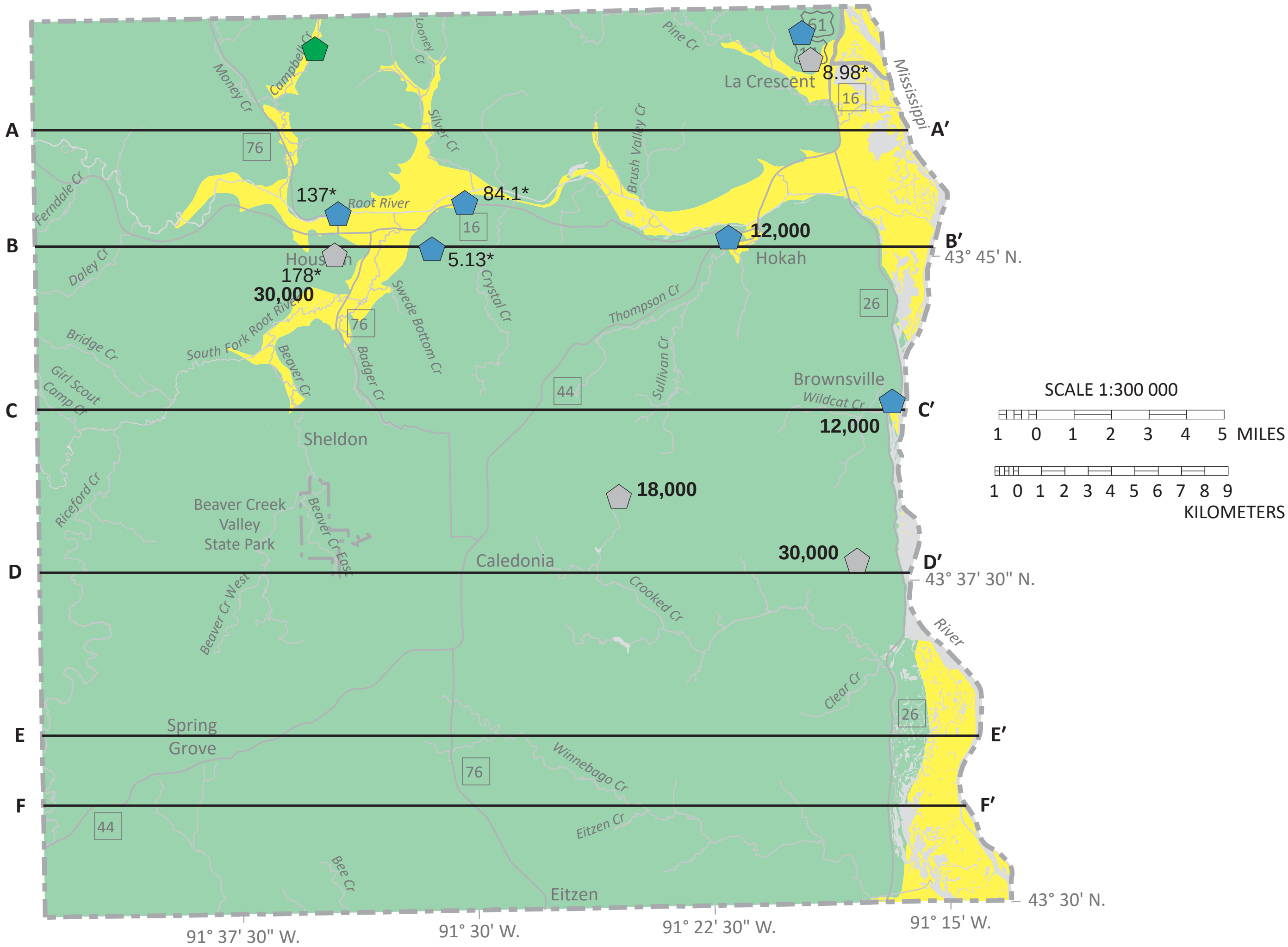
Symbols and labels

- 9.87 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)
- 1.73 Nitrate: if shown, concentration is ≥1 ppm.
- 5000 Carbon-14 (^{14}C): estimated groundwater residence time in years
- B —— B′ Line of cross section (Part B)
- Body of water

View hydrostratigraphy

Figure 28. Pollution sensitivity of the Wonewoc aquifer

Sensitivity is very low for most of the aquifer because of its position below the St. Lawrence aquitard and its distance from the land surface. In valleys, the sensitivity increases to moderate, where the Lone Rock aquifer is the only bedrock unit above the Wonewoc. Sensitivity increases to high in valleys where the Wonewoc is the first bedrock unit below the land surface.



Pollution sensitivity rating

Estimated vertical travel time.

Moderate: years to decades

Very low: a century or more

Water sample and aquifer symbols

Symbol color indicates tritium age of water sample.

Well

Tritium age

Symbol color indicates tritium age of water sample.

Mixed

Vintage

Not sampled for tritium

Symbols and labels

137* Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)

18,000 Carbon-14 (^{14}C): estimated groundwater residence time in years

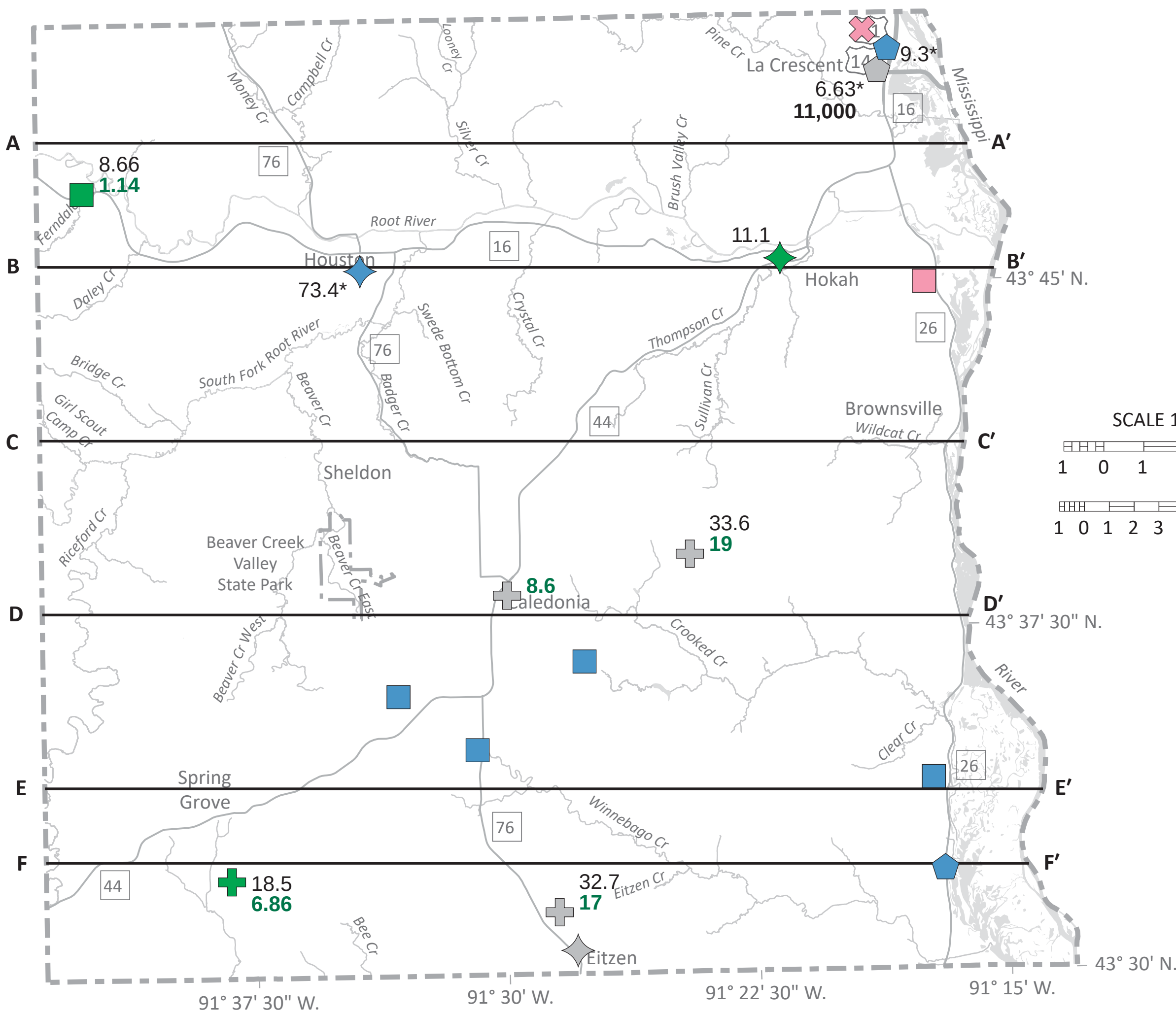
B —— B′ Line of cross section (Part B)

Body of water

View hydrostratigraphy

Figure 29. Pollution sensitivity of the Mt. Simon aquifer

Sensitivity is very low over the majority of the county and moderate in valleys and along the Mississippi River, where the overlying Eau Claire aquitard is absent.



Water sample and aquifer symbols

Symbol color indicates tritium age of water sample.

- Prairie du Chien–Jordan
- Tunnel City–Wonewoc
- Wonewoc–Eau Claire
- Eau Claire–Mt. Simon
- Wonewoc–Mt. Simon

Tritium age

Symbol color indicates tritium age of water sample.

- Recent
- Mixed
- Vintage
- Not sampled for tritium

Symbols and labels

18.5	Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)
8.6	Nitrate: if shown, concentration is ≥1 ppm.
11,000	Carbon-14 (^{14}C): estimated groundwater residence time in years
B —— B′	Line of cross section (Part B)
	Body of water

View hydrostratigraphy

Figure 30. Multiple-aquifer wells

Multiple-aquifer wells intersect more than one aquifer. The Minnesota Well Code no longer allows new wells from interconnecting aquifers separated by confining layers because they can become conduits for contamination.

Hydrogeologic cross sections (Plate 6)

The hydrogeologic cross sections shown on Plate 6 illustrate the horizontal and vertical extent of aquifers and aquitards, general groundwater flow direction, groundwater residence time, and groundwater chemistry.

The cross sections were constructed in GIS using a combination of well data from CWI and sections of Part A: Bedrock Geology (Plate 2), Surficial Geology (Plate 3), and Bedrock Topography and Depth to Bedrock (Plate 4). Most wells projected onto the trace of the cross sections are from distances of less than 0.5 kilometers; the maximum projected distance is 3.2 kilometers.

Aquifers shown on cross sections are 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 interpretations were assigned using tritium-age results from other cross sections, pollution sensitivity of the aquifers, and the relative permeability of aquitards.

Aquifers and aquitards within 50 feet of the bedrock surface are delineated with an enhanced-permeability zone, where interconnected fractures can increase the ability of aquifers to transmit water but can also degrade the ability of aquitards to protect underlying aquifers.

Northern cross sections: A–A′ and B–B′

The landscape is deeply dissected by numerous tributary valleys that flow to the Root River. The first bedrock units are the karstic Shakopee (Ops) and Oneota (Opo) formations of the Prairie du Chien Group. Streams have cut through the underlying Jordan aquifer (Ꞓj) and St. Lawrence aquitard (Ꞓs) into the Lone Rock (Ꞓtc) and Wonewoc (Ꞓw) aquifers. Mixed tritium-age waters and elevated chloride and nitrate were found in the Wonewoc aquifer. The Mt. Simon (Ꞓm) aquifer is protected by the Eau Claire (Ꞓe) aquitard, indicated by vintage tritium-age waters and carbon-14 residence times ranging from 12,000 to 30,000 years on cross section B–B′. Local groundwater movement is downward and toward rivers and creeks. Regional groundwater movement is east, where groundwater discharges to the Mississippi River.

Central cross sections: C–C′ and D–D′

The landscape is a relatively flat plateau, with fewer deeply dissected valleys in the central portions. The first bedrock units are the karstic Shakopee (Ops) and Oneota (Opo) formations of the Prairie du Chien Group, where sinkholes are common in the western and central portions. Within valleys, the St. Lawrence (Ꞓs) aquitard's protective characteristics are diminished, and springs show mixed tritium ages and elevated chloride and nitrate. In the western and central portions of cross sections C–C′ and D–D′, where not dissected, the St. Lawrence is a competent aquitard as indicated by vintage tritium age and carbon-14 residence times of 4,000 years in the Wonewoc aquifer (Ꞓw) in the west to 30,000 years in the Mt. Simon (Ꞓm) aquifer in the east. Local groundwater movement is downward and toward rivers and creeks. Regional groundwater movement is east, where groundwater discharge occurs to the Mississippi River.

Southern cross sections: E–E′ and F–F′

The western portions of these cross sections highlight the Upper Carbonate Plateau, an area roughly bound between County Highway 8 and State Highway 76. The first bedrock units are the karstic Cummingsville (Oc) aquifer and the Decorah–Platteville–Glenwood (Od and Opg) aquitards. The shallowly buried aquitards are compromised, evident from the samples on cross section E–E′ in the underlying Prairie du Chien (Opd and Opo) and Jordan (Ꞓj) aquifers, having mixed tritium ages and elevated chloride and nitrate. A carbon-14 residence time of less than 100 years in the Wonewoc aquifer (Ꞓw) on cross section E–E′ is inconsistent with the depth and number of overlying aquitards and may suggest leakage into the well or a pathway along the nearby fault to the west of the well. The Jordan (Ꞓj) aquifer is not impacted on cross section F–F′ and has a carbon-14 residence time of 2,000 years. Groundwater residence times vary greatly above and below the St. Lawrence (Ꞓs) aquitard on cross section F–F′, with a carbon-14 residence time of 2,000 years near the top of the aquitard and 16,000 years below it. Local groundwater movement is downward and toward rivers and creeks. Regional groundwater movement is east, where groundwater discharge occurs to the Mississippi River.

Groundwater flow direction and recharge

Groundwater moves from higher to lower potential energy. The direction of groundwater movement is interpreted from the equipotential contours constructed from measured water levels in wells. Equipotential contours show areas where the pressure head of groundwater is the same. Groundwater flow is perpendicular to these lines in the direction of decreasing pressure. Equipotential contours can be used to identify groundwater flow direction, recharge zones, and discharge zones.

Regional groundwater flow direction of aquifers above the Eau Claire aquitard is generally to the east, but also locally toward rivers and creeks. Groundwater flow direction of the Mt. Simon aquifer is primarily to the east, where groundwater discharges to the Mississippi River. The Mississippi River is the major groundwater discharge feature for the surficial sand and bedrock aquifers. In addition, groundwater discharge provides cool isothermal baseflow to numerous springs and trout streams.

Precipitation is the source of recharge to unconsolidated deposits, which then provide recharge to underlying aquifers. Recharge to aquifers above the Jordan is heavily influenced by karst, which has high infiltration rates. However, recharge may be limited where less permeable loess overlies bedrock. Estimated recharge to Houston County's surficial aquifers ranges from 3.6 to 12.5 inches per year (Smith and Westenbroek, 2015). Estimated recharge to confined bedrock aquifers is generally less than 1% of average precipitation, or roughly 0.37 inches per year (Delin and Falteisek, 2007). Recharge rates can be influenced by high-volume pumping, which may steepen groundwater gradients locally, increase recharge, and affect groundwater quality (Tipping, 2012).

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 lifting), the pumping-test data were obtained from CWI for wells with the following criteria:

- The casing diameter was at least 6 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 values of 15 wells in Houston County met these conditions: 2 in the water-table aquifer and 13 in bedrock aquifers. The highest mean specific capacity of 21.5 gpm/ft was calculated for a water-table well (Table 2). The wide range between minimum and maximum specific capacity values for bedrock is likely due to maximum value wells intersecting fracture networks within the respective aquifers.

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 are available for two bedrock aquifers. The Wonewoc aquifer ranged from 1,360 ft^2/day to 2,800 ft^2/day, and the Eau Claire–Mt. Simon aquifer ranged from 1,540 ft^2/day to 1,980 ft^2/day (DNR, 2025). Several consulting firms and state agencies have completed aquifer tests in Houston County, but the documentation is insufficient to include in this report.

Table 2. Specific capacity values of select wells

Aquifer	Casing diam. (in.)	Mean (gpm/ft)	Min. (gpm/ft)	Max. (gpm/ft)	No. of wells
Unconsolidated					
Water table	6	21.5	5.0	38.0	2
Bedrock					
Jordan	12	2.9	-	-	1
Jordan–St. Lawrence	16	9.9	9.4	10.2	3
Wonewoc	8–18	5.2	0.9	11.9	5
Wonewoc–Eau Claire	18	14.3	-	-	1
Eau Claire–Mt. Simon	12	14.1	-	-	1
Mt. Simon	12–18	6	1.1	10.3	2

Specific capacity data adapted from the CWI.
Dash (-) means no data

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 (DNR, 2023c).

Well nests consist of closely spaced wells that are constructed at different depths in different aquifers. Long periods of record from multiple aquifers are useful for determining trends and provide insight into how aquifers respond to recharge events, climatic conditions, and pumping stresses.

Figure 31 shows the groundwater elevation hydrographs of three monitoring wells from a well nest located between Brownsville and Reno; the well nest location is shown on Figure 32. Groundwater elevation is compared to annual precipitation collected at the National Weather Service Reporting Station 211198 in Caledonia, Minnesota.

- Well 231848 is constructed to a depth of 322 feet into the Prairie du Chien and Jordan aquifers and shows groundwater elevation changes in response to increases and decreases in precipitation and snowmelt. Groundwater elevation does not react rapidly to individual precipitation events. The largest bulk groundwater elevation changes are in response to increases or decreases in the annual precipitation. The groundwater level over the period of record ranges approximately 40 feet between highs and lows.
- Well 231847 is constructed to a depth of 565 feet in the Wonewoc aquifer. Groundwater level response to precipitation is muted, with the groundwater level over the period of record ranging approximately 8 feet between highs and lows.
- Well 231846 is constructed to a depth of 855 feet in the Mt. Simon aquifer. Groundwater level response to precipitation is muted, with the groundwater level over the period of record ranging approximately 6 feet between highs and lows.

Groundwater elevations of these aquifers differ by over 200 feet, showing a large vertical hydraulic gradient downward from the combined Prairie du Chien and Jordan to the Wonewoc and Mt. Simon aquifers at this location. Groundwater elevation differences between the Wonewoc and Mt. Simon aquifers at this location show a hydraulic gradient upward from the Mt. Simon aquifer to the Wonewoc aquifer.

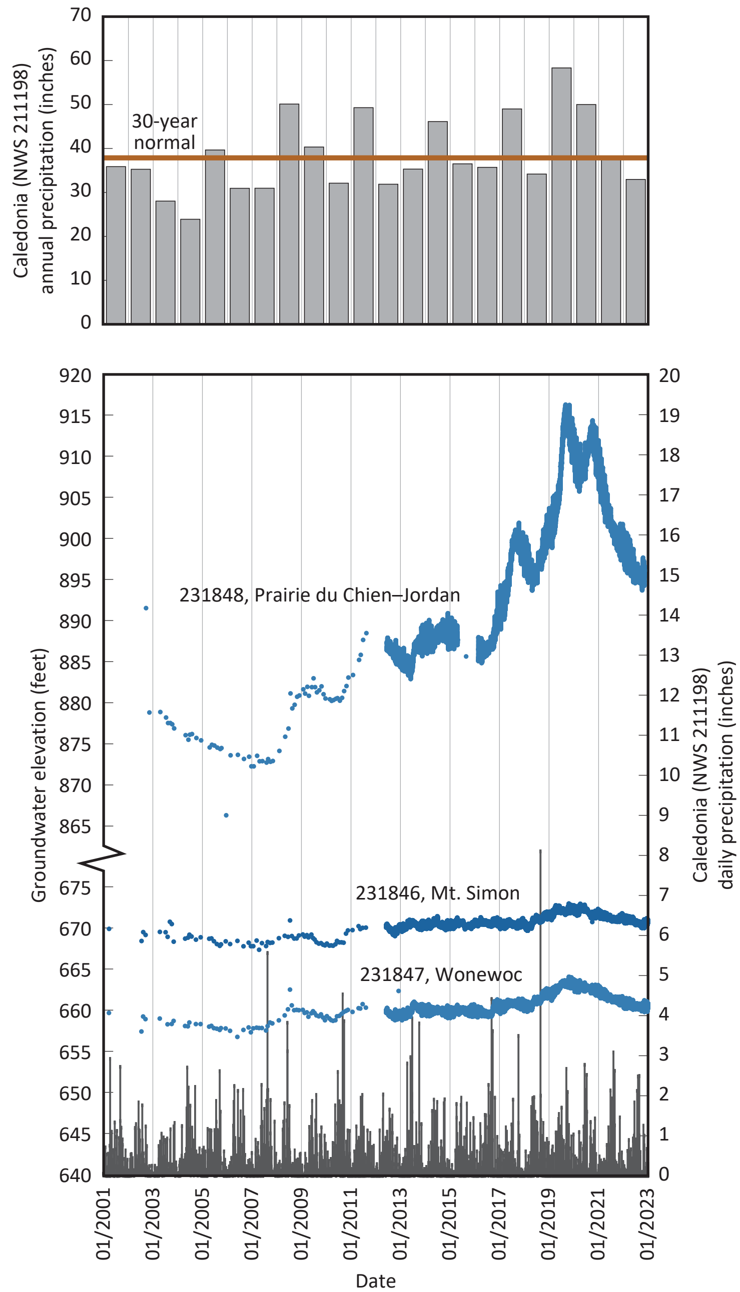


Figure 31. Hydrographs of groundwater level monitoring wells near Brownsville, Minnesota

Groundwater elevations of a combined Prairie du Chien–Jordan aquifer well, a Wonewoc aquifer well, and a Mt. Simon aquifer well are compared to annual precipitation data for the years 2001 to 2023. Climate data from DNR (2023a, 2023b). Well nest location is shown on Figure 32.

Groundwater use

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

Reported water use of high-volume users for 2021 is categorized in Table 3 and Figures 32 and 33 by type of water use and aquifer type (DNR, 2023d). The highest permitted groundwater use (67.4%) is for municipal and public water supply, which is primarily extracted from the Mt. Simon aquifer (or aquifer combinations that include the Mt. Simon). In general, high-volume use is centered around the cities of La Crescent, Spring Grove, Caledonia, and Houston. The second largest use (17.6%) is for pollution containment in Spring Grove, with this water coming from the St. Peter and Prairie du Chien aquifers. The third largest use (7.9%) is for livestock watering, which uses both unconsolidated and bedrock aquifers. These three water uses collectively made up approximately 93% of the permitted water used in 2021.

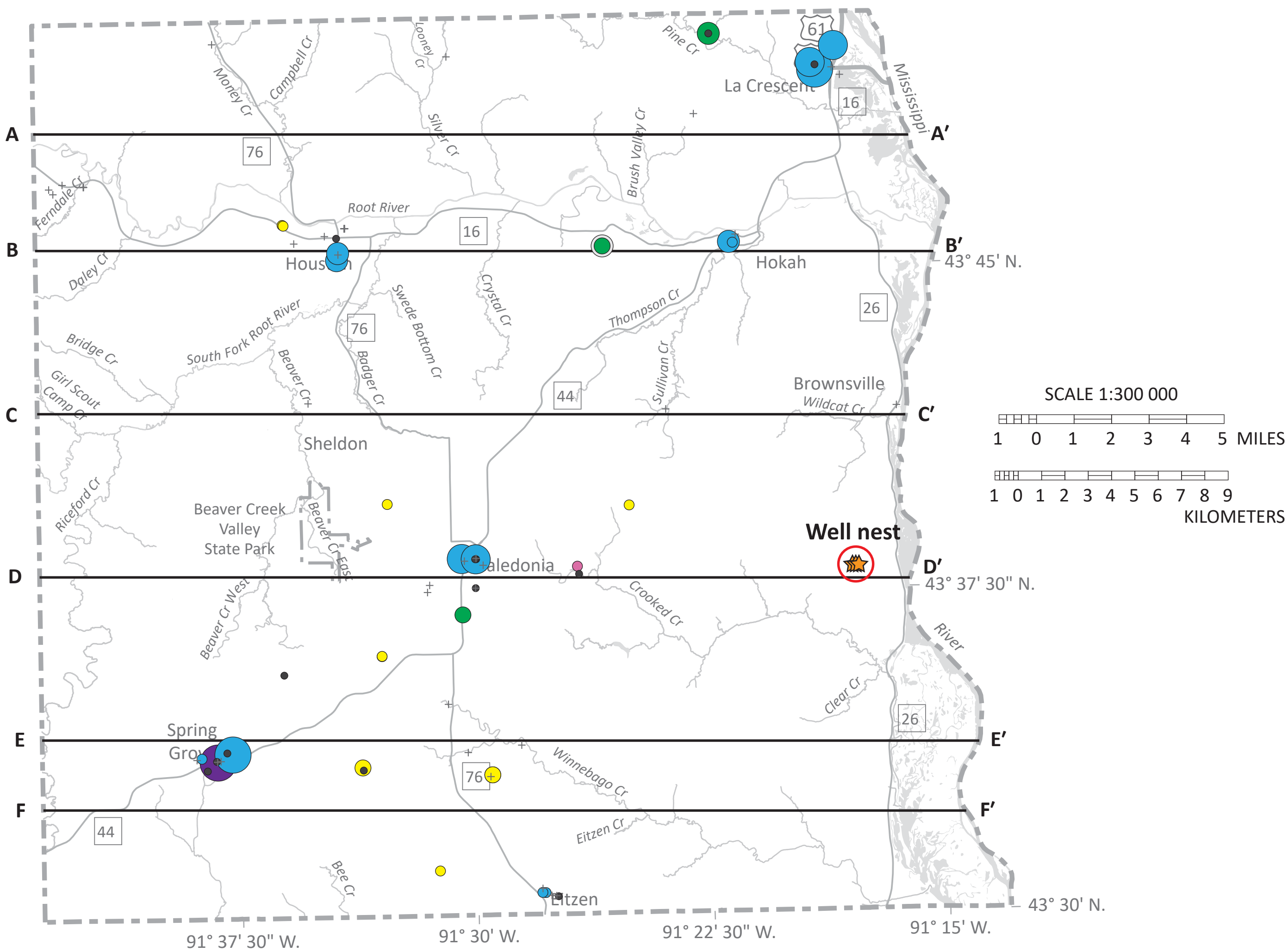
There are no reporting requirements for well owners that use less than 10,000 gallons per day or 1 million gallons per year, but the CWI maintains data for use type and aquifer type for these wells. Of the 2,222 wells with identified use codes, the majority are for domestic use (92%).

Annual water use for DNR permit holders for the years 1988 to 2021 is shown in Figure 34. Permitted water use varies annually due to annual precipitation, population growth, economic conditions, and other factors. Permitted annual water use increased in the early 1990s, climbing steadily to its peak in 2003. Since then, permitted annual water use has fluctuated. Municipal water supply had the largest use difference over the 5-year period from 2017 to 2021.

Table 3. Reported 2021 water use from DNR groundwater permit holders

Aquifer	No. of wells	Municipal/public water supply	Pollution containment	Livestock watering	Golf course irrigation	Basin (lake) level maintenance	Sand and gravel washing	Total (mgy)	Total (%)
Unconsolidated									
Water table	1	--	--	0.9	--	--	--	0.9	0.2
Bedrock									
St. Peter, St. Peter–Jordan, Prairie du Chien, Prairie du Chien–Jordan, Jordan	11	59.2	86.8	0.1	--	--	0.1	146.1	29.6
Lone Rock	2	--	--	2.5	5.7	--	--	8.2	1.7
Lone Rock–Wonewoc, Wonewoc, Wonewoc–Eau Claire	12	86.6	--	28.8	--	--	--	115.4	23.4
Wonewoc–Mt. Simon, Eau Claire–Mt. Simon	6	118.5	--	--	--	--	--	118.5	24
Mt. Simon	7	68.2	--	--	16.5	12.6	--	97.3	19.7
Unknown	3	--	--	6.8	--	--	--	6.8	1.4
Total (mgy)	**N/A**	**332.5**	**86.8**	**39.1**	**22.2**	**12.6**	**0.1**	**493.3**	**--**
Total (%)	**N/A**	**67.4**	**17.6**	**7.9**	**4.5**	**2.6**	**<0.1**	**--**	**100**
Highest annual use from 2017 to 2021 (mgy)	**N/A**	**332.5**	**91.7**	**39.1**	**22.2**	**12.6**	**2.8**	**--**	**--**

Data from MPARS; mgy, million gallons per year
Dash marks (--) indicate no use in those categories
N/A indicates not applicable
Percentages may not equal 100 due to rounding.



Water use reported by DNR groundwater appropriation permit holders in 2021
(millions of gallons per year)

- Inactive
- No use
- >0–5
- >5–10
- >10–20
- >20–50
- >50

Use type

- Municipal/public water supply
- Pollution containment
- Livestock watering
- Golf course irrigation
- Basin (lake) level maintenance
- Sand and gravel washing

Symbols and labels

- DNR groundwater level observation well (hydrograph shown on Figure 31)
- B ——B′ Line of cross section (Part B)
- Body of water

Figure 32. Distribution of groundwater appropriation permits for 2021 by volume reported and use type

Municipal and public water supply accounts for the largest permitted groundwater use.

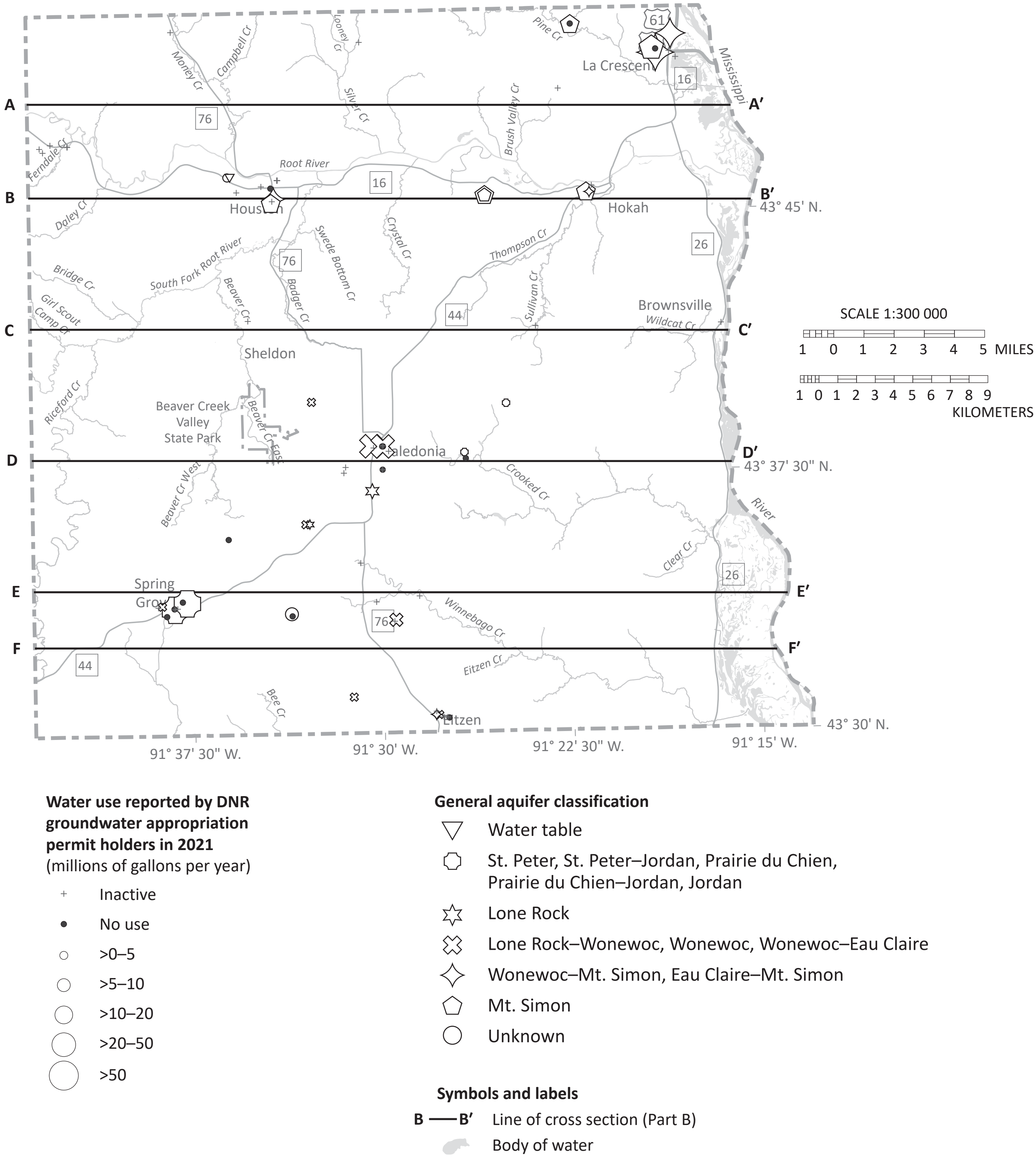


Figure 33. Distribution of groundwater appropriation permits for 2021 by volume reported and general aquifer classification

The majority of the permitted water used in the county is from bedrock aquifers.

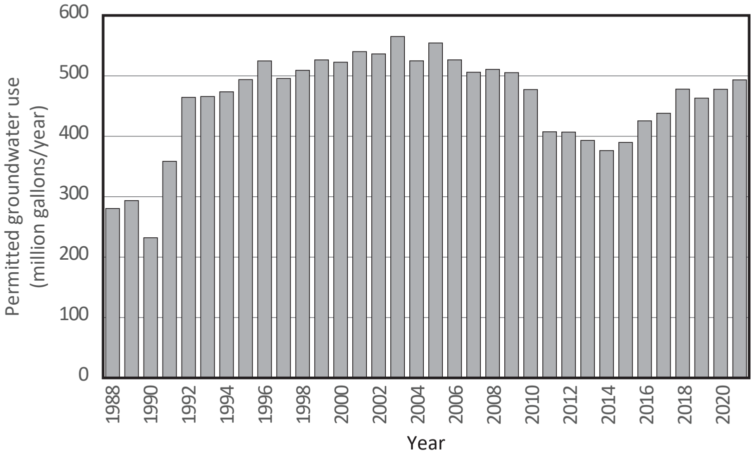


Figure 34. DNR annual permitted groundwater use for Houston County (1988 to 2021)

Conclusions

Houston County's land use is dominated by a mix of agricultural croplands, forest, and small towns. Its underlying geology influences land usage, with agricultural cropland common on the Upper Carbonate Plateau, the Prairie du Chien Plateau, and in valley bottoms. Geology affects the county's water resources. Much of the county is a karst terrain formed by precipitation and groundwater dissolving underlying carbonate sedimentary rock. Karst provides rapid water movement between the land surface and underlying aquifers, increasing their pollution sensitivity. It is one of the wettest counties in the state, with an average annual precipitation of approximately 37 inches. Rapid recharge can occur to aquifers above the St. Lawrence aquitard or where aquitards are not present, such as areas within deeply incised valleys.

Pollution sensitivity ratings were developed for aquifers using a combination of tritium and carbon-14 data for residence time and the inorganic chemicals chloride and nitrate. Human-caused occurrences of chloride and nitrate are relatively widespread in the water-table aquifer, comprised of the Prairie du Chien and Jordan aquifers in upland settings and the sand and gravel aquifer in lowland valley settings. Chloride and nitrate are relatively widespread in shallow aquifers, especially in wells completed above the St. Lawrence aquitard. Springs, not commonly used as sources of water, have elevated levels of both chloride and nitrate. A portion of the water emanating from springs is anthropogenically impacted water that mixes with older water. Below the St. Lawrence aquitard, groundwater shows long residence times and less human-influenced contamination. Wells completed in aquifers below the St. Lawrence can provide groundwater unimpacted by human activities if properly installed according to the Minnesota Well Code.

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Glossary

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

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

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

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

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

arsenic (As)—a chemical element that is sometimes dissolved in groundwater and is toxic to humans.

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

box plot—a graphical representation of a dataset's distribution.

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

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

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

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

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

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

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.

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

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

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

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

hydraulic—relating to water movement.

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

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

incised valley—a valley formed by flowing water cutting or eroding underlying geological strata.

infiltration—the movement of water from the land surface into the subsurface under unsaturated conditions.

isotope—variants of a particular chemical element. All isotopes of an element share the same number of protons but a different number of neutrons.

karstification—a process where precipitation chemically dissolves soluble rocks, such as limestone and dolostone, creating voids and pathways in the rock.

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

nitrate (NO_3, nitrate-nitrogen, nitrate-N)—a common form of nitrogen (N), the water-soluble anion NO_3^-. Elevated nitrate in water samples is a useful indicator of groundwater pollution from human activities. Humans are subject to nitrate toxicity, with infants especially vulnerable to methemoglobinemia, also known as blue baby syndrome. Nitrogen is an important nutrient, a major component of fertilizers, and a significant component of animal and human waste.

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

plateau—a landscape of relatively level topography that is elevated higher than the surrounding land and has a steep slope on its edge.

pseudokarst (hydrology)—groundwater moves through conduit-like voids that were developed through a process other than dissolution.

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

Quaternary—geologic time period that began approximately 2.6 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—a chemical or isotope used to interpret groundwater residence time.

saprolite—a residuum created from extensive chemical weathering of bedrock into clay minerals.

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

stable isotopes—chemical isotopes that are not radioactive.

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

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

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

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

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

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

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

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

Project samples collected before 2016 were analyzed by DNR staff; the University of Minnesota, Department of Earth and Environmental Sciences Laboratory (UMN); or the University of Waterloo Environmental Isotope Laboratory (Waterloo). Those collected in 2016 and 2017 were analyzed by DNR staff; MDA; MDH; UMN; or Waterloo.

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

Appendix Table A-1. Groundwater field sample collection and handling details for project samples collected prior to 2016

Parameter	**Enriched tritium**	**^{18}O and ^{2}H (Deuterium)**	**Cations**	**Anions**	**Trace constituents**	**Alkalinity**	**Carbon-14 (^{14}C)**
Lab	**Waterloo**	**Waterloo**	**UMN**	**UMN**	**UMN**	**DNR**	**UMN**
Sample container	500 ml HDPE	60 ml HDPE	15 ml Fisherbrand blue cap	50 ml Argos black bottle***	15 ml Sarstedt red cap	500 ml plastic	30-gallon barrel
Head space	yes	yes	yes	yes	yes	no	yes
Rinse	no	no	yes*	yes*	yes*	yes**	no
Filter	no	no	yes	yes	yes	no	yes
Preservation	no	no	1 drop 6N HCl	no	5 drops 15N HNO_3	no	NH_4OH added to adjust pH
Refrigeration	no	no	yes	yes	yes	yes, if not analyzed onsite	no
Shelf life	long	long	2 to 3 weeks	2 to 3 weeks	2 to 3 weeks	24 to 48 hours	years
Field duplicate	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	none
Field blank	none	none	1 for every 20 samples****	1 for every 20 samples****	1 for every 20 samples****	none	none
Storage duplicate	yes	yes	no	no	no	no	no

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

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

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

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

Appendix Table A-2. Groundwater field sample collection and handling details for project samples collected in 2016 and 2017

Parameter	Enriched tritium	^{18}O and ^{2}H (Deuterium)	Nitrate/ Nitrite & Total Phosphorus	F, Cl, SO_4	Metals	Bromide	Alkalinity	Carbon-14 (^{14}C)
Lab	**Waterloo**	**Waterloo**	**MDA**	**MDA**	**MDA**	**MDH**	**DNR**	**UMN**
Sample container	500 ml HDPE	60 ml HDPE	250 ml plastic	250 ml plastic	250 ml plastic	125 ml plastic	500 ml plastic	30-gallon barrel
Head space	yes	yes	yes	yes	yes	yes	no	yes
Rinse	no	no	yes*	yes*	yes*	yes*	yes**	no
Filter (micron)	no	no	0.45	0.45	0.45	0.45	no	no
Preservative	no	no	5 ml 10% H_2SO_4 (yellow cap)	no	2.5 ml 20% HNO_3 (red cap)	no	no	NH_4OH to pH 8.5
Refrigeration	no	no	yes	yes	yes	yes	yes, if not analyzed onsite	no
Holding time	long	long	28 days	28 days	6 months	28 days	24 to 48 hours	years
Field duplicate	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	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***	1 for every 20 samples***	none	none
Storage duplicate	yes	yes	no	no	no	no	no	no

*Rinse the bottle three times with sample water prior to collecting the sample (filtered if the sample is filtered). Rinsing process was filling the bottle with sample water and then pouring the contents out over the cap.

**Rinsed the bottle three times with sample water prior to collecting the sample. Bottle and cap were submerged and sealed to ensure no remnant bubbles.

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

Appendix B

Tritium values from precipitation

Samples were analyzed for enriched tritium by the University of Waterloo Environmental Isotope Laboratory for the determination of tritium values. Precipitation composites were collected at a Minnesota DNR MNgage climatology monitoring station in Maplewood (Twin Cities metropolitan area). Samples were composited over the course of 30-day periods between spring and fall over the years 2012 through 2017.

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

For additional weather station information, contact MNgage (climateapps.dnr.state.mn.us/HIDENsityEdit/HIDENweb.htm).

Appendix Table B-1. Enriched tritium results from MNgage precipitation station 62 29 22 9 BOULAY P

Sample date range	Tritium (TU)	Analytical error	Sample type
05/21/2012 to 06/20/2012	8.7	0.7	Precipitation composite
09/30/2012 to 10/30/2012	6.7	0.7	Precipitation composite
05/09/2014 to 06/09/2014	7.0	0.7	Precipitation composite
10/01/2014 to 10/31/2014	6.7	0.7	Precipitation composite
05/01/2015 to 05/31/2015	5.3	0.6	Precipitation composite
08/17/2016 to 09/16/2016	8.3	0.8	Precipitation composite
04/01/2017 to 04/30/2017	8.1	0.7	Precipitation composite
09/06/2017 to 10/06/2017	6.5	0.6	Precipitation composite

Tritium-age methodology

The Part B atlas series uses tritium data to assess the residence time of groundwater, which is then used to evaluate the atlas pollution sensitivity models. Where current data is insufficient, historical data is used from collaborating partners.

Residence time is classified for the time the sample was collected. Historic tritium unit (TU) values change over time because of tritium's relatively short half-life of 12.32 years (Lucas and Unterweger, 2000). Historic values were converted to coincide with the time of sample collection for this atlas, as shown in Table B-2.

The Cold War era classification is a special case and implies that groundwater sampled for an atlas infiltrated into the ground in the 1960s. This classification is only assigned to samples collected contemporaneously with an atlas. No samples collected for the Houston project had a Cold War era classification.

Appendix Table B-2. Tritium classification by date of sample collection

Tritium age	2015 to 2017	2013 to 2014	2012 or before
Cold War era	>15 TU	NA	NA
Recent	≥8 to 15 TU	≥8 TU	≥10 TU
Mixed	>1 to <8 TU	>1 and <8 TU	>1 and <10 TU
Vintage	≤1 TU	≤1 TU	≤1 TU

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