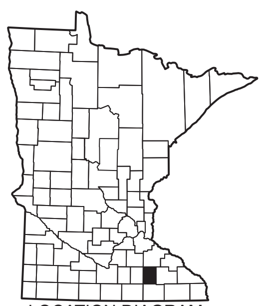
Groundwater Atlas of Dodge County, Minnesota

County Atlas Series C-50, Part B - Hydrogeology



LOCATION DIAGRAM

Report

To accompany these atlas components:

Plate 7, Water Chemistry

Plates 8–9, Hydrogeologic Cross Sections

DEPARTMENT OF NATURAL RESOURCES

St. Paul 2024

mndnr.gov/groundwatermapping

The County Atlas Series

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

Part A - Geologic Atlas

The precursor to this atlas is the *Geologic Atlas of Dodge County, Minnesota, C-50, Part A* (Steenberg, 2019), published by the Minnesota Geological Survey. It contains Plate 1, Data-Base Map (Bauer and Chandler); Plate 2, Bedrock Geology (Retzler); Plate 3, Surficial Geology (Marshall and McDonald); Plate 4, Quaternary Stratigraphy (Meyer, Marshall, and McDonald); Plate 5, Sand Distribution Model (Meyer, Lively, and Retzler); and Plate 6, Bedrock Topography and Depth to Bedrock (Retzler).

Information is available on the Minnesota Geological Survey page.

Part B - Groundwater Atlas

This atlas was published by the Minnesota Department of Natural Resources, which expanded on the geologic information from Part A. Completed atlases, chemistry data, and more information are available through the Minnesota Department of Natural Resources, Groundwater Atlas Program page.

Citation for this atlas:

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Acknowledgments

Authors Randy J. Bradt and John D. Barry, GIS/Cartography Randy J. Bradt and Holly Johnson, Editor Susan Montgomery.

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Contributors from staff at the Minnesota Department of Natural Resources include Dan Cronquist, Rachel Lindgren, Nicholas Budde, Emma Young, Vanessa Baratta-Person, Scott Pearson, and Todd Petersen.

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

Report Contents

Report Figures

Report Tables

Plates (accompanying folded inserts)

Technical reference

Maps were compiled and generated in a geographic information system. Digital data products are available from the Minnesota Department of Natural Resources Groundwater Atlas Program through the following page.

Maps were prepared from Minnesota Department of Natural Resources and other publicly available information. Every reasonable effort has been made to ensure the accuracy of the data on which the report and map interpretations were based. However, the Minnesota Department of Natural Resources does not warrant the accuracy, completeness, or any implied uses of these data. Users may wish to verify critical information; sources include both the references here and information on file in the offices of the Minnesota Geological Survey and the Minnesota Department of Natural Resources.

Every effort has been made to ensure the interpretations conform to sound geologic and cartographic principles. These maps should not be used to establish legal title, boundaries, or locations of improvements.

Base maps were modified from the Minnesota Geological Survey, *Geologic Atlas of Dodge County, Minnesota, 2019.* Universal Transverse Mercator projection, Zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion factors

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

Groundwater Atlas of Dodge County, Minnesota

by Randy J. Bradt and John D. Barry

Executive summary

This report and the accompanying plates describe the groundwater characteristics of the county and were produced by the Minnesota Department of Natural Resources (DNR). They build on the geology described in Part A, previously published by the Minnesota Geological Survey (MGS) (Steenberg, 2019).

The atlas illustrates the hydrogeologic setting using maps, plates, figures, tables, and text. Principal products include groundwater flow maps, illustrations summarizing the results for select water chemistry, aquifer pollution sensitivity maps, and geologic cross sections. Key elements and findings are summarized below.

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

Dodge County is in southeastern Minnesota with land use that is mostly agricultural with minor forested areas found primarily along stream corridors. It has a humid-continental climate with average temperatures of 68 degrees Fahrenheit (°F) in the summer and 17°F in the winter. The average annual precipitation is approximately 36 inches.

Hydrogeology and groundwater flow (pages 5 to 17) describes the aquifers and aquitards and identifies their hydrostratigraphic characteristics and corresponding geologic units from Part A. Groundwater-elevation maps give a broad look at the direction of groundwater flow in unconfined conditions (water-table elevation) and confined conditions (potentiometric-surface elevation).

The county lies within three surface watersheds: the Zumbro River, Cedar River, and Root River. Western portions of the county are dominated by thick layers of unconsolidated glacial sediment; sand and gravel within these deposits are rarely used for water supply. Eastern portions, especially northeastern and east-central, are dominated by karst. Karst provides rapid water movement between the land surface and underlying aquifers. It is noticeable on the surface where there are sinkholes and sinking streams.

Beneath the glacial deposits is a thick sequence of Paleozoic sedimentary bedrock layers. A regionally significant aquitard, the Decorah–Platteville–Glenwood, subdivides these layers into two aquifer systems: an upper carbonate aquifer and the deeper combined St. Peter–Shakopee aquifer. Groundwater flow in the upper carbonate aquifer system is generally consistent with surface topography, with flow beginning at higher elevations and discharging at lower elevations along the margins of the aquifer, where springs, streams, and wetlands are often found.

Groundwater flow in the St. Peter–Shakopee aquifer system is generally westward, becoming more southerly toward Iowa. In the northeast, groundwater in a small portion of this aquifer system flows east toward Olmsted County.

Water chemistry (pages 18 to 27, Plate 7) provides information about the following.

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

Groundwater chemistry indicates direct infiltration of precipitation is the primary source of groundwater recharge in Dodge County.

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

Water that recharged since 1953 is largely limited to portions of the upper carbonate aquifer system within or near areas of karst where depth to bedrock is less than 50 feet. In the St. Peter–Shakopee aquifer system, two samples had water that recharged since 1953; these samples were from eastern Dodge County, where the overlying Decorah–Platteville–Glenwood aquitard is thin or absent.

Groundwater that recharged before 1953 was found in both the upper carbonate and St. Peter–Shakopee aquifer systems. Residence times ranged from 600 to 10,000 years.

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

Anthropogenically sourced chloride was largely limited to the upper carbonate aquifer system, where depth to bedrock is less than 50 feet. The presence of anthropogenic chloride in the deeper St. Peter–Shakopee aquifer system is limited to areas where the overlying Decorah–Platteville–Glenwood aquitard is thin to absent. Nitrate concentrations suggesting anthropogenic sources were found in 8 of 130 samples (approximately 6%) and mostly limited to the upper carbonate aquifer system in areas where depth to bedrock is less than 50 feet.

There are a variety of naturally occurring chemicals in water. Some can affect the aesthetics, while others may pose a health concern. Arsenic was detected in 70 of 119 samples, with none exceeding the drinking water standard of 10 parts per billion. Arsenic detections and concentrations were greater in the upper carbonate aquifer system than in the St. Peter–Shakopee aquifer system and Jordan aquifer. Manganese was detected in all but 5 of 106 samples, with 11 samples exceeding the health-based drinking water value of 100 parts per billion. Concentrations of manganese were higher in the upper carbonate aquifer system than in the St. Peter–Shakopee aquifer system and Jordan aquifer.

Pollution sensitivity (pages 28 to 43) is based on the time required for a contaminant to travel vertically from the land surface to the water table, a buried aquifer, or the bedrock surface. Two models are used to estimate pollution sensitivity. Pollution sensitivity of the near-surface materials estimates travel time to the water table. Pollution sensitivity of buried aquifers and the bedrock surface estimates travel time to a buried aquifer or the bedrock surface.

Pollution sensitivity of **near-surface materials** ranges from high to very low, with most of the county rated as low. Karst is a special condition in near-surface pollution sensitivity. In the approximately 19% of the county where karst is mapped, karst hydrology (extremely rapid contaminant travel) is assumed.

Pollution sensitivity of **buried sand and gravel aquifers** varies from very high to very low, based on the cumulative thickness of fine-grained sediment above the aquifer. Aquifers closest to the land surface have high pollution sensitivities over much of their extent. In contrast, more deeply buried sand and gravel aquifers are often assigned a very low sensitivity.

Pollution sensitivity of the **bedrock surface** is highest in the east and northeast, where depth to bedrock is less than 50 feet. The remainder is very low, with localized areas of higher sensitivity where overlying fine-grained sediment is thin to absent.

Hydrogeologic cross sections (pages 44 and 45, Plates 8 and 9) illustrate the horizontal and vertical extent of aquifers and aquitards, the relative hydraulic conductivity of aquitards, general groundwater flow direction, and groundwater residence time. The upper carbonate aquifer system is overlain by fine-grained sediment that helps to protect groundwater in much of the county. In portions of the east and northeast, where sediment is less than 50 feet thick, groundwater is less protected, as evidenced by the presence of younger groundwater and anthropogenic chemicals. Karst in these areas likely allows for the rapid transport of water to the upper carbonate aquifer system.

At depth, the St. Peter–Shakopee aquifer system is very well protected as this aquifer is overlain by a combination of glacial sediment, the upper carbonate aquifer system, and the very competent Decorah–Platteville–Glenwood aquitard that extends across most of the county.

Aquifer characteristics and groundwater use (pages 46 to 53) summarizes aquifer and specific capacity tests, groundwater level data, and water use records. Domestic wells are the most common well type and rarely require a use permit. Permits are required for large-volume users that withdraw greater than 10,000 gallons per day or 1 million gallons per year.

Groundwater use from large-volume users has increased approximately threefold since 1988. Municipal water supply is the largest use, followed by ethanol production and livestock watering. In 2021, these three made up about 79% of permitted groundwater use.

Physical setting and climate

Dodge County (Figure 1) is in southeastern Minnesota and had a population of 20,873 on April 1, 2020 (U.S. Census Bureau, 2020). Most of the county has flat to gently rolling terrain, with much of the land in cultivation. Exceptions are forested areas of steep slopes in the east and northeast.

Surface water and groundwater are replenished solely by precipitation; consequently, surface-water flow and groundwater levels fluctuate with wet and dry years. There is little standing water, with a small portion of Rice Lake and scattered wetlands covering approximately 2% of the county's 439-square-mile surface area. Surface waters flow toward three separate watersheds: the Zumbro River, Cedar River, and Root River. Over 80% of the surface area drains to the east and northeast via the Zumbro River and its tributaries. The southwest portion drains south to the Cedar River, and a very small portion of the southeast drains eastward to the Root River.

The climate is humid-continental, with warm to hot summers, cool to 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 68.4°F, with December through February averaging 17.4°F (DNR, 2023a). Average annual precipitation is approximately 36 inches, placing it on 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 approximately four times greater than during the winter.

From 1895 through 2022, average annual temperatures increased by 2.0°F, which is less than the statewide average temperature increase of 2.9°F. The increases were fastest during winter, at night, and especially since 1970, when daily minimum temperatures have risen more than two times faster than daily maximum temperatures, and average winter temperatures have risen more than five times faster than average summer temperatures. Annual precipitation has increased by 7.6 inches since 1895, and intense rainfall events producing daily totals over 1, 2, and 3 inches were more common since 1990 than during any other period on record.

Climate projections summarized in the 2014, 2017, and 2018 National Climate Assessments, and others available for the state of Minnesota, indicate that Dodge County is predicted to warm by an additional 2 to 4°F by 2050, while annual precipitation is predicted to increase by an additional 1 to 3 inches. Short-term variations can be expected, leading to episodes of cooler conditions and drought, even as trends toward warmer and wetter conditions continue (Easterling and others, 2017; Jay and others, 2018; Pryor and others, 2014; Vose and others, 2017).

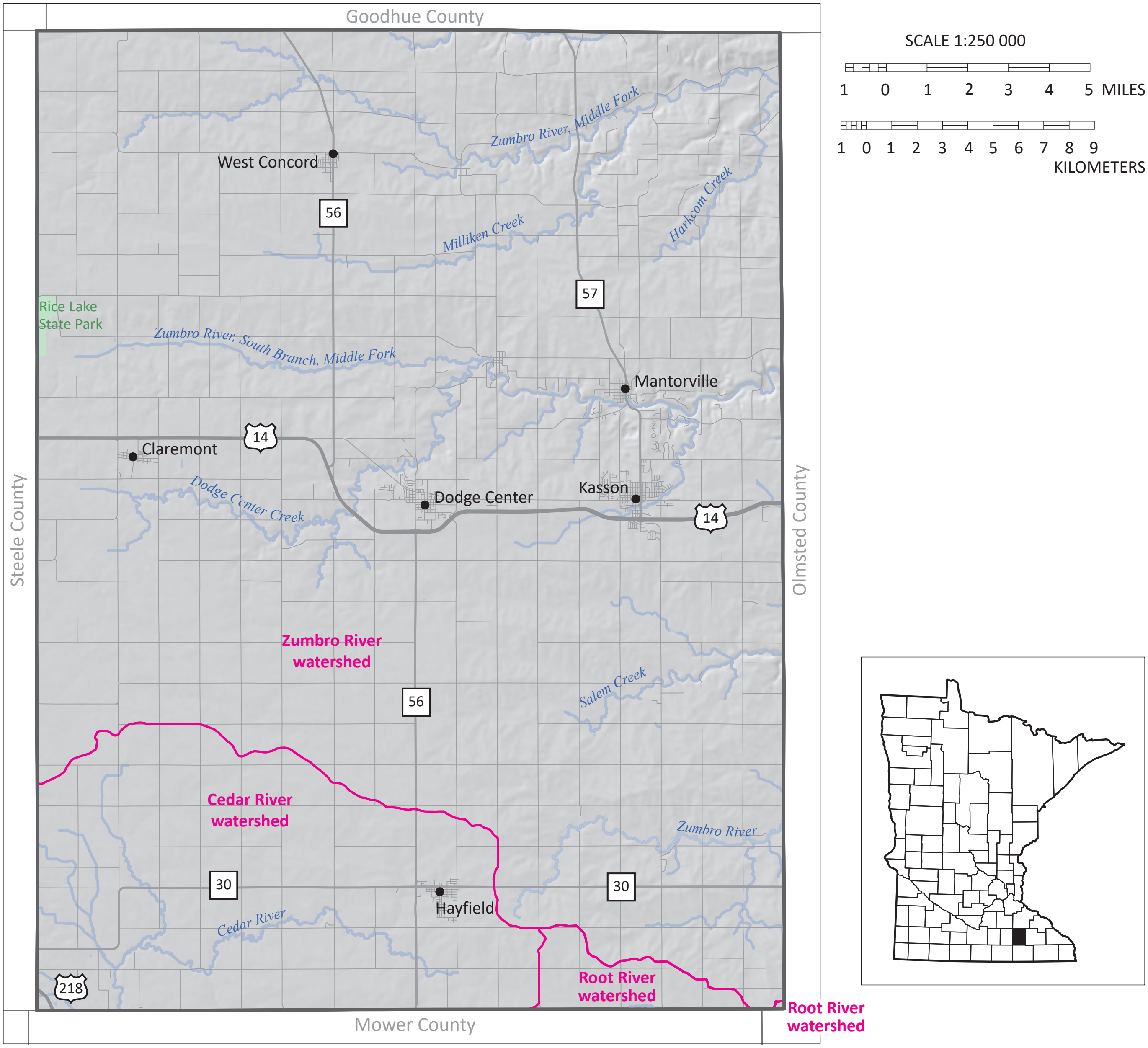


Figure 1. Dodge County, Minnesota

Hydrogeology and groundwater flow

Hydrogeology

The geology consists of unconsolidated glacial sediment averaging slightly more than 100 feet thick overlying much older bedrock. The thickness of glacial sediment varies greatly and is thin to absent in portions of the east and northeast and thickest (over 200 feet) where these deposits coincide with valleys in the bedrock surface (Part A, Plate 6). Unconsolidated surficial and buried sands may be sufficient to yield water for domestic water supplies; however, most wells use bedrock aquifers, which are often more protected from pollution and generally have higher yields.

Quaternary hydrostratigraphy

The Part A stratigraphic column (Figure 2) shows the vertical sequence of unconsolidated geologic units found in the county, with the youngest on top and the oldest units on the bottom. This sediment was deposited during the Quaternary, the most recent geologic period, encompassing the last 2.6 million years. In Minnesota, sediment deposited during this timeframe includes interglacial and postglacial deposits. The Part B hydrostratigraphic column depicts these units as either aquifers or aquitards based on their ability to transmit water.

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

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

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

Surficial sand aquifers

Surficial sands are associated with modern streams and include coarse-grained sediment in channels and finer-grained sediment in adjacent floodplains. Others are present as terraces above modern river valleys, where downcutting streams have left older sand deposits at higher elevations. Surficial sand also includes glacial outwash, with the most widespread deposits extending north to south near Claremont (Figure 3). This outwash is often less than 20 feet thick but, in some areas, exceeds 40 feet.

Surficial sand and gravel aquifers are generally not targeted as a water source in the county. However, the actual number of wells using surficial sand and gravel aquifers in Dodge County is likely higher than indicated in the County Well Index (CWI) database, as drive-point wells are not included in the CWI and are known to exist within the county (Dean Schrandt, personal communication).

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

Buried sand aquifers

Beneath the surficial geologic deposits are alternating layers of sand, gravel, and fine-grained material from earlier glacial advances. The naming convention for the buried sand and gravel aquifers in this atlas is based on the underlying till unit, as described in the associated Part A atlas.

Aquitards enclose the sand and gravel layers and include unsorted sediment deposited directly by the ice (till) and bedded sediment of clay, silt, and fine-grained sand deposited in ponds and lakes. Thicknesses of the buried sand and gravel vary greatly but rarely exceed 40 feet (Part A, Plate 5, Figures 5 through 9). Less than 1% of known wells are completed in Quaternary buried sand and gravel aquifers, with the majority used for groundwater monitoring purposes.

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

Formation	Sediment type	Part A	Part B
	fill	Qfi	fi
	alluvium	Qal*	al
	peat	Qpe	pe
	silt and clay	Qsc	sc
	colluvium	Qco	co
	sand	Qte*	te
	loess	Qlo	lo
New Ulm Formation	sand	Qno*	no
	sand	Qmc*	mc
	till (loam diamicton)	Qmt	mt
Browerville Formation	loam diamicton	Qbu	bu
	sand	Qbs†	bs
	loam diamicton	Qbl	bl
	sand	Qrs†	rs
Rose Creek Formation	loam diamicton	Qrc	rc
	sand	Qes†	es
Elmdale Formation	loam diamicton	Qeu	eu
	sand	Qeg	eg
	loam diamicton	Qeb	eb
	sand, undifferentiated	Qus	us
	undifferentiated	Qup	up

*Map units Qal, Qte, Qno, Qmc, and Quo† make up the surficial sands on the surficial geology plate of Part A.
†Map units Qbs, Qrs, and Qes make up Quo, which can occur as surficial or buried sand.

Figure 2. Hydrostratigraphy of Quaternary unconsolidated sediment

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

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

Percent sand in aquitard

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

- Several units near the surface have ***unknown matrix textures*** and are shown as ***dark brown***.
- ***Undifferentiated sediment*** is shown as ***light brown***.

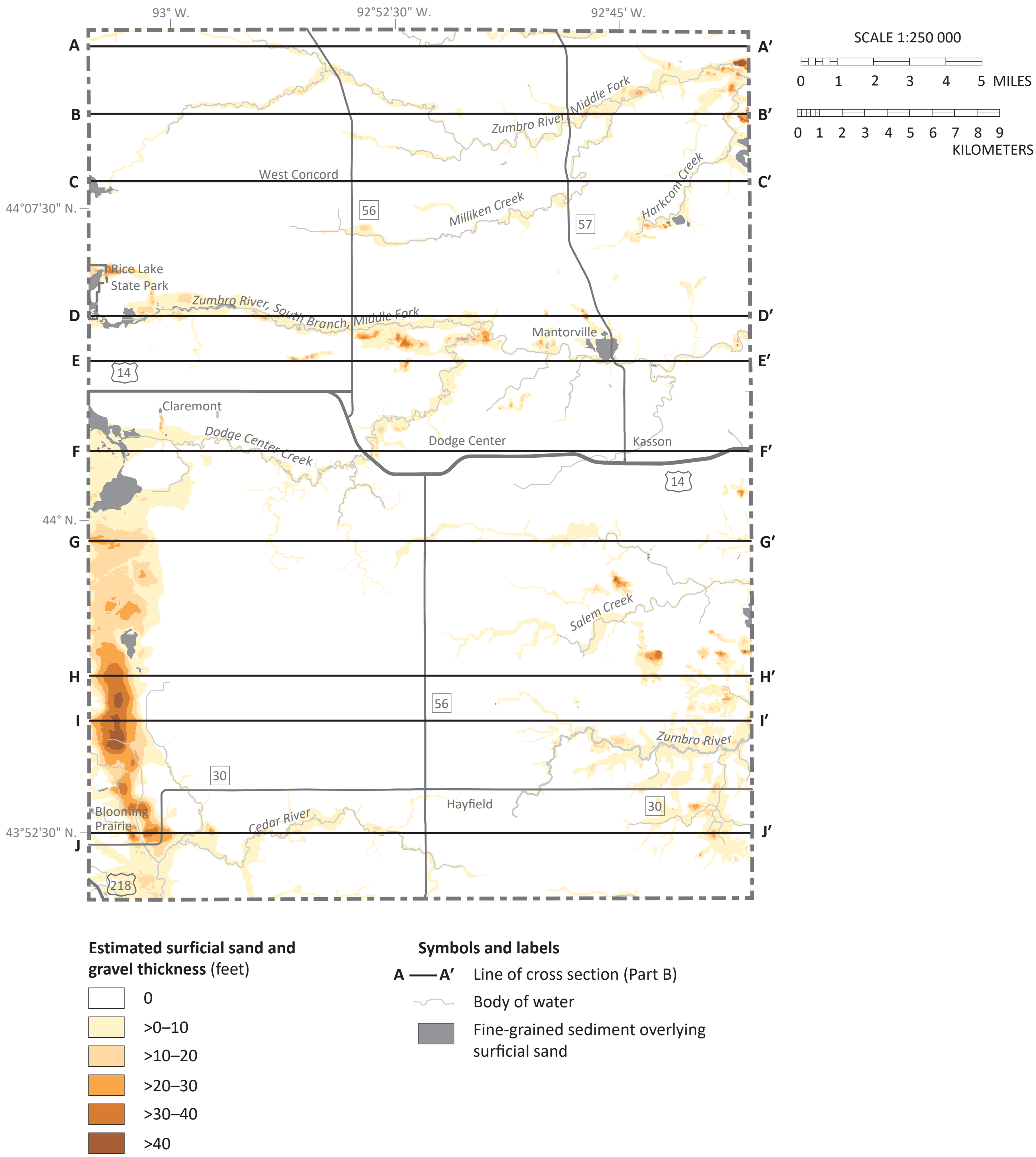


Figure 3. Surficial sands

The thickest and most widespread surficial sands are glacial outwash deposited just southwest of Claremont and south to the Mower County border. The thickness of these deposits varies greatly but rarely exceeds 40 feet.

Bedrock aquifers

In general, the bedrock geologic units underlying Dodge County are composed of limestone or dolostone (carbonate), siltstone or shale (fine-clastic), or sandstone (coarse-clastic) (Figure 4). The ability of these rock units to store water (porosity) and transmit water (permeability) ultimately governs whether they behave hydraulically as aquifers or aquitards.

Bedrock aquifers are water-bearing rocks that yield economic quantities of groundwater to a well. Some bedrock aquifers also provide continual cold-water discharge to springs and streams.

Bedrock aquitards are layers of material with low permeability, such as siltstone and shale, which 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.

Rock classifications can be divided into three principal matrix hydrostratigraphic components: carbonate rocks of low porosity and permeability, fine-clastic rocks of low porosity and permeability, and coarse-clastic rocks of high to moderate porosity and permeability. The transmission rate of water through rocks is often enhanced by the development of interconnected networks of fractures and dissolution features that make up secondary porosity and permeability, which are often responsible for transmitting most of the water.

In shallow bedrock conditions (less than 50 feet below the bedrock surface), fractures are more abundant, better connected, and larger compared to conditions of deeper burial (Barry and others, 2023; Runkel and others, 2018). The use of 50 feet to distinguish shallow and deep bedrock conditions is somewhat arbitrary as these changes are transitional and will vary across rock units and spatially throughout the county.

Fracturing can increase the ability of an aquifer to transmit water but can also degrade an aquitard's ability to protect underlying aquifers. Fracturing typically decreases with depth below the bedrock surface.

Karst

The term karst describes both carbonate aquifers and the unique surface landforms resulting from precipitation and groundwater dissolving carbonate rock. Karst aquifers have distinct hydrology dominated by rapid conduit flow. Surface karst is characterized by sinkholes, sinking streams, and springs on the landscape and is present in far eastern and northeast Dodge County. However, where surface karst features are absent, there can still be rapid connections between the land surface and underlying aquifers and within the county's carbonate aquifers because those carbonate aquifers were subject to karst dissolution before being buried by glacial deposits (Alexander and others, 2013).

In shallow bedrock conditions, there are three major carbonate-dominated karst systems. In descending stratigraphic order, they include the Cedar Valley, Galena–Spillville, and Prairie du Chien (Figure 4). Each karst system is characterized by relatively abundant secondary porosity, including cavities, dissolution-enlarged fractures, and rapid direct connections between the surface and groundwater (Runkel and others, 2003). The Platteville Formation is considered karst in shallow bedrock conditions elsewhere in Minnesota (Runkel and others, 2014); however, it is relatively thin and has limited distribution as the bedrock surface in Dodge County.

In karst areas, there is a close relationship between the land surface and underlying aquifers. 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.

In Dodge County, 96% of mapped sinkholes and stream sinks occur where there is 50 feet or less of unconsolidated sediment overlying bedrock (Figure 5; Part A, Plate 6, Figure 1), consistent with other areas of karst in southeastern Minnesota (Alexander and Maki, 1988). In Dodge County, almost all mapped sinkholes and stream sinks occur where the Galena Group is the first bedrock below the land surface.

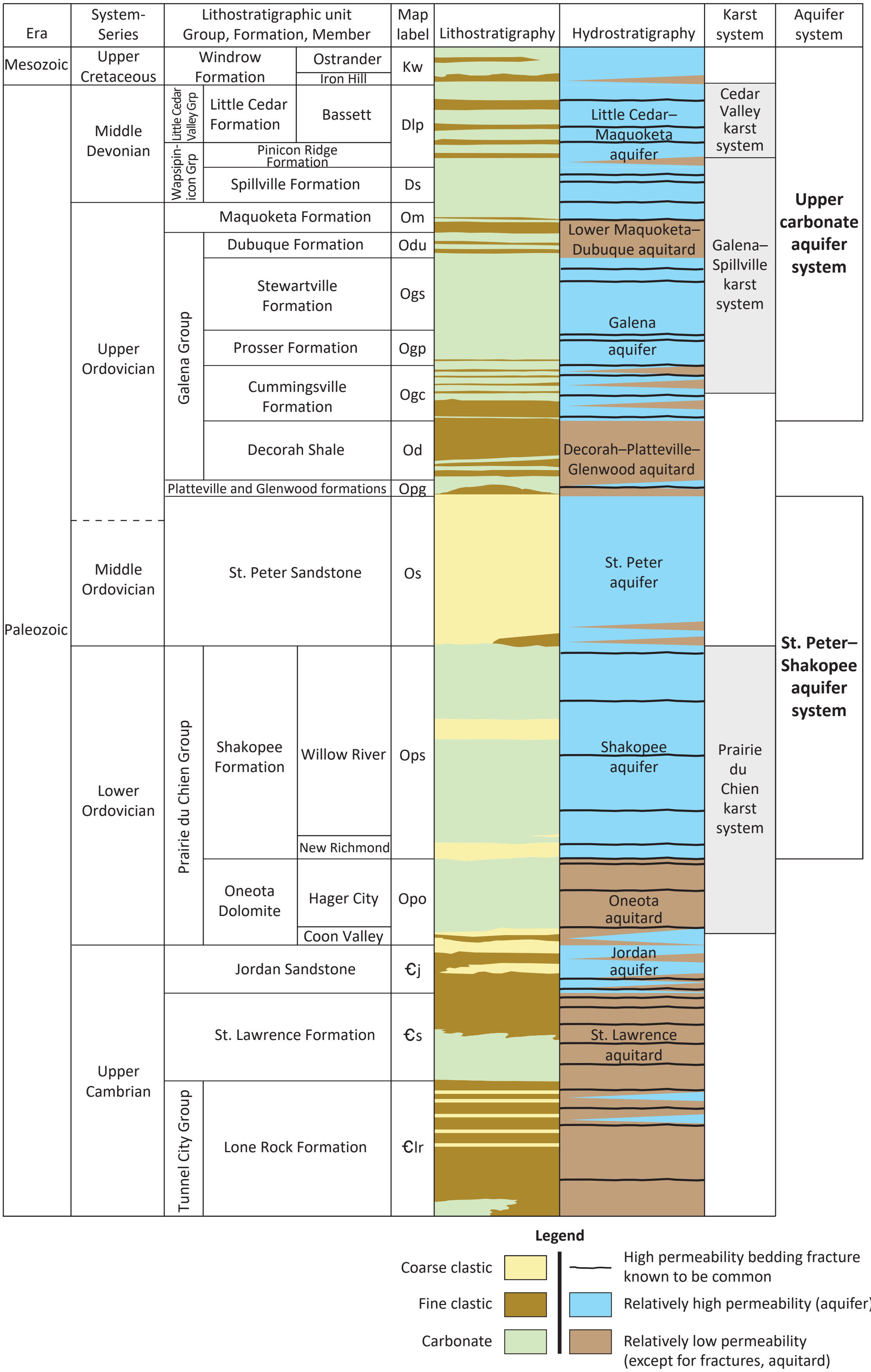


Figure 4. Bedrock stratigraphy and hydrostratigraphy

A generalized stratigraphic column portraying bedrock lithostratigraphy, hydrostratigraphy, karst systems, and aquifer systems. Geologic units (formations or groups) do not always correspond to hydrogeologic units (aquifers and aquitards).

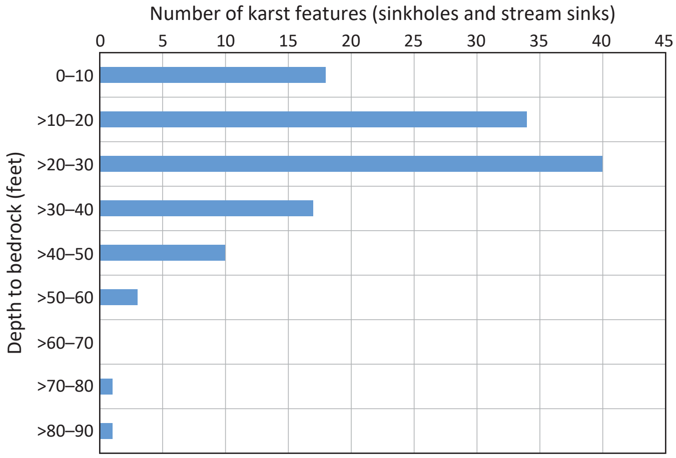


Figure 5. Sinkhole and stream sink occurrence versus depth to bedrock

In Dodge County, 96% of mapped sinkholes and stream sinks occur where there is 50 feet or less of unconsolidated sediment overlying bedrock. Depth to bedrock was determined using GIS files (Steenberg, 2019). Sinkhole and stream sink locations are from the Karst Feature Inventory database available through the Geospatial Commons (DNR, 2023c).

Groundwater flow

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

1. The **water-table map** illustrates the shallowest groundwater flow, where groundwater is unconfined and at equilibrium with atmospheric pressure. Groundwater flows from higher to lower elevations.
2. **Potentiometric surface maps** describe groundwater flow for aquifers, where groundwater is confined and hydrostatic pressure exceeds atmospheric pressure. 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. The water table occurs in both aquifer and aquitard sediment across the entire county. Although it is shown in the figure as a static surface, it fluctuates over time. Surficial sand aquifers are present where there is sufficient saturated thickness and yield to install a well and pump water.

The water table mostly exists within unconsolidated glacial sediment, except in the northeast and far east-central, where it exists in shallowly buried bedrock. In glacial sediment, the water table is generally a subdued expression of surface topography with flow directions consistent with surface watershed boundaries. In shallow karstic bedrock, the water table may not uniformly follow surface watershed divides, and springs are commonly found where the water table intersects the land surface.

The map 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.

- Elevation of surface-water bodies like rivers, perennial streams, lakes, and open-water wetlands
- Static water levels in water-table wells obtained from the 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

Potentiometric surface maps show the general horizontal direction of groundwater flow in confined aquifers. In confined aquifers, hydrostatic pressure is greater than atmospheric pressure, causing the water level in a well to rise above the top of an aquifer. The elevations of these water levels are contoured similarly to land-surface elevations on a topographic map.

The potentiometric surface of an aquifer represents the potential energy to move groundwater. As groundwater moves from higher to lower potentiometric elevations, it flows perpendicular to the contours, depicted with arrows on the maps.

Potentiometric surface maps were created using static water-level data from the CWI and LiDAR-derived surface elevation points along the major rivers and streams, where a stream is likely in hydraulic connection with the aquifer being contoured. The CWI records represent water levels collected under various climatic and seasonal conditions spanning more than 70 years (MGS and MDH, 2018). This data variability creates some uncertainty in potentiometric surface elevations.

Most wells in Dodge County are completed in one of four bedrock aquifers separated by three bedrock aquitards (Figure 4). The uppermost aquifer includes the combined Little Cedar, Pinicon Ridge, Spillville, and upper Maquoketa formations and is referred to as the **Little Cedar–Maquoketa aquifer**. It is found mostly in south-central and southwestern portions of the county, bound from above by greater than 50 feet of glacial sediment and from below by the **Lower Maquoketa–Dubuque aquitard**.

The next aquifer includes the combined Stewartville, Prosser, and Cummingsville formations and is referred to as the **Galena aquifer**. This aquifer is found throughout most of the county but is absent in portions of the northwest and northeast, where it has been removed by erosion.

Contouring a potentiometric surface for the Little Cedar–Maquoketa separately from the Galena requires that the intervening Lower Maquoketa–Dubuque aquitard effectively limits the hydraulic connection between these two aquifers. This aquitard depicted in Figures 4 and 7 has many erosional windows bisecting the aquitard and areas where the aquitard is less than its full thickness. Additionally, almost three-quarters of this aquitard is in a shallow bedrock condition (less than 50 feet below the bedrock surface). Together, these factors significantly reduce the effectiveness of this aquitard. Countywide CWI water-level data could not establish hydraulic separation between the Little Cedar–Maquoketa and Galena aquifers. Therefore, these aquifers were combined to create the **upper carbonate aquifer system** (Figures 4 and 8). Due to the limitations of data distribution in CWI, site-specific water-level studies may better be able to distinguish subtle groundwater-level differences across the Lower Maquoketa–Dubuque aquitard.

Situated beneath the upper carbonate aquifer system is the **Decorah–Platteville–Glenwood aquitard**. It is present throughout the county except in the northeast and northwest, where it has been thinned or removed by erosion. The Decorah portion of this combined aquitard has the greatest aquitard integrity of all bedrock aquitards in southeastern Minnesota. It is regarded as having the greatest ability to protect underlying aquifers from contamination (Runkel and others, 2014). When combined with the Platteville and Glenwood formations, the difference in groundwater head elevations between aquifers above and below this aquitard can be significant, with groundwater-level differences ranging from less than 50 feet in the northeast to over 250 feet in portions of the southwest (Figure 9).

Underneath the Decorah–Platteville–Glenwood aquitard are the St. Peter Sandstone and Shakopee Formation (Figure 4). Wells completed in the St. Peter and Shakopee aquifers have no intervening aquitard and were combined to create the **St. Peter–Shakopee aquifer system** for contouring a potentiometric surface (Figure 10). Although there are limited wells in the southwest, the potentiometric surface is consistent with regional contouring by the Minnesota Department of Health (MDH) (MDH, 2011).

Beneath the St. Peter–Shakopee aquifer system is the **Oneota aquitard**. There is evidence that the Oneota aquitard is sufficiently competent in deep bedrock settings to hydraulically separate the underlying **Jordan aquifer** from the overlying St. Peter–Shakopee aquifer system. In one case, observed at the Oronoco landfill site in nearby Olmsted County, there was an approximate 9-foot difference in groundwater elevation (Donahue and Associates, Inc., 1991; RMT, Inc., 1992). There are an insufficient number of wells in the Jordan aquifer to contour a potentiometric surface.

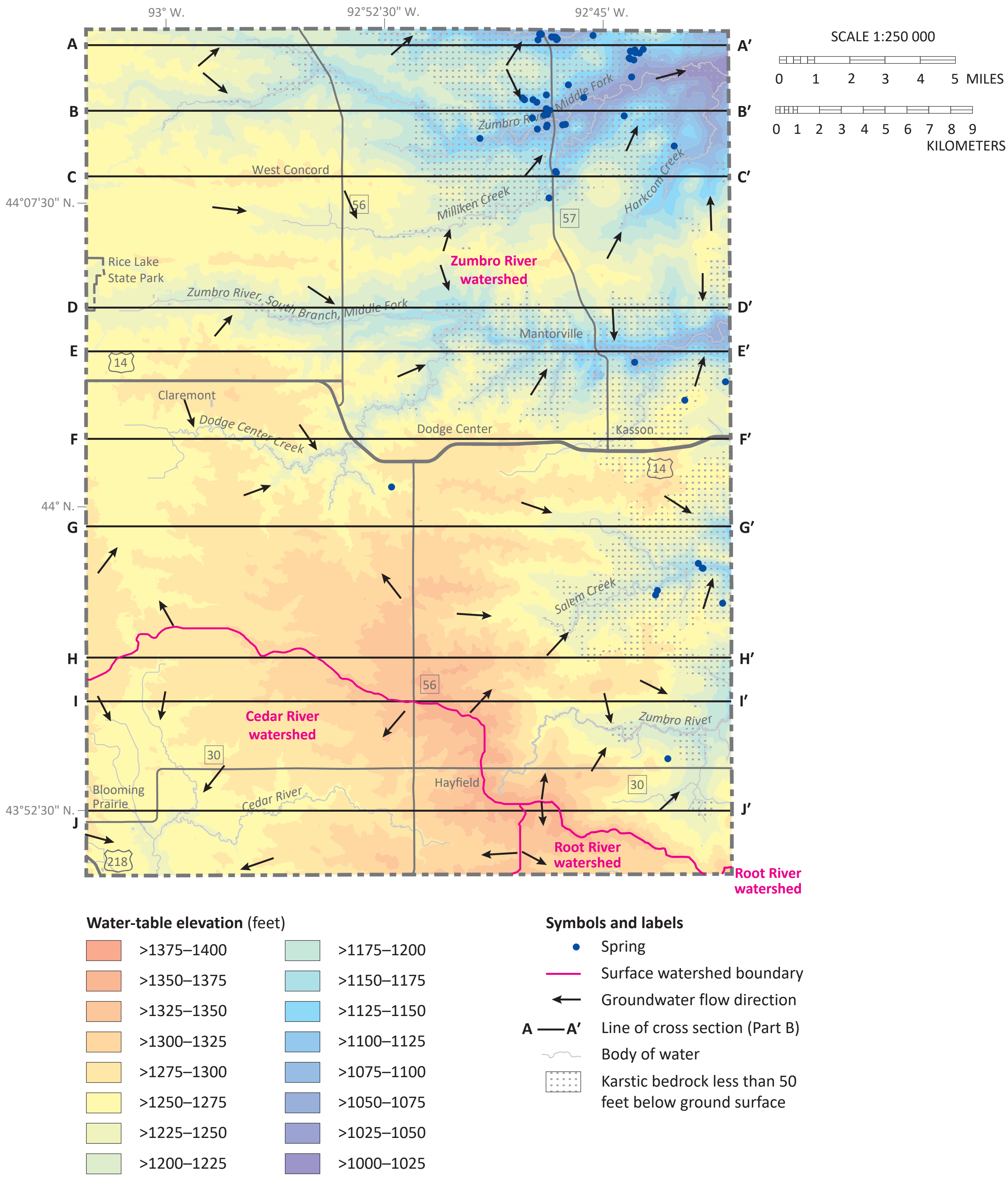


Figure 6. Water-table elevation and groundwater flow directions

The water-table elevation is generally a subdued expression of surface topography with flow directions consistent with surface watershed boundaries. Locally, flow direction is typically from topographic highs toward lowlands and streams. In karstic areas, the water table may not uniformly follow surface watershed divides and may be deeper along stream margins. Karstic bedrock extent is from *Minnesota regions prone to surface karst feature development* (DNR, 2016d).

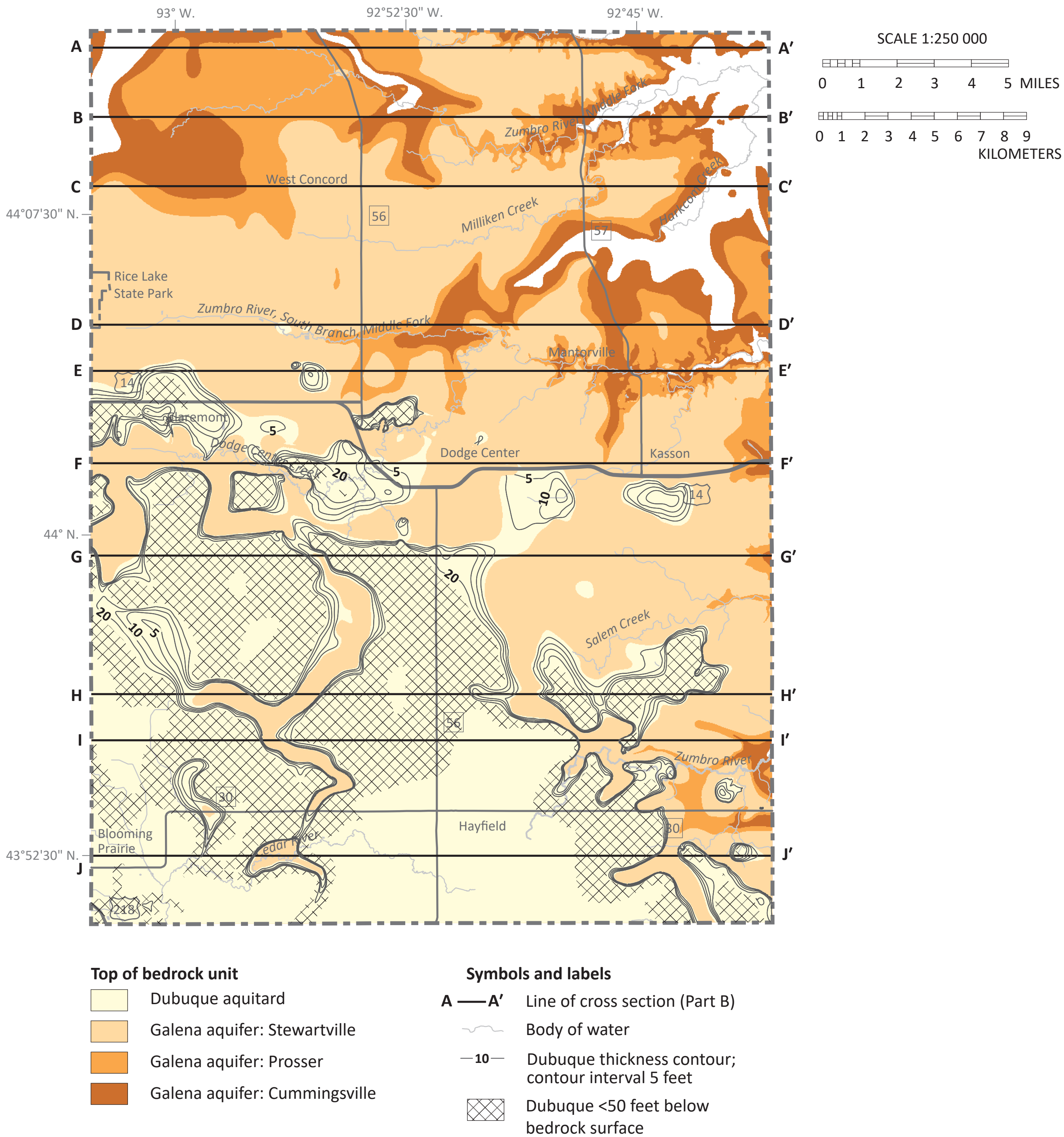
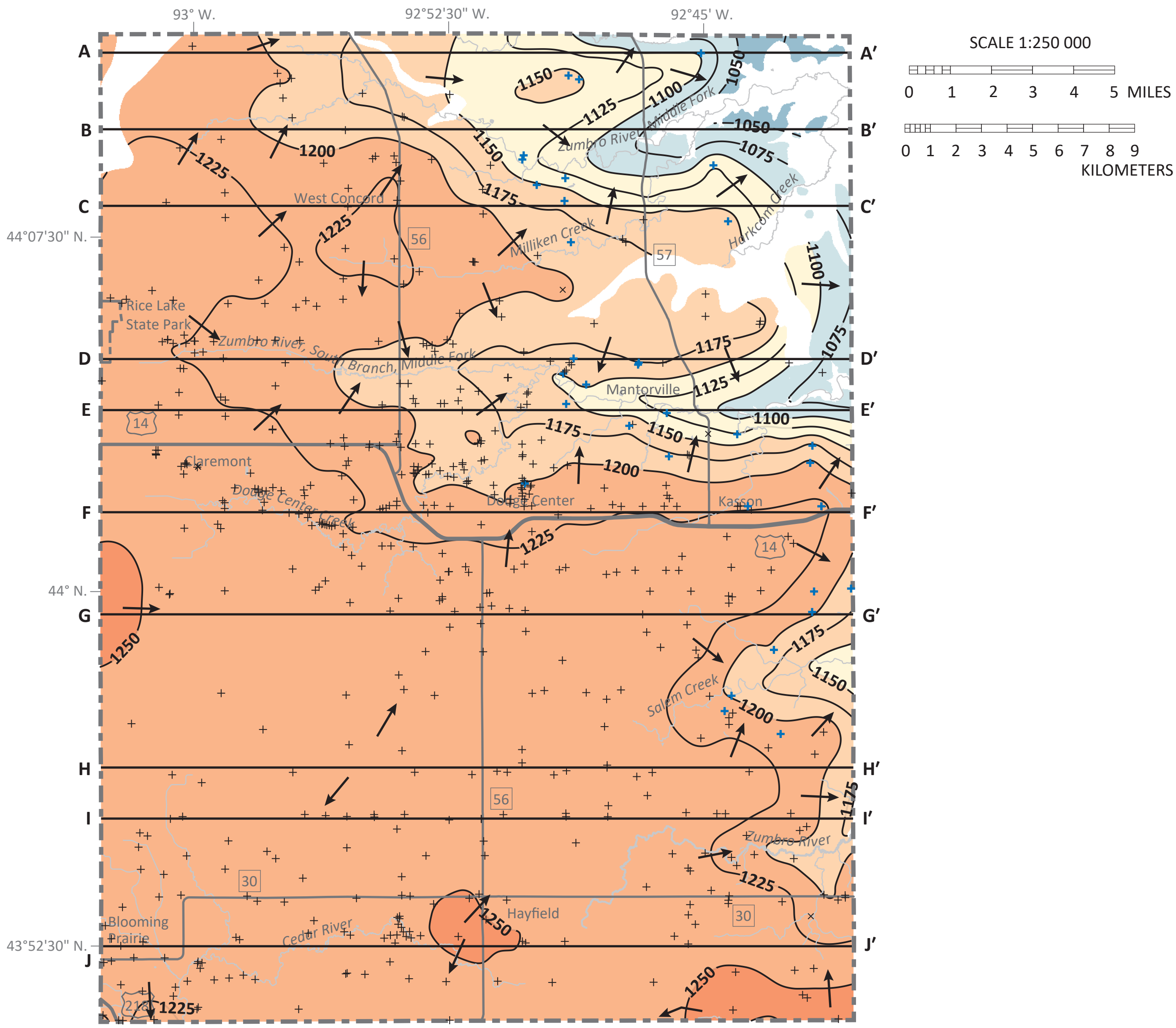


Figure 7. Lower Maquoketa–Dubuque aquitard and Galena aquifer

The Lower Maquoketa–Dubuque aquitard has many erosional windows, areas where it is less than its full thickness of 25 feet and nearly three-quarters of it is in a shallow bedrock condition (less than 50 feet below the bedrock surface). Together, these factors significantly reduce its effectiveness to hydraulically separate the overlying Little Cedar–Maquoketa and underlying Galena aquifers.



Potentiometric surface elevation (feet)

- >1250–1300
- >1200–1250
- >1150–1200
- >1100–1150
- >1050–1100
- >1000–1050
- Aquifer not present

Symbols and labels

- \+ Static water level above the bedrock surface
- \+ Static water level below the bedrock surface
- × Static water level, depth to bedrock unknown
- ← Groundwater flow direction
- —1125— Potentiometric surface contour; contour interval 25 feet
- A —— A′ Line of cross section (Part B)
- Body of water

Figure 8. Potentiometric surface of the upper carbonate aquifer system

The upper carbonate aquifer system is composed of carbonate rock units of the Little Cedar Valley Group, Wapsipinicon Group (Pinicon Ridge and Spillville formations), the Maquoketa and Dubuque formations, and the Galena Group (Stewartville, Prosser, and Cummingsville formations). Groundwater flow for most of the county is generally east to northeast toward the Middle Fork and South Branch, Middle Fork of the Zumbro River. In the southwest, it is generally south toward the Cedar River. Slightly over half of the wells are completed in this aquifer system, with the most in the Galena aquifer.

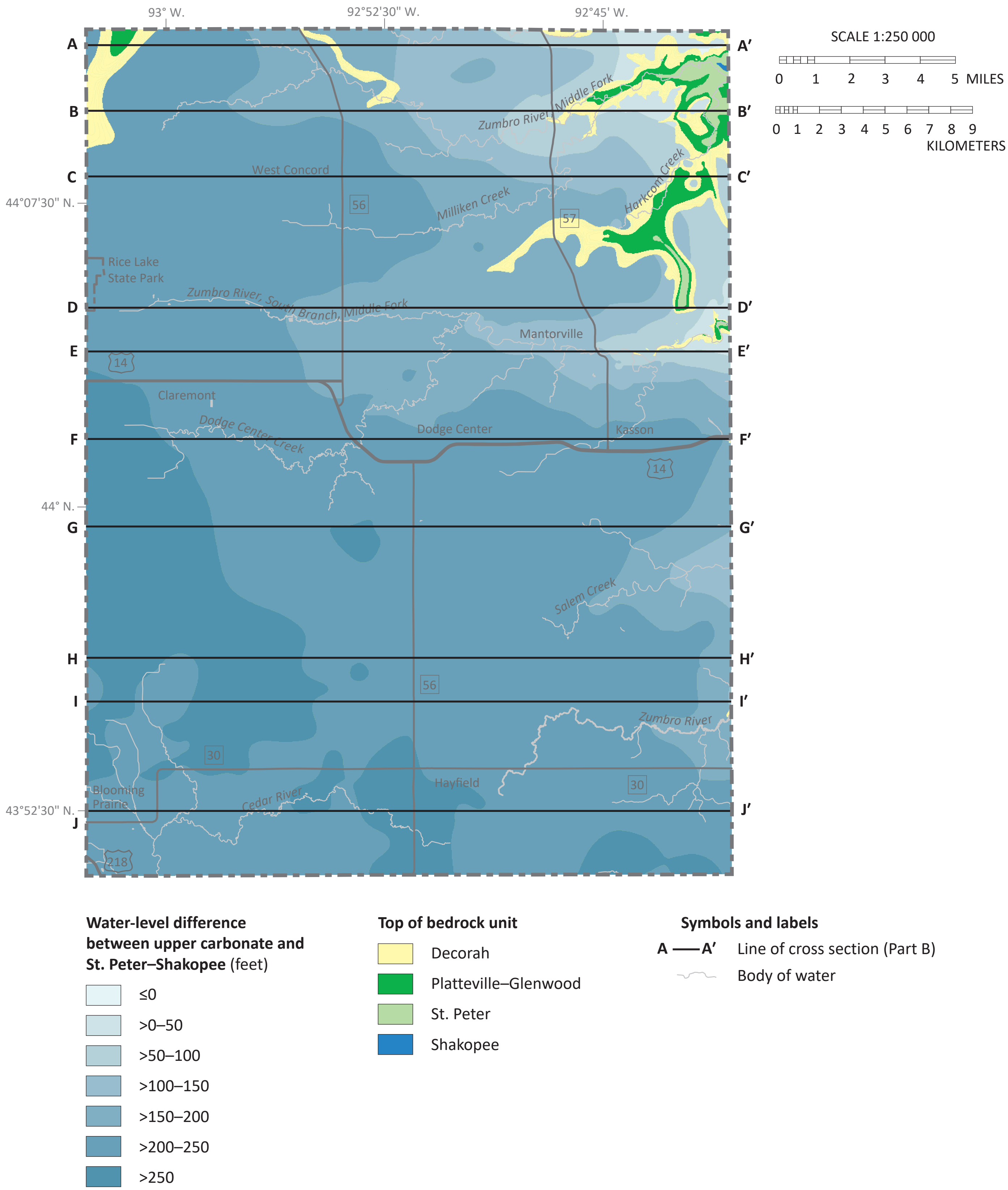


Figure 9. Water-level difference across Decorah–Platteville–Glenwood aquitard

The combined aquitard is present throughout the county except in the northeast and northwest, where it's thinned or removed by erosion. Water-level differences from wells completed in aquifers above and below this aquitard vary from less than 50 feet in the northeast to over 250 feet in portions of the southwest, illustrating its ability to impede groundwater flow in a vertical direction.

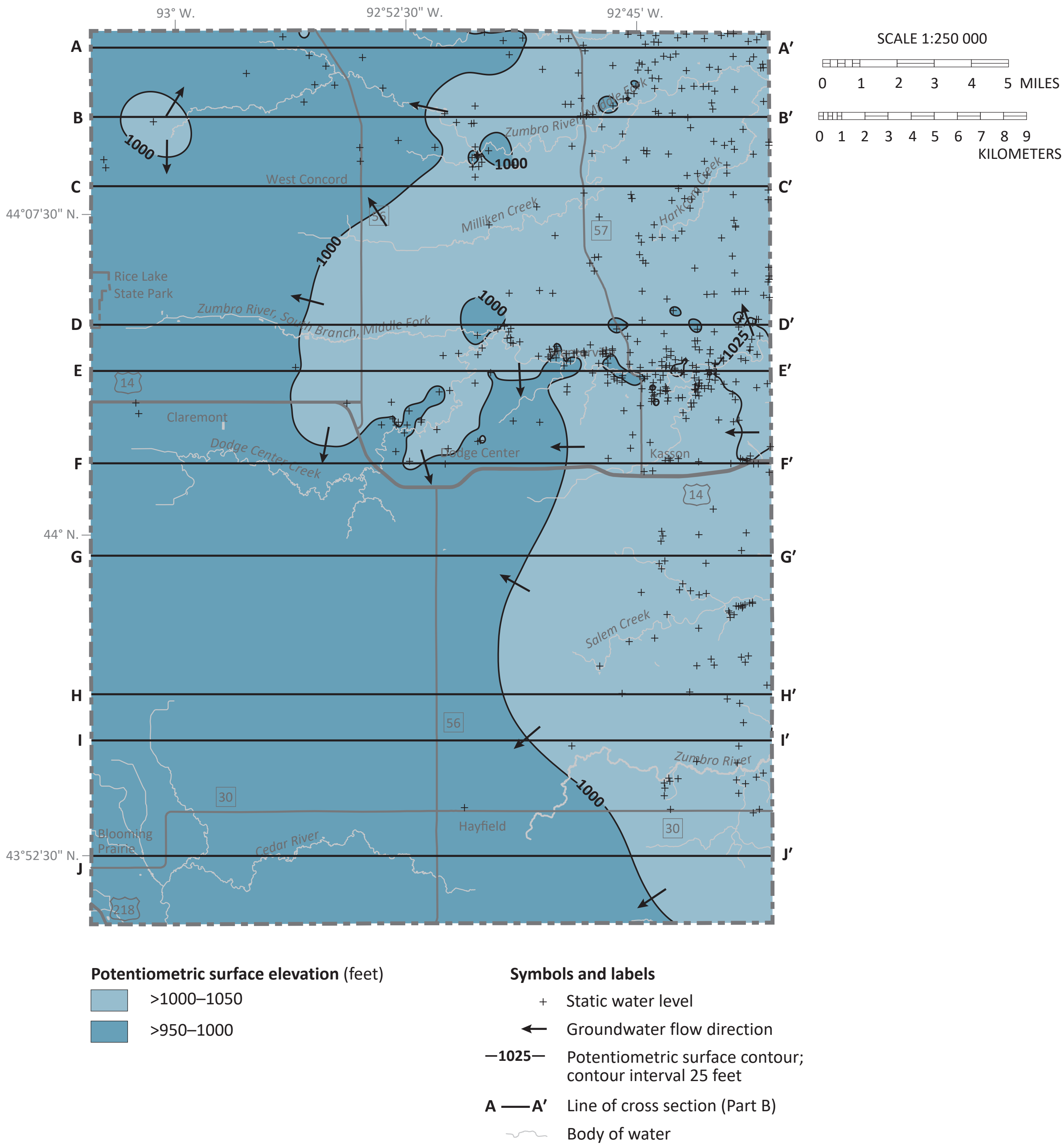


Figure 10. Potentiometric surface of the St. Peter–Shakopee aquifer system

The St. Peter Sandstone and Shakopee Formation of the Prairie du Chien Group form an aquifer system beneath the Decorah–Platteville–Glenwood aquitard. Almost half of the wells are completed in this aquifer system, with the majority in the east and northeast. Groundwater flow is mostly west and southwest, with the highest groundwater elevations in the east-central portion of the county.

Water chemistry (Plate 7)

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

Water chemistry provides information about the following:

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

Water sampling

Samples were collected from wells used for domestic and municipal water supply. Wells were selected to collect water samples from a range of aquifers across the county, include populated areas, and target surface-water and groundwater interaction. Wells with grouting (a process that limits water flow down a well casing's side) were preferred; however, some wells with no grouting or unknown grouting records were sampled to target shallower wells (30 of 145). Approximately 1,000 well owners were contacted for permission to sample.

The final network sampled depended on the willingness of citizens to participate. Groundwater samples were collected according to the protocols outlined in Appendix A.

The DNR collected water samples and standard field parameters from 90 wells and 1 lake. These results were combined with historical chemistry data, including 48 well samples from the MDH, 3 well samples associated with a calcareous fen collected by the DNR, and 4 well samples from earlier carbon-14 work compiled by the University of Minnesota (Alexander and Alexander, 2018).

Groundwater recharge pathways

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

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

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

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

Definition of delta (δ)

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

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

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

Results

Figure 11 compares county stable isotope results to the **global meteoric water line** (GMWL), developed from precipitation data from around the world (Craig, 1961). Groundwater samples collected from 90 wells plot parallel to the GMWL, indicating that most groundwater is recharged by precipitation directly infiltrating into the subsurface. Groundwater samples plotting above the GMWL is in contrast to 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 observed in Olmsted, Houston, and Winona counties.

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 Dodge County is +13.6. The higher 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.

A sample collected from Rice Lake plots far to the right of the groundwater samples and below the GMWL. Evaporation of water in the lake fractionated the stable isotopes to give it this unique isotopic signature. A well water sample from an aquifer that receives some portion of recharge from infiltrating lake water should plot along a trend between the groundwater sample points on the GMWL and the point representing the lake source. No well water samples had evidence of lake recharge.

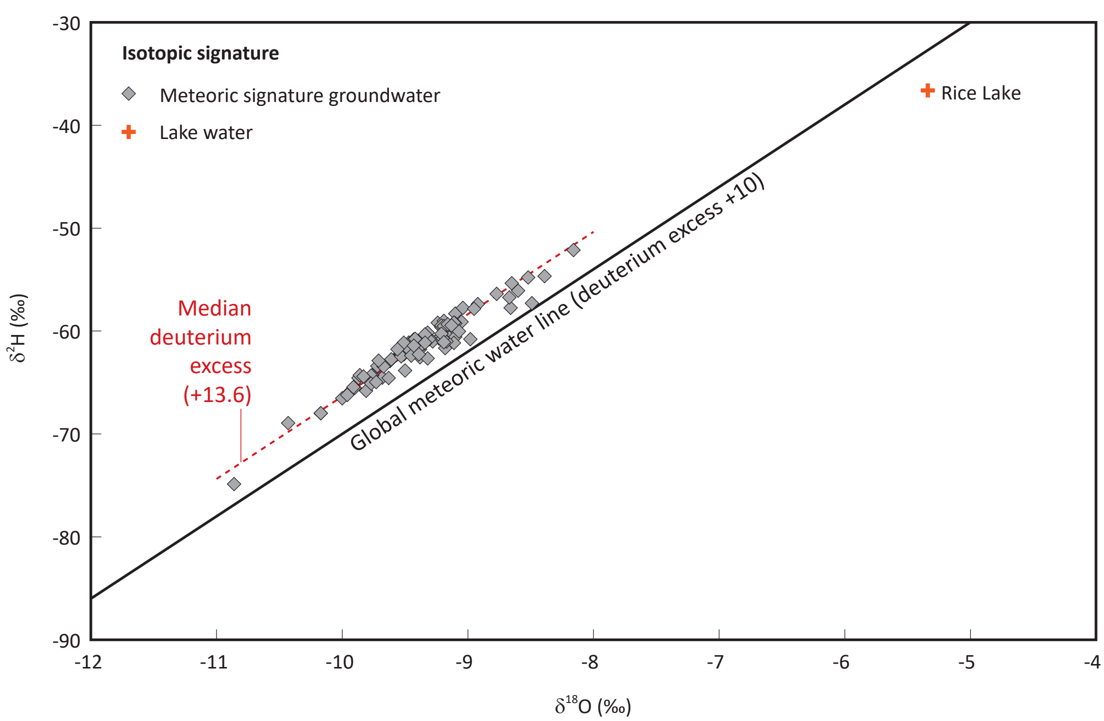


Figure 11. Stable isotope values from water samples

The **meteoric water line** represents the isotopic composition of precipitation. Groundwater that plots along the meteoric water line indicates recharge of directly infiltrated precipitation. The **GMWL** was developed using precipitation samples from around the world and is described by the following equation: $\delta^2H = 8.0\ \delta^{18}O + 10.0$ (Craig, 1961). Dodge County data plot above the GMWL, consistent with other southeastern Minnesota counties and regional values (Kendall and Coplen, 2001).

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 surface water. Short residence time generally suggests short travel paths or high recharge rates; long residence time suggests long travel paths or low recharge rates. The residence time of groundwater was estimated using analysis of two radioactive isotopes: tritium and carbon-14.

Tritium

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

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

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

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

Tritium was analyzed in samples from 105 wells and 1 lake to assist in groundwater residence time interpretations. Of the 105 groundwater samples analyzed for tritium, 11 were modern, 14 were mixed, and 80 were premodern. Results are summarized using four depth-to-bedrock categories for the upper carbonate aquifer system and with a general summary for the St. Peter–Shakopee aquifer system and Jordan aquifer.

The upper carbonate aquifer system:

- Depth to bedrock, 0 to 50 feet: of 13 wells total, 77% (10) had modern or mixed tritium-age water.
- Depth to bedrock, >50 to 100 feet: of 16 wells total, 50% (8) had modern or mixed tritium-age water.
- Depth to bedrock, >100 to 150 feet: of 21 wells total, 14% (3) had modern or mixed tritium-age water.
- Depth to bedrock, >150 feet: of 11 wells total, 9% (1) had mixed tritium-age water. It is possible this well has grouting or construction issues that allowed younger water to enter the well and it is not representative of the residence time of groundwater at this depth.

Modern and mixed tritium ages of some wells in the upper carbonate aquifer system may be influenced by well construction standards before the adoption of the 1974 well construction codes (MDH, 2011). Twenty-two of 61 samples collected from wells completed in the upper carbonate aquifer had modern or mixed tritium ages; 14 of the 22 had no grouting or unknown grouting.

St. Peter–Shakopee aquifer system and Jordan aquifer:

- Of 43 wells total, 3 had modern or mixed tritium-age water, and 40 had premodern tritium-age water.
- Of the 3 wells with modern or mixed tritium age, 2 are from areas where the overlying Decorah–Platteville–Glenwood aquitard is thin or completely eroded.
- The other well, a Jordan well, is in an area where glacial till and both the overlying Decorah–Platteville–Glenwood and Oneota aquitards are present; therefore, it is likely this well has grouting or construction issues that allowed younger water to enter the well.

More details by aquifer are found in the pollution sensitivity results section and on Plate 7.

Carbon-14

Selected wells with premodern tritium-age results were further sampled for carbon-14 (^{14}C) to estimate longer residence times of less than 100 to greater than 40,000 years. One mixed tritium-age well was included that had a minor amount of detectable tritium (1.0 tritium unit). Carbon-14 is a naturally occurring isotope with a half-life of 5,730 years. Carbon-14 sample collection, analysis, and modeling are described in Alexander and Alexander, 2018.

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

Groundwater residence times for 14 well samples were estimated using the carbon-14 methodology (Alexander and Alexander, 2018). Ten samples were collected for this project and combined with 4 from a previous University of Minnesota study completed in 2001.

Seven samples were collected from the upper carbonate aquifer system; groundwater residence times ranged from 950 to 10,000 years. No patterns were evident in age distribution. Six samples were collected from the St. Peter–Shakopee aquifer system and 1 from the Jordan aquifer; groundwater residence times ranged from 600 to 9,500 years. The youngest of these deeper aquifer samples is from a well in the northeast where overlying aquitards are thin to absent.

Inorganic chemistry of groundwater

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

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

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

Drinking Water Guidelines

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

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

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

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

Minnesota Department of Health (MDH, 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

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

Calcium, magnesium, sodium, potassium, and bicarbonate

No drinking water guidelines. Reported in ppm.

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

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

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

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

Chloride

SMCL 250 ppm

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

Samples at or above 5 ppm chloride are assigned a source (Davis and others, 1998).

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

Sampling results

Of the 140 well samples analyzed for chloride, 30 were above 5 ppm and could be assigned a source. Of these 30 samples, 23 were assigned an anthropogenic source and 7 a natural source.

Of the 23 anthropogenic samples, 2 were from shallow Quaternary water-table wells: both were in a calcareous fen with depths of 6 and 20 feet. These 2 samples lacked bromide analysis; however, their high chloride values (52.4 and 22.5 ppm) and shallow well depths strongly suggest an anthropogenic source.

Most of the anthropogenic chloride samples (18) were from the upper carbonate aquifer system. Fourteen of the 18 were from within or close to areas mapped as karst. The remaining 3 anthropogenic chloride samples were from the St. Peter–Shakopee aquifer system. This significant difference between the two bedrock aquifer systems was not the result of a large sample bias. The number of samples collected for chloride from the upper carbonate aquifer system and the St. Peter–Shakopee aquifer system were similar: 72 and 65, respectively. Anthropogenic chloride was more likely to be found above the Decorah–Platteville–Glenwood aquitard, supporting the interpretation of the unit as a regional aquitard (Runkel and others, 2014).

Of the 3 anthropogenic samples from the St. Peter–Shakopee aquifer system, 1 sample was from a well in the southeast, where the Decorah–Platteville–Glenwood aquitard should offer protection; anthropogenic chloride likely from a well grouting or construction issue allowed younger water to enter the well. The other 2 samples were from areas adjacent to the South Branch, Middle Fork of the Zumbro River, where Quaternary sediment is thin to absent, and erosion likely degraded the protective characteristics of the Decorah–Platteville–Glenwood aquitard.

Nitrate-nitrogen (nitrate)

MCL and HRL 10 ppm

Nitrate can occur naturally, but concentrations greater than 1 ppm can indicate anthropogenic impacts from fertilizer or animal and human waste (Dubrovsky and others, 2010; MDH, 1998; Wilson, 2012). Nitrate concentrations may lessen with time (denitrification) when there is little oxygen in the groundwater. In general, groundwaters with long residence times typically have little available oxygen and little to no nitrate.

Nitrate concentrations are classified as follows.

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

Sampling results

Of the 130 samples analyzed for nitrate, 8 had concentrations suggesting an anthropogenic source.

Of the 8 samples, 1 was completed in the shallow (6 feet) Quaternary water table, and 7 were completed in the Galena portion of the upper carbonate aquifer system. Two samples exceeded the MCL for nitrate: the shallow Quaternary well (17.1 ppm) and a Galena well (11 ppm).

Of the 7 upper carbonate aquifer system wells, all but 1 was within or near areas where depth to bedrock is less than 50 feet. The one exception was a well west of Dodge Center with anthropogenic chloride (29 ppm) and nitrate (5.1 ppm).

The final well network sampled by the DNR did not specifically target wells with potentially elevated (anthropogenic) nitrate concentrations. However, a study published by the Minnesota Department of Agriculture (MDA) (MDA, 2019) targeted domestic wells in seven townships with likely elevated nitrate due to intensive row crop agriculture and vulnerable geology. The median depth of the MDA-sampled wells was 243 feet. The MDA found that 59 of the 588 wells had anthropogenic nitrate levels (defined by MDA as 3 ppm or greater), and 13 had concentrations equaling or exceeding the MCL. Wells with nitrate equaling or exceeding the MCL in each of the seven townships ranged from 0 to 4.8% of the wells sampled, with Concord, Milton, and Westfield townships, each having greater than 3% of wells sampled exceeding the MCL.

Arsenic

MCL 10 ppb; MCLG 0 ppb

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

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

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

Sampling results

Of the 119 samples analyzed, arsenic was detected in 70, with no samples exceeding the MCL. The maximum concentration was 8.6 ppb.

The single confined Quaternary well sampled had a concentration of 0.147 ppb. Arsenic detections and concentrations were higher in the upper carbonate aquifer system than in the St. Peter–Shakopee aquifer system and Jordan aquifer: median concentrations were 1.5 and 0.1 ppb, respectively. Recharge to the upper carbonate aquifer system largely occurs through overlying glacial sediment that was the likely source of arsenic. Lower concentrations in the St. Peter–Shakopee aquifer system and Jordan aquifer may be due to groundwater recharge that occurs east of the county, where there is little northwest-derived glacial sediment (Marshall and McDonald, 2020).

Manganese

HBV 100 ppb; SMCL 50 ppb

Manganese is a naturally occurring element beneficial to humans at low levels but can harm the nervous system at high levels (MDH, 2012). 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 sampled (MDH, 2012). Although there are no clear patterns of manganese distribution across most of Minnesota, the MDH has found that southeastern Minnesota tends to have low levels of manganese (below 50 ppb), and southwestern Minnesota tends to have higher levels (some over 1,000 ppb) (MDH, 2021).

Sampling results

Of the 106 samples analyzed, manganese was detected in all but 5 samples, with 11 samples exceeding the HBV. The highest concentration was 293 ppb.

The single confined Quaternary well sampled had a concentration of 94.8 ppm. Concentrations of manganese were higher in the upper carbonate aquifer system than in the St. Peter–Shakopee aquifer system and Jordan aquifer: median concentrations were 60 ppm and 22 ppm, respectively. All 11 exceedances of the HBV were in the upper carbonate aquifer system.

Boron

RAA 500 ppb

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

Sampling results

Of the 90 samples analyzed, boron was detected in each, and none were greater than the RAA.

The single confined Quaternary well had a concentration of 12.6 ppb. Concentrations of boron in the upper carbonate aquifer system were slightly lower than in the St. Peter–Shakopee aquifer system: median concentrations were 25 ppb and 41 ppb, respectively.

Iron

SMCL 0.3 ppm

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

Sampling results

Of the 93 samples analyzed, iron was detected in 82, with 77 equaling or exceeding the SMCL. The maximum concentration was 6.1 ppm. The 2 Quaternary water-table wells had a median concentration of 0.06 ppm; the single confined Quaternary well had a concentration of 1.6 ppm. Concentrations in the upper carbonate aquifer system were higher than in the St. Peter–Shakopee aquifer system: median concentrations were 1.3 ppm and 0.6 ppm, respectively.

Sulfate

SMCL 250 ppm

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

Sampling results

Of the 108 samples analyzed for sulfate, 103 had detectable concentrations, and none were greater than the SMCL. The maximum concentration was 142 ppm.

The 2 Quaternary water-table wells had a median concentration of 35.6 ppm; the single confined Quaternary well had a concentration of 50.8 ppm. Concentrations of sulfate in the upper carbonate aquifer system were lower than in the St. Peter–Shakopee aquifer system: median concentrations were 6.8 ppm and 24.7 ppm, respectively.

Piper diagrams

Piper diagrams graphically represent the water chemistry of the most common ionic constituents in natural waters: calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and nitrate.

The diagrams can reveal information about the following:

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

Piper diagrams have three components: a cation triangle, an anion triangle, and a central diamond. The cations and anions are shown in the left and right triangles, respectively. The center diamond shows a composite of cations and anions. Samples are represented by one data point on each component. The sample points on each triangle reflect the relative percentages of the major cations (lower left triangle) and anions (lower right triangle). These are projected onto the diamond grid. The dashed arrows show an example of this relationship. The sample points in the figure are color-coded according to tritium age to show chemical relationships.

The most common water type in Dodge County is calcium-magnesium bicarbonate. Two piper diagrams illustrate major ion differences in Dodge County's aquifer systems. Figure 12 shows samples collected from the upper carbonate aquifer system, and Figure 13 shows samples collected from the St. Peter–Shakopee aquifer system.

On the cation diagram in Figure 12, the upper carbonate aquifer system has a slightly greater cation spread than the St. Peter–Shakopee aquifer system in Figure 13. This may be due, in part, to the presence of a greater number of modern and mixed tritium-age water samples in the upper carbonate aquifer system that are geochemically immature or possibly to differences in mineralogy along groundwater flow paths. Groundwater flow paths to the deeper St. Peter–Shakopee aquifer system are likely longer, as demonstrated by the largely premodern tritium-age water in the deeper aquifer system (Figure 13).

On the anion diagram, premodern tritium-age water in the upper carbonate aquifer system (Figure 12) plots close to the lower left bicarbonate axis. Modern and mixed tritium-age water plot toward the chloride-plus-nitrate and sulfate axes. Most of the highest sulfate values in this aquifer system are associated with modern and mixed tritium-age water, which suggests that sulfate, like chloride and nitrate, may be from an anthropogenic source, such as atmospheric deposition (Crawford and Lee, 2015). Samples from the St. Peter–Shakopee aquifer system (Figure 13) are almost all premodern tritium-age water, and the source of sulfate in this deeper and more isolated system is more likely from natural sources. The two wells with modern tritium-age water in Figure 13 are located in far eastern Dodge County, adjacent to the South Branch, Middle Fork of the Zumbro River, where erosion has removed some or all of the overlying Decorah–Platteville–Glenwood aquitard. These two wells also have anthropogenic chloride.

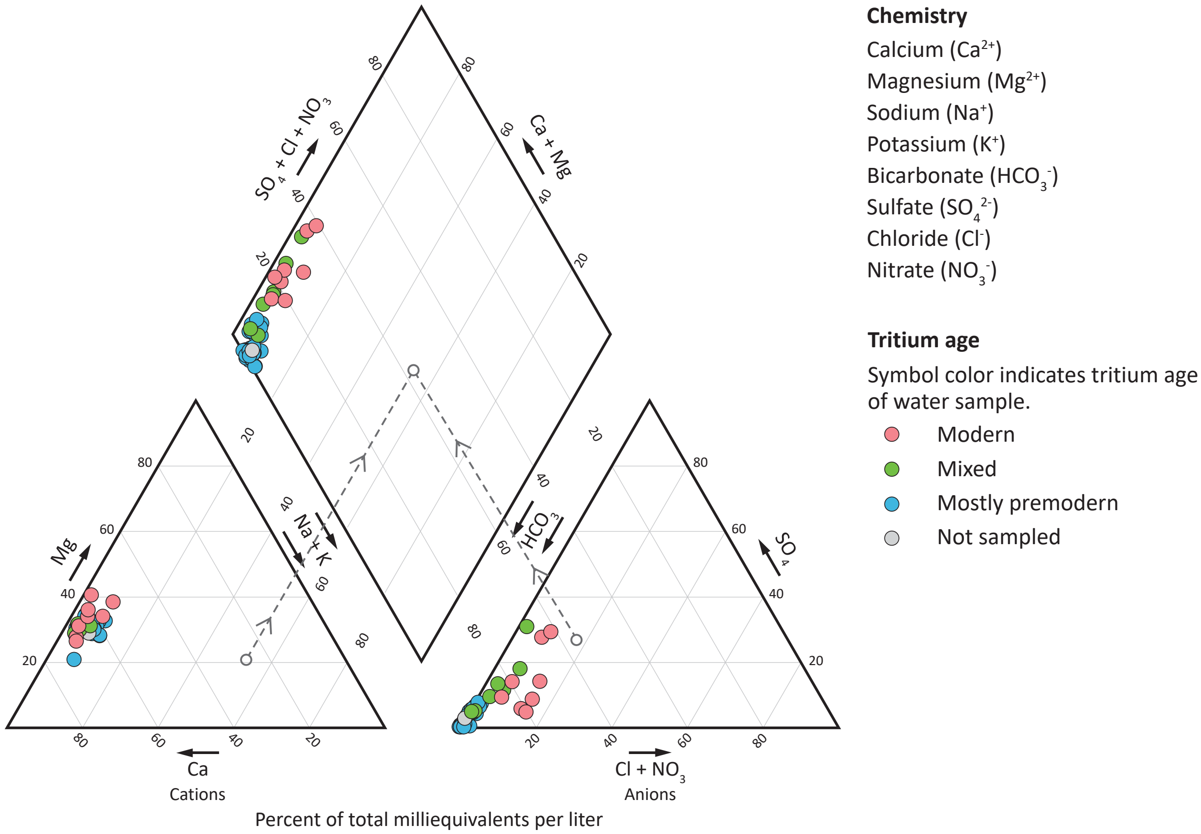


Figure 12. Piper diagram for 51 groundwater samples collected from the upper carbonate aquifer system

Modern and mixed tritium-age water was found in 15 samples; 13 are near or within areas of less than 50 feet to bedrock. With less overlying protective fine-textured sediment, these samples often have anthropogenic chemicals present, causing them to plot on the anion diagram away from the bicarbonate axis (lower left corner) toward the chloride+nitrate (lower right) and sulfate (top center) axes.

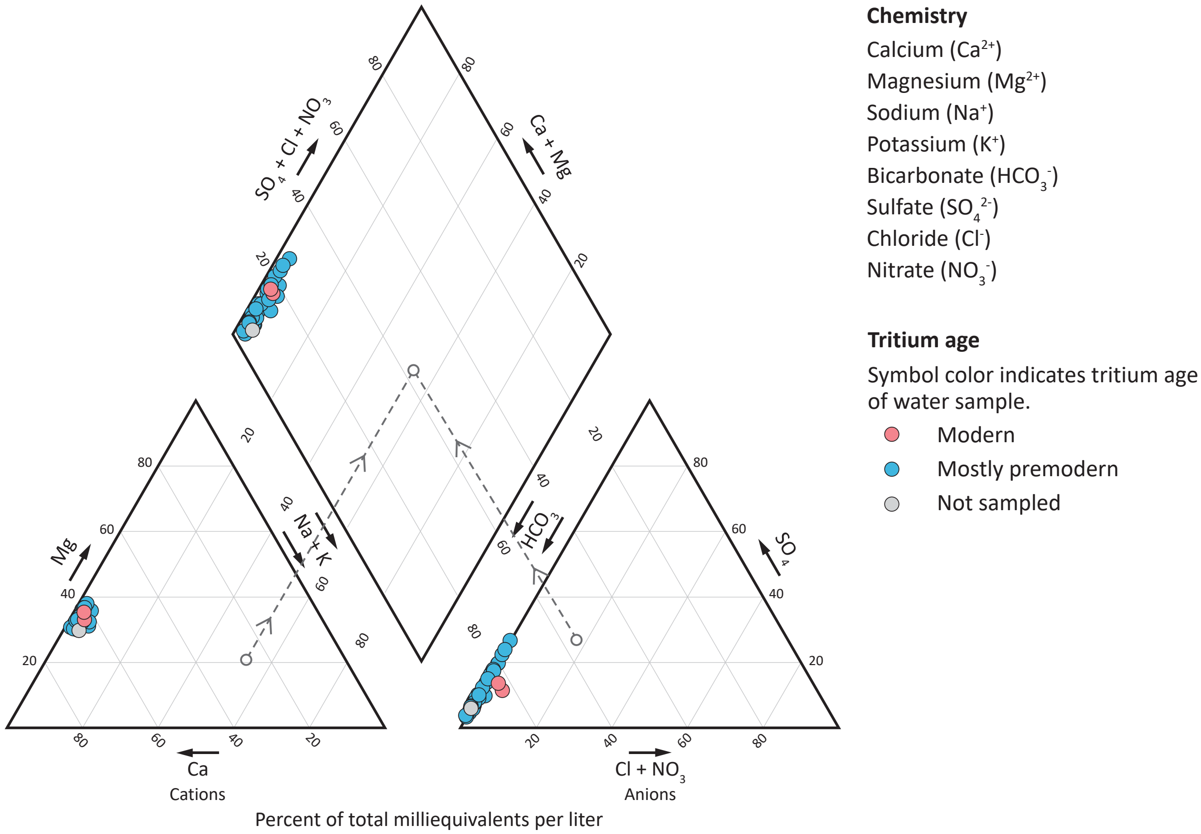


Figure 13. Piper diagram for 42 groundwater samples collected from the St. Peter–Shakopee aquifer system

The Decorah–Platteville–Glenwood aquitard overlies and protects the St. Peter–Shakopee aquifer system over most of the county, except in eastern Dodge County adjacent to the South Branch, Middle Fork of the Zumbro River, where erosion has removed some or all of the aquitard. Two samples from this area have modern tritium-age water and anthropogenic chloride that shift their plots slightly toward the chloride+nitrate (lower right) axis on the anion diagram.

Pollution sensitivity

For this report, pollution sensitivity is defined as the time for a contaminant to travel from the land surface to a specific target: the water table, a buried aquifer, or the bedrock surface. There are two pollution sensitivity models:

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

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

Both methods include the following general assumptions:

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

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

Near-surface materials model

Method

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

The transmission rate varies depending on texture. Coarse-grained materials generally have faster transmission rates than fine-grained materials. The two primary inputs used to estimate transmission rate are the hydrologic soil group (Table 1) (Natural Resources Conservation Service, 2023) and the surficial geologic matrix texture (Part A, Plate 3). Attributes of both are used to estimate the time of travel. Travel time varies from hours to approximately a year; ratings are shown in Figure 14. For further details, see *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

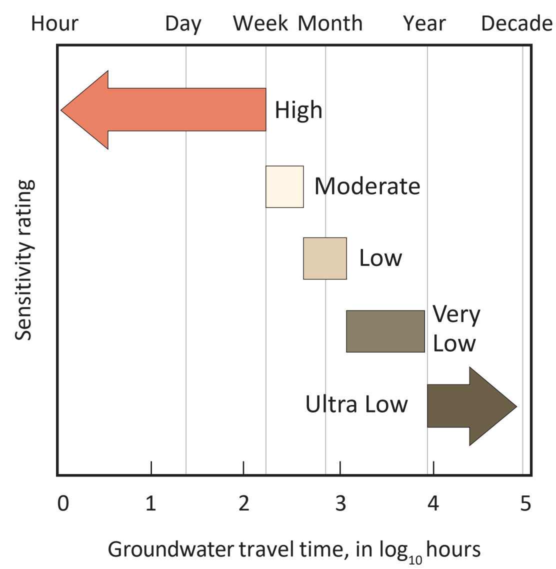


Figure 14. Pollution sensitivity rating of near-surface materials: travel time and ratings

Results (Figure 15)

High sensitivity is associated with glacial outwash and terrace sands. The largest area of high sensitivity is found on the western edge of the county, south of Claremont.

Moderate sensitivity is mapped adjacent to rivers and streams and is associated with sandy loam to silt loam-textured floodplain alluvium in stream channels. Moderate sensitivity is common along the Zumbro rivers and creeks.

Low sensitivity is mapped across large portions of the county and is associated with loam-textured deposits of the New Ulm, Browerville, and Rose Creek formations (tills).

Very low sensitivity areas are sparse and cover less than 1% of the county. These areas occur where soils have very slow infiltration rates defined by Hydrologic Soil Group D (Table 1). They are mostly found where colluvium is mapped, and rarely in other settings.

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. These are referred to as **special conditions** in the *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

Karst covers approximately 19% of the county and is largely found in the east and northeast. Karst features, such as sinkholes and sinking streams, are direct evidence that karst processes are active both on the surface and in the subsurface. These features provide a direct and very rapid exchange between surface water and groundwater and significantly increase groundwater contamination risk from surface pollutants. However, karst may still be present even where karst features are not visible at the surface. In Dodge County, surface karst features primarily occur where 50 feet or less of unconsolidated sediment overlies Paleozoic carbonate bedrock. In areas mapped as karst, the potential for extremely rapid contaminant travel is assumed.

Bedrock at or near the surface makes up less than 1% of the county and mainly occurs in the east and northeast. Bedrock at or near the surface cannot be assigned a transmission rate as there are no data for the bedrock from which to estimate travel times.

Disturbed lands make up less than 1% of the county and occur in locations like quarries and gravel pits. The largest disturbed land area is north of Claremont near the South Branch, Middle Fork of the Zumbro River. Disturbed lands cannot be assigned a transmission rate as there are no textural data from which to estimate travel times.

Table 1. Transmission rates through unsaturated materials

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

Hydrologic Soil Group (0 to 3 feet)		Surficial Geologic Texture (3 to 10 feet)		
Group*	**Transmission rate (in/hr)**	**Classification**	**Transmission rate (in/hr)**	**Surficial geology map unit (Part A, Plate 3)**
A, A/D	1	gravel, sandy gravel, silty gravel	1	Qmc, Quo, Qte, Qno
		sand, silty sand	0.71	Qal
B, B/D	0.50	silt, loamy sand	0.50	Not mapped in county
		sandy loam, peat	0.28	Not mapped in county
C, C/D	0.075	silt loam, loam	0.075	Qbv, Qel, Qco, Qmt, Qrc, Qsc
		sandy clay loam	0.035	Not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Not mapped in county

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

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

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

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

Group C: Water transmission is somewhat restricted.

Group D: Water movement is restricted or very restricted.

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

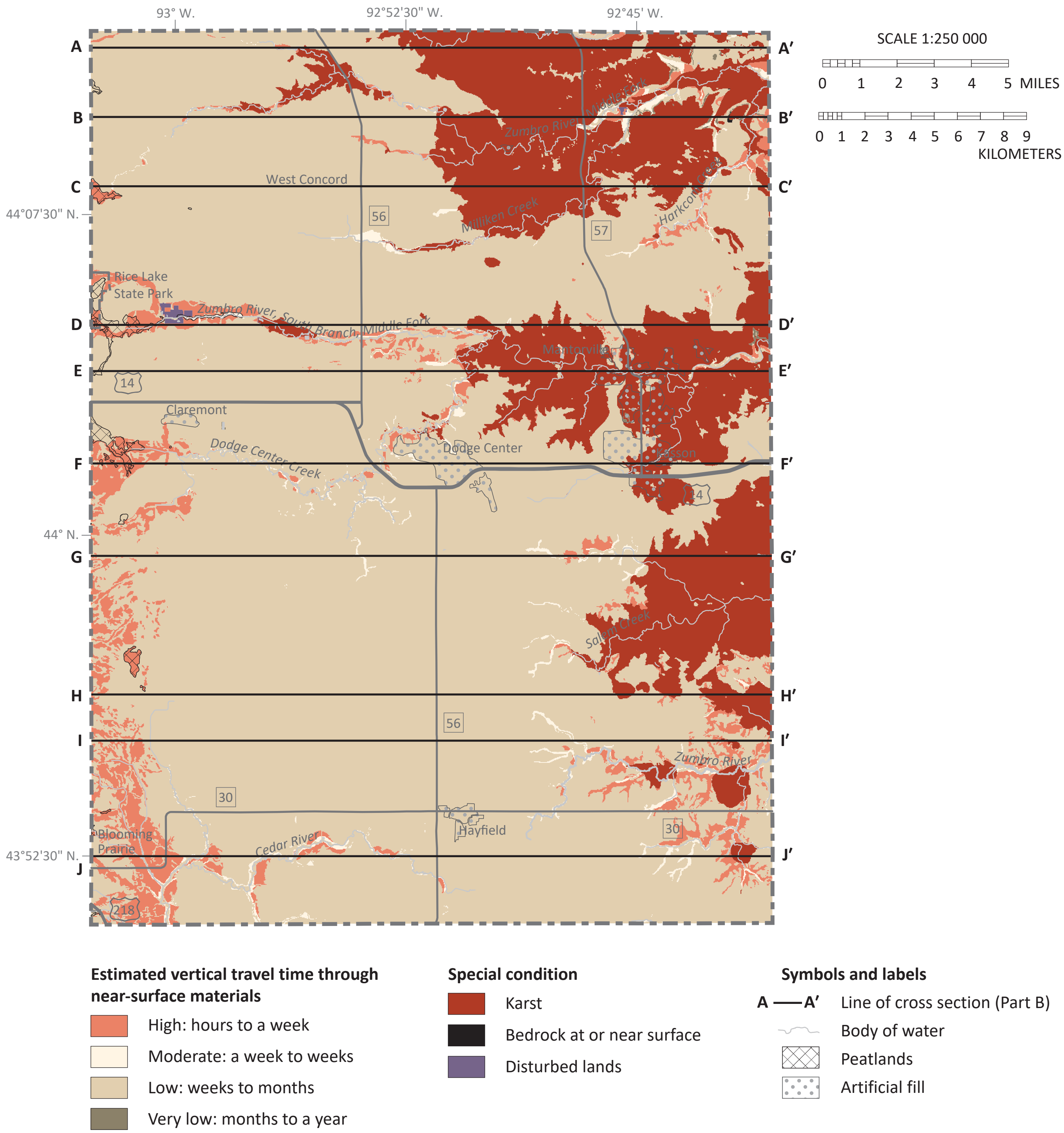


Figure 15. Pollution sensitivity rating of near-surface materials

Near-surface pollution sensitivity is low across most of the county. In areas where karst is mapped, the potential for extremely rapid contaminant travel is assumed.

Buried sand aquifer and bedrock surface model

Method

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

The model applies to unconsolidated geologic sediment and assumes that all sediment above and between buried sand aquifers and down to the bedrock surface is an aquitard: fine-grained with low hydraulic conductivity.

The estimated travel time is assumed to be proportional to the cumulative fine-grained sediment (CFGS) thickness overlying a buried sand aquifer or the bedrock surface (Figure 16 and Figure 17). The thicker the fine-grained sediment, the longer it takes for water to move through it. The model does not consider differences in sediment texture or permeability of aquitard materials. For more details, see *Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment thickness* (DNR, 2016c).

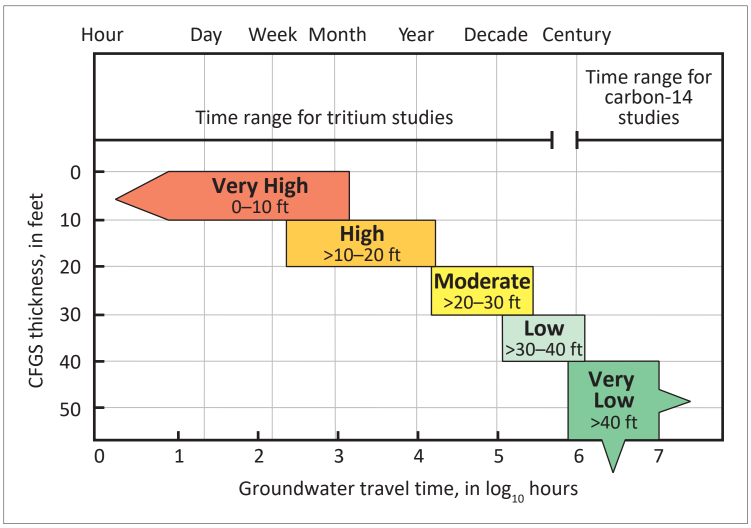


Figure 16. Pollution sensitivity rating for the buried sand aquifers and the bedrock surface

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

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

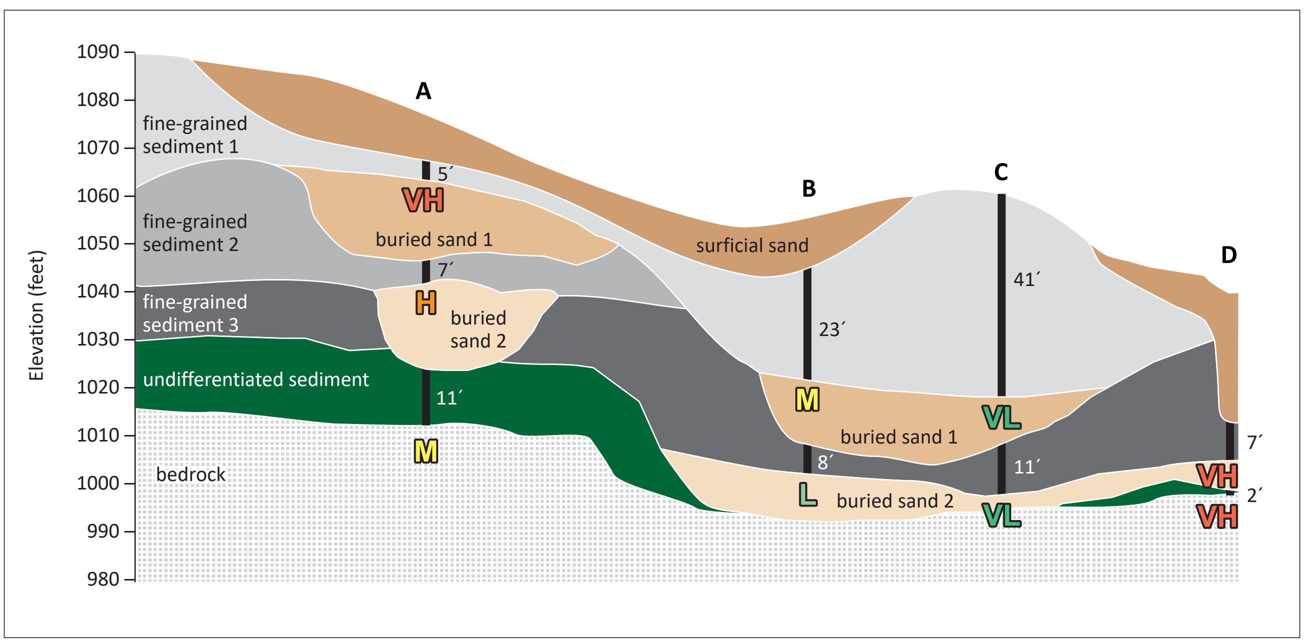


Figure 17. Cross section illustration of the pollution sensitivity model

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

Site A: 5 feet (buried sand 1: very high) + 7 feet = 12 feet (buried sand 2: high) + 11 feet = 23 feet (bedrock surface: moderate)

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

Groundwater conditions

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

Aquifers with very low pollution sensitivity ratings are generally expected to have premodern tritium-age water. Where this is not the case, the following groundwater conditions provide alternative explanations for how modern or mixed tritium-age water has traveled to an aquifer (Figure 18).

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

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

Ⓤ **Unknown**: neither the pollution sensitivity model nor groundwater conditions explained the presence of modern or mixed tritium-age water, possibly due to well construction issues at this or nearby wells.

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

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

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

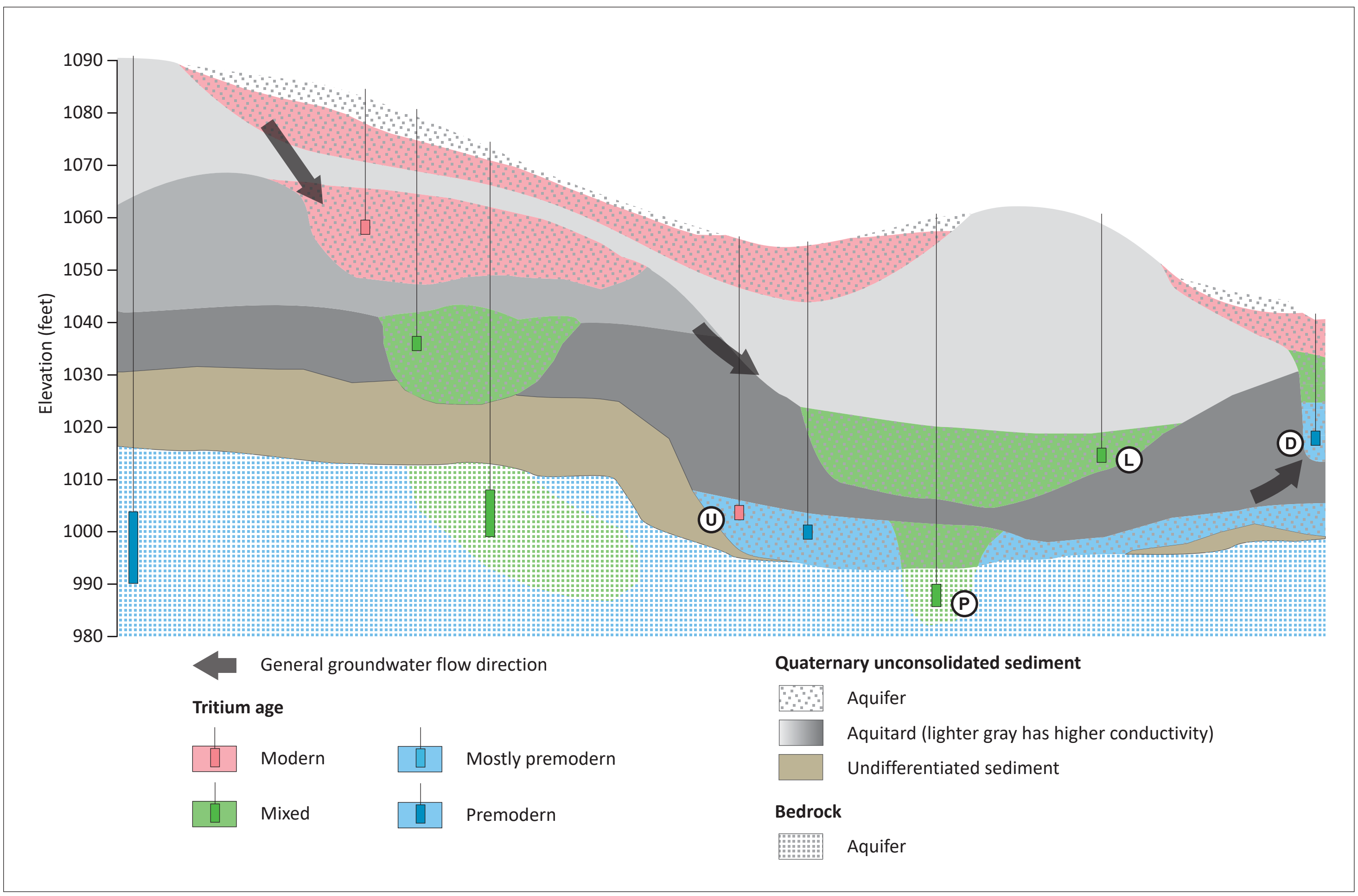


Figure 18. Cross section illustration of groundwater conditions

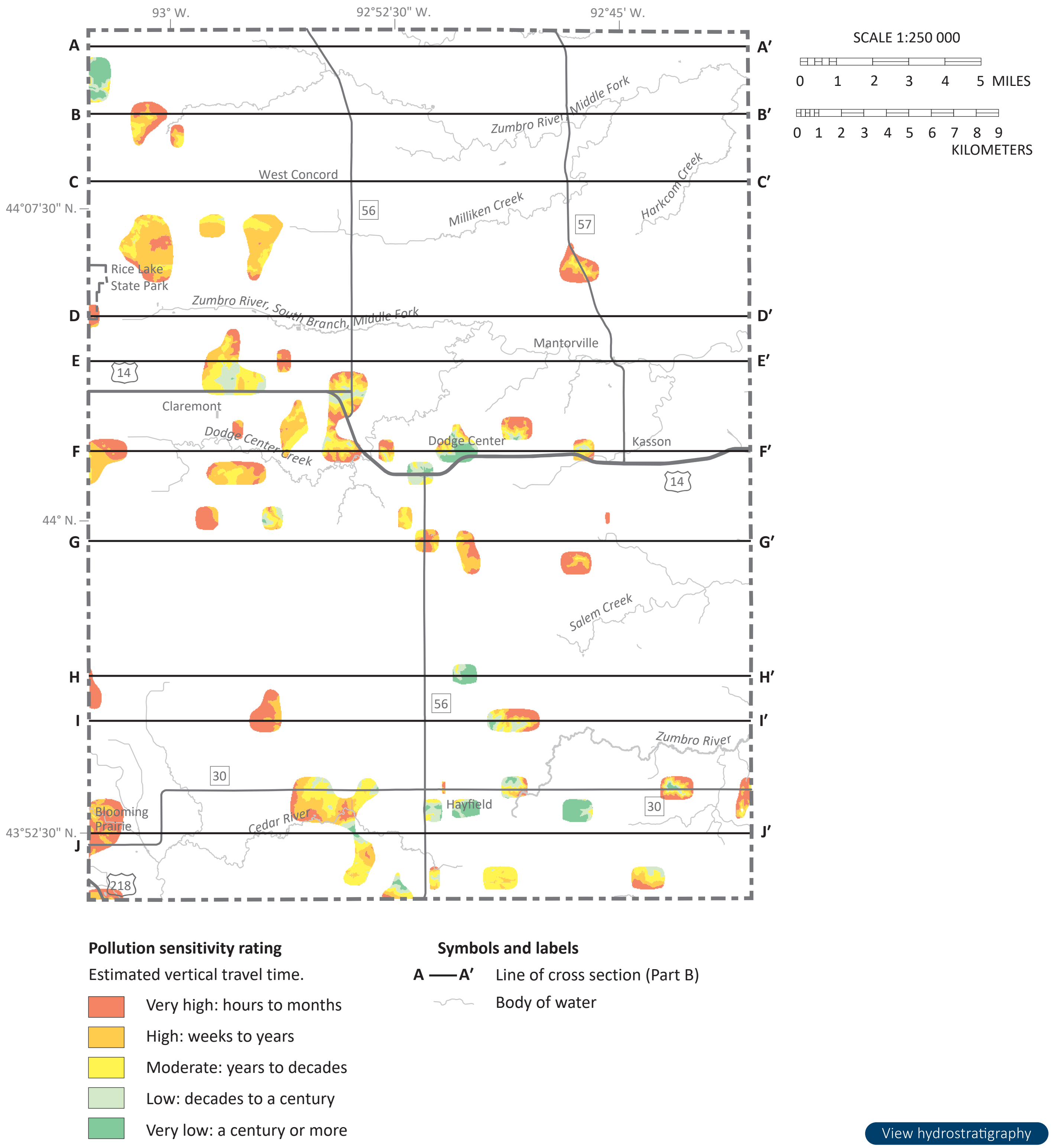
Buried sand and bedrock aquifers are shaded to indicate modern, mixed, or premodern tritium-age water. Wells sampled for tritium are shown for comparison. Groundwater condition labels are present where the tritium age of a water sample is at odds with the pollution sensitivity rating for the aquifer where the sample was taken.

Buried sand aquifer results

Five pollution sensitivity maps (Figures 19 to 23) were generated for buried sand aquifers (bs, rs, es, eg, and us). Two samples were collected from Quaternary aquifers: 1 from a shallow sand and gravel well in a calcareous fen and 1 from the rs buried sand aquifer.

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

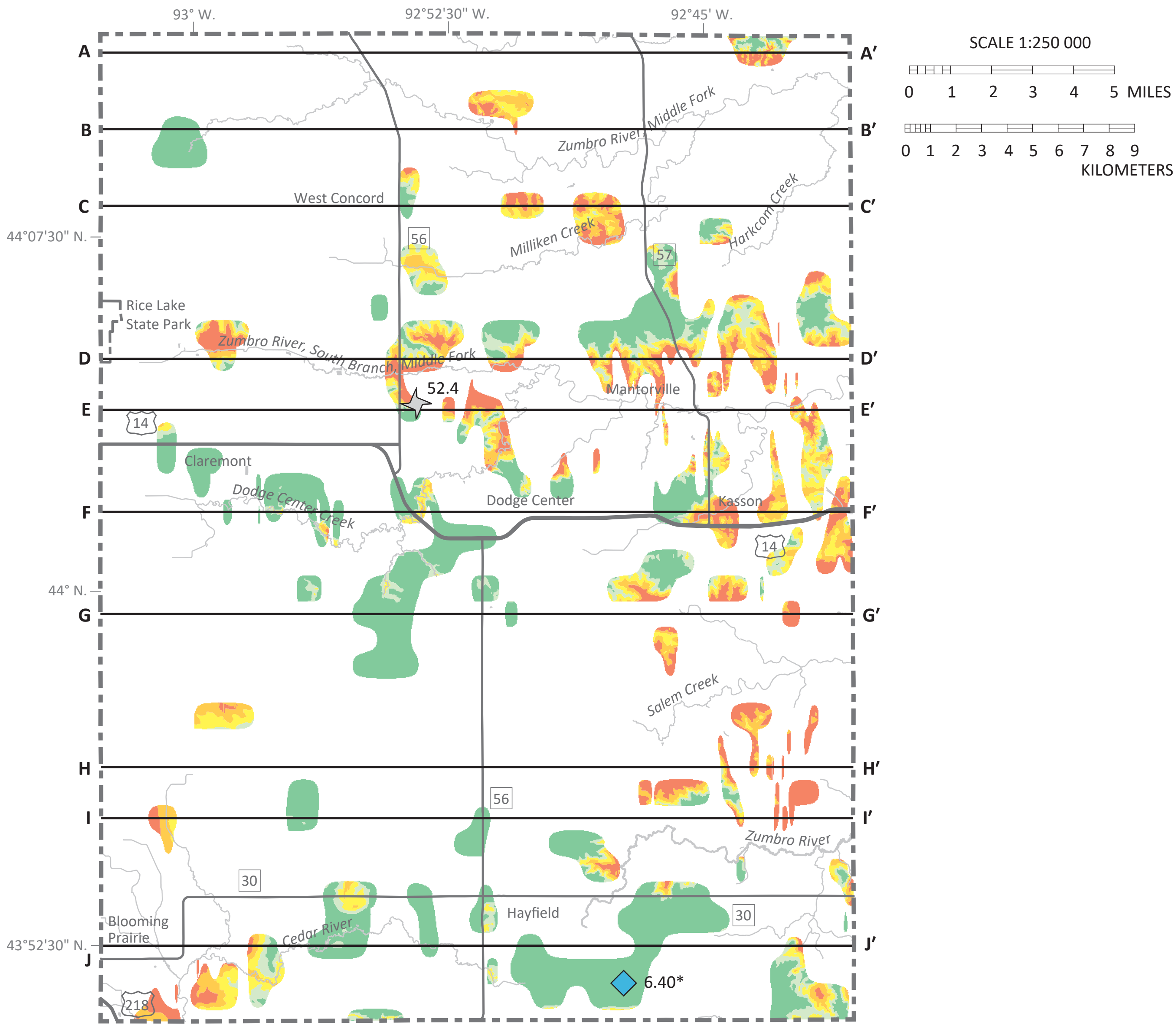
One sample was collected from a shallow Quaternary aquitard (bl) in a calcareous fen. It showed anthropogenic impacts of chloride (22.5 ppm) and nitrate (17.1 ppm).



View hydrostratigraphy

Figure 19. Pollution sensitivity of the bs aquifer

The bs aquifer is scattered throughout the county. Depths to the top of the aquifer range from approximately 0 to 45 feet, with a mean of 19 feet. No sample was collected from this aquifer.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Mostly premodern
- Not sampled for tritium

Water sample and aquifer symbol

- rs (surficial)
- rs (buried)

Symbols and labels

- 6.40* Chloride: if shown, concentration is ≥5 ppm. (*naturally elevated)
- A —— A′ Line of cross section (Part B)
- Body of water

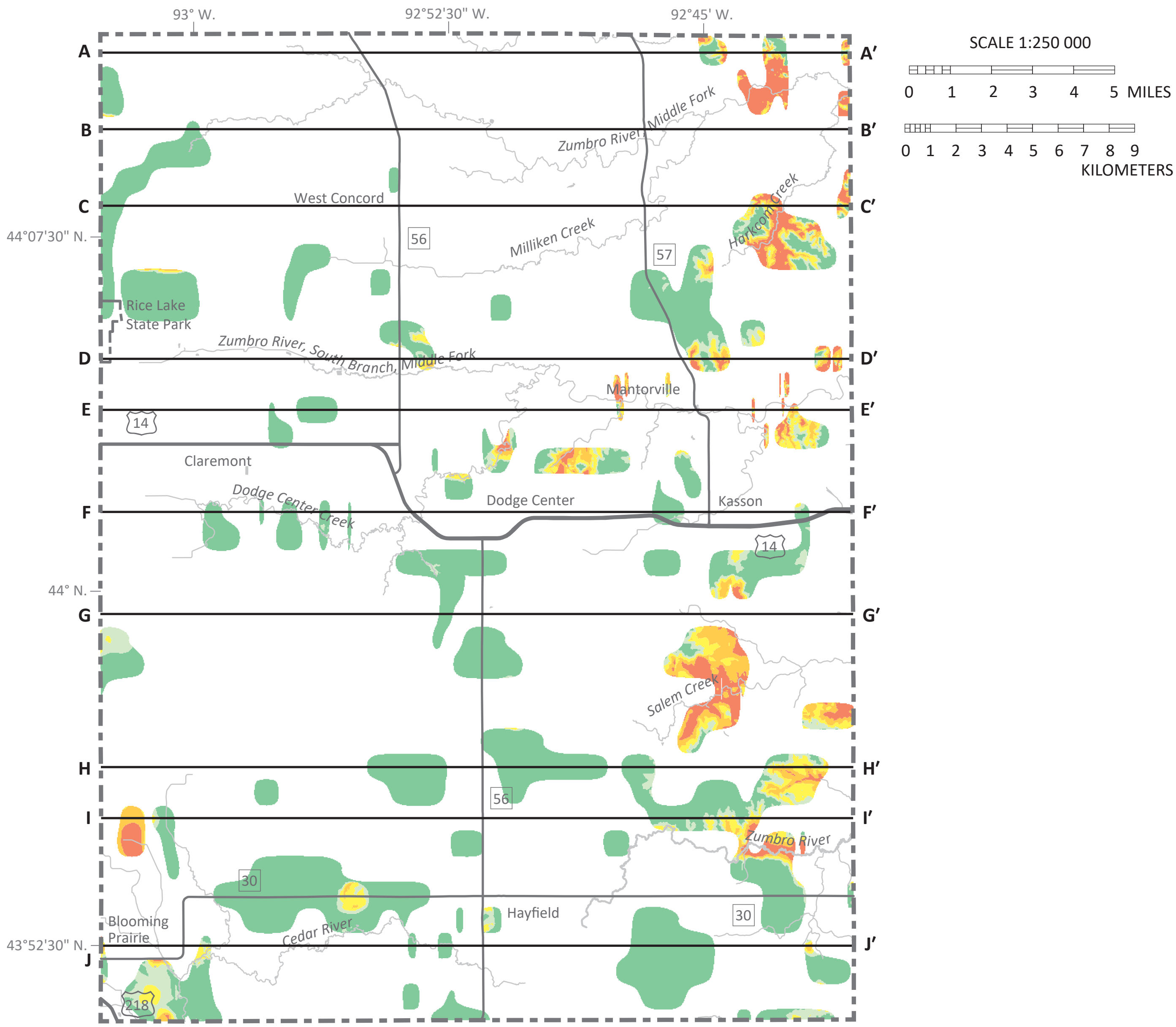
View hydrostratigraphy

Figure 20. Pollution sensitivity of the rs aquifer

The rs aquifer is scattered throughout the county, and depths to the top of the aquifer range from approximately 0 to 99 feet; the mean is 42 feet.

A surficial, 20-foot water-table well in a fen just over 2 miles northwest of Dodge Center had significantly elevated chloride (52.4 ppm), likely from an anthropogenic source, consistent with the aquifer's assigned high pollution sensitivity. Nitrate was below detection.

A 96-foot well 3.5 miles southeast of Hayfield had premodern tritium-age water, consistent with the predominantly very low pollution sensitivity rating assigned at this location. Chloride was over 5 ppm and determined to be from a natural source. Nitrate was not detected.



Pollution sensitivity rating

Estimated vertical travel time.

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

Symbols and labels

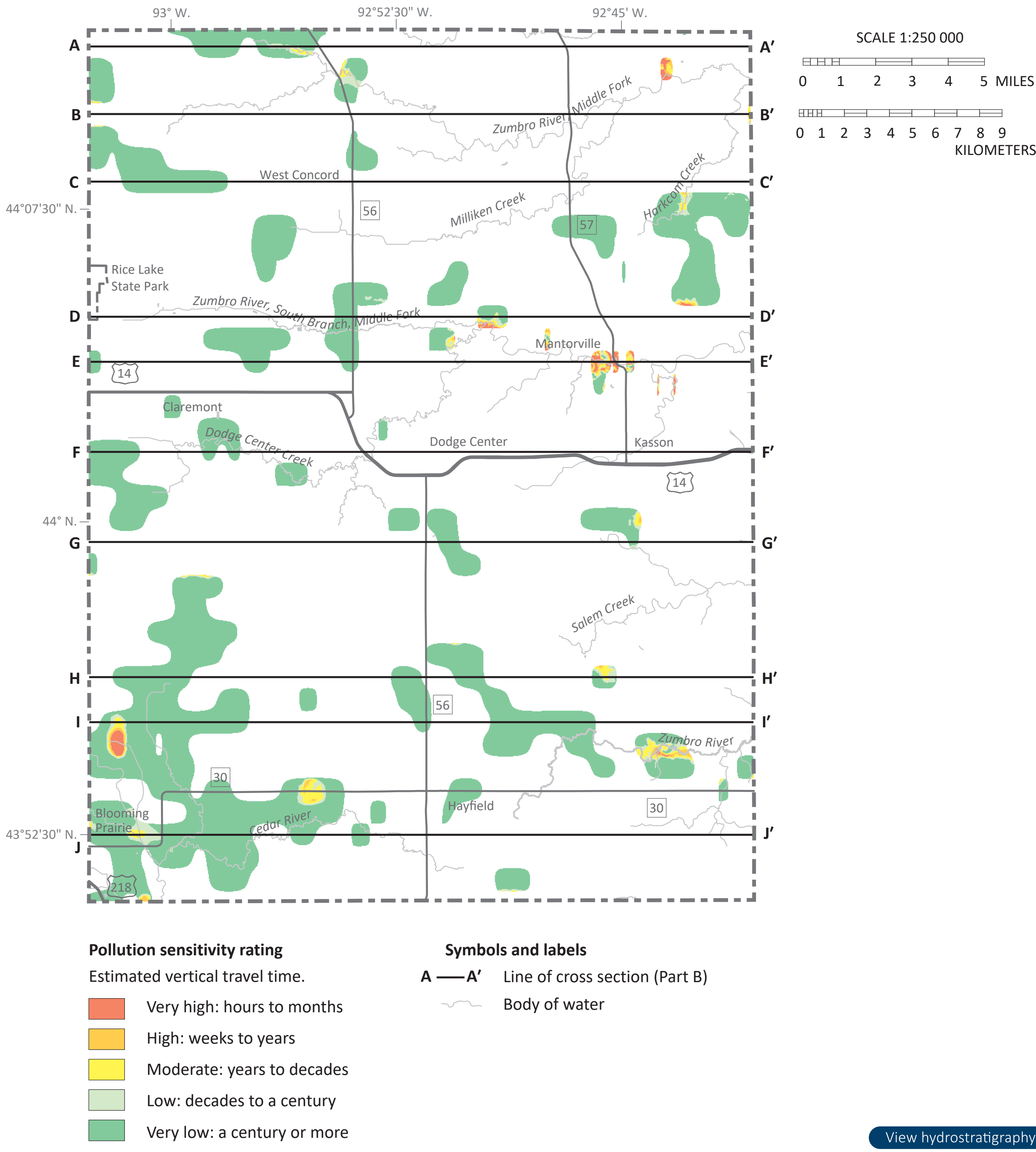
A —— A' Line of cross section (Part B)

Body of water

View hydrostratigraphy

Figure 21. Pollution sensitivity of the es aquifer

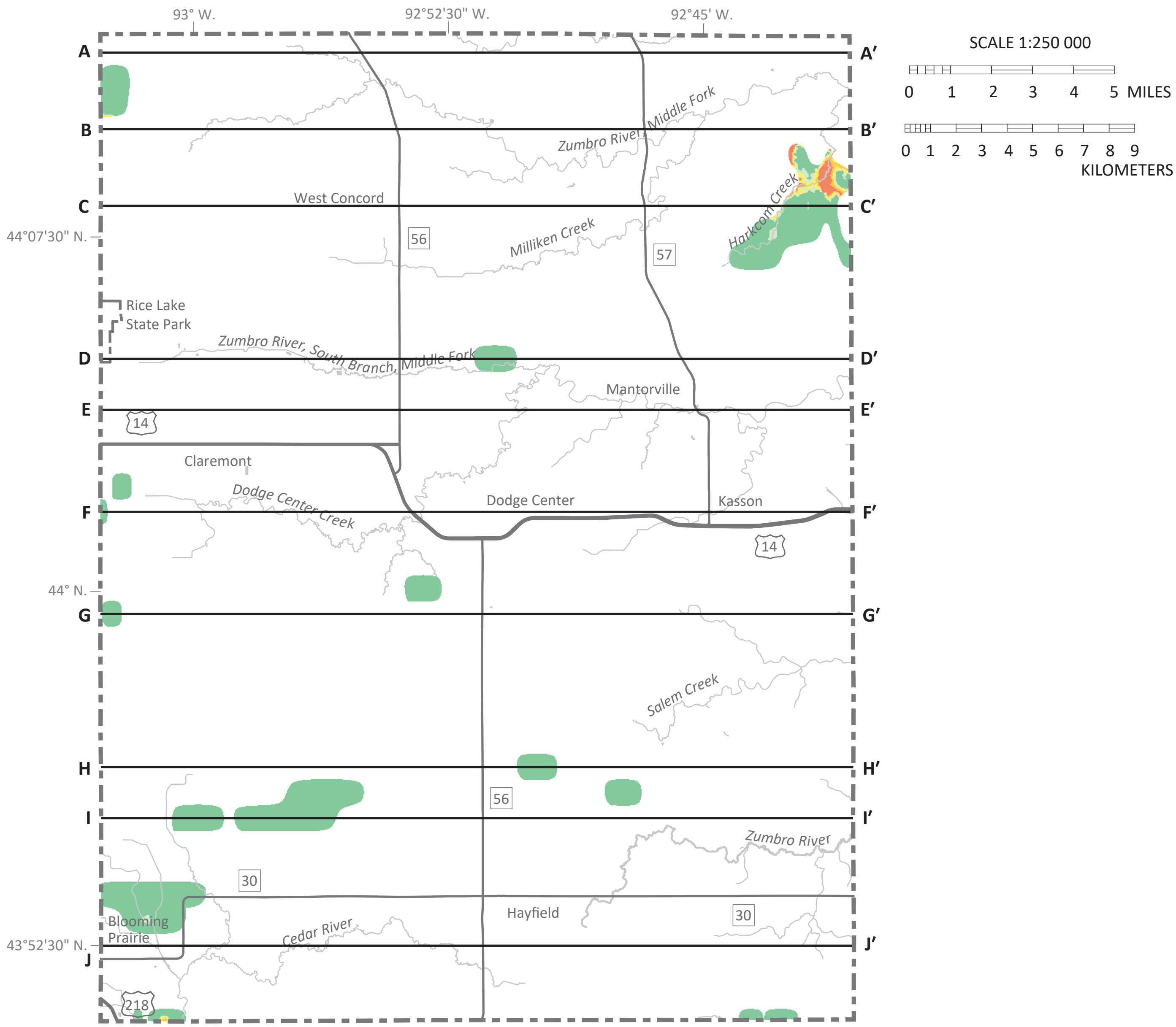
The es aquifer is scattered throughout the county. Depths to the top of the aquifer range from approximately 34 to 170 feet, with a mean of 68 feet. No sample was collected from this aquifer.



View hydrostratigraphy

Figure 22. Pollution sensitivity of the eg aquifer

The eg aquifer is scattered throughout the county. Depths to the top of the aquifer range from approximately 0 to 138 feet, with a mean of 102 feet. No sample was collected from this aquifer.



Pollution sensitivity rating

Estimated vertical travel time.

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

Symbols and labels

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

Body of water

View hydrostratigraphy

Figure 23. Pollution sensitivity of the us aquifer

The us aquifer is widely scattered throughout the county. Depths to the top of the aquifer range from approximately 33 to 209 feet, with a mean of 121 feet. No sample was collected from this aquifer.

Bedrock surface results

Pollution sensitivity maps were developed for the bedrock surfaces of the two primary aquifer systems. Estimated travel times to the bedrock surfaces were assigned according to the cumulative thickness of overlying Quaternary aquitards. The first map (Figure 24) estimates the pollution sensitivity at the surface of the upper carbonate aquifer system. The second map (Figure 25) removes the upper carbonate aquifer system in order to show the extent of the Decorah–Platteville–Glenwood aquitard and the pollution sensitivity of the underlying St. Peter–Shakopee aquifer system.

The following section describes the two primary bedrock aquifer systems of Dodge County (Figure 4), including their extent, depth, thicknesses, approximate percentage of wells, pollution sensitivity, groundwater residence time, and presence of anthropogenic indicators. Bedrock distribution, depth, and thicknesses are from Part A, Plates 2 and 6.

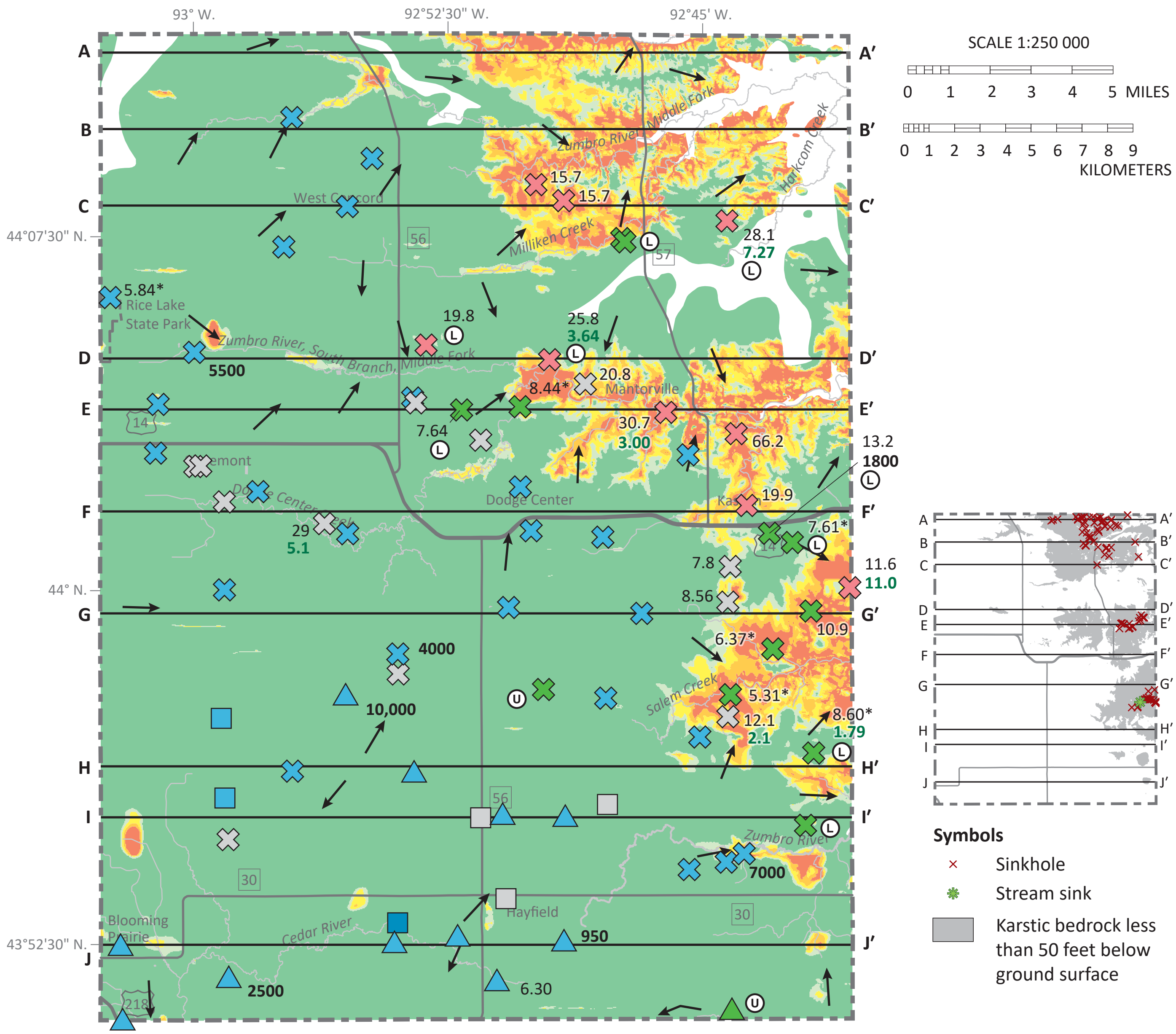
The modeled bedrock surface pollution sensitivity results are compared to groundwater residence times from tritium and carbon-14 samples and to the presence of anthropogenic chemical indicators (nitrate greater than 1 ppm or chloride greater than or equal to 5 ppm with a chloride/bromide ratio greater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

Pollution sensitivity of the upper carbonate aquifer system (Figure 24)

- *Extent:* The bulk of the uppermost bedrock surface is the upper carbonate aquifer system, including geologic units of the Little Cedar Formation through the upper Maquoketa Formation that are limited to the south and the stratigraphically deeper Galena Formation, extending throughout most of the rest of the county, except the northwest and northeast.
- *Depth:* Quaternary sediment of variable thickness overlies this aquifer system, with areas of less than 50 feet in the east and northeast along the Middle Fork and South Branch, Middle Fork of the Zumbro River and Salem Creek, where sediment has eroded away. Elsewhere, sediment thicknesses average just over 100 feet and can be greater than 200 feet in buried bedrock valleys.
- *Thickness:* The combined upper carbonate aquifer system has an approximate maximum thickness of 400 feet. The upper portion, including the Little Cedar Formation through the upper Maquoketa Formation, makes up approximately half the thickness, with the Galena Formation making up the rest.
- *Use:* Just over half (53%) of wells are completed in this aquifer system.
- *Pollution sensitivity:* Karstic bedrock is less than 50 feet below ground surface over much of the east and northeast, where pollution sensitivity predominately ranges from very high to moderate. Very low sensitivity dominates elsewhere except for small areas of higher sensitivity, where stacked unconsolidated sands and minimal aquitards increase sensitivity.
- *Residence time:* Of the 61 samples analyzed for tritium, 9 were modern, 13 were mixed, and 39 were premodern tritium age. Of the mixed tritium-age samples, 1 analyzed for carbon-14 had a residence time of 1,800 years. Of the premodern tritium-age samples, 6 were dated using carbon-14 and had residence times ranging from 950 to 10,000 years.
- *Anthropogenic chemical indicators:* Of the 72 samples collected for chloride, 24 were greater than 5 ppm: 18 from anthropogenic sources and 6 from natural sources. Of the 66 samples analyzed for nitrate, 7 were anthropogenic. Anthropogenic chloride and nitrate are largely found within or near areas where depth to bedrock is less than 50 feet. These same areas are mapped as karst and have mapped karst features (Figure 5; Part A, Plate 6, Figure 1).
- *Summary:* Nearly all modern and mixed tritium-age samples were found within or close to areas where karstic bedrock is less than 50 feet from the land surface. Wells located in very low sensitivity areas that have modern and mixed tritium-age water may have recharge from upgradient areas of higher sensitivity (labeled L). Two wells located in areas of very low sensitivity had tritium where not expected (labeled U). One well with a mixed tritium age located between cross sections G–G’ and H–H’ was sampled by the MDH; the presence of tritium in this well may be due to poor well condition or compromised grouting. A second well located in the far southeast had 0.8 tritium units. This value is at the detection limit for tritium and may not be indicative of younger water in the aquifer.

Pollution sensitivity of the St. Peter–Shakopee aquifer system (Figure 25)

- *Extent:* The St. Peter–Shakopee aquifer system underlies the entire county. It is largely overlain by the Decorah–Platteville–Glenwood aquitard, except in areas of the northeast where the aquifer system is either exposed or directly overlain by glacial sediment.
- *Depth:* The mean depth of the top of the St. Peter is 360 feet but varies widely from at or near the surface in the northeast to over 500 feet in the south-central part of the county.
- *Thickness:* The combined aquifer system has an approximate maximum thickness of 290 feet: 110 feet of St. Peter Sandstone plus 180 feet of Shakopee Formation.
- *Use:* Just under half (46%) of wells are completed in this aquifer system.
- *Pollution sensitivity:* Pollution sensitivity is very low in areas where the Decorah–Platteville–Glenwood aquitard is at full thickness. Where the aquitard has been reduced to less than full thickness or completely removed by erosion, pollution sensitivity varies from very high to very low. Where the Decorah Shale has been completely removed and the underlying Platteville and Glenwood formations are less than their full thickness (shown with the cross-hatch pattern), sensitivity was determined by the thickness of the overlying glacial sediment.
- *Residence time:* Of the 43 samples analyzed for tritium, 2 were modern, 1 was mixed, and 40 were premodern tritium age. Both modern tritium-age samples are located in far eastern Dodge County, adjacent to the South Branch, Middle Fork of the Zumbro River, where glacial and bedrock aquitards are thin to absent (Figure 25, inset). Each well also had anthropogenic chloride. A well in the north-central part of the county, completed in the Jordan aquifer (labeled with groundwater condition U), was found to have mixed tritium-age water. This well is in an area where glacial and bedrock aquitards are sufficient to protect the aquifer; therefore, it is likely this well has grouting or construction issues that allowed younger water to enter the well. The 40 premodern tritium-age samples are from areas where the Decorah–Platteville–Glenwood aquitard is intact and uneroded. Groundwater residence times estimated using carbon-14 ranged from 600 to 9,500 years.
- *Anthropogenic chemical indicators:* Of the 65 samples collected for chloride, 3 were greater than 5 ppm; all were from anthropogenic sources. Two samples were from wells where glacial and bedrock aquitards are thin to absent. One sample, collected just north of Hwy 30 in the southeast, is in an area where surrounding samples suggest a premodern tritium age; this well likely has grouting or construction issues. Of the 61 samples analyzed for nitrate, none were anthropogenic.
- *Summary:* The dominance of premodern tritium-age samples supports that the combined overlying glacial and Decorah–Platteville–Glenwood aquitards are very effective at protecting this aquifer system. Where glacial sediment is less than 50 feet thick and the Decorah–Platteville–Glenwood aquitard is thin to absent, protection is diminished: for instance, the two wells with modern tritium-age water and anthropogenic chloride sampled between cross sections D–D′ and E–E′ (each labeled with groundwater condition L).



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

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

Water sample and aquifer symbol

- Little Cedar–Maquoketa
- Galena Group
- Cedar Valley–Galena, Spillville–Galena, Maquoketa–Galena

Symbols and labels

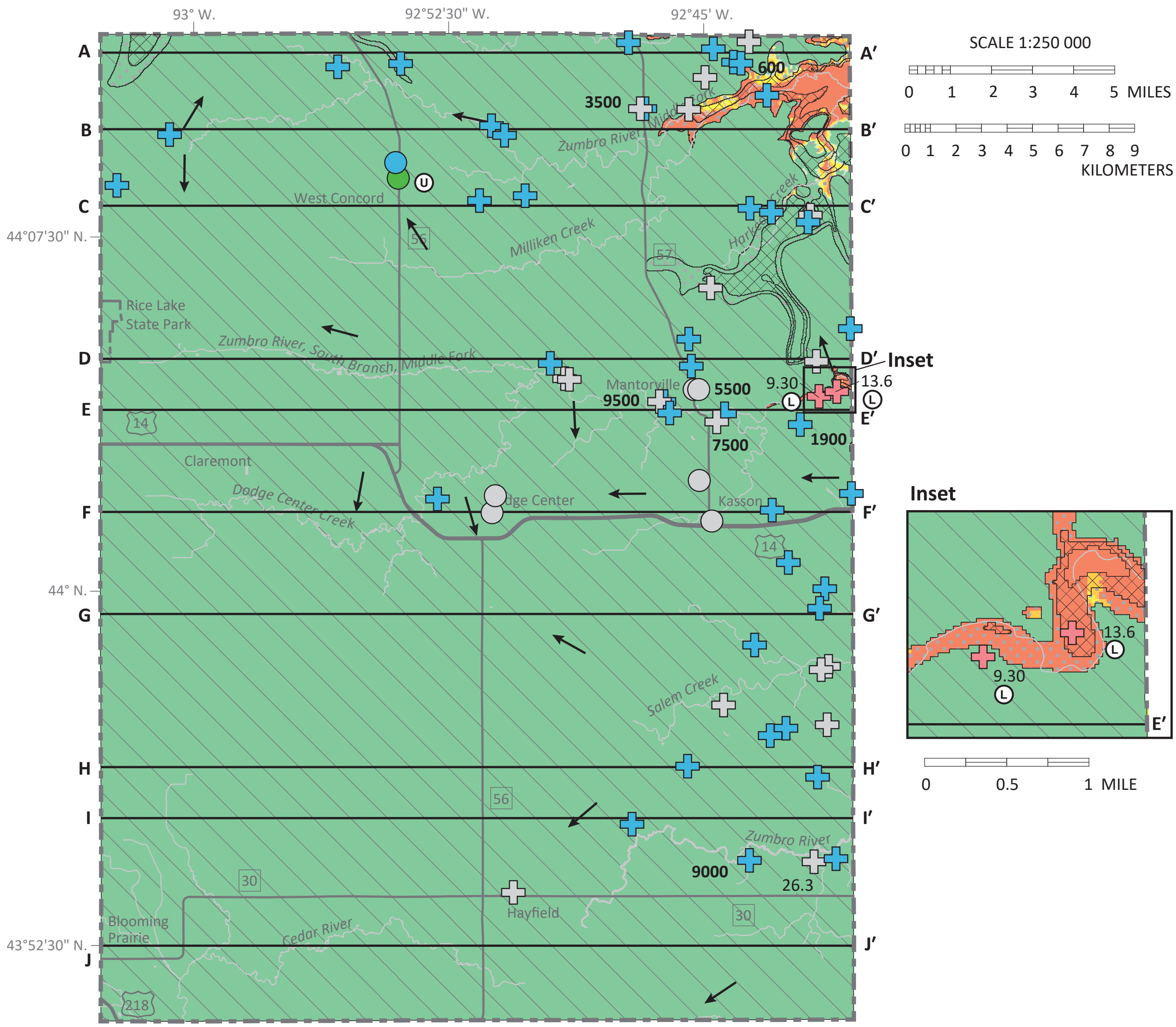
- 20.8 Chloride: if shown, concentration is ≥5 ppm. (*naturally elevated)
- 1.79 Nitrate: if shown, concentration is >1 ppm.
- 5500 Carbon-14 (^{14}C): estimated groundwater residence time in years.
- Groundwater flow direction
- A —A′ Line of cross section (Part B)
- Body of water

Groundwater conditions

- L Lateral flow
- U Unknown

Figure 24. Pollution sensitivity of the upper carbonate aquifer system and groundwater flow directions

Most of the bedrock surface forms the upper carbonate aquifer system except in the northeast and northwest, where erosion exposed the St. Peter–Shakopee. Overlying Quaternary sediment is protective except in areas of karstic bedrock less than 50 feet below ground surface. Karstic bedrock extent is from *Minnesota regions prone to surface karst feature development* (DNR, 2016d).



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

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

Water sample and aquifer symbol

- St. Peter–Shakopee
- Jordan

Groundwater conditions

- Ⓛ Lateral flow
- Ⓤ Unknown

Symbols and labels

- 13.6 Chloride: if shown, concentration is ≥5 ppm. (*naturally elevated)
- **9500** Carbon-14 (^{14}C): estimated groundwater residence time in years.
- ← Groundwater flow direction
- A —— A′ Line of cross section (Part B)
- Body of water
- Decorah–Platteville–Glenwood at full thickness
- Decorah less than full thickness
- Platteville and Glenwood less than full thickness. Decorah not present.

Figure 25. Pollution sensitivity of the St. Peter–Shakopee aquifer system and groundwater flow directions

The St. Peter–Shakopee aquifer system is well protected over most of the county by glacial sediment and the overlying Decorah–Platteville–Glenwood aquitard. Sensitivity is very low in areas where the aquitard is less than full thickness. In the northwest and northeast, where glacial sediment and the Decorah are eroded, pollution sensitivity ranges from very high to very low.

Hydrogeologic cross sections (Plates 8 and 9)

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

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

Relative hydraulic conductivity of Quaternary aquitards

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

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

Sediment that makes up the Quaternary aquitards (typically till) is shown on the cross sections as shades of gray based on its assumed ability to transmit water. Hydraulic conductivity values are not available for each Quaternary aquitard; therefore, the percent sand content is used as a proxy for hydraulic conductivity. Aquitards with higher sand content (lighter shades of gray) are assumed to transmit water more readily and, therefore, have a higher hydraulic conductivity. Percent sand is based on the average matrix texture of each aquitard (Part A, Plate 4). Bedrock aquitards are defined using content from Part A, Plate 2, and shown on cross sections as an olive hue.

Groundwater flow and residence time

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

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

Cross sections A–A′ through E–E′ (Plate 8)

Glacial sediment along cross sections A–A′ through E–E′ is generally thicker to the west and thinner to the east. Sediment thickness is generally less than 50 feet to the east of County Road 7 (middle of all cross sections). The Galena Group portion of the upper carbonate aquifer system makes up the shallowest bedrock. Areas where depth to bedrock is less than 50 feet thick generally correspond to locations where groundwater has modern or mixed tritium-age water and the presence of anthropogenic chloride and nitrate. In some areas to the west, where the presence of surficial or buried sand reduces the cumulative thickness of overlying glacial aquitards, there is increased pollution sensitivity, such as the west end of cross section A–A′ near the Middle Fork of the Zumbro River and the west end of cross section D–D′ near County Road 5.

Where the glacial sediment is over 50 feet thick, the upper carbonate aquifer system is reasonably well protected, as evidenced by the dominance of premodern tritium-age water and carbon-14 ages ranging from 950 to 10,000 years. An example is at the west end of cross section D–D′, near County Road 1.

The St. Peter–Shakopee aquifer system is largely well protected by a combination of the overlying glacial sediment, the upper carbonate aquifer system, and the Decorah–Platteville–Glenwood aquitard. The upper carbonate aquifer system provides some degree of protection due to the presence of internal aquitards (Figure 4). All but two samples had premodern tritium-age water and carbon-14 residence times that ranged from 600 to 9,500 years. The St. Peter–Shakopee aquifer system is less protected in portions of the far east and northeast, where the overlying Decorah–Platteville–Glenwood aquitard is thin to absent. An example is at the far east end of cross section B–B′, near Harkcom Creek.

Cross sections F–F′ through J–J′ (Plate 9)

Glacial sediment along cross sections F–F′ through J–J′ is generally thicker to the west and thinner to the east. In contrast to cross sections A–A′ through E–E′, glacial aquitard thicknesses greater than 50 feet are common. The shallowest bedrock is primarily the Galena Group, with increasing occurrence of the Spillville, Maquoketa, and Dubuque formations to the south. Depth to bedrock less than 50 feet generally corresponds with areas of modern or mixed tritium-age water and anthropogenic nitrate and chloride. In some areas to the west, where the presence of surficial or buried sand reduces the cumulative thickness of overlying glacial aquitards, there is increased pollution sensitivity, such as the west ends of cross sections I–I′ and J–J′ near the Cedar River, West Fork. Areas where depth to bedrock is greater than 50 feet are generally well protected, as indicated by the presence of premodern tritium-age water. A carbon-14 sample collected along cross section J–J′ near 210th Avenue had a residence time of 950 years.

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

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

Specific capacity is the pumping rate per unit depth of drawdown. It is typically expressed in gallons per minute per foot (gpm/ft) and determined from short-term pumping or well-development tests performed after a well is drilled. Well contractors commonly determine specific capacity to confirm well yield and help set the well pump depth. It can also help estimate the hydraulic properties of the aquifer, with higher specific capacities often associated with more productive aquifers.

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

- The casing diameter was at least 8 inches.
- The well was pumped for at least 4 hours.
- The pumping water level was inside the well casing, at least 2 feet above the well screen or open hole.

Eleven wells met the criteria for determining specific capacity (Table 2). The highest mean specific capacity of 23.1 gpm/ft was calculated for a Jordan aquifer well.

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). Aquifer testing is an effective method to determine aquifer characteristics and classification, such as water table, leaky, or confined. This information greatly assists hydrologists in addressing potential water-use concerns.

Transmissivity values are available from four aquifer tests, all in bedrock aquifers. Testing from the Galena aquifer ranged from 1,800 to 31,700 ft^2/day, a Prairie du Chien–Jordan test ranged from 16,700 to 20,400 ft^2/day, and two Jordan aquifer tests ranged from 1,500 to 14,800 ft^2/day.

Table 2. Specific capacity and transmissivity of selected wells

Bedrock aquifer	Specific capacity (gpm/ft)				Transmissivity (ft^2/day)			
	Casing diam. (in.)	Min.	Max.	No. of tests	Casing diam. (in.)	Min.	Max.	No. of tests
Galena	8–12	9.5	26.7	4	12	1,800	31,700	1⁺
St. Peter–Prairie du Chien	16	--	--	1	--	--	--	--
Prairie du Chien–Jordan	--	--	--	--	12	16,700	20,400	1⁺
Jordan	10–18	9.7	55.7	6	16–18	1,500	14,800	2

Transmissivity data are from the aquifer properties database (DNR, 2023d)

⁺For a single aquifer test, multiple transmissivity values may be calculated using different models.
Specific capacity data adapted from the CWI.

Dash marks (--) indicate 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.

Hydrographs depict groundwater levels over time. They are useful for determining trends and provide insight into how aquifers respond to recharge events, pumping stresses, and changing climatic conditions. These data are critical to understanding the magnitude of periods of drought and high precipitation.

Hydrographs from well nests reveal information that is more useful than individual wells. Well nests consist of closely spaced wells constructed in different aquifers. The hydraulic relationship between the different aquifers, known as vertical gradient, is critical to understanding groundwater flow and the impacts of water use and other changes on the groundwater system. Eight actively measured DNR observation wells in Dodge County record groundwater elevation of the water table, Galena, and St. Peter aquifers (Table 3).

Three groups of observation well locations are well nests, with two wells completed in each (Figure 26). Hydrographs were created for these well nests (Figures 27 to 29), produced from data retrieved online from the DNR Cooperative Groundwater Monitoring Program (DNR, 2023e). Monthly gridded precipitation data were obtained through the Minnesota State Climatology Office (DNR, 2024).

Table 3. Actively measured DNR observation wells of Dodge County

Well nest	Aquifer system	Aquifer (formations)	Well depth (ft)	Unique well number
Nest 1	-	water table	16.5	809286
Nest 1	upper carbonate	Galena (Stewartville–Prosser)	162	798791
–	upper carbonate	Dubuque–Galena	248	843403
Nest 2	upper carbonate	Galena (Stewartville–Prosser)	158	843404
Nest 2	St. Peter–Prairie du Chien	St. Peter	385	843405
–	upper carbonate	Galena (Stewartville–Cummingsville)	100	217464
Nest 3	upper carbonate	Galena (Stewartville–Cummingsville)	180	843406
Nest 3	St. Peter–Prairie du Chien	St. Peter	380	843407

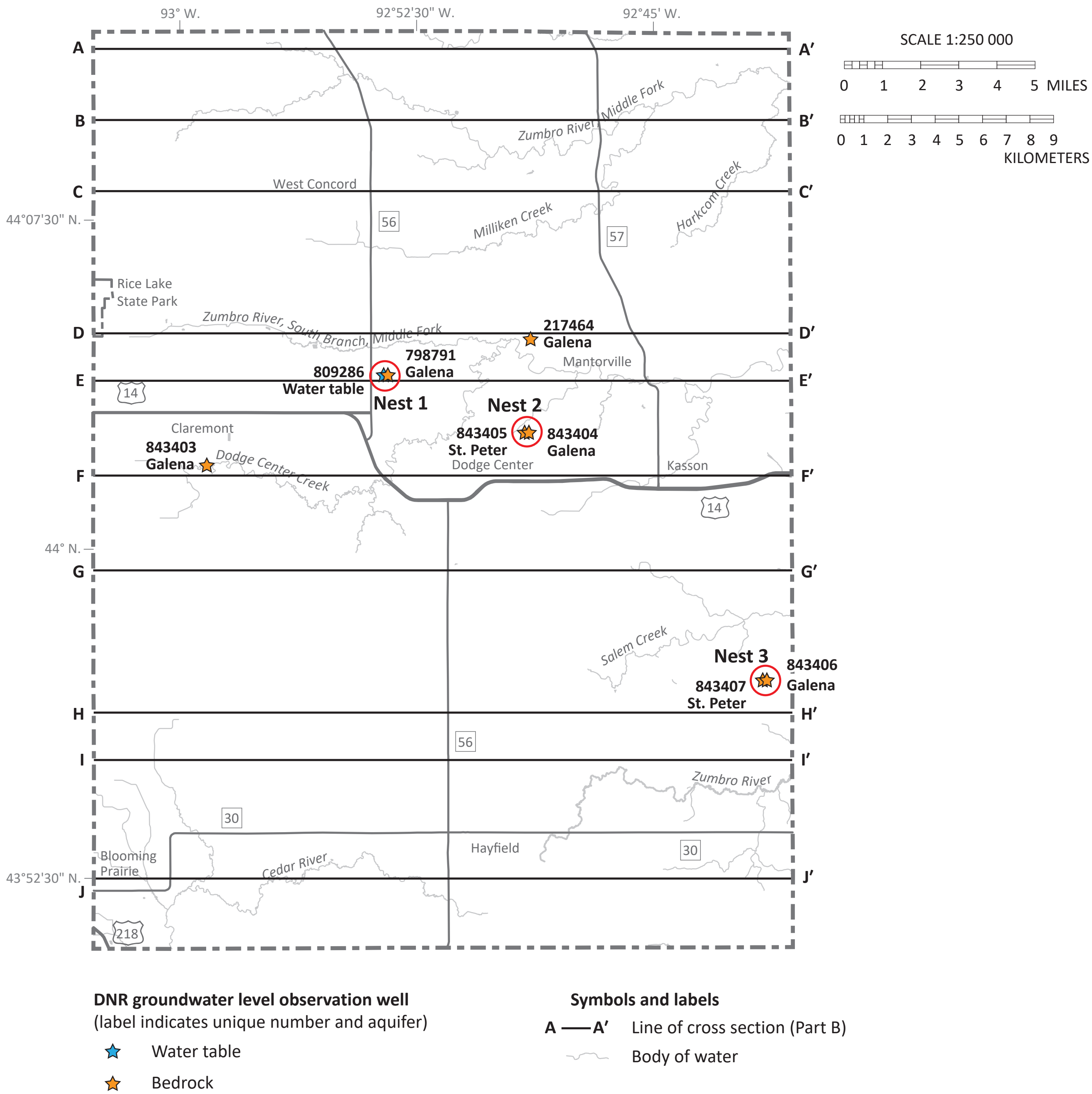


Figure 26. Locations of DNR cooperative groundwater observation wells

Before 2015, there was only one actively measured observation well in the Galena aquifer. Since then, seven additional observation wells were added to include groundwater level monitoring of the Quaternary water table, Galena, and St. Peter aquifers. The red circles denote the locations of hydrographs illustrated in Figures 27 to 29.

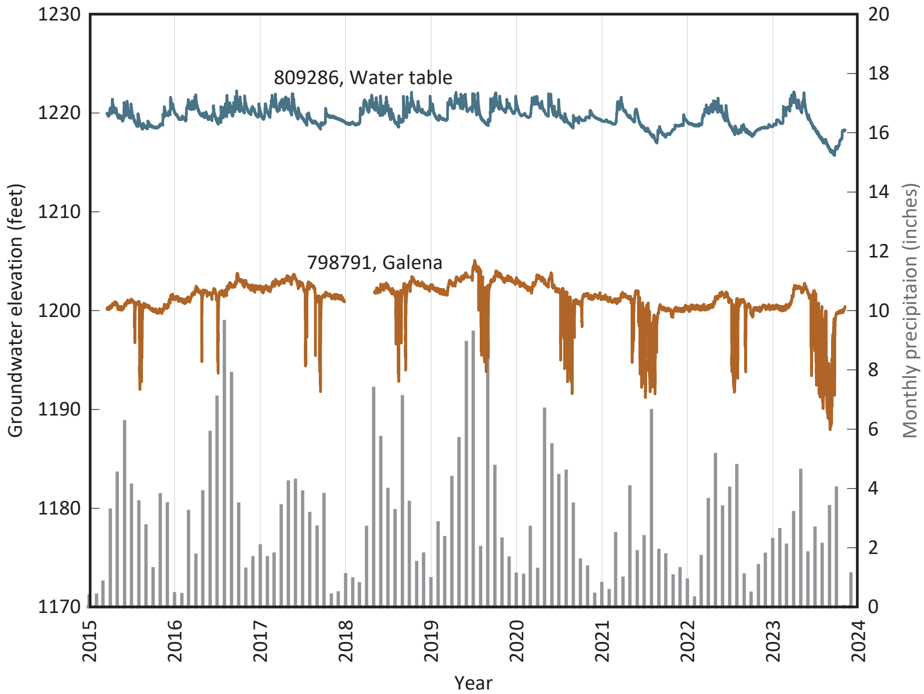


Figure 27. Well nest 1 hydrograph

Well nest 1 monitors groundwater conditions of the water table and Galena aquifers near a calcareous fen at the Wasioja Wildlife Management Area (WMA). The shallow water-table aquifer shows rapid responses to recharge events and seasonal declines, typically in the fall. Water level response to recharge in the deeper Galena aquifer is more muted. The Galena aquifer shows large instantaneous drops in water level from nearby large groundwater appropriators, with rapid water level recovery. Groundwater elevation differences for these aquifers show the vertical hydraulic gradient is downward from the water table to the Galena.

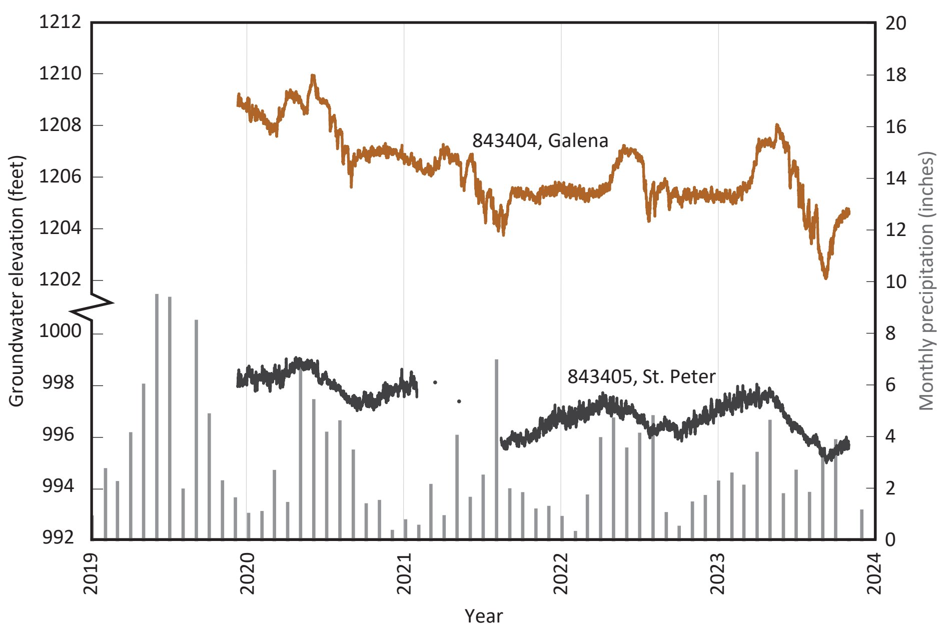


Figure 28. Well nest 2 hydrograph

Well nest 2 monitors groundwater conditions of the Galena and St. Peter aquifers at the Pheasants Forever WMA. Water level response to recharge in the Galena aquifer is greater than the St. Peter. The Galena aquifer groundwater level over the period of record ranges approximately 8 feet from highs to lows, whereas the St. Peter range is approximately 4 feet. Groundwater elevations of these aquifers differ by approximately 200 feet, showing a large vertical hydraulic gradient downward from the Galena to the St. Peter.

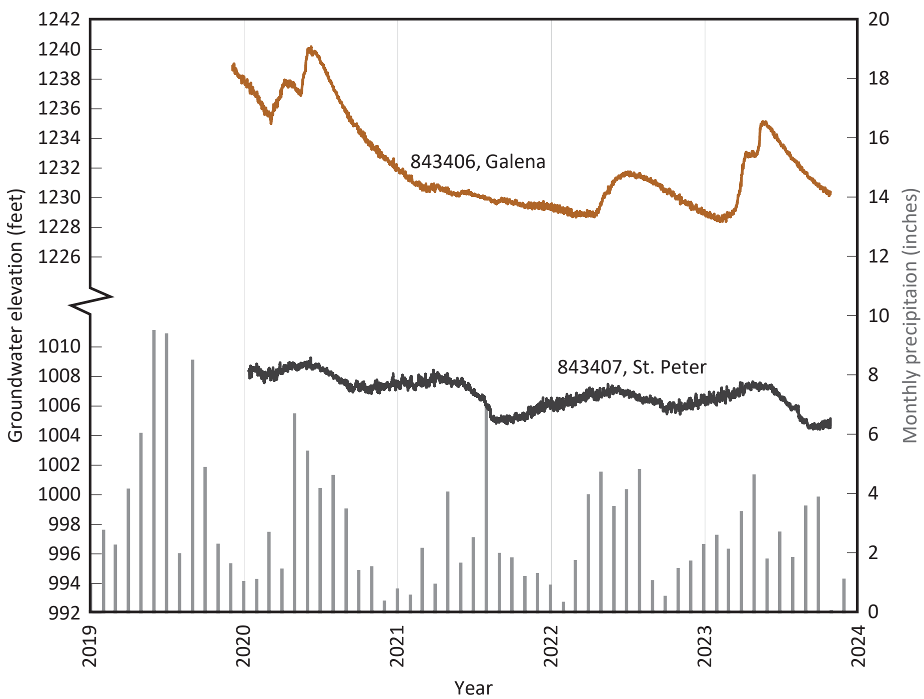


Figure 29. Well nest 3 hydrograph

Well nest 3 monitors groundwater conditions of the Galena and St. Peter aquifers at the Tri-Cooperative WMA. The water level response to recharge in the Galena aquifer is greater than the St. Peter. The Galena aquifer groundwater level over the period of record ranges approximately 10 feet from highs to lows, whereas the St. Peter range is approximately 4 feet. Groundwater elevations of these aquifers differ by approximately 200 feet, showing a large vertical hydraulic gradient downward from the Galena to the St. Peter.

Groundwater use

The CWI provides water well information for the 2,811 wells in Dodge County. Specific information, such as the depth of the well, is required to determine the aquifer. Only 1,346 of the wells had sufficient information to determine the aquifer. Of these, most were completed in the bedrock aquifers (98%). Only 16 wells report drawing from Quaternary aquifers (less than 1%). The majority of wells are for domestic use (94%), municipal supply (1%), agricultural irrigation (1%), or other uses (3%). Other uses include ethanol processing, livestock watering, and golf course irrigation.

A water appropriation permit is required from the DNR for groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year. This provides the DNR with the ability to assess which aquifers are being used and for what purpose. Permits require annual water-use reporting. This information is recorded using the Minnesota Permitting and Reporting System (MPARS), which helps the DNR track the volume, source aquifer, and type of water use (DNR, 2023f) (Table 4). Annual water use for DNR permit holders for the years 1988 to 2021 is shown in Figure 30. Permitted water use varies annually due to annual precipitation, population growth, economic conditions, and other factors. Permitted annual water use has approximately tripled since the late 1980s.

Water use for DNR permit holders in 2021 is shown by water use type in Figure 31 and by general aquifer classification in Figure 32 (DNR, 2023f). Table 4 uses data from 75 permitted wells with appropriations in 2021 and the highest annual use in each use type for the period from 2017 to 2021. Permitted water use is dominated by public water supply (36%) for the cities of Claremont, Dodge Center, Hayfield, Kasson, Mantorville, and West Concord. Other water uses are the production of ethanol (29%), livestock watering (14%), agricultural crop irrigation (14%), quarry dewatering (6%), and golf course irrigation (1%).

Public water supply wells primarily use aquifers below the Decorah–Platteville–Glenwood aquitard, with the largest use coming from the Jordan, Prairie du Chien–Jordan, and St. Peter–Shakopee, respectively. The ethanol plant in Claremont uses the Prairie du Chien–Jordan and Galena aquifers. The bulk of groundwater used by permit holders from the upper carbonate aquifer system is for agricultural irrigation and comes from the Galena aquifer.

Permitted water use varies annually due to factors such as annual precipitation and economic conditions. Municipal/public water supply had the largest use difference over the 5-year-period from 2017 to 2021 (Table 4).

Table 4. Reported 2021 water use from DNR groundwater permit holders

Aquifer	No. of wells	Use (mgy) Municipal/ public water supply	Petroleum-chemical processing/ethanol	Livestock watering	Agricultural crop irrigation	Quarry dewatering	Golf course irrigation	Total (mgy)	Total (%)
Little Cedar Valley–Wapsipinicon Group*	6	--	--	5.3	14.7	--	--	20	2.2%
Cedar Valley–Galena*	1	13.9	--	--	--	--	--	13.9	1.6%
Spillville–Galena*	3	--	--	1.3	15.6	--	3.4	20.3	2.3%
Maquoketa–Galena*	5	--	--	4.7	23.6	--	--	28.3	3.2%
Galena Group*	29	0.9	46.1	26.5	66.8	54.6	5.8	200.7	22.5%
Galena–St. Peter*†	1	--	--	0.6	--	--	--	0.6	0.1%
St. Peter–Shakopee†	15	16.6	--	67.4	--	--	--	84	9.4%
Prairie du Chien–Jordan	2	45.7	216.9	--	--	--	--	262.6	29.4%
Jordan	7	248.6	--	--	--	--	--	248.6	27.8%
Unknown	6	--	--	14.7	--	--	--	14.7	1.6%
Total (mgy)	**N/A**	**325.7**	**263**	**120.5**	**120.7**	**54.6**	**9.2**	**893.7**	**N/A**
Total (%)	**N/A**	**36.4%**	**29.4%**	**13.5%**	**13.5%**	**6.1%**	**1.0%**	**N/A**	**N/A**
Highest annual use 2017 to 2021 (mgy)	N/A	480.9	335.7	162.6	132.1	64.2	9.2	N/A	N/A

Data from MPARS; mgy, million gallons per year; dash marks (--) indicate no use, N/A indicates not applicable
Percentages do not equal 100 due to rounding.
* Aquifers part of upper carbonate aquifer system
† Aquifers part of St. Peter–Prairie du Chien aquifer system

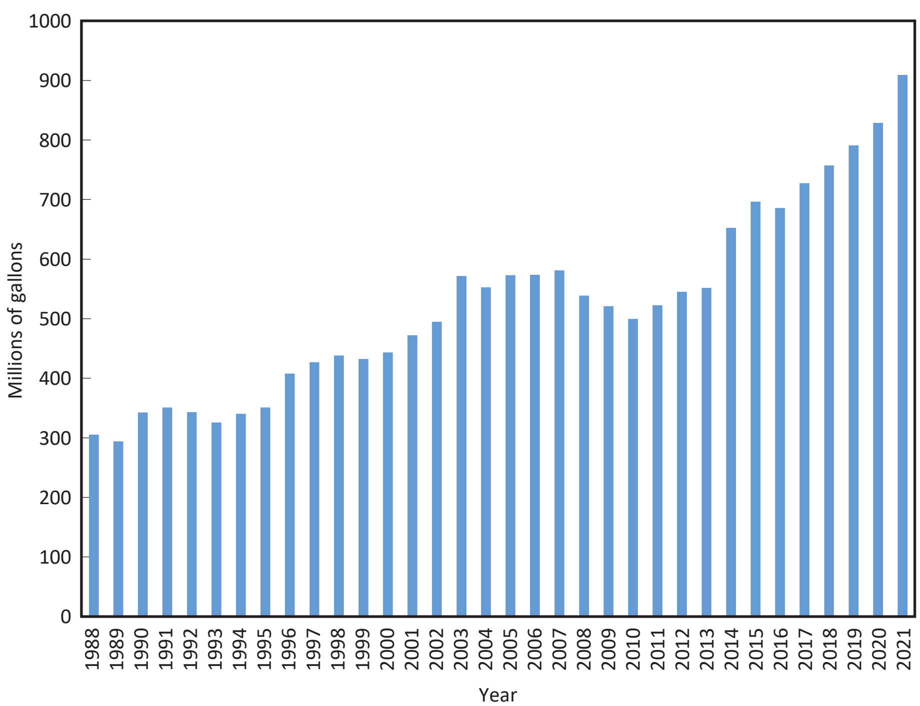


Figure 30. DNR groundwater reported use (1988 to 2021)

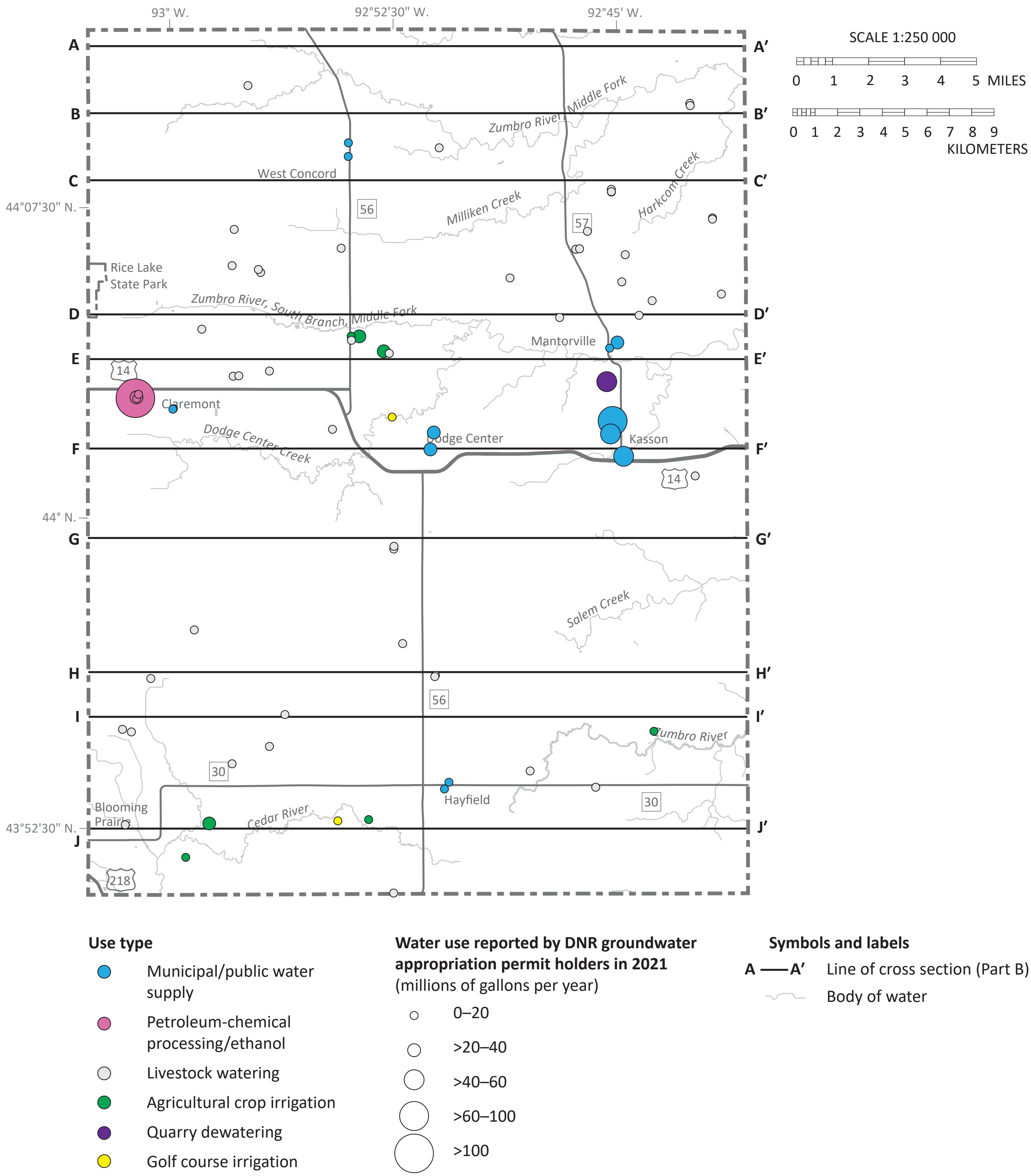


Figure 31. Distribution of groundwater appropriation permits for 2021 by volume reported and use type

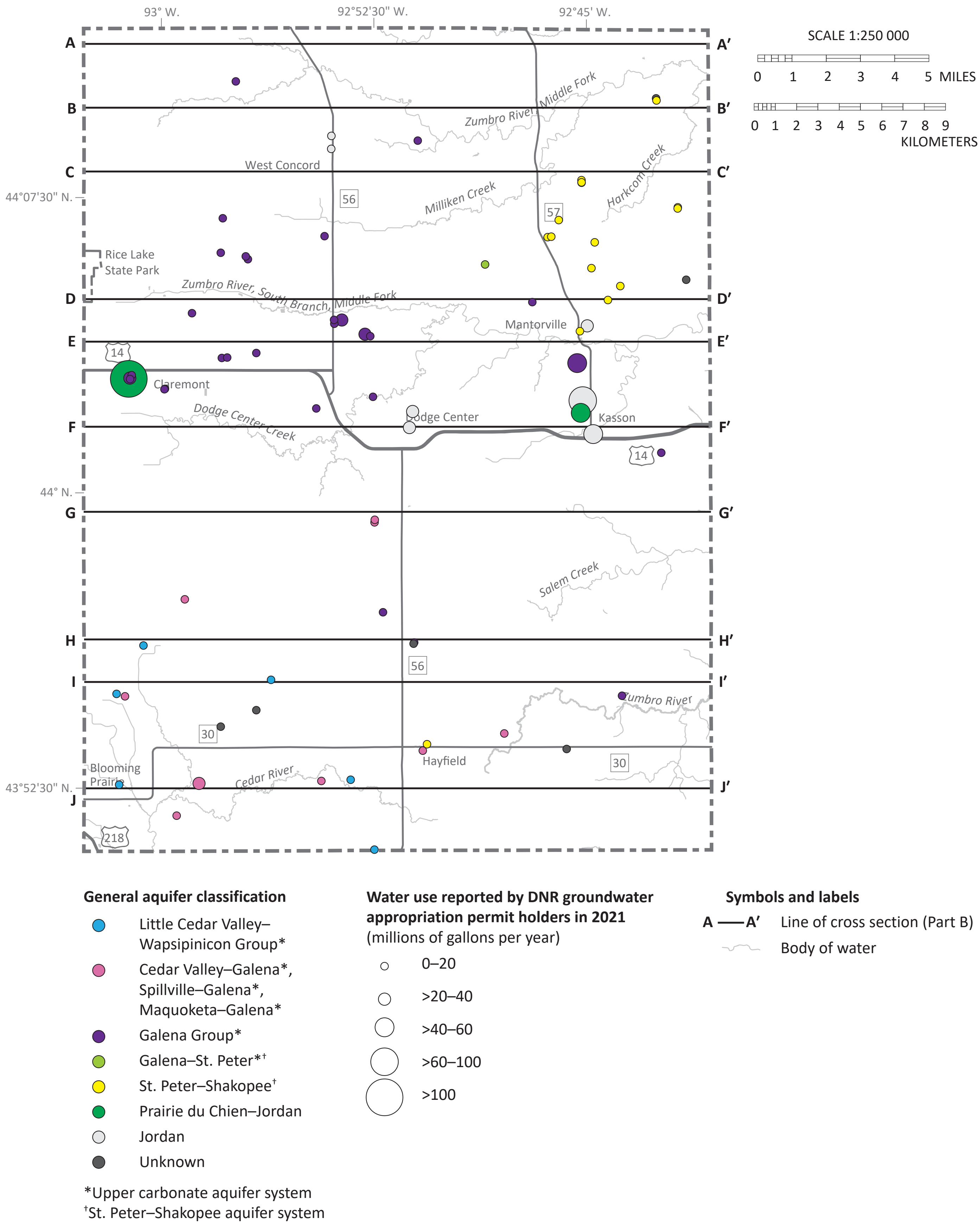


Figure 32. Distribution of groundwater appropriation permits for 2021 by volume reported and general aquifer classification

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Glossary

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

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

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—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.

brine—a natural and highly concentrated solution of salty groundwater.

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

calcareous fen—rare and distinctive peat-accumulating wetlands dependent upon a constant supply of upwelling groundwater rich in calcium and other minerals.

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

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

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

colluvium—unconsolidated sediment that accumulates at the base of hillslopes.

confining layer—a specific type of aquitard where the hydraulic head in the underlying aquifer is greater than the bottom of the aquitard.

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

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

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

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

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

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

fluvial—relating to or formed by rivers and streams.

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

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

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

groundwater head (hydraulic head)—a measurement of the height to which a column of water will rise above a reference elevation (or datum), such as mean sea level.

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

hydraulic—relating to water movement.

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

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

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

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

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

loam—a soil mixture made up of roughly equal parts of sand, silt, and clay.

matrix—fine grained and unaltered (unfractured/dissolved) portion of a bedrock aquifer that stores the largest volume of groundwater. The matrix has lower permeability than water, yielding conduits and fractures.

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

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

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

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

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

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

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

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

stable isotope—chemical isotope that is not radioactive.

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

stratigraphy—a branch of geology that studies rock layers and layering (stratification).

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

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

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

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

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

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

upgradient—a location with a higher potentiometric surface (hydraulic head) than a reference point of interest.

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 in different aquifers.

Appendix A

Groundwater field sample collection protocol

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

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

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

Appendix Table A. Groundwater field sample collection and handling details

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

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

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

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

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

Appendix B

Tritium values from precipitation and surface water

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

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

For additional tritium information, contact the DNR Groundwater Atlas Program.

For additional weather station information, contact the administering program.

- MNgage
- CoCoRaHS

Appendix Table B: Enriched tritium results

Sample location	Sample date range	Tritium (TU)	Sample type
MNgage precipitation station (MWDM5)	05/21/2012–06/20/2012	8.7	Precipitation composite
	09/30/2012–10/30/2012	6.7	Precipitation composite
	05/09/2014–06/09/2014	7.0	Precipitation composite
	10/01/2014–10/31/2014	6.7	Precipitation composite
	05/01/2015–05/31/2015	5.3	Precipitation composite
	08/17/2016–09/16/2016	8.3	Precipitation composite
	04/01/2017–04/30/2017	8.1	Precipitation composite
	09/06/2017–10/06/2017	6.5	Precipitation composite
	10/03/2018–11/01/2018	3.7	Precipitation composite
	4/11/2019	13.4	Snow
	04/04/2019–05/04/2019 (excluding 04/11/2019)	12.1	Precipitation composite
	09/09/2019–10/03/2019	5.0	Precipitation composite
	09/01/2020–09/30/2020	7.7	Precipitation composite
CoCoRaHS precipitation station (MN-SL-137)	09/01/2020–10/01/2020	8.1	Precipitation composite
Lake-water sample (Rice Lake-74000100)	8/8/2019	8.6	Littoral zone

Tritium-age methodology

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

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

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

The following is true for the purposes of all atlases.

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

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