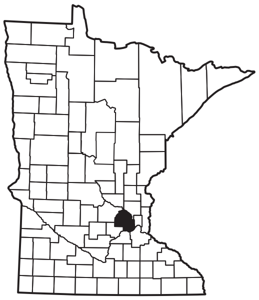
Groundwater Atlas of Hennepin County, Minnesota

Report



County Atlas Series C-45
Part B - Hydrogeology

To accompany these atlas components:

Plate 7, Water Chemistry

Plates 8 and 9, Hydrogeologic Cross Sections

DEPARTMENT OF
NATURAL RESOURCES

St. Paul 2021

mndnr.gov/groundwatermapping

The County Atlas Series

The Minnesota County Geologic and Groundwater 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 prior to 2019 both were titled the "*Geologic* Atlas of X County." The Part B title was changed to "*Groundwater* Atlas of X County" to distinguish the content.

Part B - Groundwater Atlas

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

A list of completed atlases can be found by searching: Groundwater Atlas Program, Minnesota DNR.

Citation for this atlas:

Berg, J.A., 2021, Groundwater atlas of Hennepin County, Minnesota: Minnesota Department of Natural Resources, County Atlas Series C-45, Part B, report, 3 pls., GIS files.

Acknowledgments

Author James A. Berg, GIS/Cartography James A. Berg and Holly Johnson, Editing Ruth MacDonald and Holly Johnson.

The author would like to thank the following people for their help in reviewing this report and providing helpful suggestions: Bob Tipping of the Minnesota Department of Health, Tim Cowdery and Melinda Erickson of the U.S. Geological Survey, Andrew Retzler and Angela Berthold of the Minnesota Geological Survey, and Dave Scheer of the Minnesota Pollution Control Agency.

Contributors from the staff at the Minnesota DNR include: John Barry, Paul Putzier, Todd Petersen, Randy Bradt, Scott Pearson, Wes Rutelonis, Vanessa Baratta, and Rachel Lindgren.

Part A - Geologic Atlas

The precursor to this atlas is Part A, *Geologic Atlas of Hennepin County* (Steenberg and others, 2018), 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 (Berthold); Plate 4, Quaternary Stratigraphy (Berthold); Plate 5, Sand Distribution Model (Berthold and Lively); and Plate 6, Bedrock Topography and Depth to Bedrock (Retzler).

Information is available online at Minnesota Geological Survey > County Geologic Atlas.

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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.

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 Minnesota Geological Survey, Geologic Atlas of Hennepin County, Minnesota, 2018. Universal Transverse Mercator projection, zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion factors

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

Groundwater Atlas of Hennepin County, Minnesota

by James A. Berg

Executive summary

This report and the accompanying plates are Part B of the Hennepin County atlas. It describes the groundwater characteristics of the county and was produced by the Minnesota Department of Natural Resources (DNR). It builds on the geology described in Part A, previously published by the Minnesota Geological Survey (MGS).

The purpose is to illustrate the hydrogeologic setting, aquifer distribution, pollution sensitivity, groundwater recharge, and subsurface flow of the aquifers within the county. This information can be used to make land-use and natural resource decisions that take into account aquifer sensitivity, water quality, and sustainability.

This **report** details the methods, results, and interpretations for the county. **Plate 7** illustrates the water chemistry; **Plates 8 and 9** use hydrogeologic cross sections to show groundwater flow directions and residence time within the aquifers. This executive summary gives an outline of the detailed sections that follow.

Hennepin County is in east-central Minnesota (Figure 1) with land use that that varies widely from densely populated urban and suburban (Minneapolis and surrounding communities) in the eastern part of the county, to a mix of agricultural, rural, and small towns in the west. The population in 2018 was approximately 1,270,000 (U.S. Census Bureau, 2019). The county lies within the watersheds of the Mississippi (Twin Cities), North Fork Crow, South Fork Crow, and Lower Minnesota rivers.

Hennepin County is in the northern continental United States and is characterized as a cool, subhumid climate with a large temperature difference between summer and winter seasons. From 2010 to 2019 the average temperatures were approximately 71 degrees Fahrenheit June through August, and 17 degrees Fahrenheit December through February (NOAA, 2020). Average annual precipitation (30 year) was approximately 32 inches, placing it in the upper portion of the statewide range of 20 to 36 inches.

Geology and physical hydrogeology (pages 5–34) describes characteristics of geologic units in the county. Aquifers and aquitards are identified by 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).

  Hennepin County is underlain by multiple sequences of glacial sediment that include buried sand and gravel aquifers with intervening fine-grained aquitards. The glacial sediment is underlain by a relatively thick sequence of Paleozoic sedimentary bedrock. The sandstone and carbonate bedrock formations provide large volumes of groundwater for high-capacity users such as cities and manufacturers.

- Water-table groundwater flow directions are regionally toward the major rivers that form most of the county boundaries including the Mississippi River to the east, the Minnesota River to the south, and the Crow River to the north. Locally, groundwater also flows toward the tributaries of larger rivers (Elm, Bassett, Minnehaha, Ninemile, Purgatory, Riley, and other creeks), and toward lakes and smaller water bodies.

  Water-table depths are split into three overlapping and transitional zones. The central, west, and most of the northern portions of the county have relatively shallow and uniform depths to the water table (0 to 20 feet). Most of the deeper water-table areas are in the southeastern portion adjacent to the bluff areas of the Mississippi and Minnesota rivers. The other areas of deeper water-table conditions are also in the southeast but not directly adjacent to the major bluff areas. This includes communities from the northern portion of Bloomington to New Hope, Crystal, Robbinsdale, and northern Minneapolis.

- Buried sand and gravel, and bedrock aquifer potentiometric surface maps show a consistent pattern of flow from the highest part of the county in the northwest. This location approximately coincides with the intersection of three major watersheds near Loretto, which is also near the intersection of the Greenfield, Corcoran, Independence, and Medina townships. Groundwater flow is influenced by the major groundwater discharge features of the Mississippi and Minnesota rivers to the northeast, east, and southeast; and the Crow River to a lesser extent in the northwest.

Hydrographs show short (annual), medium (several years) and long-term (decades) trends in water-elevation fluctuation. The short-term trends are caused by increased pumping during the summer and early fall. The medium-term trends are caused by local water use and rainfall patterns as summer water use (such as lawn watering) decreases during rainy periods. The long-term trends of the combined Prairie du Chien–Jordan aquifers appeared to have two phases: declining water levels from the 1950s and the 1990s followed by stabilization and increasing levels from approximately 2010.

Water chemistry (pages 35–46, Plate 7) provides information about the water source, flow path, travel time, and residence time of groundwater. The groundwater chemistry supports the results of the pollution sensitivity models and is used to identify areas of interest, such as those with high pollution sensitivity or elevated levels of potentially harmful chemicals. These can indicate sensitivity to contamination from the land surface or problems with naturally-occurring geologic contaminants.

- Chloride in groundwater is relatively widespread in the county, especially in the populated east and south-central portions. The prevalence of elevated and anthropogenic chloride in these areas coincides with dense road networks that are heavily salted in the winter months and the distribution of highly transmissive sand, gravel, and sandy sediment. Affected aquifers include surficial sand, shallow buried sand, and shallower bedrock aquifers such as the Prairie du Chien and Jordan aquifers.
- Nitrate was not commonly found because most of the developed area has sewers and the less-developed areas have limited row crop agriculture. Elevated occurrences of nitrate were mostly in residential areas in the surficial sand and gravel, upper buried sand, and shallow bedrock aquifers and may be because of fertilizer application.
- Arsenic is a naturally occurring, geologically-sourced contaminant in Minnesota. The majority of groundwater samples contained arsenic that exceeded the laboratory method detection limit and several samples exceeded the maximum contaminant level (MCL, 10 ppb). Those at or above the MCL were in the western part of the county where glacial till is common at the surface. Most of the samples with elevated concentrations were from buried sand and gravel aquifers.
- Manganese is a naturally occurring, geologically-sourced contaminant in Minnesota. Approximately half of groundwater samples analyzed for manganese were greater than or equal to the health based value (HBV, 100 ppb). These were found throughout the county in most of the mapped buried sand and gravel aquifers and all of the bedrock aquifers.
- Residence time of groundwater in aquifers reflects a wide range of permeability conditions. A high proportion of tritium detection (indicating shorter residence time) reflects the relatively permeable nature of glacial sediment and bedrock in the eastern portions of the county. Carbon-14 analysis found water ranging from less than 100 to greater than 40,000 years.

The **pollution sensitivity** (pages 47–69) of an aquifer is estimated based on the time it takes water to flow from the land surface through various types and thicknesses of soils and geologic materials. Anthropogenic pollutants are assumed to travel with water at the same rate. The sensitivity is modeled with different methods for the 1) near-surface materials and 2) buried sand and gravel aquifers and the bedrock surface. The model results are evaluated by comparing the pollution sensitivity ratings to chemical constituents such as tritium and carbon-14 data for residence time, and to inorganic chemicals for contamination.

- Pollution sensitivity of *Near-surface materials* is highly variable. The broad patterns include moderate and high conditions in the eastern third of the county and along the northern and southern boundaries. A complex distribution of very low to low sensitivity dominates the western two-thirds, with the exception of the northern and southern boundaries. High sensitivity occurred mostly in areas with coarse-textured sediment such as surficial sand and gravel. Very low and low sensitivity exist in the remainder of the county where fine-grained till and lake sediment are at the surface. Possible karst conditions exist in the east because of the relatively shallow Platteville Formation and St. Peter Sandstone.
- The *Buried sand and gravel aquifers* exhibit a wide range of pollution sensitivities depending primarily on depth and location within the county.

  In the shallower units, the western portion has sensitivity ranging from very low to very high because of a complex distribution of geologic materials. The eastern portion is dominated by very high sensitivity.

  All the deeper units are dominated by very low to low sensitivity, but also include a few areas in the eastern portion with moderate to high sensitivity.
- The *Bedrock surface* is similar to the deeper buried sand and gravel units. It is dominated by very low to low sensitivity with limited areas in the eastern portion of moderate to high sensitivity.

Hydrogeologic cross sections (pages 70–73, Plates 8 and 9) illustrate groundwater flow, residence time, and distribution of chemical indicators, and help define areas of interest such as locations of important groundwater recharge, discharge, and sensitivity to pollution. Groundwater flow in the county is initially downward, then laterally toward creeks and rivers. In many areas recharge to the deeper aquifers can take hundreds to thousands of years, where there is no focused recharge through interconnected buried sand and gravel aquifers.

Hennepin County reported groundwater-pumping volumes (from wells with DNR appropriation permits) are among the highest in the state. Much of this is from municipal and commercial well fields (areas of closely spaced wells). This type of groundwater pumping is evident on cross sections where modern and mixed tritium-age water is drawn down deeper than expected under natural groundwater-gradient conditions.

Aquifer characteristics and groundwater use (pages 74–85) summarizes the capacity of county aquifers to produce water for pumping. Data is summarized from specific capacity tests, aquifer tests, water use records, and groundwater level monitoring data for each aquifer. These data can be used to characterize aquifer recharge in the county and plan for new well installations.

- The highest mean specific capacity is from the combined Prairie du Chien–Jordan aquifers, followed by the surficial sand aquifers.
- The highest transmission rates also include the combined Prairie du Chien–Jordan and surficial sand aquifers, as well as the buried sand and Upper Tunnel City aquifers.
- The highest use by volume is from the combined Prairie du Chien–Jordan aquifers, followed by the Jordan aquifer.
- The most common water use is for municipal/public water supply, which dominates the highly populated suburban area of eastern Hennepin County. There are approximately 20,500 located wells* in the county: 76 percent are domestic, 10 percent are monitoring wells at contamination sites, and 4 percent are public supply. Minneapolis obtains its water supply from the Mississippi River and distributes some of that water to surrounding communities.

**Well locations that have been verified under the supervision of MGS for the atlas project.*

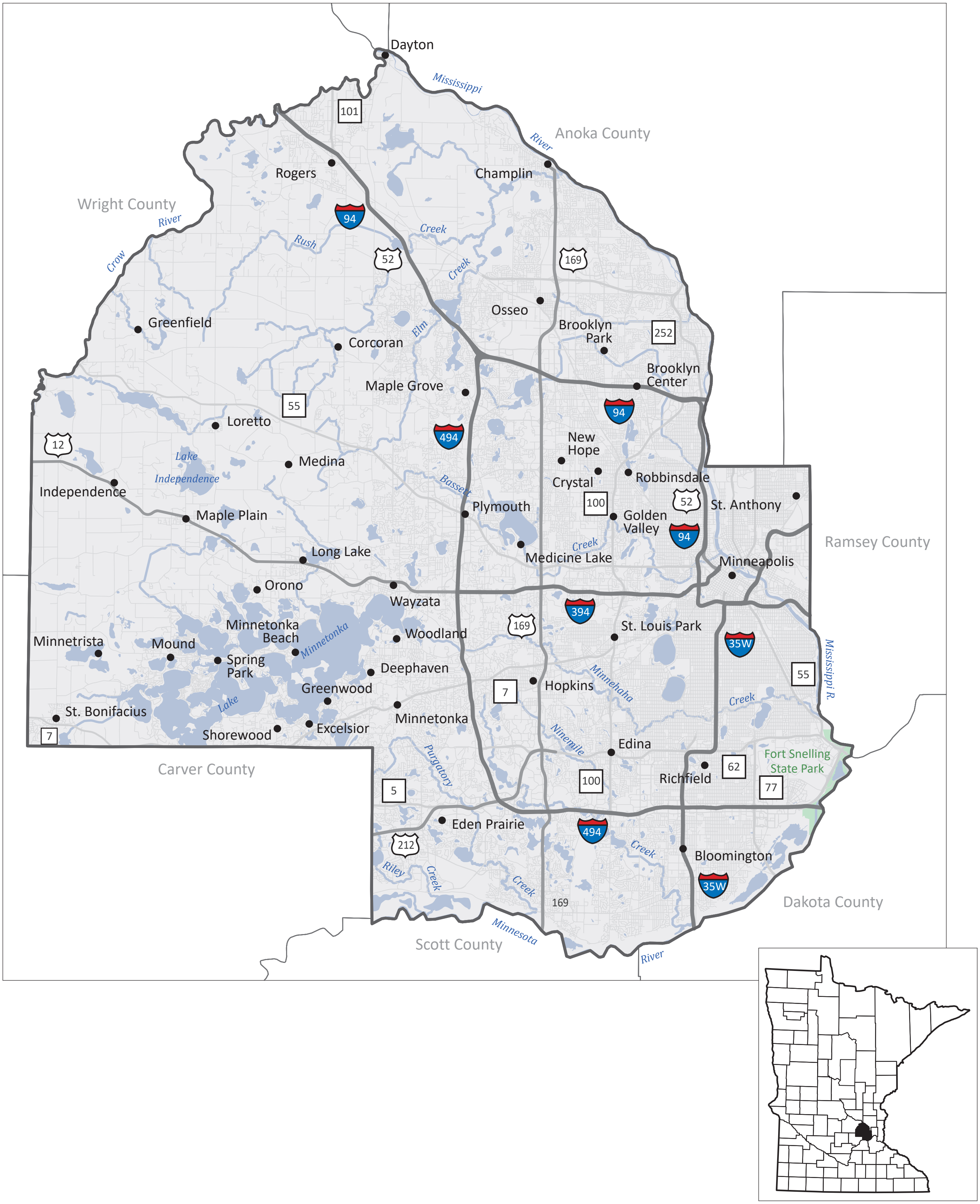


Figure 1. Hennepin County, Minnesota

Geology and physical hydrogeology

Surficial materials

The topography and surficial deposits of the county originated with advances and retreats of glacial ice (Part A, Plate 3) that deposited sediment with various textures (Figure 2). **Aquitards** consist of fine-grained sediment that includes a mixture of sand, silt, clay, and gravel (till) that generally slow water movement and create confining layers.

Aquifers consist of coarser-grained sediment that holds and transmits abundant water. This includes a mixture of sand and gravel from glacial outwash (deposited in moving water) and other coarse-grained deposits. The complex distribution of surficial sand and gravel is the most important factor controlling groundwater recharge and the pollution sensitivity of underlying aquifers.

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

The following is a summary of the late glacial and post-glacial events during the Pleistocene (2,600,000 to 11,700 years ago) and Holocene (11,700 years ago to present) epochs and is included to help explain some of the complex stratigraphy and distribution of aquifers and aquitards (Figure 5). In the geological unit abbreviations (for example Qs3, Qvt, or Ql) the “s” usually stands for sand (aquifer) and the “t” and “l” usually stand for till and lake deposits (aquitards).

The major ice advances into Hennepin County from the northeast during the late Wisconsinan glaciation included three phases of the Superior lobe including the Emerald (Qce and Qs3 units), St. Croix (Qcs and Qs2 units), and Automba (Qcl, Qca, and Qs1 units). These Cromwell Formation units covered most of Hennepin County. During these phases, the Superior lobe built the extensive St. Croix moraine that is mapped in adjoining counties but has no surface expression in Hennepin County.

Following the retreat of the Superior lobe, Hennepin County was glaciated for the final time by ice of the Des Moines lobe, which advanced into northwestern Minnesota from the Winnipeg region. Its deposits are the New Ulm Formation. The till units are distinguished by finer texture (loam to clay loam) and shale content.

An offshoot of ice from the Des Moines lobe, the Grantsburg sublobe, advanced to the northeast from southwest of the county. Grantsburg-sublobe deposits have variable composition, especially in shale content, which is the basis for the distinction between the Villard (Qvt) and Heiberg (Qht) members (Figure 2). Mixed provenance sediment distinguishes the Twin Cities Member (Qtt) of the New Ulm Formation, which includes till from both the Superior and Des Moines lobe deposits.

Throughout the advance and active retreat of the Grantsburg sublobe, meltwater channels deposited sand and gravel to a broad outwash plain covering much of eastern Hennepin County (Qts). Lake Minnetonka is just west of this outwash plain and has numerous bays that were formed from remnants of sublobe ice. The isthmuses and peninsulas are former gaps or lows between ice blocks that were later filled during the melting of the Grantsburg sublobe (Qsh).

The county has many other lakes. Similar to Lake Minnetonka, each lake is a former ice block left behind by previous ice lobes. During the warmer Holocene Epoch, these lakes decreased in size and left organic material (unit Qp) and lake sediment at the land surface (unit Ql).

As the Grantsburg ice continued to melt, water flowed northeast into Anoka County to form glacial Lake Anoka. In east and central Golden Valley one meltwater channel formed a delta at the lake (Qnb), creating the New Brighton Formation (Qnd) north of the channel. Eventually, the lake drained through an area of north Minneapolis (Camden breach) and created wide river terraces (Qat).

Other river terrace deposits were created by meltwater from the drainage of glacial Lake Agassiz in northwestern Minnesota. These flowed through the large valley of the modern Minnesota River along the southern part of the county. The establishment of these river valleys was the final episode of the area’s glacial history.

Large areas on the eastern side of the county have been regraded and refilled with altered material (artificial fill). The three artificial fill units, Aftci, Afsi, and Afhl exist in the highly developed eastern portion of the county.

Water table

The water table is the surface between the unsaturated and saturated zones where water pressure equals atmospheric pressure. It occurs in both aquifer and aquitard sediment across the entire county. Although it is shown in the figures as a static surface, it fluctuates over time. Surficial sand and gravel aquifers are present below the water table where there is sufficient saturated thickness and yield to install a well and economically pump groundwater.

The water table is generally a subdued expression of the surface topography. Shallow water-table flow directions are typically consistent with surface-water flow and follow the watershed boundaries.

The water-table maps provide guidance for many applications, but additional site-specific information should be used to refine this information at local scales. Certain conditions affect the fluctuation of the water table and can create locally different results from the maps created for this atlas. Some of these include seasonal weather conditions, extent and composition of surficial geology units, land-use practices, vegetation composition and distribution, and pumping of high-volume wells.

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

- Elevation of surface-water bodies (e.g., rivers, perennial streams, lakes, and open-water wetlands)
- Static water levels in surficial sand wells obtained from the County Well Index 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 LiDAR (Light Detection and Ranging) technology.*

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

Regionally, groundwater in the water table flows toward the major rivers that form most of the county boundaries including the Mississippi River to the east, the Minnesota River to the south, and the Crow River to the north. Locally, groundwater also flows toward tributaries of the larger rivers (Elm, Bassett, Minnehaha, Ninemile, Purgatory, Riley, and others) and toward lakes and smaller water bodies (Figure 3).

Water-table depths are split into three overlapping and transitional zones (Figure 4). Relatively shallow and uniform depths (0 to 20 feet) are found in the central, western, and most of the northern portions. These areas have relatively fine-grained textured surficial sediment (mostly New Ulm Formation) and are farther from the high hydraulic gradient of the Mississippi and Minnesota river valley bluffs.

Most of the deeper water-table areas (greater than 30 feet) are in the southeastern portion, created by high topographic relief. This includes bluffs of the Minnesota and Mississippi rivers in a zone approximately 0.5 to 1.5 miles wide, and smaller bluffs in the northwest along the Crow River. The Platteville and Glenwood formations (Part A, Plate 2) underlie most of the Mississippi River bluff area through downtown Minneapolis to the confluence of the Minnesota River. The Glenwood Formation is a thin (3 to 7 feet) shale aquitard at the base of the Platteville limestone. The Platteville and overlying glacial sediment may contain a perched water table (above the regional water table) over unsaturated portions of the underlying St. Peter Sandstone (Anderson and others, 2011). Examples of these conditions are shown on the eastern portions of cross sections I–I′ and J–J′ (Plate 9).

Another area of deeper water-table conditions is also in the southeast but not directly adjacent to the major bluffs. This includes communities from the northern portion of Bloomington to New Hope, Crystal, Robbinsdale, and northern Minneapolis. This sandy area has a variable topography. The water-table depths are similarly variable ranging from 0 to 40 feet over relatively short distances. Examples of these conditions are shown on the eastern portions of cross sections F–F′ through L–L′.

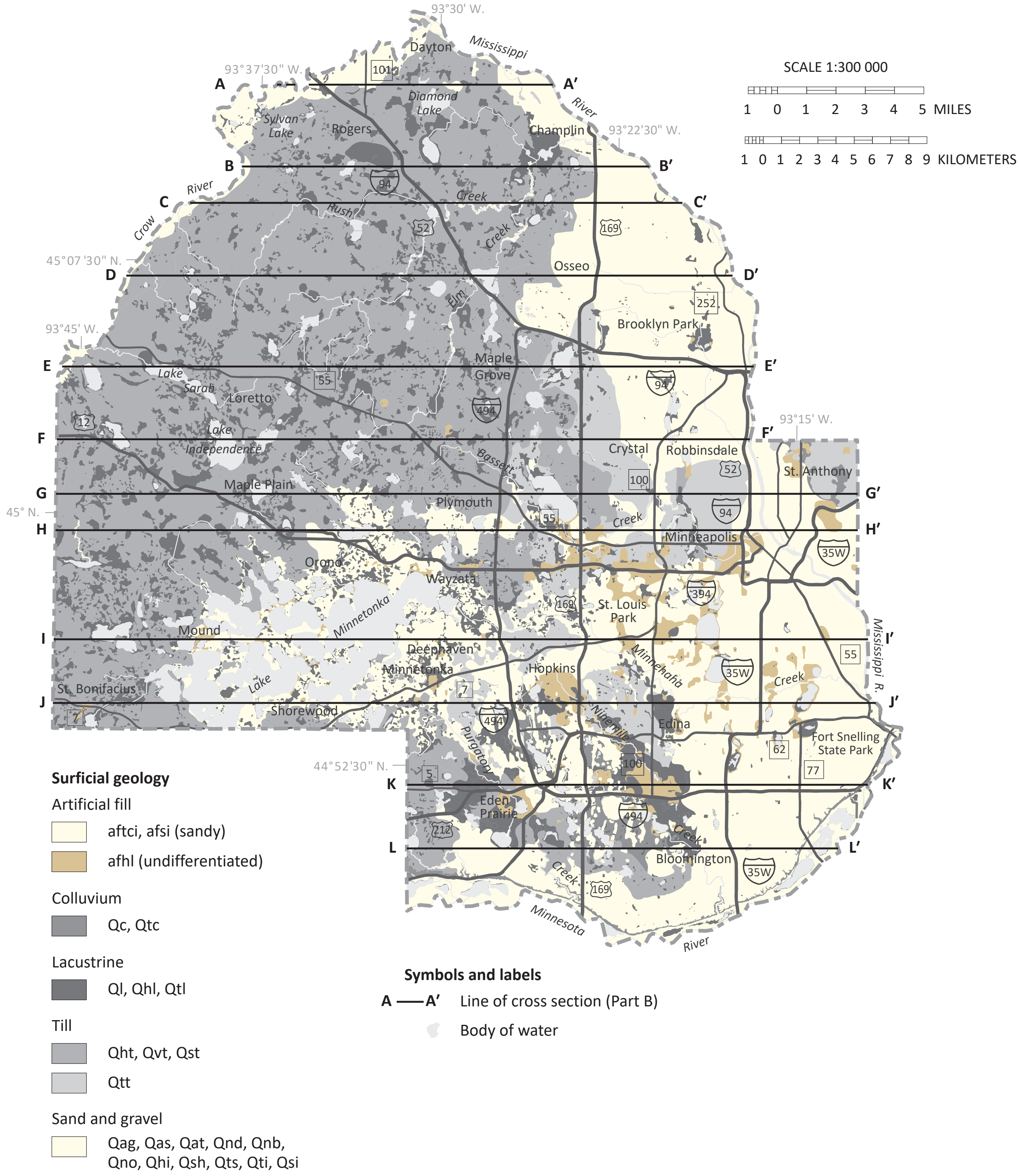


Figure 2. Generalized surficial geologic units

The distribution of surficial sand in Hennepin County was mostly controlled by late stage glacial events. The distribution of highly permeable surficial sand and gravel is one of the most important factors controlling groundwater recharge and the pollution sensitivity of underlying aquifers. (Map is modified from Part A GIS data.)

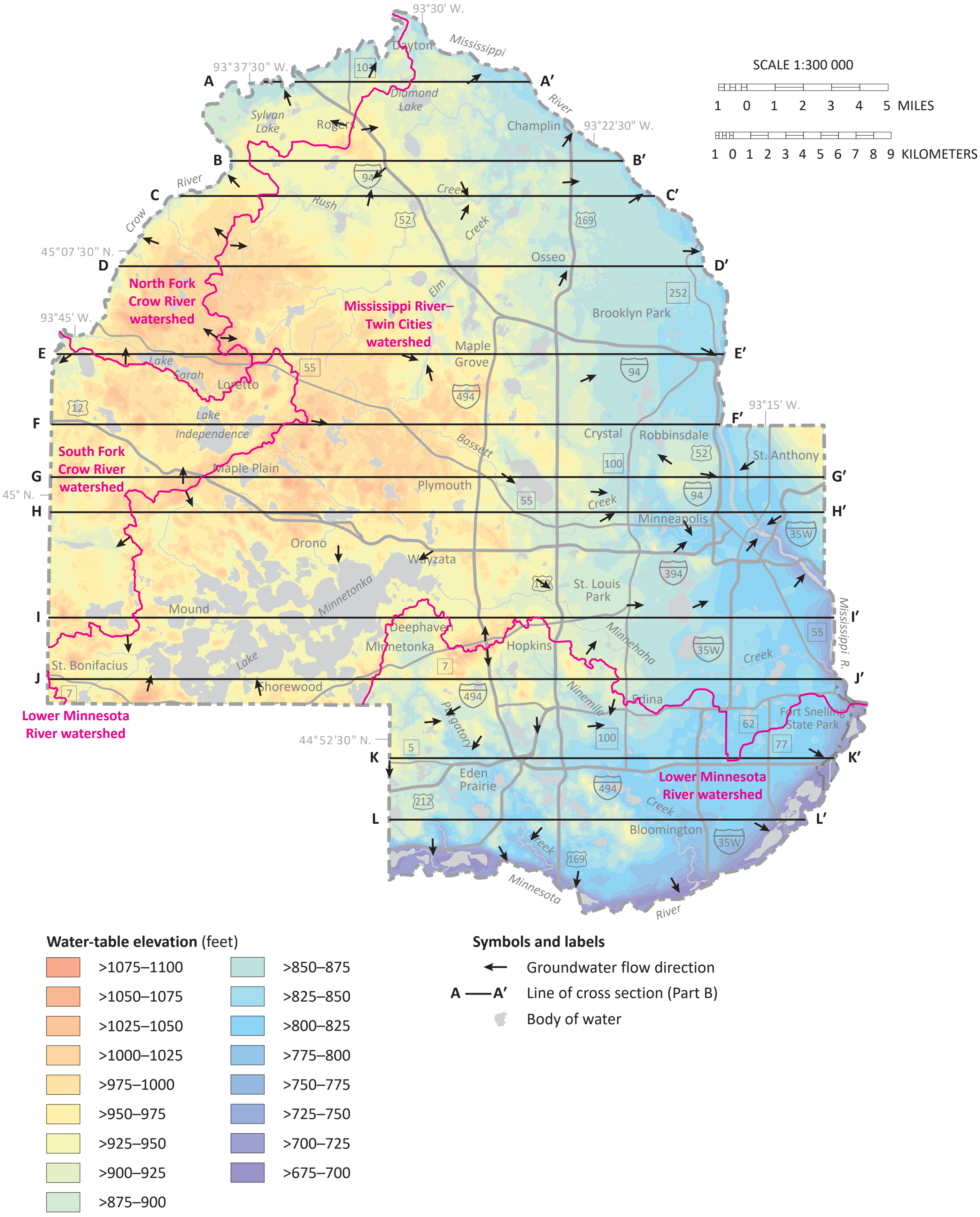


Figure 3. Water-table elevation and groundwater flow directions

Water-table elevations cover a wide range of values with the lowest near the major rivers (Crow, Mississippi, and Minnesota) around the northern, eastern, and southern portions of the county. The highest elevations are in the west-central area. Groundwater flows regionally from the west-central area toward the major rivers, and locally toward smaller water bodies.

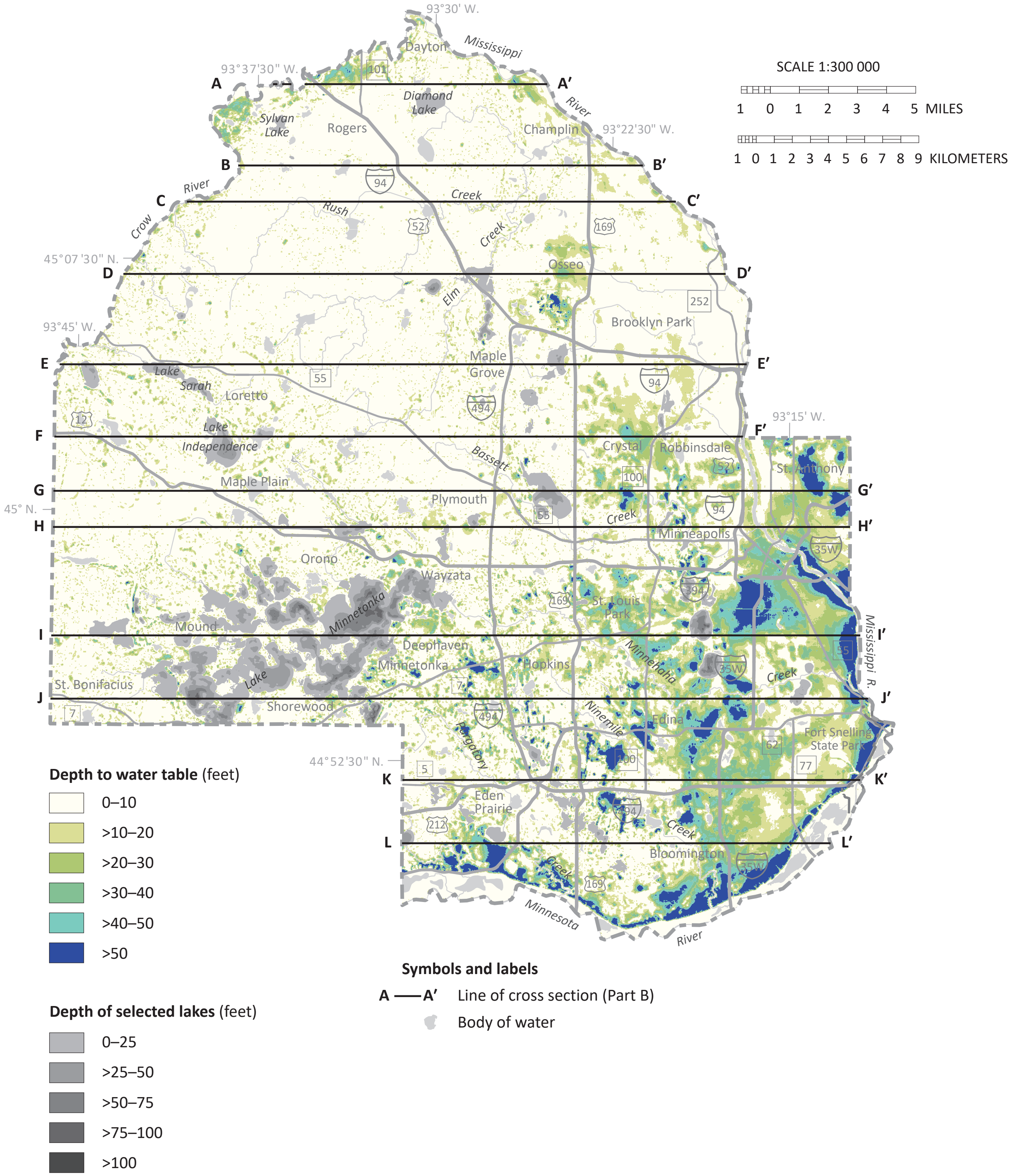


Figure 4. Depth to water table

Water-table depths are shallow (0–20 feet) across most of the county. The water table may be deeper along the Crow, Mississippi, and Minnesota river bluffs and beneath the sand hills in the southeastern portion of the county.

Buried aquifers

Sand and gravel

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

Detailed descriptions regarding the origin, thickness, and distribution of these glacial deposits are described on Part A, Plate 3, Surficial Geology (Glacial History); Plate 4, Quaternary Stratigraphy; and Plate 5, Sand Distribution Model.

Multiple sequences of sand and gravel were deposited by meltwater from the ice lobes through successive advances and retreats. The sand and gravel bodies are confined by aquitards that were formed by unsorted sediment deposited directly by the ice (till), and bedded sediment of clay, silt, and fine-grained sand deposited in ponds and lakes. These till units tend to be more laterally extensive than the buried sand and gravel layers. Approximately 50 percent of the wells in the county are completed in buried sand and gravel aquifers. Reported county water use from this type of aquifer in 2018 was 9 percent.

The stratigraphic column in Figure 5 correlates the glacial geologic units from Part A with the hydrogeologic units of Part B. Part A descriptions are generally classified as 1) *sand and gravel* or 2) *till* or *lake (lacustrine) clay*. These are broadly converted into the hydrogeologic descriptions of 1) *aquifer* or 2) *aquitard*.

Other aquifer units include alluvium, terrace sand, outwash, and ice-contact sediment. Other aquitard units include colluvium and stagnation sediment.

The eastern half of the county is a highly developed portion of the state. Large areas have been regraded and refilled with altered material (artificial fill). Since the fill is typically sourced from nearby areas, the Part A classification has associated it with three natural units. Two are assumed to have the same sandy texture as the parent material, Aftci and Afsi. Unit Afhl is derived from Holocene lake sediment and possibly dredged lake material. This unit may have a wide range of textures and is classified as undifferentiated.

The Part B units are shown on the cross sections as follows:

- **Aquifers** are shown with *patterns*.
- **Aquitards** are shown as *shades of gray,* representing the relative hydraulic conductivity. Lighter shades represent units with more sand, implying a higher hydraulic conductivity. The shades of gray are based on the average sand content of the aquitard, which is determined from the matrix texture (portion that is less than 2 millimeter grain size).

Percent sand in aquitard

>60%	□
>50% and ≤60%	░
>40% and ≤50%	▒
>30% and ≤40%	▓
≤30%	█

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

In this atlas the *buried sand and gravel aquifers* are referred to as *buried sand aquifers.*

Formation/epoch	Member/ phase	Sediment type	Part A	Part B	Remarks	Potentiometric surface figure	Pollution sensitivity figure
Holocene sediment		Peat	Qp	p			
		Lake sediment/fill	Ql/afhl	l afhl			
		Alluvium	Qas	as	unconfined	Figure 3	-
		Alluvium	Qag	ag	unconfined	Figure 3	-
		Colluvium	Qc	c			
		Terrace sand	Qat	at	unconfined	Figure 3	-
		Lake sediment	*Qlt*	lt			
New Brighton Formation		Sand and gravel	Qnd	nd	unconfined	Figure 3	-
		Sand	Qnb	nb	unconfined	Figure 3	-
New Ulm Formation	Heiberg Member	Outwash	Qno	no	unconfined	Figure 3	-
		Lacustrine	Qhl	hl			
		Ice-contact	Qhi	hi	unconfined	Figure 3	-
		Stagnation	Qsh	sh			
		Till	Qht	ht			
	Villard Member	Sand	*Qvs*	vs	mostly confined	-	Figure 36
		Till	Qvt	vt			
	Twin Cities Member	Outwash	Qts	ts	mostly unconfined	Figure 7	Figure 37
		Sand	*Qts2*	ts2	mostly unconfined	Figure 7	Figure 37
		Colluvium	Qtc	tc			
		Lacustrine	Qtl	tl			
		Stagnation	Qst	st			
		Ice-contact/fill	Qti/aftci	ti/aftci	mostly unconfined	Figure 8	Figure 38
		Till	Qtt	tt			
		Sand below till	*Qts1*	ts1	mostly unconfined	Figure 8	Figure 38
	Moland Member	Sand	*Qms*	ms	mostly unconfined	-	-
		Till	*Qmt*	mt			
Cromwell Formation		Ice-contact/fill	*Qsi/afsi*	si/afsi	mostly confined	Figure 9	Figure 39
	Automba phase	Outwash	*Qs1*	s1	mostly confined	Figure 9	Figure 39
		Till	*Qca*	ca			
		Lacustrine	*Qcl*	cl			
	St. Croix phase	Outwash	*Qs2*	s2	mostly confined	Figure 10	Figure 40
		Till	*Qcs*	cs			
	Emerald phase	Outwash	*Qs3*	s3	mostly confined	Figure 11	Figure 41
		Till	*Qce*	ce			
Lake Henry Formation	Sauk Centre Member	Outwash	*Qh1*	h1	confined	-	-
		Till	*Qsc*	sc			
St. Francis Formation		Outwash	*Qf1*	f1	confined	Figure 12	Figure 42
		Till	*Qsf1*	sf1			
Lake Henry Formation	Meyer Lake Member	Outwash	*Qh2*	h2	confined	Figure 13	Figure 43
		Till	*Qml*	ml			
St. Francis Formation		Outwash	*Qf2*	f2	mostly confined	Figure 14	Figure 44
		Till	*Qsf2*	sf2			
Unnamed Rainy provenance		Outwash	*Qwo*	wo	confined	Figure 15	Figure 45
		Till	*Qwt*	wt			
Elmdale Formation		Outwash	*Qeo*	eo	mostly confined	Figure 15	Figure 45
		Till	*Qet*	et			
Unnamed Superior provenance		Outwash	*Qvo*	vo	confined	Figure 16	Figure 46
		Till	*Qot*	ot			
Undifferentiated		Sand	*Qsu*	su	confined	Figure 16	Figure 46
		Undifferentiated	*Qu*	u			

Dash (-) indicates limited or no data.

Figure 5. Hydrostratigraphy of Quaternary unconsolidated sediment

The maps in this report primarily represent single mapped sand units as shown in the Part A atlas (Plate 5, Figures 5 through 15).

Bedrock aquifers

Bedrock aquifers are commonly used by municipalities and commercial operations because of their thickness, extent, predictability, and hydrologic characteristics that affect water yield. In sandstone aquifers, water moves through intergranular pore spaces and larger macropores such as fractures as in the St. Peter, Jordan, Mazomanie (Upper Tunnel City), Wonewoc, and Mt. Simon aquifers. In carbonate aquifers water moves through enlarged fractures or macropores as in the Platteville and Prairie du Chien.

In Hennepin County, many high-volume wells are completed across multiple formations to increase yield. Typical combinations shown on Plates 8 and 9 include the Prairie du Chien Group and Jordan Sandstone; Tunnel City Group and Wonewoc Sandstone; and Mt. Simon Sandstone and the Mesoproterozoic sedimentary formations (Mss).

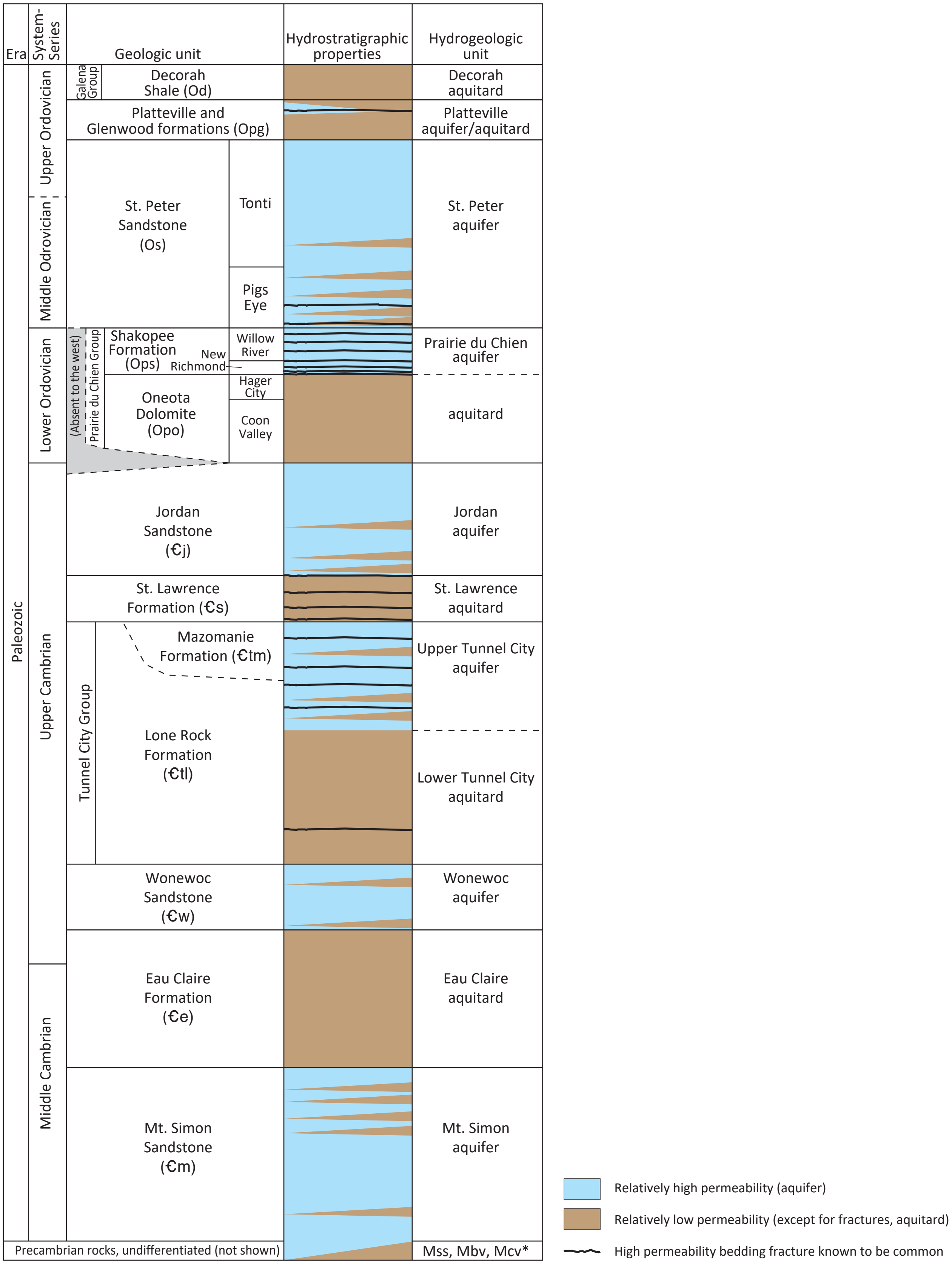
An enhanced-permeability zone exists in the uppermost 50 feet of the bedrock surface (shallow bedrock conditions) and bedrock valleys where bedrock and glacial sediment are in contact (Runkel and others, 2006). This zone developed when the bedrock surface was exposed at the land surface. The fractures generally increase the yield from aquifers but may compromise the protective character of aquitards.

The bedrock formations of Hennepin County are part of regionally extensive, gently dipping layers of Paleozoic sandstone, shale, and carbonate rock that range from 30 to 300 feet in thickness (Figure 6 and Part A, Plate 2, Figure 1). These sedimentary rocks were originally deposited in shallow marine settings during the Paleozoic era (Part A, Plate 2).

Paleozoic bedrock is underlain by a thick sequence of Mesoproterozoic rocks (Plates 8 and 9). These rocks include sandstone, siltstone, and shale of the Hinckley Sandstone, Solor Church, and Fond du Lac formations (unit Mss), as well as volcanic rocks composed mostly of basalt (units Mbv and Mcv). Because of limited subsurface data, the distribution of these units is less certain than the Paleozoic formations.

Cambrian-aged formations are primarily siliciclastic (sandstones and siltstones) and include in ascending order (oldest to youngest) the Mt. Simon Sandstone, Eau Claire Formation, Wonewoc Sandstone, Tunnel City Group (Lone Rock and Mazomanie formations), St. Lawrence Formation, and Jordan Sandstone. On the cross sections (Plates 8 and 9) the contact between the upper and lower Tunnel City Group is approximate. The Mazomanie Formation (Upper Tunnel City aquifer) is shown as approximately 50 feet thick in the northern part of the county. It thins southward and is absent in the southern part (Part A, Plate 2).

The stratigraphically higher and younger Ordovician bedrock formations are mostly carbonate rock (limestone and dolostone) with some sandstone and shale. They include in ascending order: the Prairie du Chien Group (Oneota Dolomite and Shakopee Formation), St. Peter Sandstone, Glenwood Formation, Platteville Formation, and Decorah Shale.



*includes clastic aquifer (Mesoproterozoic Hinckley and other units [Mss]) and volcanic aquitard units (Mbv and Mcv)

Figure 6. Bedrock stratigraphy and hydrostratigraphy

Groundwater flow

Potentiometric surface maps show the direction of groundwater flow. In confined aquifers, pressure causes the water level in a well to rise above the aquifer. These levels are measured and the groundwater elevations are contoured to create a map of the *potentiometric surface* for each aquifer, similar to how topographic maps show land-surface elevations.

The potentiometric surface of an aquifer represents the potential energy available to move groundwater. Groundwater moves from higher to lower potentiometric elevations, flowing perpendicular to the contours. Flow directions are shown on the maps.

Groundwater flows from recharge areas to discharge locations within a wide continuum of depth, distance, and time. Flow into, through, and out of shallow aquifers can take days to weeks to travel distances of up to a mile. Flow in deeper aquifers can take centuries to millennia to travel dozens of miles. Important recharge areas ould be indicated by high-elevation areas on the potentiometric surface, when combined with other information. River valleys are typical examples of low elevation discharge areas.

Potentiometric surface maps were created using static water-level data from the County Well Index (CWI), measurements made by the DNR staff, and river elevation points (1 kilometer spacing) along the major rivers. River elevation points are included where groundwater discharge is likely. The CWI records represent various climatic and seasonal conditions from the 1950s to 2018 (MGS and MDH, 2018). This data variability creates some uncertainty in potentiometric surface elevations.

Potentiometric surface maps for the buried sand and most bedrock aquifers (Figures 7 through 22) show a consistent pattern of flow away from the topographically highest northwestern part of the county. This location approximately coincides with the intersection of the three major watersheds near Loretto (Figure 3). Groundwater flow is influenced by the major groundwater discharge features of the Mississippi and Minnesota rivers to the northeast, east, and southeast, and to a lesser extent northwest toward the Crow River.

Surficial aquifers

Water table (Figures 3 and 4)

The water-table elevation and depth maps include water-level data from the various sources listed in the previous water-table section. Separate maps of the surficial units ts, ts2 and ti, ts1 are also included in this report using only the well data. These unit-specific maps may provide some benefit for local investigations or applications.

ts, ts2 (Figure 7) and ti, ts1 (Figure 8)

All of these aquifers have a limited extent in the southeastern part of the county. Aquifers ts, ts2 and ti, ts1 are more unit specific and are shown using only well data. Groundwater flow is toward major rivers (Mississippi and Minnesota) and portions of their larger tributaries including Minnehaha, Ninemile, and Purgatory creeks. Use for pumping is limited except in St. Louis Park, Richfield, and portions of Bloomington.

Buried sand aquifers

si, s1 (Figure 9)

These aquifers have limited extent and use, with the exceptions of local areas in Dayton and communities east of Lake Minnetonka. They appear to indirectly discharge to portions of Elm Creek in the north, and three of the larger tributaries in the southeast (Minnehaha, Ninemile, and Purgatory creeks). Otherwise groundwater flows dominantly northeast or east toward the Mississippi River in the Dayton, Champlin, Maple Grove, Brooklyn Park, and Crystal areas; and south to southeast toward the Minnesota River in the city of Minnetonka and eastern Lake Minnetonka areas.

s2 (Figure 10) and s3 (Figure 11)

The s2 aquifer has the widest extent and greatest use of the buried aquifers with additional dense clusters in Richfield and northern Bloomington. The s3 aquifer has a broad extent similar to the s2 aquifer but is used less in eastern Minneapolis and more in southeastern Medina. Both aquifers are used extensively around Lake Minnetonka, Dayton, Champlin, and Rogers.

Both aquifers show the full pattern of groundwater flow from the high area near Loretto toward major rivers. Both have a broad area of high elevation that includes portions of four townships in the northwest. Gradients are low in the central and northern parts of the county because of the relatively large distance from the discharge area. Gradients are much steeper nearer the major rivers, especially the Minnesota River in the areas of Bloomington and Eden Prairie.

f1 (Figure 12) and h2 (Figure 13)

Aquifers f1 and h2 are both mapped with limited extents and low gradients in the western part of the county. Flow from the broad high elevation in the Loretto area is toward the major rivers. Dense areas of f1 wells are found in the Greenfield and Independence areas and in the h2 aquifer across most of its extent.

f2 (Figure 14)

The f2 is mapped across most of the county with the exception of the Minneapolis area and has a relatively even distribution of wells with the exception of the southeast. Groundwater flow is toward the major rivers with a low gradient.

wo and eo (Figure 15)

The wo and eo aquifers are mostly mapped in the north and have a relatively even distribution of wells.

Groundwater flow is toward the major rivers with a low gradient.

vo and su (Figure 16)

The vo and su aquifer extents are limited to the north and have mostly been mapped in bedrock valleys (Part A, Plate 6, Bedrock Topography). Groundwater flow is commonly to the north and northeast with the possible exception of small parts in Medina, which may flow east or southeast.

Bedrock aquifers

Bedrock aquifers range from the relatively shallow, thin, and limited extent Platteville in the southeast to the deep, thick, and regionally extensive Mt. Simon and Mt. Simon–Hinckley aquifers that are found beneath the entire county.

Platteville (Figure 17)

The Platteville aquifer is limited to the southeast in a band that extends from Wayzata in the west to St. Anthony Village east of the Mississippi River. Groundwater flow directions on the west side of the Mississippi River are to the northeast, east, and southeast, and on the east side of the Mississippi River to the southwest. In the area along the Mississippi River this shallow urban aquifer is commonly the uppermost bedrock aquifer and a common target of contamination investigations. Therefore, many of the wells shown in that area are monitoring wells. The wells shown to the west are mostly domestic wells, with the exception of monitoring wells in and around the sites of the Reilly Tar Superfund and St. Louis Park solvent plume.

St. Peter (Figure 18)

The St. Peter aquifer is mostly limited to the central and eastern parts of the county. An uplifted fault block (horst) limits the western and northwestern extent, with the exception of a small portion of the aquifer northwest of the fault block in the Greenfield area.

Groundwater flow east of the fault block and west of the Mississippi River is east and southeast. East of the Mississippi River the flow is south and southwest. The St. Peter is commonly the uppermost bedrock aquifer where the Platteville is absent and is commonly the target of contamination investigations. Many of the wells along the Mississippi River and in St. Louis Park are monitoring wells, whereas the remainder are mainly domestic wells. This aquifer is commonly used by domestic wells in communities along the eastern portion of Lake Minnetonka and some areas of Edina.

Prairie du Chien (Figure 19)

The Prairie du Chien aquifer is limited to the central and eastern parts of the county. Groundwater flow west of the Mississippi River is east, southeast, and south. East of the Mississippi River flow is south and southwest. The most common use of this aquifer is domestic, shown as dense clusters of wells in the western and southern portions of the county. The apparent cone of depression (area of lower water levels) in the St. Louis Park area may be caused by local high-volume irrigation and industrial groundwater pumping.

Jordan (Figure 20)

The Jordan aquifer has a countywide extent with only smaller and thinner patches occupying the fault block area, oriented from southwest to northeast from St. Bonifacius to Champlin. Wells east and south of Brooklyn Park are commonly constructed with the open-hole portion of the well straddling both the Prairie du Chien and Jordan aquifers. Wells in the west and north are commonly completed only in the Jordan aquifer and less commonly in the Jordan aquifer and underlying St. Lawrence aquitard.

Large-scale flow is toward the major rivers (east, southeast, and south), but some local patterns of flow may be due to the combined effects of high-volume municipal and industrial pumping. The combined Prairie du Chien–Jordan aquifers and Jordan aquifer are heavily used in the Twin Cities metropolitan area (TCMA) for high-volume public, commercial, and industrial use (see "Groundwater use"). All of the highly populated suburban communities in the eastern part of the county obtain water from multiple municipal wells that are commonly clustered in close proximity (well fields). This can create a cumulative lowering of the water levels (cone of depression) where the potentiometric surface of the aquifer is depressed over a relatively wide area.

The CWI dataset is not ideal for mapping these cones of depression because of the wide range of water-elevation data dates, but Figure 20 suggests cones of depression in Plymouth, Hopkins, Eden Prairie, Edina, and downtown Minneapolis.

Upper Tunnel City (Figure 21)

The Upper Tunnel City aquifer has a countywide extent, but is rarely used in the southeastern half of the county where shallower aquifers are more available.

Groundwater flows radially from an area northeast of Loretto toward the Crow River, east and northeast to the Mississippi River, and southeast toward the Minnesota River.

Wonewoc

The Wonewoc aquifer only has approximately 20 located wells. Most are in the northwestern half of the county similar to the overlying Upper Tunnel City aquifer. Because of insufficient data, no groundwater flow map was developed.

Mt. Simon (Figures 22–24)

The Mt. Simon aquifer is the deepest commonly used aquifer in the county and surrounding TCMA. Deep aquifers tend to recharge slower than overlying shallower aquifers. The primary recharge areas of the Mt. Simon for Hennepin County are to the northwest in the adjoining counties of Wright and Sherburne (Berg and Pearson, 2013).

The combination of many years of high-volume pumping and its limited recharge characteristics has created a cumulative cone of depression that includes portions of Hennepin, Ramsey, and Dakota counties (Figure 22a and b). This large and persistent cone of depression has created concern that the Mt. Simon aquifer could be overused to the extent that it may not be a viable source of groundwater in the future. New high-volume use is limited for this aquifer in the 7 counties of the TCMA by Minnesota statute 103G.271, Subdivision 4a, enacted in 1989 (Minnesota Legislature 2020).

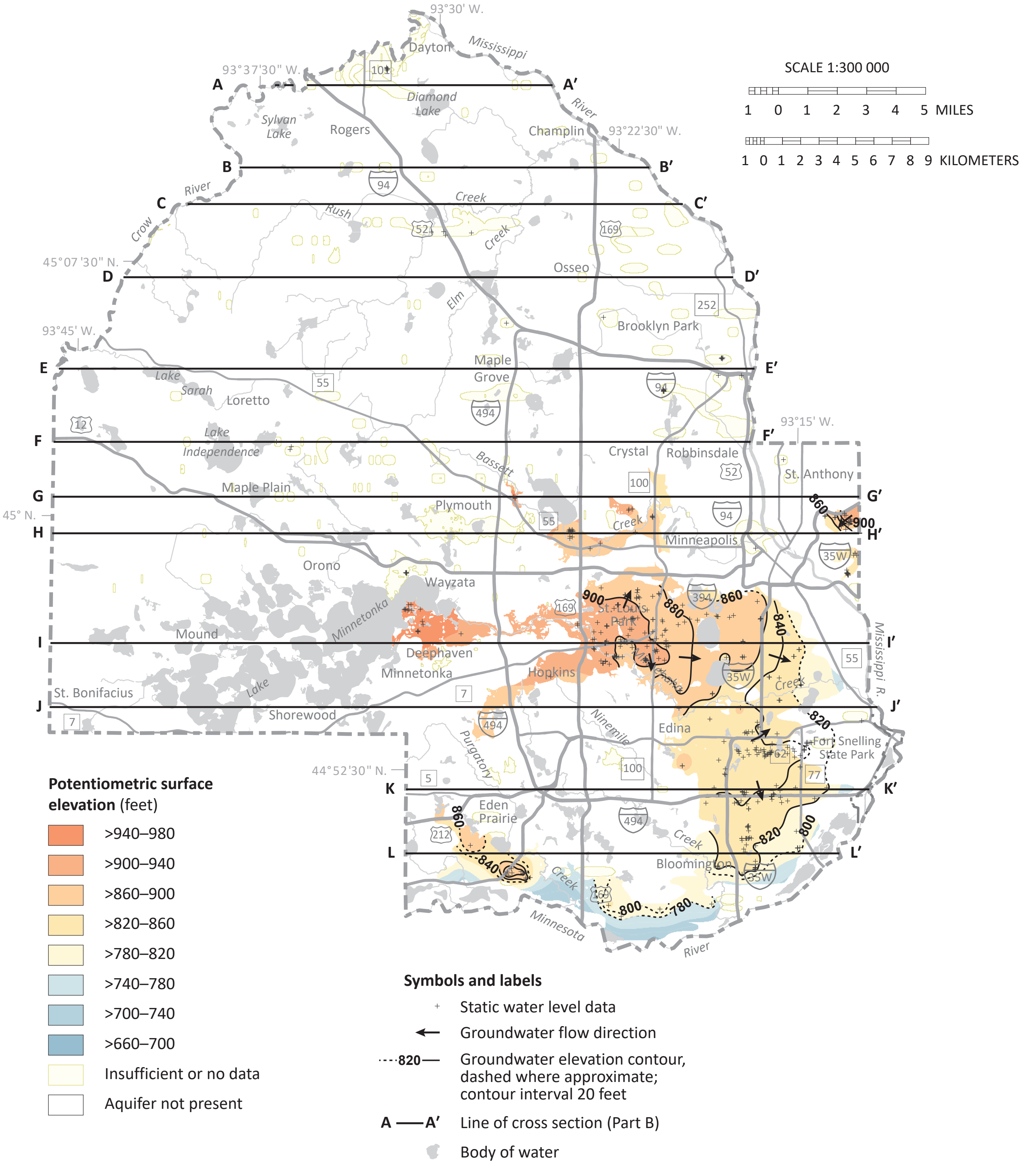
To better monitor this aquifer and the overlying units, an extensive network of observation well nests (closely spaced wells that are completed in different aquifers) was installed by the DNR in Hennepin County, and adjoining counties from 2009 to 2014. Water-elevation fluctuations in these new wells have been monitored continuously to help understand the nature of the aquifer recharge areas, the extent of the cumulative cone of depression, the groundwater flow directions and gradients, and to provide long-term information on sustainable aquifer use.

Examples of these continuous data since 2010 are shown in Figure 23 at the Luce Line well nest in the central part of the county (Figure 24). The seasonal pattern of groundwater elevations matches the seasonal pattern of pumping for the combined Prairie du Chien–Jordan aquifers and the Jordan aquifer within the 5-mile radius of the observation well nest. This indicates that the fluctuations of the upper aquifers are influenced by local pumping.

However, the patterns of the lower aquifers (Wonewoc and Mt. Simon) suggest wider regional influences, where relatively low volumes are pumped within the 5-mile radius and all of the wells are at least 1 mile from the observation well nest. Furthermore, fluctuations are offset by a few months, with the peaks coinciding with the beginning of seasonal drawdown in the overlying Jordan aquifer. This offset suggests a combination of controlling factors that may include pressure changes from decreasing amounts of water in the overlying aquifers (water table, shallow buried sand, and bedrock) and pumping of distant wells in the TCMA from the Wonewoc and Mt. Simon aquifers. The cyclic hydrograph pattern is characteristic of all the continuous data hydrographs in the TCMA for the Mt. Simon aquifer (see “Groundwater level monitoring”). The yearly change can be as much as 20 to 30 feet in southeastern Hennepin County and adjoining areas.

Continuous data allow mapping of these annual changes by comparing the water elevation in all the wells for the same date (synoptic) that represent the approximate seasonal high and low. These synoptic measurements show a shallower cumulative cone of depression in the spring, before summer municipal pumping increases for noncrop irrigation and other water uses (Figure 22a).

In early fall the cumulative cone of depression has deepened by as much as 20 to 30 feet (Figure 22b), as shown by change in depth values next to the observation well symbols and the expansion of the deepest elevation interval.



Potentiometric surface elevation (feet)

🟥	>940–980
🟧	>900–940
🟧	>860–900
🟨	>820–860
🟨	>780–820
🟦	>740–780
🟦	>700–740
🟦	>660–700
☐	Insufficient or no data
☐	Aquifer not present

Symbols and labels

+	Static water level data
←	Groundwater flow direction
····820——	Groundwater elevation contour, dashed where approximate; contour interval 20 feet
A ——A′	Line of cross section (Part B)
●	Body of water

Figure 7. Potentiometric surface of the ts and ts2 aquifers

These aquifers have a limited extent in the southeastern part of the county. Use is also limited except in St. Louis Park, Richfield, and portions of Bloomington. Flow is toward the major rivers and portions of the major tributaries of the Mississippi and Minnesota rivers including Minnehaha, Ninemile, and Purgatory creeks.

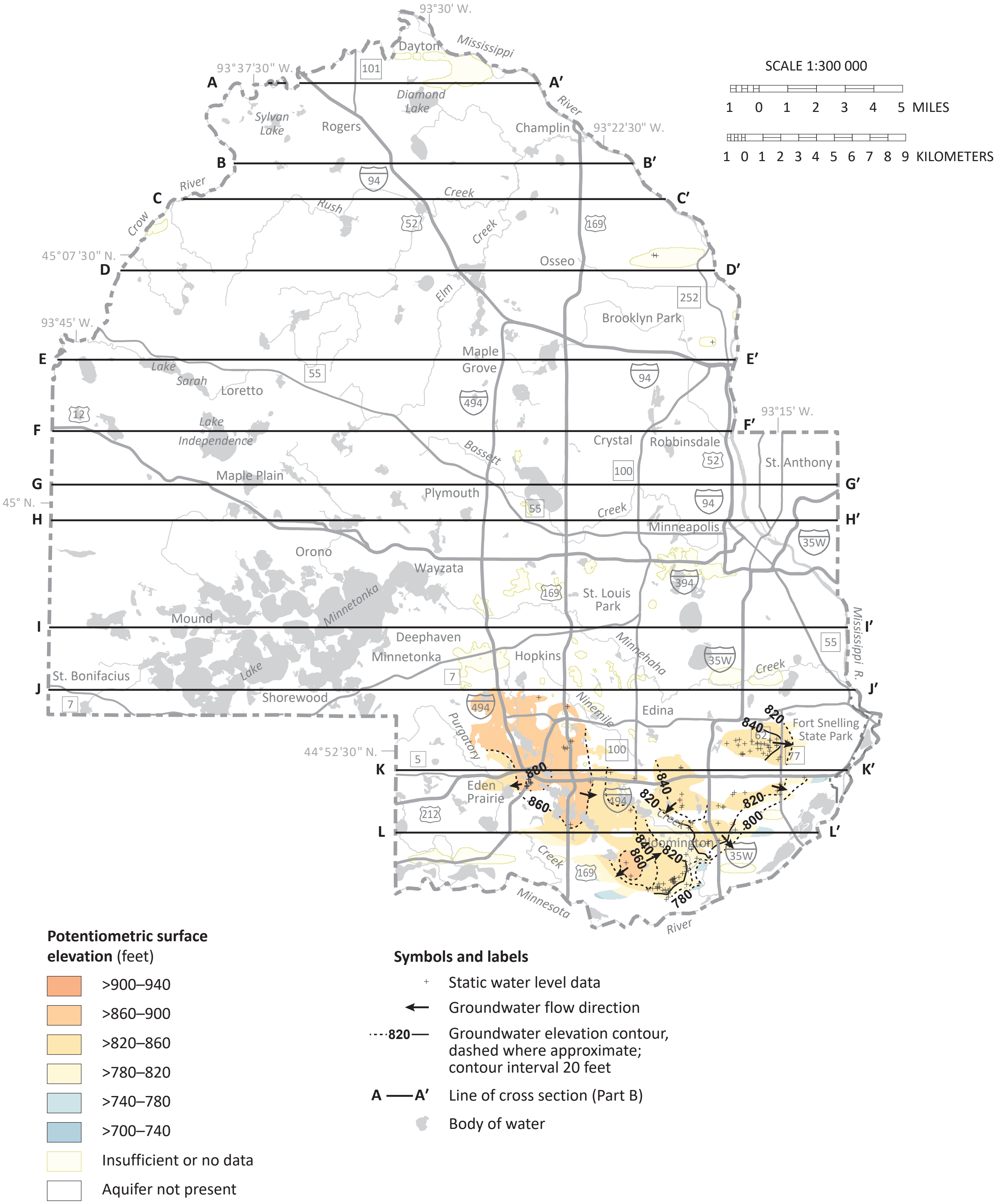


Figure 8. Potentiometric surface of the ti and ts1 aquifers

All of these aquifers have a limited extent in the southeastern part of the county. Use is also limited except in St. Louis Park, Richfield, and portions of Bloomington. Flow is toward the major rivers and portions of the major tributaries of the Mississippi and Minnesota rivers including Minnehaha, Ninemile, and Purgatory creeks.

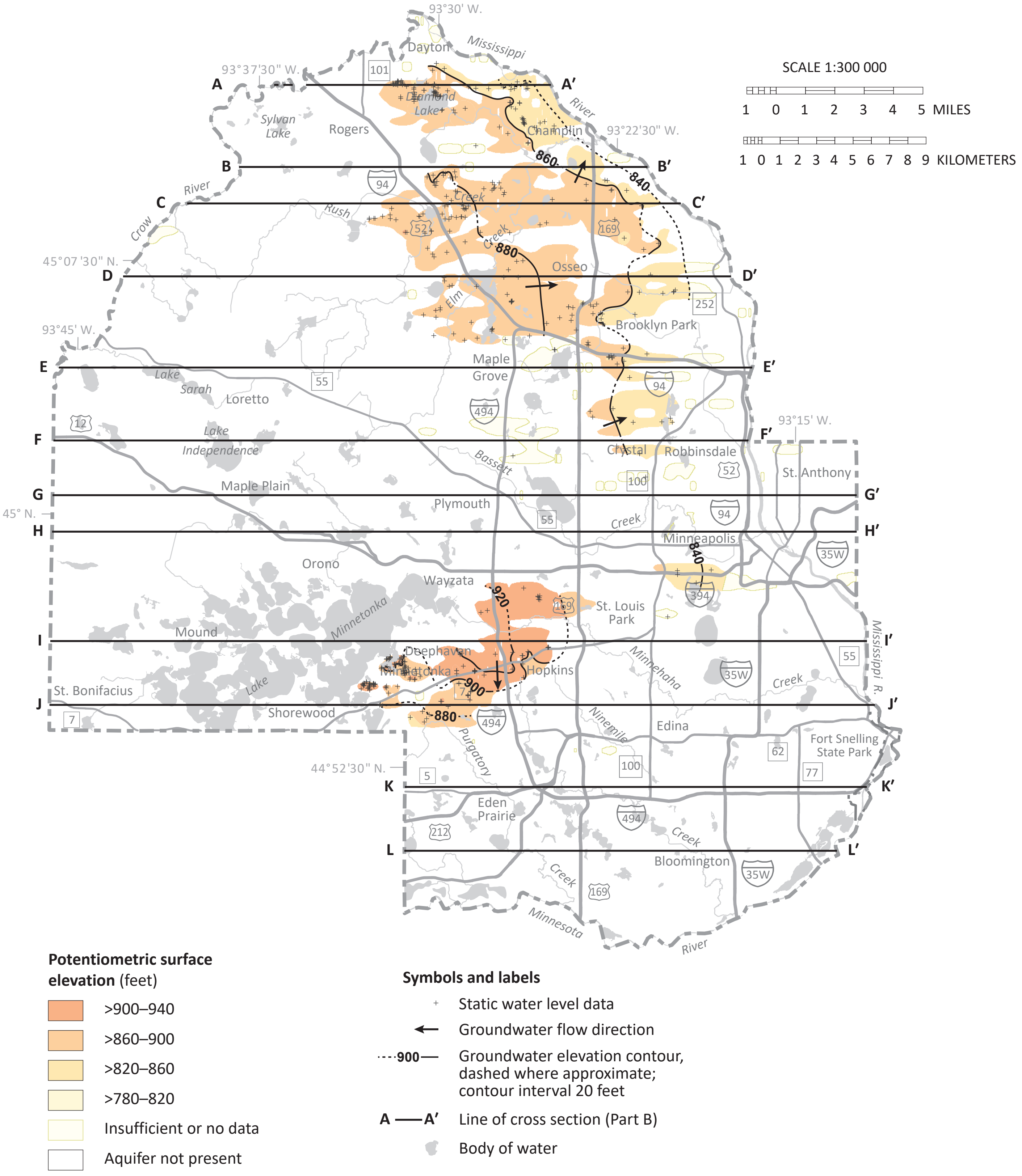


Figure 9. Potentiometric surface of the si and s1 aquifers

These aquifers have a limited extent and limited use, with the exception of local areas in Dayton and communities of eastern Lake Minnetonka. They are mostly buried and appear to indirectly discharge to portions of Elm Creek in the northern part of the county, and three of the larger creeks in the southeast (Minnehaha, Ninemile, and Purgatory). Otherwise groundwater flow is dominantly east or northeast toward the Mississippi River in the Dayton, Champlin, Maple Grove, Brooklyn Park, and Crystal areas; and south to southeast toward the Minnesota River in the city of Minnetonka and eastern Lake Minnetonka areas.

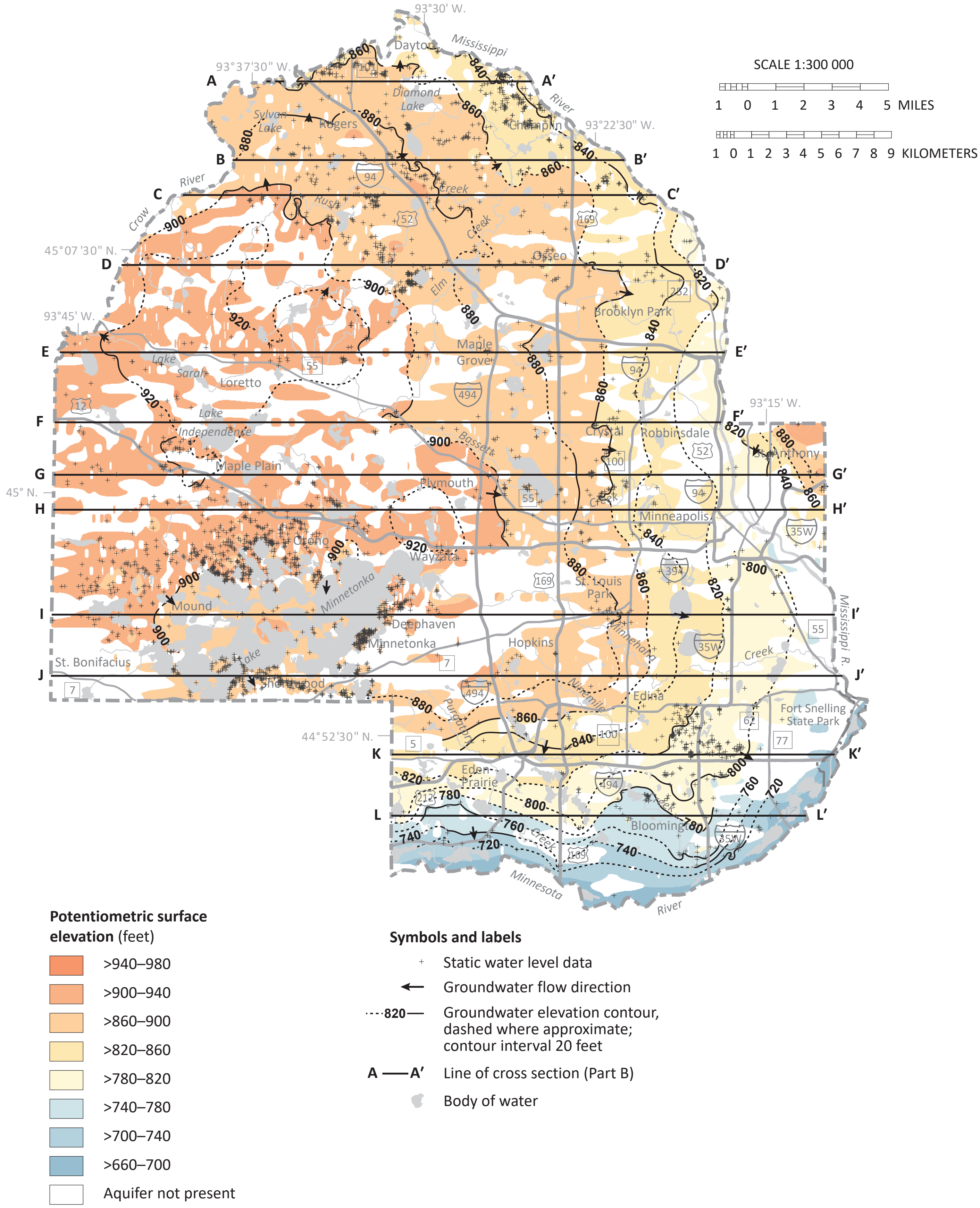


Figure 10. Potentiometric surface of the s2 aquifer

This aquifer has a broad high-elevation area that includes portions of four townships in the northwest. Flow shows the full radial pattern away from the elevated area near Loretto toward the major rivers. Gradients are low in the central and northern parts of the county because of a greater distance from the discharge area. Gradients are much steeper nearer the major rivers, especially the Minnesota River, in the areas of Bloomington and Eden Prairie.

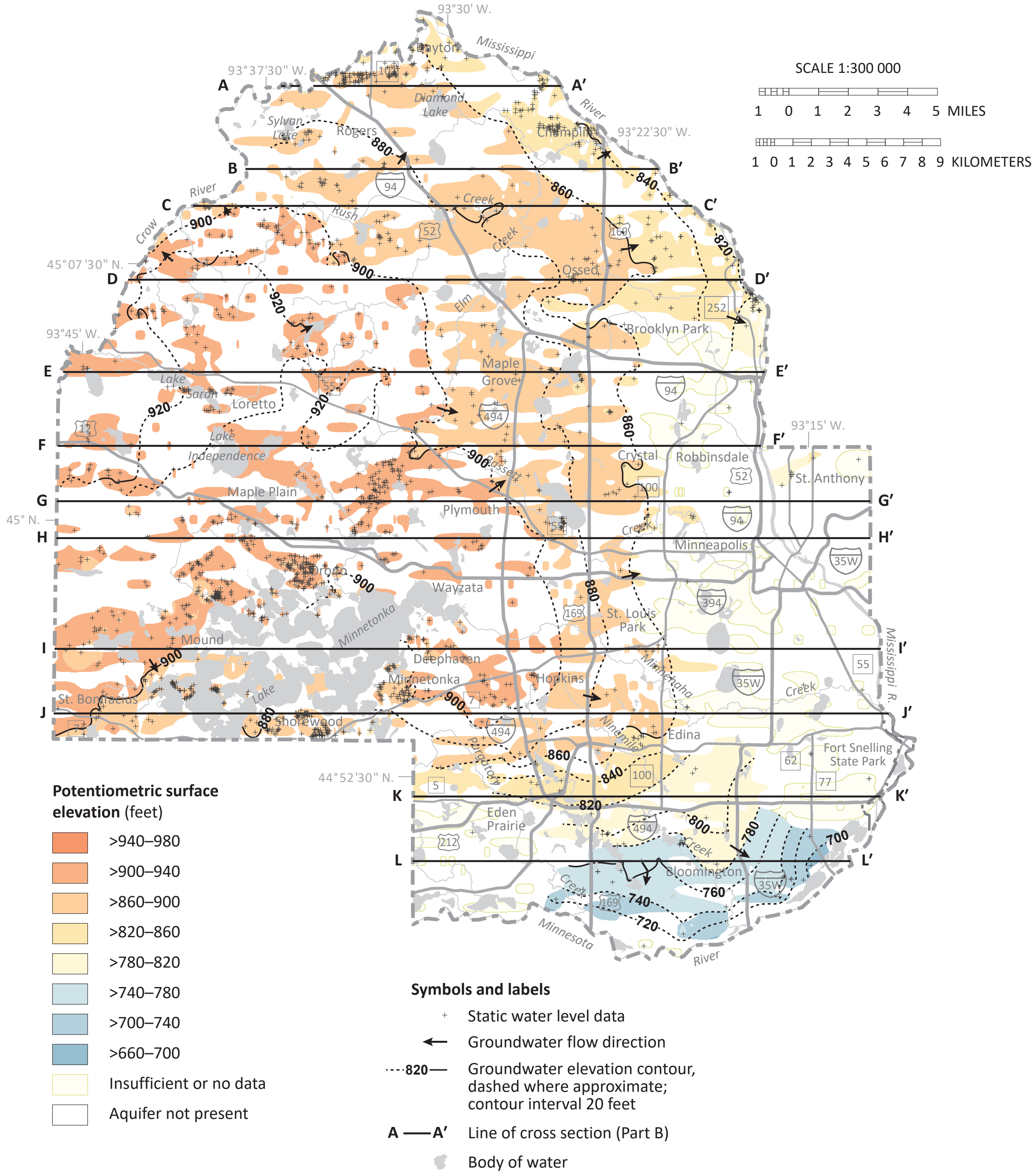


Figure 11. Potentiometric surface of the s3 aquifer

This aquifer has a broad high-elevation area that includes portions of four townships in the northwest. Flow shows the full radial pattern away from the elevated area near Loretto toward the major rivers. Gradients are low in the central and northern parts of the county because of a greater distance from the discharge area. Gradients are much steeper nearer the major rivers, especially the Minnesota River, in the areas of Bloomington and Eden Prairie.

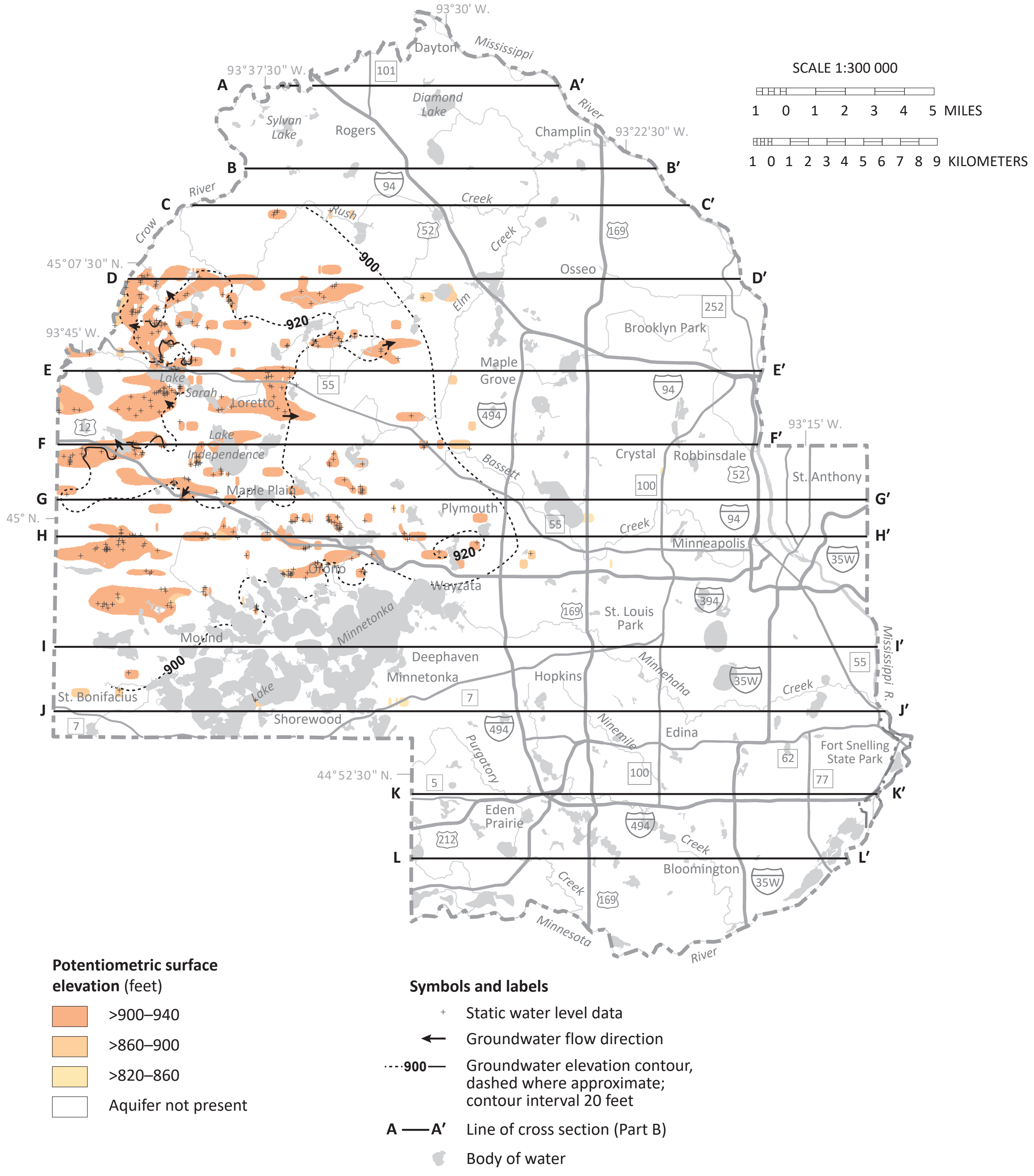


Figure 12. Potentiometric surface of the f1 aquifer

Dense clusters of wells are shown in the Greenfield and Independence areas (Figure 1) and across most of the extents. Groundwater flow is away from the broad high-elevation area around Loretto toward the major rivers. Limited extents and low gradients occur in the western part of the county.

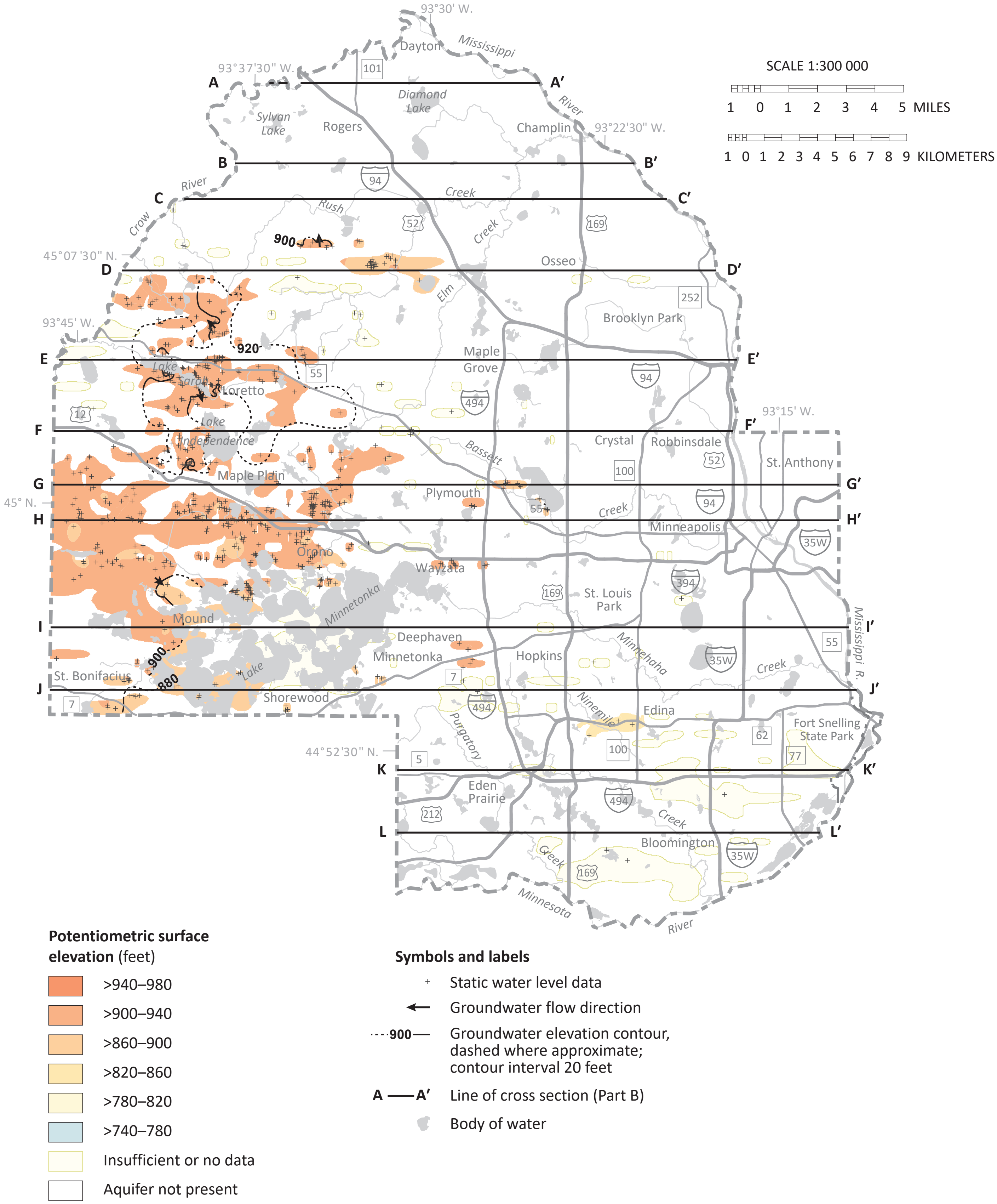


Figure 13. Potentiometric surface of the h2 aquifer

Dense clusters of wells are shown in the Greenfield and Independence areas (Figure 1) and across most of the extents. Groundwater flow is away from the broad high-elevation area around Loretto toward the major rivers. Limited extents and low gradients occur in the western part of the county.

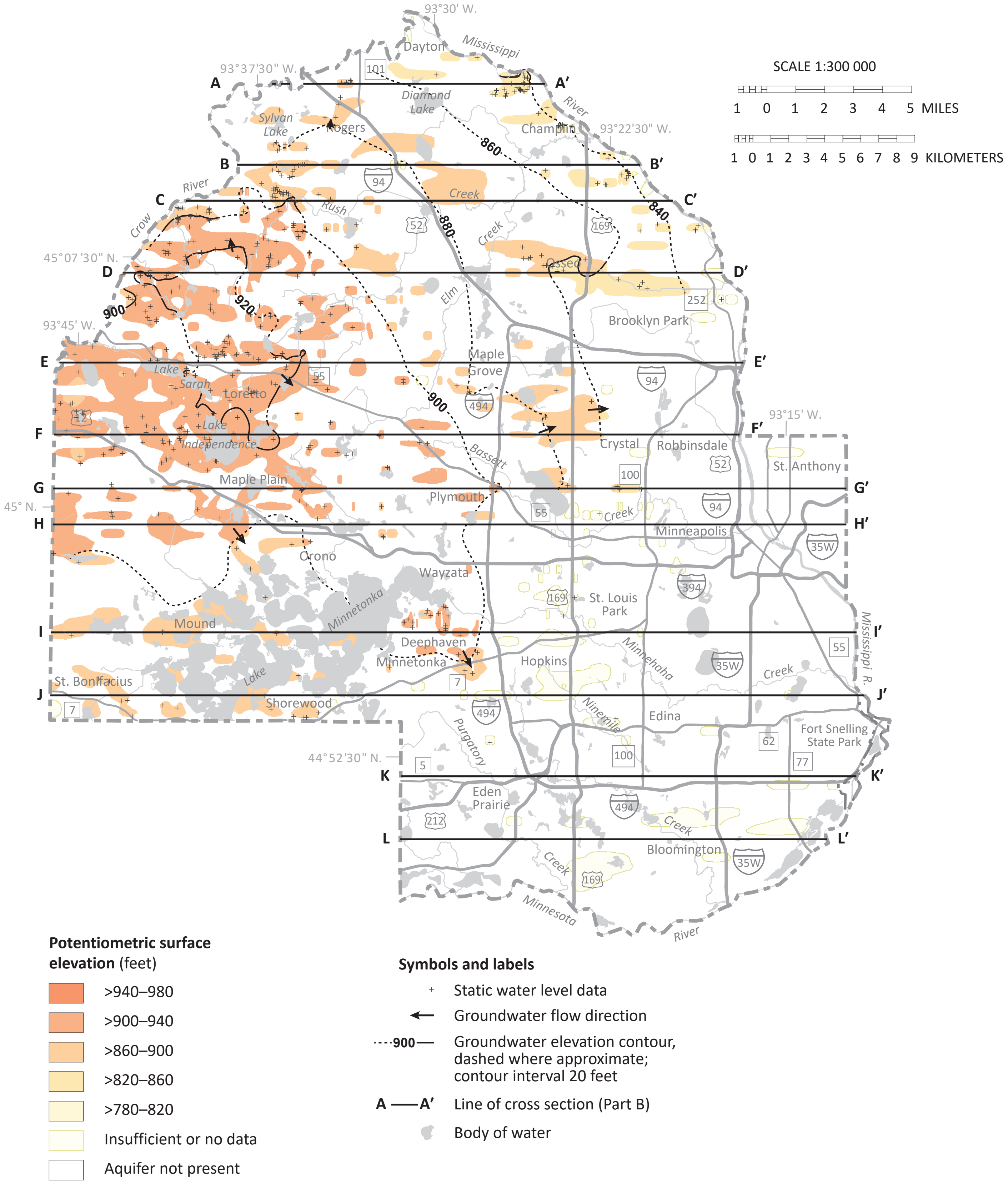


Figure 14. Potentiometric surface of the f2 aquifer

The f2 aquifer is mapped across most of the county with the exception of the Minneapolis area and has a relatively even distribution of wells, with the exception of the southeast. Groundwater flow is toward the major rivers with a low gradient.

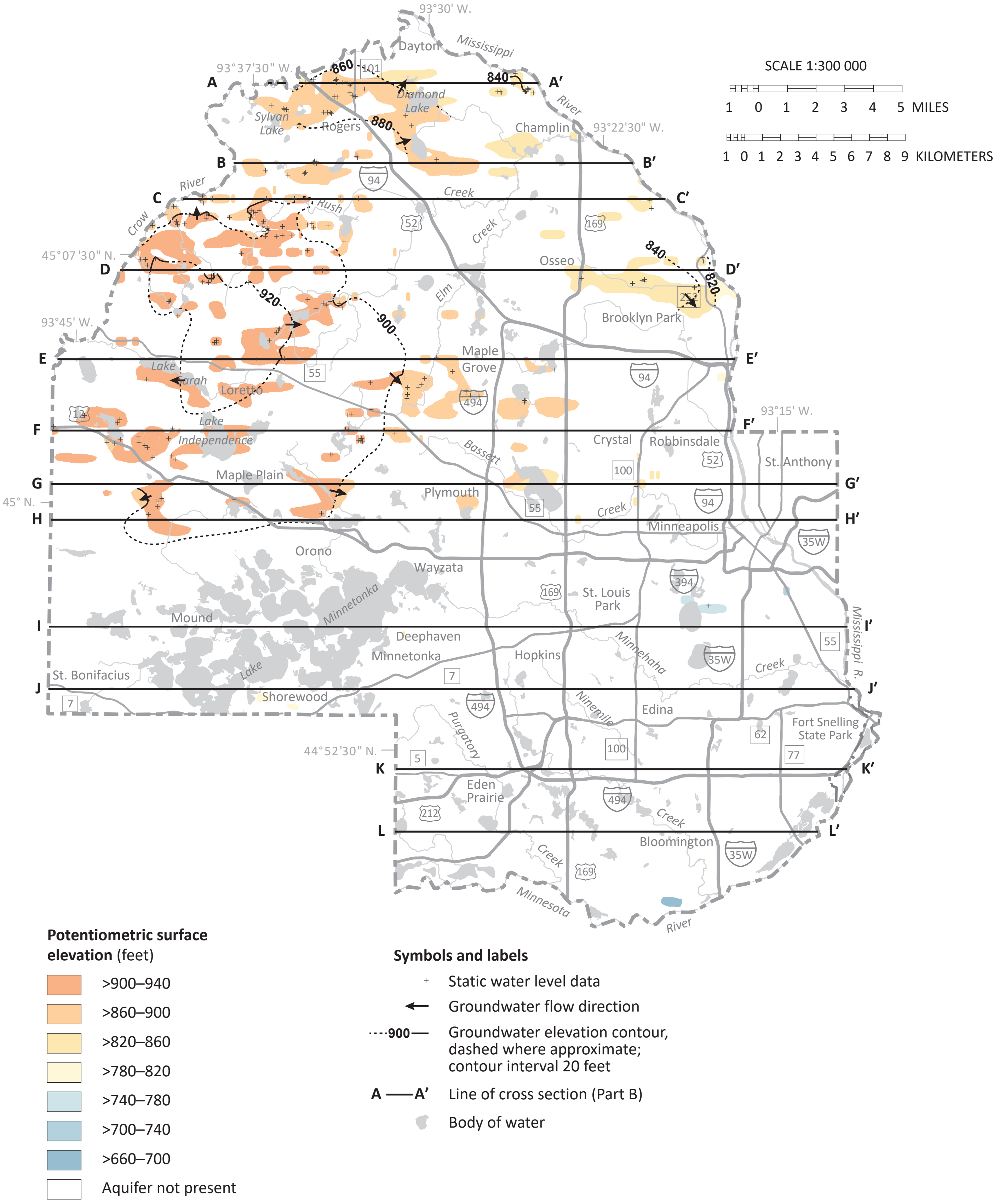


Figure 15. Potentiometric surface of the wo and eo aquifers

The wo and eo aquifers are mostly mapped in the north and have a relatively even distribution of wells. Groundwater flow is toward the major rivers with a low gradient.

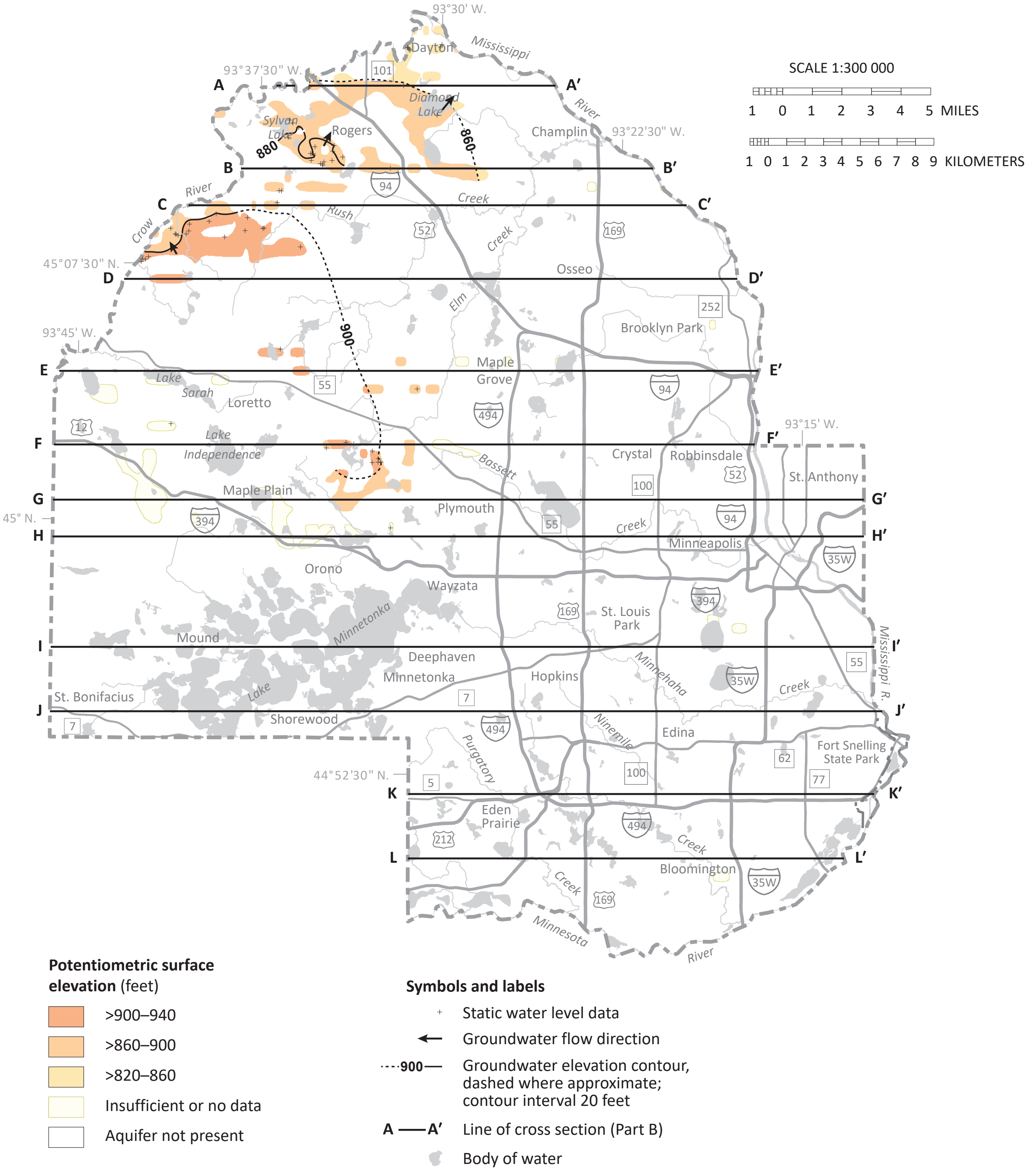


Figure 16. Potentiometric surface of the vo and su aquifers

Extents are limited to the north. Both of these aquifers are mostly mapped in bedrock valleys. Flow is common to the north and northeast with the possible exception of small parts in Medina, which may flow east or southeast.

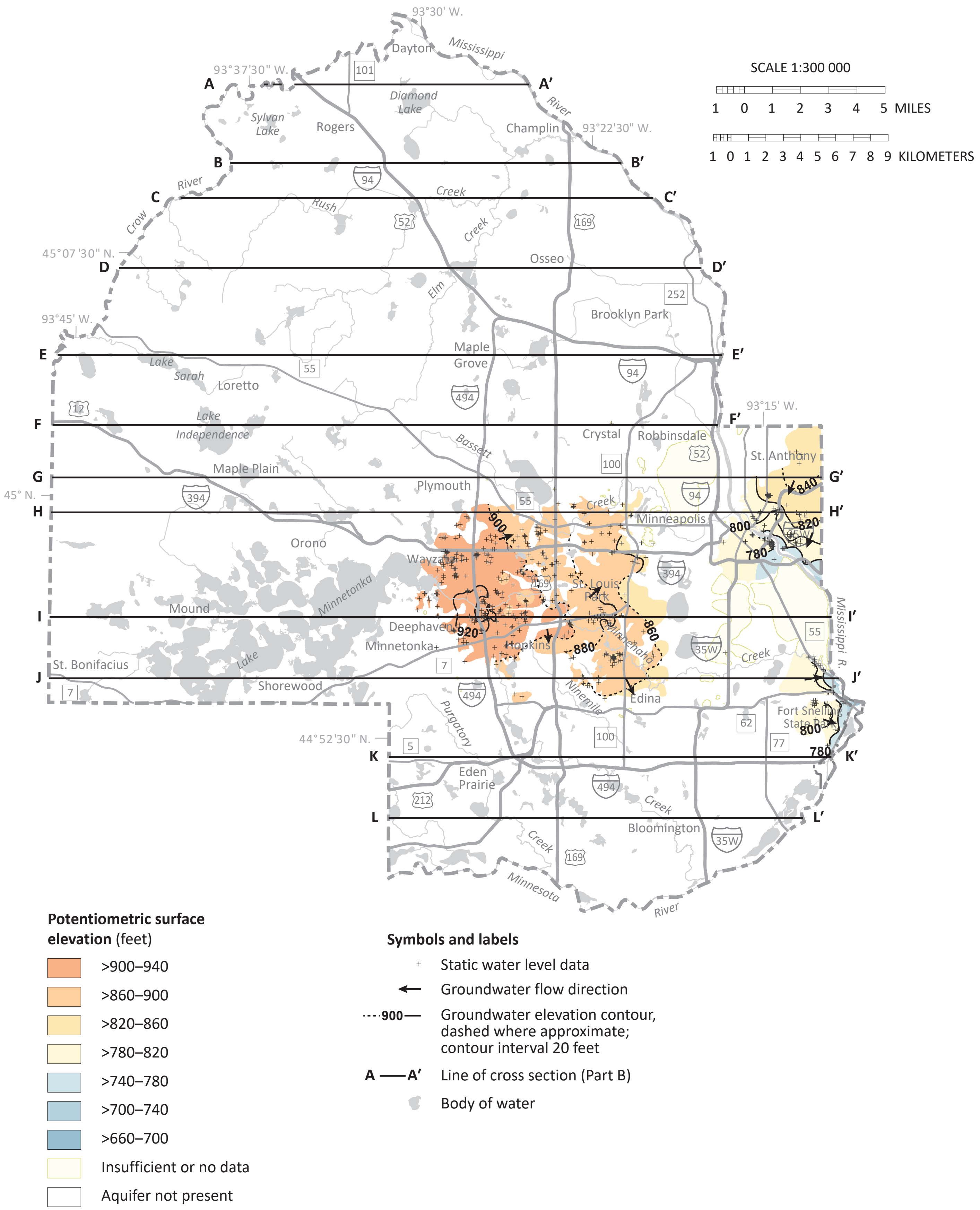


Figure 17. Potentiometric surface of the Platteville aquifer

Extent is limited to the southeast in a band that extends from Wayzata in the west to St. Anthony Village east of the Mississippi River. Groundwater flow is to the east, northeast, and southeast on the west side of the Mississippi River and southwest on the east side of the Mississippi River.

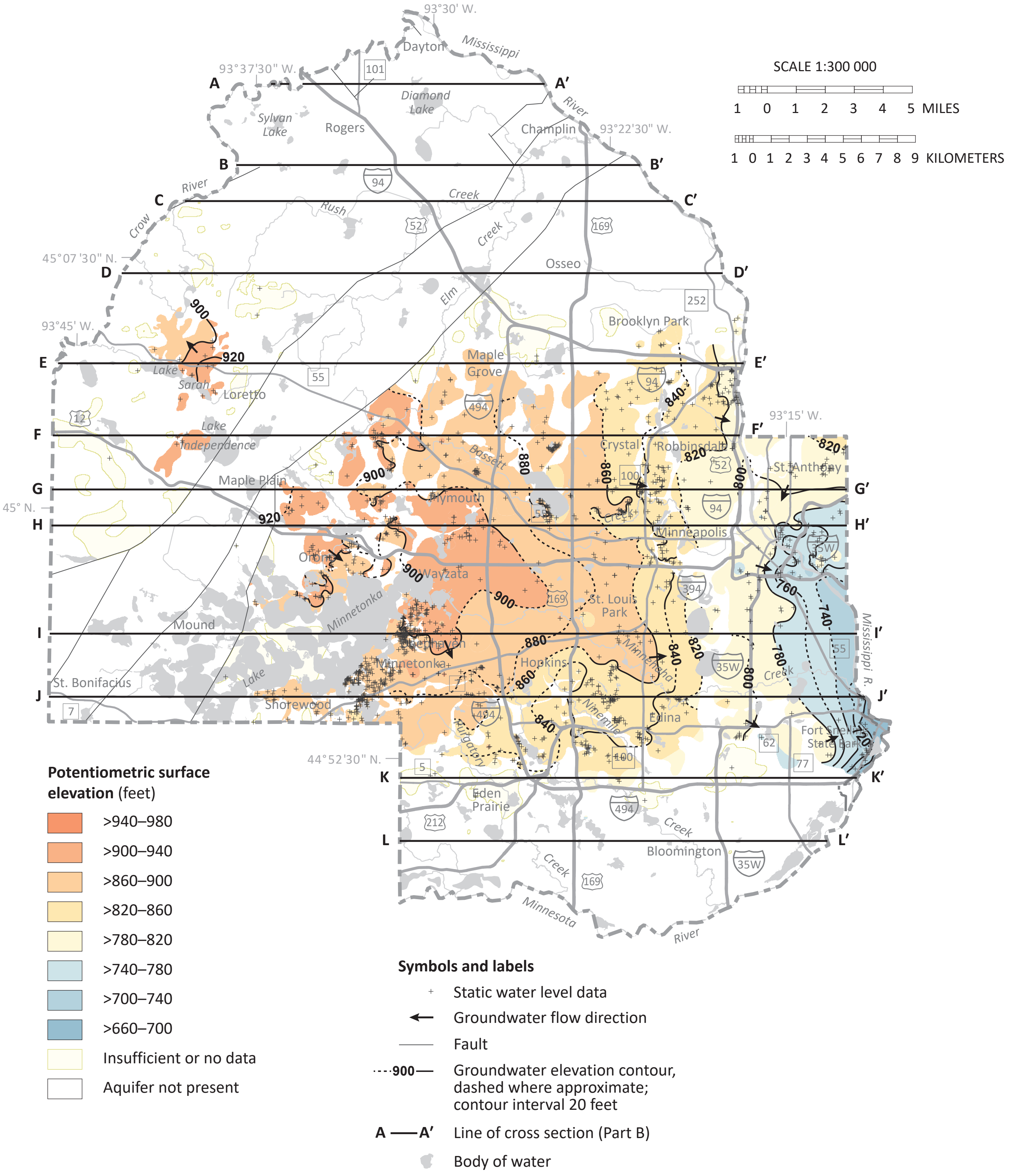


Figure 18. Potentiometric surface of the St. Peter aquifer

Extent is mostly limited to the central and eastern parts of the county. An uplifted fault block (horst) limits the western and northwestern extent of this aquifer with the exception of a small portion northwest of the fault block in the Greenfield area (Figure1). Groundwater flow east of the fault block and west of the Mississippi River is to the east and southeast. East of the Mississippi River flow is to the south and southwest.

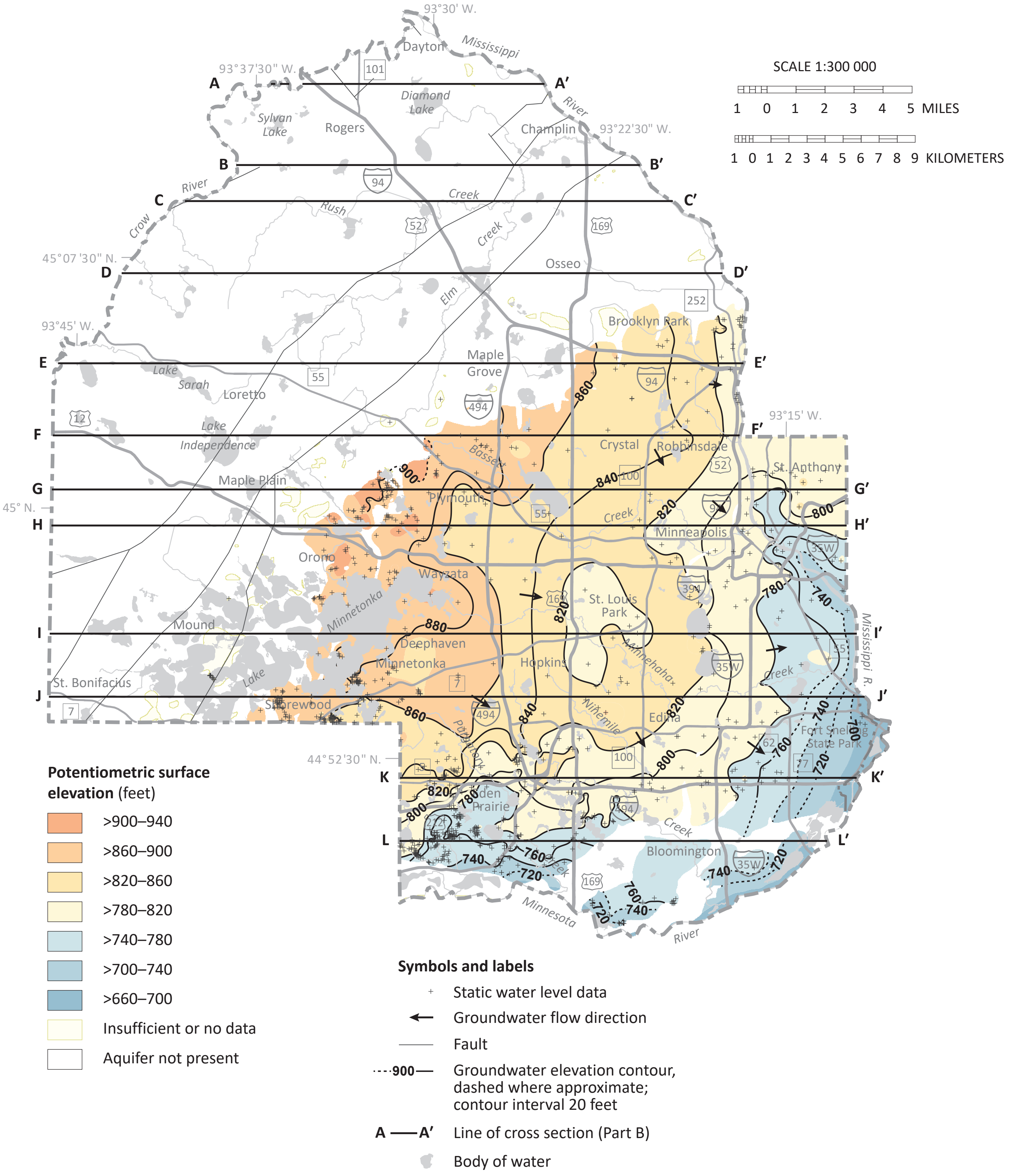


Figure 19. Potentiometric surface of the Prairie du Chien aquifer

Extent is limited to the central and eastern parts of the county. Groundwater flow west of the Mississippi River is to the east, southeast, and south. East of the Mississippi River flow is south and southwest.

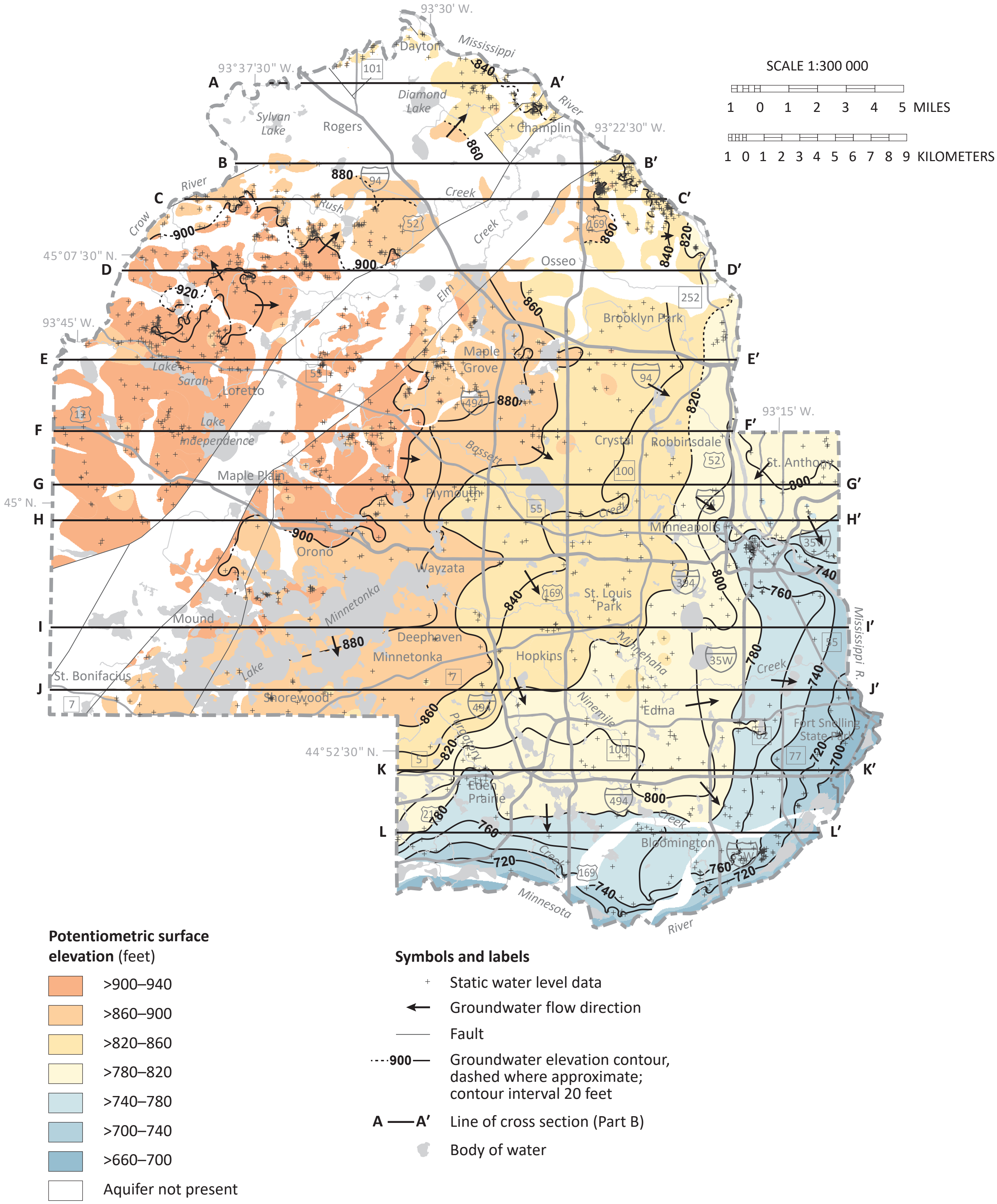


Figure 20. Potentiometric surface of the combined Prairie du Chien–Jordan and Jordan wells.

The Jordan aquifer has a countywide extent with only smaller and thinner patches occupying the fault block area. Wells in the east and south of Brooklyn Park are commonly constructed with the open-hole portion of the well straddling both the Prairie du Chien and Jordan aquifers. Wells in the west and north are mostly completed only in the Jordan aquifer, or less commonly, the Jordan aquifer and underlying St. Lawrence aquitard. Large-scale flow is to the east, southeast, and south toward the major rivers. Additional local patterns of flow may be because of the combined effects of pumping.

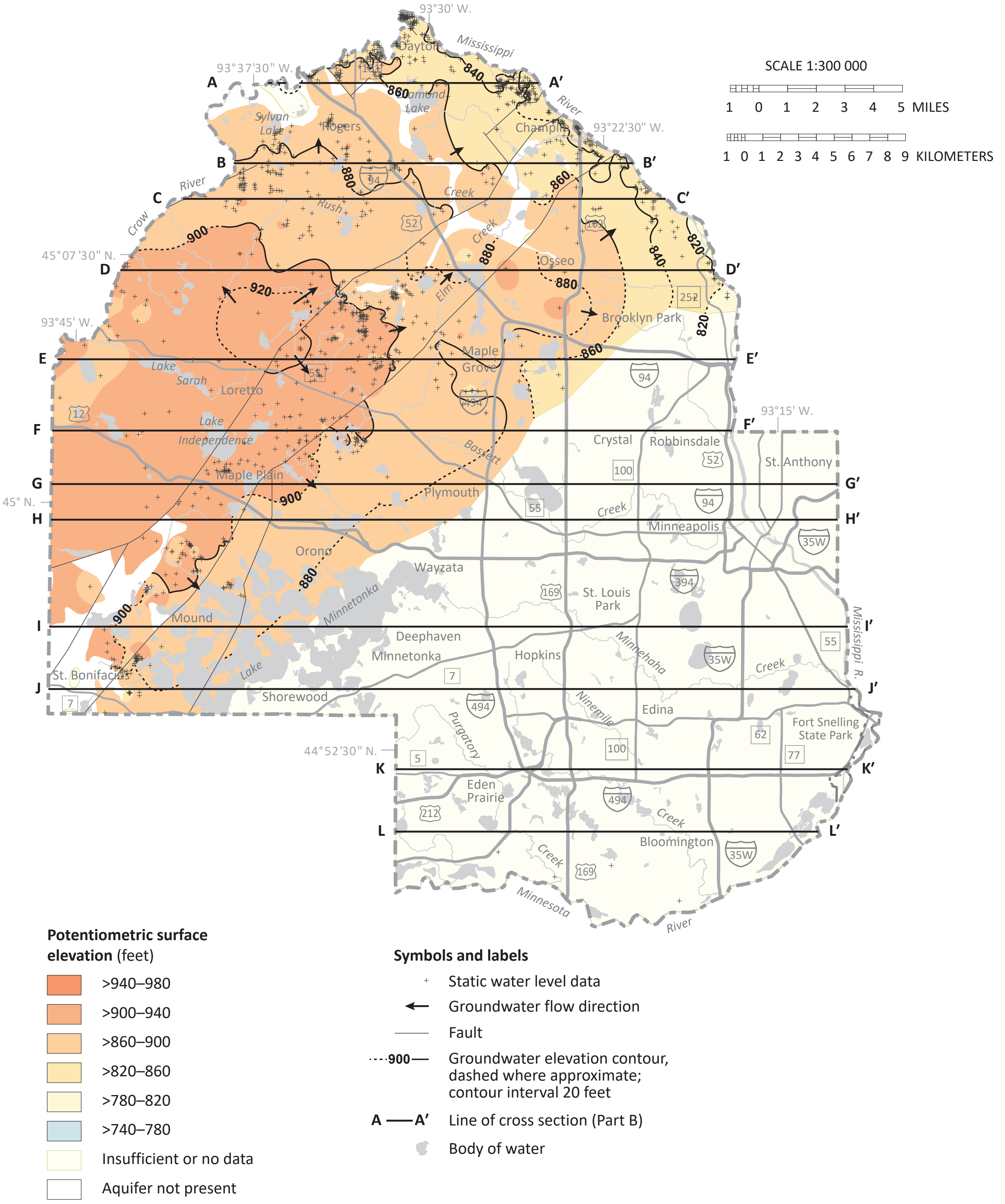
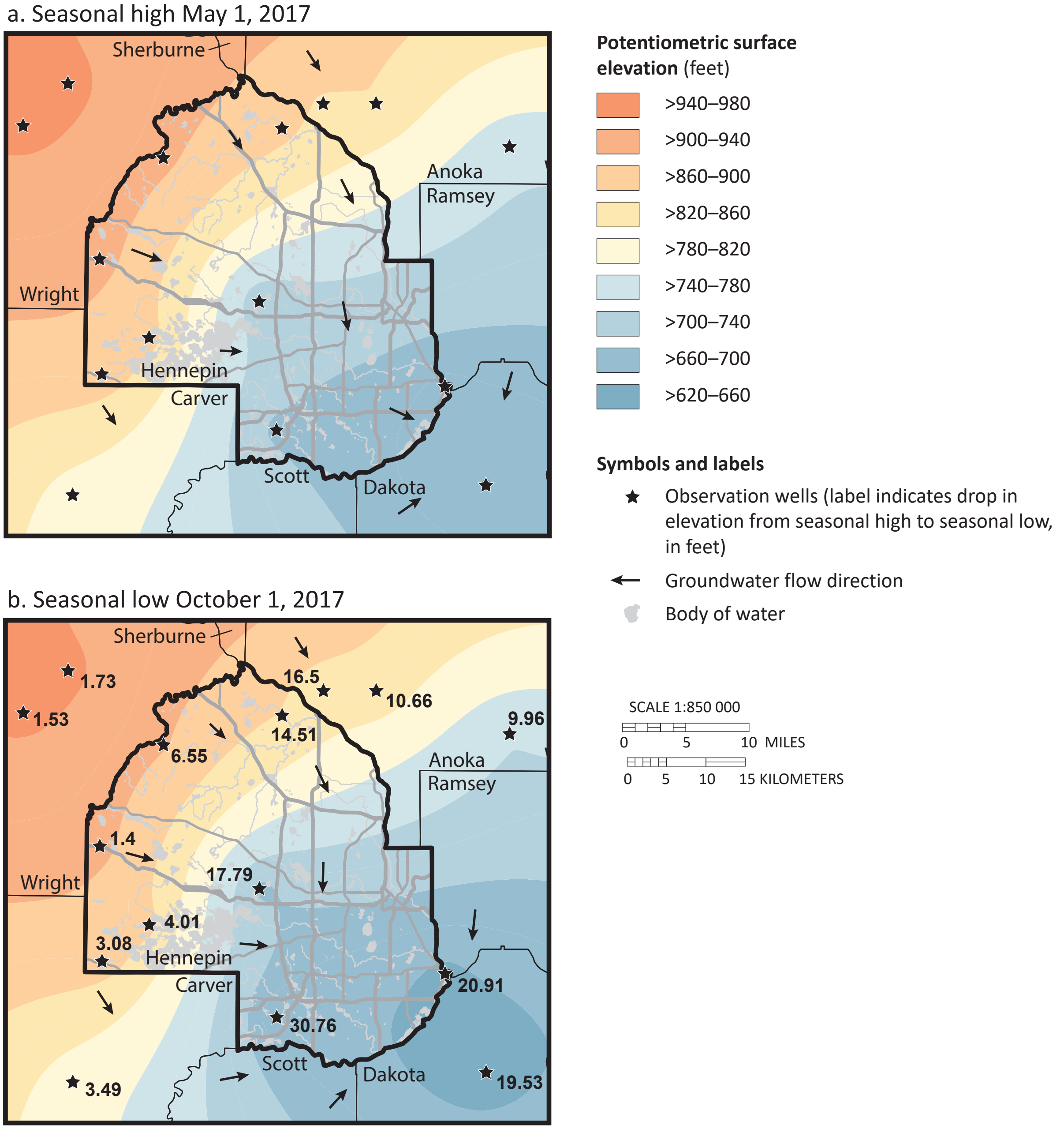


Figure 21. Potentiometric surface of the Upper Tunnel City aquifer

Extent is countywide, but the aquifer is rarely used in the southeastern half of the county where shallower aquifers are more available. Groundwater flows radially from an area northeast of Loretto toward the Crow River, east and northeast to the Mississippi River, and southeast toward the Minnesota River.



a. Seasonal high May 1, 2017

b. Seasonal low October 1, 2017

Figure 22. Potentiometric surface of the Mt. Simon aquifer

a. Synoptic measurements from continuous data loggers show a cumulative cone of depression that is shallower in the spring before municipal pumping increases for summertime demand.

b. By early fall the cumulative cone of depression may deepen by as much as 20 to 30 feet, shown by change in depth values next to the observation well symbols and expansion of the deepest elevation interval.

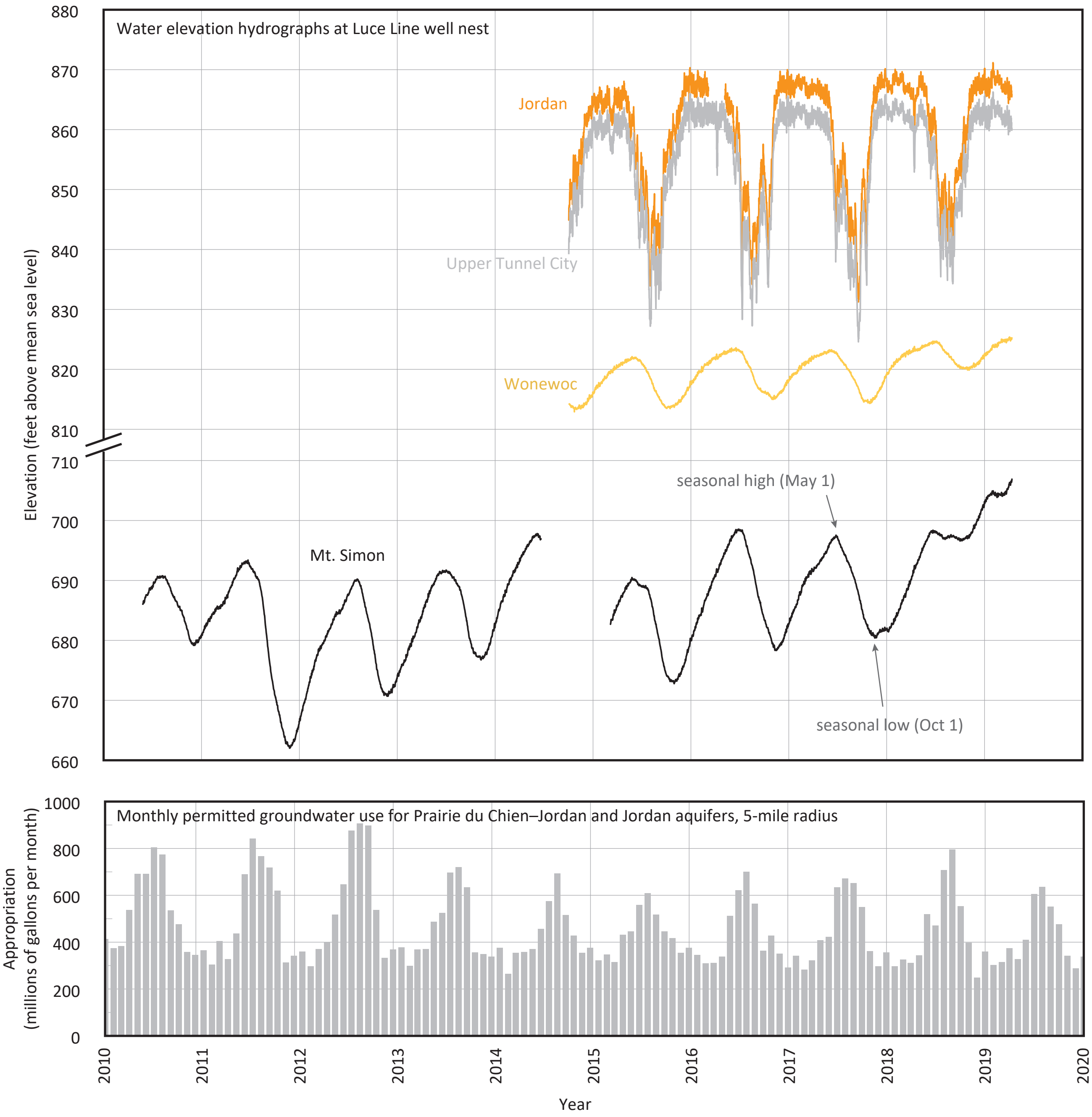


Figure 23. Hydrographs from a central Hennepin County well nest (Luce Line parking area)

Continuous groundwater elevation data since 2010 shows seasonal patterns that match the seasonal pumping patterns from the combined Prairie du Chien–Jordan aquifers and the Jordan aquifer within the 5-mile radius of the observation well nest (Figure 24).

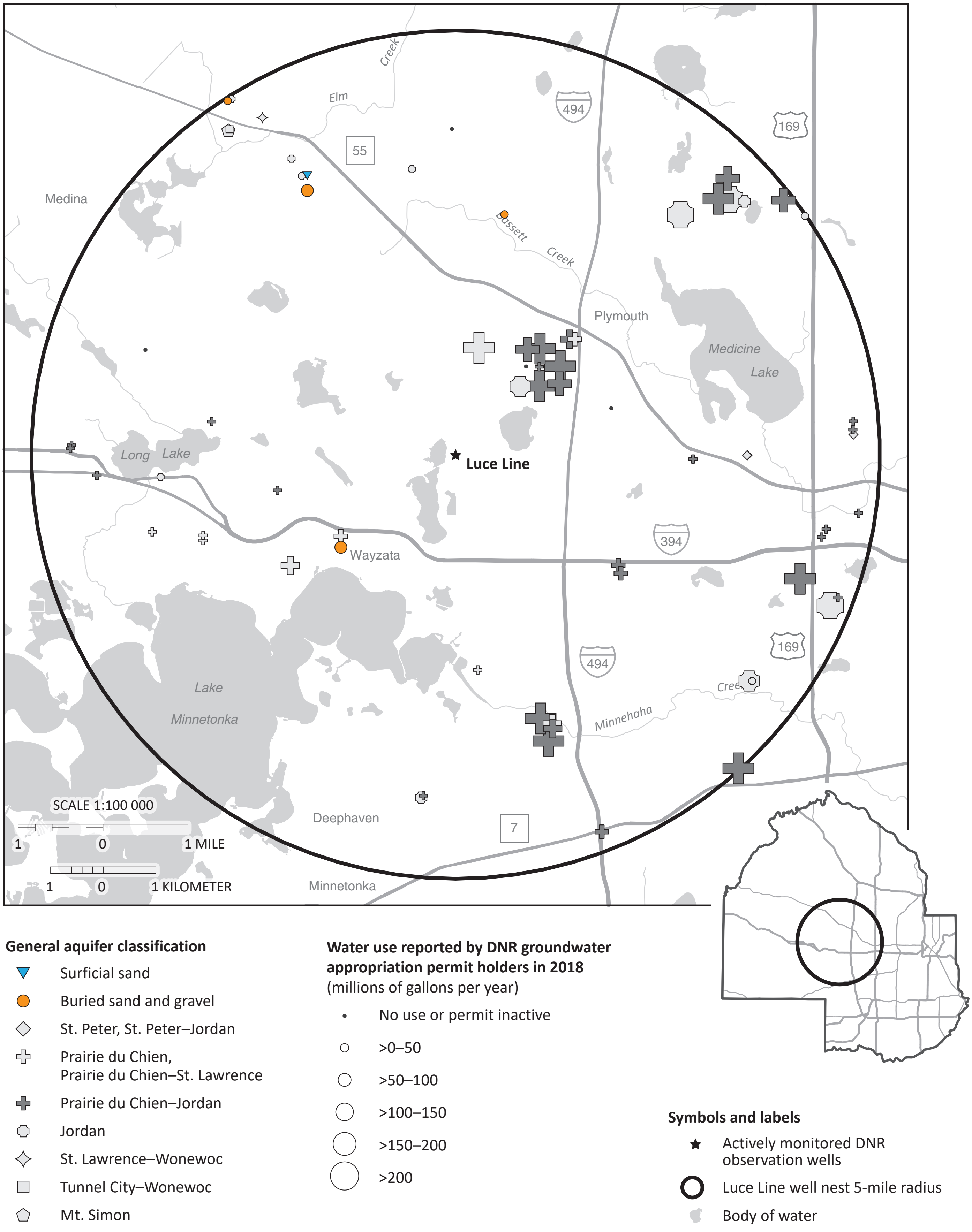


Figure 24. Groundwater use shown by aquifer within a 5-mile radius of the Luce Line well nest

The dominant groundwater use is from the combined Prairie du Chien–Jordan aquifers and the Jordan aquifer.

Water chemistry (Plate 7)

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

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

Water sampling

To better understand groundwater movement and pollution sensitivity in the county, samples were collected from wells in aquifers most important for domestic water supply. Wells were selected based on their aquifer characteristics and distribution and were collected according to the protocols outlined in Appendix A. Chemical data from well-water samples were used along with physical measurements (static water level and aquifer tests) to understand water movement.

An ideal well-sampling network for the atlas would be distributed evenly across the county, includes populated areas, and targets surface water and groundwater interaction around lakes and larger rivers. The final network sampled depends on citizen willingness to participate. Approximately 1000 well owners were contacted for permission to sample; approximately 90 were selected according to county atlas protocol. Water chemistry data for Hennepin County included wells sampled for this atlas by the DNR along with historical water samples that were incorporated into the interpretations of this report. Groundwater samples from 606 wells and 3 springs were collected by the following agencies:

- DNR: 91 samples collected in 2010 and during the summer of 2019
- Minnesota Department of Health (MDH): 370 samples collected from 1988 to 2018
- Minnesota Geological Survey and the University of Minnesota: 50 samples collected from 1990 to 2006
- Minnesota Pollution Control Agency (MPCA): 47 samples collected from 1996 to 2008
- U.S. Geological Survey: 51 samples collected from 1979 to 2013

Additionally, 10 surface-water samples (2 MDH and 8 DNR) were included with dates from 2010 to 2019.

Groundwater recharge

Chemical changes occur as water moves from precipitation to groundwater. These can help determine whether groundwater was recharged through the land surface, through lakes and open-water wetlands, or a mixture of the two. Stable isotopes of oxygen and hydrogen were used for determining groundwater and surface-water interactions.

Oxygen and hydrogen each have two main stable isotopes: ^{18}O and ^{16}O, and ^{2}H and ^{1}H. The different masses cause each to evaporate at a different rate, which results in *fractionation*, leaving behind different ratios of heavy to light isotopes. This results in isotopic signatures unique to groundwater with different recharge sources (Kendall and Doctor, 2003).

- Groundwater recharged directly from **precipitation** has a **meteoric** isotopic signature. The water infiltrated directly into the ground, leaving the isotopic ratio unchanged.
- Groundwater recharged from **surface water**, such as lakes or open-water wetlands, has an **evaporative** isotopic signature. This water has been subjected to fractionation where light isotopes evaporated into the atmosphere, leaving water enriched in heavier isotopes.

To identify the source (precipitation or surface water) 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 was Vienna Standard Mean Ocean Water (VSMOW).

Definition of delta (δ)

The stable isotope composition of oxygen and hydrogen are reported as δ values:

$\delta\ (^0/_{00}) = (R_x/R_s-1)*1000$, where R represents the ratio of the heavy to light isotope $^{18}O/^{16}O$ or $^2H/^1H$. R_x represents the ratio of the sample, and R_s represents the ratio in VSMOW. Delta values are reported in units of parts per thousand ($^0/_{00}$ or permil) relative to VSMOW.

County results were compared to the global meteoric water line, which was developed from precipitation data from around the world (Craig, 1961).

Meteoric signatures were found in the majority of the groundwater samples, plotting along the meteoric water line in the center and left portions of the stable isotope graph (Figure 25). This suggests these samples were sourced from precipitation (rain and snow melt) that infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies.

Evaporative signatures were found in 29 groundwater samples (Figures 25 and 26). These samples were further classified into low and high groups based on the position of the data points along the evaporation line. Samples that plotted to the right contain higher proportions of fractionated isotopes. High and low evaporative signatures probably relate to residence time in a lake. Larger lakes with longer residence time generally lead to more isotope fractionation. Many of the high evaporative signature samples are from the southern and eastern downgradient side of Lake Minnetonka. This association indicates that the lake is a significant recharge source for underlying and adjoining aquifers, which include the s2, s3, and Prairie du Chien.

Other high evaporative signatures were found downgradient from Diamond Lake in the north (city of Dayton), near Lake Schwappauff in the northwest (f1 aquifer, the Greenfield area), and near Lake Independence in the west (h2 and Jordan aquifers). A St. Peter aquifer sample near the center of the county (the eastern boundary of Orono) is in a complicated groundwater flow area surrounded by many lakes. This high evaporative signature could be sourced from more than one lake in the area.

Some of the locations where source-water features for the low evaporative samples seem likely include: an s2 sample near Long Lake (city of Orono); f2 and h2 samples near Lake Sarah and Lake Independence, respectively (western part of county); and an eo sample downgradient of Sylvan Lake (northwest of Rogers). The data suggest these surface-water sources have at least some definable groundwater connections. Groundwater recharge from surface water in the area could be increasing as a result of high-volume pumping.

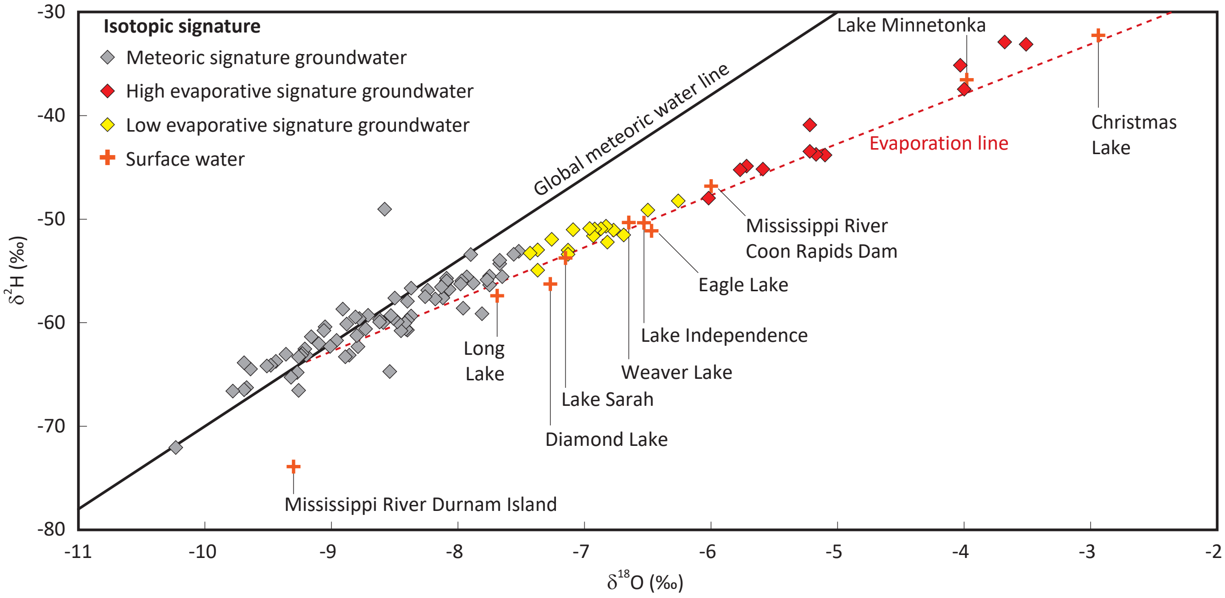


Figure 25. Stable isotope values from water samples

The meteoric water line represents precipitation values from rapid infiltration. The *global meteoric water line* was developed using precipitation samples from around the world and is described by the following equation: $\delta^2H = 8.0\ \delta^{18}O + 10.0$.

The evaporation line represents groundwater recharge that was partially from surface-water sources. The local evaporation water line is described by the following equation: $\delta^2H = 4.9\ \delta^{18}O - 20.4$.

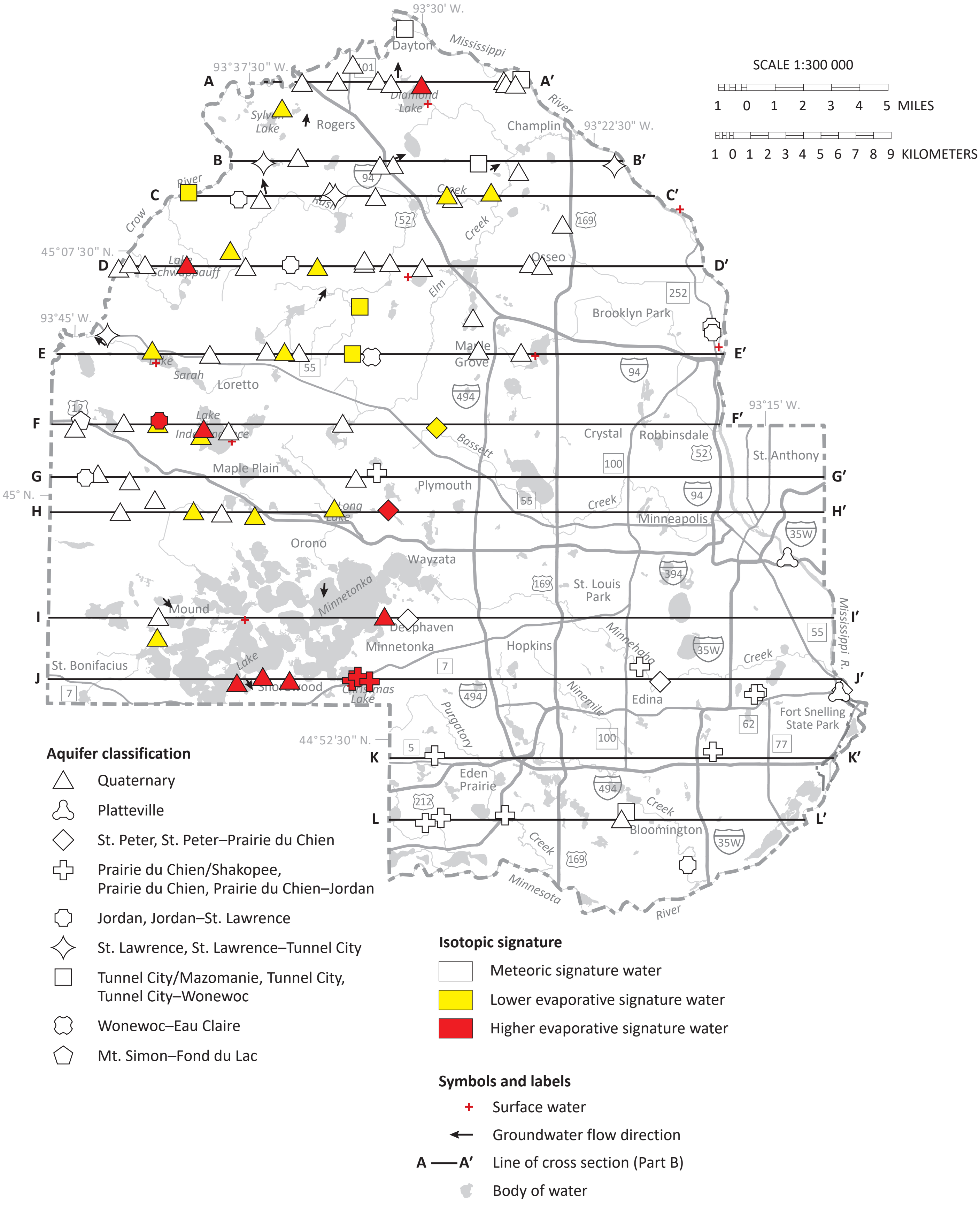


Figure 26. Stable isotope characteristics of groundwater samples

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

Groundwater residence time indicators

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

Tritium

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

The highest tritium concentrations in precipitation occurred between 1953 and 1983 (Michel and others, 2018). 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, GW-05* (DNR and MDH, 2020).

- **Modern**: water entered the ground since about 1953.
- **Mixed**: water is a mixture of modern and premodern.
- **Mostly premodern:** tritium not detected and the premodern threshold is below the detection limit. Because of analytical limitations, it is not possible to determine whether the actual tritium value is above or below the premodern cutoff. Samples categorized as mostly premodern are presumed to consist predominantly of premodern groundwater, with the possibility of a small amount of modern water.
- **Premodern**: water entered the ground before 1953.

In the **report text** *premodern* is used for both *mostly premodern* and *premodern* for hydrogeologic interpretation.

On the **figures and plates** both *mostly premodern* and *premodern* are shown for consistency with the dataset.

Atlases through C-39 used ***recent***, ***mixed***, and ***vintage*** tritium age from the Alexander and Alexander (1989) method.

Atlases from C-40 on use ***modern***, ***mixed***, and ***premodern*** tritium age from the Minnesota modified method from GW-05 (DNR and MDH, 2020).

The method to calculate tritium age was changed because there is no longer enough tritium in the atmosphere to use the Alexander and Alexander method. 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.

Carbon-14

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

Carbon-14 sample collection, analysis, and modeling is described in Alexander and Alexander, 2018. When precipitation infiltrates the unsaturated zone it adsorbs carbon dioxide, including carbon-14, from biogenic soil gases forming carbonic acid. This mildly acidic water dissolves calcite and dolomite present in the soil or bedrock. Plant communities present at the time of infiltration determine soil $\delta^{13}C$ ratios that are used within the model to estimate the groundwater residence time. Approximately half of the dissolved carbon in the groundwater comes from atmospheric carbon in the soil zone during infiltration and half comes from very old bedrock sources where carbon-14 has decayed completely.

A total of 10 carbon-14 samples were collected for this study and combined with 14 other existing samples for evaluation in this report. Carbon-14 residence times ranged from less than 100 years to greater than 40,000 years. See details in “Hydrogeologic cross sections.”

Inorganic chemistry of groundwater

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

Groundwater contamination can come from human (anthropogenic) pollution or from naturally occurring geologic contamination (dissolved from the resident material). Elevated levels can indicate short groundwater residence time, high sensitivity, or a potential health problem for drinking water. Anthropogenic sources can be identified by comparing concentrations to naturally occurring (background) levels.

Water quality evaluations describe contaminants that are potentially harmful (naturally occurring or anthropogenic) or that affect aesthetics. This atlas uses the following guidelines.

U.S. Environmental Protection Agency
(EPA, 2017 July; EPA, 2017 March)

- **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 may cause aesthetic effects or taste and odor problems in drinking water.

Minnesota Department of Health
(MDH, 2012a)

- **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 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.

Minnesota Department of Natural Resources
Groundwater Atlas Program

- **Anthropogenic**: caused by human activity.
- **Elevated**: values above the indicated levels in the chemical descriptions.
- **Naturally occurring (geologically sourced)**: waters contain natural dissolved minerals from the rock and soil. Most are harmless, but certain levels in drinking water can be harmful to health.

Some chemicals are harmful at elevated levels; some can be elevated by anthropogenic activities. Water quality guidelines and sample results are presented for inorganic chemistry and include the following:

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

The following chemicals are naturally occurring. Organic chemicals were not studied but can be found in reports from other state agencies (pesticides and their breakdown products, solvents, degreasers, and others).

Chemical descriptions and results

Chloride (Figure 27)

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

Chloride can occur naturally from deep sources such as residual brine, or it can come from an anthropogenic source such as road salt, water softener salt, or fertilizer (Davis and others, 1998; Panno and others, 2006). Chloride concentrations above 5 ppm with chloride/bromide mass ratios above 250 may indicate anthropogenic sources of chloride. The 250 break point was determined using a combination of chloride and nitrate concentrations and tritium and carbon-14 residence time estimates. In addition, elevated chloride samples with modern or mixed tritium age were classified as anthropogenic regardless of bromide analysis or chloride/bromide ratios.

Results

- Of the 363 wells and springs sampled and analyzed for chloride, 142 of those with elevated chloride had anthropogenic sources, and 12 samples exceeded the SMCL.
- Anthropogenic chloride in groundwater is relatively widespread in the county, especially in the east and south-central portions that have a distribution of sand, gravel, and sandy sediment (Figure 27a). It is prevalent in areas down-gradient from major highways where road salt application is used for winter time de-icing, including salt application (Andrews and others, 1997; Andrews and others, 2005; Stefan and others, 2008).

  The anthropogenic occurrences were found in all of the county but were more common in the east. Affected aquifers include surficial sand, shallow buried sand, and shallower bedrock aquifers such as the Prairie du Chien and Jordan aquifers.

- Most of the other elevated chloride samples may also be anthropogenic but were not also analyzed for bromide, therefore they are shown as unknown. The unknown group also includes 10 samples with elevated chloride/bromide ratios (greater than 250) but were also premodern. These apparent mismatched chemical indicators may be caused by a number of factors including: a tritium detection limit that isn't low enough or complex subsurface groundwater mixing conditions.
- Lower concentrations are more common in the north, west, and southwest because of the fine-grained material (till and lake clay) that helps protect the underlying aquifers. Lower concentrations also occur in less developed areas that have fewer paved roads and surfaces that require de-icing (Figure 27b).

Nitrate-nitrogen (nitrate) (Figure 28)

MCL and HRL 10 ppm, elevated ≥1ppm

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

Results

- Of the 375 well and spring samples analyzed for nitrate, 20 had elevated concentrations indicative of anthropogenic sources, and 2 were above the MCL (10 ppm) with concentrations of 12 and 18.2 ppm. The relative lack of high concentrations may be a function of land use and soil texture distribution.
- Elevated occurrences were found mostly in residential areas in the surficial, upper buried sand, and shallow bedrock aquifers. Higher pollution sensitivity was found in the east where the land use is predominantly urban and not heavily fertilized for agriculture, but where the soil is coarse.
- Lower pollution sensitivity was found in the more intensively fertilized row crop areas, but where there is finer-grained soil: the five western and northwestern townships (Dayton, Rogers, Greenfield, Corcoran, and Independence). The highest nitrate pollution potential is in the lower pollution sensitivity portions of the county. See Figure 1 and Plate 7 for township locations.

Arsenic (Figure 29)

MCL 10 ppb, MCLG 0

Arsenic is a naturally occurring element that has been linked to negative health effects, including cancer. If arsenic is present the Minnesota Department of Health advises domestic well owners to treat drinking water (MDH, 2018a). Current science cannot predict which wells will have high arsenic concentrations, therefore all newly constructed drinking-water wells are analyzed for arsenic per Minnesota Administrative Rules 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).

Nicholas and others (2017) found that changes in redox conditions are largely responsible for releasing solid phase arsenic into groundwater via one of three mechanisms: desorption, reductive dissolution, or oxidative dissolution, and that the aquitard-aquifer interface is very geochemically active. Erickson and others (2019) found that both reductive and oxidative arsenic mobilization mechanism are active in Minnesota drinking water aquifers.

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

Results

- Of the 257 well and spring samples analyzed for arsenic, 197 exceeded the method detection limits and 24 exceeded the MCL (10 ppb).
- Those at or above the MCL were in the western part of the county where Des Moines lobe glacial till at the surface is most common. Most of the elevated concentration samples (18 of 24) were from buried sand aquifers.

Manganese (Plate 7)

HBV 100 ppb, SMCL 50 ppb

Manganese is a naturally occurring element beneficial to humans at low levels, but at high levels it can harm the nervous system (MDH, 2018b). In addition to health effects, elevated 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 percent of water-table aquifers and 63 percent of buried sand aquifers sampled (MDH, 2012b). 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).

Results

- Of the 317 well and spring samples analyzed for manganese, 149 were greater than or equal to the HBV (100 ppb).
- The elevated values ranged from 102 to 2,220 ppb and were found throughout the county. Elevated levels were found in most of the mapped buried sand aquifers and all of the bedrock aquifers.

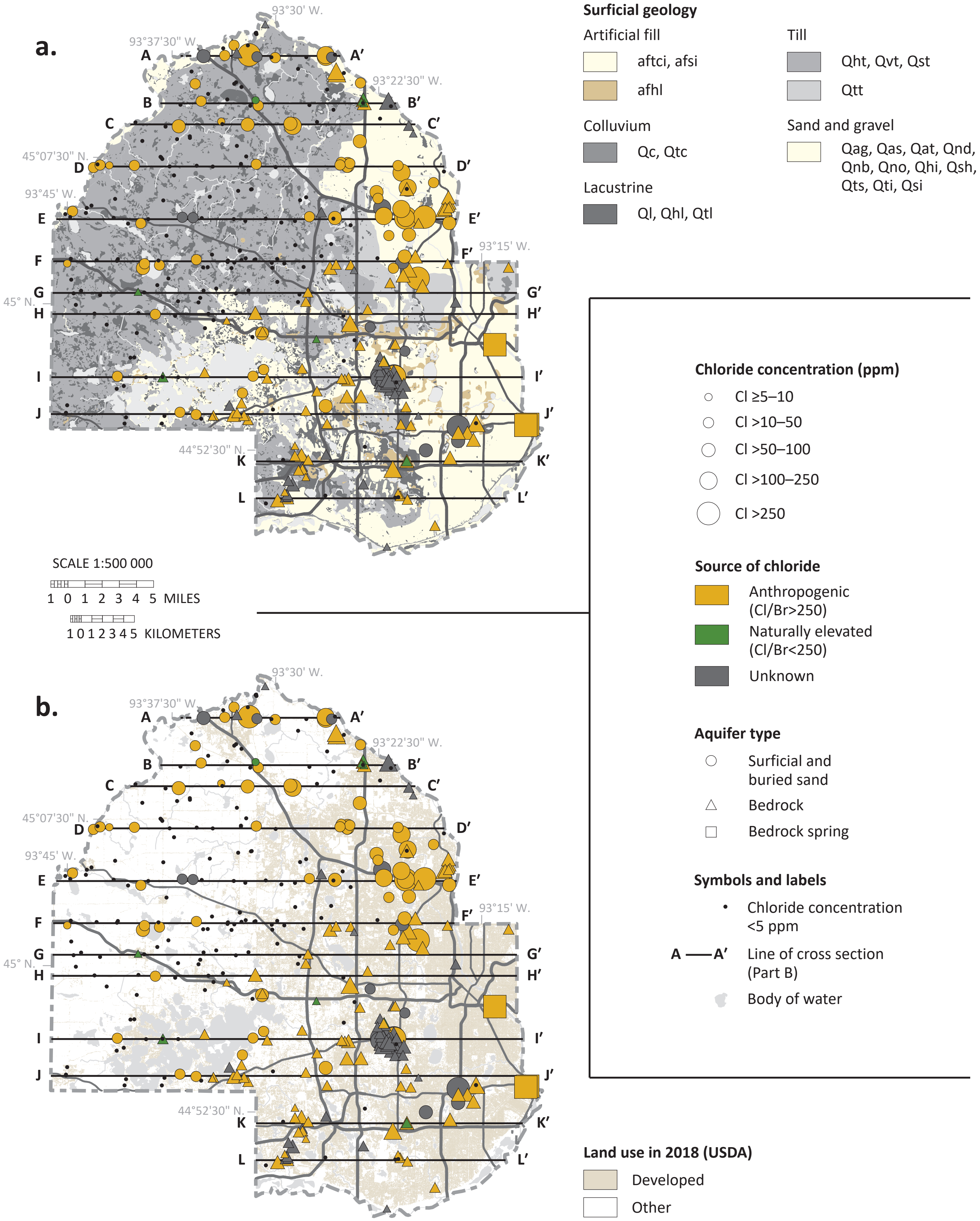


Figure 27. Elevated chloride concentrations from groundwater samples

a. Anthropogenic chloride in groundwater is relatively widespread.

b. Of the 363 groundwater samples analyzed for chloride, 142 with elevated chloride had anthropogenic sources, and 12 samples exceeded the SMCL.

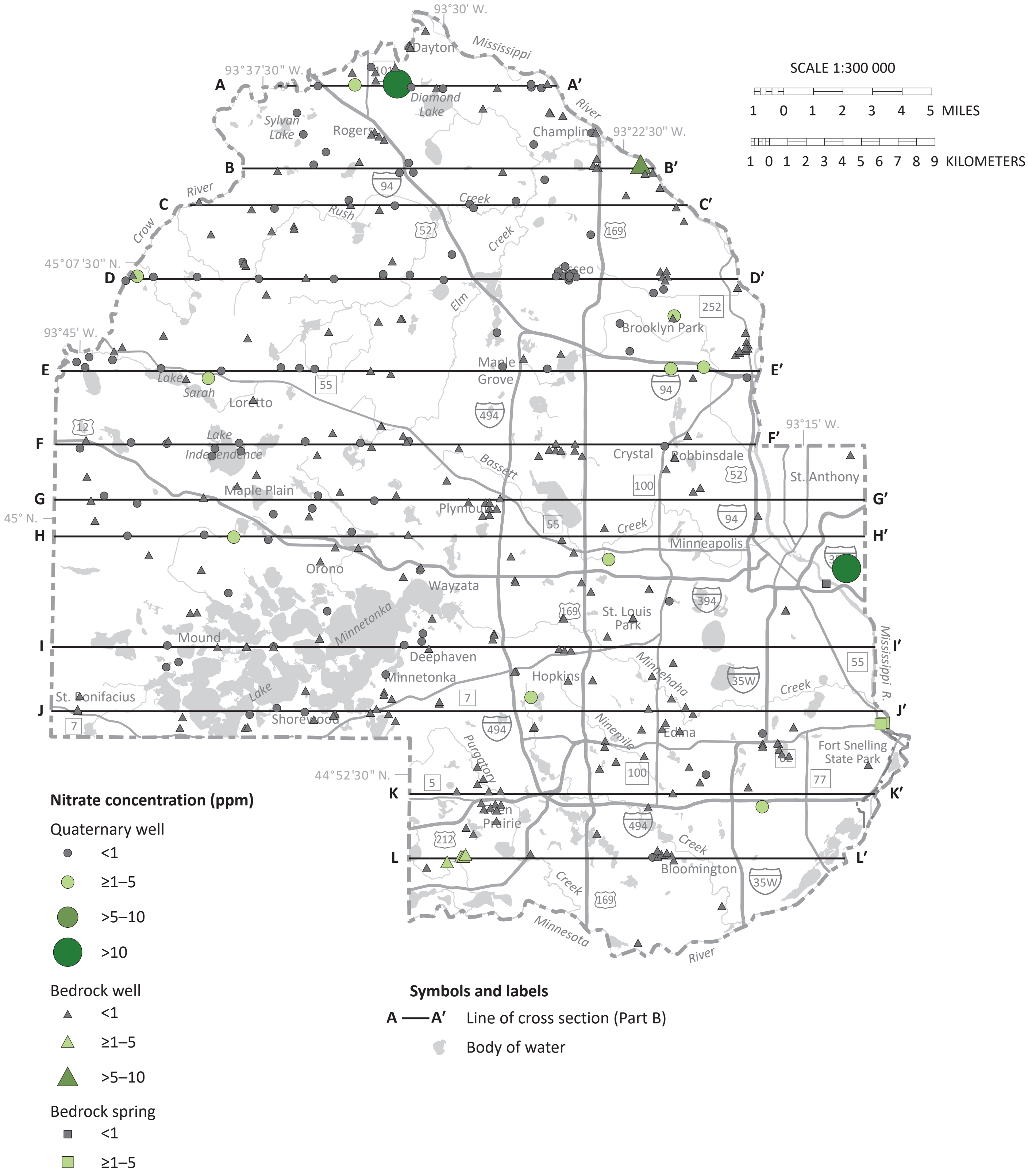


Figure 28. Elevated nitrate concentrations from groundwater samples

The elevated occurrences of nitrate were mostly in residential parts of the county in the surficial, upper buried sand, and shallow bedrock aquifers. Of the 375 groundwater samples analyzed for nitrate, 2 exceeded the MCL (10 ppm).

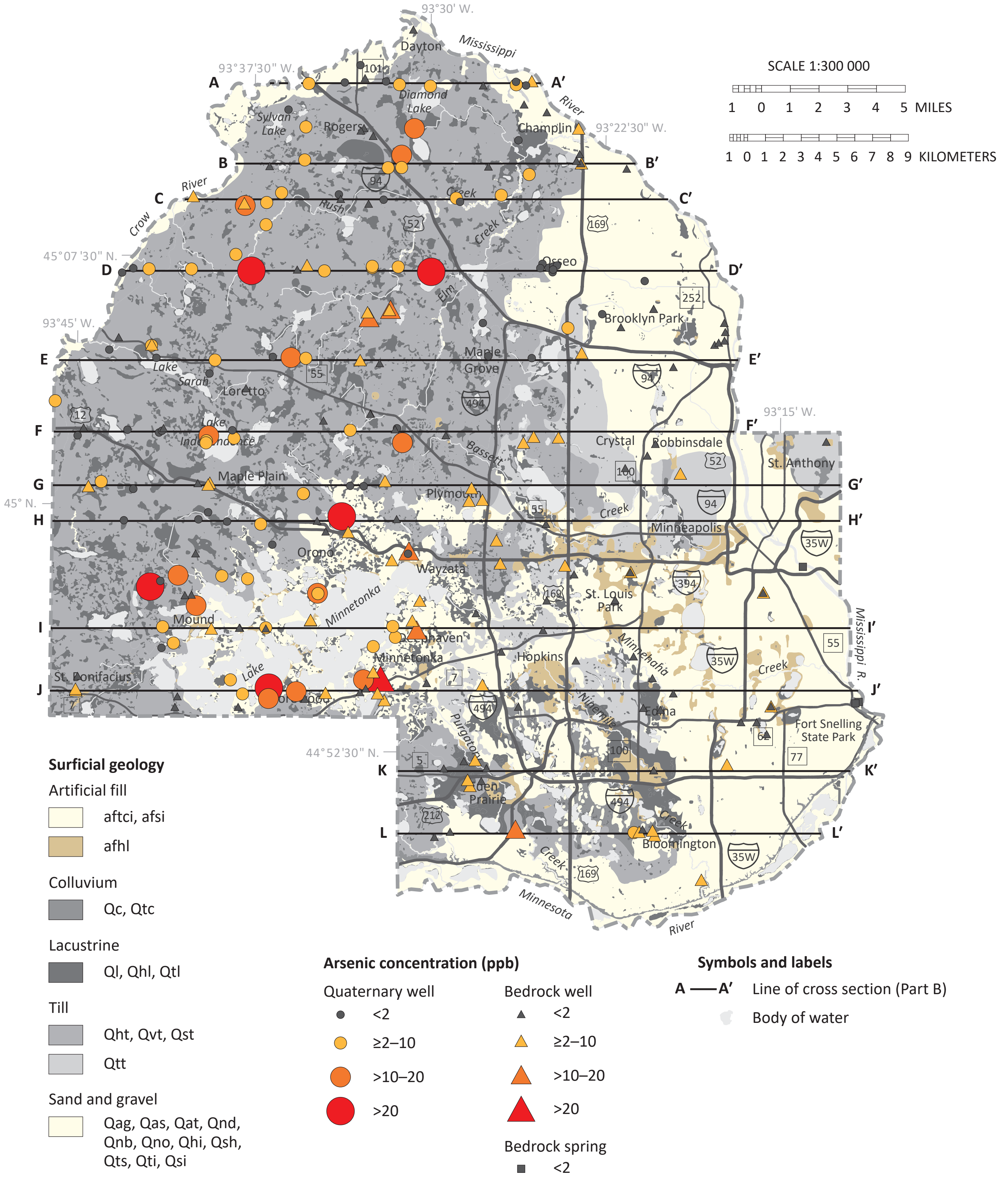


Figure 29. Elevated arsenic concentrations from groundwater samples

Of the 257 samples analyzed for arsenic, 197 exceeded the method detection limits and 24 exceeded the MCL (10 ppb). Groundwater sample concentrations at or above the MCL were in the western part of the county where Des Moines lobe glacial till is most common at the surface.

Major cations and anions and the Piper diagram

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

Sodium is often present in deep aquifers or at mineral interfaces. As groundwater moves through aquifer systems, calcium and magnesium ions are exchanged for sodium ions (Hounslow, 1995). Potassium is naturally released from the weathering of silicate minerals (Hem, 1985). In agricultural areas, fertilization, provides an additional source of potassium.

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

The Piper diagram (Figure 30a) graphically represents each water sample for the most common ionic constituents in natural waters: calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and nitrate.

The Piper diagram can reveal information about the following:

- The source of dissolved chemicals as water travels through the aquifers and aquitards
- Water chemistry changes along the groundwater flow path because of ion exchange, precipitation, solution, and mixing of different water types
- Distribution of water types

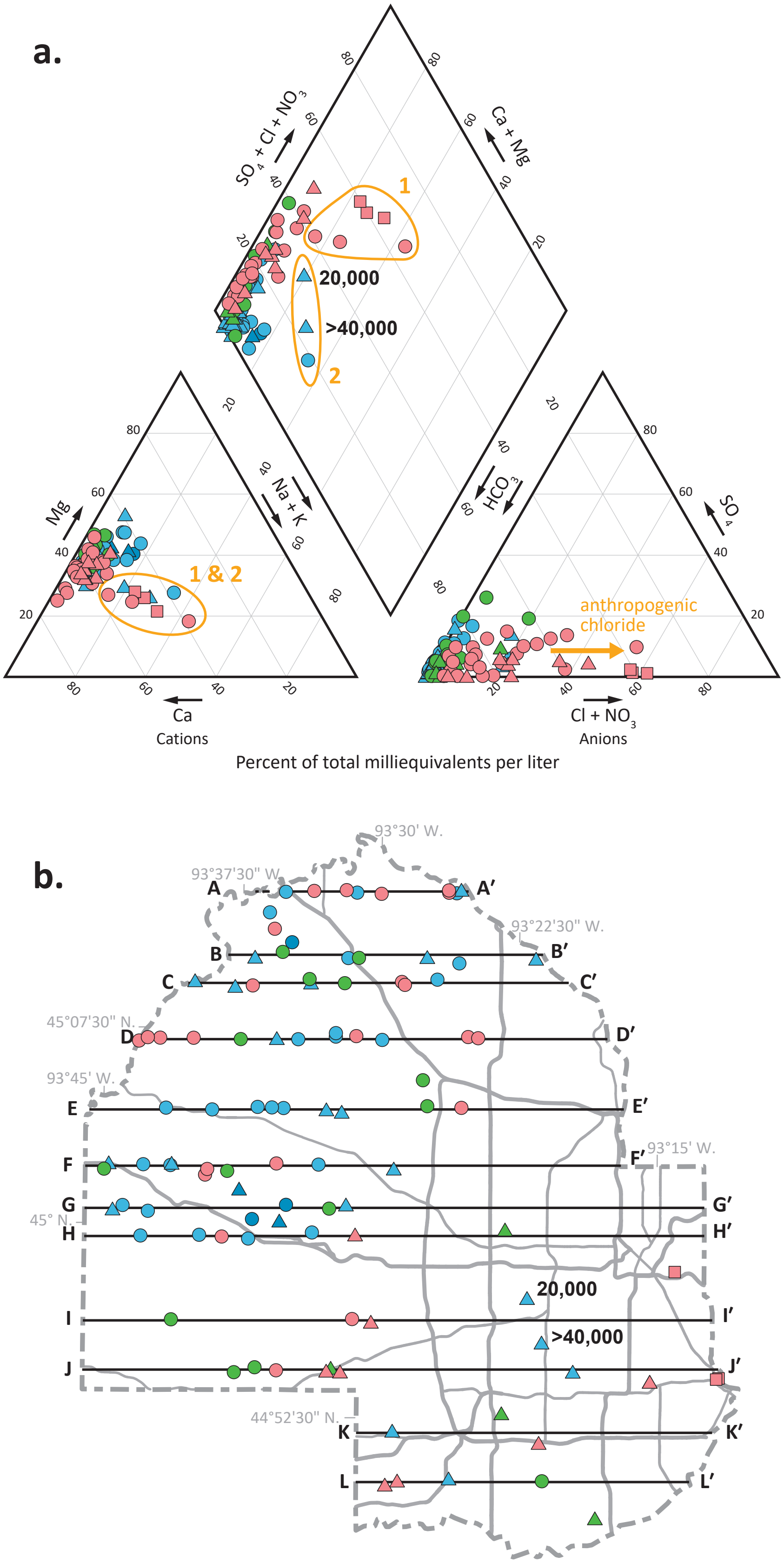
The Piper diagram has three components: a cation triangle, an anion triangle, and a central diamond. Each sample collected by the DNR, MGS, and MPCA is represented by one data point on each. The sample points on each triangle (ternary diagram) reflect the relative percentages of the major cations (lower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

Results

The general type of water that is prevalent in the county is calcium+magnesium bicarbonate (Figure 30a). However, many of the samples shown on the anion triangle are also shifted toward the chloride+nitrate corner. These shifted samples are also predominately modern tritium age. This association suggests that most of the additional chloride and nitrate in these samples is anthropogenic. The modern tritium-age samples, many with anthropogenic chloride, are found throughout the county in the unconsolidated and bedrock aquifers (Figure 30b).

The cation triangle shows a sample cluster (groups 1 and 2) of modern and premodern tritium age that are shifted toward the sodium+potassium corner of the diagram indicating higher proportions of sodium. The modern samples in this cluster are further differentiated on the central diamond grid as an anthropogenic group 1 with higher proportions of chloride+nitrate. The three premodern samples (group 2) are very old water (Mt. Simon and h2 aquifers) that appear to have acquired higher proportions of sodium, not from anthropogenic sources but through cation exchange over long time periods.

The carbon-14 residence time values of the 2 Mt. Simon samples in group 2 range from 20,000 to greater than 40,000 years (Figures 30a and 30b).



Chemistry

Calcium (Ca^{2+})
Magnesium (Mg^{2+})
Sodium (Na^{+})
Potassium (K^{+})
Bicarbonate (HCO_3^{-})
Sulfate (SO_4^{2-})
Chloride (Cl^{-})
Nitrate (NO_3^{-})

Aquifer type

○ Surficial and buried sand
△ Bedrock
☐ Bedrock spring

Tritium age

Symbol color indicates tritium age of water sample.

🟥 Modern
🟩 Mixed
🟦 Mostly premodern
🟦 Premodern

Symbols and labels

20,000	Carbon-14 (^{14}C): estimated groundwater residence time in years shown on select wells
A——A′	Line of cross section (Part B)

Figure 30. Piper diagram of groundwater samples and tritium age

a. The cation triangle (lower left) shows that groundwater with a mixture of calcium and magnesium is common in the county with calcium as the dominant ion. This type of water was from the buried sand and bedrock aquifers.

The anion triangle (lower right) shows several samples from buried sand and bedrock aquifers that trend toward the chloride and nitrate corner of the triangle because of infiltration and recharge from modern tritium-age water with anthropogenic sources of chloride and nitrate.

b. Modern tritium-age samples, many with anthopogenic chloride, are found throughout the county in the unconsolidated and bedrock aquifers.

Pollution sensitivity

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

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

River valleys can be important groundwater discharge areas (see "Hydrogeologic cross sections") where groundwater movement is characteristically upward and the actual pollution sensitivity may be less than rated.

Two models were used to estimate the pollution sensitivity, based on the different properties of the aquifer materials or the thickness of the geologic layers. The central concept for both models is the relative rate of water movement. This is described as *infiltration* in the unsaturated zone, and *recharge* in the saturated zone.

The following assumptions were applied in the two models:

- **Near-surface materials** (unsaturated flow to a depth of 10 feet, the assumed depth of the water table): sediment texture is the primary property used to create a sensitivity map. The permeability of the sediment matrix texture is estimated based on hydrologic theory and empirical data to establish a downward flow rate. The vertical travel time is then estimated using the downward flow rate multiplied by the vertical travel distance.
- **Buried aquifers**: sediment above and between buried sand aquifers is fine grained with low hydraulic conductivity. The method only considers the cumulative thickness of fine-grained sediment overlying aquifers. It does not consider differences in sediment texture or permeability of aquitard materials.

The model results are evaluated by comparing the pollution sensitivity ratings to tritium and carbon-14 for residence time and to other chemistry for anthropogenic sources.

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

Near-surface materials

Methods

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

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

The time of travel through near-surface sediment varies from hours to approximately a year (Figure 31).

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

Further details are available in *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

Table 1. Transmission rates through unsaturated materials

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

Hydrologic Soil Group (0–3 feet)		Surficial Geologic Texture (3–10 feet)		
Group*	**Transmission rate (in/hr)**	**Classification**	**Transmission rate (in/hr)**	**Surficial geology map unit (Part A, Plate 3)**
A, A/D	1.0	gravel, sandy gravel, silty gravel	1.0	Qag, Qno, Qsi, Qts
		sand, silty sand	0.71	Qat, Qnd
B, B/D	0.50	silt, loamy sand	0.50	Qas, Qhi, Qnb, Qti
		sandy loam, peat	0.28	Qc, Qtc, Qtt
C, C/D	0.075	silt loam, loam	0.075	Qhl, Qsh, Qht, Qvt, Qtl, Qst
		sandy clay loam	0.035	Not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Ql
–	–	glacial lake sediment of Lake Agassiz	0.000011	Not present in the county

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

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

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

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

Group C: water transmission is somewhat restricted.

Group D: water movement is restricted or very restricted.

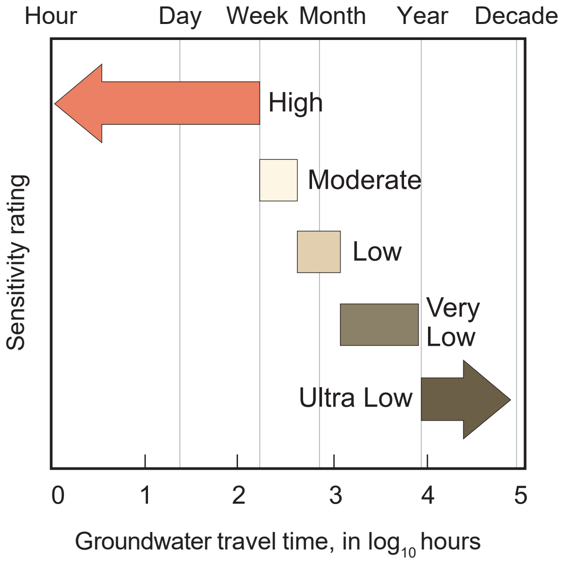


Figure 31. Pollution sensitivity rating of near-surface materials: travel time and ratings

Results

The broad patterns of pollution sensitivity include moderate and high conditions in the eastern third of the county and along river terraces in the northern and southern boundaries (Figure 32). The high sensitivity areas mostly match the areas of sand and gravel shown on Figure 2.

A complex distribution of very low and low sensitivity dominates the western two-thirds portion where fine-grained till and lake sediment are at the surface.

Possible karst conditions exist in the east because of relatively shallow depths of the Platteville Formation and St. Peter Sandstone. Karst may allow direct and very rapid exchange between surface water and groundwater, significantly increasing the risk of groundwater contamination from surface pollutants.

Karst is defined as "terrain with distinctive landforms and hydrology created primarily from the dissolution of soluble rocks" (DNR, 2016c). For mapping purposes possible karst areas are defined as karst-prone bedrock (carbonate formations of the St. Peter and Hinckley sandstones) within 50 feet of the land surface.

The pollution sensitivity shown in Figure 32 is compared with 20 groundwater samples that were collected from shallow wells with casing depths no greater than 30 feet, and 3 springs within the karst areas. All of these samples are in or near the high sensitivity or karst areas.

- The 16 samples that were analyzed for tritium were all modern tritium age.
- The 21 samples analyzed for chloride all had values that were elevated (12 to 1,400 ppm) and anthropogenic, or unknown.
- Of the 12 samples analyzed for nitrate, 9 had elevated values (1.75 to 12 ppm).

All of these chemistry results are consistent with this sensitivity evaluation.

Karst features and locations can be downloaded as a GIS layer from the *Karst Feature Inventory Points* through the Geospatial Commons (University of Minnesota, 2018). Springs can be found in the *Minnesota Spring Inventory*, as an online interactive map or GIS layer (DNR, 2019a).

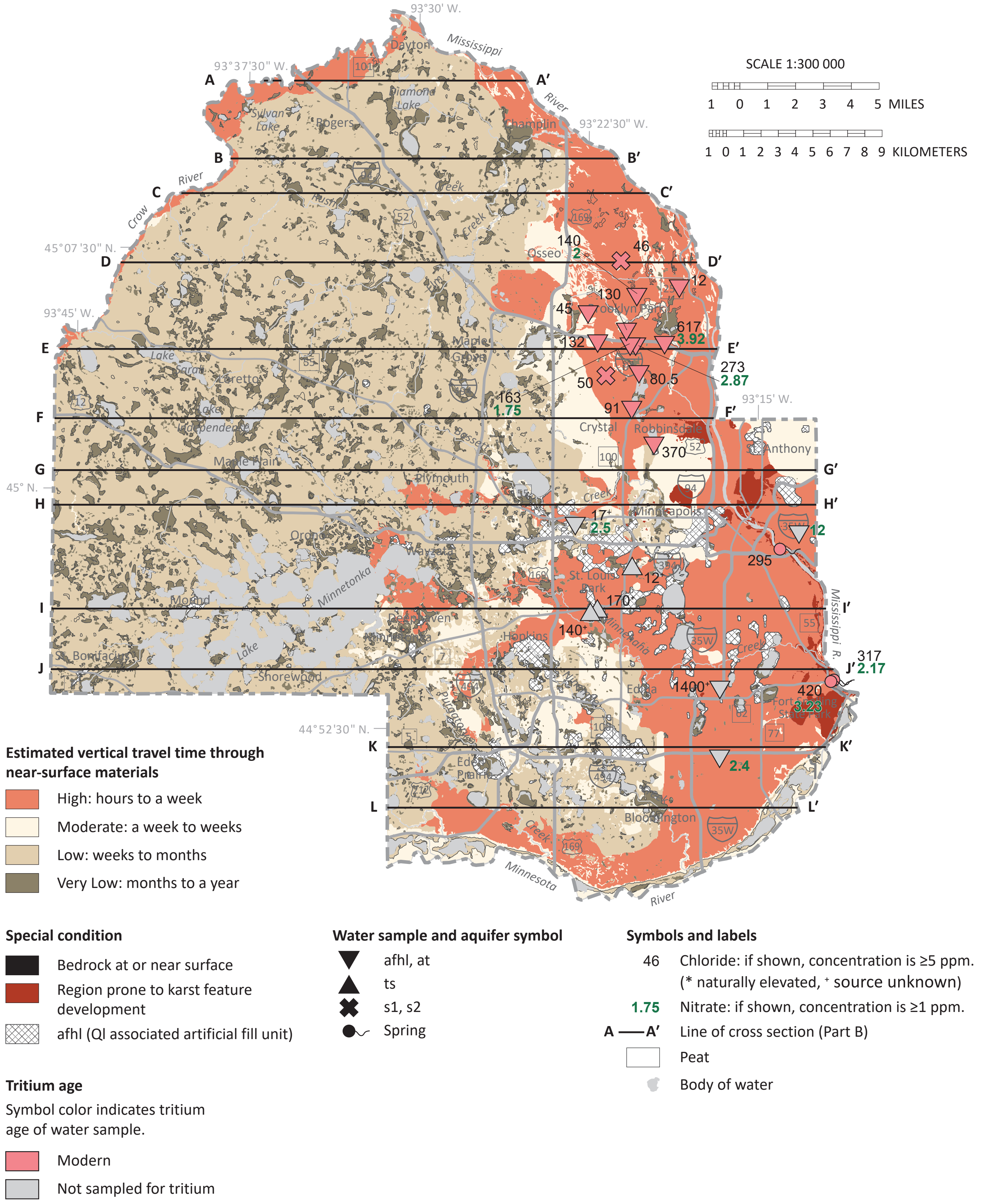


Figure 32. Pollution sensitivity of near-surface materials

The broad patterns of pollution sensitivity include moderate and high conditions in the eastern third of the county and along the northern and southern boundaries where coarse-textured terrace deposits are common. A complex distribution of very low and low sensitivity dominates the western two-thirds portion, with the exception of the northern and southern boundaries.

Buried sand aquifers and bedrock surface

Methods

The sensitivity rating for the buried sand aquifers and the bedrock surface is based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with ratings of high or very high have relatively short travel times of less than a few years. Areas rated very low or low have estimated travel times of decades or longer (Figure 33).

The DNR developed a pollution sensitivity model that represents how precipitation infiltrates the land surface and recharges portions of deeper aquifers. The central concept is that focused (relatively rapid) recharge occurs where aquifers overlap and are connected by complex pathways. The model assumes that the thickness of fine-grained sediment overlying an aquifer is inversely proportional to the sensitivity of an aquifer. The thicker the fine-grained sediment, the longer it takes for water to move through it (Figure 34).

Geographic Information System (GIS) software is used to calculate cumulative thickness of the fine-grained sediment layers in the county. Thicknesses of 10 feet or less are rated very high sensitivity, thicknesses greater than 40 feet are rated very low, and thicknesses between 10 and 40 are given intermediate ratings. More details are available in *Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment thickness* (DNR, 2016d).

The model results were combined with groundwater flow directions (derived from potentiometric surfaces) to help understand the distribution of particular chemical constituents. The pollution sensitivity values and spatial distributions were compared to the tritium age of groundwater.

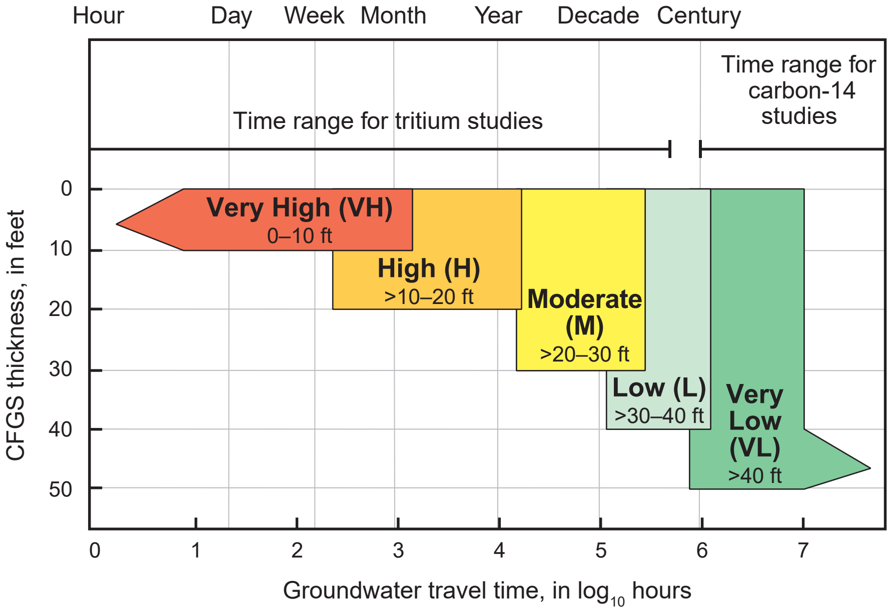


Figure 33. Pollution sensitivity rating for the buried sand aquifers and the bedrock surface
Sensitivity is defined by estimated vertical travel time. The numbers following each rating represent the *cumulative fine-grained sediment (CFGS) thickness* overlying an aquifer.

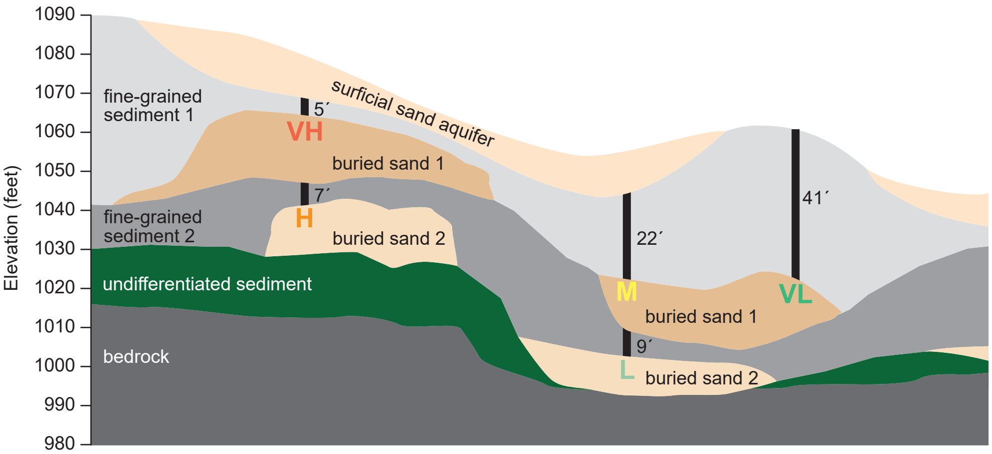


Figure 34. Cross section depicting examples of pollution sensitivity ratings
Sensitivity ratings are based on the cumulative thickness of overlying fine-grained sediment. Each vertical black line is labeled with the thickness of fine-grained sediment. The letter at the base of the line indicates the sensitivity rating.

Groundwater conditions

Groundwater recharge, presumed flow paths, and discharge can be evaluated using the combination of the concentrations of tritium-age water samples, equipotential contours, water chemistry, and relative hydraulic conductivity. The following conditions provide a way of linking pollution sensitivity with residence time and anthropogenic indicators (tritium, anthropogenic chloride and nitrate).

① Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.

② Groundwater moves from an overlying surficial aquifer to a buried aquifer.

③ Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.

Ⓛ Groundwater flows laterally.

Ⓟ Tritium concentrations are likely artificially elevated by high-volume pumping.

Ⓤ Groundwater flowpath is unknown.

Ⓓ Groundwater discharges to a surface-water body.

In general, conditions 1, 2, 3, and the associated tritium-age water (modern and mixed) match the type of vertical groundwater flow and focused recharge that is assumed in the pollution sensitivity model. These conditions provide some validation of the model in areas of moderate to very high sensitivity (Figure 35).

Limitations of the model are represented by conditions L (lateral) and U (unknown). Condition L indicates that modern or mixed tritium-age water flowed laterally from upgradient sources. Condition U indicates the model can't explain the origin of modern or mixed tritium-age water in deep, isolated, or protected settings.

Evaporative signatures, if present, are noted in the following pollution sensitivity evaluations. These signatures may or may not relate directly to pollution sensitivity since they are not residence-time indicators but indicate recharge source.

The conditions are displayed on the pollution sensitivity figures, chemistry plate, and cross section plate. Conditions vary across the state and may not be present in every county.

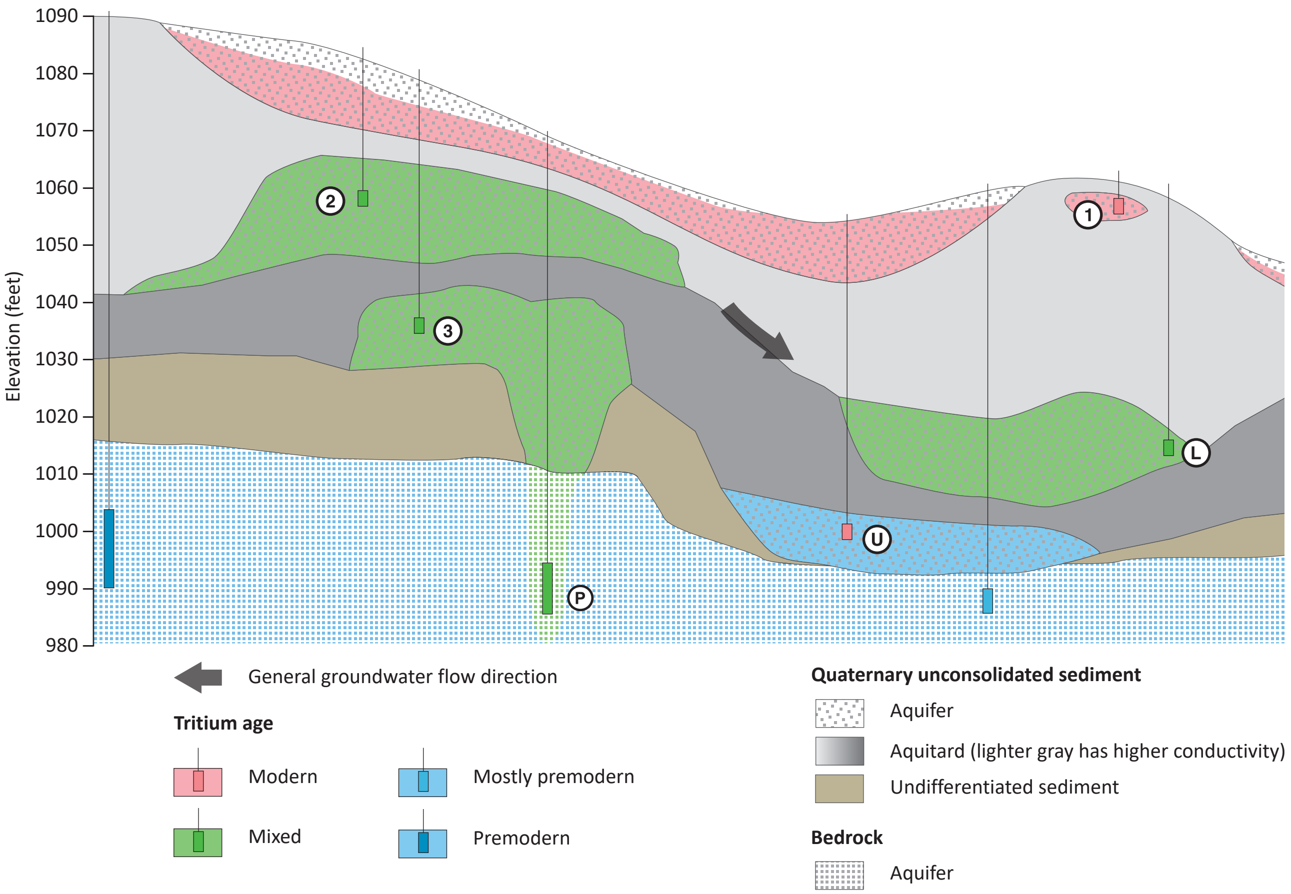


Figure 35. Hypothetical cross section illustrating groundwater conditions

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

Results

This section describes the results from the buried aquifers in descending stratigraphic order (Figure 5) and includes the depth, thickness, spatial distribution, and pollution sensitivity. The model results include groundwater flow direction derived from potentiometric surfaces to aid in understanding the groundwater conditions and the distribution of particular chemical constituents.

The model information is compared with the tritium age of groundwater and the presence or absence of other anthropogenic chemical indicators (nitrate and chloride). Higher sensitivity is associated with the following results.

- Tritium age is modern or mixed.
- Nitrate is elevated and anthropogenic if concentrations are greater than or equal to 1 ppm.
- Chloride is elevated if concentrations are greater than or equal to 5 ppm. It is anthropogenic if chloride/bromide ratios are greater than 250.

The tritium dataset was a combination of sampling efforts by the DNR, MDH, MGS, MPCA, the University of Minnesota, and the U.S. Geological Survey. Descriptions of groundwater chemistry and pollution sensitivity were qualitatively compared to the results of the pollution sensitivity modeling. Tritium detections in groundwater samples from aquifers in areas mapped as very low sensitivity should rarely occur, assuming that flow of modern tritium-age water to the aquifer is vertical and not altered by nearby pumping or well integrity issues (Figure 35).

vs aquifer (Figure 36)

The vs aquifer is found in western portion of the county. Depths range from less than 10 to approximately 80 feet. Less than 1 percent of wells in the county are completed in this aquifer.

- Pollution sensitivity ranges from very low to very high.
- No samples were collected from this aquifer.

ts and ts2 aquifers (Figure 37)

The ts and ts2 aquifers are found mostly in the eastern portion of the county. Depths range from less than 10 to approximately 100 feet. Approximately 2 percent of wells are completed in these aquifers.

- Pollution sensitivity ranges from very low to very high.

  Of the 9 samples collected from the ts aquifer, two were analyzed for tritium and both were modern tritium age.

  One sample from the ts2 aquifer was collected in Dayton. This sample had a mixed tritium age and was not analyzed for any other constituents. The sample was collected near low to moderately sensitive areas, which may be the source of the tritium.
- Two samples were analyzed for nitrate; neither was elevated.
- Of the 6 samples analyzed for chloride, all were elevated (12 to 303 ppm). All of these samples were on or near areas of high to very high sensitivity.

ti, ts1, and ms aquifers (Figure 38)

The ti and ts1 aquifers are found mostly in the southeastern portion of the county. The ms aquifer is of limited extent and is found in the west. Depths range from less than 10 to approximately 80 feet. Less than 1 percent of wells are completed in these aquifers.

- Pollution sensitivity ranges from very low to very high but is mostly very high in the southeast.
- No samples were collected from these aquifers.

si and s1 aquifers (Figure 39)

The si and s1 aquifers are found mostly in the eastern portion of the county. Depths range from less than 10 to approximately 80 feet. Approximately 2 percent of wells are completed in these aquifers.

- Pollution sensitivity ranges from very low to very high but is mostly very high in the eastern areas.

  Of the 13 total samples collected from both aquifers, 10 were analyzed for tritium with the following results: 6 modern, 3 mixed, and 1 premodern tritium age.

  Of the 9 modern and mixed tritium-age samples, 4 were in very high sensitivity areas. The remainder were in very low sensitivity areas or downgradient from higher sensitivity areas, which could have been the source of the detected tritium from lateral movement of groundwater.

  A high evaporative signature was detected downgradient of Diamond Lake in the north (Dayton).
- Of the 9 samples analyzed for nitrate, 1 was elevated.
- Of the 9 samples analyzed for chloride, 8 were elevated and 6 of those were anthropogenic.

s2 aquifer (Figure 40)

The s2 aquifer is extensive and mapped in most portions of the county. Depths range from less than 10 to approximately 200 feet. Approximately 14 percent of wells in the county are completed in this aquifer.

- Pollution sensitivity ranges from very low to very high with most of the very high areas in the east.

  Of the 71 total samples collected, 51 were analyzed for tritium with the following results: 19 modern, 18 mixed, and 14 premodern tritium age.

Of the 37 modern and mixed tritium-age samples, 9 were in low to very high sensitivity areas.
Of the 28 samples in very low sensitivity areas, 22 were near or downgradient from higher sensitivity areas which could have been the source of the detected tritium because of lateral groundwater flow.

High evaporative signatures were found at 3 locations downgradient from Lake Minnetonka (Plate 7) in Shorewood and Deephaven. The recharge conditions of 6 modern and mixed tritium-age samples are unknown.

Of the 14 premodern samples, most were in very low sensitivity areas. The one exception was in the north along the Crow River in a high sensitivity area. The Crow River valley is a groundwater discharge area. The premodern sample at that location is probably caused by upwelling older water from deeper aquifers. One premodern sample in the western part of the county had a carbon-14 residence time of 400 years.

- Of the 31 samples analyzed for nitrate, 1 was elevated.
- Of the 32 samples analyzed for chloride, 24 were elevated and 18 of those were anthropogenic. The remainder of the elevated chloride sample sources were unknown with one possible natural occurrence.

s3 aquifer (Figure 41)

- The s3 aquifer is extensive and was found in most portions of the county. Depths range from less than 10 to approximately 260 feet. Approximately 14 percent of wells are completed in this aquifer.
- Pollution sensitivity ranges from very low to very high with most of the very high areas in the east.

  Of the 55 total samples collected, 42 were analyzed for tritium with the following results: 15 modern, 13 mixed, and 14 premodern tritium age.

  Of the 28 modern and mixed tritium-age samples, 6 were in moderate to high sensitivity areas.

  Of the 22 samples in very low sensitivity areas, 16 were near or downgradient from higher sensitivity areas which could have been the source of the detected tritium.

  The recharge conditions of 6 modern and mixed tritium-age samples were considered unknown.

  Of the 14 premodern samples, all were in very low sensitivity areas. Two samples from this aquifer in the western part of the county had carbon-14 residence times of less than 100 years and 1,600 years.
- Of the 28 samples analyzed for nitrate, only 1 was elevated.
- Of the 28 samples analyzed for chloride, 17 were elevated and 12 of those were anthropogenic; the remainder were unknown.

f1 aquifer (Figure 42)

- The f1 aquifer is limited to the west-central portion of the county. Depths range from approximately 50 to 230 feet. Approximately 2 percent of wells are completed in this aquifer.
- Pollution sensitivity is mostly very low.

  Of the 10 total samples collected, 9 were analyzed for tritium with the following results: 1 modern, 2 mixed, and 6 premodern tritium age.

  Of the 3 modern or mixed tritium-age samples the source of the detected tritium is unknown for 2, and the other is possibly from a lateral source. The laterally sourced sample, near Lake Schwappauff (northwestern part of the county in the Greenfield area) also had a high evaporative signature.

  Of the 6 premodern samples, all were in very low sensitivity areas. One of the premodern samples in the western part of the county had a carbon-14 residence time of 850 years.
- Of the 5 samples analyzed for nitrate, none were elevated.
- Of the 6 samples analyzed for chloride, 3 were elevated, 2 of those were anthropogenic and the other sample was unknown.

h2 aquifer (Figure 43)

- The h2 aquifer is mostly limited to the western and southeastern portions of the county. Depths range from approximately 80 to 300 feet. Approximately 3 percent of wells are completed in this aquifer.
- Pollution sensitivity is mostly very low with some smaller scattered areas of higher sensitivity in the south.

  Of the 18 total samples collected, 14 were analyzed for tritium with the following results: 3 modern, 3 mixed, and 8 premodern tritium age.

  Of the 6 modern and mixed tritium-age samples, 2 were downgradient from areas of higher sensitivity and 2 were near Lake Independence. The 2 samples near Lake Independence also had evaporative signatures.

  Of the 8 premodern samples, all were in very low sensitivity areas.
- Of the 12 samples analyzed for nitrate, 2 were elevated.
- Of the 13 samples analyzed for chloride, 4 were elevated and all of those were anthropogenic.

f2 aquifer (Figure 44)

- The f2 aquifer is mapped at scattered locations throughout the county. Depths range from approximately 60 to 340 feet. Approximately 2 percent of wells are completed in this aquifer.
- Pollution sensitivity is mostly very low with some smaller scattered areas of higher sensitivity in the east and north.

  Of the 21 total samples collected, 15 were analyzed for tritium with the following results: 5 modern, 3 mixed, and 7 premodern tritium age.

  Of the 8 modern and mixed tritium-age samples, 1 was in a very high sensitivity area; 1 was downgradient from an area of higher sensitivity and was a possible source of detected tritium. For the other 6 samples the source of the detected tritium was unknown.

  Of the 7 premodern samples, all were in very low sensitivity areas. One of the premodern samples downgradient of Lake Sarah (western part of the county in the Greenfield area) had a low evaporative signature (Figure 26 and Plate 7).
- Of the 12 samples analyzed for nitrate, none were elevated.
- Of the 9 samples analyzed for chloride, 5 were elevated, 4 were anthropogenic, and 1 was unknown.

wo and eo aquifers (Figure 45)

- The wo and eo aquifers are mostly found in the northern part of the county. Depths range from approximately 80 to 360 feet. Approximately 1 percent of wells are completed in this aquifer.
- Pollution sensitivity is mostly very low with some smaller scattered areas of higher sensitivity in the east and north.

  Of the 9 total samples collected, all were analyzed for tritium with the following results: 4 modern, 2 mixed, and 3 premodern tritium age.

  Of the 6 modern and mixed tritium-age samples, 1 was in a low to high sensitivity area; 3 were near or downgradient from areas of higher sensitivity and a possible source of detected tritium. For the other 2 samples the source of the detected tritium was unknown.

  Of the 3 premodern samples, all were in very low sensitivity areas. One of the premodern samples in the Sylvan Lake and Cowley Lake area (north, Rogers) had a low evaporative signature (Figure 26 and Plate 7).
- Of the 5 samples analyzed for nitrate, 1 was elevated.
- Of the 5 samples analyzed for chloride, 2 were elevated and both were anthropogenic.

vo and su aquifers (Figure 46)

- The vo and su aquifers are mostly found in the western part of the county. Depths range from approximately 80 to 380 feet. Less than 1 percent of wells are completed in this aquifer.
- Pollution sensitivity is mostly very low.

  Of the 2 total samples collected from the vo aquifer, both were premodern tritium age and were in very low sensitivity areas.

  One sample was in the northern part of the county with a carbon-14 residence time of 1,200 years. One sample was analyzed for nitrate and chloride and it was not elevated for either constituent.

Bedrock surface (Figure 47 and Plate 7)

Values for groundwater chemistry and conditions are shown on plate 7 because of the volume of data.

The sedimentary bedrock layers underlying Hennepin County dip, resulting in varying types of bedrock at the bedrock surface. In the central and most of the southeastern part of the county, the Platteville and Glenwood formations, St. Peter Sandstone, and formations of the Prairie du Chien Group (Shakopee and Oneota) are commonly at the bedrock surface. More common in the north and western portions are the Jordan Sandstone, St. Lawrence Formation, and Lone Rock Formation (Upper Tunnel City aquifer) (Part A, Plate 2).

Depths to the bedrock surface are also variable although some trends are apparent (Part A, Plate 6, Depth to Bedrock). Most of the deepest bedrock areas coincide with buried bedrock valleys throughout the county. Depths to bedrock in the major buried bedrock valleys are commonly 300 to over 500 feet (Part A, Plate 5, Depth to Bedrock). Elsewhere depths to bedrock tend to be shallower (less than 50 to 150 feet) in the north and east, and deeper (150 to 300 feet) in the west and southeast. The shallower depths in the east combined with the thick surficial sand creates many zones of moderate to very high sensitivity in that part of the county.

The bedrock pollution sensitivity is evaluated in two ways. The method most representative of conditions at the bedrock surface uses chemistry results from wells completed with the bottom of the casing no deeper than 40 feet below the bedrock surface (Figure 47). Chemistry data from wells completed in deeper bedrock (bottom of casing greater than 40 feet below the bedrock surface) are less representative of pollution sensitivity for the bedrock surface (Figure 48).

- Of the 177 wells completed near the bedrock surface and 3 bedrock springs, 115 were analyzed for tritium, resulting in 32 modern, 16 mixed, and 67 premodern tritium-age samples.

Of the 48 modern and mixed tritium-age samples, 14 were in low to very high sensitivity areas, which is consistent with the pollution sensitivity model.

The other 34 samples in very low sensitivity areas are mostly the result of circumstances that are not accounted for in the sensitivity model such as lateral flow. Of the 34 samples, 22 were near or downgradient from higher sensitivity areas which could have been a lateral source of the detected tritium (condition L). Lateral recharge sources appear to be the cause of high evaporative signatures of 3 samples collected downgradient of Lake Minnetonka (Christmas Lake area), 1 sample in the Mooney Lake area (east of Orono), and 1 sample downgradient from Lake Independence (northwest of Maple Plain).

Of the 34 samples, 5 mixed tritium-age samples were at very low sensitivity areas from municipal water supply wells (Bloomington and Eden Prairie). The higher artificial gradient created by these high-volume wells may have enhanced the recharge of tritium water from shallower aquifers that might not have gotten that deep with normal gradients (condition P).

The recharge conditions of 7 modern and mixed tritium-age samples were considered unknown (condition U).

Of the 67 premodern samples, most were in very low sensitivity areas. One premodern sample in the northwest (Hanover) was in a low to moderate sensitivity area. This sample may represent upwelling of older water from deeper aquifers to the river as discharge.

Five of the premodern samples in the northwestern part of the county had carbon-14 residence times that ranged from 350 to 3,000 years.

- Of the 180 samples (wells and springs), 108 were analyzed for nitrate; 6 were elevated at residential locations in Eden Prairie and 2 elevated spring samples were from Fort Snelling State Park and Cold Water Spring (Mississippi National River and Recreation Area).
- Of the 128 samples analyzed for chloride, 56 were elevated and mostly in the southeastern part of the county. Of the elevated samples, 26 of those were anthropogenic and the remainder were unknown.

Deeper bedrock (Figure 48 and Plate 7)

Values for groundwater chemistry and conditions are shown on plate 7 because of the volume of data.

- Of the 190 wells completed deeper in the bedrock, 99 were analyzed for tritium, resulting in 20 modern, 36 mixed, and 43 premodern tritium-age samples.

Of the 56 modern and mixed tritium-age samples, 19 were in low to very high sensitivity areas.

Of the 37 samples in very low sensitivity areas, 9 were near or downgradient from higher sensitivity areas which could have been a lateral source (condition L) of the detected tritium. Even though the chemistry data described here were from the deeper portions of the bedrock aquifers, the data match the bedrock surface pollution sensitivity map with some notable exceptions: 1) a greater influence of high-volume pumping drawing modern and mixed tritium-age waters to depths where not naturally expected, and 2) premodern samples in higher sensitivity areas because of overlying bedrock aquitards that are not factored into the pollution sensitivity model.

Most (25) of the mixed tritium-age samples in areas of very low sensitivity were from municipal water supply wells (Bloomington, Eden Prairie, Hopkins, Edina, Champlin, and Plymouth). The higher artificial gradient created by these high-volume wells may have enhanced the recharge of modern tritium-age water from shallower aquifers (condition P).

Of the 43 premodern samples, most were in very low sensitivity areas, but 6 were in moderate to very high sensitivity areas. One of these samples, near Minnehaha Creek (northeastern part of Edina) is from the St. Peter aquifer and may represent upwelling of older water from deeper aquifers to the creek as discharge. The other 5 samples, in the eastern part of the county are from aquifers that are not at the surface (Prairie du Chien, Jordan, and Mt. Simon) and have at least one overlying bedrock aquitard.

Of the 43 deeper premodern samples, 14 samples were analyzed for carbon-14 residence time. All of the samples were from the Mt. Simon aquifer or combinations of the Mt. Simon and other units. Estimated residence time values from these deeper aquifers ranged from 3,000 to greater than 40,000 years.

- Of the 190 samples, 147 were analyzed for nitrate, and 1 was elevated.
- Of the 105 samples analyzed for chloride, 66 were elevated. Of the elevated samples, 42 of those were anthropogenic, 8 were natural, and 16 unknown. The anthropogenic samples were mostly in the eastern and southeastern part of the county. Most of the natural samples were from the Mt. Simon aquifer at scattered locations.

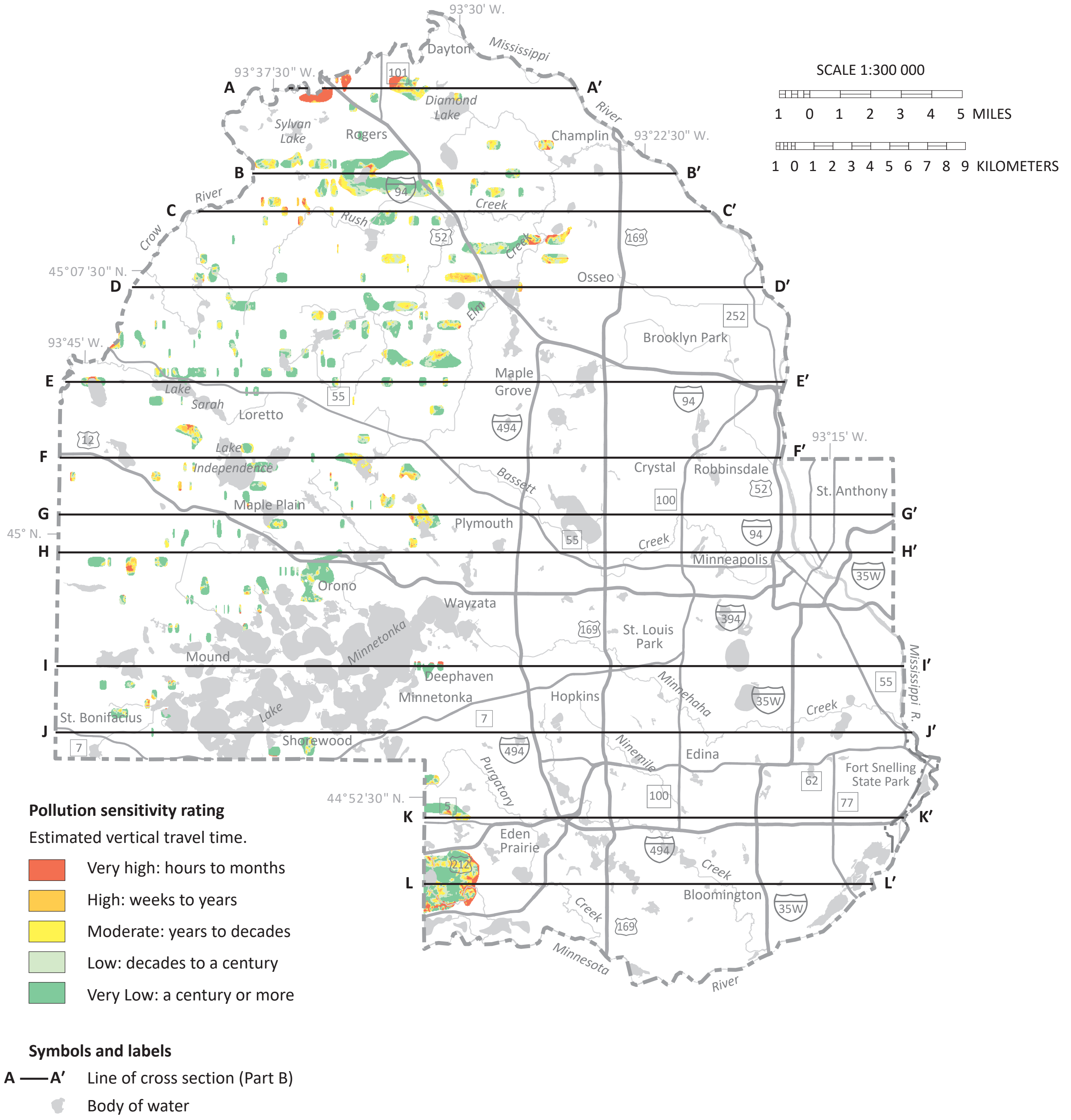


Figure 36. Pollution sensitivity of the vs aquifer

Depths range from less than 10 to approximately 80 feet. Less than 1 percent of wells in the county are completed in this aquifer. Pollution sensitivity ranges from very low to very high. No samples were collected from this aquifer.

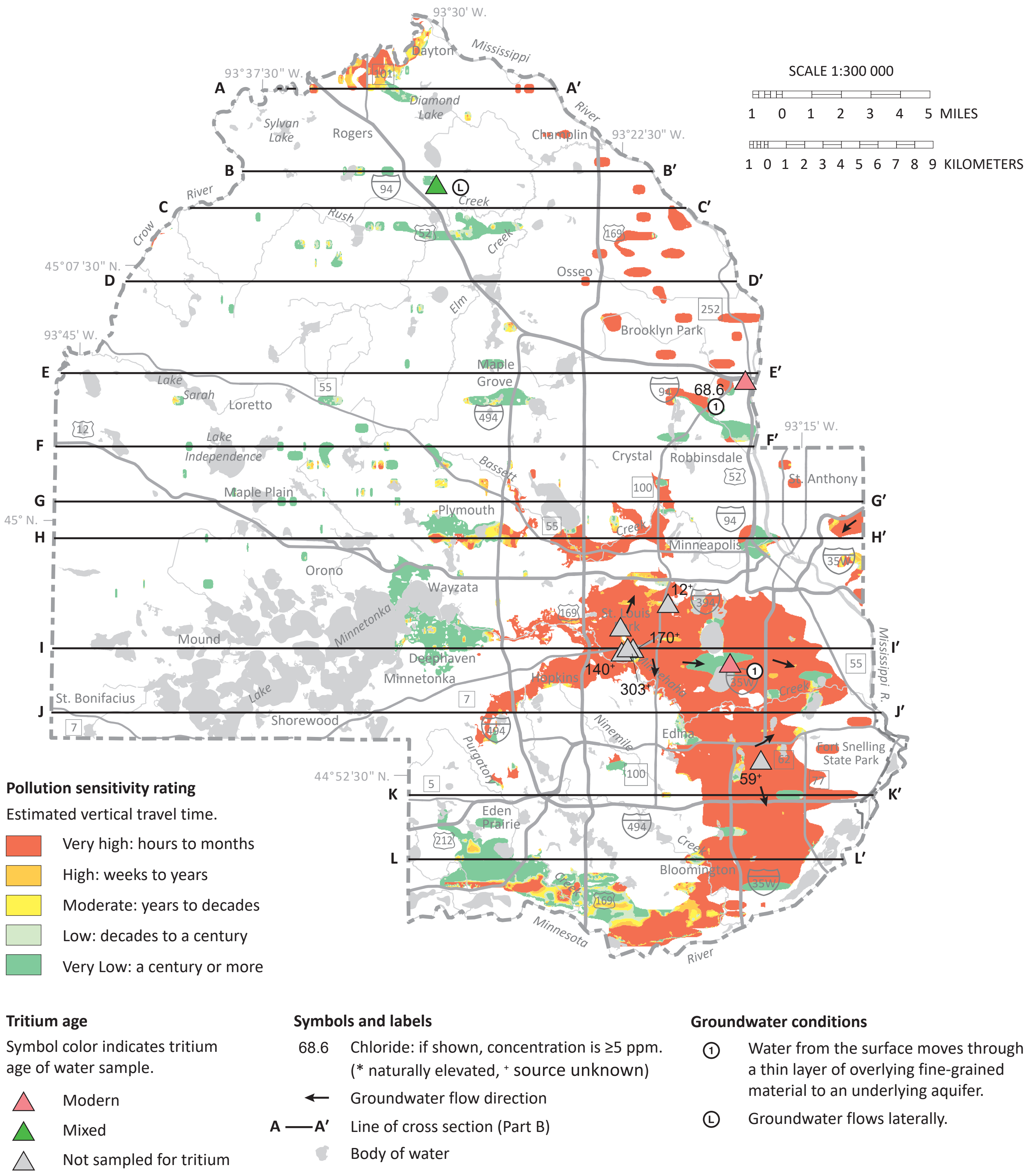


Figure 37. Pollution sensitivity of the ts and ts2 aquifers and groundwater flow directions

Depths range from less than 10 to approximately 100 feet. Approximately 2 percent of wells in the county are completed in these aquifers. Pollution sensitivity ranges from very low to very high.

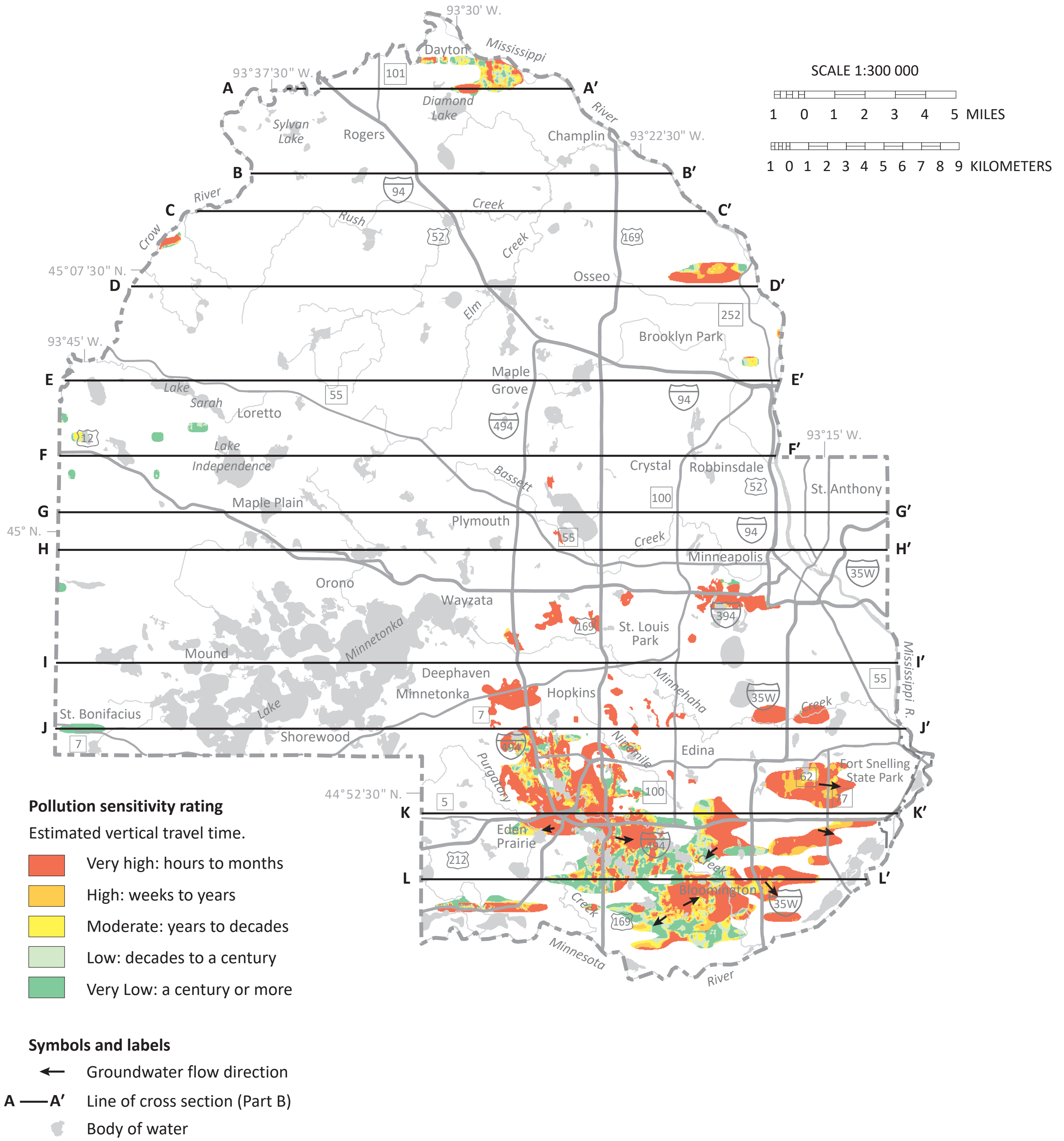
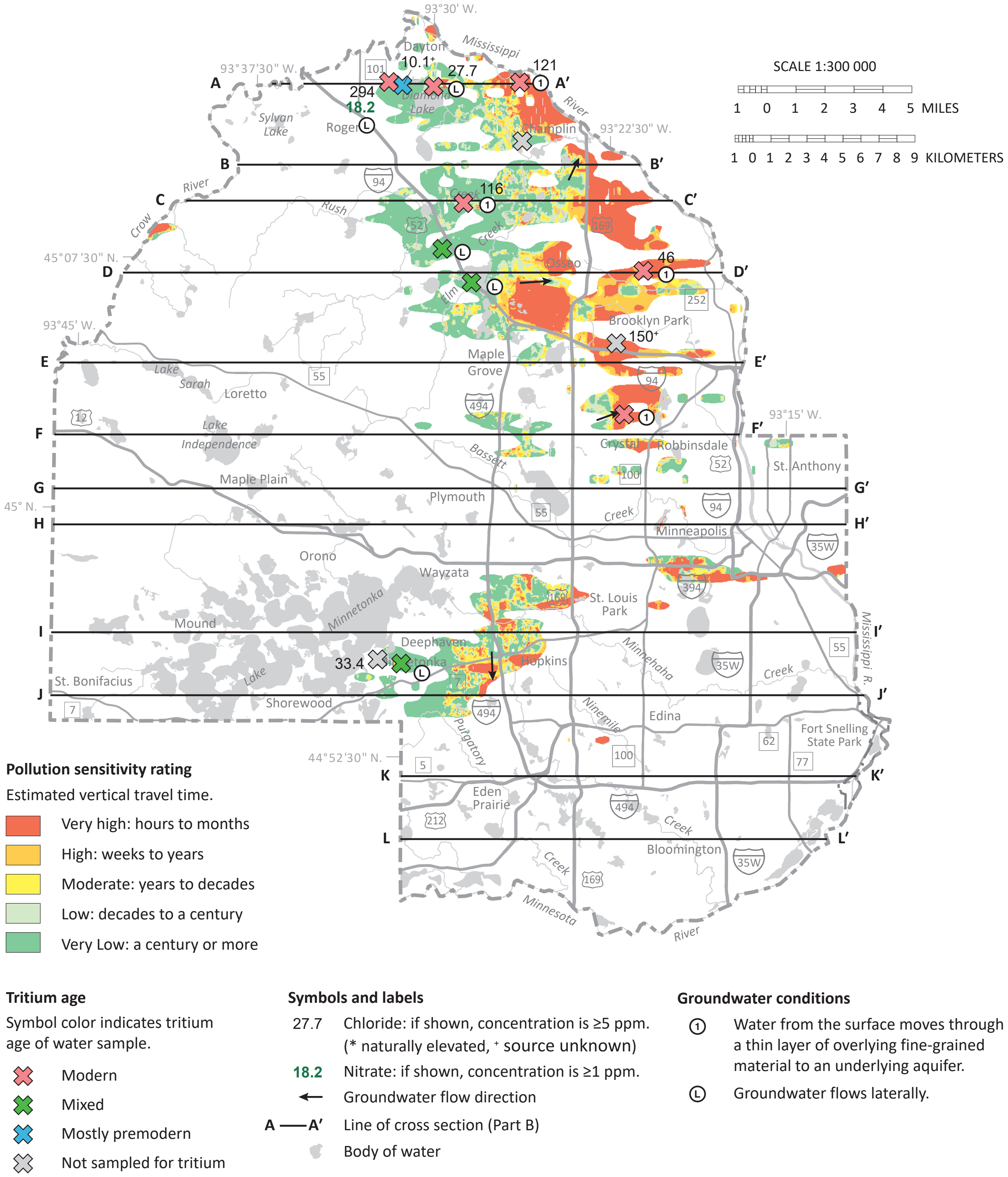


Figure 38. Pollution sensitivity of the ti, ts1, and ms aquifers and groundwater flow directions

Depths range from approximately 10 to 80 feet. Less than 1 percent of wells in the county are completed in these aquifers. Pollution sensitivity ranges from very low to very high but is mostly very high in the southeast.



Pollution sensitivity rating

Estimated vertical travel time.

- 🟥 Very high: hours to months
- 🟧 High: weeks to years
- 🟨 Moderate: years to decades
- ▨ Low: decades to a century
- 🟩 Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

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

Symbols and labels

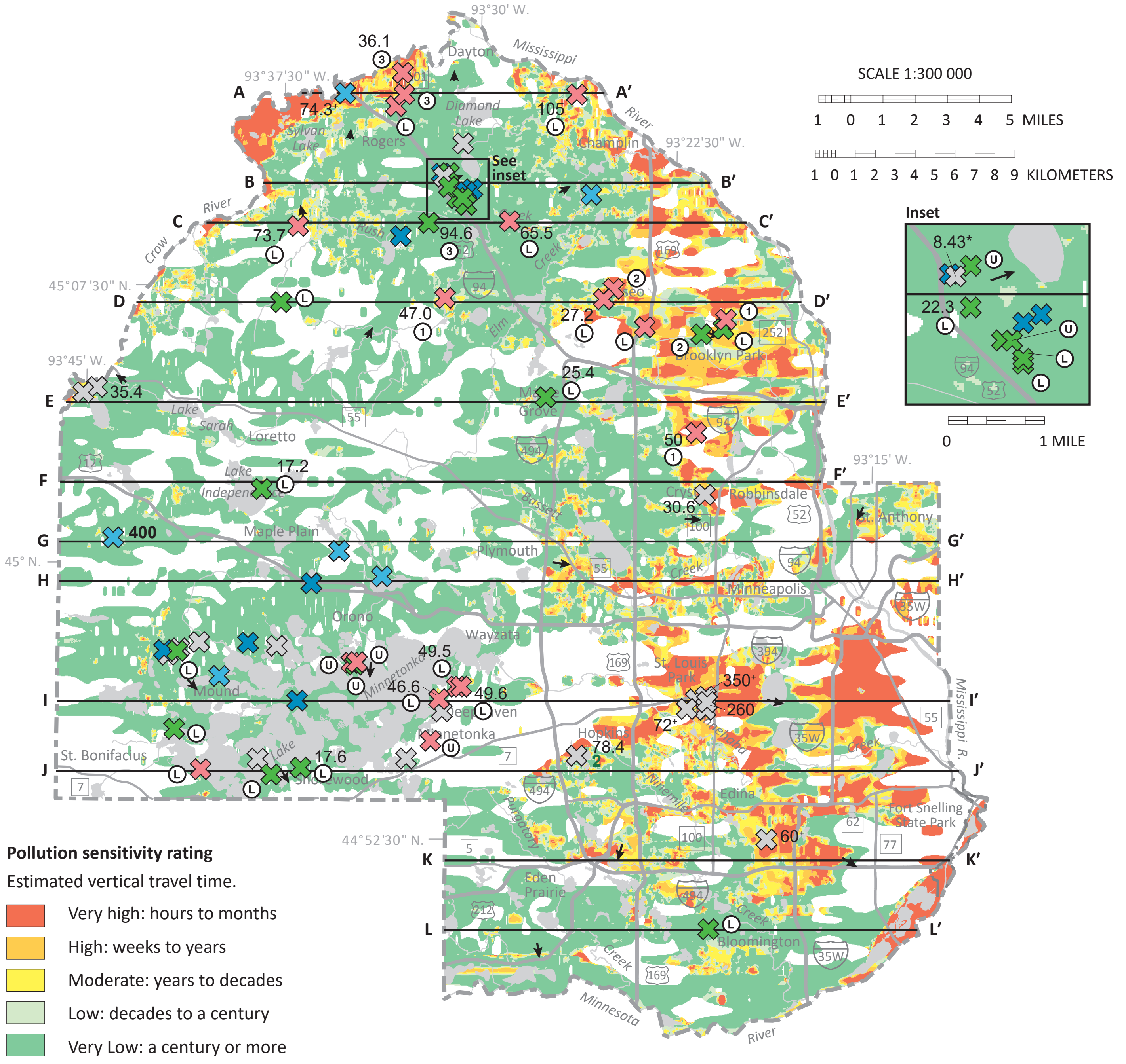
27.7	Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, ⁺ source unknown)
18.2	Nitrate: if shown, concentration is ≥1 ppm.
←	Groundwater flow direction
A —— A′	Line of cross section (Part B)
●	Body of water

Groundwater conditions

①	Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
Ⓛ	Groundwater flows laterally.

Figure 39. Pollution sensitivity of the si and s1 aquifers and groundwater flow directions

Depths range from approximately 10 to 80 feet. Approximately 2 percent of wells in the county are completed in these aquifers. Pollution sensitivity ranges from very low to very high but is mostly very high in the eastern areas.



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

Symbols and labels

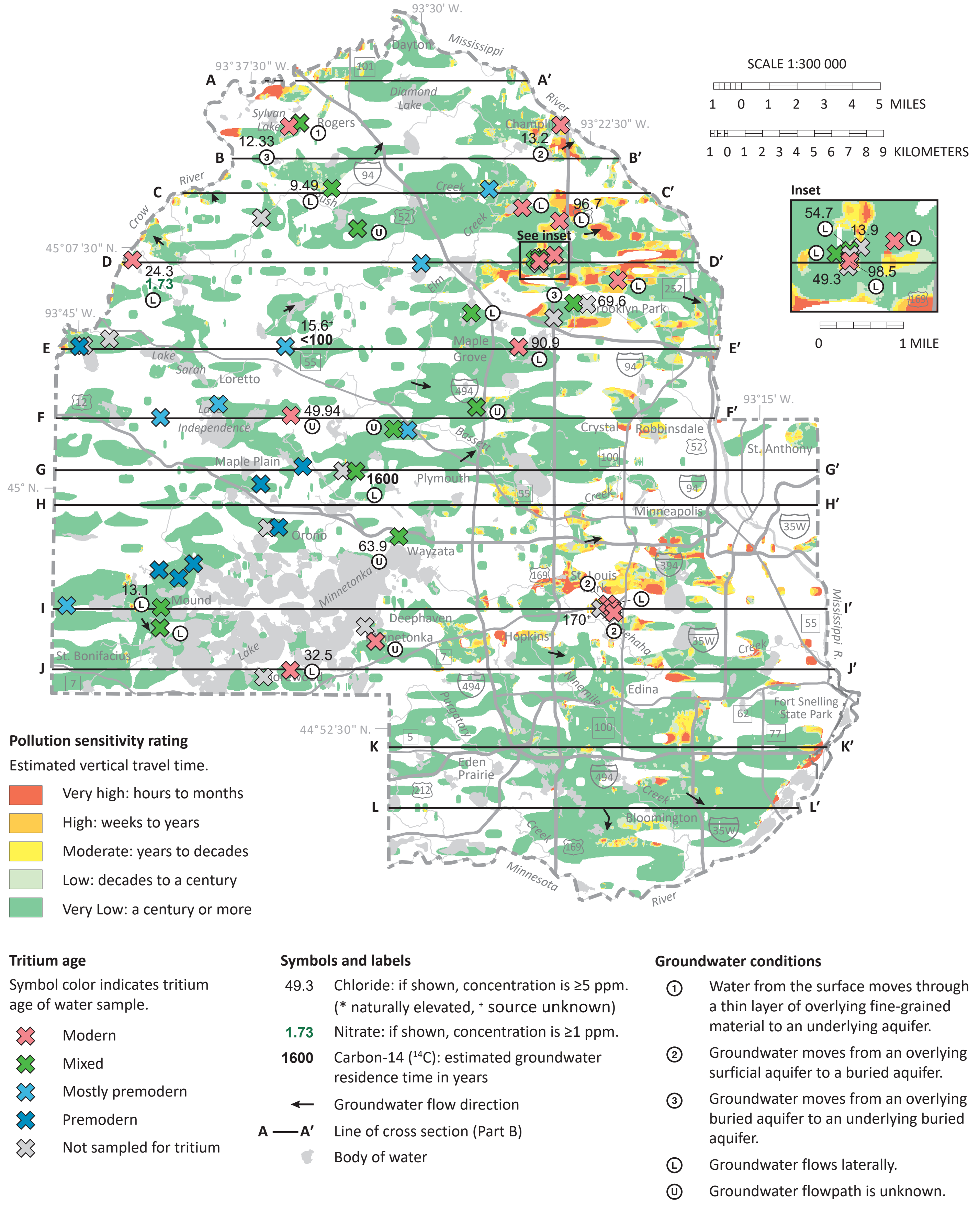
49.6	Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)
2	Nitrate: if shown, concentration is ≥1 ppm.
400	Carbon-14 (^{14}C): estimated groundwater residence time in years
←	Groundwater flow direction
A —— A′	Line of cross section (Part B)
●	Body of water

Groundwater conditions

①	Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
②	Groundwater moves from an overlying surficial aquifer to a buried aquifer.
③	Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
Ⓛ	Groundwater flows laterally.
Ⓤ	Groundwater flowpath is unknown.

Figure 40. Pollution sensitivity of the s2 aquifer and groundwater flow directions

Depths range from approximately 10 to 200 feet. Approximately 14 percent of wells in the county are completed in this aquifer. Pollution sensitivity ranges from very low to very high with most of the very high areas in the east.



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

Symbols and labels

49.3	Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)
1.73	Nitrate: if shown, concentration is ≥1 ppm.
1600	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

①	Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
②	Groundwater moves from an overlying surficial aquifer to a buried aquifer.
③	Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
Ⓛ	Groundwater flows laterally.
Ⓤ	Groundwater flowpath is unknown.

Figure 41. Pollution sensitivity of the s3 aquifer and groundwater flow directions

Depths range from approximately 10 to 260 feet. Approximately 14 percent of wells in the county are completed in this aquifer. Pollution sensitivity ranges from very low to very high with most of the very high areas in the east.

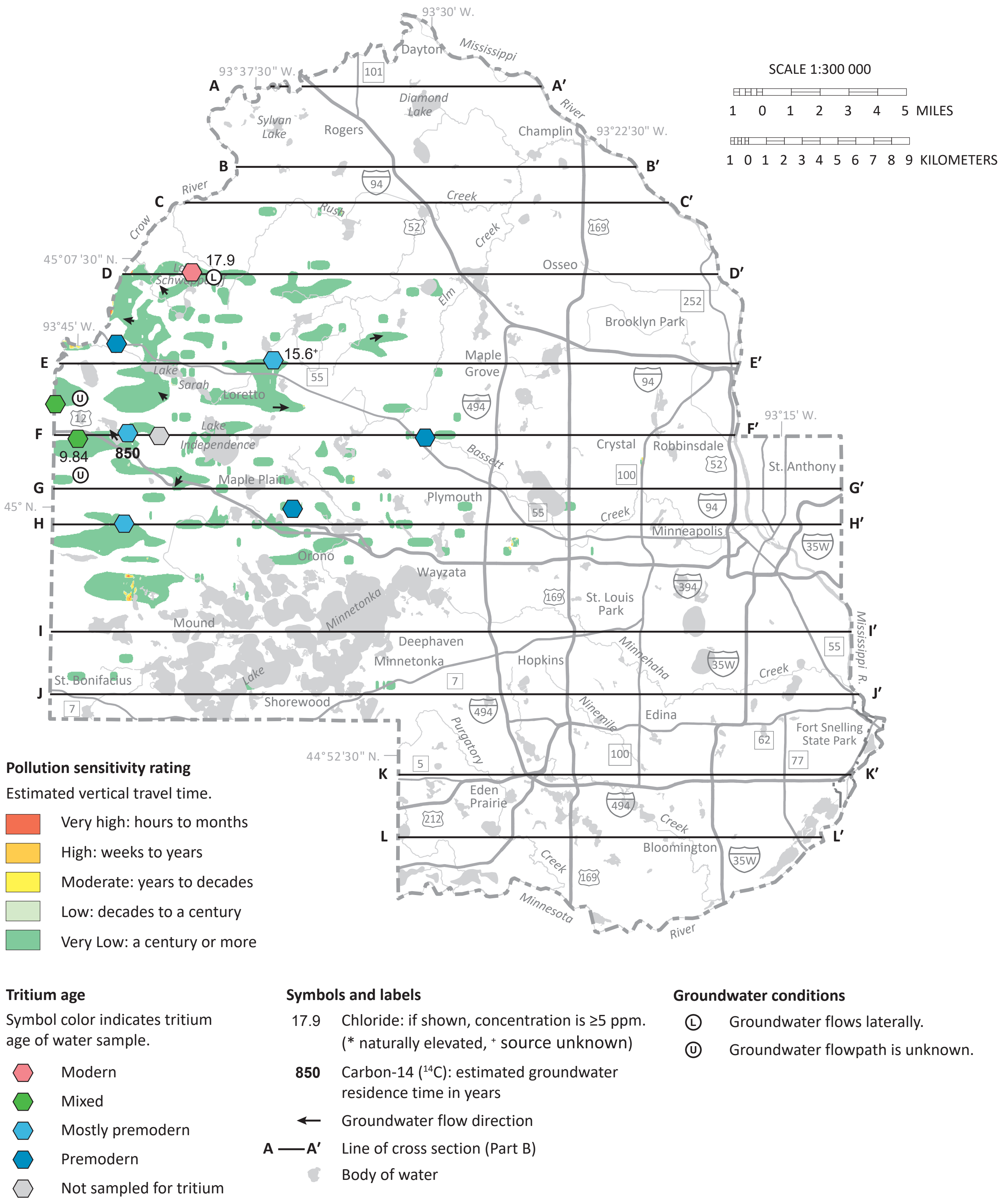


Figure 42. Pollution sensitivity of the f1 aquifer and groundwater flow directions

Depths range from approximately 50 to 230 feet. Approximately 2 percent of wells in the county are completed in this aquifer. Pollution sensitivity is mostly very low.

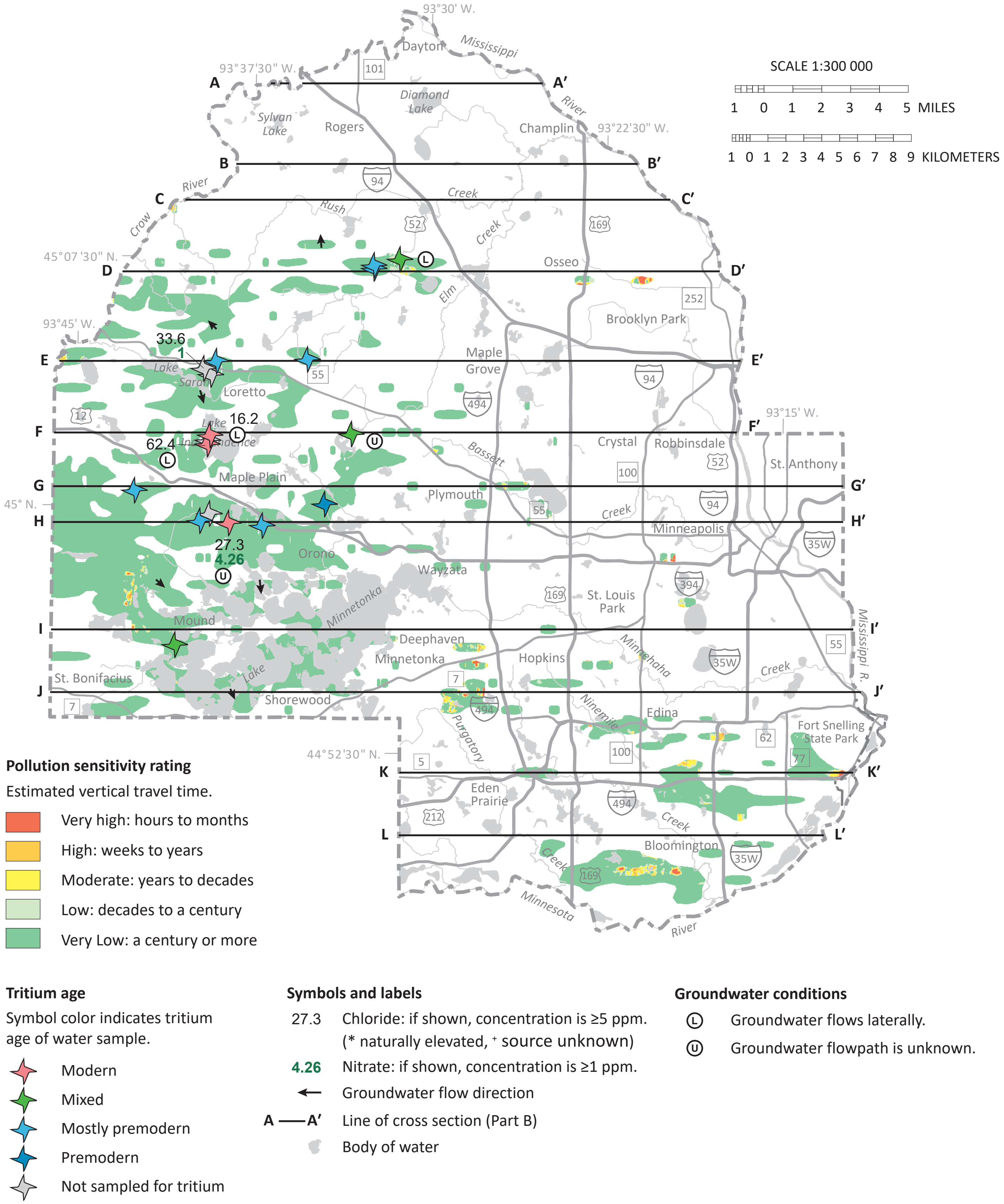
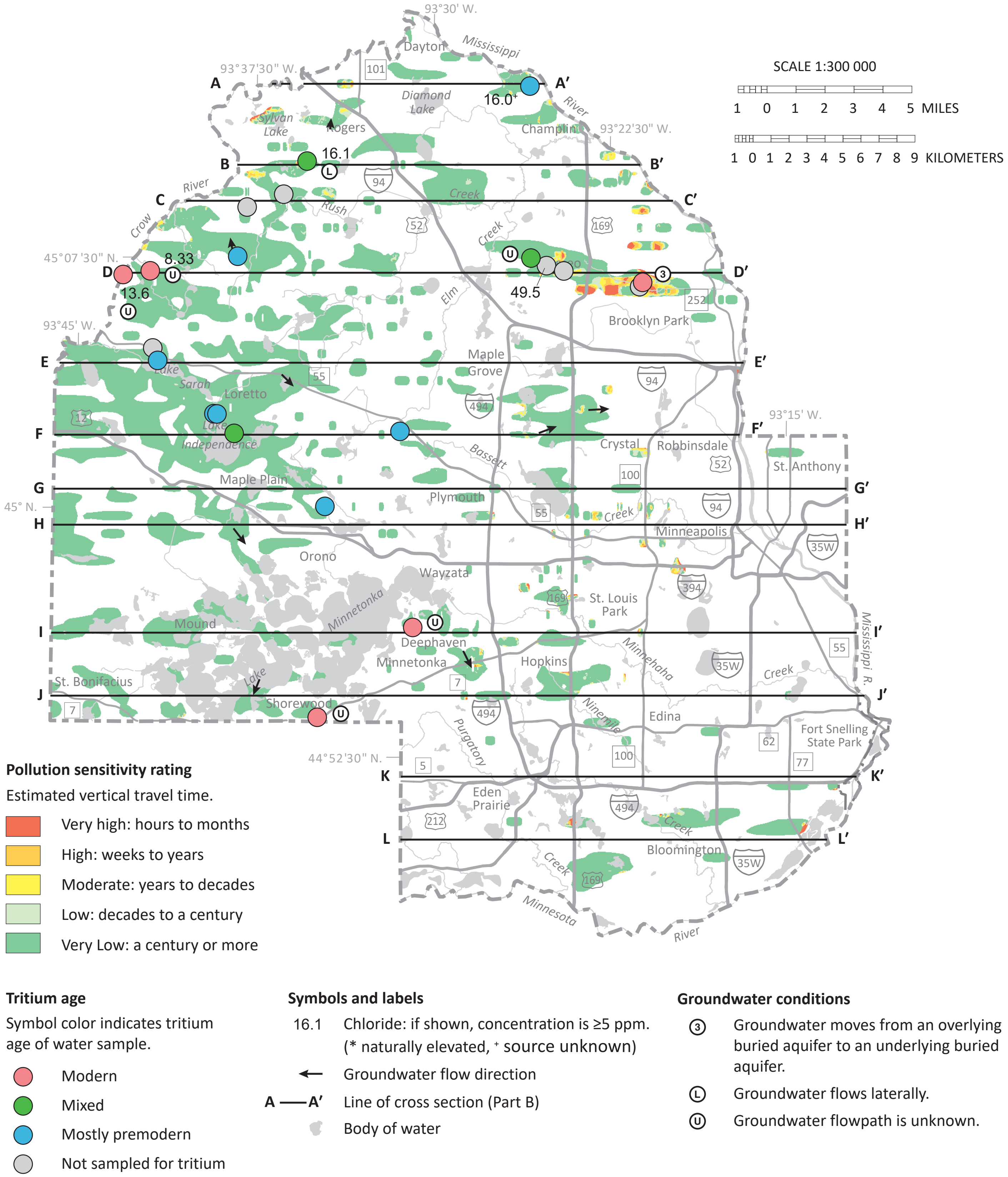


Figure 43. Pollution sensitivity of the h2 aquifer and groundwater flow directions

Depths range from approximately 80 to 300 feet. Approximately 3 percent of wells in the county are completed in this aquifer. Pollution sensitivity is mostly very low with some smaller scattered areas of higher sensitivity in the south.



Pollution sensitivity rating

Estimated vertical travel time.

🟥 Very high: hours to months

🟧 High: weeks to years

🟨 Moderate: years to decades

🟩 Low: decades to a century

🟩 Very Low: a century or more

Tritium age

Symbol color indicates tritium age of water sample.

● Modern

● Mixed

● Mostly premodern

○ Not sampled for tritium

Symbols and labels

16.1	Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, ⁺ source unknown)
←	Groundwater flow direction
A —A'	Line of cross section (Part B)
	Body of water

Groundwater conditions

③	Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
Ⓛ	Groundwater flows laterally.
Ⓤ	Groundwater flowpath is unknown.

Figure 44. Pollution sensitivity of the f2 aquifer and groundwater flow directions

Depths range from approximately 60 to 340 feet. Approximately 2 percent of wells in the county are completed in this aquifer. Pollution sensitivity is mostly very low with some smaller scattered areas of higher sensitivity in the east and north.

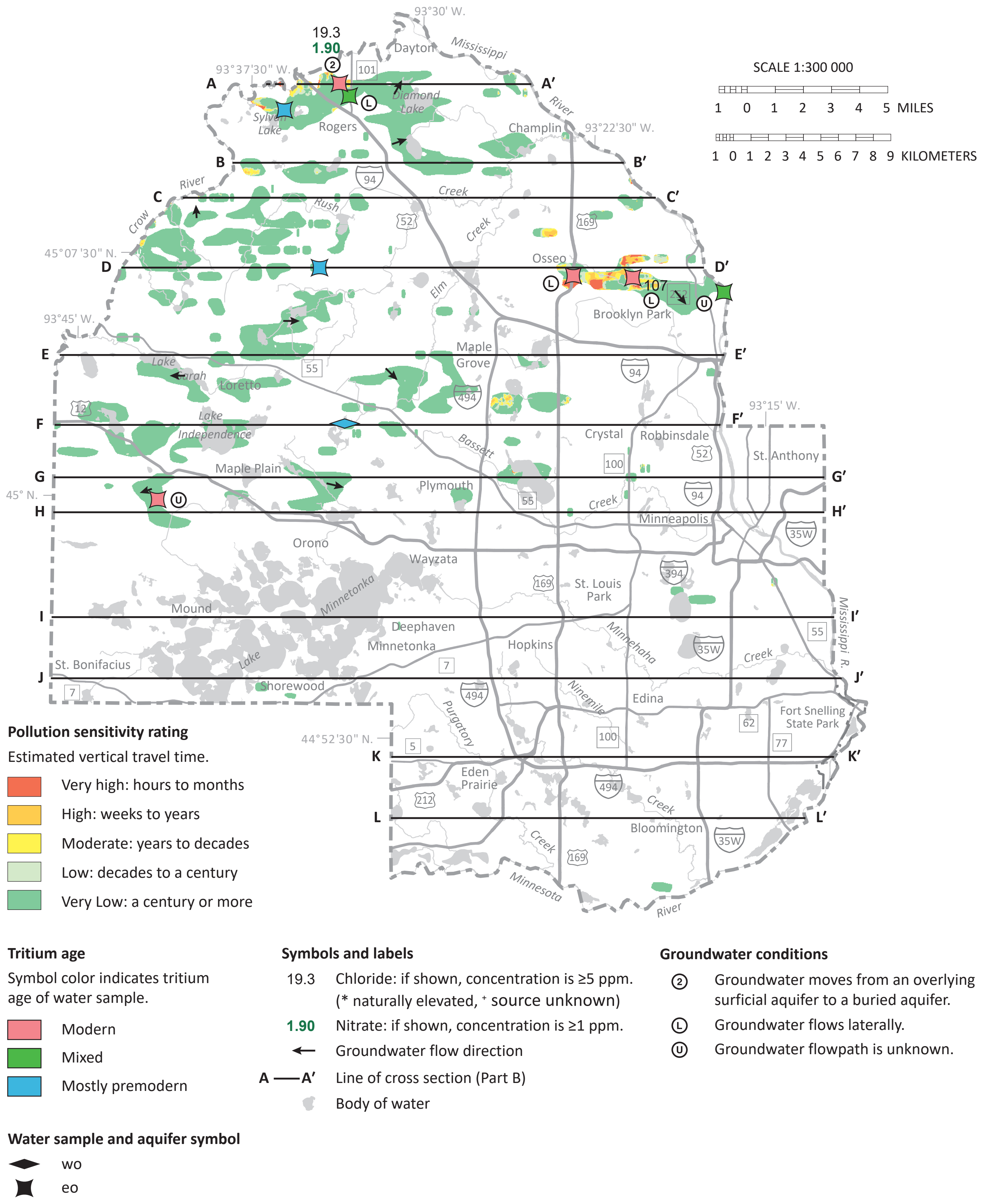


Figure 45. Pollution sensitivity of the wo and eo aquifers and groundwater flow directions

Depths range from approximately 80 to 360 feet. Approximately 1 percent of wells in the county are completed in this aquifer. Pollution sensitivity is mostly very low with some smaller scattered areas of higher pollution sensitivity in the east and north.

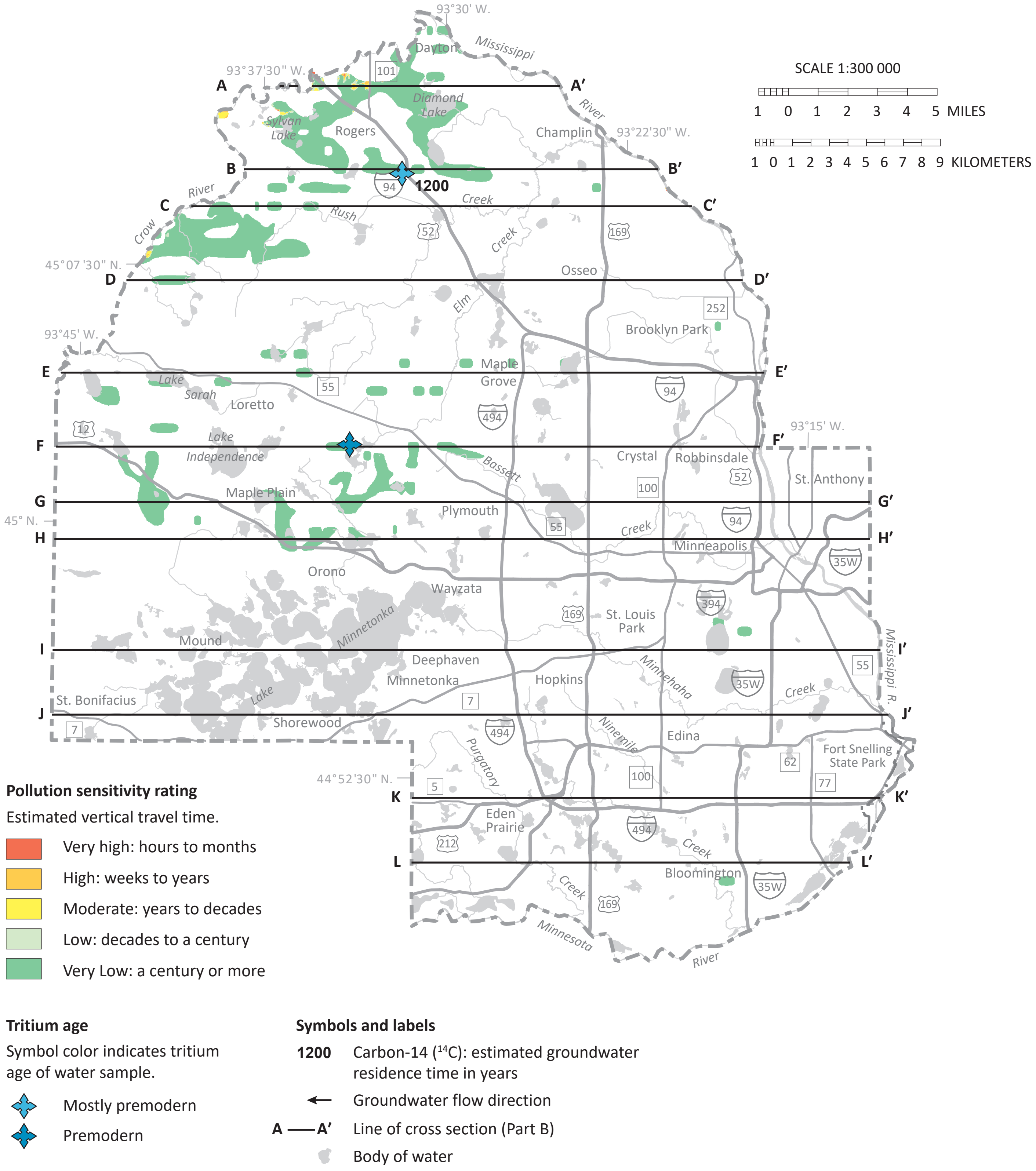


Figure 46. Pollution sensitivity of the vo and su aquifers and groundwater flow directions

Depths range from approximately 80 to 380 feet. Less than 1 percent of wells in the county are completed in this aquifer. Pollution sensitivity is mostly very low.

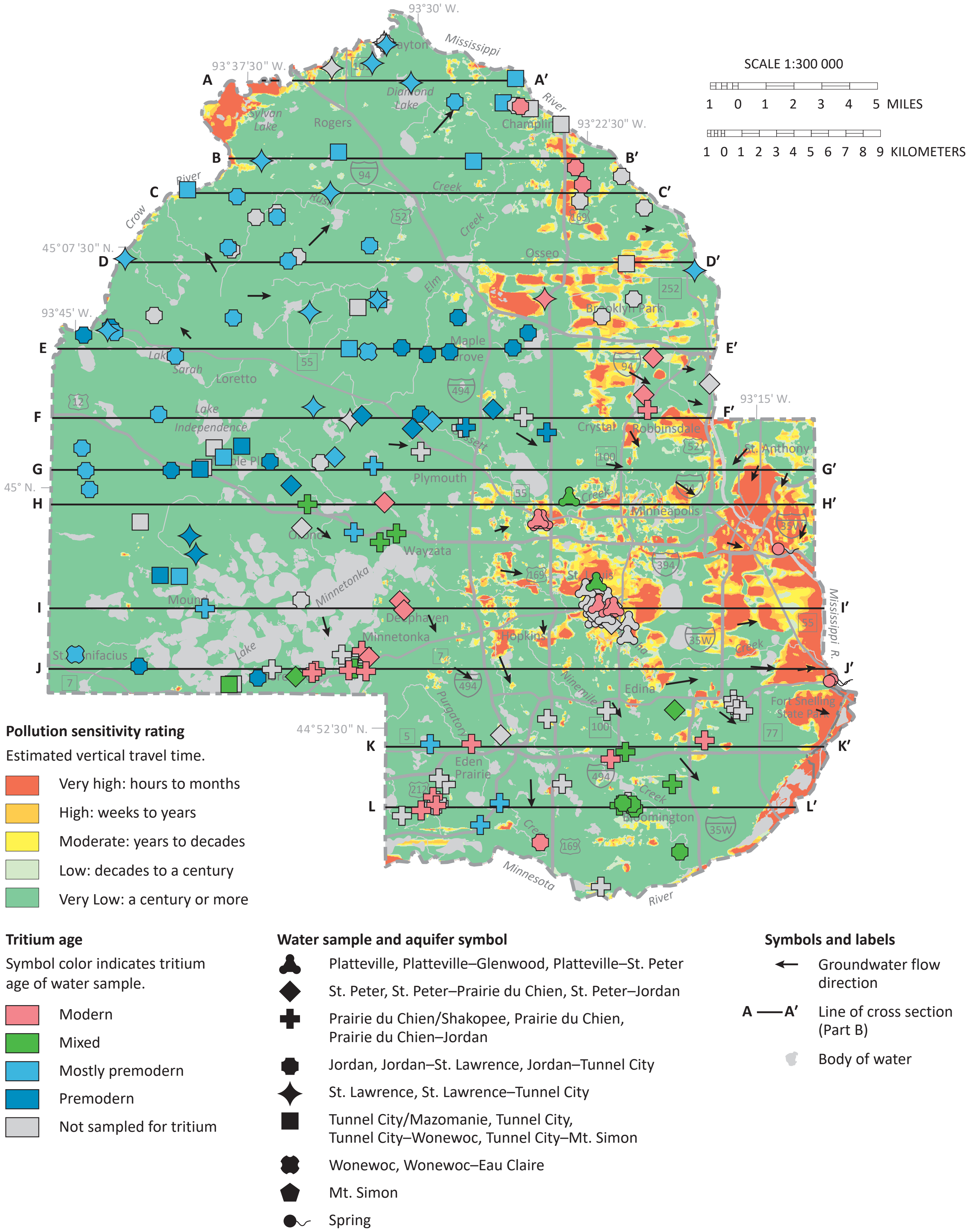


Figure 47. Pollution sensitivity of the bedrock surface and groundwater flow directions

The bedrock pollution sensitivity is shown on Figures 47 and 48. Chemistry values and groundwater conditions are shown on Plate 7 because of the high density of data and the scale of the maps. This map of the bedrock surface uses chemistry results from wells completed with the base of casing no deeper than 40 feet below the bedrock surface.

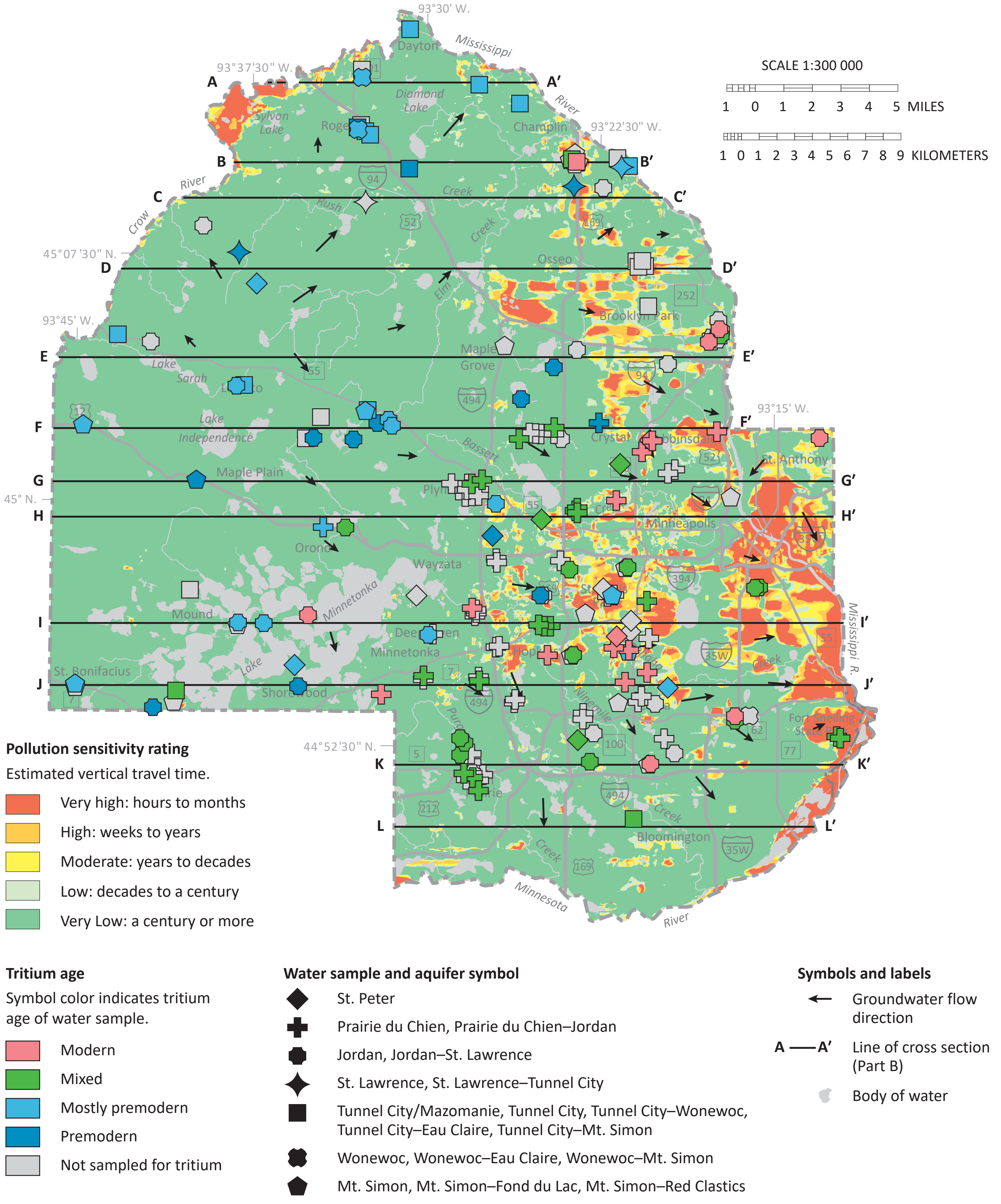


Figure 48. Pollution sensitivity of deeper bedrock aquifers and groundwater flow directions

Most of the deeper chemistry data match the bedrock surface pollution sensitivity map with some exceptions. In some areas high-volume pumping may have drawn modern and mixed tritium-age water into areas where they would not otherwise be expected. In addition, premodern samples coincide with higher sensitivity in some areas where overlying bedrock aquitards are not factored into the sensitivity model. Chemistry values and groundwater conditions are shown on Plate 7.

Hydrogeologic cross sections (Plates 8 and 9)

The hydrogeologic cross sections shown on Plates 8 and 9 illustrate the horizontal and vertical extent of aquifers and aquitards, the relative hydraulic conductivity of aquitards, general groundwater flow direction, areas of groundwater recharge and discharge, and groundwater residence time. These were chosen to incorporate existing data, to align with groundwater level monitoring wells, and to intersect areas with high-volume municipal pumping.

The 12 cross sections were selected from a set of 103 regularly-spaced (0.5 kilometer) west-to-east cross sections created by the MGS. Each was constructed in GIS using a combination of well data from CWI and sections of Part A: Bedrock Geology (Plate 2), Surficial Geology (Plate 3), and Quaternary Stratigraphy (Plate 4). Well information was projected onto the trace of the cross section from distances no greater than one kilometer.

Relative hydraulic conductivity

Hydraulic conductivity is a function of the porosity (volume of pores) and permeability (connectedness of pores) of a sediment or rock layer. Percent sand content in the glacial sediment matrix is a proxy for permeability because coarse grains typically add permeability to sediment. Percent sand is based on the average matrix texture of each glacial aquitard (Part A, Plate 4, Table 4). Glacial aquitards with higher sand content are assumed to have higher hydraulic conductivity. This assumption does not account for the occurrence of larger clasts (pebbles, cobble, and boulders), the potential for fine sediment to fill pore spaces, or fractures in the shallow till units. Glacial sediment layers that act as aquitards (till units) are shown in shades of gray. Lighter shades indicate higher relative hydraulic conductivity.

Groundwater flow direction

Groundwater moves from areas with higher potential energy to areas with lower potential energy. The direction of groundwater movement is interpreted from the *equipotential contours* constructed from measured water levels in wells. These contours can be used to identify the groundwater flow direction, recharge zones, and discharge zones.

The equipotential contours and flow arrows show that the groundwater flow is initially downward, then laterally toward surface-water discharge areas such as major rivers or lakes. Discrete groundwater recharge areas are identified in the following section based on occurrences of connected aquifers (focused recharge) and geochemical data such as tritium, chloride, and nitrate.

Groundwater recharge and discharge

Discharge to surface water (condition Ⓓ)

Downward and lateral flow directions are most common across all of these cross sections, except for areas near the Crow River, Mississippi River, and Minnesota River, where flow is likely upward indicating discharge to surface-water bodies.

Examples that are supported by water-elevation data include flow to the Crow Wing River shown on the west side of A–A′, and to the Mississippi River shown on the east side of D–D′ and E–E′.

Very slow recharge (carbon-14 residence time)

In many areas, recharge to the deeper aquifers can take hundreds to thousands of years, provided rapid focused recharge does not occur through interconnected aquifers. This is indicated by carbon-14 residence time data.The carbon-14 relationships shown on the cross sections help visualize very slow recharge through aquitards.

Residence time values in Hennepin County are from 4 buried sand and 5 bedrock aquifers and range from less than 100 years to greater than 40,000 years (carbon-14 maps on Plates 8 and 9). Examining these data and associated hydrostratigraphic information in cross section is typically the best way of understanding the very slow three-dimensional groundwater flow that is common in the less sensitive and moderately deep aquifers in the western part of the county and deeper aquifers throughout the county.

Data collected to date show carbon-14 residence-time values in the buried sand aquifer are less than approximately 1,600 years; the upper bedrock aquifer values (Prairie du Chien, Jordan, and Upper Tunnel City) were equal to or less than 3,000 years; and the Mt. Simon aquifer values were 3,000 years to as high as the method detection limit of greater than 40,000 years. The 3,000-year value from the Jordan aquifer west of Lake

Independence (cross section F–F′) is also notable for the evaporative signature with that lake as the likely source.

Many of the samples analyzed for carbon-14 residence time were collected in selected groups or pairs of wells along the same cross section to help illustrate the typical situation of younger water in the shallower well versus older water in the deeper well. These data are shown at the following cross sections:

B–B′ center and east:

- Beneath Highway I-94, 1,200 years (vo aquifer)
- West of Elm Creek, 2,500 years (Tunnel City aquifer)
- Near Highway 169, 5,500 and 8,000 years (Mt. Simon aquifer)

E–E′ center:

- Near Morin lake, less than 100 years (s3 aquifer)
- East of Morin Lake, 2,500 years (Upper Tunnel City aquifer)
- Near Highway 494, 7,000 years (Mt. Simon aquifer)

F–F′ west:

- East of Robina Lake, 850 years (f1 aquifer)
- Between Robina Lake and Lake Independence, 3,000 years (Jordan aquifer)
- West of Robina Lake, 17,000 years (Mt. Simon aquifer)

G–G′ west:

- West of Maple Plain, 400 years (s2 aquifer) and 350 years (Jordan aquifer)
- East of Wolsfeld Lake, 1,600 years (s3 aquifer) and 3,000 years (Prairie du Chien aquifer)

I–I′ east and west, Mt. Simon aquifer:

- East of Minnehaha Creek, 25,000 years. This is typical of older values in southern Hennepin County.
- Between Mound and Orono, 3,000 years. This is an apparent anomaly which may be explained by more rapid recharge to the Mt. Simon aquifer along the fault near that location.

Focused recharge (conditions ①②③)

Focused recharge through thin or absent overlying aquitards (**condition 1**) is shown in the following locations:

- East sides of A–A′, B–B′, D–D′, E–E′, F–F′, beneath the thick surficial sand of the eastern part of the county
- Near the middle of C–C′, Rush Creek area (s1 aquifer) and the middle of D–D′, west of Rice Lake (s2 aquifer) beneath thinner layers of glacial aquitards (Qht and Qvt)

Of the 10 samples that indicate this kind of focused recharge, 9 were analyzed for chloride with elevated and anthropogenic values ranging from 46 to 617 ppm. Of the 7 samples analyzed for nitrate, 3 had elevated values ranging from 1.75 to 3.92 ppm.

Focused recharge is also common through interconnected aquifers (**conditions 2 and 3**), in the buried sand or bedrock aquifers. Examples are shown in the following locations:

A–A′ west:

- Near Highway 101 (s2 and eo aquifer)

C–C′ center:

- East of Rush Creek (s2 aquifer)

D–D′ east:

- Near Maple Grove and Brooklyn Park (s2 and f2 aquifers)

F–F′ east:

- Near Shingle Creek (Prairie du Chein aquifer)

H–H′ east:

- West of Bassett Creek (St. Peter aquifer)

I–I′ east:

- St. Louis Park area (s3 and Platteville aquifers)

L–L′ west:

- East of Lake Riley (Prairie du Chien aquifer)

Of these 13 samples, 5 were analyzed for chloride with 4 elevated concentrations (19.3 to 96.6 ppm) that were anthropogenic or unknown. Of the 13 samples, 5 were analyzed for nitrate and only 2 were elevated (1.9 and 2.29 ppm).

Lateral flow (condition Ⓛ)

Modern and mixed tritium-age samples that had no obvious downward recharge pathways were possibly recharged at some upgradient location. These types of water migrated laterally and downgradient because of normal groundwater flow gradients.

This condition is found on all the cross sections. It is common in both buried sand and bedrock aquifers and is often created by complex stratigraphic conditions that may be difficult to visualize from cross sections alone.

However, 4 examples of lateral flow shown on the western side of J–J′ near Lake Minnetonka may be the most obvious. These samples are found between Halsteds Bay to the west and Gideon Bay to the east. The thick overlying till aquitard, the close proximity to Lake Minnetonka, and the high evaporative signatures in 3 of the 4 samples indicate these samples were sourced laterally from locations out of the plane of the cross section, and beneath Lake Minnetonka.

Of the 46 samples with assumed lateral flow conditions, 32 were analyzed for chloride and 33 for nitrate. Of the chloride samples, 28 were elevated (9.49 to 294 ppm) and all were anthropogenic or unknown. Of the nitrate samples, only 3 were elevated (1.73 to 18.2 ppm).

Unknown (condition Ⓤ)

There were other detections of modern and mixed tritium-age water where the source is unknown. These occur in the following locations:

D–D′ west:

Near Schwappauff Lake and the Crow River (f2 aquifer)

F–F′ center:

Plymouth area and east of Spurzem Lake (s3 aquifer)

H–H′ west:

West of Highway 12 (h2 aquifer) and west of Long Lake (Prairie du Chien aquifer)

J–J′ west:

Near Lake Minnetonka (Wonewoc–Mt. Simon, and Prairie du Chien–Jordan wells)

Possible reasons for this unknown condition include the following:

- Corroded or ungrouted well casings leak surface water or surficial groundwater to otherwise buried aquifers.
- Unmapped buried sand aquifers have hydraulic connections to the surface.
- Sandy loam aquitards allow seepage of modern or mixed tritium-age groundwater faster than the pollution sensitivity model would predict.

Pumping (condition Ⓟ)

Hennepin County reported groundwater-pumping volumes (from wells with DNR appropriation permits) are among the highest in the state. Much of this is from municipal and commercial well fields (areas of closely spaced wells). This type of groundwater pumping has been observed in the TCMA (Tipping, 2012) and is evident on cross sections where modern and mixed tritium-age water and associated contaminants are drawn down deeper than expected under natural groundwater gradient conditions. This condition is typical of the deeper buried aquifers and aquifers in the upper bedrock zone because wells for public and commercial use tend to be constructed in the deeper aquifers to ensure a better long-term water supply, and to avoid interfering with the shallower domestic wells in the area. These occur in the following locations.

B–B′ east:

Champlin area, Champlin municipal well field (Tunnel City and Wonewoc aquifers)

F–F′ east:

Plymouth and Robbinsdale and associated well fields (Prairie du Chien and Jordan aquifers)

G–G′ center:

Plymouth area and well field (Prairie du Chien and Jordan aquifers)

I–I′ east of center:

Hopkins area and well field (Prairie du Chien and Jordan aquifers)

J–J′ east:

Edina area and well field (Prairie du Chien and Jordan aquifers)

K–K′ west and east:

Purgatory Creek and France Avenue areas, Eden Prairie and Edina well fields (Prairie du Chien and Jordan aquifers)

L–L′ east of center:

Bloomington area and well field (Jordan aquifer)

Of the 21 samples in this group, 15 were analyzed for chloride and 21 were analyzed for nitrate. Of the 15 chloride samples, 14 were elevated (14.6 to 127 ppm) and all were anthropogenic. None of the nitrate samples were elevated which matches expectations since all of samples were from deep bedrock aquifers with reduced conditions.

Recharge from open-water bodies–Evaporative signature water (E)

Detecting evaporative signatures in wells can be a first step to evaluating the risk of cumulative groundwater pumping to long-term lake levels. High-volume pumping from multiple municipal, commercial, or irrigation wells, can draw excess water from surface-water bodies. All of these examples, with one exception, were from low-volume domestic wells. However, these results, along with other information, could be used to inform future decisions regarding high-volume well locations and permitted pumping amounts.

A–A′ center (s1 aquifer):

This aquifer may be sourced from nearby Lake Laura as suggested by the cross section, but is more likely partially sourced from Diamond Lake which is out of the plane of the cross section (Figure 26 and Plate 7).

C–C′ west (near Crow River) and east (along Rush Creek):

All of these samples have low evaporative signatures and source locations that are not obvious.

D–D′ west:

Near Schwappauff Lake (f1 aquifer) and east of Highway 10 (eo aquifer). The Schwappauff Lake location has a high evaporative signature and is likely partially sourced from that lake. The sample east of Highway 10 has a low evaporative signature and a source that is not obvious.

E–E′ west:

Near Lake Sarah (f2 aquifer), Morin Lake (s3 aquifer), and east of Morin lake (Upper Tunnel City aquifer). Those near Lake Sarah and Morin Lake were likely partially sourced from those lakes. The sample east of Morin Lake also had a low evaporative signature and a source that is not obvious.

F–F′ west and center:

West of Lake Independence (s3, h2, and Jordan aquifers) and near Turtle Lake (St. Peter aquifer) east of Highway 55. All of the locations west of Lake Independence could have been partially sourced by that lake. The low evaporative signature sample near Turtle Lake may also have been partially sourced from that lake.

H–H′ west:

West of Highway 12 (h2 aquifer) and east of Long Lake (s2 and St. Peter aquifers). These could have been partially sourced from multiple lakes in the area. Long Lake may have been the most significant source of evaporative water for the sample nearest the lake.

I–I′ west of center:

East of Lake Minnetonka (s2 aquifer). This is downgradient of, and likely partially sourced from Lake Minnetonka.

J–J′ west:

Shorewood east of Lake Minnetonka, (s2 and s3 aquifers), and east of St. Albans Bay (Prairie du Chien aquifer). All of these samples had high evaporative signatures. They are all downgradient of, and likely partially sourced from Lake Minnetonka.

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

Aquifer characteristics such as specific capacity and transmissivity are used to describe how water is transmitted by an aquifer. Larger values of each of these parameters indicate more productive aquifers.

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

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

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

Wells completed in both the Prairie du Chien and Jordan have the highest mean value (116 gpm/ft) followed by the surficial sand aquifers (105 gpm/ft). The other aquifers have lower values (2 to 48 gpm/ft, Table 2).

Transmissivity is an aquifer's capacity to transmit water. It provides a more accurate representation of the 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).

The highest mean transmissivity values include surficial sand (107,000 ft^2/day), buried sand (16,700 ft^2/day) and Upper Tunnel City–Eau Claire (14,000 ft^2/day). These values may not be representative of typical values because of the low number of tests (2, 3, and 1, respectively). The combined Prairie du Chien–Jordan aquifers have the next highest value (13,000 ft^2/day) and because of the greater number of tests (27) may be more representative of actual conditions.

Table 2. Specific capacity and transmissivity of selected wells

Aquifer	Specific capacity (gpm/ft)					Transmissivity (ft^2/day)				
	Casing diam. (in.)	Mean	Min	Max	No. of tests	Casing diam. (in.)	Mean	Min	Max	No. of tests
Unconsolidated										
Surficial sand (QWTA)	8–24	105	43	184	10	12–20	107,000	15,500	198,600	2
Buried sand (QBAA)	8–24	48	1	199	26	20–24	16,700	2,600	28,000	3
Bedrock										
Platteville (OPVL)	8	2	--	--	1	4–6	7,900	7,200	8,600	2
St. Peter (OSTP)	12–20	32	5	71	5	6	2,500	--	--	1
St. Peter–Prairie du Chien (OSPC)	8–14	26	21	31	3	--	--	--	--	--
Prairie du Chien (OPDC)	8–24	36	7	117	11	10	5,300	--	--	1
Prairie du Chien–Jordan (OPCJ)	8–24	116	6	2,414	86	8–24	13,000	2,300	47,000	27
Jordan (CJDN)	8–30	33	6	116	28	8–30	3,800	1,000	8,400	13
Upper Tunnel City–Wonewoc (CTCW)	8–24	33	6	85	24	12–24	2,100	500	5500	7
Upper Tunnel City–Eau Claire (CTCE)	8–24	9	2	269	7	24	14,000	--	--	1
Upper Tunnel City–Mt. Simon (CTCM)	16	17	6	31	6	--	--	--	--	--
Mt. Simon (CMTS)	10–24	19	8	29	10	16	2,100	2,000	2,200	2
Mt. Simon–Hinckley (CMSH)	12–18	11	10	12	2	--	--	--	--	-

Specific capacity data adapted from the CWI

Transmissivity data are from aquifer test data compiled by the DNR

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 (DNR, 2020).

Well nests consist of closely spaced wells that are constructed in different aquifers. Long periods of record from multiple aquifers are useful for determining trends and provide insight into how aquifers respond to recharge events, climatic conditions, and pumping stresses. Figure 49 shows the locations of the well nests and groups and surrounding permitted appropriations considered in the evaluation. Most of the observation wells and well nests in Hennepin County and the TCMA have relatively short records because of low funding to gather this type of data prior to 2008. However, two of the well nests shown in the following figures include wells that have been monitored since 1945 (Prairie du Chien–Jordan well, Figure 50) and 1991 (Prairie du Chien–Jordan well of the Staring Lake well group, Figure 52). The longer well records provide valuable insight into the long-term trends of water use and available water supply. Precipitation, changing groundwater use amounts, and other factors can have a large effect on the historical trends.

The shorter-term records (Figures 53 through 55) are also valuable for providing multiple types of information, such as effects of nearby pumping and vertical direction of groundwater flow, but lack the data necessary to determine long-term trends. The proximity of the well nests and groups to areas of concentrated pumping are a primary factor controlling the annual fluctuations of water levels shown on the hydrographs. Proximity to major discharge areas (mainly major rivers) can be a primary factor controlling vertical groundwater flow directions.

The high-volume pumping records in the following hydrographs use cumulative values with radial distances of 5 and 6 miles. These are somewhat arbitrary but are informed by USGS synopotic water-level evaluations in the TCMA (Sanocki and others, 2008; Jones and others, 2013). The Sanocki investigation found seasonal water-level changes from March to August 2008 in the combined Prairie du Chien–Jordan aquifers with effects greater than a 10-mile radius in east-central Hennepin County and smaller areas within nearby Washington and Dakota counties. Jones identified a similar cumulative cone of depression in Washington County in March, April, and August 2011, with radial dimensions of 3 to 5 miles.

Minnetonka Boat Works (Figure 50)

One of the longest water-level records in the TCMA monitors the most heavily used combination of aquifers: wells that intersect the combined Prairie du Chien–Jordan (OPCJ) and Jordan (CJDN). The Prairie du Chien–Jordan hydrograph is near the eastern end of Lake Minnetonka in Orono (Figure 49 and 50). This hydrograph shows short (annual), medium (several years) and long-term (decades) trends (Figure 50).

The short-term trends are caused by increased pumping during the summer and early fall. Beginning in the late 1950s, the summer season low water levels typically have not returned to the yearly high water levels of the previous year, creating a steady decline.

The medium-term trends are illustrated by a comparison of the Minnetonka Boat Works hydrograph, local water use trends since the mid-1980s, and local rainfall patterns (Figure 50). Since the mid-1980s groundwater use was relatively stable but fluctuated with the medium-term rainfall trends. For example, an overall increase in rainfall from 2012 to 2018 matched a reduction in groundwater pumping and a small increase in Prairie du Chien–Jordan water levels. This pattern commonly occurs as fewer people water lawns during rainy periods. A drought during the late 1980s matches a several-year period of lower groundwater levels. This was followed by increased rainfall in the early 1990s and a recovery.

The long-term trends of combined Prairie du Chien–Jordan aquifers appeared to have two phases: declining water levels from the 1950s and the 1990s followed by stabilization and increasing levels from approximately 2010. Insights into the phases are provided by the history of permitted well installations near the Minnetonka Boat Works observation well and the urbanized area to the east. The Minnetonka Boat Works observation well is on the western fringe of an area of intensive groundwater use in the eastern portion of the county (Figure 51).

1. From 1960 to approximately 1972 only a few high-volume permits were issued per year and only a few were within the local area of the well.
2. From 1973 to 1978 there was a large increase in permits issued and associated groundwater pumping from the combined Prairie du Chien–Jordan and Jordan aquifers. This increased pumping in the 1980s through the early 2000s probably caused the steady decline of water levels shown on the hydrograph (Figure 50).

3. From 1979 to 2018, the number of permits issued declined to only a few per year. Water Levels appear to have stabilized since 2010 (though at a lower elevation). This may have been caused by the slowdown of additional pumping from new permits since approximately 1990, gradual increase in long-term rainfall, and conservation efforts.

Staring Lake (Figure 52)

A well group near Staring Lake in the southern part of the county (Figure 49) also has long-term water-level data (1991 to 2018) from the Prairie du Chien–Jordan aquifers and shorter records for the water table, Wonewoc, and Mt. Simon aquifers (Figure 52).

Most of the use shown in the groundwater-use graph is from the nearby Eden Prairie well field to the north, and the Chanhassen well field to the west. The Prairie du Chien–Jordan hydrograph appears to be influenced by appropriations from these two areas. The slightly depressed water levels from 1996 through approximately 2014 match the higher-use amounts during that same period.

The hydrographs of the Wonewoc and Mt. Simon aquifers show a similar increase in water levels since 2014, which matches a period of increased precipitation relative to the previous several years. None of the high-volume wells shown in the local area are completed in the Wonewoc and Mt. Simon aquifers. The fluctuations and trends are therefore likely because of regional pumping that changes the pressure from overlying units.

Robina (Figure 53)

The Robina well nest is included to show “background” hydrologic conditions because this area has similar geology and precipitation to other parts of the county but limited high-volume groundwater use. Background well nests typically show water levels from multiple aquifers that show minimal or no influence from nearby pumping wells. The Robina well nest is at the western county border, far from most of the heavily used suburban areas. The annual fluctuations in all the hydrographs appear to be dominantly from annual precipitation patterns.

The separation of the water levels between individual aquifers is relatively narrow compared to other well nests that are in heavily used suburban areas such as the Staring Lake well nest in Eden Prairie. For instance, the Robina Mt. Simon levels are only about 3 feet lower than the Wonewoc levels and about 5 feet lower than the Jordan aquifer levels. The same comparison at Staring Lake (Figure 52) shows separations of approximately 90 and 100 feet.

Luce Line (Figure 54)

The Luce Line well nest is near the Minnetonka Boat Works well. Both locations are near the center of the county. However, the Luce Line location is closer to the zone of suburban well fields in eastern Hennepin County, and approximately 1 mile southwest of Plymouth well field (Figure 49). The proximity to the Plymouth well field creates a larger seasonal fluctuation from pumping of the combined Prairie du Chien–Jordan aquifers and Jordan aquifer (Figure 54). Summer drawdowns at the Luce Line location are approximately 30 feet compared to 5 to 10 feet at the Minnetonka Boat Works location.

Also, at this more developed location, there is a large separation between water levels from the various aquifers, similar to the Staring Lake location. The typical vertical distance between the Mt. Simon and Wonewoc water levels at the Luce Line location is over 120 feet. Separation between the Mt. Simon and the Jordan water levels is over 160 feet.

Elm Creek (Figure 55)

In the previous three examples (Staring Lake, Robina, and Luce Line) none of the wells were near major groundwater discharge locations such as major rivers. The water levels in the shallower aquifers were higher than the deeper aquifers, indicating a downward gradient of groundwater flow and recharge conditions.

For the Elm Creek example the well nest is approximately 2 miles southwest of the Mississippi River, and approximately 2 to 3 miles west of wells operated by the city of Champlin (Figure 49). The Champlin well field includes wells completed in the Mt. Simon aquifer and combinations of the Mt. Simon and other aquifers. The seasonal pumping peaks of the Mt. Simon wells in this area match the seasonal low water levels in the Mt. Simon observation wells (Figure 55).

Unlike the previous Mt. Simon hydrograph examples, the elevations during the winter months are higher than those of the overlying Wonewoc, Mazomanie (Upper Tunnel City), Jordan, and buried sand aquifers, indicating an upward gradient from the Mt. Simon aquifer and discharge to the nearby Mississippi River most of the year. The shallower aquifers show a downward gradient.

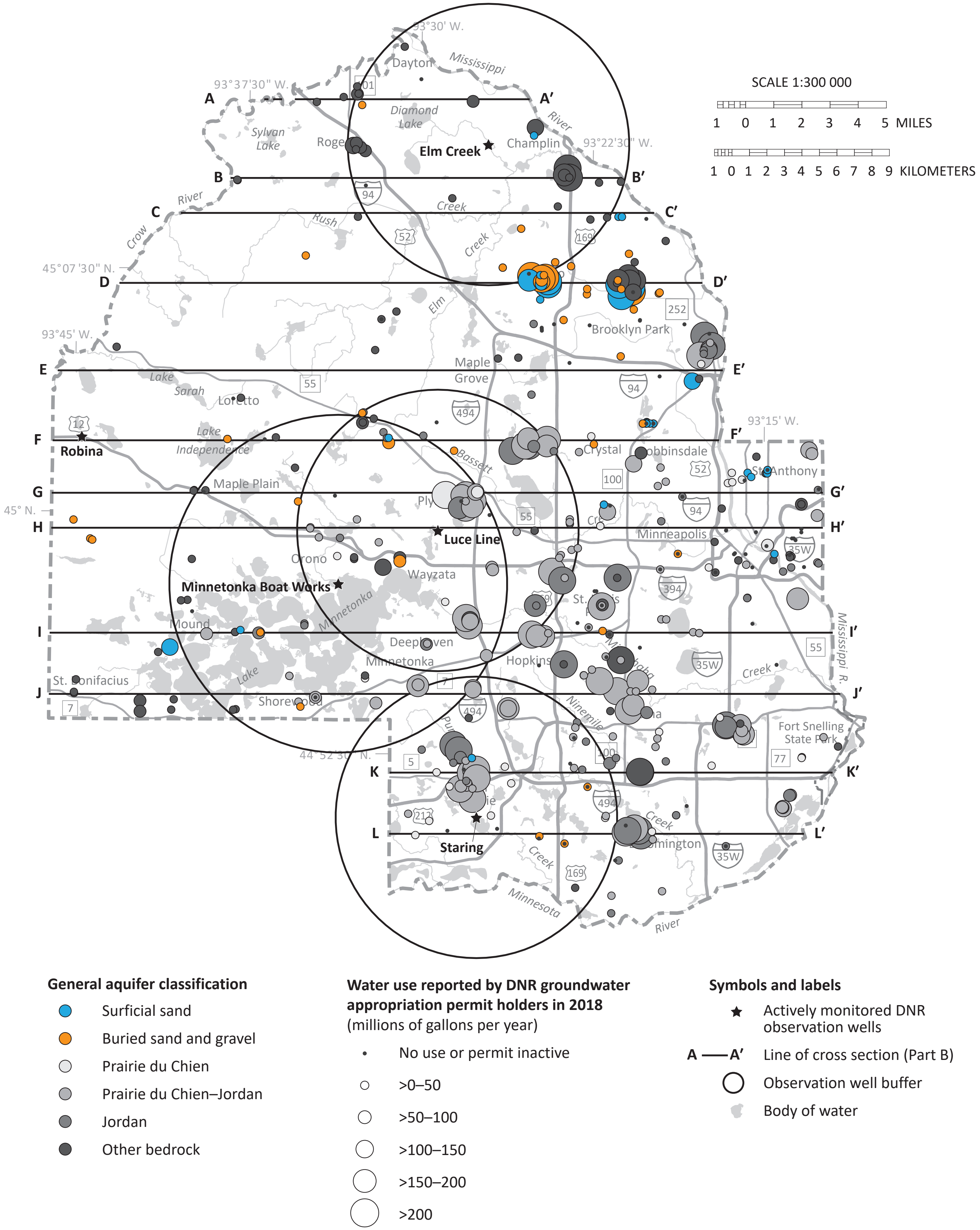


Figure 49. Groundwater use by aquifer and observation well groups

Use is shown by aquifer classification or name and the location of DNR observation well nest/groups. The four observation well nests at the center of the large circles (Boat Works, Staring, Luce Line, and Elm Creek) are evaluated as described in the previous text and Figures 50–54, including water-level comparisons of various aquifers against precipitation and cumulative pumped groundwater.

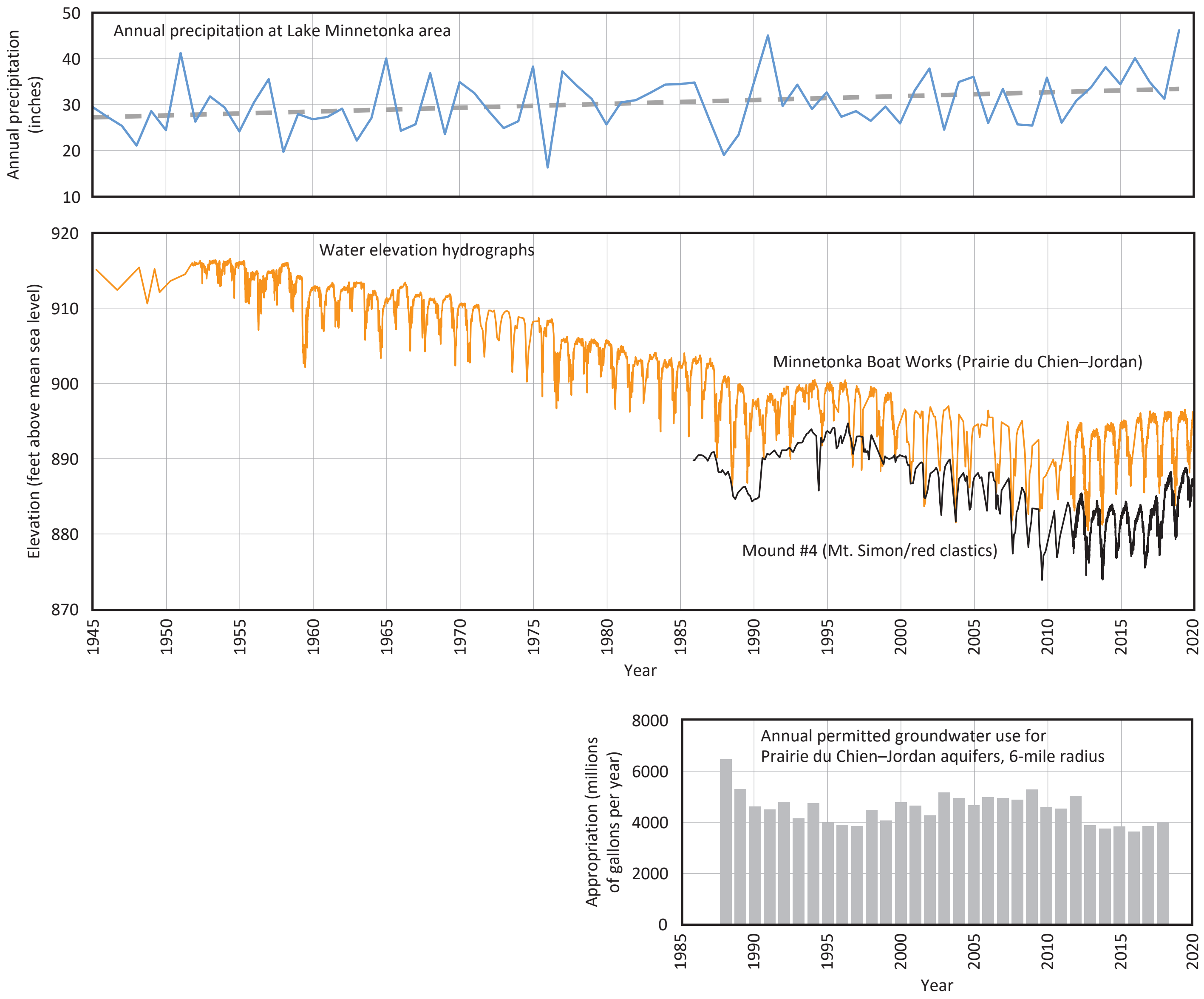


Figure 50. Minnetonka Boat Works hydrograph, Prairie du Chien and Jordan aquifers

Hydrograph represents the groundwater use the Prairie du Chien and Jordan aquifers within a 6-mile radius, as well as precipitation from 1945 to 2018. This is one of the longest water-level records in the TCMA and monitors the most heavily used combination of aquifers: wells that intersect both the combined Prairie du Chien–Jordan (OPCJ) and Jordan (CJDN).

The hydrograph shows short (annual), medium (several years) and long-term (decades) trends. The short-term trends are caused by increased pumping during the summer and early fall. The low water levels of summer season typically have not returned to the yearly high water levels of the previous year since the 1950s, creating a steady decline to approximately 2010.

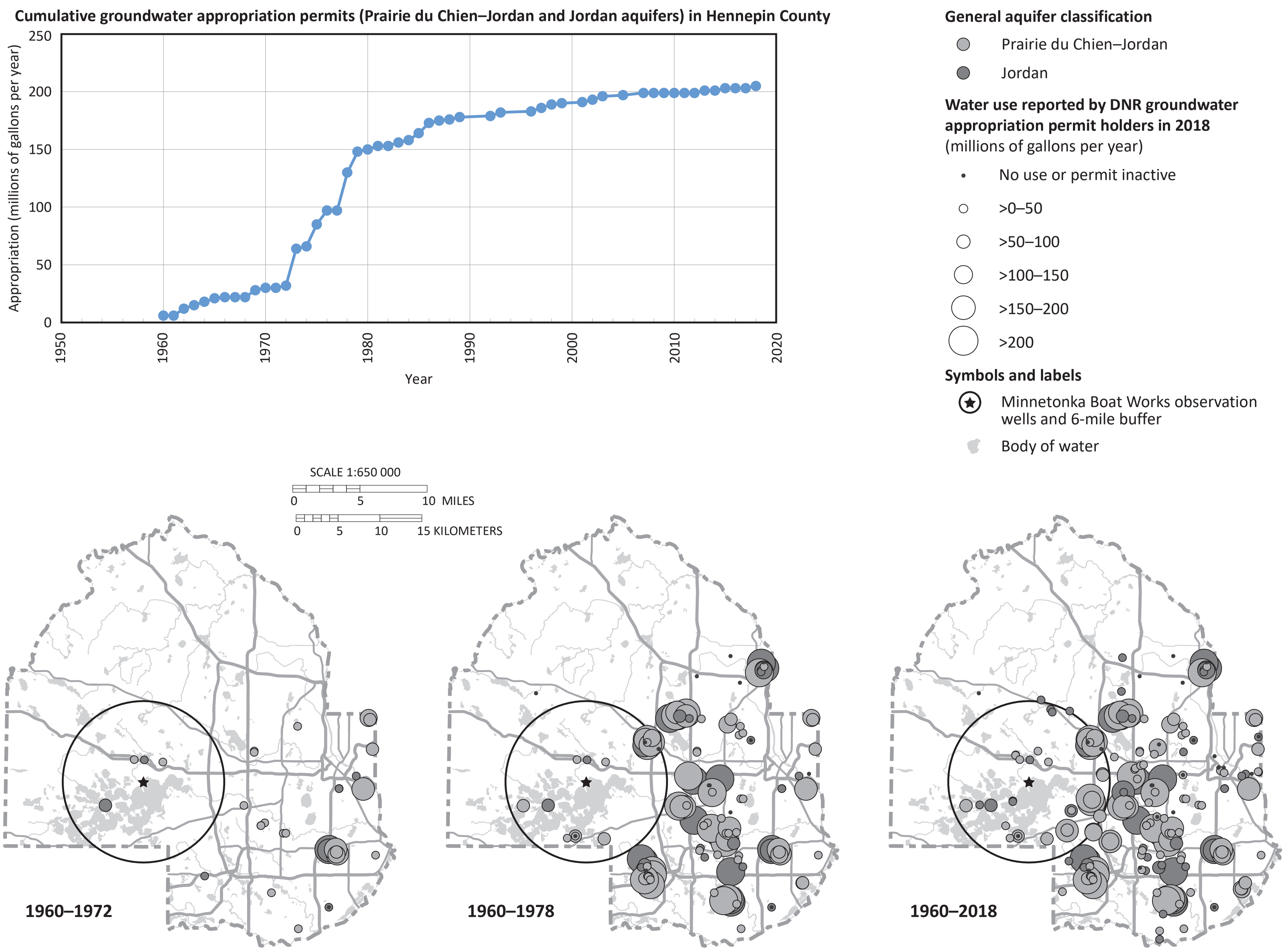


Figure 51. Groundwater use of the combined Prairie du Chien–Jordan and Jordan aquifers from 1960–2018

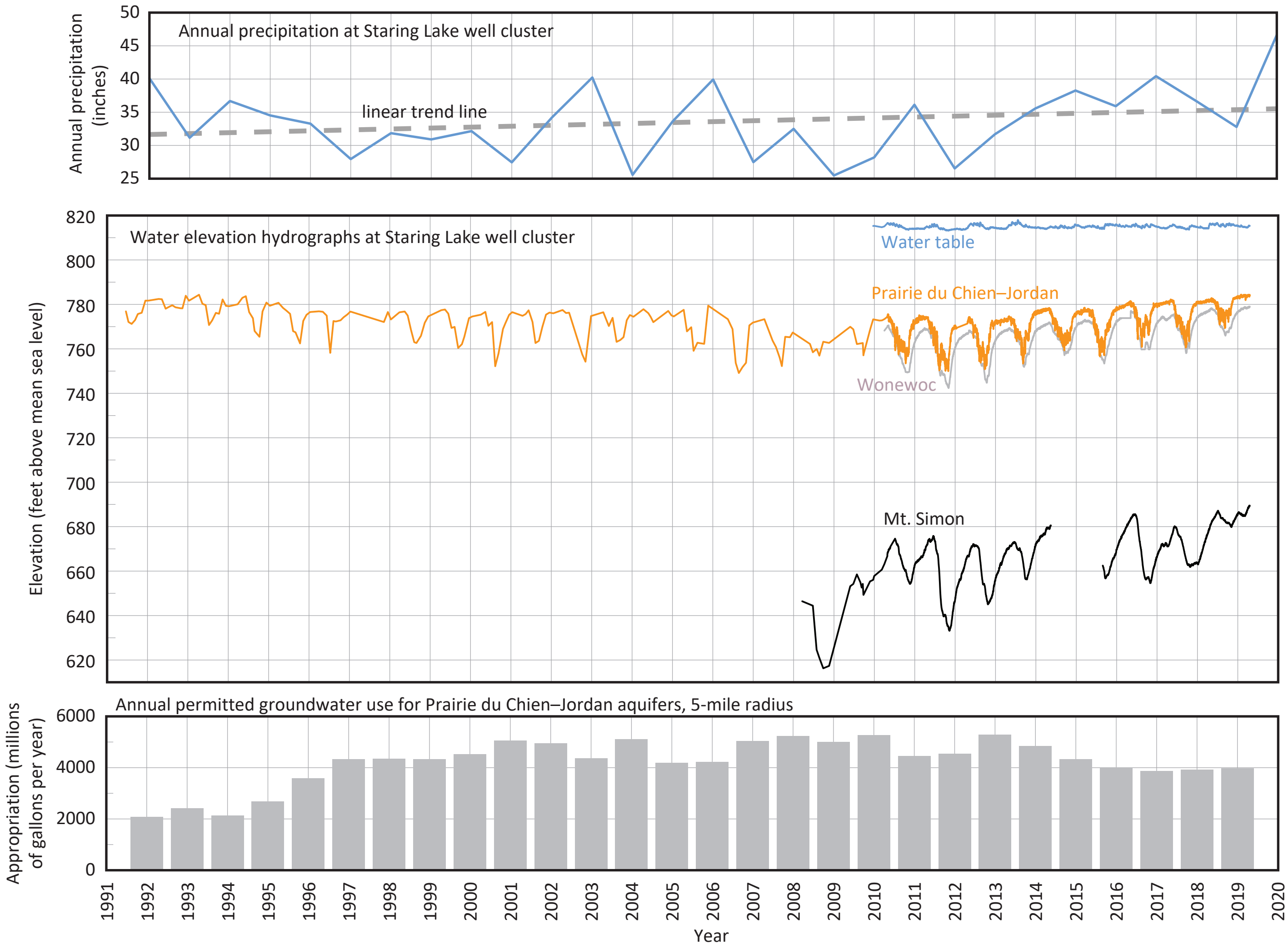


Figure 52. Staring Lake well cluster hydrographs, Prairie du Chien–Jordan

Hydrographs represent annual groundwater use of the Prairie du Chien–Jordan in a 5-mile radius, and annual precipitation. The groundwater-use graph shows the majority is from the nearby Eden Prairie well field to the north, and the Chanhassen well field to the west. The Prairie du Chien–Jordan hydrograph appears to be influenced by appropriations from these two areas. The graphs show slightly depressed water levels from 1996 through approximately 2014 matching the higher-use amounts during that same period.

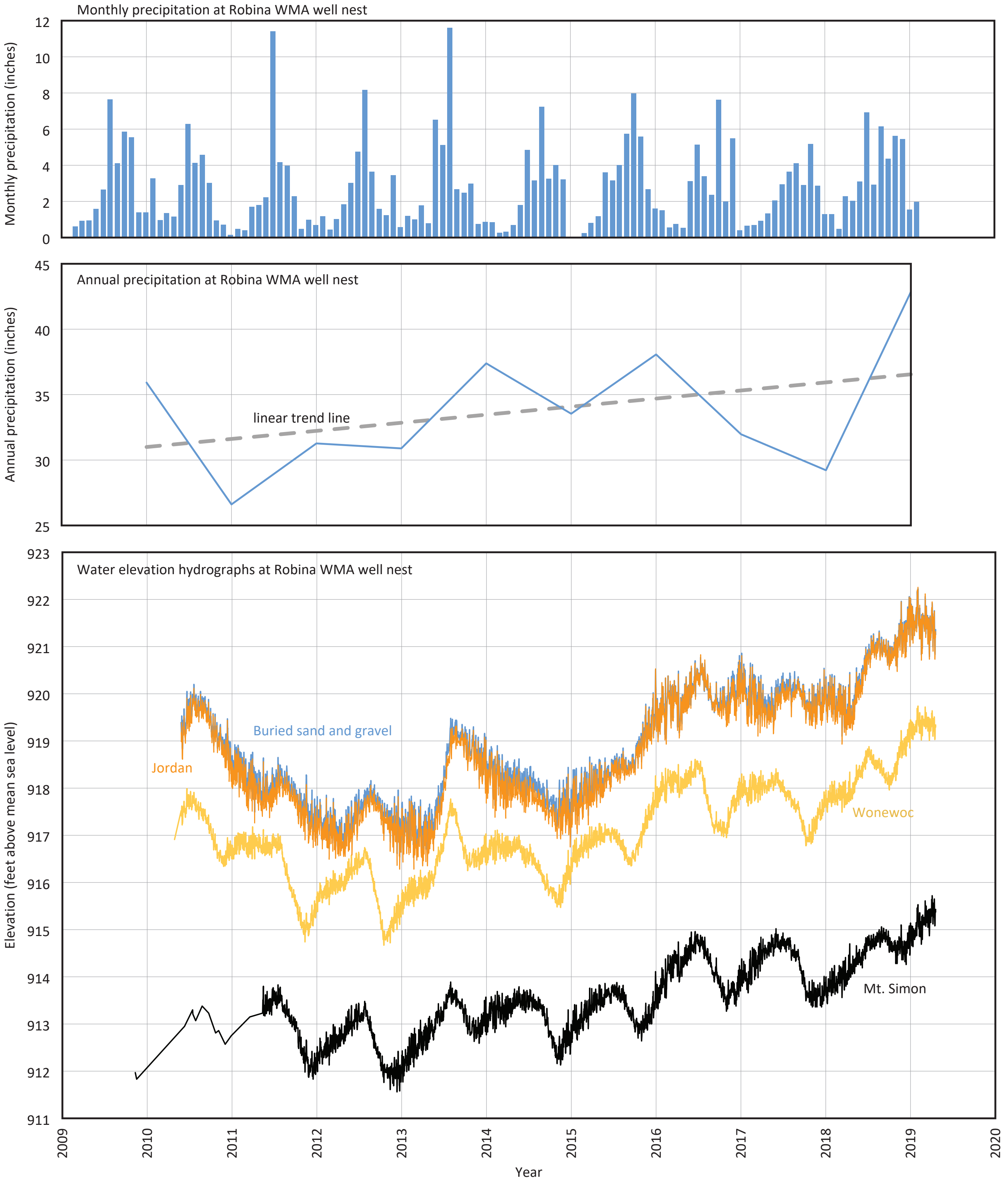


Figure 53. Robina well nest hydrographs, monthly and annual precipitation

The Robina well nest is at the western county border, far from most of the heavily used suburban areas. The annual fluctuations in all the hydrographs appear to be dominantly because of annual precipitation patterns.

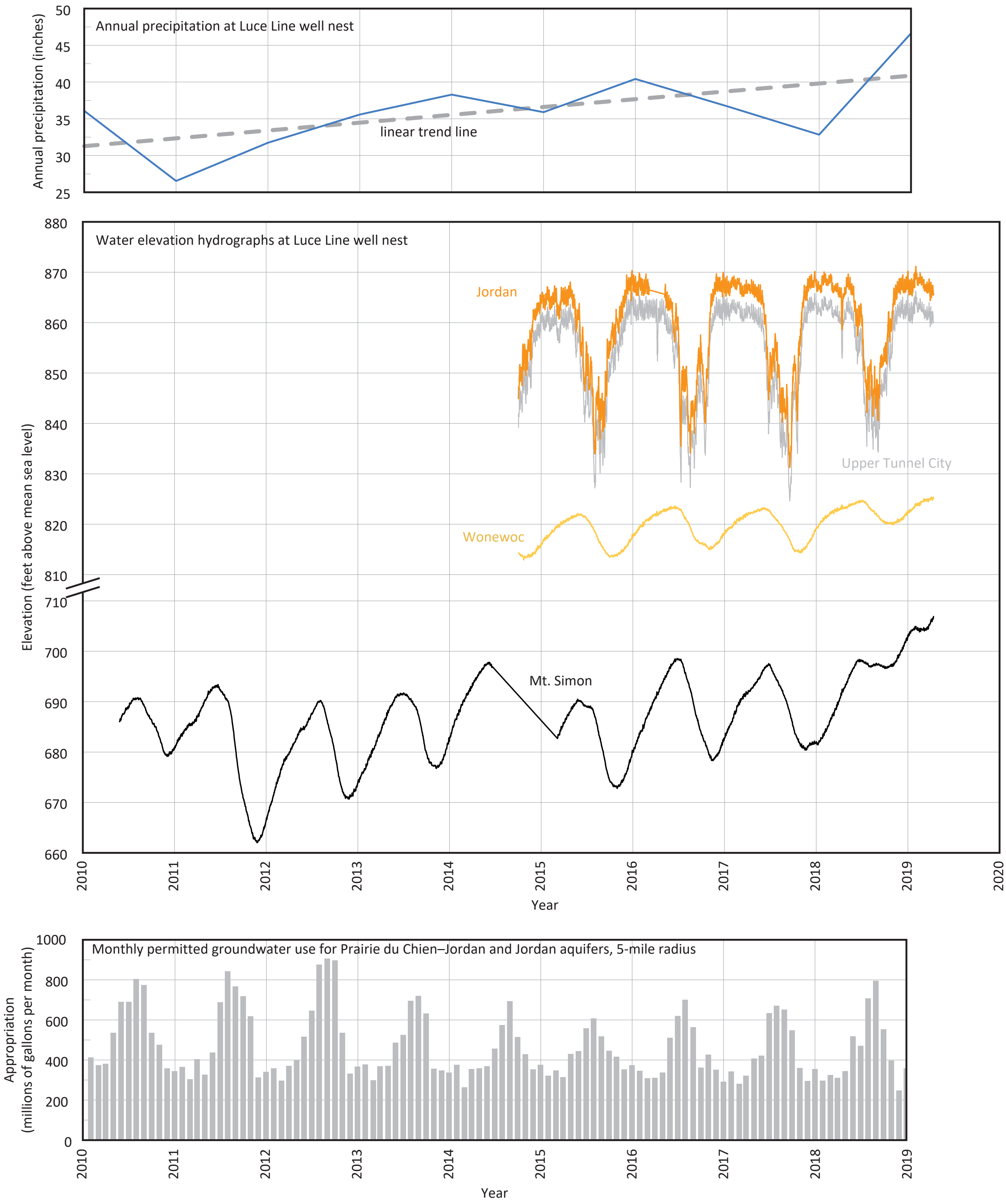


Figure 54. Luce Line well nest hydrographs, precipitation, and Prairie du Chien–Jordan appropriation

The nest is near the center of the county and approximately 1 mile southwest of the Plymouth well field. The proximity to the well field creates a large seasonal fluctuation from pumping of the combined Prairie du Chien–Jordan and Jordan aquifers. Summer drawdowns are approximately 30 feet. The typical water levels between the Mt. Simon and Wonewoc is over 120 feet. Separation between the Mt. Simon and the Jordan aquifer levels is over 160 feet.

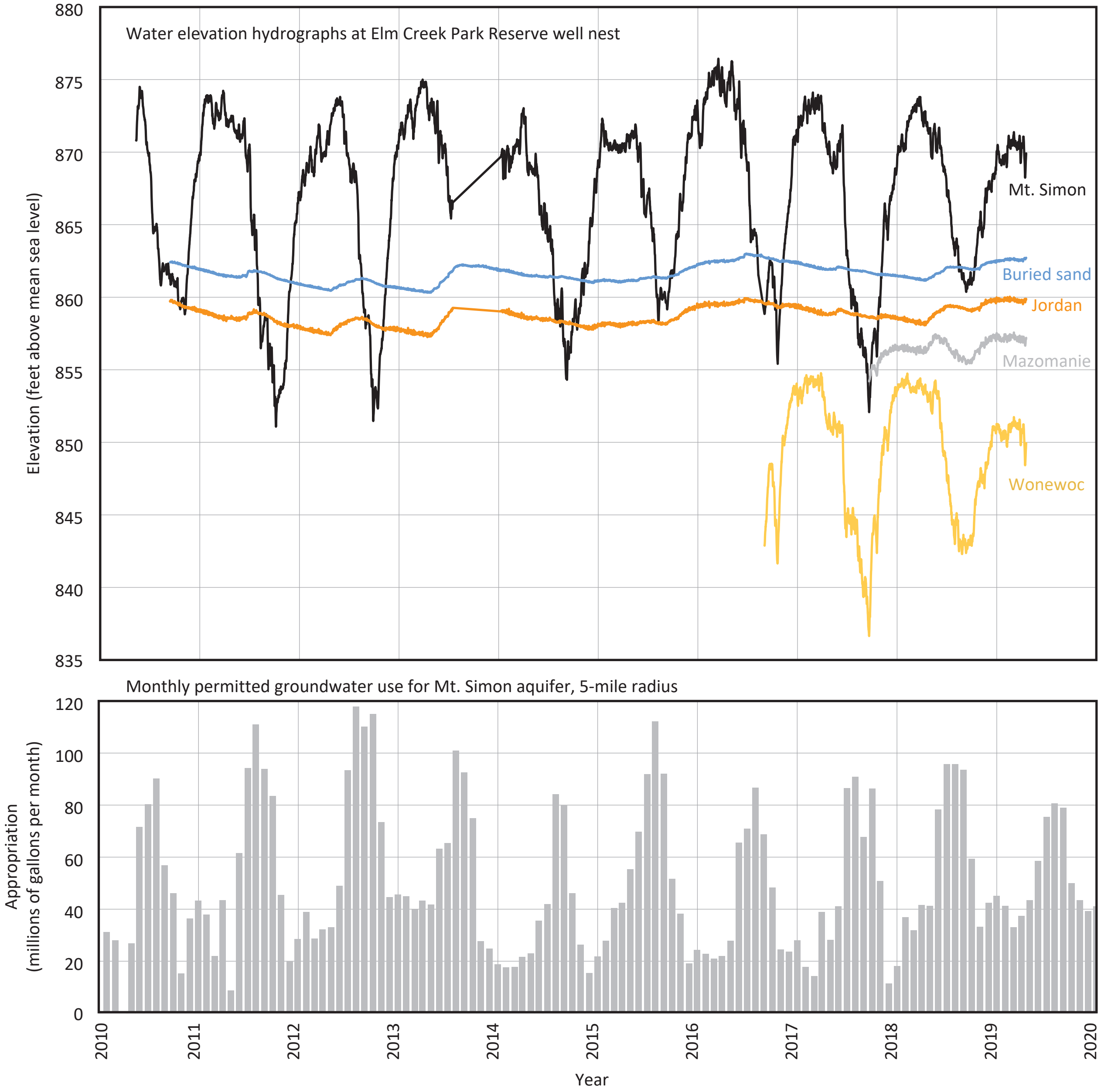


Figure 55. Elm Creek well nest hydrographs of multiple aquifers

Hydrographs represent the buried sand, Jordan, Mazomanie (Upper Tunnel City), Wonewoc, and Mt. Simon aquifers, and monthly groundwater use from the Mt. Simon aquifer in a 5-mile radius. This well nest is approximately 2 miles southwest of the Mississippi River, and approximately 2 to 3 miles west of wells operated by the city of Champlin. The Champlin well field includes the Mt. Simon aquifer and combinations of other aquifers.

The seasonal Mt. Simon pumping peaks match the seasonal low water levels. The winter Mt. Simon water levels are higher than those of the overlying Wonewoc, Mazomanie (Upper Tunnel City), Jordan, and buried sand aquifers, indicating an upward gradient from the Mt. Simon aquifer and discharge to the nearby Mississippi River most of the year. The shallower aquifers show a downward gradient.

Groundwater use

A water appropriation permit is required from the DNR for groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year. This 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 Minnesota Permitting and Reporting System (MPARS), which helps the DNR track the volume, source aquifer, and type of water use (DNR, 2019b).

Permitted groundwater use is presented by water use category in Table 3 and Figure 56. Aquifers in Table 3 are listed by general aquifer type in Figure 49. The highest volume use by general aquifer type is from the combined Prairie du Chien and Jordan aquifers (41 percent) followed by the Jordan aquifer (22 percent). Other significant aquifer or aquifer combinations include the unconsolidated water table (11 percent) and buried sand aquifers (9 percent).

The other bedrock aquifers such as the Tunnel City multiple aquifer completions (6 percent) and the Mt. Simon (4 percent), are used at a much lower percentage compared to the Prairie du Chien–Jordan and Jordan aquifers.

The most common water use is for municipal/public water supply (90 percent) which dominates in the highly populated suburban eastern Hennepin County. Industrial processing (5 percent) is one of the more common uses in Minneapolis. Noncrop irrigation (3 percent) for golf courses, landscaping, and athletic fields is a very common but relatively low volume and highly dispersed across most of the county.

There are approximately 20,500 located wells in the county. By total wells, 76 percent are domestic, 10 percent are monitoring wells at contamination sites, and 4 percent are public water supply.

Table 3. Reported 2018 water use from DNR groundwater permit holders in millions of gallons per year (mgy)

Aquifer	Number of wells	Use category									Total (mgy)	Total (percent)
		Agricultural irrigation	Heating/ cooling	Industrial processing	Noncrop irrigation	Pollution containment	Power generation	Special categories	Water-level maintenance	Water supply		
Quaternary aquifers												
Water table	45	3	--	3	14	85	--	--	131	3,108	3,344	11
Buried sand	57	7	--	1	152	9	--	--	7	2,452	2,628	9
Bedrock aquifers												
Platteville (OPVL)	6	--	--	--	--	21	--	--	--	--	21	<1
St. Peter (OSTP)	20	--	--	--	15	9	--	--	87	7	118	<1
St. Peter multiples* (OPDC, CJDN, CSTL, CTCG, CWOC)	14	--	39	7	6	--	--	--	--	121	173	<1
Prairie du Chien (OPDC)	48	--	--	268	84	--	47	14	6	234	653	2
Prairie du Chien–Jordan (OPCJ)	171	--	38	881	304	18	--	8	2	10,961	12,212	41
Prairie du Chien multiples* (CSTL, CTCG, CWOC)	9	--	--	--	31	--	--	--	--	293	324	1
Jordan (CJDN)	75	--	2	216	86	--	--	14	--	6,223	6,541	22
St. Lawrence (CSTL)	2	--	--	--	2	--	--	--	2	--	4	<1
St. Lawrence multiples* (CTCG, CWOC, CMTS)	18	1	--	78	9	--	--	--	--	33	121	<1
Tunnel City (CTCG)	4	--	--	--	29	--	--	--	--	--	29	<1
Tunnel City multiples* (CWOC, CECR, CMTS)	48	3	--	<1	87	--	--	--	--	1,768	1,858	6
Wonewoc (CWOC)	3	--	--	--	--	--	--	--	--	58	58	<1
Wonewoc multiples* (CECR, CMTS)	4	--	--	--	--	--	--	--	--	201	201	<1
Mt. Simon (CMTS)	14	--	--	60	--	--	--	--	--	1,060	1,120	4
Mt. Simon multiples* (PMHN, PMFL)	3	--	--	--	--	--	--	--	--	331	331	1
Hinckley–Fond du Lac (PMHF)	1	--	--	--	--	--	--	--	--	30	30	<1
Total (mgy)	na	14	79	1,515	819	142	47	36	235	26,880	29,766	na
Total (percent)	na	<1	<1	5	3	<1	<1	<1	<1	90	na	na

Data from MPARS;
mgy, million gallons per year; dash marks (--) indicate no use in those categories. na indicates not applicable.
Percentage might not equal 100 because of rounding.
*Multiple aquifer wells include wells completed with the first aquifer listed as the uppermost unit and combinations of other aquifers listed in parentheses. Multiple aquifer wells are typically open to all units within the stratigraphic interval defined by the units listed.

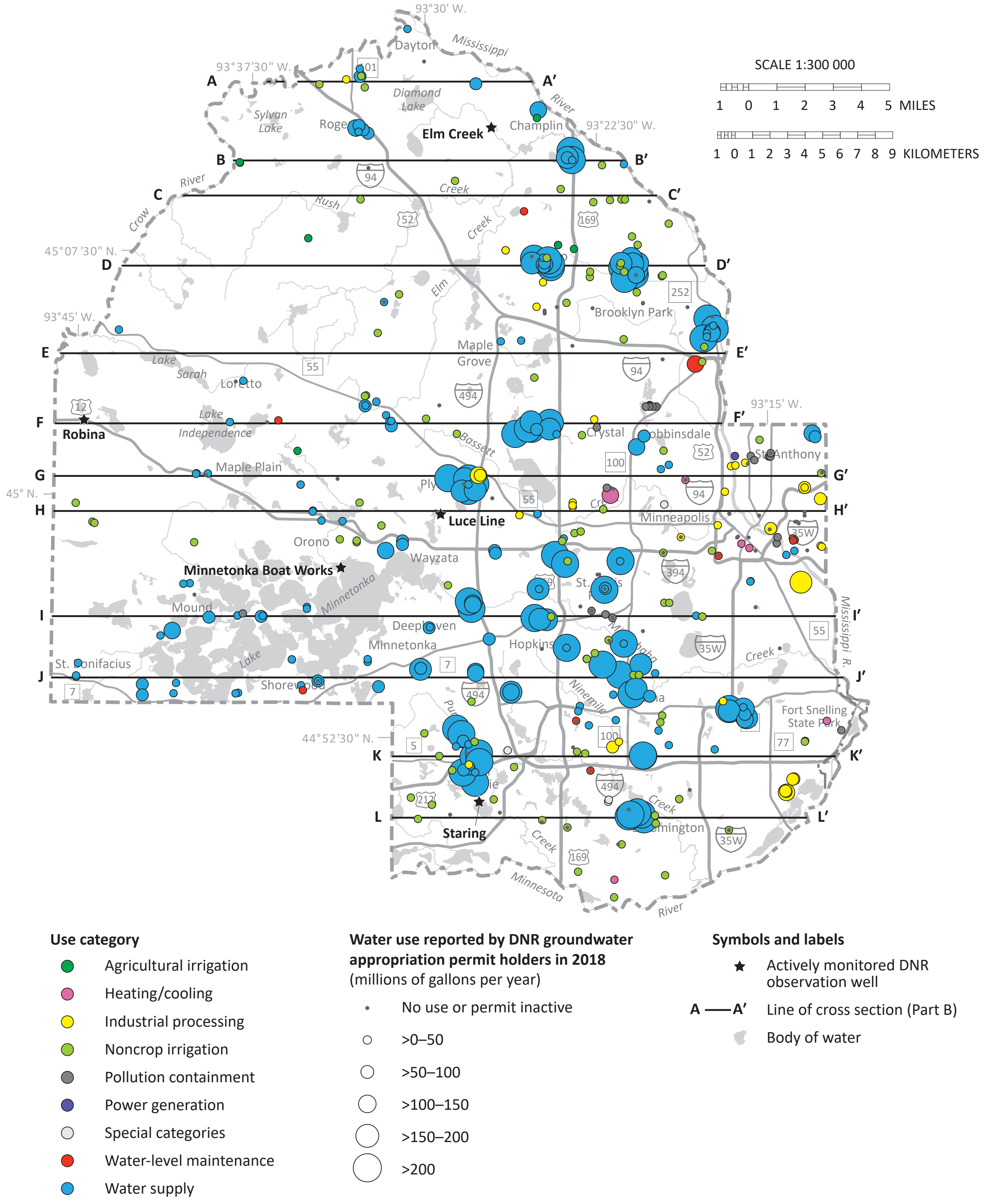


Figure 56. Groundwater use by use category and volume

Water use is reported from DNR groundwater appropriation permit holders in 2018 (millions of gallons per year).

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Glossary

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

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

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

aquitard (or confining layers)—layers made up of materials with low permeability, such as clay and shale, which prevent rapid or significant movement of water.

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

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

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

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

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

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

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

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

formation—a fundamental unit of lithostratigraphy. A formation consists of a certain 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 level monitoring well—a well that is used to monitor the water level of groundwater. It is usually not used as a water source.

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

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

hydraulic—relating to water movement.

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

ice-contact sediment—deposited in direct contact with, or in the immediate proximity of glacier ice.

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

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

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

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

nitrate (nitrate-N, NO_3)—humans are subject to nitrate toxicity, with infants being especially vulnerable to methemoglobinemia, also known as blue baby syndrome. Elevated nitrate (greater than or equal to 1 ppm) is primarily from fertilizer sources.

Paleozoic—an era of geologic time from approximately 542–251 million years ago.

perched water table—a water saturated zone above an aquitard that is underlain by an unsaturated zone.

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

provenance—the place of origin of a glacier.

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 radioactive particles.

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

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

stable isotope—chemical isotopes that are not radioactive.

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

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

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

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

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

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

undifferentiated sediment—includes till, sand, gravel, and fine-grained lake sediment. Shown in areas where control data were scarce or absent.

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

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

Samples were analyzed by DNR staff; the Minnesota Department of Agriculture (MDA); the University of Minnesota, Department of Earth and Environmental Sciences Laboratory (UMN); or the University of Waterloo Environmental Isotope Laboratory (Waterloo).

The well owners received a copy of the results including some 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**	**^{14}C**
Lab	Waterloo	Waterloo	MDA	MDA	MDA	DNR	UMN
Sample container	500 ml HDPE	60 ml HDPE	250 ml plastic	250 ml plastic	250 ml plastic	500 ml plastic	30 or 55 gallon plastic-lined drum
Head space	yes	yes	yes	yes	yes	no	yes
Rinse	no	no	yes*	yes*	yes*	yes**	no
Filter	no	no	yes	yes	yes	no	yes
Preservation	none	none	Sulfuric acid (H_2SO_4) to pH <2, Cool to ≤ 6°C	Cool to ≤ 6°C	Nitric acid (HNO_3) to pH<2 ***	Cool to ≤ 6°C, if not analyzed onsite	NH_4OH to pH 10 to precipitate carbonate
Holding time	long	long	28 days	28 days	6 months	24–48 hours	long
Field duplicate	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	none
Field blank	none	none	1 for every 20****	1 for every 20****	1 for every 20****	none	none
Storage duplicate	yes	yes	no	no	no	no	no

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

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

***Metals sample bottle is stored at 0–6°C for convenience. Refrigeration is not required.

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

Appendix B

Tritium values from precipitation and surface water

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

- **Precipitation composites** were collected at the Minnesota DNR MNgage climatology monitoring station MWDM5 in Maplewood (Twin Cities metropolitan area). Precipitation was collected daily and composited for approximately 30 days.
- **Lake-water sample** was collected near the shore where the water depth is approximately 1 meter.

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

For additional weather station information, contact the MNgage program.
https://climateapps.dnr.state.mn.us/HIDENsityEdit/HIDENweb.htm

Appendix Table B. Enriched tritium results

Sample date range	Tritium	Sample type
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
04/11/2019	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
06/05/2019	8.5	Lake-water, Diamond Lake

Tritium age of historic groundwater samples

The groundwater atlas uses tritium data to assess the residence time of groundwater, which is then used to evaluate atlas pollution sensitivity models and recharge conditions of the aquifer. Data from other studies prior to the DNR project sample period (historic data) are used to inform our understanding of groundwater residence time where we lack current data. Tritium ages for all samples (current and historic) are calculated based on sample date using the method described in *Tritium-age classification–revised method for Minnesota* (DNR and MDH, 2020).

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Funding for this project was provided by the following:

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

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