COUNTY ATLAS SERIES C-26, PART B
Blue Earth County, Minnesota Scales 1:100,000 to 1:500,000

MINNESOTA DEPARTMENT OF NATURAL RESOURCES

GEOLOGIC ATLAS OF BLUE EARTH COUNTY, MINNESOTA

COUNTY ATLAS SERIES C-26

PART A

(Published separately by the Minnesota Geological Survey)

Plate 1, Data-Base Map; *Plate 2,* Bedrock Geology;
Plate 3, Surficial Geology; *Plate 4,* Quaternary Stratigraphy;
Plate 5, Sand Distribution Model;
Plate 6, Bedrock Topography *and* Depth to Bedrock

PART B

Report

***Plate 7*, Bedrock Groundwater Flow Directions**

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2016

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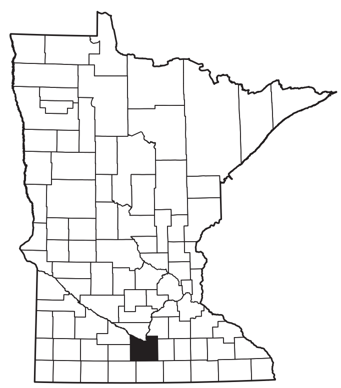
Geologic Atlas of Blue Earth County, Minnesota

County Atlas Series C-26, Part B

By James A. Berg

2016



LOCATION DIAGRAM

State of Minnesota
Department of Natural Resources
Division of Ecological and Water Resources

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

The trust fund is a permanent fund constitutionally established by Minnesotans to assist in the protection, conservation, preservation and enhancement of the state's air, water, land, fish, wildlife and other natural resources.

The Clean Water Fund receives 33 percent of the sales tax revenue from the Clean Water, Land and Legacy Amendment, which was approved by voters in November 2008. The Clean Water Fund's purpose is to protect, enhance and restore water quality in lakes, rivers, streams and groundwater.

At least 5 percent of the money is targeted for the protection of drinking water sources. The Legislature allocates funds for water quality work and drinking water protection based on recommendations from the Clean Water Council.

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Technical Reference

Maps were compiled and generated in a geographic information system (GIS). Digital data products, including chemistry and geophysical data, are available from the Department of Natural Resources, Division of Ecological and Water Resources page (mndnr.gov/groundwatermapping).

Maps were prepared from DNR and other publicly available information. Every reasonable effort has been made to ensure the accuracy of the factual data on which the report and map interpretations were based. However, the DNR 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 modified from Minnesota Geological Survey, Blue Earth County Geologic Atlas, Part A, 2012.

Universal Transverse Mercator projection, zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

GIS and cartography by James A. Berg, Shana Pascal, and Holly Johnson. Edited by Carrie Jennings and Ruth MacDonald.

Geologic Atlas of Blue Earth County, Minnesota, Part B

by James A. Berg

Abstract

This Blue Earth County report describes the distribution and physical characteristics of the most important aquifers in the county and assesses their sensitivity to pollution from surface sources. The pollution sensitivity evaluations indicated that the water table, at an assumed depth of 10 feet below ground surface, generally had slow infiltration rates (weeks to a year) in the eastern and southern portions of the county resulting in low to very low pollution sensitivity ratings. All the major river valleys and a large sandy area in the northwestern area of the county showed higher infiltration rates (a week to weeks) to the water table and therefore have a moderate sensitivity rating. The majority of the buried aquifers, ranging in depths from approximately 50 to 200 feet below ground surface, were interpreted to have generally low or very low sensitivity ratings with an interpreted vertical travel rate of a pollutant from decades to centuries or more. The major river valleys in the northern portion of the county (Watonwan, Blue Earth, Le Sueur, Maple, and Minnesota) showed moderate to very high sensitivity rating (pollutant infiltration rate of decades to hours) for most of the aquifers. Other notable local exceptions included some shallow buried portions of aquifers. Younger water samples (recent and mixed tritium age) were typically found in areas of moderate to very high sensitivity whereas older water samples (vintage tritium age) were typically found in areas of low to very low sensitivity. Isotopic ratios that are characteristic of surface water were detected for long distances downgradient of Madison Lake suggesting a significant connection between the lake and the underlying aquifer system. Other topics covered in the atlas include water-table depth and flow directions; water-use distribution; and distribution of chemicals that exceed human-health thresholds such as arsenic, manganese, and nitrate.

Introduction

The purpose of this atlas is to help citizens and local governments understand the geologic setting and inherent pollution sensitivity of the aquifers in the county. This information can potentially be used to make land-use decisions that take aquifer sensitivity, water quality, and sustainability into account. Protecting the quality and quantity of all groundwater ensures long-term access.

The report describes the distribution and physical characteristics of the most important aquifers in the county and assesses their sensitivity to contamination from surface sources. The accompanying plates illustrate the bedrock hydrogeology (Plate 7) and eight hydrogeologic cross sections (Plates 8 and 9) showing groundwater flow directions within the buried sand and gravel aquifers (shortened to buried sand aquifers for the remainder of the report) and bedrock aquifers. This information should help the reader visualize subsurface groundwater flow and residence-time conditions within the county.

The Minnesota Department of Natural Resources (DNR) produces this report as Part B of a two-part series. It is based on the geologic components of Part A (Plates 1 through 6), produced by the Minnesota Geological Survey (MGS). Additional information is available regarding the history and purpose of the program, various atlas applications, and descriptions of the Part A components (Setterholm, 2012b).

The focus of the atlas is the pollution sensitivity assessment in Blue Earth County for the water-table aquifer, seven buried sand aquifers, and the bedrock surface. Pollution sensitivity is defined by the physical properties that affect downward migration of pollutants to the groundwater. The main variable is the rate that water travels from the surface to the aquifers.

Simplifying assumptions used to produce the maps in this atlas are: flow paths are vertical and downward; pollutants move at the same rate as water (advection);

and sediment texture, if known, is the primary factor controlling permeability. In confined-aquifer settings the texture and permeability of the aquitards are often unknown but assumed to be fine-grained and low, respectively. Therefore, the thickness of the layers overlying the sensitivity target layer (often an aquifer) is the primary variable affecting the sensitivity rating.

The pollution sensitivity models used geologic data provided by the MGS. The model results for seven buried sand aquifers and the bedrock surface were evaluated with residence-time indicators from 116 water samples. Groundwater residence time was estimated by the concentration of radioactive tritium (^3H) in the groundwater. Source water connections were determined from characteristic ratios of stable isotopes of oxygen and hydrogen in the samples. Also discussed are the presence of naturally occurring arsenic and manganese, elements of health concern in groundwater, and groundwater-use information categorized by aquifer and type of use.

Study area

Blue Earth County is located in the central portion of southern Minnesota. The Minnesota River forms more than half of the northern county border and drains most of the county, along with its three major tributaries. The county lies within the watersheds of the Minnesota, Blue Earth, Le Sueur, Watonwan, and Cannon rivers. As of 2010, the county had 64,000 residents with most of them living in the county seat and regional center of Mankato (population 40,000).

The topography is level to rolling in most of the county. In the Mankato area, the Minnesota River and its tributaries are deeply incised into the surface, creating river gorges with wooded bluffs and tributary ravines. Springs or seeps are common in these valleys.

Surficial geologic units and aquifers

The origin of the topography and surficial deposits can be traced back to late-glacial events (Part A, Plate 3) as ice retreated from the county and a proglacial lake formed. Layers of silt and clay that settled out of the glacial lake form the level surface that covers much of the county. The glacial lake was bounded on the east and south by a slightly higher arc of more rolling terrain that formed as debris-covered ice stagnated at the margin of a glacier.

The lake sediment overlies layers of fine-grained glacial sediment (till). Areas of sand and gravel are generally thin (0 to 20 feet) and are located north of the Watonwan River and south of Lake Crystal where meltwater streams entered the lake from the west, depositing a sandy delta.

As ice receded north, the sudden drainage of a much larger glacial lake (glacial Lake Agassiz) created the 200-foot-deep, mile-wide, glacial River Warren valley now occupied by the Minnesota River. The incision of this valley caused all tributary streams to begin adjusting their gradients to this new local base level by downcutting, a process that is ongoing. The sediment delivered by the tributaries forms fans at the tributary mouths and partly fills their lower reaches near the confluences with the Minnesota River. Locally thick sand and gravel (up to 80 feet) is found in the Minnesota River valley and the lower reaches of the Watonwan, Blue Earth, and Le Sueur rivers (Figure 1).

A water-table aquifer occurs where a surficial sand layer is saturated. The water table may periodically drop below the base of the sand layer during dry periods, as is the case with a relatively thin sand layer north of the Watonwan River and south of Lake Crystal.

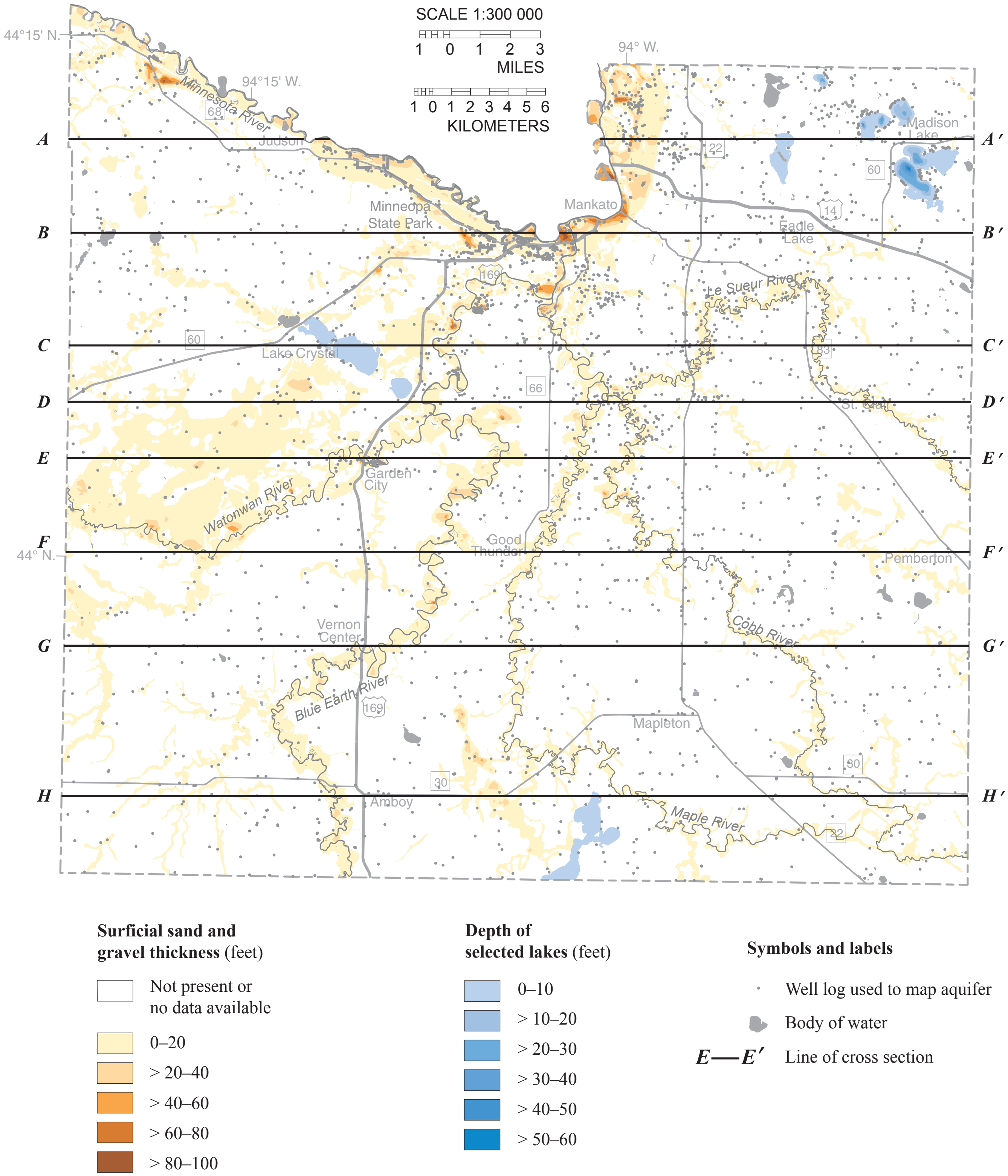


Figure 1. Surficial sand and gravel thickness

The surficial sand and gravel is generally thin (0 to 20 feet) across most of the county except locally. The aquifer this layer hosts is a minor source of human water supply except in the Mankato area along the Minnesota River valley.

Quaternary stratigraphy

Deeper sediment layers were deposited during multiple episodes of glaciation during the past 2 million years (Part A, Plates 4 and 5). An unsorted mixture of clay, silt, sand, and gravel was brought to the region by glaciers and was deposited directly by the ice (till). In places it was sorted as it was deposited by meltwater streams (primarily sand and gravel) and lakes (primarily silt and clay) (Part A, Plate 4 and Part B, Plate 7). Glacial deposits are highly variable and the associated sand aquifers are typically thin (20 to 50 feet thick) and discontinuous with lateral extents rarely exceeding several miles. Buried aquifers are typically surrounded by fine-grained, lake- and glacial-sediment layers that serve as aquitards.

A stratigraphic column that summarizes the material and hydrogeologic properties of the glacial sequence shows the corresponding Part A and B unit names and map labels (Figure 2). Part B maps and cross sections build on the geologic framework and GIS map elements to describe the hydrogeology of the subsurface. Aquitards (Part B) are shown as light or medium shades of gray to represent presumed relative hydraulic conductivity and sand content: light gray equals 50–56 percent sand, medium gray equals 31–39 percent sand. The brown units are undifferentiated sediments with an unknown texture.

Part B	Part A	
ss		surficial sand and gravel
	Quh	clayey till (Heiberg)
sh	*Qsh*	sand and gravel
	Qlh	clayey till (lower Heiberg)
sm	*Qsm*	sand and gravel
	Qmt	sandy till (Moland)
st	*Qst*	sand and gravel
	Qtt	sandy till (Traverse)
sg	*Qsg*	sand and gravel (not shown)
	Qg1	clayey till (Good Thunder)
s2	*Qs2*	sand and gravel
	Qg2	till (Good Thunder)
se	*Qse*	sand and gravel
	Qet	till (Elmdale)
su	*Qsu*	sand and gravel
	Qut	till, fine-grained lake sediment
ups	*Qu*	undifferentiated sediment
		bedrock

Figure 2. Hydrostratigraphy of Quaternary unconsolidated sediments

Bedrock geologic units and aquifers

The bedrock formations of Blue Earth County are regionally extensive, gently dipping layers of sandstone, shale, and carbonate rock that range from 50 feet to greater than 200 feet in thickness (Figure 3). The sandy, silty, clayey, and calcareous sedimentary rocks were originally deposited in mostly shallow marine settings during the Paleozoic era (500 to 450 million years ago) (Part A, Plate 2). They potentially endured periods of weathering while at or near the surface.

These formations include in ascending order (oldest to youngest) the relatively thick Mt. Simon Sandstone, Eau Claire Formation, Wonewoc Sandstone, Lone Rock (Tunnel City Group) and St. Lawrence Formations, and the Jordan Sandstone. The stratigraphically higher and younger layers (Ordovician age) comprise mostly carbonate rock (limestone, and dolostone) and include units such as the Prairie du Chien Group and the Platteville Formation.

There are limited occurrences of the Ordovician St. Peter Sandstone in the southeastern portion of the county and scattered occurrences of much younger, Cretaceous marine rocks including shale and sandstone. The Cretaceous Dakota Formation and the unnamed Ka unit have limited aquifer potential. The extent of these units is shown in Part A, Plate 2 but has not been represented on any of the bedrock maps in this report (Plate 7).

The aquifers associated with the non-Cretaceous bedrock layers are more commonly used for water by municipalities and commercial operations because of their thickness, extent, predictability, and features that affect water yield. In sandstone aquifers such as the Jordan and Wonewoc, water moves through intergranular pore spaces and larger macropores such as fractures. Groundwater in the Prairie du Chien and Upper Tunnel City aquifers mainly moves through enlarged fractures or macropores. An enhanced-permeability zone is generally found in approximately the uppermost 50 feet of all sedimentary bedrock units (Runkel and others, 2006). It likely developed when the bedrock surface was at the land surface. The fractures in this zone generally increase the yield from aquifers but compromise the protective character of aquitards.

Geologic Period	Geologic Unit		Hydrogeologic Unit	Hydrogeologic Unit Properties
Cretaceous	Dakota Formation			Moderate intergranular permeability
	Unnamed Unit (Ka)		Ka aquifer	Low to moderate intergranular permeability, thin sandstones are interlayered with siltstone and claystone, probably low yielding aquifer.
Ordovician	Platteville Formation			Relatively low intergranular permeability with high permeability fractures
	Glenwood Formation			Aquitard, aquifer-shallow conditions
	St. Peter Sandstone		St. Peter aquifer	Moderate intergranular permeability
	Prairie du Chien Group	Shakopee Formation	Prairie du Chien aquifer	Relatively low intergranular permeability with high permeability fractures
		Oneota Dolomite		Aquitard, aquifer-shallow conditions
Cambrian	Jordan Sandstone		Jordan aquifer	Relatively high intergranular permeability with high permeability fractures
				Aquitard, aquifer-shallow conditions
	St. Lawrence Formation			Aquitard, aquifer-shallow conditions
	Tunnel City Group	Lone Rock Formation	Upper Tunnel City aquifer	Relatively low intergranular permeability with high permeability bedding fractures
				Aquitard, aquifer-shallow conditions
	Wonewoc Sandstone		Wonewoc aquifer	Moderate intergranular permeability
	Eau Claire Formation			Aquitard, aquifer-shallow conditions
	Mt. Simon Sandstone		Mt. Simon aquifer	Moderate intergranular permeability

Explanation

- Aquifer
- Low to moderate permeability aquifer, thin sandstones interbedded with siltstone and claystone
- Aquitard, generally low permeability
- High permeability bedding fracture
- Permeable fractures at shallow conditions

Figure 3. Bedrock stratigraphy and hydrostratigraphy (not to scale)

Geologic stratigraphic units (formations or groups) do not always correspond to hydrogeologic units (aquifers and aquitards).

Groundwater use and aquifer capacity

A water-use appropriation permit from the DNR is required for all groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year (with some exceptions). This provides the DNR with the ability to assess and regulate which aquifers are being used and for what purpose. Combined with an understanding of aquifer characteristics (specific capacity and transmissivity), it is possible to project whether the supply is adequate and uses are sustainable.

Groundwater use

The reported water use for 2013 (Table 1) is categorized for all large capacity users in the county by the type of aquifer (Figure 4) and type of use (Figure 5). The majority (56 percent) of the water used is municipal and mainly draws from the bedrock aquifers and the surficial sand aquifer. Of the approximately 3350 wells in the mapped area, only a few communities in the Minnesota River valley draw water from the surficial sand aquifer for domestic consumption. The largest municipal users from the bedrock aquifers are in the Mankato and Lake Crystal areas.

The next highest user is categorized as industrial or commercial (37 percent). These wells draw water exclusively from the bedrock aquifers and are mainly located in the north-central part of the county. Irrigation is a small percentage (5 percent) of water use, draws primarily from buried sand aquifers, and is mainly located in the western portion of the county.

There are no reporting requirements in Minnesota for well owners that use smaller quantities of groundwater, but the aquifer being used can be determined in many cases. Of the approximately 2700 active wells in the county with identified aquifers, most wells are completed in the sedimentary bedrock aquifers (55 percent) and buried sand aquifers (42 percent). Only 4 percent are completed in the surficial sand aquifer. The large majority of wells in the county are domestic wells (81 percent), followed by public supply (5 percent), commercial (2 percent), and other minor categories.

The DNR maintains approximately 1000 observation wells to monitor the cumulative effect of groundwater appropriation across the state. There is only one active observation well in the county near Lake Crystal. Because this well was only recently constructed, no data were available when this report was written.

Table 1. Reported 2013 water use from DNR groundwater permit holders

[Data from Minnesota Department of Natural Resources Permit and Reporting System (MPARS). MGY, million gallons per year; dash marks (--), no use in those categories. Percentages do not total 100 due to rounding]

	Aquifer (County Well Index aquifer code)				
Use 2013 MGY	Surficial sand (QWTA)	Buried sand and gravel (QBAA)	Bedrock	Total (MGY)	Total (percent)
Waterworks (municipal and private)	856	--	1,313	2,169	56
Industrial or commercial	--	--	1,396	1,396	37
Irrigation	--	160	32	192	5
Other	--	10	47	57	1
Total (MGY)	856	170	2,788	3,814	
Total (percent)	22	4	73		

QWTA , Quaternary water-table aquifer

QBAA , Quaternary buried artesian aquifer

Other includes aquaculture, livestock watering, pollution containment, and snow and ice making.

Aquifer specific capacity and transmissivity

Estimating the yield of groundwater from an aquifer requires information about the capacity of the aquifer and how quickly water moves through it. All the following contribute to an understanding of yield: an aquifer's extent and saturated thickness, the relationship to recharge sources and other aquifers, and its transmissivity. Transmissivity is an aquifer's ability to transmit water, measured as a volume moving a specific distance, typically gallons per day per foot (gpd/ft). The extent, thickness, and elevation for most of the geologic layers that serve as aquifers have been mapped in Part A, Plates 2 and 5. Data to estimate the ease with which water moves through the geologic layers are obtained by pumping water from a well at a constant rate for a certain period of time. The simplest test of this type, the specific capacity test, measures well discharge in gallons per minute (gpm) and compares that to the water-level drawdown in the pumped well (gpm/ft). Generally the well is pumped for a limited amount of time, such as an hour. Aquifers with high specific-capacity values for a particular well indicate that large amounts of groundwater can be withdrawn with limited water-level drawdown in that well. In addition, high specific capacity usually indicates the aquifer has high hydraulic conductivity. The few specific capacity data that were available from the County Well Index (CWI) for the mapped area are grouped by general aquifer type in Table 2.

The surficial sand aquifer had the best average specific capacity value (mean value of 97 gpm/ft) and the broadest range of values. The more commonly used buried sand aquifers (mean specific capacity value of 16 gpm/ft) and bedrock aquifers (mean specific capacity values of 7 to 27 gpm/ft) had lower mean values. An aquifer test requires pumping the well for a longer period of time than a specific capacity test. These data are available from a municipal well (city of Mankato, Well #5) and a snow-making well (Mt. Kato ski area) (Table 2).

Table 2. Specific capacity and transmissivity of selected wells

[Specific capacity data adapted from the County Well Index (CWI); gpm/ft, gallons per minute per foot. Transmissivity data are from USGS tests compiled by the DNR; gpd/ft, gallons per day per foot]

Aquifer (CWI aquifer code)	Specific capacity (gpm/ft)					Transmissivity (gpd/ft)
	Well diameter (inches)	Mean	Min	Max	Number of tests	
Surficial sand (QWTA)	10–228	97	13	257	7	
Buried sand and gravel (QBAA)	8–16	16	1	57	5	
Prairie du Chien (OPDC)	8–12	7	5	9	3	
Jordan (CJDN)	10	9	--	--	1	
Multiple aquifers (OPDC and CJDN)	8–16	27	7	104	6	
Multiple aquifers (CSTL, CTCG, and CWOC)	8–16	8	<1	34	5	20,750 (one test reported as CFRNCIGL*, well diameter 16)
Multiple aquifers (CTCG, CWOC, and CMTS)	10–20	26	11	41	2	92,000 (one test reported as CIGLCMTS*, well diameter 24)
Mt. Simon (CMTS)	12–24	7	6	10	6	

*CWI codes CFRN and CIGL (Cambrian Franconia aquifer and Cambrian Ironton–Galesville aquifer) have been replaced by CTCG and CWOC.

QWTA, Quaternary water-table aquifer

QBAA, Quaternary buried artesian aquifer

OPDC, Ordovician Prairie du Chien aquifer

CJDN, Cambrian Jordan aquifer

CSTL, Cambrian St. Lawrence Formation

CTCG, Cambrian Tunnel City aquifer

CWOC, Cambrian Wonewoc aquifer

CMTS, Cambrian Mt. Simon aquifer

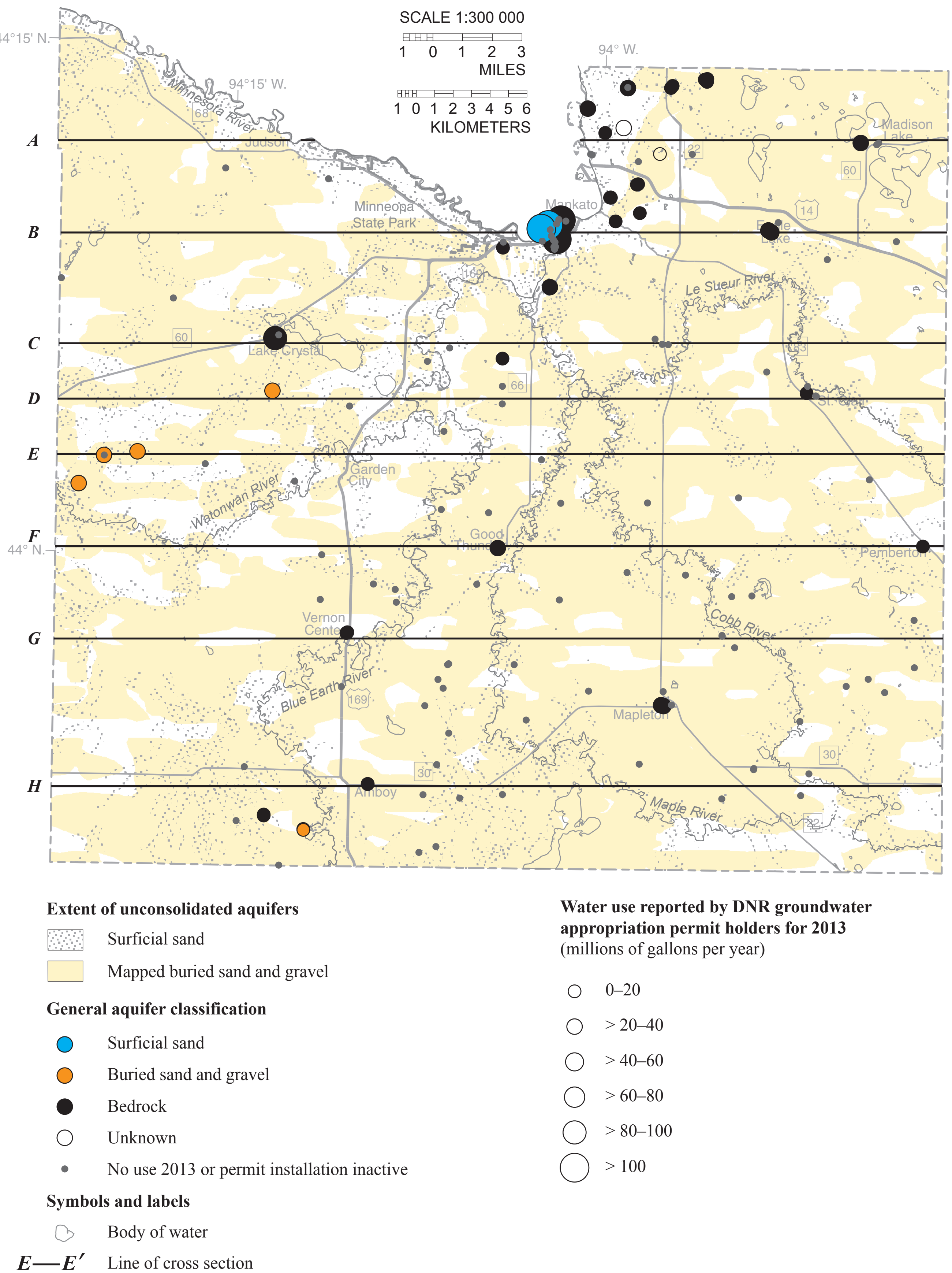
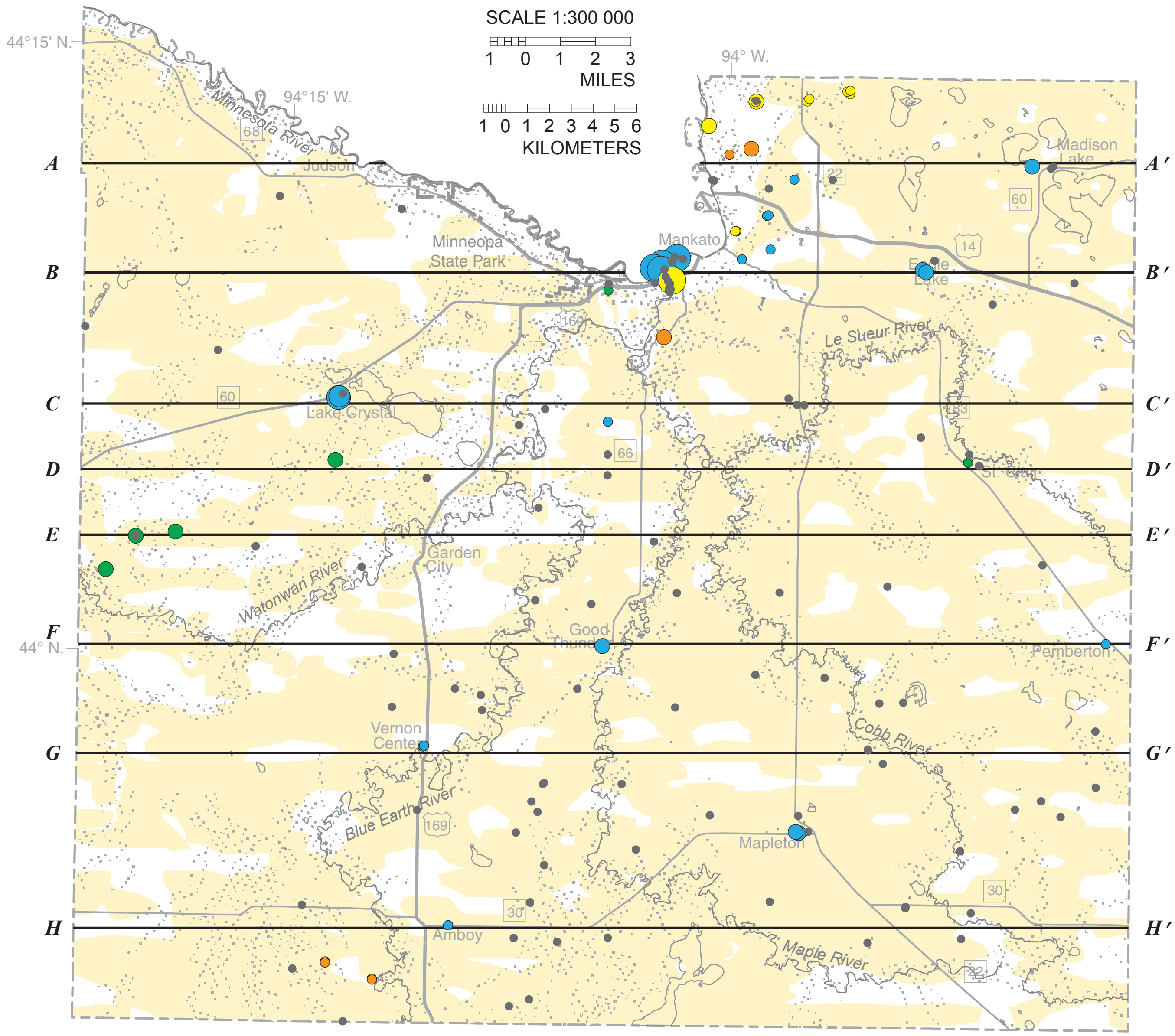


Figure 4. Locations of DNR groundwater appropriation permit holders by aquifer

Symbols represent aquifer type and reported 2013 water-use amount. Municipal water use is mainly from the bedrock aquifers, widely located across the county, and the surficial sand aquifer located mainly in the Mankato area.



Extent of unconsolidated aquifers

Surficial sand

Mapped buried sand and gravel

Water use categories

Water supply

Industrial processing

Irrigation

Other

No use 2013 or permit installation inactive

Symbols and labels

Body of water

E—*E′* Line of cross section

Water use reported by DNR groundwater appropriation permit holders for 2013 (millions of gallons per year)

0–20

> 20–40

> 40–60

> 60–80

> 80–100

> 100

Figure 5. Locations of DNR groundwater appropriation permit holders by water use

Symbols represent water-use type and reported 2013 water-use amount. Industrial activities use water exclusively from the bedrock aquifers and are mainly located in the north-central part of the county. Irrigation represents a small percentage of water use, is mainly located in the western portion of the county, and is mostly from buried sand aquifers.

Water-table elevation and depth

Water-table elevation controls groundwater flow direction, both where a surficial sand aquifer is present and absent. The lakes and streams that intersect the surficial sand aquifer are assumed to represent the water-table elevation at that location because most streams and lakes receive groundwater contributions. Water-table divides are typically very similar to the surface divides so the watershed boundaries may be considered to approximate groundwater flow divides for the water-table system.

Blue Earth County spans five watersheds (Figure 6). The northern part is covered by a portion of the much larger Minnesota River watershed. The eastern-southeastern portion is covered by the Le Sueur River watershed, including the Maple and Cobb rivers. The Cannon covers a small portion of the northeastern corner. The southwestern and central parts are occupied by the Watonwan and a narrow portion of the Blue Earth River watersheds.

Water-table-elevation maps can be useful in groundwater pollution remediation where groundwater flow direction and velocity are required. Groundwater flow gradients are derived from maps of water-table elevation and used with other geologic information to estimate groundwater flow velocity.

A water-table-elevation map (Figure 6) was derived from the mapped elevation of lakes and ponds, surface elevations along rivers and streams, and estimates of wet soil conditions from the Blue Earth County Soil Survey (USDA-NRCS, 2011). The effects that artificial drainage had on lowering the water table were not taken into account. The water-table depth (Figure 7) is derived by subtracting the water-table elevation from the land-surface elevation.

Elevation and depth maps

Shallow water-table conditions (0–10 feet) are common in the county with the exception of the upland valley edges and terraces of the Minnesota River; and uplands along the incised lower reaches of the Blue Earth, Maple, and Le Sueur rivers (Figure 7). In these areas the depth to the water table may be much greater than the estimated shallow conditions for the rest of the county. The surficial sand aquifer is a minor source of human water supply but is a critical source of water for most aquatic habitats including rivers, lakes, and wetlands that intersect the aquifer.

Buried aquifer potentiometric surface maps

A potentiometric surface is defined as “a surface that represents the level to which water will rise in a tightly cased well” (Fetter, 1988). The potentiometric surface of an aquifer represents the potential energy that is available to move groundwater in a confined aquifer. The contour lines that illustrate the potentiometric surface are similar to the contour lines on a topographic map: they provide a visual model of the water surface. As groundwater moves from higher to lower potentiometric elevations it flows perpendicular to the potentiometric elevation contours. Flow directions are shown as arrows in Figures 8 through 12.

Groundwater paths lead from recharge areas through the aquifer to discharge locations that are described by a wide continuum of depth, distance, and time. Flow into, through, and out of shallow aquifers can vary from days or weeks over short distances of less than a mile, to centuries or millennia across dozens of miles through deeper aquifers.

When combined with other information, high elevation areas on the potentiometric surface can indicate important recharge areas. Deeply incised river valleys are examples of low elevation areas that are typically discharge areas.

Static (nonpumping) water-level data from the CWI and measurements from the DNR were plotted and contoured to create potentiometric contour maps. These records represent various climatic and seasonal conditions from the 1960s to 2011. This data variability creates some uncertainty in potentiometric surface elevations. All the potentiometric surface maps (Figures 8 through 12) show a general pattern of groundwater flow toward the Minnesota River valley. Groundwater discharge to portions of its major tributaries (Watonwan, Blue Earth, Maple, Cobb, and Le Sueur) appears to influence local groundwater flow direction patterns.

The map of uppermost bedrock groundwater flow directions (Figure 12) was created from water-level data with open-hole portions no deeper than 100 feet below the bedrock surface. For general reference the contours are symbolized stratigraphically into three groups: 1) units above the St. Lawrence Formation, 2) units below the St. Lawrence Formation, 3) and fractured bedrock aquitards including the St. Lawrence and Eau Claire.

This map combines data from multiple geologic units and was created for the following reasons:

1. This shallow bedrock zone is the target of the pollution sensitivity evaluation that is presented later. Groundwater flow directions derived from data within this zone are useful for understanding some of the chemistry and pollution sensitivity comparisons.
2. Research since 2003 (Runkel and others, 2003, 2006, and 2014) has shown that formations in this shallow bedrock zone are more heavily fractured and permeable than where they are more deeply buried by overlying bedrock. This applies to aquitards such as the St. Lawrence Formation, as well as aquifers. Most aquitards in such conditions have sufficient horizontal hydraulic conductivity that they provide an adequate yield of water to domestic wells. Furthermore, even though vertical hydraulic conductivity may be sufficiently low that the aquitards can locally protect underlying aquifers, they are less likely to serve as significant barriers to groundwater flow at county-scale.
3. Potentiometric contours that represent groundwater elevations from the St. Lawrence and Eau Claire units are represented with a distinct pattern to communicate an extra degree of uncertainty regarding these groundwater elevation data. The groundwater in these units exists predominantly in bedding plane or horizontal fractures that are poorly connected vertically. Water level information from wells constructed in these units can vary locally depending on exactly how the wells are constructed, thereby creating uncertainty regarding groundwater flow directions.

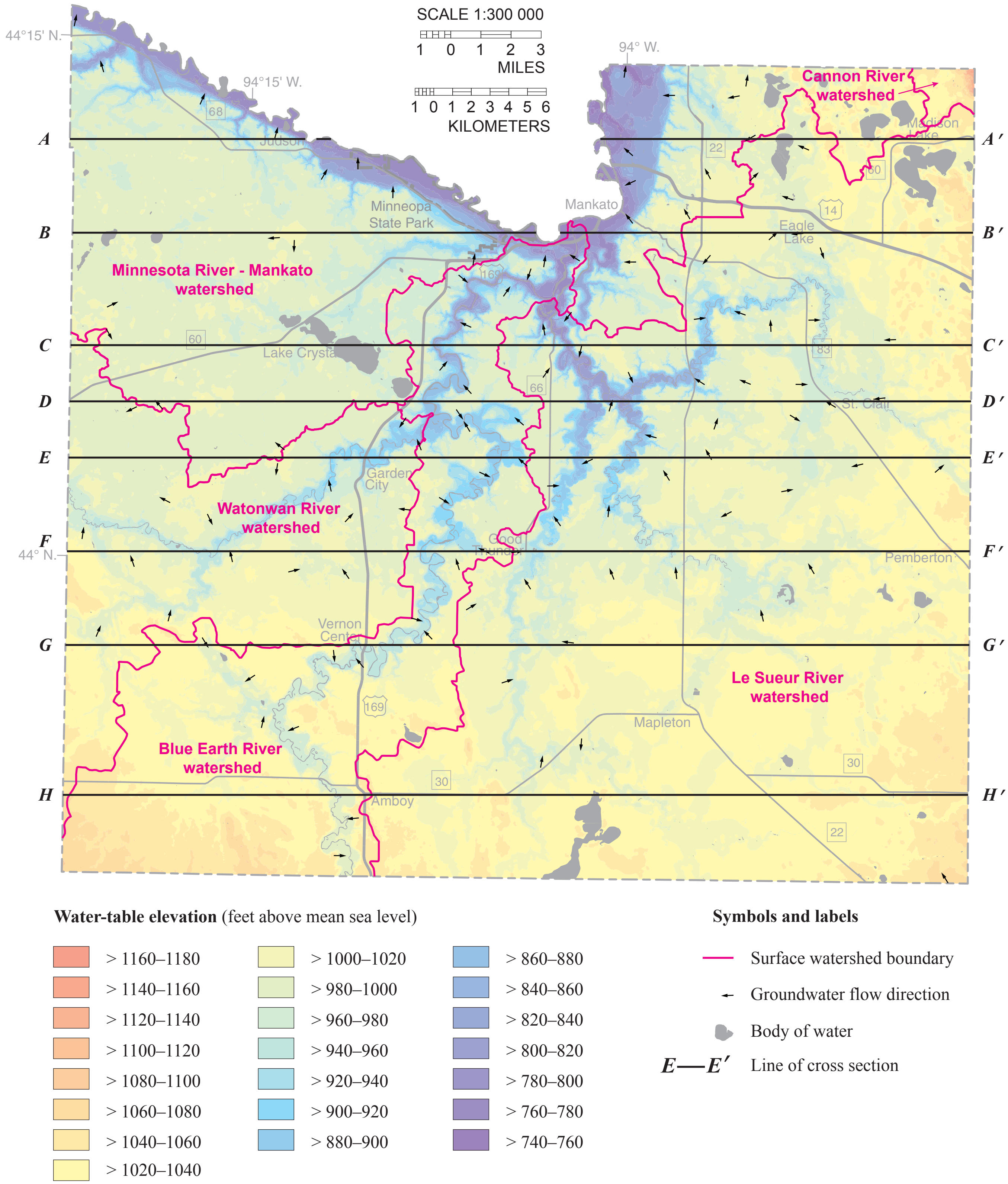
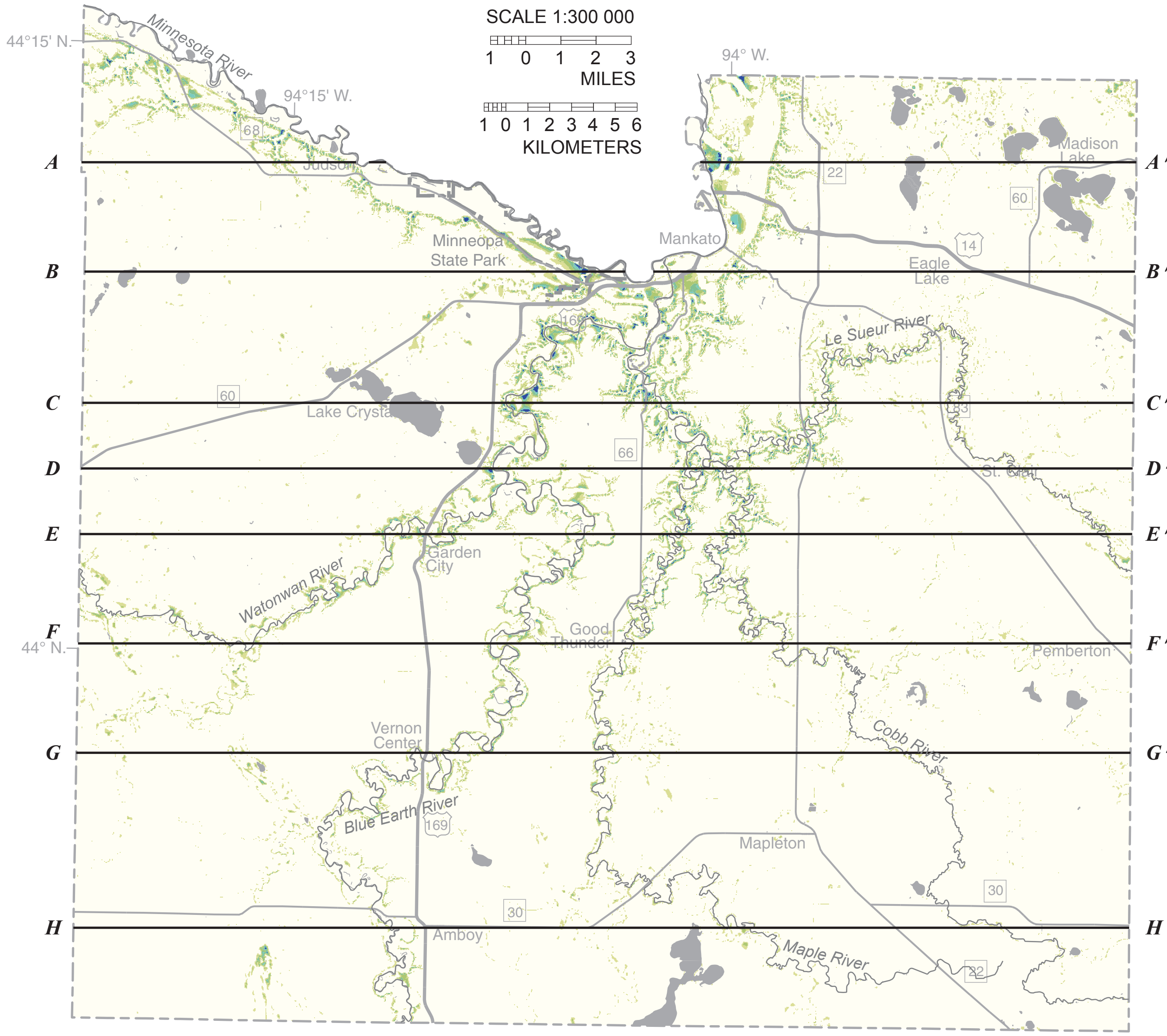


Figure 6. Water-table elevation and groundwater flow directions

The water-table elevation map depicts groundwater flow toward the major river valleys within the county. Surficial watersheds are labeled.



Depth to water table (feet below land surface)

	0–10		> 30–40
	> 10–20		> 40–50
	> 20–30		> 50

Symbols and labels

Body of water

E—E′ Line of cross section

Figure 7. Depth to water table

Shallow water-table conditions are common in the county, with the exception of the valley edges and terraces of the Minnesota River and other major river valleys.

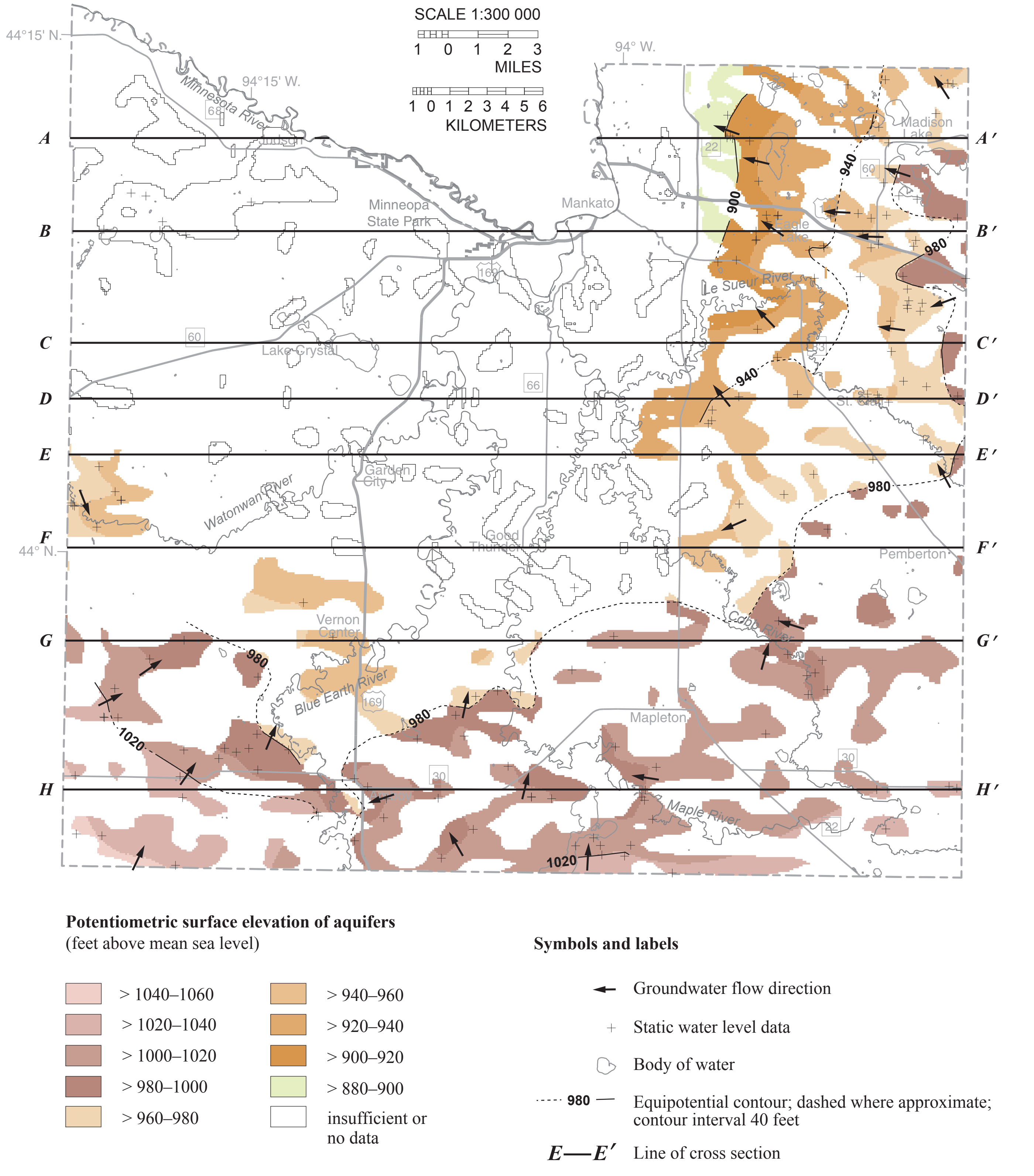


Figure 8. Potentiometric surface of the sm aquifer

General groundwater flow directions are toward the Minnesota River. Groundwater discharge to the Minnesota River tributaries creates local convergent flow within these valleys as shown in the upstream portions of the Blue Earth, Maple, Cobb, and Le Sueur rivers.

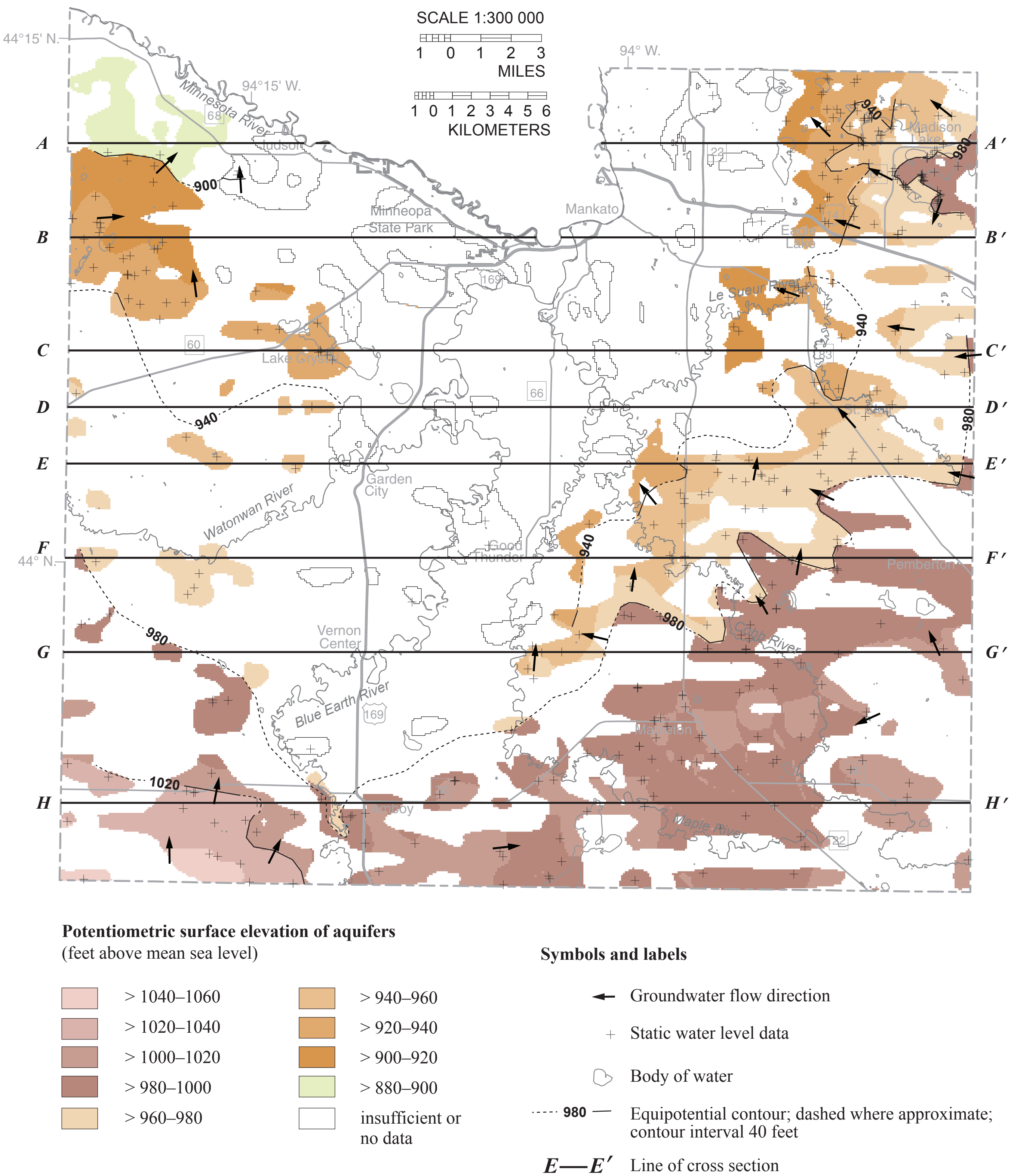
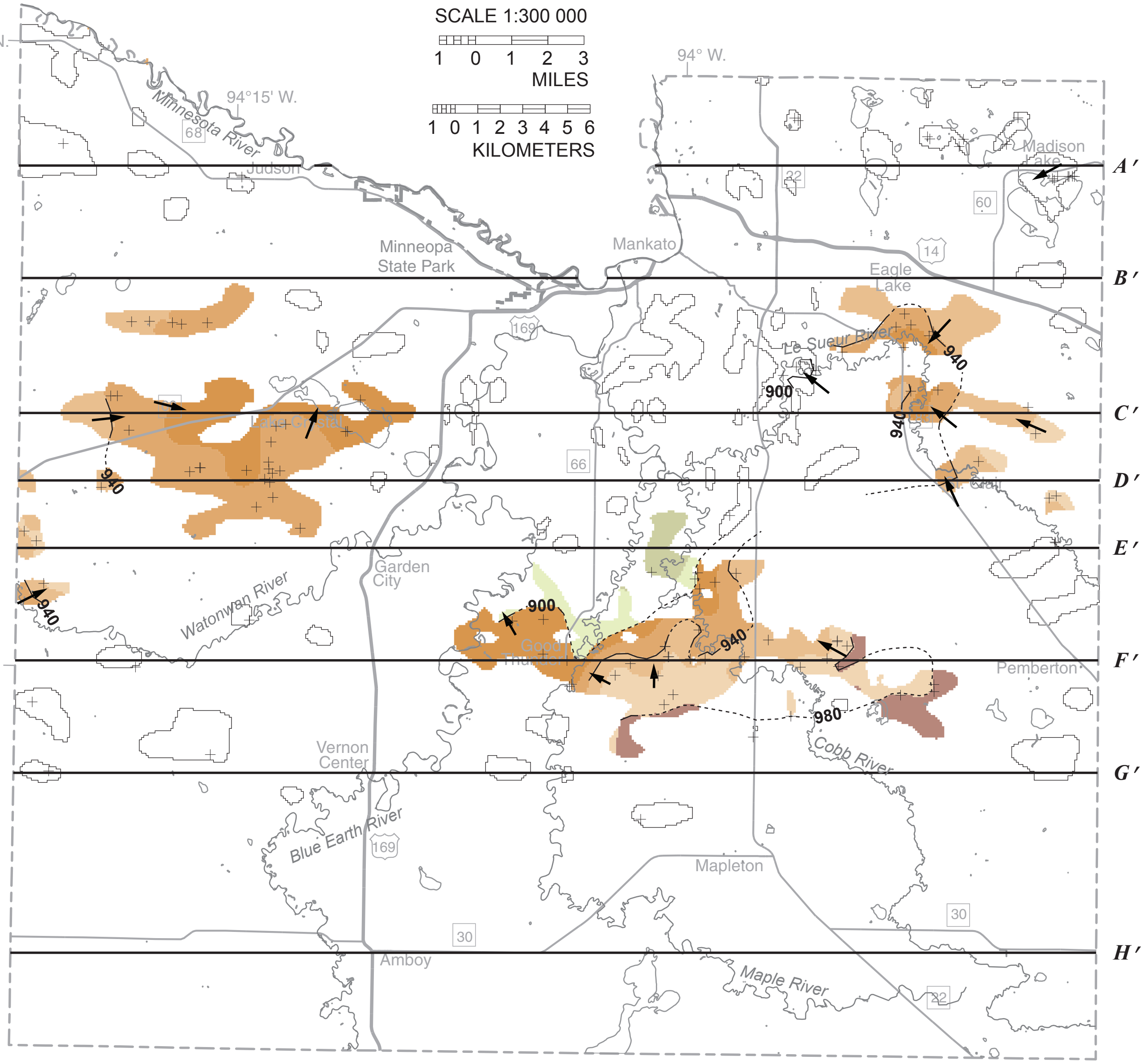


Figure 9. Potentiometric surface of the st aquifer

Groundwater discharge to tributaries of the Minnesota River valley creates local convergent flow. These areas are evident in the upstream portions of the Blue Earth, Maple, and Cobb rivers.



Potentiometric surface elevation of aquifers
(feet above mean sea level)

- > 980–1000
- > 960–980
- > 940–960
- > 920–940
- > 900–920
- > 880–900
- > 880–900
- insufficient or no data

Symbols and labels

- Groundwater flow direction
- Static water level data
- Body of water
- 980 — Equipotential contour, dashed where approximate; contour interval 40 feet
- *E*—*E′* Line of cross section

Figure 10. Potentiometric surface of the s2 aquifer

Localized groundwater flow created by groundwater discharge to area rivers is shown along the Maple and Le Sueur rivers.

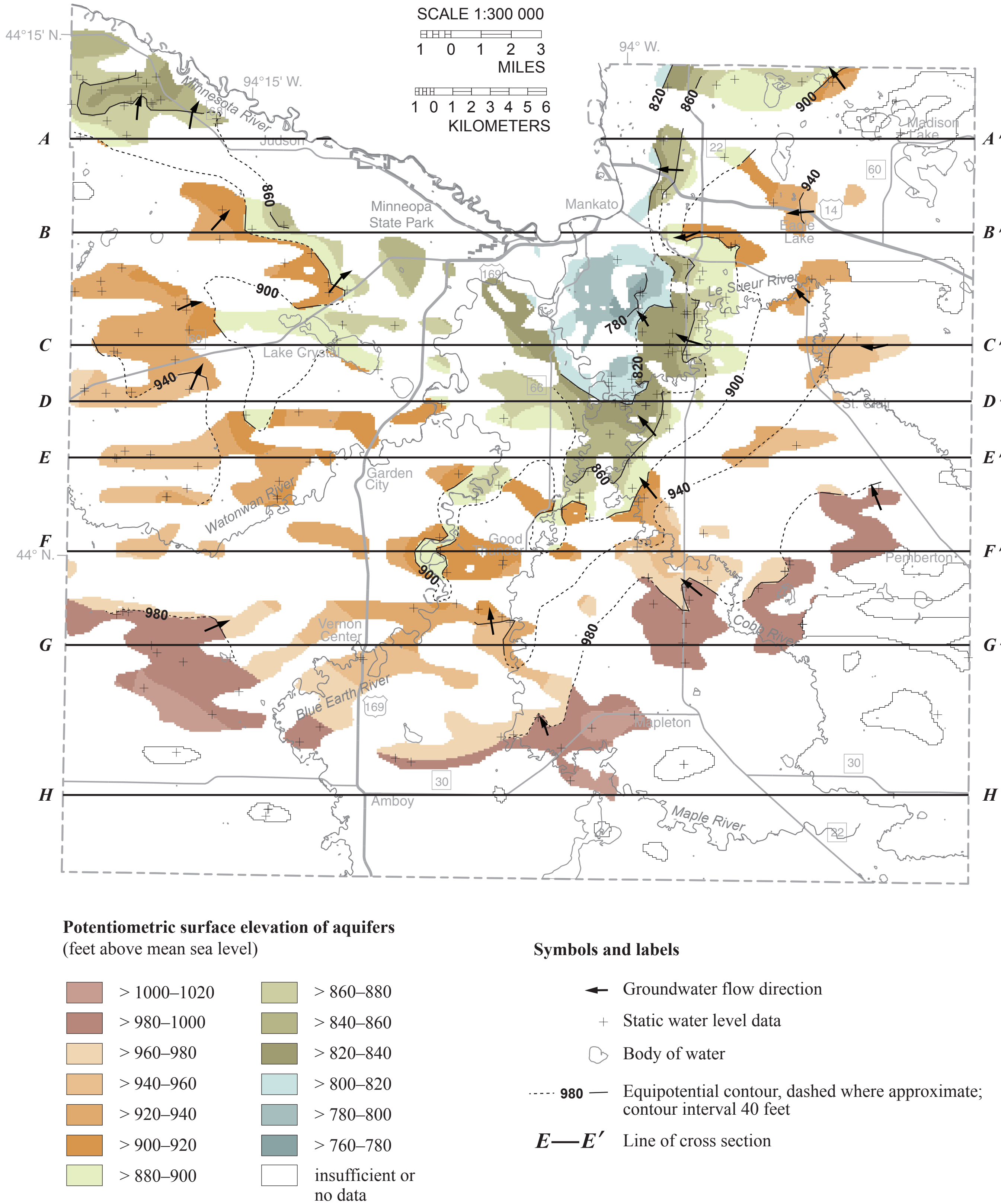
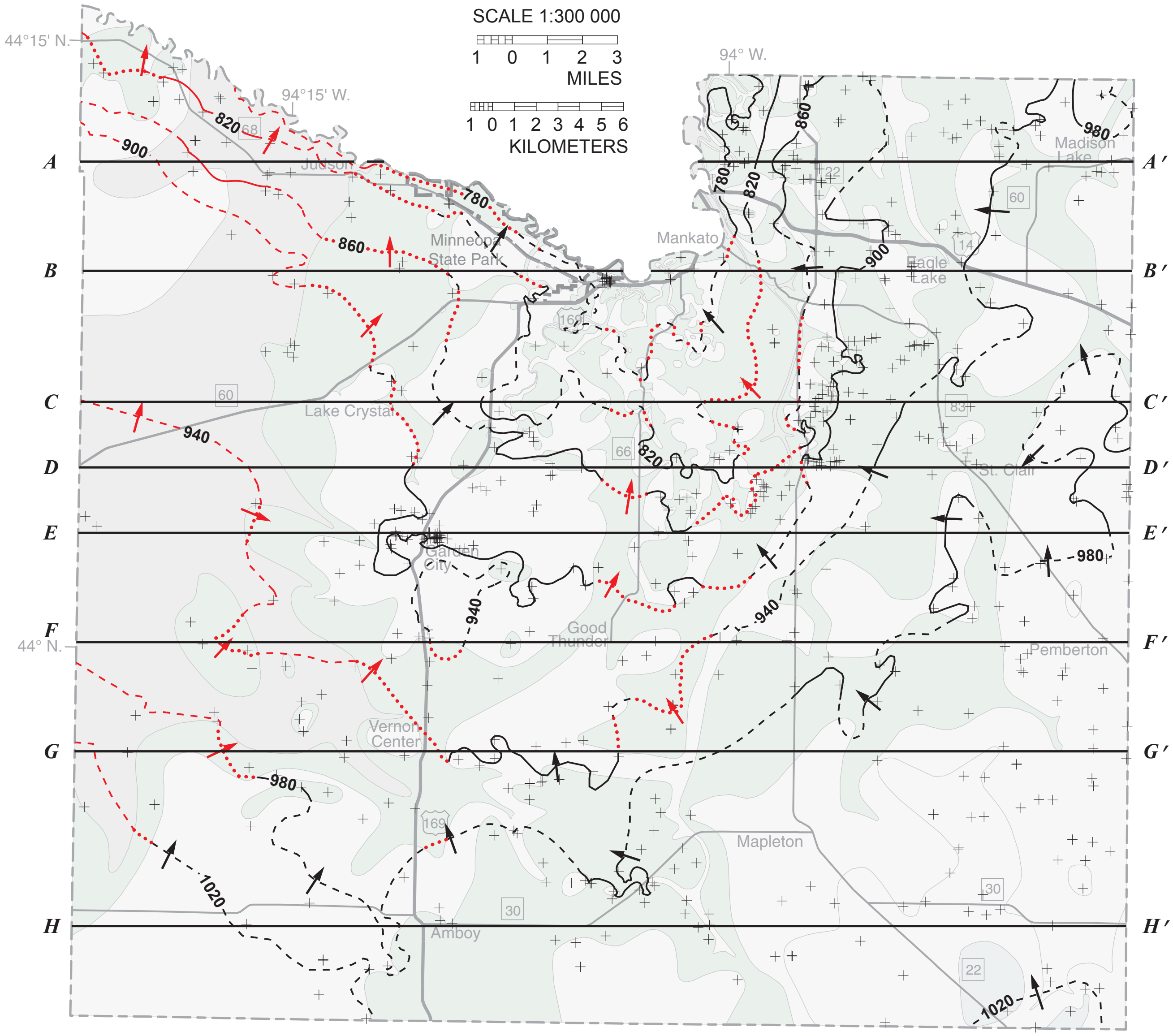


Figure 11. Potentiometric surface of the se aquifer

General groundwater flow directions are toward the Minnesota River valley. Groundwater discharge to the Minnesota River tributaries creates local convergent flow within these valleys as shown in portions of the Watonwan, Blue Earth, Maple, and Cobb rivers.



Bedrock aquifers and aquitards

- Platteville-Glenwood formations[1]
- Prairie du Chien Group (Oneota Dolomite), St. Lawrence Formation, Eau Claire Formation
- St. Peter, Prairie du Chien Group (Shakopee), Jordan, Wonewoc, Mt. Simon
- Tunnel City

[1]The Glenwood Formation acts as an aquitard but the overlying Platteville Formation is a thin aquifer. Combined, these units are shown as an aquitard.

Symbols and labels

- + Static water level data
- *E—E′* Line of cross section

Potentiometric surface contour
(dashed where approximate)

- - -940— Upper geologic unit (St. Peter Sandstone, Prairie du Chien Group, and Jordan Sandstone)
- ···940··· Fractured aquitard (St. Lawrence Formation and Eau Claire Formation)
- - -940— Lower geologic unit (Tunnel City Group, Wonewoc Sandstone, Eau Claire Formation, and Mt. Simon Sandstone)

Groundwater flow direction

- ← Upper geologic unit (St. Peter Sandstone, Prairie du Chien Group, and Jordan Sandstone)
- ← Lower geologic unit (St. Lawrence Formation, Tunnel City Group, Wonewoc Sandstone, Eau Claire Formation, and Mt. Simon Sandstone)

Figure 12. Uppermost bedrock groundwater flow directions and bedrock geology

The contours were derived from wells in the top 100 feet of the bedrock. Under these relatively shallow conditions aquitards may behave like aquifers because of the presence of fractures (Figure 3). Therefore the potentiometric surface is shown as continuous across unit boundaries. General groundwater flow directions are toward the Minnesota River valley. Discharge to the Minnesota River tributaries creates locally convergent flow.

Groundwater chemistry

All groundwater originated as surface water that seeped into the ground and into the pores and crevices of aquifers and aquitards. Water moves into the aquifers (recharge), through the aquifers, and out of the aquifers (discharge) in complicated but definable patterns. The types of dissolved elements and compounds in groundwater convey information about the geologic layers that the water has traversed, approximately how long the groundwater has been underground, and the types of surface source areas. To better understand groundwater movement and pollution sensitivity in the county, 93 groundwater samples were collected from wells with settings in a wide range of aquifers.

Groundwater sampling: site selection and protocol

Chemical data from collected well-water samples are used along with primary physical data (static water level and aquifer test data) to understand water movement. Wells were selected for sampling based on their hydrogeologic setting. All aquifers significant for domestic water supply were sampled. An ideal well-sampling network is evenly distributed across the county, includes the more populated areas, and targets potentially interesting surface-water features such as lakes and larger rivers.

Wells are privately owned so the network distribution also depends on citizen willingness to participate. Approximately 700 well owners were contacted through U.S. mail. The letters included a description of the project and a postage-paid postcard, which they were to return to the DNR project manager if they were willing to participate. Approximately 25 percent of those contacted gave permission for sampling.

The 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. Groundwater samples were filtered and preserved according to protocols listed in the Appendix, Table A and submitted to laboratories for analysis. The well owners received a copy of the results including some background reference information regarding their meaning.

Source-water connections: stable isotopes of oxygen and hydrogen

Significant hydraulic connections between surface-water bodies and underlying aquifers can be determined by the relative proportions of the stable isotopes of oxygen and hydrogen in groundwater samples.

Methods

An isotope is a variant of an element with the same number of protons but different numbers of neutrons, giving it a slightly different mass and behavior. Isotopes respond differently to phase changes (e.g., evaporation and condensation) by separating, or fractionating, by mass. A lighter isotope is more likely to evaporate; a heavier isotope is more likely to condense from the atmosphere and fall as precipitation.

Precipitation in a region has a characteristic isotopic ratio. Surface water that begins as precipitation has an isotopic composition that lies along a regional trend line or meteoric signature (North American meteoric water line, IAEA/WMO, 2006). Repeated evaporation and precipitation cycles in surface water cause fractionation of ^{16}O and ^{18}O or ^{1}H and ^{2}H, resulting in different mass ratios in rain, snow, rivers, and lakes.

Lake recharge to groundwater can be distinguished from precipitation.

- If precipitation infiltrates the ground directly it has a higher concentration of lighter, more common isotopes (meteoric signature).
- If the water remains at the surface in a lake, it undergoes cycles of evaporation that fractionate the isotopes and leaves behind a higher concentration of heavier isotopes (evaporative signature).

Evaporative signatures resulting from fractionation will plot along a shallower slope than the meteoric water line (Figure 13) (e.g., Ekman and Alexander, 2002; Kendall and Doctor, 2003).

Because the differences in mass are very small, the ratio of ^{18}O to ^{16}O and ^{2}H to ^{1}H in the sample is divided by a standard and multiplied by 1000 ($\delta^{18}O$ or $\delta^{2}H$). The symbol δ indicates that the values are compared to a standard.

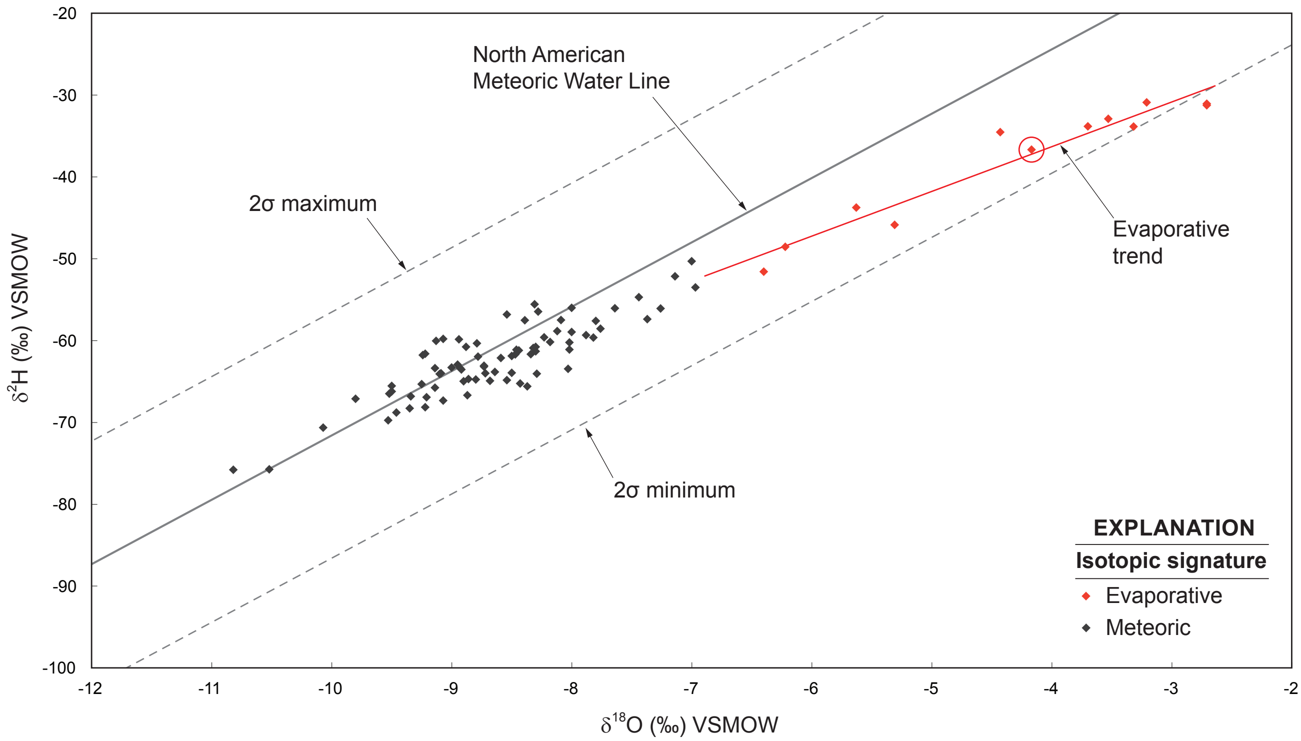


Figure 13. Graph of stable isotope values from groundwater samples

Stable isotope values from groundwater samples are compared to the meteoric water line. The red symbols that plot beneath the meteoric water line in the upper right portion of the graph represent water with an evaporative signature. Madison Lake appears to have been the evaporative source for most of these samples. The circled dot represents a sample collected from Madison Lake.

Interpretations

Stable isotope values from groundwater samples are compared to the meteoric water line. The majority of Blue Earth samples plot in the center and left portions of the stable isotope graph, along the meteoric water line (Figure 13). This suggests that for these samples, sources from precipitation (rain and snow melt) infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies.

Nine groundwater samples with evaporative signatures were collected downgradient of Madison Lake, the deepest lake in the area with a maximum depth of approximately 60 feet (Figure 14). Lake water is likely seeping into the shallow sm aquifer, which is hydraulically connected in this area to the underlying st aquifer (Figure 15).

Five occurrences of samples with evaporative signatures in this area were collected from the deeper st aquifer. As this lake-water and groundwater mixture moves downward through these interconnected aquifers, it also flows west toward the Minnesota River valley. Along this flow path the st aquifer has hydraulic connections to the underlying s2 aquifer and the Prairie du Chien–Jordan aquifer as shown by the cross sections presented here (Figure 15).

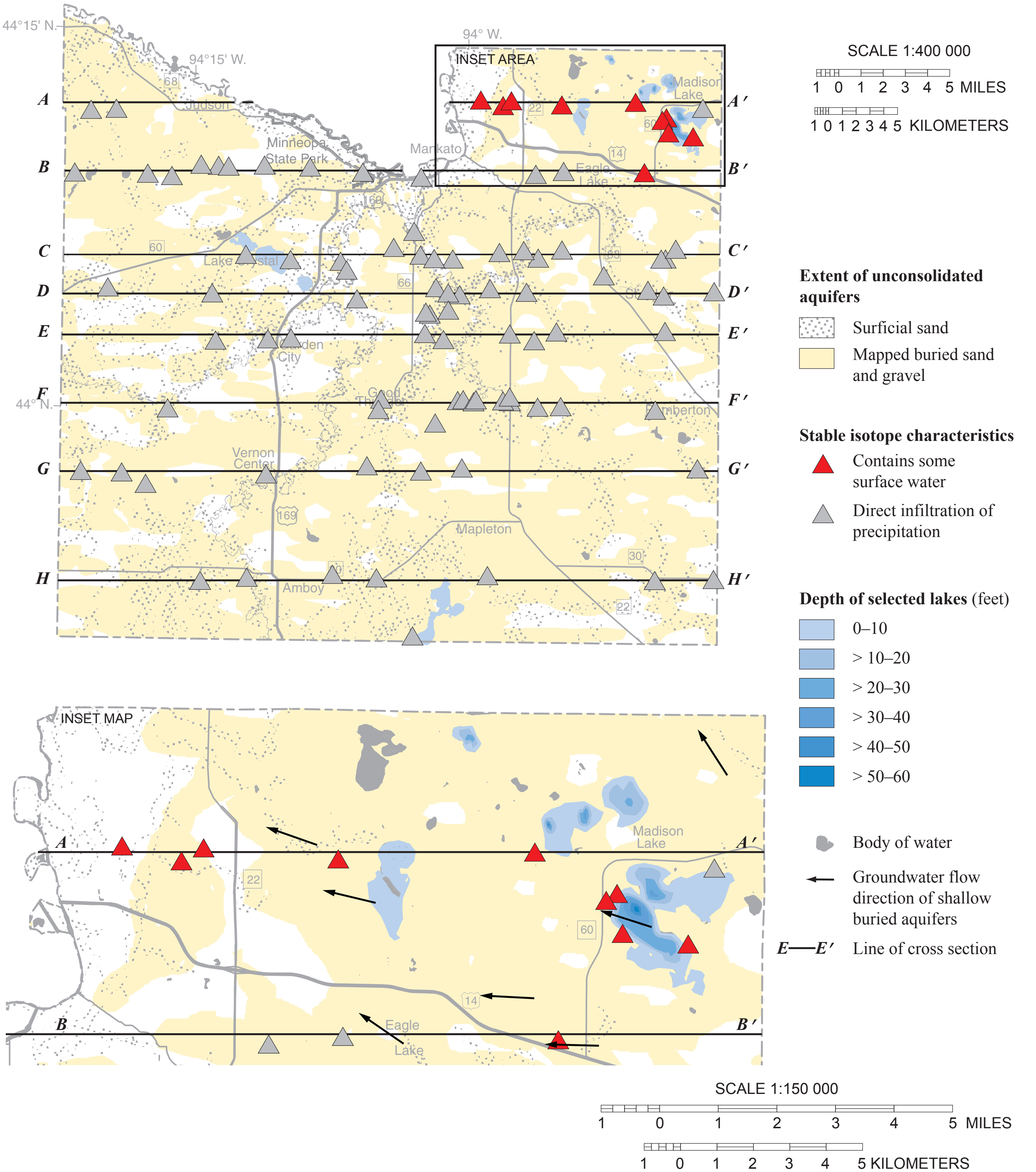


Figure 14. Stable isotope characteristics of groundwater samples

Most groundwater samples collected within the county appear to have originated as direct infiltration of precipitation (gray symbols). A group of groundwater samples located in the northeastern part of the county (red symbols) contains some water with an evaporative signature. Madison Lake appears to be a significant source of this type of water.

Groundwater residence time from radioactive isotopes

The concept of groundwater residence time as estimated by tritium concentrations is particularly useful for evaluating the pollution sensitivity of aquifers. The hydrogeologic cross sections and pollution sensitivity maps included in this report emphasize this idea. The concept of tritium age is a fundamental part of all these presentations.

Groundwater residence time is the approximate time that has elapsed since the water infiltrated the land surface to the time it was pumped from the aquifer. In general, short residence time suggests high recharge rates or short travel paths, whereas long residence time suggests low recharge rates or long travel paths. Isotopic analysis of specific radioactive elements, such as hydrogen and carbon, is a useful tool for understanding the age or residence time of the groundwater in the aquifer.

Methods

The level of tritium (^3H) present in groundwater is used to estimate the residence time. Although tritium is a naturally occurring isotope of hydrogen, the concentration of this isotope in the atmosphere was greatly increased from 1953 through 1963 by above-ground detonation of hydrogen bombs (e.g., Alexander and Alexander, 1989). This isotope decays at a known rate with a half-life of 12.32 years (Lucas and Unterweger, 2000).

Groundwater residence time is determined by the concentration of tritium units (TU) (Appendix, Table B). The following ranges of values were used.

- Recent tritium-age water (recharged since 1953): 8–15 TU
- Mixed tritium-age water (recent and vintage): more than 1 TU and less than 8 TU
- Vintage tritium-age water (recharged prior to 1953): 1 TU or less

The results of the tritium analysis are used extensively to interpret the hydrogeologic cross sections (Plates 8 and 9) and pollution sensitivity maps (Figures 26 through 32).

The carbon-14 (^{14}C) isotope is used to estimate the residence time for vintage and mixed tritium-age samples (Appendix, Table B; Plates 7 through 9). This naturally occurring isotope has a half-life of 5730 years, much longer than tritium, and is used to estimate groundwater residence time ranging from 100 to 40,000 years.

Groundwater samples were collected from clusters of wells at four locations for carbon-14 residence-time analysis (Plates 8 and 9). For assessing the general age range, the wells selected for these clusters draw groundwater from various depths.

Other source-water indicators: major cations and anions

Some evidence of distinct source-water types and mixing of groundwater can be understood by considering the relative abundances of some common cations and anions as ion concentrations. Anions are negatively charged ions whereas cations are positively charged ions. The ions selected for testing comprise the largest amount of dissolved minerals in groundwater. All the groundwater samples collected for this project were analyzed for the common cations and anions.

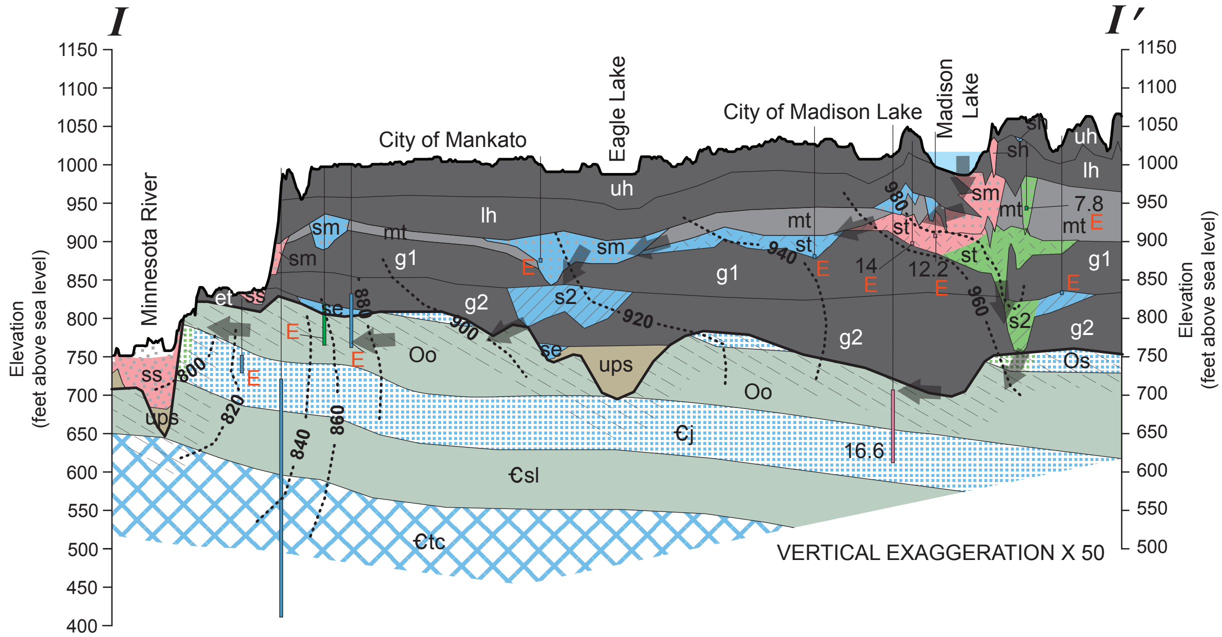
The most common type of water in Blue Earth County contains calcium (Ca^{2+}) as the predominant cation and bicarbonate (HCO_3^-) as the most common anion (Figure 16). The bicarbonate type of water is common in glacial aquifers of the Upper Midwest (Freeze and Cherry, 1979, p. 284) and is derived from dissolution of calcite and dolomite minerals in soil and glacial sediments by infiltrating precipitation. Groundwater samples from Blue Earth County exhibited similar cation and anion characteristics except for a few that were slightly more like sodium- (Na^+) and potassium- (K^+) type water.

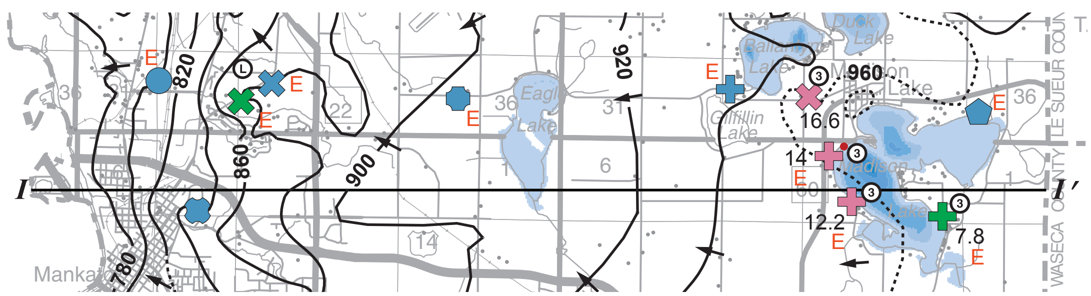
The cations, including manganese, are naturally occurring constituents of groundwater, but some may be associated with poor tasting drinking water like sulfate. Sulfate (SO_4^{2-}) has a federal secondary contaminant limit of 250 ppm (MDH, 2012). Six groundwater samples (6 percent) exceeded the federal secondary maximum contaminant limit (MCL) of 250 ppm for sulfate established for taste and aesthetic issues (Appendix, Table C). This constituent in groundwater is not a significant water-quality problem in the county.

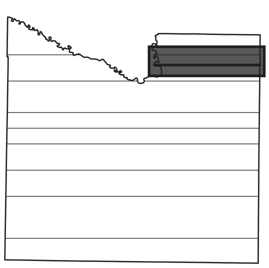
Of the anion group, chloride, bromide and nitrate can have an anthropogenic (human) origin and are used to help understand pollution sensitivity of some aquifers in the county. Chloride sources are commonly road salt or fertilizer applications. Elevated nitrate concentrations can be related to fertilizer application or animal and human waste.

Several groundwater samples in Blue Earth County had elevated concentrations of chloride (Cl^-) and nitrate (NO_3^-) (5 ppm and 1 ppm, respectively) that are probably from anthropogenic sources (Appendix, Table C). The distribution of these elevated concentrations is discussed and shown on maps in the pollution sensitivity section (p. 34).

Eight groundwater samples (9 percent) exceeded the upper limit background concentration for chloride of 5 ppm (Davis and others, 1998; Panno and others, 2006). Three groundwater samples (3 percent) contained concentrations of nitrate that exceeded an approximate background concentration of 1 ppm (MDH, 1998 and Wilson, 2012). Nitrate has a Minnesota Department of Health (MDH) health risk limit (HRL) of 10 ppm (MDH, 2012).






LOCATION DIAGRAM

SCALE 1:125 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 6 7 8 9 KILOMETERS

Figure 15. Cross section I–I′ and bedrock groundwater flow directions

Top figure: this cross section illustrates groundwater pathways from Madison Lake in a westerly direction towards the Minnesota River valley.
Bottom figure: groundwater samples with evaporative signatures (red E shown at each sample location) help trace two flow pathways from Madison Lake to the Minnesota River valley (black arrows).

Aquifers grouped by stratigraphy

Surficial sand

- ss

Buried sand and gravel

- sh
- sm
- st
- s2
- se

Bedrock aquifers and aquitards

Color overlay indicates tritium age.

- Os Shakopee (Prairie du Chien)
- Oo Oneota Dolomite (Prairie du Chien)*
- Ꞓj Jordan
- Ꞓsl St. Lawrence Formation*
- Ꞓtc Tunnel City
- Enhanced-permeability zone

*aquitard

Quaternary aquitards

Grouped by texture ranging from highest to lowest sand content, indicating relative hydraulic conductivity.

Geologic unit code	Percent sand
uh, lh, g1, g2, et	≤ 30
mt	> 30 and ≤ 40
Undifferentiated sediment (ups)	Texture unknown

Groundwater conditions

- (3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer
- (L) Groundwater flows laterally

Depth of selected lakes (feet)

0–10	> 30–40
> 10–20	> 40–50
> 20–30	> 50–60

Tritium age

Darker color in small vertical rectangle (well screen symbol) indicates tritium age of water sampled in well. The color in the surrounding area indicates interpreted age of water in aquifer.

- Recent: water entered the ground since about 1953 (8 to 15 tritium units [TU]).
- Mixed: water is a mixture of recent and vintage waters (greater than 1 TU to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).
- Well not sampled for tritium.

Sampled well and aquifer symbols

Symbol color indicates tritium age of water sampled.

- sm
- st
- s2
- Prairie du Chien
- Jordan
- St. Lawrence, Upper Tunnel City, and Wonewoc

Symbols and labels

- 14 Tritium value
- E Groundwater sample with evaporative signature
- Surface-water sample
- General groundwater flow direction
- 920 Equipotential contour; dashed where approximate; contour interval 20 feet
- Geologic contact
- Land or bedrock surface
- Lake
- Groundwater flow direction
- *I—I′* Line of cross section

Legend for Figure 15

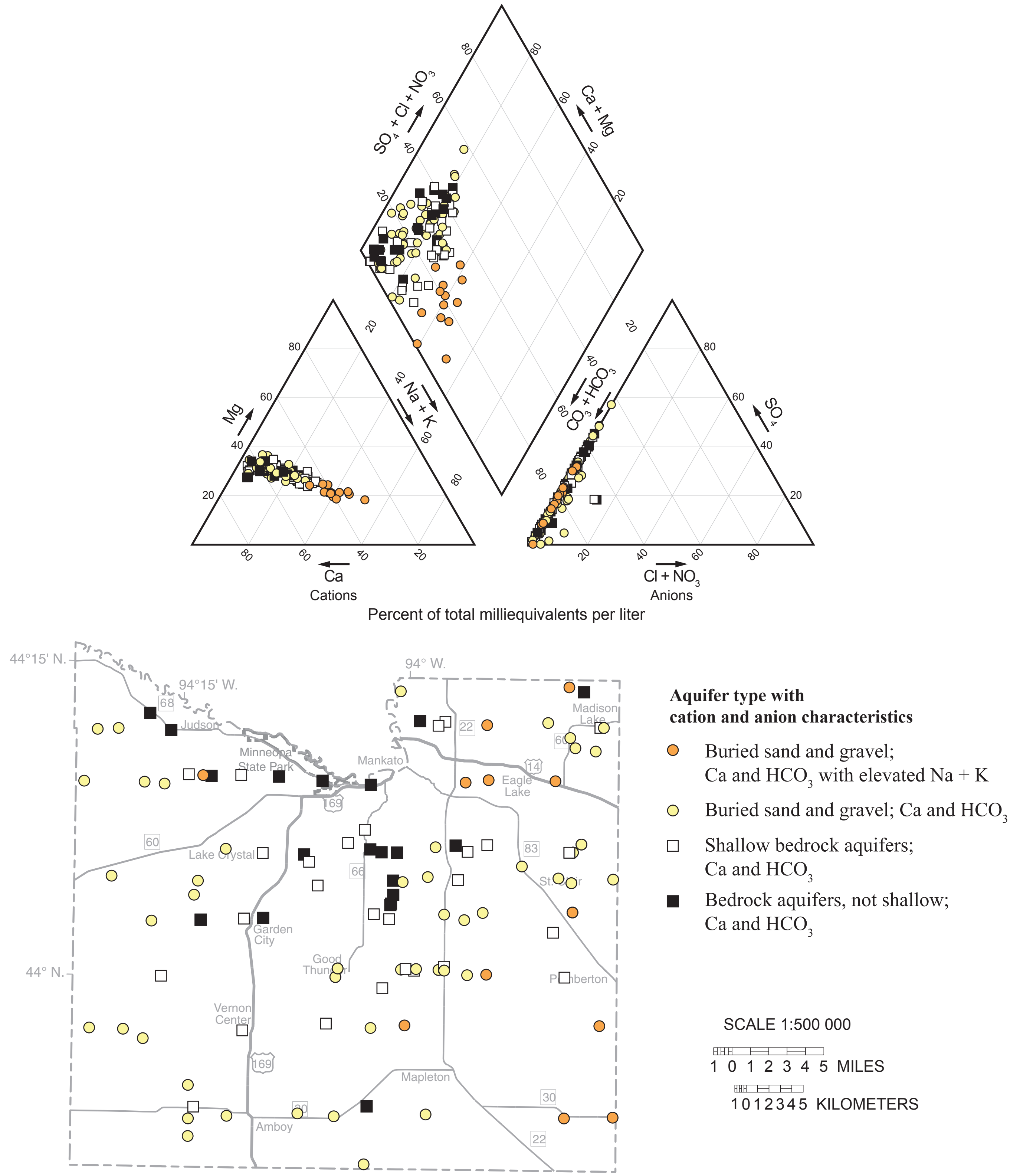


Figure 16. Ternary (Piper) diagram of groundwater samples from the DNR and Minnesota Pollution Control Agency

This diagram compares the relative proportions of cations and anions in groundwater from all the sampled wells. Most of the groundwater samples are the calcium and magnesium (Ca + Mg) and bicarbonate (HCO_3) type. The cations and anions are shown in the left and right triangles, respectively. The center diamond shows a composite of cations and anions.

Naturally occurring elements of health concern

Some chemicals present in water, such as arsenic and manganese, may be naturally occurring but can potentially pose a human health risk.

Arsenic

Arsenic is a common, naturally occurring element in Minnesota groundwater. The arsenic is thought to originate from minerals in glacial sediment. Elevated arsenic values are common in samples from wells that draw from glacial sediment of the New Ulm Formation.

This formation contains varying amounts of Cretaceous shale fragments in the coarse sand fraction (2 to 45 percent of sand that is 1 to 2 millimeter in size; Part A, Plate 4, *Description of Cross Section Units;* Table 1, and Figure 7). The shale is also ground up, forming part of the clayey matrix of these tills. The shale fragments or shale derived clay matrix could potentially contribute finely disseminated arsenic-containing minerals (Erickson and Barnes, 2005).

Other contributing factors may be the fine texture of the glacial sediment (clay and silt) and the presence of entrained carbon from wood and plant debris. Elevated arsenic levels are also associated with reducing conditions.

Twenty-two of the groundwater samples (24 percent) exceeded the federal drinking water standard of 10 parts per billion (ppb) for arsenic (MDH, 2012) (Figures 17 through 19). Sixteen of those samples (73 percent) were collected from buried sand aquifers that are hydraulically connected to the Heiberg and Moland members of the New Ulm Formation (Figure 17), the sm and st aquifers. The elevated arsenic concentrations are in the eastern and southern portions of the county. No groundwater samples were collected from the sh aquifer.

Elevated arsenic concentrations in deeper buried sand aquifers appear to be relatively rare. Only 4 of the 22 samples (19 percent) from aquifers associated with older glacial sediment (sg, s2, se, and su) exceeded the federal limit (Figure 18). Only 2 out of 37 bedrock water samples (5 percent) equaled or exceeded the federal limit of 10 ppb (Figure 19).

Manganese

A large proportion of groundwater samples (74 samples, 80 percent) contained manganese concentrations that exceeded the lower MDH Health Risk Limit (HRL) established for infants (100 ppb) indicating a natural water quality issue for the majority of well owners in the county. The standard for adults is 300 ppb. Low levels of manganese are a benefit to humans, but high exposures can harm the nervous system (MDH, 2012).

For a statewide comparison, manganese distribution in Minnesota groundwater is highly variable. Water table and buried sand aquifers have the greatest median manganese concentrations, 155 and 160 ppb, respectively. In water-table aquifers, 56.5 percent of drinking water wells have manganese concentrations greater than100 ppb. In buried sand aquifers, 63.0 percent of drinking-water wells have manganese concentrations greater than 100 ppb (MDH, 2014).

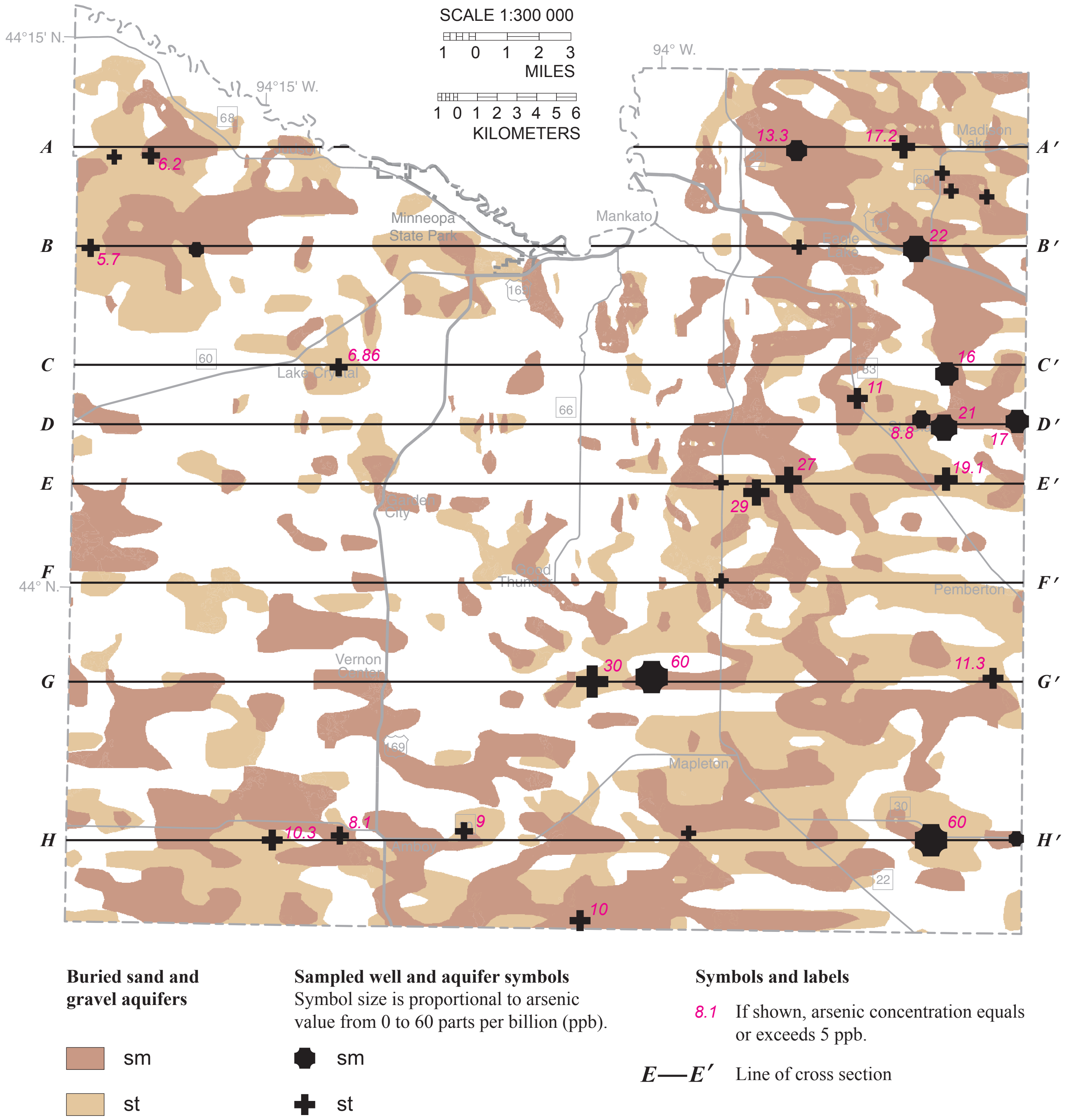
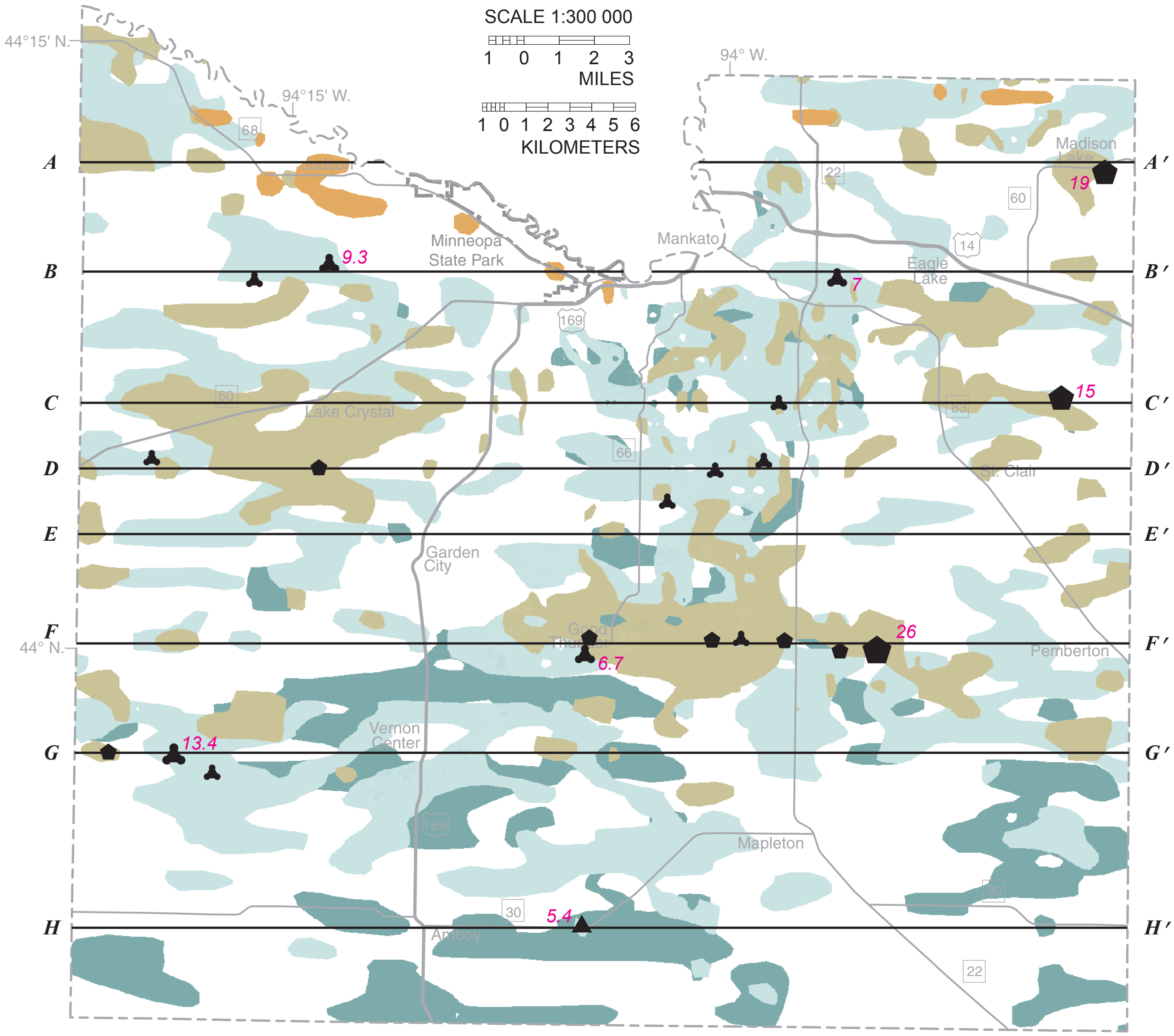


Figure 17. Arsenic values from buried sand aquifers sm and st

Arsenic concentrations that equaled or exceeded federal drinking water standards (10 ppb) were found in 16 of the 22 groundwater samples collected from these aquifers. All arsenic values 5 ppb or greater are labeled for reference. Elevated arsenic values from these buried sand aquifers are hydraulically connected to members of the New Ulm Formation (sm and st).



Buried sand and gravel aquifers

- sg
- s2
- se
- su

Sampled well and aquifer symbols
Symbol size is proportional to arsenic value from 0 to 60 parts per billion (ppb).

- s2
- se
- su

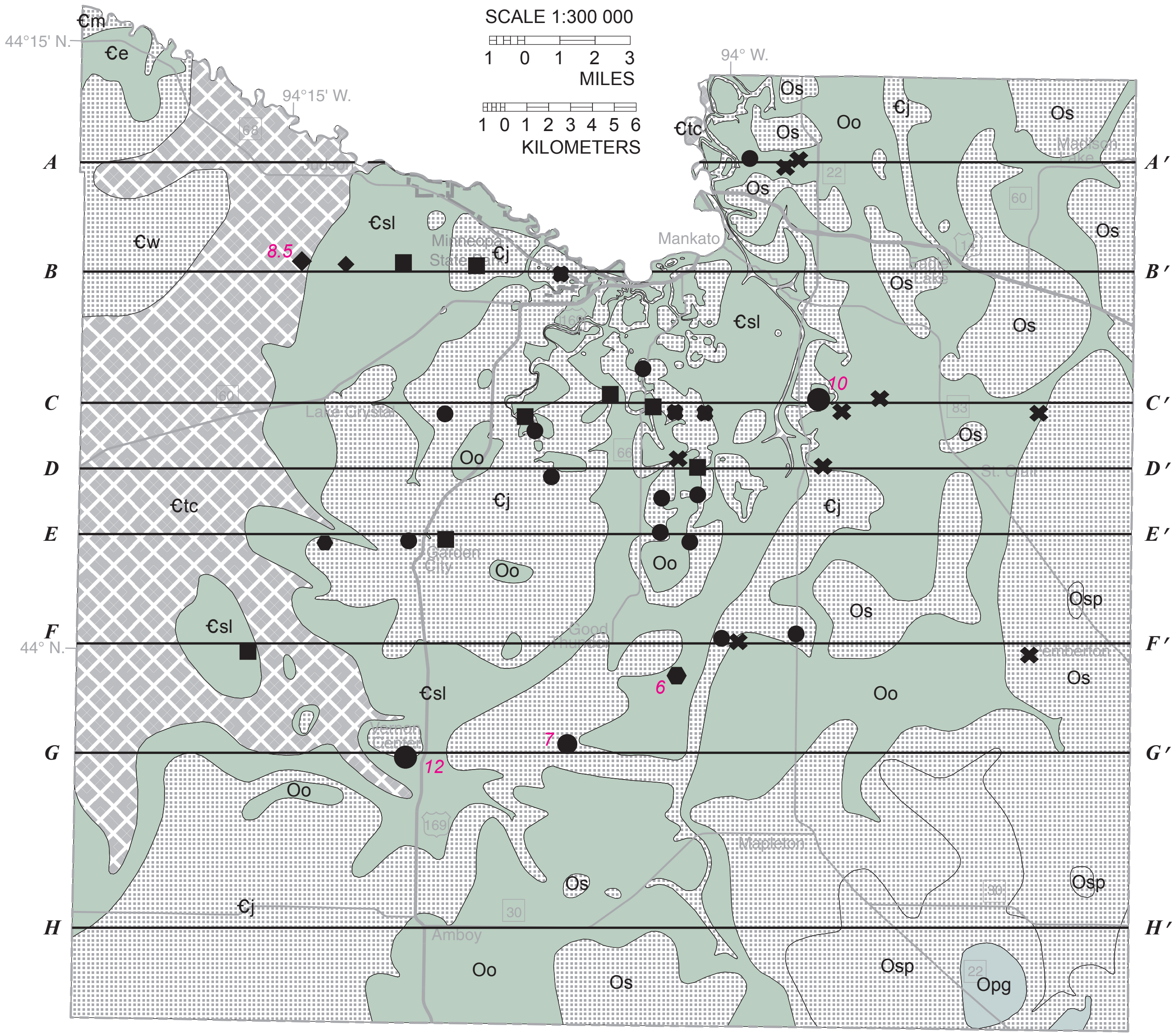
Symbols and labels

5.4 If shown, arsenic concentration equals or exceeds 5 ppb.

E—E′ Line of cross section

Figure 18. Arsenic values from buried sand aquifers sg, s2, se, and su

Arsenic concentrations that exceeded federal drinking water standards (10 ppb) were found in 4 of the 22 groundwater samples collected from this group of aquifers. All arsenic values 5 ppb or greater are labeled for reference. These buried sand aquifers are beneath and not hydraulically connected to the New Ulm Formation.



Bedrock aquifers and aquitards

- Opg — Platteville and Glenwood Formation*
- Osp — St. Peter
- Os — Shakopee (Prairie du Chien)
- Oo — Oneota Dolomite (Prairie du Chien)*
- Ꞓj — Jordan
- Ꞓsl — St. Lawrence Formation*
- Ꞓtc — Tunnel City
- Ꞓw — Wonewoc
- Ꞓe — Eau Claire Formation*
- Ꞓm — Mt. Simon

*aquitard

Sampled well and aquifer symbols

Symbol size is proportional to arsenic value from 0 to 60 parts per billion (ppb).

- ✖ Prairie du Chien
- ● Jordan
- ⬢ St. Lawrence
- ■ St. Lawrence and Upper Tunnel City
- ✸ St. Lawrence, Upper Tunnel City, and Wonewoc
- ◆ Upper Tunnel City and Wonewoc

Symbols and labels

- 8.5 — If shown, arsenic concentration equals or exceeds 5 ppb.
- *E—E′* — Line of cross section

Figure 19. Arsenic values in groundwater samples from bedrock aquifers

Arsenic concentrations that exceeded federal drinking water standards (10 ppb) were found in 2 of the 37 bedrock groundwater samples. All arsenic values 5 ppb or greater are labeled for reference. The Cretaceous units (Kd and Ka) are not shown.

Hydrogeologic cross sections

The eight hydrogeologic cross sections shown on Plate 8 and 9 illustrate the horizontal and vertical extent of aquifers and aquitards, groundwater residence time, and general directions of groundwater flow.

These cross sections were selected from a set of 47 that were regularly spaced west-to-east. These were constructed using a combination of well data from the County Well Index, bedrock geology map (Part A, Plate 2), surficial geology map (Part A, Plate 3), and Quaternary stratigraphy plate (Part A, Plate 4) of this atlas.

The well information for each cross section was projected onto the trace of the cross section from distances no greater than one-half kilometer. The locations of the eight cross sections in the county are shown on Plates 8 and 9, along with a comparison of glacial geologic units that were defined in Part A and the corresponding hydrogeologic units (Figure 2).

Relative hydraulic conductivity

Layers shown in shades of gray on these cross sections represent glacial sediment layers that act as aquitards. Hydraulic conductivity is a function of the porosity (volume of pores) and permeability (connectedness of pores) of a sediment or rock layer.

We use percent sand content in the glacial sediment matrix as a proxy for permeability because coarse grains increase porosity and permeability of a sediment. Glacial aquitards with a higher sand content are assumed to have a higher hydraulic conductivity than aquitards with lower sand content (Part A, Plate 4, Table 1). 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 the presence of macropores like shrinkage cracks in clayey sediment, animal burrows, or root traces.

The tills with the highest sand content are the Moland Member of the New Ulm Formation and the Traverse des Sioux Formation (50 to 56 percent). The lowest sand content (31 to 39 percent) is found in the Heiberg Member of the New Ulm Formation, Good Thunder 1 and 2 formations, and the Elmdale Formation.

Groundwater flow direction estimated from equipotential contours

Groundwater moves from areas with higher potential energy to areas with lower potential energy. Groundwater flow direction is indicated by the gray arrows in the cross sections (Plates 8 and 9) and 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 in Blue Earth County is initially downward, then laterally toward the major river valleys and the Minnesota River valley to the north.

Large groundwater recharge zones are not common because of the low permeability glacial sediment at the land surface and generally level topography. Smaller discrete groundwater recharge areas are identified in the following section based on occurrences of connected aquifers and some of the geochemical data such as tritium, chloride, and nitrates (*Groundwater chemistry,* p. 19).

Recharge and discharge: interpreted groundwater residence time

Aquifers that contain tritium concentrations greater than 1 TU are considered recent or mixed water. This may occur in the following situations, indicated using the symbols shown below on Figures 26 through 32 and Plates 8 and 9.

(1) Surface water infiltrates or seeps through a thin layer of overlying fine-grained material to an underlying aquifer.

(2) Groundwater from an overlying surficial aquifer has recharged the underlying buried aquifer through leakage or a direct connection.

(3) Groundwater leaks from an overlying buried aquifer to an underlying buried aquifer.

(L) Groundwater is suspected to flow laterally.

In addition, the following codes are used to highlight other groundwater flow conditions:

(D) Groundwater likely discharges from buried aquifers to surface-water bodies.

(U) The source of the recent tritium-age or mixed tritium-age groundwater is unknown.

Recharge interpretations

Recent or mixed

(1)

Shallow, relatively isolated occurrences of the sh aquifer are interpreted as recharge areas where they have tritium values that fall into the recent or mixed range. However, because the sh aquifer is generally not used in the county as a water supply, no chemistry data were obtained.

(2)

Groundwater leakage from a surficial sand aquifer to a buried aquifer is indicated by deeper occurrences of tritium. This appears to occur in the following locations.

- The Blue Earth River valley west and southwest of Mankato (Plate 7, near center of cross section C–C′)
- The Le Sueur River valley southwest of Mankato (Plate 7, near center of C–C′)
- Where the Jordan aquifer lies beneath broad sandy terraces:
  - In the Minnesota River valley: A–A′ east, B–B′ center
  - Beneath the Blue Earth River valley: D–D′ west
  - Beneath the Watonwan River valley: E–E′ west
- Where buried sand aquifers underlie or are near the following:
  - The Blue Earth River valley: D–D′ west, E–E′ center, F–F′, G–G′ west
  - The Maple River valley: between D–D′ and E–E′

(3)

Groundwater leakage from overlying buried aquifers to an underlying buried aquifer appears to be the type of recharge occurring in the following areas.

- Madison Lake area (A–A′ east)
  Leakage of lake water from Madison Lake to the underlying sand aquifers is discussed in more detail in the section titled *Source-water connections: stable isotopes of oxygen and hydrogen*).
- Possibly in an area east of St. Clair (D–D′ east)

(L)

Four examples of lateral groundwater flow are supported by tritium detections (Plate 7 and 8).

- North of the Mankato city boundary (A–A′ east)
  Groundwater with a mixed tritium age and an evaporative signature was collected from the Prairie du Chien aquifer (Figure 10). With no vertical pathways apparent for this location, a lateral pathway from somewhere in the adjacent Minnesota River valley is suspected. This location is also along a pathway from the Madison Lake area to the Minnesota River valley that contains evaporative signature groundwater in the overlying buried sand aquifers. Migration of a mixture of lake and groundwater from the east is therefore another possibility.
- Southwest of Mankato near the Blue Earth River valley (D–D′ west central)
  Surface water from the Blue Earth River valley appears to have seeped downward through the river alluvium into the underlying Jordan aquifer and migrated east toward the valleys of the Maple and Le Sueur rivers.
- East of the city of St. Clair (D–D′)
  Mixed tritium-age water in the sm aquifer appears to have migrated west to that location from an unknown focused recharge occurrence east of the Blue Earth county boundary.
- City of Good Thunder (F–F′ center)
  The mixed tritium conditions in the s2 aquifer are likely due to surface-water leakage downward through the alluvium of the Maple River and then west migration toward the Blue Earth River valley through the s2 aquifer.

Carbon-14

Four clusters of wells were sampled for carbon-14. Three of these sampled clusters show the expected pattern of increasing age with depth.

- Southeast of Lake Crystal near the Watonwan River (E–E′)
  The groundwater sample from the relatively shallow Jordan aquifer, had a carbon-14 age of 2,000 years, whereas groundwater in the deeper, Upper Tunnel City aquifer was much older with an age of 29,000 years.
- Good Thunder area (F–F′)
  Carbon-14 ages ranged from 5,000 years in the s2 aquifer to 10,000 years in the deeper se aquifer, to 15,000 years in the Upper Tunnel City aquifer (the deepest of the cluster).
- Beauford area (F–F′ east)
  Groundwater samples from a double-well cluster had carbon-14 ages of 2,000 years in the relatively shallow st aquifer and 10,000 years in the deeper s2 aquifer.
- Northeast of St. Clair (C–C′ east)
  This three-well cluster does not follow the expected pattern of the deeper samples showing older ages. The middle-depth s2 aquifer has a younger age (2,000 years) than the shallower sm aquifer sample (5,000 years). This suggests that the s2 aquifer is receiving lateral flow from a part of the aquifer that is more hydraulically connected to the surface.

Discharge interpretations

Ⓓ

Groundwater discharge to rivers, lakes, and wetlands is a common occurrence in Minnesota. It supplies water vital to aquatic ecosystems. Discharge or baseflow is most likely to occur where an underlying aquifer appears to be connected to the base of rivers or the base of the surficial sand aquifer associated with the rivers.

Examples include discharge from the following:

- The Jordan and Upper Tunnel City aquifers to the Minnesota River (A–A′ and B–B′)
- The Jordan aquifer to the Blue Earth, Maple, and Le Sueur rivers (C–C′ and D–D′)
- Buried sand aquifers to the Maple and Blue Earth rivers (E–E′ and F–F′)

Pollution sensitivity

Migration of contaminants dissolved in water through unsaturated and saturated sediments is a complex process. Because of this, large-scale assessments of pollution sensitivity require some generalizing assumptions. The rate that fluids travel from the surface to the aquifers is the main variable that affects the sensitivity of aquifers to pollution. Geologic sensitivity is defined by the physical properties and hydrologic controls that affect the ability of sediment to restrict the downward migration of pollutants to the groundwater of interest. In general, coarse-textured sediment have short travel times and high sensitivity ratings, whereas fine-textured sediment have longer travel times and low sensitivity ratings (Figures 20 and 21). Simplifying assumptions used when producing the maps in this atlas include the following.

- The flow paths from the land surface through the soil and underlying sediments to an aquifer are vertical and downward.
- A pollutant is assumed to travel at the same rate as water.
- Sediment texture is the primary property used to create a sensitivity map of unconsolidated materials (near-surface pollution sensitivity). The permeability of the sediment matrix texture is estimated based on hydrologic theory or empirical data to establish a downward groundwater flow rate. The rate multiplied by the vertical travel distance equals the estimate of the vertical travel time.
- In confined aquifer settings (sensitivity of buried aquifers) the exact sediment texture and permeability of aquitards are often unknown but are considered to be fine-grained and low, respectively. In these settings the thickness of the overlying aquitard or protective layers of the sensitivity target layer (often an aquifer) is the primary variable that determines the sensitivity rating.

Intrinsic geologic properties are not the sole factors that determine the occurrence of pollutants in groundwater. Pollutant source, presence, strength, and distance from the well are also important factors. However, these factors are not considered in this sensitivity portrayal. Also, relatively low sensitivity does not guarantee that groundwater is or will remain uncontaminated. Leakage from an unsealed or improperly constructed well may bypass the natural protection of geologic materials in a low sensitivity area, allowing contaminated water from one aquifer to directly, and unexpectedly, enter another aquifer.

The assumption of only downward vertical water movement does not account for contaminants traveling with lateral water movement at the surface or in the subsurface. Lateral movement of a pollutant through an aquifer from an upgradient, high sensitivity area to a downgradient, low sensitivity area may be possible under various hydrogeologic and land-use settings. In addition, maps depicting risk of groundwater degradation from a particular pollutant or class of pollutants will require additional factors to be added to maps of sensitive areas such as land use, the locations of pollutant sources, or the assimilative capacity of an aquifer for a particular pollutant. Some places along river valleys are important groundwater discharge areas (see *Hydrogeologic cross sections*). Local upward groundwater movement is characteristic of these areas and will tend to lower the actual pollution sensitivity in these areas. Permeability of the sediments is evaluated only qualitatively. The sensitivity assessment is an empirical method that estimates the travel time for water to move from the land surface to the pollution sensitivity target.

Methods

Two methods are used to estimate the pollution sensitivity: 1) the near-surface materials and 2) the buried sand aquifers and bedrock aquifers.

The geologic sensitivity rating of the **near-surface materials** (Figure 20) is based on the time range required for water at the land surface to travel vertically through the vadose zone to the water table. The vadose zone is the unsaturated zone between the land surface and the water table. Because the water table is not well mapped everywhere, it is assumed to be at 10 feet below land surface for this calculation.

The travel time through this thin surface layer varies from hours to approximately a year in Blue Earth County, assuming a contaminant moves conservatively with water from the surface to the target.

- Areas with relatively short travel times (hours to weeks) are rated high or very high.
- Areas with longer travel times (months to a year) are rated low or very low.

Additional details are outlined in *Methods to estimate near-surface pollution sensitivity, GW-03* (DNR, 2016).

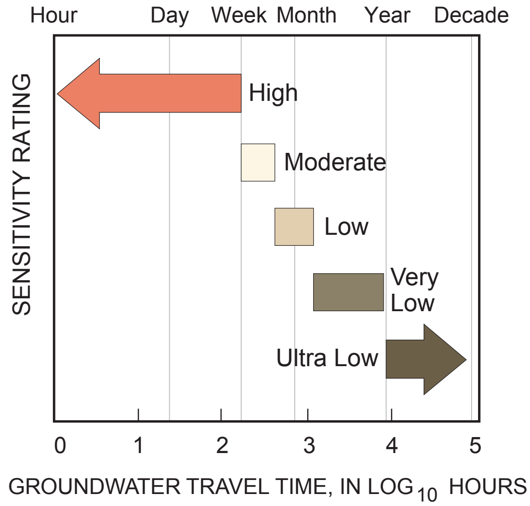


Figure 20. Geologic sensitivity rating for the near-surface materials

The mapped **buried sand aquifers and bedrock aquifers** (Figure 21) have the same geologic sensitivity rating categories as the near-surface aquifers, but represent significantly longer travel times. The buried sand aquifer and the bedrock aquifer sensitivity ratings are based on vertical travel times defined by the Geologic Sensitivity Workgroup (1991).

Tritium and carbon-14 studies indicate the relative residence times of groundwater. The travel times from the land surface to these aquifers vary from days to thousands of years.

- Areas with relatively short travel times of less than a few years are rated high or very high.
- Areas with estimated travel times of decades or longer are rated low or very low.

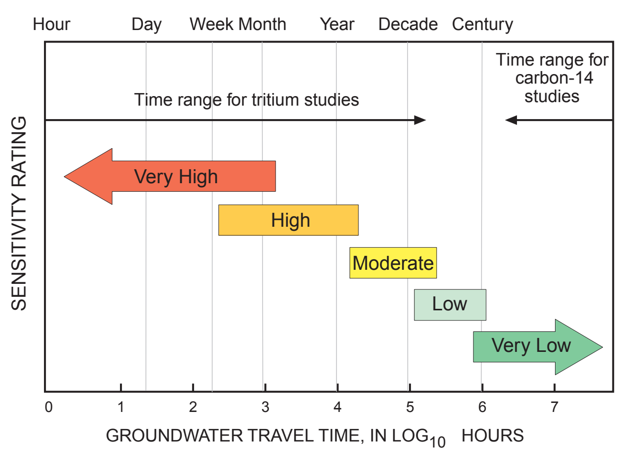


Figure 21. Geologic sensitivity rating for the buried sand aquifers and the bedrock aquifers

Near-surface materials

Methods and assumptions

The following section describes the pollution sensitivity of a 10-foot deep water table using estimated vertical travel time through near-surface sediment. Soil properties are used to estimate the travel time from the land surface to a depth of 3 feet, and surficial geology properties from the Part A atlas are used to estimate the travel time from a depth of 3 to 10 feet (Rawls, 1998; Bouwer, 2002; MPCA, 2005; NRCS, 2007; DNR, 2016) (Table 3).

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

A special karst condition is added in areas where the top of the bedrock surface is less than 50 feet from the land surface (DNR, 2016). Infiltration to the bedrock surface in these areas is potentially faster than the high sensitivity classification (hours to a week).

Results and map

The map (Figure 22) shows the combined travel-time estimate for the soil and surficial geologic sediment.

- The slower infiltration rates (low to very low pollution sensitivity) are common in the eastern and southern portions of the county. The exceptions are the larger stream valleys where sandier sediment and soil are present.
- Higher infiltration rates (moderate to high pollution sensitivity) occur in the northwestern portion of the county where sandier soil and sediment are common at the surface.
- Potentially very high infiltration rates (karst) exist in portions of the Minnesota, Blue Earth, Watonwan, Maple, Le Sueur, and Cobb river valleys.

Table 3. Transmission rates used to assess pollution sensitivity rating of near-surface materials

NRCS hydraulic group rating	Minimum soil transmission rate (inches per hour)	Surficial geology map unit (Plate 3)	Texture	Minimum transmission rate geology map unit (inches per hour)
A, A/D	1	Qat, Qat1, Qat2, Qat3, Qat4, Qat5, Qhb, Qlb, Qlf, Qs, Qsb, Qsc	gravel, sandy gravel, silty gravel	1
			sand, fine sand, silty sand	0.71
B, B/D	0.5	Qa	silt, silty fine sand, loamy sand	0.5
			sandy loam	0.28
C, C/D	0.075	Qc, Qhl, Qt, Qth, Qtc, Qtm, Qtw, Qf	loam, silt loam	0.075
			sandy clay loam	0.035
D	0.015	Qfb, Qil, Ql, Qlc, Qlw	silt and clay, clay loam, silty clay loam, sandy clay, silty clay, clay	0.015

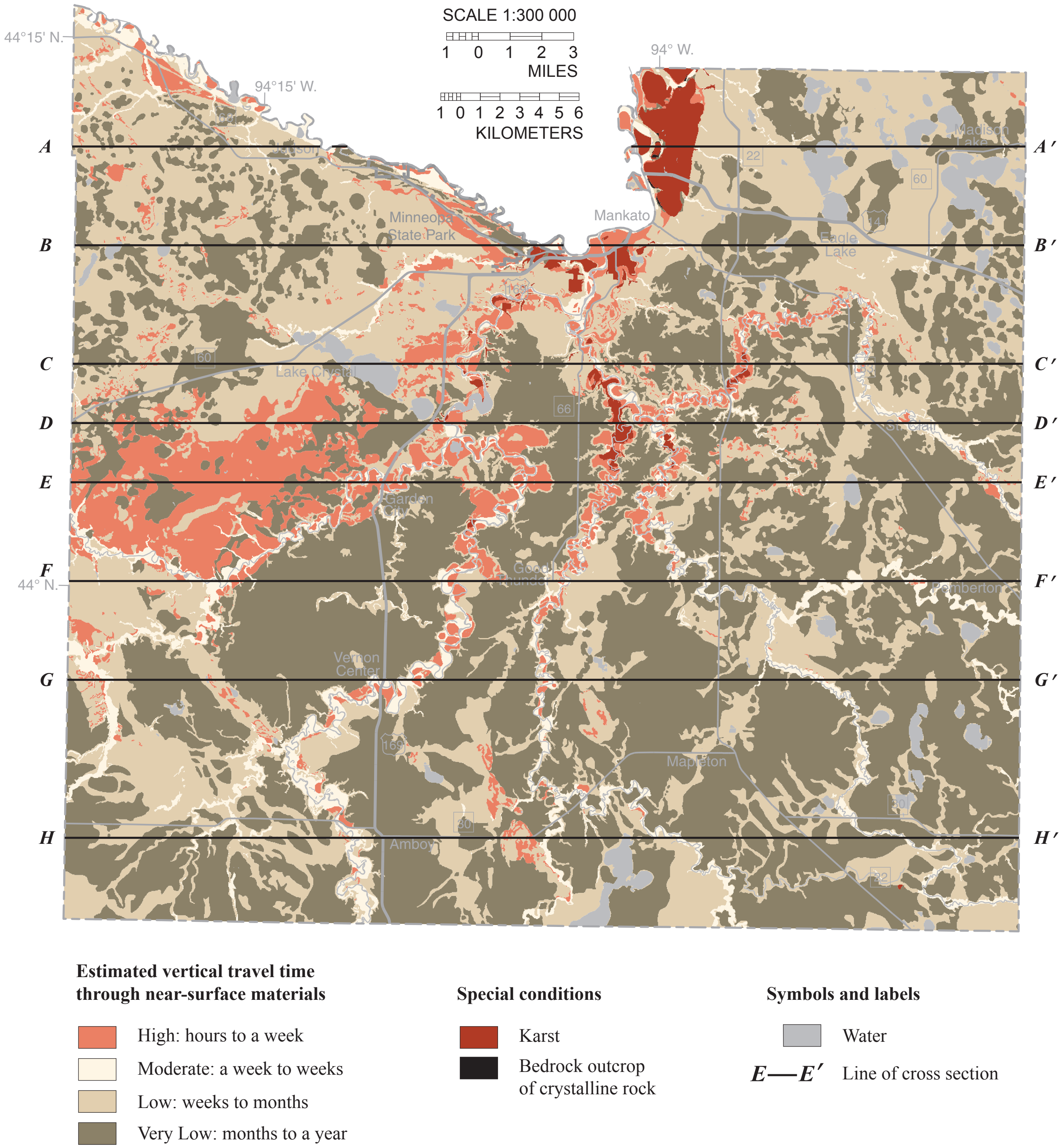


Figure 22. Pollution sensitivity of near-surface materials

Low to very low pollution sensitivity conditions are common in the eastern and southern portions of the county, with the exception of the larger stream valleys. Moderate to high pollution sensitivity conditions occur in the northwestern portion of the county. This pollution sensitivity model assumes a 10-foot-deep water table and vertical travel of possible pollutants through unsaturated, near-surface materials. The ultra-low condition shown in Figure 20 does not exist in Blue Earth County. Map files from R. Adams, 2016, electronic communication.

Karst primarily occurs where 50 feet or less of unconsolidated sediment overlies Paleozoic carbonate bedrock, the St. Peter Sandstone, or the Hinckley Sandstone. Karst allows a direct, very rapid exchange between surface water and groundwater and significantly increases groundwater contamination risk from surface pollutants.

Buried aquifers and bedrock surface

The pollution sensitivity modeling process for buried aquifers provides a qualitative evaluation of recharge rate or flow of surface water into deeper aquifers. This, along with the flow direction (indicated by the potentiometric surface contours), gives a good indication of areas at the surface that are worthy of protection.

The travel times to buried aquifers vary from days to thousands of years. Areas with relatively short travel times of less than a few years are rated high or very high pollution sensitivity. Areas with estimated travel times of decades or longer are rated low or very low pollution sensitivity.

Methods and assumptions

The pollution sensitivity interpretation uses the thickness of protective sediment (aquitard) overlying each aquifer as an indicator of how sensitive the aquifer is to pollution originating at the surface. Maps of rapid or focused recharge to specific aquifers are shown in Figures 25 through 32. Rapid recharge presents a significant risk to groundwater.

In focused recharge, overlapping portions of the aquifers may be connected by complex three-dimensional pathways and may allow surface water to penetrate into even the deepest areas. These aquifers might otherwise be assumed to be well protected because of their depth.

In areas where aquitards are thin (10 feet or less), recent recharge water can pass through to the underlying aquifers, carrying pollutants with it. This process will continue downward until it encounters a significant barrier such as a thick aquitard.

A buried aquifer with only a thin protective layer above it is rated very high sensitivity because there is little fine-grained sediment above it to retard downward groundwater movement. A thicker overlying aquitard provides additional protection to the aquifer. Sensitivity ratings are assigned based on the thickness of this layer.

The pollution sensitivity model using recharge surfaces

The sensitivity model for the buried aquifers simplifies the concept of interconnected aquifers by considering discrete recharge surfaces present at the base of each aquifer. Each buried aquifer has the potential to receive focused recharge through the base of the overlying aquifer if the aquitard layer separating them is thin or absent.

The model assumes only downward groundwater movement. For the purposes of this model, a thin protective layer is considered to be 10 feet or less in thickness. The steps used to produce the models were as follows, using a custom GIS geologic and cross section tool and GIS spatial analyst functions in ESRI ArcMap:

1. Map the aquifers and the aquitards in three dimensions (Part A).
2. Define recharge areas where aquitards are thin or missing.
3. Evaluate aquitard thicknesses to interpret pollution sensitivity.

A generalized cross section of aquifers in the county illustrate typical vertical recharge paths (Figure 23). Similar stacks of different aquifer combinations exist throughout the county. The recharge surfaces are labeled (1) generally shallow, (2) generally intermediate depth, and (3) generally deep.

1. In this conceptual model, all the recent recharge water enters the buried aquifer system (pink arrow) at recharge surface 1 (red dotted line). In areas with thick surficial sand, the generally shallow recharge surface 1 is at the base of the sand aquifer. Where little or no sand exists at the land surface, recharge surface 1 is the same as the land surface Ⓐ.
2. If the aquitard (till) between the base of recharge surface 1 and the underlying aquifer Ⓑ is 10 feet thick or less, recent recharge water moves downward to the next underlying aquifer Ⓒ and then downward to recharge surface 2 (black dotted line below Ⓒ).
3. If the same criteria are applied at recharge surface 2 the water continues downward to the next underlying aquifer until a limited amount of recent or mixed water reaches the deepest aquifer Ⓓ.

Geologic maps and associated stratigraphic information (Part A, Plates 3 through 5) were the basis for all the hydrogeologic maps and cross sections shown in this report and represent the first step of the pollution sensitivity modeling process. A three dimensional GIS model (Berg, 2006) was developed to predict how water from precipitation directly recharges portions of the first underlying aquifer and subsequently, portions of deeper aquifers. Each recharge surface is produced through a series of GIS calculations starting with the land surface elevation grid and proceeds stepwise downward to the top of the lowest mapped sand aquifer or the top of the bedrock surface.

With each succeeding step down, the deepest portion of the recharge surface becomes progressively smaller, mimicking the general reduction of recharge with depth that occurs naturally. The calculated elevations for all the aquifers and recharge surfaces were used in the third step to generate pollution sensitivity maps for each buried aquifer. The thickness of the protective layer or aquitard that covers each aquifer was calculated and a sensitivity rating was applied.

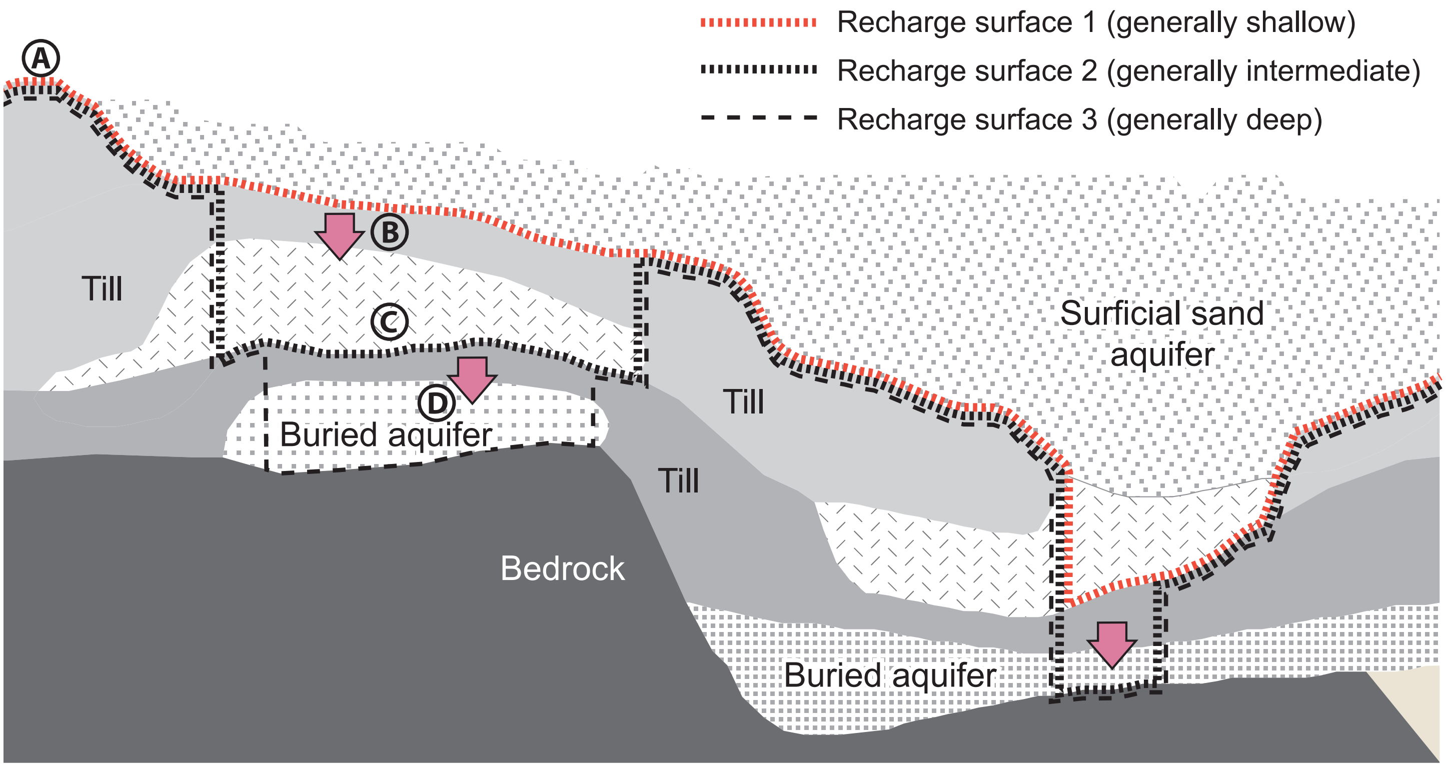


Figure 23. Generalized cross section showing recharge surfaces for sensitivity evaluations of buried aquifers and bedrock surface

The pink arrows represent the downward movement of recent tritium-age water. The sensitivity model predicts areas of rapid or focused recharge where aquitards overlying aquifers are thin or absent.

The sensitivity of the aquifer is inversely proportional to the thickness of that protective layer. The thicker the protective layer, the lower the aquifer sensitivity. The thickness of the protective layer was calculated by subtracting the elevation of the top of the aquifer from the elevation of the adjacent overlying recharge surface and then ranked for the protection it afforded (Figure 24).

Thickness of protective layer between the aquifer and the nearest overlying recharge surface (in feet)				
0–10	> 10–20	> 20–30	> 30–40	> 40
VH	H	M	L	VL

Figure 24. Pollution sensitivity rating matrix for buried aquifers and bedrock surface

The results are pollution sensitivity evaluations for each buried sand aquifer (Figures 25 through 30) and bedrock surface (Figures 31 through 32). The rapid or focused recharge referenced in the text and Figure 23 approximately corresponds to moderate, high, and very high sensitivity conditions.

We use the distribution of indicators for groundwater residence time (*Groundwater Chemistry*) to evaluate the pollution sensitivity model. The most important residence-time indicator is tritium.

- Groundwater samples with recent and mixed tritium age correspond to areas of very high to moderate sensitivity.
- Groundwater samples of vintage tritium age correspond to areas of low to very low sensitivity.
- The carbon-14 residence-time values from groundwater samples corroborate sensitivity ratings for the buried aquifers with a predicted very low sensitivity.
- Elevated chloride concentrations in groundwater samples from road salt and water softeners are an evaluation tool for areas with high pollution sensitivity ratings and are indicators of recent human activity and water infiltration. Unlike tritium, the distribution of chloride sources at the surface is uneven. Therefore the presence of elevated chloride concentrations in groundwater will indicate sensitive conditions but the absence will not necessarily indicate low or very low sensitivity.

Results and maps

Results and maps in the following discussion of the aquifers are considered in stratigraphic order from the shallowest to the deepest. The model results described in the following section include groundwater flow direction derived from potentiometric surfaces to help the user understand the distribution of some chemical constituents.

The sh aquifer (Figure 25)

The sh aquifer is generally encountered within 50 feet of the land surface and is relatively thin. This aquifer is not typically used for water-supply purposes. Few wells are completed in this aquifer, therefore no samples were collected for this project. Moderate to very high pollution sensitivity conditions are common.

The sm aquifer (Figure 26)

The sm aquifer typically has very low pollution sensitivity except where it is close to the surface in river valleys. Ten samples were collected from the sm aquifer.

- Eight of those samples had vintage tritium age which is consistent with the very low pollution sensitivity conditions shown.
- Two samples in the northeastern portion of the county east of the city of St. Clair (D–D′) had mixed tritium age. In addition, the easternmost St. Clair area sample contained elevated (greater than 5 ppm) chloride (11.3 ppm) from human sources. The mixed tritium age and elevated chloride in the St. Clair area is apparently due to west-lateral migration of groundwater from nearby zones of moderate to high pollution sensitivity.

The st aquifer (Figure 27)

The st aquifer is relatively widespread and widely used in the county. It is generally well protected and of very low pollution sensitivity. Locations in river and stream valleys where this aquifer is close to the surface show moderate to very high pollution sensitivity.

Twenty-two groundwater samples were collected from this aquifer.

- Eighteen samples had vintage tritium age consistent with the very low pollution sensitivity at those locations.
- Three samples in the Madison Lake area have recent and mixed tritium ages. The recent tritium ages of the Madison Lake area are due to the downward movement of lake water through interconnected buried sand aquifers (Figure 15).
- One sample located west of Amboy (H–H′) had a mixed tritium value. Groundwater pathways that could create this are not apparent from available information.
- Elevated concentrations (greater than 5 ppm) of chloride were detected at five locations. Those locations include the four tritium detection locations (Madison Lake area and a location west of Amboy) and a location east of Good Thunder (right side of F–F′). The water sample east of Good Thunder that had 17 ppm chloride may be due to lateral migration of groundwater from nearby areas that have pollution sensitivity in the moderate to very high range.

The sg and s2 aquifers (Figure 28)

The sg and underlying s2 aquifers have limited extents in the county, therefore the pollution sensitivity evaluations for both aquifers are shown together. Most portions of these aquifers have low or very low pollution sensitivity except where they are closer to the surface, for example in the incised portions of stream valleys.

- Eight of the nine groundwater samples collected from the s2 aquifer did not contain tritium (vintage condition).
- A groundwater sample from the s2 aquifer in the city of Good Thunder (center of F–F′) had a mixed tritium age and an elevated chloride concentration of 15.8 ppm. The pollution sensitivity mapped at that location is very low. The likely source of this groundwater is surface water from the Maple River that migrated downward into the underlying s2 aquifer and subsequently west to the Good Thunder area.

The se and su aquifers (Figures 29 and 30)

The se and su aquifers showed low chloride concentrations and vintage tritium age with the following exception. Of the 12 se groundwater samples, one sample collected in the Maple River valley south of the Mankato area had mixed tritium age, 10.2 ppm chloride, and 4.38 ppm nitrate. This was probably the result of shallow, more sensitive aquifer conditions in this area. Localized areas of moderate to very high pollution sensitivity are shown on in river valleys where the aquifers are shallow or hydraulically connected to the surface through multiple interconnected aquifers.

The bedrock surface (Figures 31 and 32)

The bedrock surface is defined as the bedrock found below the glacial sediment sequence (A–A′ through H–H′). This surface would typically have the highest pollution sensitivity of all parts of the bedrock layers since it is closest to the surface.

Groundwater samples that were collected from the shallow bedrock aquifers are shown with the larger symbols with shapes that are unique for each aquifer and colors that correspond to the tritium age: recent, mixed, and vintage. Groundwater samples collected from deeper aquifers are shown as small symbols, also colored according to tritium conditions.

Groundwater flow directions are generally north toward the Minnesota River valley or toward the incised lower reaches of its tributaries, similar to the overlying buried sand aquifers. Several probable locations of bedrock aquifer discharge to river valleys are shown in the northern half of the county (A–A′ through E–E′). In these areas of upward groundwater movement, pollution sensitivity may be lower in specific areas. For most of the county the bedrock surface has very low pollution sensitivity.

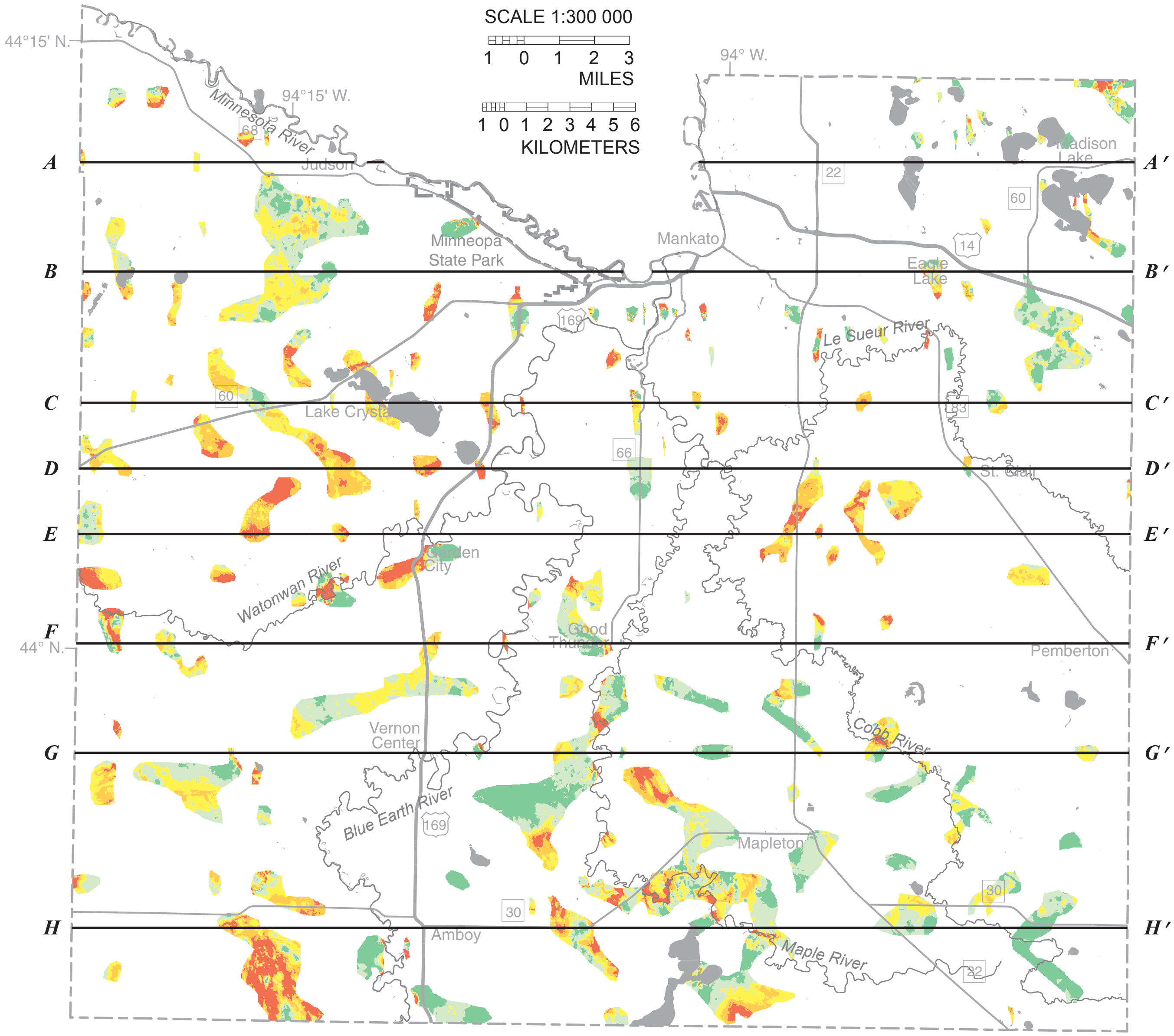
Of the 36 groundwater samples that were collected from the shallow bedrock aquifers by the DNR for this project and by the MDH for previous projects, 29 groundwater samples had vintage tritium age, 6 had mixed, and 1 had recent (Figure 31). This relative lack of recent and mixed groundwater in these aquifers supports the predominant rating of very low pollution sensitivity for the bedrock surface. In addition, elevated chloride detections in groundwater samples as indicators of pollution sensitivity were rare. The single recent tritium occurrence in groundwater from the first bedrock aquifers was in the Madison Lake area.

Five of the six mixed tritium-age groundwater samples from the Jordan and Prairie du Chien aquifers were found in river valley settings (Figure 32): in the Blue Earth River valley east of Lake Crystal, and the Le Sueur and Maple river valleys southwest of Mankato. These five samples are located in or near areas of very high pollution sensitivity. One of those samples (the north sample in the Blue Earth River valley) had a chloride concentration of 38.4 ppm (Figure 31). Lateral groundwater migration may have caused the elevated chloride levels in the southernmost Jordan aquifer sample along the Blue Earth River valley and the mixed tritium occurrence from the Prairie du Chien aquifer north of Mankato (right side of A–A′).

The mixed tritium age from the shallow bedrock aquifers in major river valleys is consistent with the moderate to very high pollution sensitivity of the bedrock surface in the Minnesota River valley and the lower, incised reaches of its major tributaries.

The deeper bedrock aquifers (Figure 31)

Typically samples collected from the deeper bedrock aquifers in these river valley settings, such as the Upper Tunnel City, Wonewoc, or Mt. Simon aquifers, show vintage tritium values (Figure 31). This general lack of tritium suggests that the intervening bedrock aquitards act as protective layers. One exception was a sample collected from a deeper bedrock unit (St. Lawrence Formation) that had a recent tritium value consistent with very high pollution sensitivity. It was located west of Mankato and the Blue Earth River in Riverbend Estates, which is located on a high terrace in the glacial River Warren valley.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

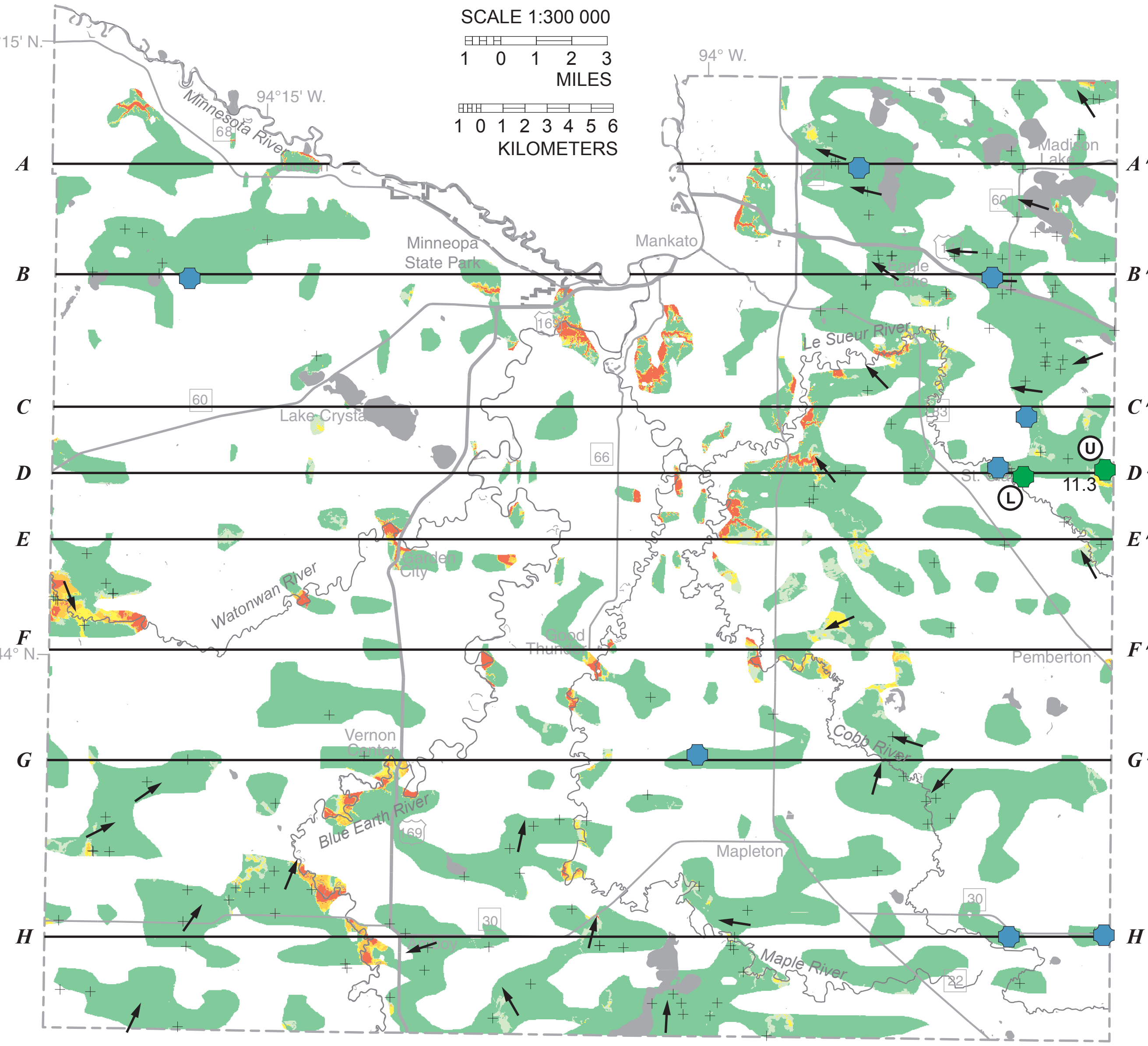
- Very High: hours to months
- High: weeks to years
- Moderate: years to decades
- Low: decades to a century
- Very Low: a century or more

Symbols and labels

- Body of water
- *E—E′* Line of cross section

Figure 25. Pollution sensitivity of the buried sand aquifer sh

This aquifer is generally shallow (less than 50 feet), relatively thin, commonly exhibits moderate to very high sensitivity, and is not usually used for water-supply purposes.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- 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 sampled.

- Mixed: water is a mixture of recent and vintage waters (greater than 1 tritium unit [TU] to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).

Symbols and labels

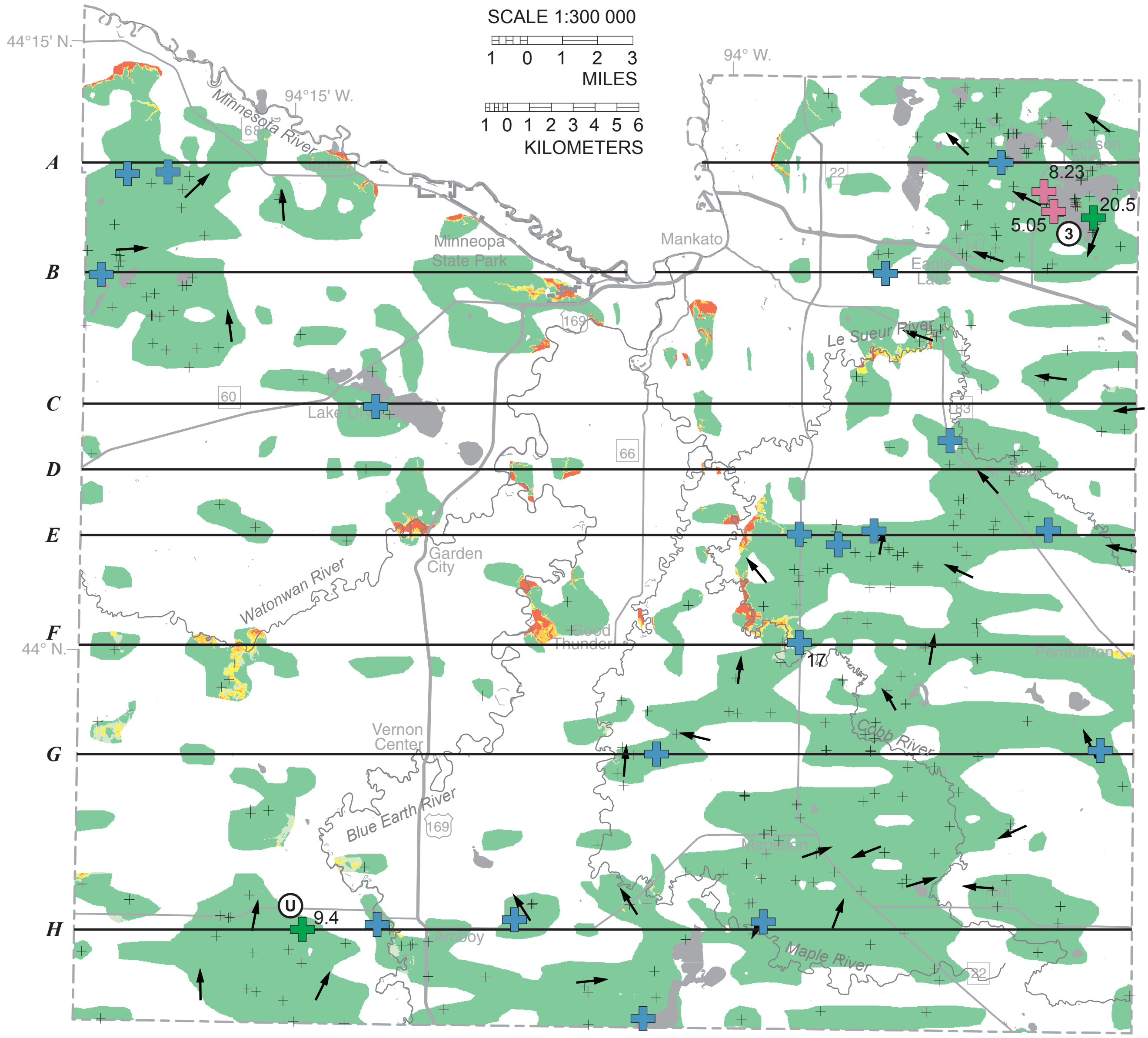
- 11.3 If shown, chloride concentration equals or exceeds 5 parts per million.
- Groundwater flow direction
- Static water level data
- Body of water
- *E—E′* Line of cross section

Groundwater conditions

- (L) Groundwater flows laterally
- (U) Groundwater flowpath is unknown (deep groundwater with recent or mixed tritium age)

Figure 26. Pollution sensitivity of the buried sand aquifer sm and groundwater flow directions

This aquifer typically has a very low pollution sensitivity except for shallower occurrences in river valleys.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- 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 sampled.

- Recent: water entered the ground since about 1953 (8 to 15 tritium units [TU]).
- Mixed: water is a mixture of recent and vintage waters (greater than 1 TU to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).

Symbols and labels

20.5 If shown, chloride concentration equals or exceeds 5 parts per million.

Groundwater flow direction

Static water level data

Body of water

E—E′ Line of cross section

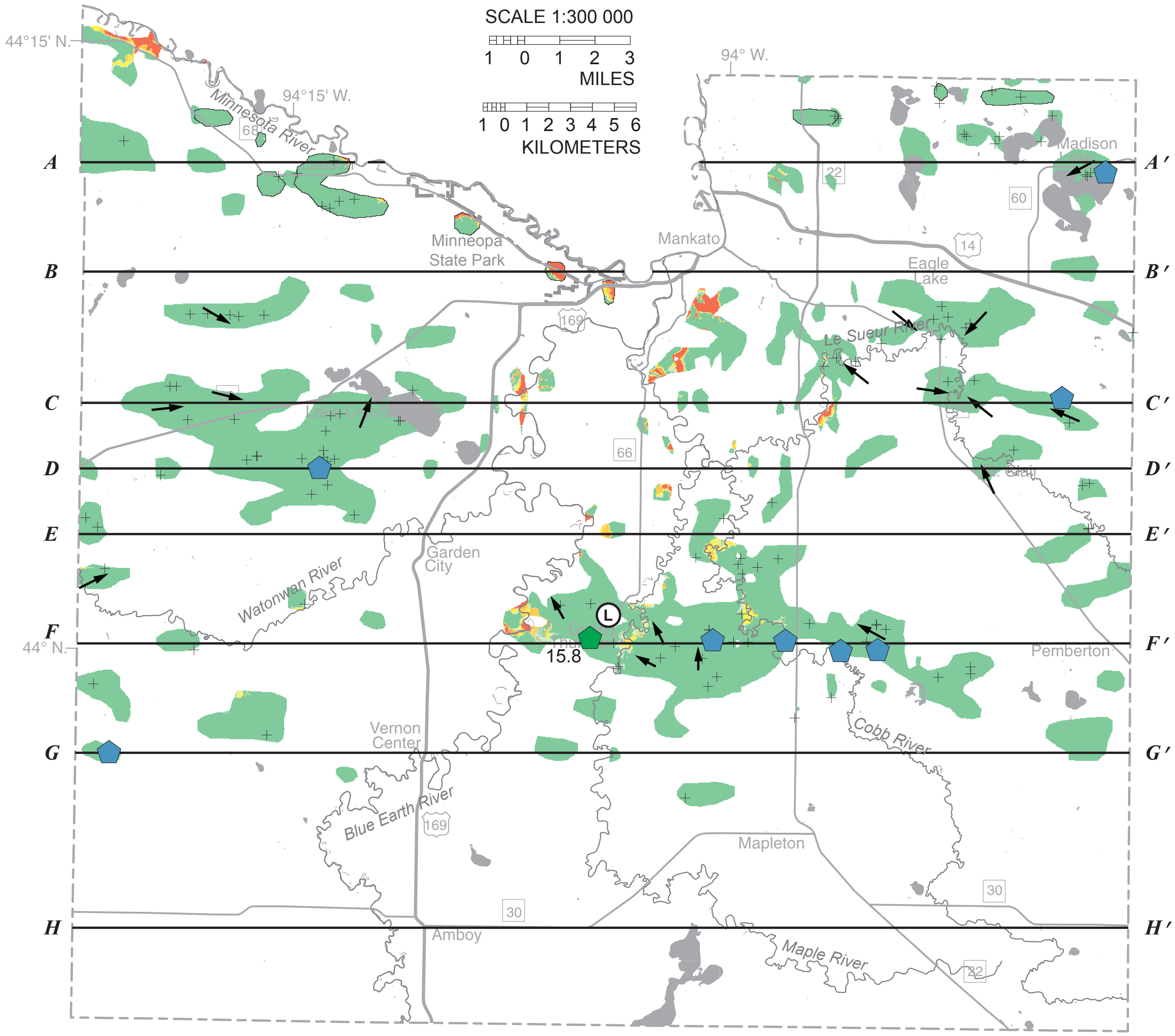
Groundwater conditions

(3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer

(U) Groundwater flowpath is unknown (deep groundwater with recent or mixed tritium age)

Figure 27. Pollution sensitivity of the buried sand aquifer st and groundwater flow directions

This aquifer typically has a very low pollution sensitivity except for shallower occurrences in river valleys.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- 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 sampled.

- Mixed: water is a mixture of recent and vintage waters (greater than 1 tritium unit [TU] to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).

Symbols and labels

15.8 If shown, chloride concentration equals or exceeds 5 parts per million.

Groundwater flow direction

Static water level data

Body of water

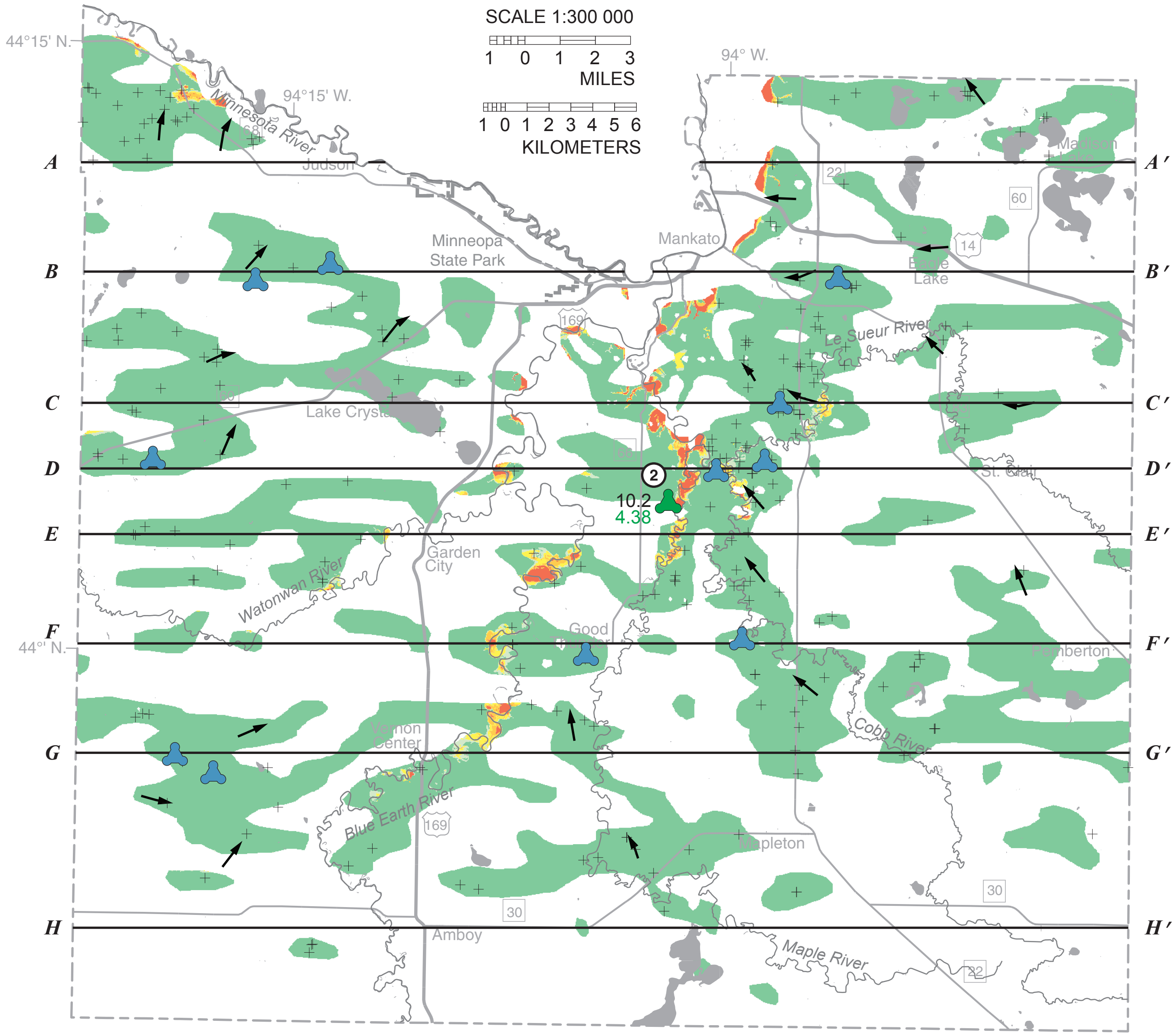
E—E′ Line of cross section

Groundwater conditions

(L) Groundwater flows laterally

Figure 28. Pollution sensitivity of the buried sand aquifers sg and s2 and groundwater flow directions

These aquifers typically has a very low pollution sensitivity except for shallower occurrences in river valleys. The s2 unit area is stratigraphically above the sg aquifer (shown with outline) in the area shown.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

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

Groundwater conditions

(2) Groundwater moves from an overlying surficial aquifer to a buried aquifer

Tritium age

Symbol color indicates tritium age of water sampled.

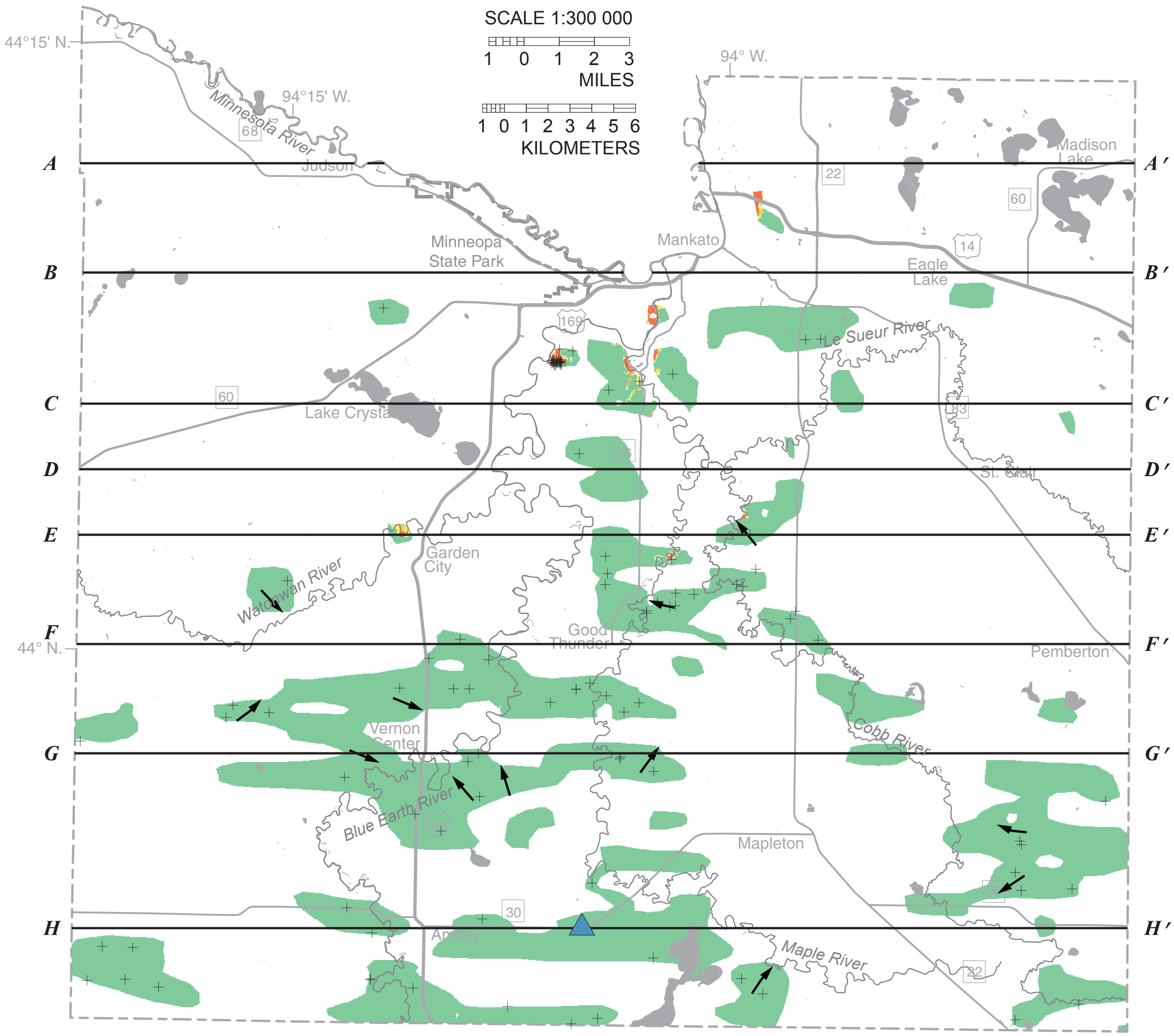
- Mixed: water is a mixture of recent and vintage waters (greater than 1 tritium unit [TU] to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).

Symbols and labels

- 10.2 If shown, chloride concentration equals or exceeds 5 parts per million.
- 4.38 If shown, nitrate-nitrogen concentration equals or exceeds 1 part per million.
- Groundwater flow direction
- Static water level data
- Body of water
- *E—E′* Line of cross section

Figure 29. Pollution sensitivity of the buried sand aquifer se and groundwater flow directions

This aquifer typically has a very low pollution sensitivity except mainly for shallower occurrences in river valleys.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- 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 sampled.

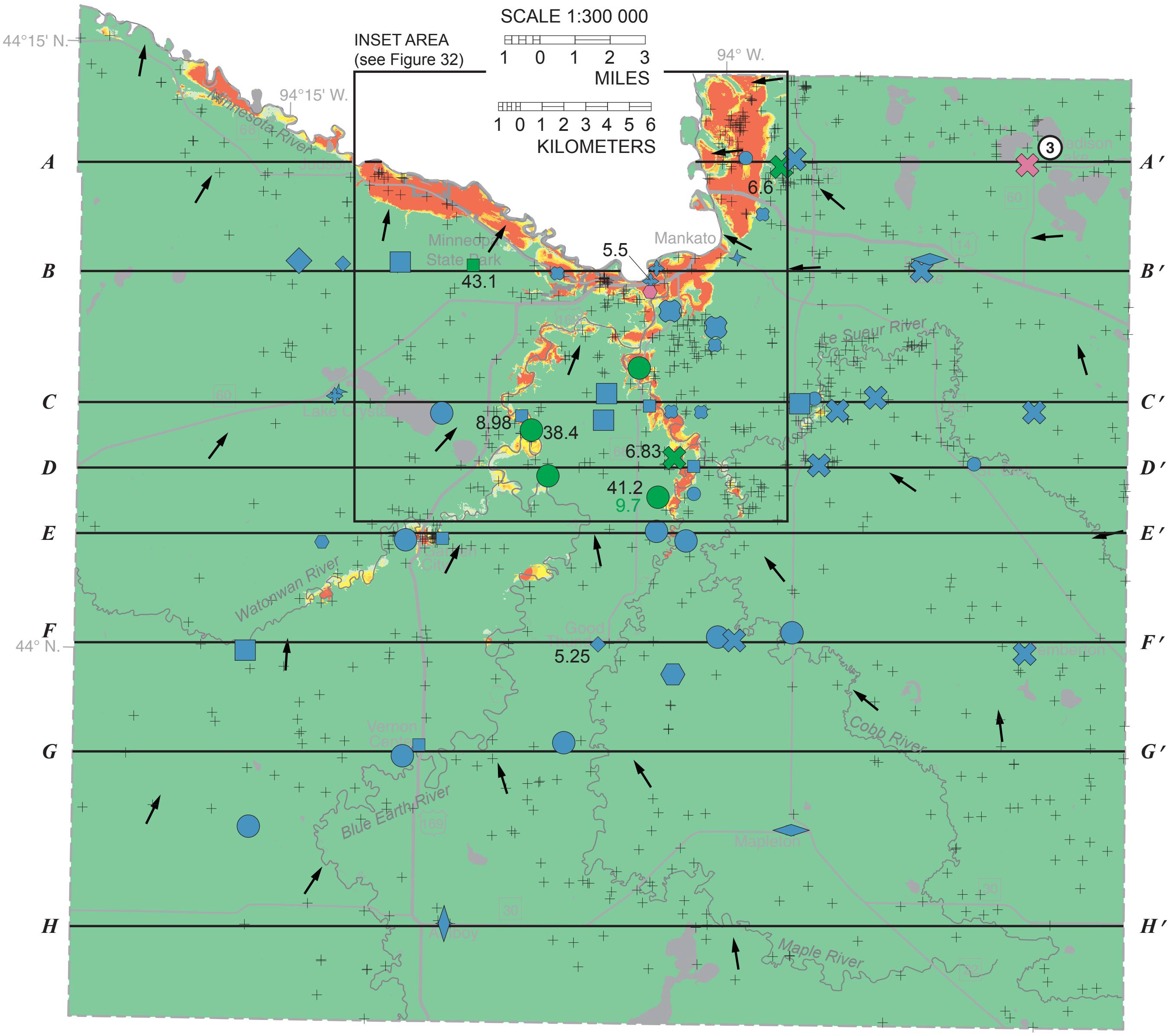
- Vintage: water entered the ground before 1953 (less than or equal to 1 tritium unit).

Symbols and labels

- Groundwater flow direction
- Static water level data
- Body of water
- *E—E′* Line of cross section

Figure 30. Pollution sensitivity of the buried sand aquifer su and groundwater flow directions

This aquifer typically has a very low pollution sensitivity except mainly for shallower occurrences in river valleys.



Pollution sensitivity rating

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target)

- 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 sampled.

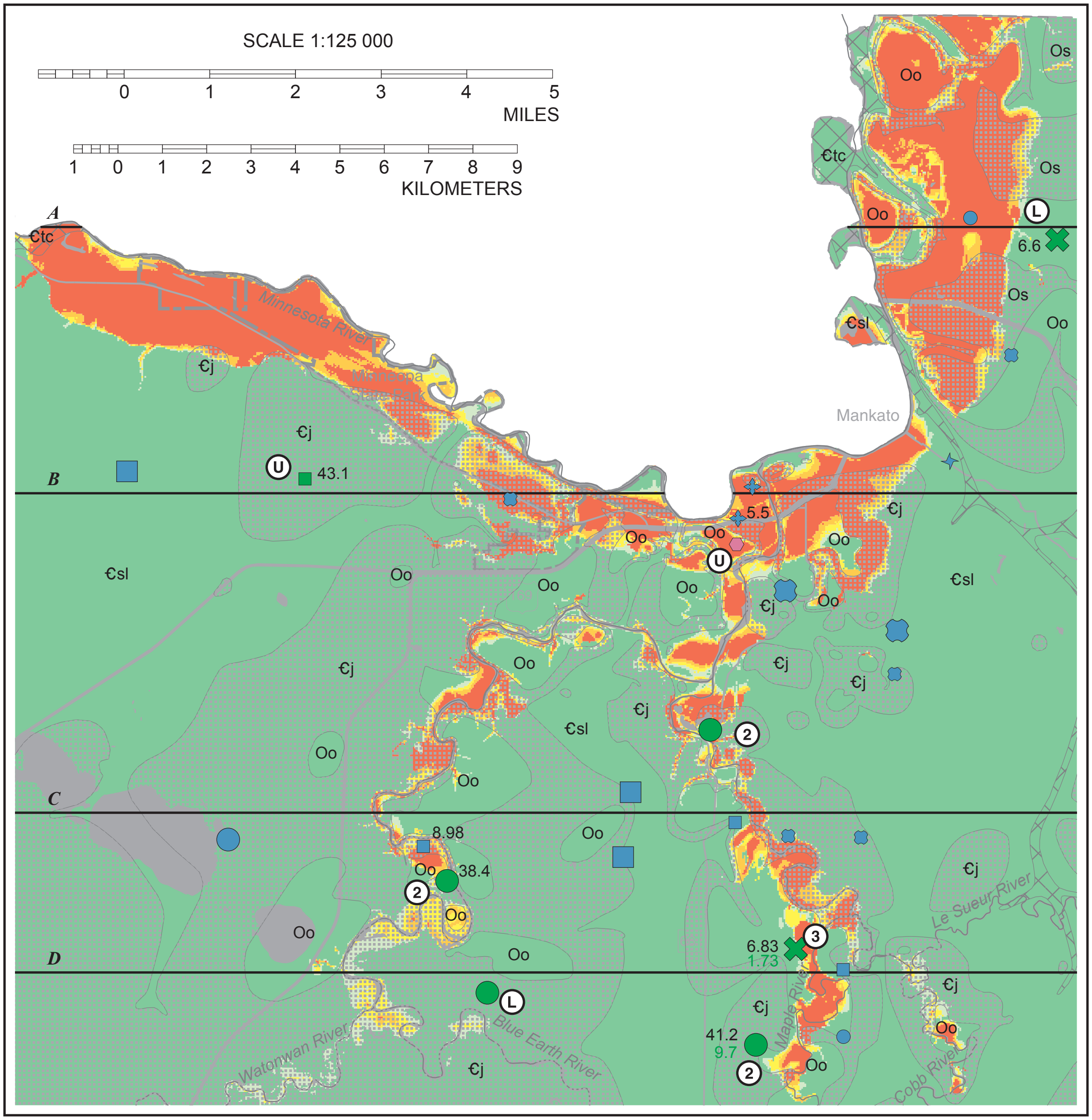
- Recent: water entered the ground since about 1953 (8 to 15 tritium units [TU]).
- Mixed: water is a mixture of recent and vintage waters (greater than 1 TU to less than 8 TU).
- Vintage: water entered the ground before 1953 (less than or equal to 1 TU).

Symbols and labels

- 5.5 If shown, chloride concentration equals or exceeds 5 parts per million.
- 9.7 If shown, nitrate-nitrogen concentration equals or exceeds 1 part per million.
- Groundwater flow direction
- Static water level data
- Body of water
- *E—E′* Line of cross section

Figure 31. Pollution sensitivity of the bedrock surface and bedrock groundwater flow directions

The legends on Figures 31 and 32 apply to both.



Sampled well and aquifer symbols

- Prairie du Chien
- Prairie du Chien–Jordan
- Jordan
- Jordan, St. Lawrence, and Upper Tunnel City
- St. Lawrence
- St. Lawrence, Upper Tunnel City
- St. Lawrence, Upper Tunnel City, Wonewoc
- Upper Tunnel City
- Upper Tunnel City, Wonewoc
- Upper Tunnel City, Wonewoc, Mt. Simon
- Mt. Simon

Large symbols: samples from the shallow bedrock aquifers

Small symbols: samples from the underlying bedrock aquifer

Bedrock geologic unit

- Os Shakopee Formation (Prairie du Chien)
- Oo Oneota Dolomite (Prairie du Chien)
- Ꞓj Jordan Sandstone
- Ꞓsl St. Lawrence Formation
- Ꞓtc Tunnel City Group

Groundwater conditions

- (2) Groundwater moves from overlying surficial aquifer to a buried aquifer
- (3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer
- (L) Groundwater flows laterally
- (U) Groundwater flowpath is unknown (deep groundwater with recent or mixed tritium age)

Figure 32. Inset area of Figure 31 with bedrock hydrogeology

The legends on Figures 31 and 32 apply to both.

Summary and conclusions

Although shallow water-table conditions are common in the county (0–10 feet), there is limited use of this aquifer for human consumption. However, shallow groundwater flows towards and sustains surface-water features and emerges as springs in the valley walls of the Minnesota River and the lower, incised reaches of its tributaries. Slow infiltration rates (low to very low pollution sensitivity) are common in the eastern and southern portions of the county, with the exception of the larger stream valleys where sandier sediment is present. The northwestern portion of the county has near-surface sensitivity values of moderate to high where sandier sediment is common.

The surficial and bedrock aquifers supply much of the high capacity (municipal and industrial) needs in the county (22 percent and 73 percent, respectively). The buried sand aquifers are important water sources for rural domestic use. The majority (56 percent) of permitted water use in the county is for water works (municipal and private). The main aquifers for this use are the bedrock aquifers and the surficial sand aquifer in the Minnesota River valley. The next highest use is industrial or commercial (37 percent) which uses water exclusively from the bedrock aquifers. Irrigation uses a small percentage (5 percent) of water in the county.

The majority of groundwater samples collected for stable isotope analysis across the county showed that most precipitation (normal rain and snowmelt) infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies. Isotopic signatures around and downgradient of Madison Lake differ; water with an evaporative signature that was detected in the bedrock aquifers is interpreted as demonstrating a connection between the lake and underlying buried aquifers.

Residence-time analysis of groundwater samples using the radioactive isotope tritium and other chemical species validated sensitivity models that were based on the presence of a specified thickness of protective material (aquitard) overlying each aquifer. Groundwater samples with recent and mixed tritium values correspond to areas of very high to moderate sensitivity and those with vintage tritium values correspond to areas of low to very low sensitivity.

In stratigraphic order from shallowest to deepest, the major aquifer characteristics are summarized here.

- sh aquifer—generally less than 50 feet deep and relatively thin and is therefore not usually used for water-supply purposes. Moderate to very high pollution sensitivity conditions are common for this aquifer.
- sm aquifer—typically shown with very low pollution sensitivity except where it is nearer to the surface in river valleys. Three samples in the northeastern portion of the county had mixed tritium age: one east of Madison Lake and two east of the city of St. Clair.
- st aquifer—relatively widespread and widely used in the county. This aquifer is generally well protected with very low pollution sensitivity. However, there are many locations in river and stream valleys where this aquifer is close to the surface and is shown with moderate to very high pollution sensitivity. Two samples in the Madison Lake area had recent tritium age and one sample located west of Amboy had a mixed tritium age.
- sg and s2 aquifers—limited extents in the county and typically low pollution sensitivity except in river and stream valleys where these buried sand aquifers are closer to the surface.
- se and su aquifers—very low pollution sensitivity at most locations. Similar to the overlying aquifers, localized areas of moderate to very high pollution sensitivity in stream and river valleys where the aquifers are shallow or hydraulically connected to the surface through multiple interconnected aquifers.
- Bedrock aquifers—very low pollution sensitivity for most of the county and the bedrock surface. Five groundwater samples from the Jordan and Prairie du Chien aquifers in river valley settings of the Blue Earth, Le Sueur, and Maple rivers had mixed tritium age. These are of very high pollution sensitivity.
- Vintage tritium values are shown in several deeper aquifer sample locations in or near the Minnesota River valley and the Blue Earth or Le Sueur river valleys from the Upper Tunnel City, Wonewoc, and Mt. Simon aquifers. This suggests that the bedrock aquitards are effective protective layers.

Elevated, naturally occurring arsenic values are common in groundwater samples from wells in contact with glacial sediment of the New Ulm Formation (73 percent or 16 of the 22 sampled wells in the New Ulm Formation) (Figures 7 and 8).

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Glossary

alluvium—a general term for unconsolidated sediments deposited from a river, including river beds, floodplains, lakes and fans.

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

anthropogenic—of, relating to, or resulting from the influence of human beings on nature.

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

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

arsenic—a chemical element with symbol As and atomic number 33. Arsenic occurs in many minerals, usually in conjunction with sulfur and metals, and also as a pure elemental crystal. Arsenic is toxic to multicellular life, although a few species of bacteria are able to use arsenic compounds as respiratory metabolites. Natural arsenic contamination of groundwater is a problem that affects millions of people across the world.

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

buried aquifer(confined aquifer)—a volume of porous and permeable sediment, either sand or gravel or a mixture of sand and gravel which is buried beneath the ground surface by an impermeable or low permeability layer.

carbon-14 (^{14}C)—a radioactive isotope of carbon with a nucleus containing 6 protons and 8 neutrons. Its presence and gradual decay in organic materials is the basis of the radiocarbon dating method (half-life of 5,730 years).

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

County Well Index (CWI)—a database developed and maintained by the Minnesota Department of Health and Minnesota Geological Survey containing basic information for wells drilled in Minnesota such as location, depth, and static water level. The database contains construction and geological information from the well record (well log) for many wells. It is available online through the Minnesota Well Index mapping application (http://www.health.state.mn.us/divs/eh/cwi/index.html).

deuterium (D or ^2H)—also known as heavy hydrogen, one of two stable isotopes of hydrogen.

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

Formation—formally defined and 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 certain quantity of a mixture (solid, liquid, solute, suspension, or isotope) is divided up in a number of smaller quantities (fractions) in which the composition varies according to a gradient. Fractions are collected based on differences in a specific property of the individual components. In this case, isotopes are fractionated by mass.

glacial—of, relating to, or derived from a glacier.

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

habitat—an ecological or environmental area that is inhabited by a particular species of animal, plant, or other type of organism.

half-life—the time required for a quantity to fall to half its value as measured at the beginning of the time period, typically in reference to a radioactive element.

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

hydraulic—relating to water movement.

hydraulic conductivity—the volume of fluid that flows through a unit area of porous medium for a unit hydraulic gradient perpendicular to that area.

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

isotope—variants of a particular chemical element. While all isotopes of a given element share the same number of protons, each isotope differs in its number of neutrons.

karst—terrain with distinctive landforms and hydrology created primarily from the dissolution of soluble rocks. It is characterized by sinkholes, caves, springs, and underground drainage dominated by rapid conduit flow. Karst allows a direct, very rapid exchange between surface water and groundwater and significantly increases groundwater contamination risk from surface pollutants.

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

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

nitrate—a polyatomic ion with the molecular formula NO_3. Nitrates are primarily derived from fertilizer. Humans are subject to nitrate toxicity, with infants being especially vulnerable to methemoglobinemia, also known as blue baby syndrome. Excess nitrate concentrations in aquatic systems from agricultural runoff may lead to increased algae blooms. When excess algae die they use up oxygen as they decompose depleting oxygen and creating dead zones.

observation well—a well that is used to measure the elevation of the water table or the potentiometric surface.

potentiometric surface—a surface that results from calculating water elevations from wells that tap a confined aquifer. The plotted and contoured data create a surface representation. The potential is determined by elevation (gravitational potential) and pressure.

radioactive—a property of an element that spontaneously emits radiation such as the emission of energetic alpha particles, beta particles, and gamma rays. Radioactive half-life is the time it takes for half of the material to decay or change to another element through the emission of these particles.

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

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

specific capacity—the quotient created when you divide the discharge of a well by the drawdown in the well.

stable isotope—chemical isotopes that are not radioactive, that is, they do not spontaneously undergo radioactive decay.

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. Also used to refer to the sequence of rock layers in a region.

till—unsorted glacial sediment derived from the subglacial erosion and entrainment of rock and sediment over which the glacier has passed and deposited directly by ice. It is no longer till if it has been modified or redeposited.

transmissivity—the rate that groundwater flows horizontally through an aquifer.

tritium (^3H)—a radioactive isotope of hydrogen. The nucleus of tritium contains one proton and two neutrons.

unconfined—refers to an aquifer that has a water table and implies direct contact of the water table with the atmosphere through an unsaturated layer.

vadose zone—also termed the unsaturated zone, the layer between the land surface and the top of the water table. Water in the vadose zone has a pressure head less than atmospheric pressure, and is retained by a combination of adhesion and capillary action.

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

watershed—the area of land drained by a single stream or river.

Appendix

Table A. CGA field sample collection and handling details

Parameter	Lab	Sample container	Head space	Rinse	Filter	Preservative	Refrigeration	Shelf life	Field duplicate	Field blank	Storage duplicate
Tritium	Waterloo	500 ml HDPE	yes	NO	no	no	no	long	1 for every 20	none	yes
$\delta\ ^{18}O$ $\delta\ ^{2}H$	Waterloo	60 ml HDPE	yes	NO	no	no	no	long	1 for every 20	none	yes
Cations	U of M	15 ml, Fisherbrand BLUE cap	yes	yes*	yes	1 drop 6N HCl	yes	2–3 weeks	1 for every 20	1 for every 20****	no
Anions	U of M	50 ml Argos BLACK***	yes	yes*	yes	no	yes	2–3 weeks	1 for every 20	1 for every 20****	no
Trace constituents	U of M	15 ml Sarstedt RED cap	yes	yes*	yes	5 drops 15N HNO_3	yes	2–3 weeks	1 for every 20	1 for every 20****	no
Alkalinity	onsite	500 ml plastic	NO	yes**	no	no	Yes, if not analyzed onsite	24–48 hours	none	none	no
^{14}C	U of M	30 gallon barrel	yes	no	yes	NH_4OH to pH 8.5	no	years	none	none	no

*Rinse the bottle once with FILTERED sample water prior to collecting the sample. Rinsing means fill the bottle with sample water (FILTERED if sample is filtered) 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.

***Fill 50 ml anion bottle unless filtering is very difficult. Bottle must be at least 1/3 full.

****Use DI water from small bottle for field blanks. Pour DI water into the back of the syringe when the plunger is removed. Fill bottles through filter.

Table B. Selected trace element and isotopic data from groundwater samples

[Arsenic values shown in red exceeded the Minnesota Department of Health's health risk limits of 10 ppb. **ppb = parts per billion, Tr = trace; ***reported in tritium units, ****delta values reported in units per thousand relative to a standard]

Aquifer code:

QBAA = Quaternary buried artesian aquifer

QBUA = Quaternary buried unconfined aquifer

OPDC = Ordovician Prairie du Chien Group

CJDN = Cambrian Jordan Sandstone

CJSL = Cambrian Jordan Sandstone and St. Lawrence Formation

CSLT = Cambrian St. Lawrence Formation and Tunnel City Group

CTCW = Cambrian Tunnel City Group and Wonewoc Sandstone

CTCG = Cambrian Tunnel City Group

*Quaternary lithostratigraphy designations from the Part A atlas of unconsolidated sand and gravel are used as aquifer designations.

Well information		**Aquifer codes**			**Trace element**	**Residence time indicators**		**Stable isotopes******	
MN unique	Depth (feet)	CWI	Part A*	Date sampled	Arsenic (ppb)**	^{14}C (years)	Tritium (TU)***	$\delta\ ^{2}H$	$\delta\ ^{18}O$
102510	90	QBAA	st	4/23/2012	3.4		7.8	-34.54	-4.43
112903	125	CJDN		5/18/2012	0.9		5.6	-55.58	-8.31
138411	155	CJDN		5/1/2012	3.16		<0.8	-61.77	-9.24
138420	156	QBAA	st	4/30/2012	Tr		<0.8	-63.18	-8.73
145140	517	CTCW		4/25/2012	1.9		<0.8	-69.75	-9.53
154670	277	CSLT		5/7/2012	1.1		5.9	-57.50	-8.09
160549	155	CTCG		5/1/2012	ND		<0.8	-65.77	-9.14
167142	112	QBAA	s2	5/2/2012	Tr		<0.8	-66.94	-9.21
171310	110	QBAA	sm	5/17/2012	60		<0.8	-75.79	-10.82
171315	92	QBAA	st	5/17/2012	10		<0.8	-58.96	-8.00
171324	120	QBAA	sm	5/17/2012	60		<0.8	-62.96	-8.95
171338	80	QBAA	st	5/16/2012	Tr	2000	<0.8	-59.80	-9.07
183808	115	QBAA	se	4/30/2012	0.3		<0.8	-63.55	-8.92
186109	240	QBAA	se	4/24/2012	0.5		<0.8	-70.65	-10.07
190633	160	CJDN		5/1/2012	1.1		<0.8	-66.24	-9.50
193660	232	OPDC		4/23/2012	1.2		3.2	-43.76	-5.63
196339	142	QBAA	st	4/30/2012	5.7		<0.8	-64.76	-8.80
209871	262	CTCG		5/1/2012	1.7		<0.8	-58.55	-7.76
211753	240	CJDN		4/30/2012	1.41		<0.8	-63.95	-8.50
405350	172	QBAA	se	5/8/2012	9.3		<0.8	-62.13	-8.59
413169	311	OPDC		4/24/2012	Tr	6000	<0.8	-55.22	-6.94
423367	207	QBAA	s2	4/23/2012	19		<0.8	-53.51	-6.97
423380	120	QBAA	st	4/26/2012	19.1		<0.8	-56.07	-7.64
423382	80	QBAA	sm	6/11/2012	21		1.4	-54.71	-7.44
423396	136	QBAA	st	4/25/2012	3.5		14	-30.89	-3.21
433342	138	QBUA	sm	4/25/2012	13.3		<0.8	-32.91	-3.53
439395	232	CSLT		5/9/2012	Tr	29000	<0.8	-60.17	-8.18
444688	70	QBAA	st	5/16/2012	27		<0.8	-60.92	-8.32
444739	101	QBAA	st	5/8/2012	8.1		<0.8	-63.29	-9.00
445924	223	OPDC		4/24/2012	0.97		<0.8	-67.33	-9.07
455937	165	QBAA	se	5/2/2012	13.4		<0.8	-58.85	-8.12
463613	130	QBAA	s2	5/1/2012	4.3	5000	2.8	-59.86	-8.94
488105	237	QBAA	se	6/21/2012	3		0.9	-61.20	-8.44
508823	130	QBAA	se	5/8/2012	4.8		<0.8	-60.24	-8.02

Table B. (continued)

Well information		Aquifer codes			Trace element	Residence time indicators		Stable isotopes****	
MN unique	Depth (feet)	CWI	Part A*	Date sampled	Arsenic (ppb)**	^{14}C (years)	Tritium (TU)***	δ ^{2}H	δ ^{18}O
511487	214	CJDN		5/9/2012	2.7		<0.8	-64.00	-8.72
516891	290	CJSL		5/2/2012	0.5		<0.8	-60.77	-8.30
520800	174	QBAA	s2	4/24/2012	15	2000	<0.8	-51.59	-6.40
520808	95	QBAA	sm	6/11/2012	8.8		0.9	-50.31	-7.00
525383	121	QBAA	sm	4/30/2012	1.7		<0.8	-61.10	-8.02
525497	95	QBAA	st	5/16/2012	29		<0.8	-60.34	-8.79
537117	138	QBAA	st	4/25/2012	2.5		12.2	-31.25	-2.71
552616	125	CJDN		5/2/2012	12		<0.8	-63.83	-8.64
552624	95	QBAA	sm	4/23/2012	22		<0.8	-45.86	-5.31
552638	200	QBAA	se	5/1/2012	6.7	10000	<0.8	-61.90	-8.50
560689	232	OPDC		4/30/2012	0.36		<0.8	-68.28	-9.35
560723	109	QBAA	st	6/21/2012	11		<0.8	-63.35	-8.93
561970	220	OPDC		4/24/2012	3.1		<0.8	-68.15	-9.22
562114	96	QBAA	st	5/1/2012	6.86		<0.8	-59.64	-7.82
570179	172	QBAA	su	6/12/2012	5.4		1.0	-57.52	-8.39
570182	68	QBAA	s2	4/30/2012	0.4	10000	<0.8	-63.09	-8.73
570215	285	CJDN		5/1/2012	0.5		<0.8	-64.93	-8.68
570226	170	CJDN		12/3/2012	0.3		5.7	-62.39	-8.81
579847	210	OPDC		6/11/2012	2.6		<0.8	-66.69	-8.87
579900	138	OPDC		5/1/2012	3.03		<0.8	-65.59	-8.37
592794	97	CJDN		4/23/2012	4		<0.8	-31.06	-2.71
593329	72	QBAA	st	5/9/2012	Tr		<0.8	-61.71	-8.47
611711	155	QBAA	st	4/30/2012	6.2		<0.8	-63.46	-8.03
611725	149	QBAA	se	12/3/2012	2.3		5.2	-61.08	-9.07
614133	172	QBAA	st	4/25/2012	17.2		<0.8	-36.68	-4.17
614136	150	CJDN		5/2/2012	4.2	2000	<0.8	-56.08	-7.26
620949	410	CSLT		4/25/2012	2.5		<0.8	-64.98	-8.90
623155	130	QBAA	s2	4/30/2012	26		<0.8	-66.83	-9.34
623163	236	CJDN		5/8/2012	7		<0.8	-65.26	-8.43
623172	65	QBAA	sm	6/21/2012	17		4.6	-61.13	-8.46
639352	340	CTCW		5/7/2012	Tr		<0.8	-67.11	-9.80
644405	47	CJSL		5/16/2012	3.62		1.1	-64.01	-9.09
644414	205	CJDN		5/16/2012	2.86		<0.8	-61.96	-8.78
648500	93	QBAA	st	5/17/2012	30		<0.8	-56.01	-8.00
652889	340	CSLT		6/21/2012	2		<0.8	-65.32	-9.25
652891	320	CTCW		5/7/2012	8.5		<0.8	-61.66	-8.34
653887	134	QBAA	st	5/18/2012	10.3		5.1	-60.04	-9.13
659495	212	QBAA	se	6/11/2012	0.7		<0.8	-65.54	-9.50
662551	120	CJDN		4/24/2012	10		<0.8	-68.80	-9.46
674503	115	QBAA	st	5/17/2012	1.51		<0.8	-64.72	-8.86
674522	105	QBAA	st	6/12/2012	9		<0.8	-61.61	-9.22

Table B. (continued)

Well information		Aquifer codes			Trace element	Residence time indicators		Stable isotopes****	
MN unique	Depth (feet)	CWI	Part A*	Date sampled	Arsenic (ppb)**	^{14}C (years)	Tritium (TU)***	$\delta\ ^{2}H$	$\delta\ ^{18}O$
682283	213	QBAA	se	4/24/2012	7		<0.8	-48.54	-6.22
686872	240	OPDC		4/23/2012	3.4		<0.8	-33.86	-3.32
691265	190	QBAA	se	4/30/2012	0.7		<0.8	-64.07	-8.29
691288	168	QBAA	se	6/12/2012	0.5		<0.8	-64.09	-9.10
696440	174	CSLT		5/8/2012	Tr		<0.8	-63.37	-9.14
712070	105	QBAA	st	5/17/2012	11.3		<0.8	-75.75	-10.52
712079	115	QBAA	s2	4/30/2012	3.7		<0.8	-61.33	-8.30
731514	92	QBAA	sm	4/24/2012	16	5000	<0.8	-57.38	-7.37
733604	283	CTCW		5/1/2012	Tr		<0.8	-57.61	-7.80
733626	327	CSLT		5/16/2012	6		<0.8	-56.82	-8.54
734648	111	QBUA	st	4/24/2012	4		<0.8	-52.17	-7.14
736546	155	CJDN		6/12/2012	1.9		2.0	-60.78	-8.88
747586	111	QBAA	sm	5/17/2012	0.26		<0.8	-56.46	-8.28
751078	480	CTCW		4/25/2012	4		<0.8	-66.50	-9.52
751093	152	QBAA	s2	6/12/2012	4		<0.8	-59.61	-8.23
751096	380	CSLT		4/25/2012	0.7		<0.8	-59.33	-7.88
751097	86	OPDC		12/3/2012	Tr		7.8	-68.29	-9.94
769354	114	QBAA	s2	5/1/2012	4.4		<0.8	-64.85	-8.54

Table C. Selected cations and anions

[Tr = trace, ND = not detected. Values shown in red indicate elevated concentrations
(≥ 5 ppm chloride, ≥ 1 ppm nitrate) or values that exceed the MDH HRL (> 0.100 ppm manganese)]

Aquifer code:

QBAA = Quaternary buried artesian aquifer

QBUA = Quaternary buried unconfined aquifer

OPDC = Ordovician Prairie du Chien Group

CJDN = Cambrian Jordan Sandstone

CJSL = Cambrian Jordan Sandstone and St. Lawrence Formation

CSLT = Cambrian St. Lawrence Formation and Tunnel City Group

CTCW = Cambrian Tunnel City Group and Wonewoc Sandstone

CTCG = Cambrian Tunnel City Group

*Quaternary lithostratigraphy designations from the Part A atlas of unconsolidated sand and gravel are used as aquifer designations.

Well information		Aquifer codes			Anions mg/l					Cations mg/l					
MN unique	Depth (feet)	CWI	Part A*	Date sampled	Cl^-	NO_3	SO_4^{2-}	Br^-	Cl^-/Br^-	Ca	Mg	Na	K	Fe	Mn
102510	90	QBAA	st	4/23/2012	20.5	Tr	12.8	0.05	410	72	25	7.8	5	4	1.14
112903	125	CJDN		5/18/2012	38.4	0.334	71.7	0.05	768	95	37.4	22.6	2.81	1.97	0.51
138411	155	CJDN		5/1/2012	0.63	0.05	9.5	0.2	3	78.2	19.5	6.13	3.39	4.06	0.362
138420	156	CJDN	st	4/30/2012	1.24	Tr	339	0.027	46	166	57.4	85.3	4.1	4.57	0.618
145140	517	CTCW		4/25/2012	3.53	ND	237	0.078	45	131	44	52	8.8	2.18	0.056
154670	277	CSLT		5/7/2012	43.1	0.128	73.7	0.04	1078	101	36.7	15.4	5.8	0.61	0.124
160549	155	CTCG		5/1/2012	0.43	Tr	27	Tr	0	66	20	44	6.4	0.8	0.012
167142	112	QBAA	s2	5/2/2012	2.14	0.018	332	0.034	63	146	59	59	5.7	2.09	0.071
171310	110	QBAA	sm	5/17/2012	3.34	0.01	Tr	0.204	16	70	21.9	76	3.7	4.66	0.033
171315	92	QBAA	st	5/17/2012	0.785	0.004	170	0.021	37	135	43.3	41	5.39	1.67	0.578
171324	120	QBAA	sm	5/17/2012	0.365	Tr	96	Tr	0	90	27.6	83.5	10	2.23	0.13
171338	80	QBAA	st	5/16/2012	17	ND	152	0.056	304	136	46.1	30	4.9	0.46	0.71
183808	115	QBAA	se	4/30/2012	1.24	ND	200	0.036	34	125	41.7	69	3.52	1.75	1.16
186109	240	QBAA	se	4/24/2012	1.8	0.005	170	0.054	33	112	38	74	3.2	3.05	0.215
190633	160	CJDN		5/1/2012	2.08	0.024	180	0.026	80	113	39.5	27.2	6.2	1.14	0.0629
193660	232	OPDC		4/23/2012	6.6	Tr	101	0.024	275	82	29	53	2.8	1.09	0.75
196339	142	QBAA	st	4/30/2012	1.28	Tr	356	0.024	53	172	59.5	63	5.8	1.89	0.409
209871	262	CTCG		5/1/2012	0.432	0.006	79	Tr	0	91	33	72.6	4.91	0.96	0.028
211753	240	CJDN		4/30/2012	1.19	ND	206	0.031	38	126	39.7	63	3.5	7.39	0.28
405350	172	QBAA	se	5/8/2012	0.46	0.006	175	0.027	17	95	33.1	122	3.4	1.74	0.091
413169	311	OPDC		4/24/2012	0.65	Tr	27.1	0.024	27	79	27	39	2.7	1.53	0.74
423367	207	QBAA	s2	4/23/2012	1.44	Tr	53.3	0.037	39	81	28.5	47	3.7	0.51	0.236
423380	120	QBAA	st	4/26/2012	1.38	0.03	120	0.2	7	94.8	30.4	105	3.59	1.54	0.989
423382	80	QBAA	sm	6/11/2012	2.6	0.03	32.2	0.2	13	74.9	25.1	21.8	3.36	1.65	0.121
423396	136	QBAA	st	4/25/2012	8.23	0.004	2.2	0.045	183	45	17.7	3.8	4.3	2.12	0.32
433342	138	QBUA	sm	4/25/2012	0.96	0.005	27.5	0.029	33	57	20.7	52.4	4.1	1.36	0.114
439395	232	CSLT		5/9/2012	1.49	Tr	19.4	Tr	0	109	32.5	13.9	10	0.78	0.015
444688	70	QBAA	st	5/16/2012	1.93	ND	88.3	0.029	67	107	34.8	44.5	4.7	1.55	0.243
444739	101	QBAA	st	5/8/2012	1.07	Tr	217	0.022	49	123	44.6	55	5.1	5.7	0.71
445924	223	OPDC		4/24/2012	1.63	0.006	149	0.048	34	102	34.3	78	3.5	2.4	0.54
455937	165	QBAA	se	5/2/2012	0.507	Tr	96	Tr	0	123	40.7	25.6	4.8	2.6	0.156
463613	130	QBAA	s2	5/1/2012	15.8	ND	89.2	0.053	298	129	40.1	16.2	4.7	2.88	0.725
488105	237	QBAA	se	6/21/2012	1.33	ND	161	0.031	43	114	40.1	43.6	4	5	0.117
508823	130	QBAA	se	5/8/2012	0.374	0.01	90.5	Tr	0	132	41	23	5.9	4.56	0.229
511487	214	CJDN		5/9/2012	1.08	0.004	191	0.026	42	121	43.3	43.6	4.66	5.04	0.2

Table C. (continued)

Well information		Aquifer codes			Anions mg/l					Cations mg/l					
MN unique	Depth (feet)	CWI	Part A*	Date sampled	Cl^-	NO_3	SO_4^{2-}	Br^-	Cl^-/Br^-	Ca	Mg	Na	K	Fe	Mn
516891	290	CJSL		5/2/2012	3.96	0.006	146	0.022	180	105	38.4	35.8	7.5	2.18	0.022
520800	174	QBAA	s2	4/24/2012	0.445	0.019	12.1	0.016	28	87	29	17	4.1	3.89	0.372
520808	95	QBAA	sm	6/11/2012	2.39	Tr	63	0.023	104	80	28	31	4	2.05	0.12
525383	121	QBAA	sm	4/30/2012	0.746	Tr	175	0.02	37	117	38.6	87	5	0.07	0.93
525497	95	QBAA	st	5/16/2012	0.919	0.021	37.8	Tr	0	99.6	30.7	26	5.8	1.48	0.225
537117	138	QBAA	st	4/25/2012	5.05	0.005	Tr	0.043	117	42	16.9	5.9	3.7	1.74	0.101
552616	125	CJDN		5/2/2012	1.06	Tr	152	0.022	48	116	38.9	48	5.7	5.34	0.058
552624	95	QBAA	sm	4/23/2012	0.7	0.006	33.8	0.022	32	53	19.8	106	4.42	1.51	0.068
552638	200	QBAA	se	5/1/2012	1.09	ND	170	0.024	45	122	43.6	50.4	4.5	5.2	0.108
560689	232	OPDC		4/30/2012	1.65	ND	116	0.036	46	98.9	30.5	62.9	2.6	7.72	0.413
560723	109	QBAA	st	6/21/2012	0.78	0.024	125	0.028	28	93	30.9	59	3	1.48	0.177
561970	220	OPDC		4/24/2012	1.53	0.004	142	0.046	33	98	34	75	3.4	1.55	0.4
562114	96	QBAA	st	5/1/2012	3.21	0.004	11.8	0.023	140	83	22.4	6	4.2	1.91	0.154
570179	172	QBAA	su	6/12/2012	0.582	ND	122	0.017	34	116	36.4	33	5	1.83	0.322
570182	68	QBAA	s2	4/30/2012	1.22	ND	208	0.033	37	127	39.8	60.1	3.3	0.967	0.426
570215	285	CJDN		5/1/2012	1.34	ND	252	0.035	38	131	44.2	65	3.7	4	0.25
570226	170	CJDN		12/3/2012	41.2	9.7	25.2	0.03	1373	94	28.8	19	2.85	0.004	ND
579847	210	OPDC		6/11/2012	1.87	ND	169	0.062	30	114	38.4	71.7	3	3.94	0.185
579900	138	OPDC		5/1/2012	1.26	ND	250	0.034	37	132	41.7	75	2.9	4.3	0.6
592794	97	CJDN		4/23/2012	1.07	0.004	20.5	Tr	0	52	19.4	24.1	2.5	0.96	0.105
593329	72	QBAA	st	5/9/2012	0.629	Tr	56.7	0.021	30	107	33.5	31.8	4.7	0.22	0.345
611711	155	QBAA	st	4/30/2012	2.01	ND	500	0.034	59	209	73.3	68.7	5.2	3.39	0.396
611725	149	QBAA	se	12/3/2012	10.2	4.38	32.9	0.03	340	95	30.6	9.3	2.29	1.11	0.127
614133	172	QBAA	st	4/25/2012	1.42	0.004	111	0.021	68	105	35	14	5	2.68	0.313
614136	150	CJDN		5/2/2012	0.23	ND	3.2	Tr	0	87	24.5	6.7	3.6	2.67	0.396
620949	410	CSLT		4/25/2012	1.97	0.005	50.5	0.051	39	92	30.4	21	8.2	0.7	0.011
623155	130	QBAA	s2	4/30/2012	4.16	ND	117	0.085	49	91	34	95	2.3	2.83	0.128
623163	236	CJDN		5/8/2012	0.78	0.004	211	0.023	34	114	46.5	76.2	3.9	3.5	0.123
623172	65	QBAA	sm	6/21/2012	11.3	0.071	57.1	0.07	161	104	35	4.7	3	1.8	0.239
639352	340	CTCW		5/7/2012	1.15	Tr	214	0.026	44	130	44.1	57	5.6	1.7	0.154
644405	47	CJSL		5/16/2012	2.6	0.007	54	0.026	100	95.3	31.4	19.3	3	1.91	0.622
644414	205	CJDN		5/16/2012	1.1	Tr	161	0.03	37	113	41.4	67	3.8	3.88	0.225
648500	93	QBAA	st	5/17/2012	0.67	Tr	92	Tr	0	97	32.6	35.8	5.8	0.45	0.138
652889	340	CSLT		6/21/2012	3.18	Tr	191	0.06	53	116	42.7	31	5	1.65	0.0554
652891	320	CTCW		5/7/2012	0.63	Tr	178	0.024	26	108	38.6	90	4.7	1.16	0.171
653887	134	QBAA	st	5/18/2012	9.4	Tr	64	0.046	204	93	28.9	7.09	3.54	4.2	0.4
659495	212	QBAA	se	6/11/2012	1.59	ND	135	0.05	32	112	35.8	48	3	1.55	0.318
662551	120	OPDC		4/24/2012	1.69	0.004	152	0.05	34	103	34.6	72	3.3	3.2	0.193
674503	115	QBAA	st	5/17/2012	1.27	0.004	264	0.033	38	142	44.5	61	3.34	10.1	0.45
674522	105	QBAA	st	6/12/2012	0.536	ND	140	Tr	0	115	37.3	46	6	1.89	0.46
682283	213	QBAA	se	4/24/2012	0.923	Tr	115	0.027	34	71.9	27.8	108	3.7	2.04	0.25

Table C. (continued)

Well information		Aquifer codes			Anions mg/l					Cations mg/l					
MN unique	Depth (feet)	CWI	Part A*	Date sampled	Cl^-	NO_3	SO_4^{2-}	Br^-	Cl^-/Br^-	Ca	Mg	Na	K	Fe	Mn
686872	240	OPDC		4/23/2012	0.8	0.004	36	Tr	0	56	21	38	2.9	0.27	0.206
691265	190	QBAA	se	4/30/2012	0.835	0.007	184	0.021	40	126	43.6	72.5	3.8	0.06	1.29
691288	168	QBAA	se	6/12/2012	1.08	ND	204	0.026	42	141	47	38	4	5	0.19
696440	174	CSLT		5/8/2012	8.98	0.022	28.8	0.032	281	84	26.1	15	8.1	4.24	0.09
712070	105	QBAA	st	5/17/2012	2.86	0.005	157	0.061	47	90	28.1	94	4.58	1.91	0.199
712079	115	QBAA	s2	4/30/2012	1.31	ND	164	0.039	34	117	37	64	3.4	3.4	0.68
731514	92	QBAA	sm	4/24/2012	0.6	0.006	71.7	Tr	0	105	36.7	27	5.24	1.44	0.25
733604	283	CTCW		5/1/2012	0.74	0.008	27.9	ND	0	79	22.6	6.5	2.8	0.92	0.0416
733626	327	CSLT		5/16/2012	0.739	ND	87.8	0.02	37	105	36.2	34.1	4.69	2.38	0.084
734648	111	QBUA	st	4/24/2012	1.43	0.082	75.9	0.031	46	69	25.3	105	4.1	0.22	0.27
736546	155	CJDN		6/12/2012	3.76	0.103	38.9	0.028	134	100	30.4	5	3	0.62	0.304
747586	111	QBAA	sm	5/17/2012	2.52	ND	82.5	0.027	93	81.5	24.1	91.3	6.39	0.02	0.213
751078	480	CTCW		4/25/2012	3.47	0.01	225	0.074	47	130	43.4	45	7.94	3.4	0.061
751093	152	QBAA	s2	6/12/2012	1.66	ND	19.1	Tr	0	98	29	21.3	4.7	4	0.15
751096	380	CSLT		4/25/2012	1.33	Tr	9.4	0.03	44	90.8	31.6	15.1	7.02	0.47	0.01
751097	86	OPDC		12/3/2012	6.83	1.73	33.2	0.03	228	93	29.1	4.4	1.35	0.002	ND
769354	114	QBAA	s2	5/1/2012	1.26	0.004	259	0.034	37	133	42.5	76.9	3.1	2.97	0.918

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COUNTY ATLAS SERIES C-26, PART B
Blue Earth County, Minnesota Scales 1:100,000 to 1:500,000

MNDNR

The DNR Information Center

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