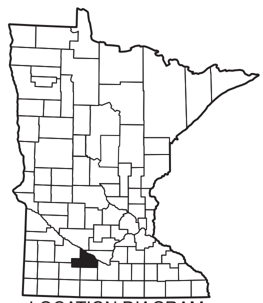
Groundwater Atlas of Brown County, Minnesota

County Atlas Series C-37, Part B



Report

To accompany these atlas components:

Plate 6, Water Chemistry

Plate 7, Hydrogeologic Cross Sections

DEPARTMENT OF NATURAL RESOURCES

St. Paul
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mndnr.gov/groundwatermapping

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This **Part B Groundwater** atlas was published by the Minnesota Department of Natural Resources (DNR), who expanded on the Part A geology information after its completion. Program information and completed atlases can be found on the DNR County Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

County atlas program

The Minnesota County Atlas series has been produced since 1982. Recent atlases are produced in two parts, A and B.

This atlas is based on the Part A Geologic Atlas that was previously completed in 2016 by the Minnesota Geological Survey (MGS). Part A contains Plate 1, Data-Base Map; Plate 2, Bedrock Geology; Plate 3, Surficial Geology; Plate 4, Quaternary Stratigraphy; Plate 5, Bedrock Topography, Depth to Bedrock, and Sand Distribution Model. The Minnesota Geological Survey - County Geologic Atlas page (cse.umn.edu/mgs/county-geologic-atlas). has access to completed atlases, information about the history and purpose of the program, atlas applications, user guides, map sales, and descriptions of the components.

The citation for the Part A Geologic Atlas of Brown County (C-37) is listed in the reference section of this atlas under Boerboom, Terrence J. (2016).

Technical reference

Maps were compiled and generated in a geographic information system. Digital data products are available from the DNR County Groundwater Atlas Program 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 MGS and the DNR. Every effort has been made to ensure the interpretations conform to sound geologic and cartographic principles. These maps should not be used to establish legal title, boundaries, or locations of improvements.

Base maps were modified from the MGS, *C-37 Geologic Atlas of Brown County, Minnesota Part A*, *2016*. Universal Transverse Mercator projection, Zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion factors

1 inch per hour = 7.056 x 10^{-6} meter per second

1 part per million = 1 milligram per liter

1 part per billion = 1 microgram per liter

1 milligram per liter = 1000 micrograms per liter

1 $foot^2$ per day = 7.48 gallons per day per foot

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Groundwater Atlas of Brown County, Minnesota

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Executive summary

This report and the accompanying plates are Part B of the Brown County Atlas. It describes the groundwater characteristics of the county and was produced by the Minnesota Department of Natural Resources (DNR). It builds on the geology described in Part A, previously published by the Minnesota Geological Survey (MGS) (Boerboom, 2016).

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

This report details the methods, results, and interpretations for the county. Plate 6 illustrates the water chemistry; Plate 7 uses hydrogeologic cross sections to show groundwater flow directions and residence time within the aquifers. This executive summary gives an outline of the detailed sections that follow.

Brown County is in southwestern Minnesota (Figure 1) with land use that is a mix of agricultural, rural, and small towns. The population in 2018 was approximately 25,000 (U.S. Census Bureau, 2019). The county lies within portions of the Minnesota River watershed (Mankato) and the Cottonwood and Watonwan river watersheds. The Minnesota River forms the northeastern border of the county.

Brown County is in the northern continental United States and is characterized as a cool, subhumid climate with a large temperature difference between summer and winter seasons. Average temperatures are approximately 70 degrees Fahrenheit June through August, and 16 degrees Fahrenheit December through February (NOAA, 2019). Average annual precipitation is approximately 28 inches, placing it in the middle of the statewide range of 20 to 36 inches.

Geology and physical hydrogeology (pages 4–19) describes characteristics of geologic units in the county. Aquifers and aquitards are identified by their hydrostratigraphic characteristics and corresponding geologic units from Part A. Groundwater elevation maps give a broad look at the direction of groundwater flow in unconfined conditions (water-table elevation) and confined conditions (potentiometric-surface elevation).

Brown County is typical of the southwestern and western portions of Minnesota where bedrock is mostly hard crystalline (gneissic and granitic) bedrock, which is partially overlain by layers of Cretaceous shale, mudstone, and sandstone. In addition, the eastern portion of the county is also underlain by Cambrian sandstone, shale, siltstone, and carbonate. These bedrock units are overlain by multiple layers of glacial sediment including fine-grained till, some ancient lake deposits, and coarser-grained sand and gravel from the melted glaciers. The subsurface distribution of glacial sand and gravel is highly complex and variable. Groundwater availability from these units is similarly variable depending on location.

Water table (pages 4–7) elevations in Brown County cover a wide range of values with the lowest values in the Minnesota River valley. A broad area of similar values and low gradients exist between the Minnesota River valley and the southwestern portion of the county. Groundwater flow directions are regionally toward the Minnesota River and locally toward the Cottonwood, Little Cottonwood, and Watonwan rivers. Water-table depths are shallow (0–20 feet) across most of the county. Some deeper water-table conditions likely exist along the Minnesota and Cottonwood river bluff areas.

Buried sand and gravel, and bedrock aquifers (pages 8–19) show potential groundwater flow patterns that are similar to the water table. Groundwater flows northeast toward the Minnesota River and locally toward the Cottonwood River.

Water chemistry (pages 20–27, Plate 6) provides information about the water source, flow path, travel time, and residence time of groundwater. The groundwater chemistry supports the results of the pollution sensitivity models and is used to identify areas of interest, such as those with high pollution sensitivity or elevated levels of potentially harmful chemicals. For more resources, see the guidelines in the gray box on page 22.

- **Chloride** is generally not a significant contaminant in groundwater from the buried sand and gravel and bedrock aquifers in Brown County. In 11 percent of the samples, chloride was elevated (greater than or equal to 5 parts per million [ppm]), anthropogenic (human caused), and none equaled or exceeded the secondary drinking water standard (250 ppm).
- **Nitrate** was not commonly found. Only 3 percent of the samples had elevated concentrations (greater than or equal to 1 ppm) and were considered anthropogenic.
- **Arsenic** is a naturally occurring constituent in the county (derived from natural or geologic materials) with 79 percent of samples exceeding the laboratory method detection limits, and 27 percent exceeding the Maximum Contaminant Limit of 10 parts per billion (ppb).
- **Manganese** is a naturally occurring constituent in the county with 69 percent of samples greater than or equal to the Health Based Value of 100 ppb. These values were found throughout the county and in most of the mapped aquifers.
- **Sulfate** is a naturally occurring groundwater constituent with 28 percent of samples exceeding the secondary maximum contaminant level of 250 ppm.
- **Carbon-14** residence times in aquifers reflected the wide range of groundwater conditions in the county, ranging from 700 to 30,000 years.

The **pollution sensitivity** (pages 28–43) of an aquifer is estimated based on the time it takes water to flow from the ground surface through various types and thicknesses of soils and geologic materials. Anthropogenic pollutants are assumed to travel with water at the same rate. The sensitivity is modeled with different methods for the 1) near-surface materials and 2) buried sand and gravel aquifers and the bedrock surface. The model results are evaluated by comparing the pollution sensitivity ratings to chemical constituents such as tritium and carbon-14 data for residence time, and to inorganic chemicals for contamination.

- **Near-surface materials** (pages 28–30) exhibit predominantly low sensitivity with smaller areas of high sensitivity. High sensitivity exists in areas where glacial outwash is at the surface in the southern portion of the county and near the larger rivers (Minnesota, Cottonwood, and Little Cottonwood) and smaller streams (Sleepy Eye, Coal Mine, and Mound creeks).
- **Buried sand and gravel aquifers** (pages 31–41) exhibit limited areas of moderate to very high sensitivity. Some of these higher sensitivity areas are found in river valleys. Very low to low sensitivity are the most common ratings with the exception of the uppermost buried sand and gravel aquifer.
- **Bedrock aquifers** (pages 34–35, 42–43) are predominantly Cretaceous sandstone aquifers and the Cambrian Mt. Simon sandstone aquifer. These aquifers are mostly covered by thick glacial till. The **bedrock surface** has mostly very low pollution sensitivity, with the exception of areas near the Minnesota and Cottonwood rivers and in some areas of the western part of the county where bedrock is shallow.

Hydrogeologic cross sections (pages 44–45, Plate 7) illustrate groundwater flow, residence time, and distribution of chemical indicators. Cross sections help define areas of interest such as locations of important groundwater recharge, discharge, and sensitivity to pollution. The cross sections show that the groundwater flow is initially downward, then laterally toward rivers. In many areas recharge to the deeper aquifers can take centuries to millennia. The residence time can be hundreds or thousands of years where focused recharge does not occur through interconnected buried sand and gravel aquifers.

Aquifer characteristics and groundwater use (pages 46–50) summarizes specific capacity tests, aquifer tests, water use records, and groundwater level monitoring data for each aquifer. These data can be used to characterize aquifer recharge in the county and plan for new well installations. The highest volume use is from the buried sand and gravel aquifers, followed by surficial sand and the Dakota aquifer (Cretaceous sandstone). The most common water use is for crop irrigation, followed by municipal and public water supply, food processing, and livestock watering. There are approximately 1,600 nonregulated wells in the county (not requiring a permit). By numbers of wells, 82 percent are domestic, 4 percent are public supply, and 4 percent are irrigation.

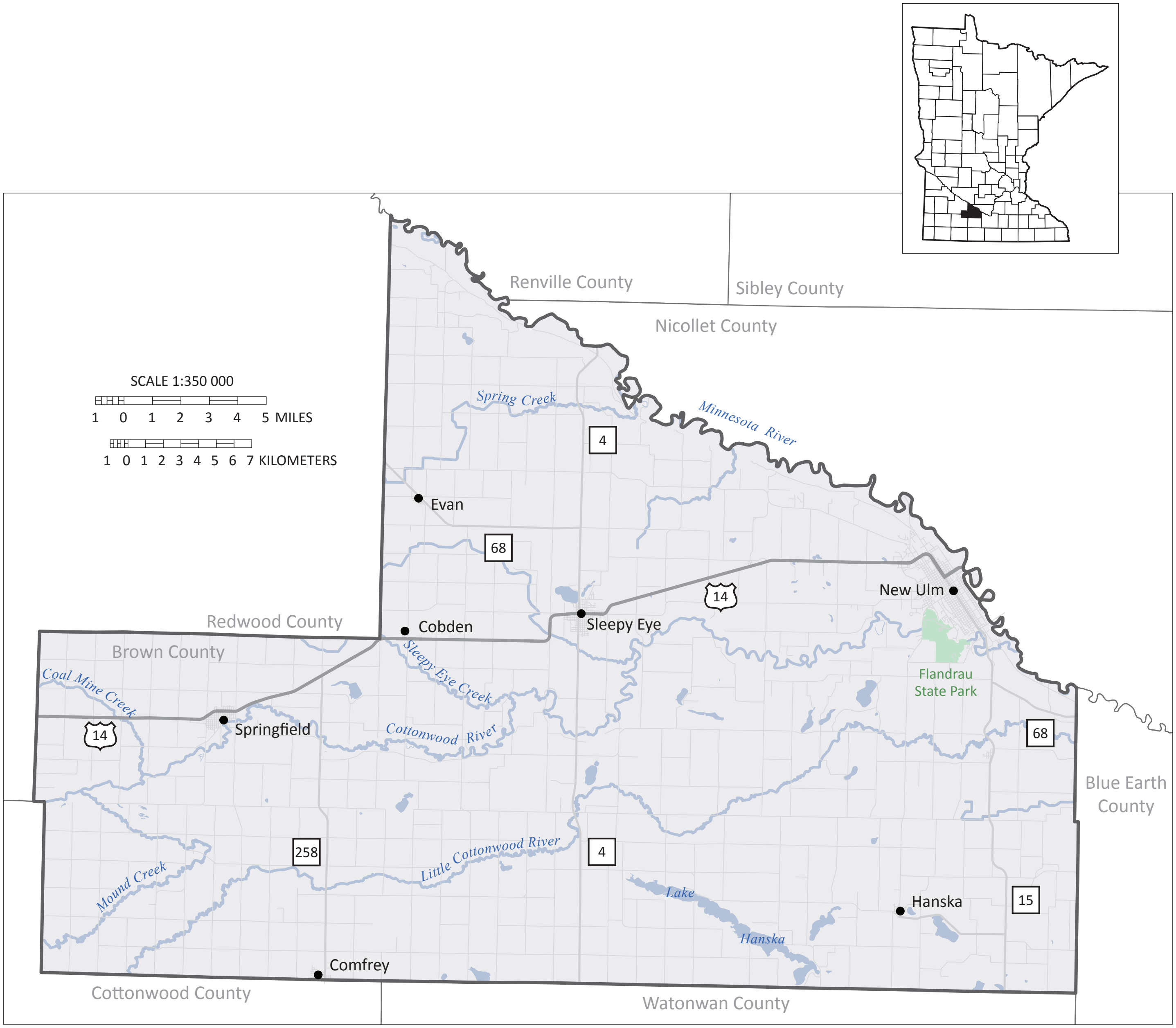


Figure 1. Brown County, Minnesota

Geology and physical hydrogeology

Surficial aquifers

The origin of the topography and surficial deposits of the county can be traced back to advances and retreats of glacial ice (Part A, Plate 3) that deposited fine-grained and coarse-grained sediment (Figure 2). The fine-grained sediment includes a mixture of sand, silt, clay, and gravel referred to as till (also diamicton). Coarser-grained sediment includes glacial outwash that is commonly composed of sand and gravel. Its complex distribution is one of the most important geologic features controlling groundwater recharge and the pollution sensitivity of underlying aquifers.

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

Much of the distribution of surficial sand in Brown County was controlled by two major glacial events: multiple local advances and retreats of the last major ice advance in the area (Heiberg member ice; Part A, Plate 3, Figure 5), and the drainage of vast amounts of glacial meltwater through glacial River Warren in the present day location of the Minnesota River valley. The ice lobe that deposited the Heiberg member sediment advanced to five different locations, each location progressively behind and north of the previous advance. At each location the ice front remained long enough to establish meltwater drainages that were parallel or subparallel to the ice fronts. These temporary drainages deposited relatively wide zones (approximately one quarter to 2 miles) of sand and gravel outwash (coarse-grained unit, Figure 2). Some of these glacial stream routes are currently occupied by the present day streams, creeks, and lakes including:

- The Cottonwood and Little Cottonwood rivers
- The Sleepy Eye and Coal Mine creeks
- Several lakes including Lake Hanska

Approximately 11,500 years ago, the present day Minnesota River valley was created by a glacial meltwater river (glacial River Warren) that drained southeastward from glacial Lake Agassiz (in northwestern Minnesota and Canada). Thick sand and gravel deposits (surficial sand aquifers where saturated) associated with this major drainage exist in and near the Minnesota River valley, especially in the New Ulm area and to the southeast (map unit Qsw*)*.

Thinner sandy deposits, including the map unit Qa, were deposited in the post-glacial era (Holocene) by smaller and narrower streams. This generally finer-grained sediment is typically superimposed on, or adjacent to, most of the glacial outwash sediment.

Water table

The water table is the surface between the unsaturated and saturated zones where water pressure equals atmospheric pressure. It occurs in both aquifer and aquitard sediment across the entire county. Although it is shown in the figures as a static surface, it fluctuates over time. Surficial sand aquifers are present below the water table where there is sufficient saturated thickness and yield to install a well and economically pump groundwater. The water table is generally a subdued expression of the surface topography. Shallow water table flow directions are typically consistent with surface flow and follow the watershed boundaries. Flow is generally from local highs to river tributaries, lakes, and wetlands.

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

Water-table elevation (Figure 3) was estimated from several sources of data:

- Elevation of surface-water bodies (rivers, perennial streams, lakes, and open water wetlands)
- Static water levels in surficial sand wells obtained from the County Well Index (CWI) database (converted to elevations*)
- Estimates of depth to wet soil conditions from the Natural Resources Conservation Service (NRCS) county soil survey (converted to elevations*)

**Data were converted to elevations using a digital elevation model derived from LiDAR (Light Detection and Ranging) technology.*

Depth to water table (Figure 4) was derived by subtracting the water-table elevation from the land-surface elevation. More details can be found in *Methods for estimating water-table elevation and depth to water table* (DNR, 2016a).

Only 2 percent of the wells in the county are completed in the surficial sand, but they account for 21 percent of the permitted water use in 2017. Water-table elevations cover a wide range with the lowest values in the

Minnesota River valley. A broad area of similar values and low gradients are characteristic of the area between the Minnesota River valley and the Cottonwood River.

The highest elevations, with steeper gradients, are south of the Cottonwood River in the southwestern portion of the county. Groundwater flow directions are regionally toward the Minnesota River and locally toward the Cottonwood and Little Cottonwood rivers, and many smaller water bodies.

Water-table depths are shallow (0–20 feet) across most of the county. The water table can be deeper along the Minnesota and Cottonwood river bluff areas and in the lower portions of the Little Cottonwood River.

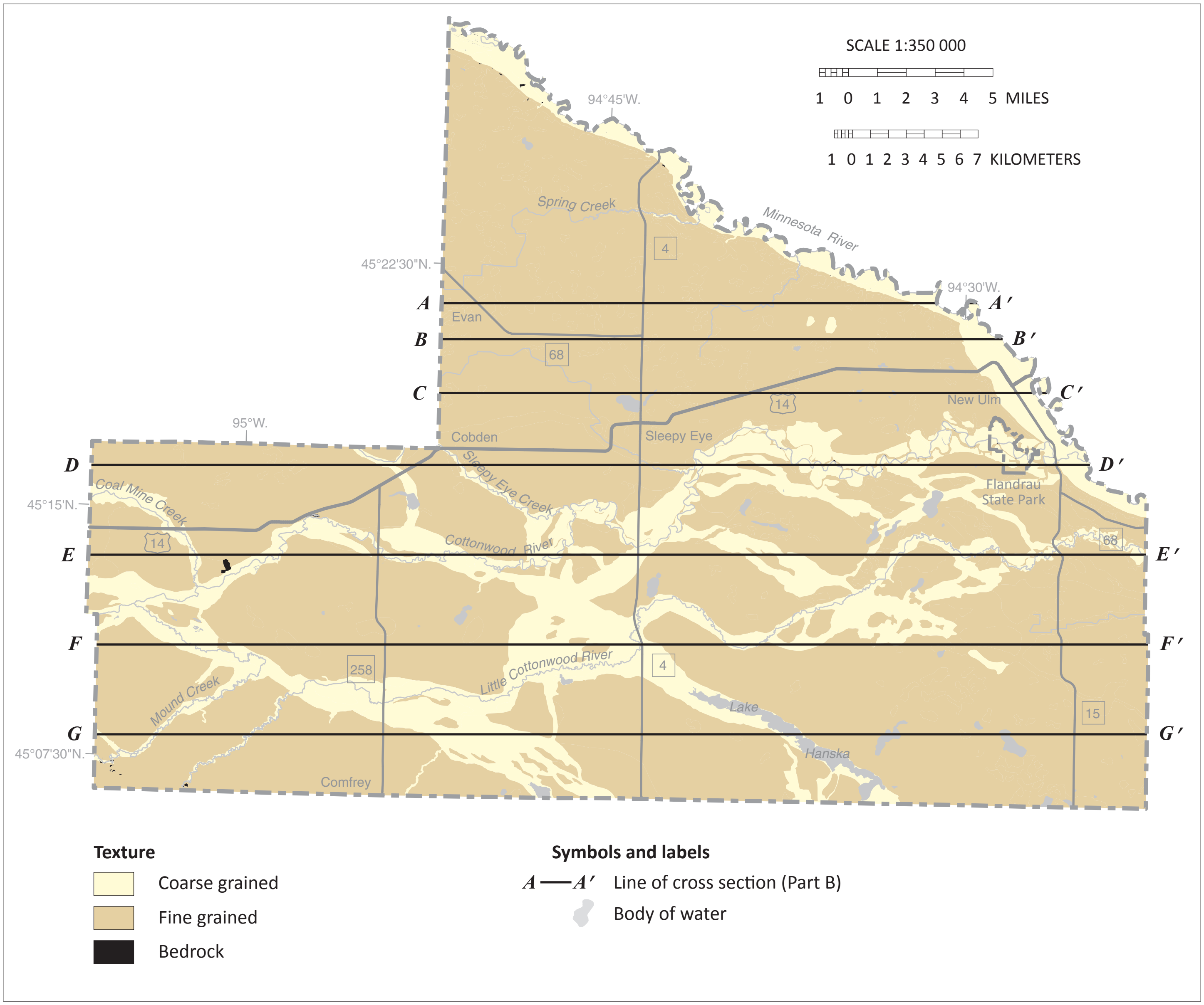


Figure 2. Generalized surficial geologic units

Much of the distribution of surficial sand in Brown County was controlled by two late stage glacial events: advances and retreats of the last major ice advance in the area and the drainage of glacial meltwater through glacial River Warren. The distribution of surficial sand and gravel is one of the most important geologic features controlling groundwater recharge and the pollution sensitivity of underlying aquifers (modified from Part A, Plate 3).

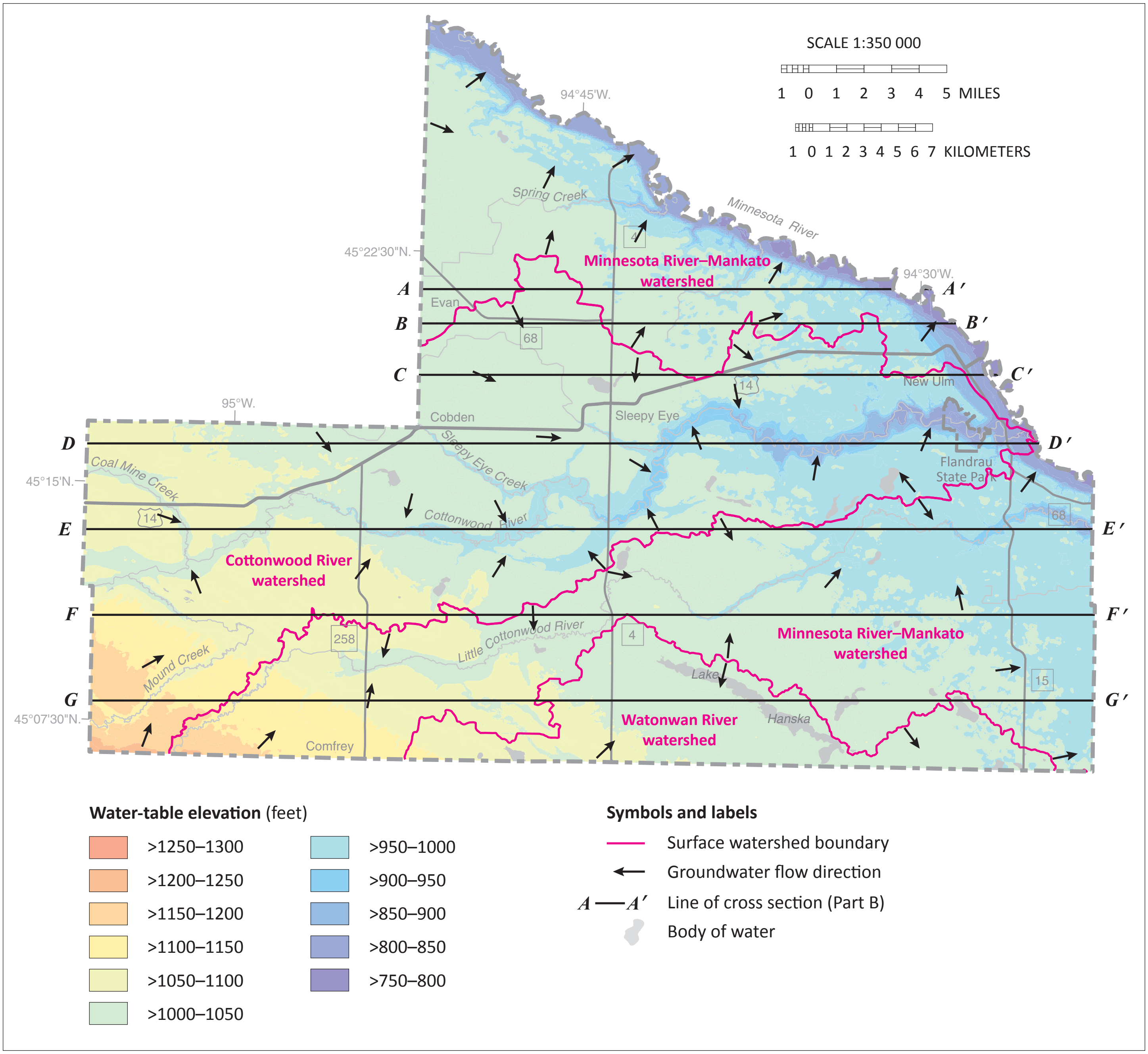


Figure 3. Water-table elevation and groundwater flow directions

Groundwater in the water table flows regionally toward the Minnesota River. Locally, groundwater flows toward the Cottonwood and Little Cottonwood rivers, Lake Hanska, and many smaller water bodies.

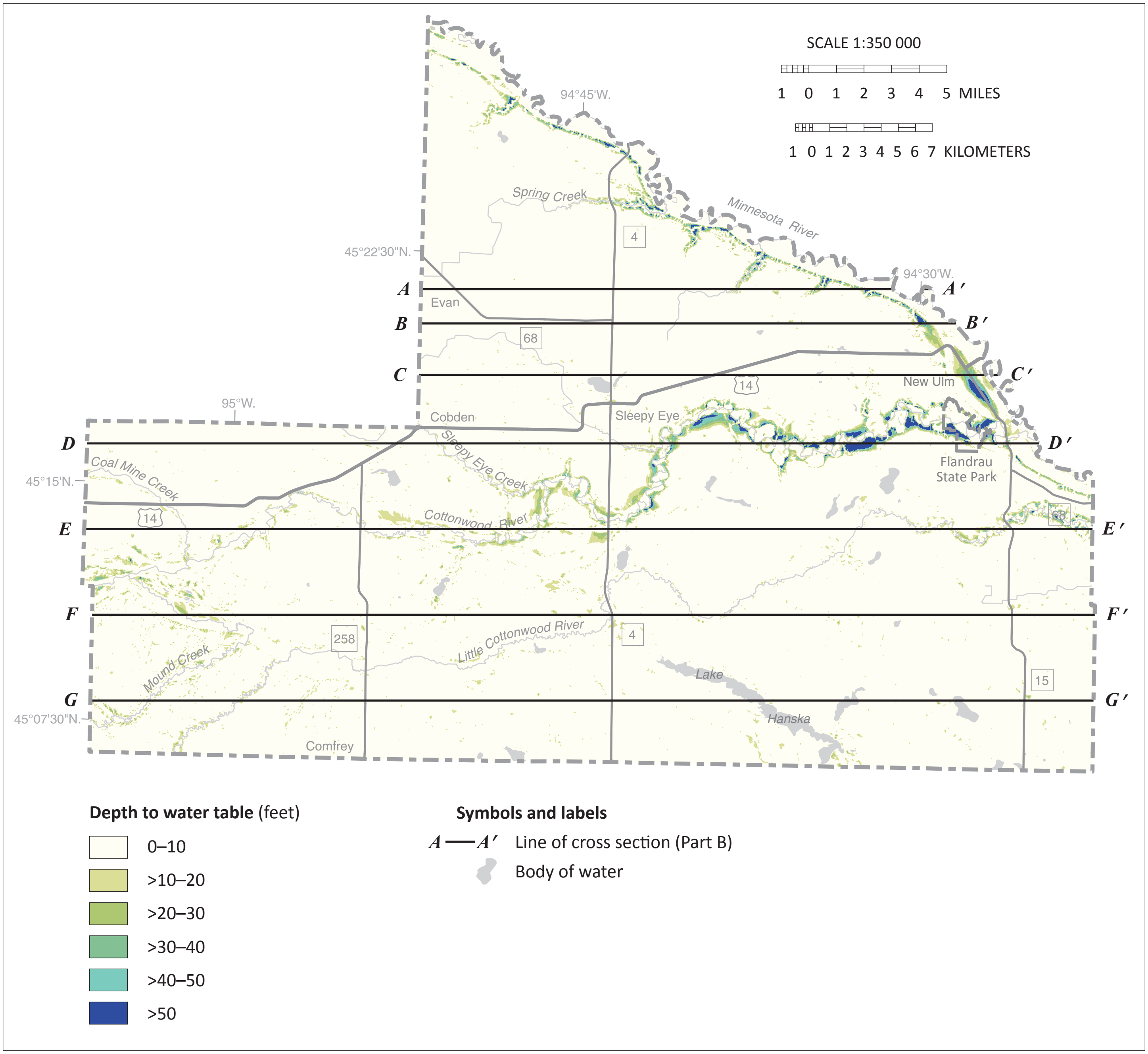


Figure 4. Depth to water table

Water-table depths are shallow (0–20 feet) across most of the county. The water table can be deeper along the Minnesota and Cottonwood river bluff areas and in the lower portions of the Little Cottonwood River.

Buried aquifers

Sand and gravel

Beneath the surficial geologic deposits are alternating layers of older sand, gravel, and fine-grained deposits from previous glacial advances. Detailed descriptions regarding the origin, thickness, and distribution of these glacial deposits are found in Part A, Plate 3 (Glacial History Summary), Plate 4 (Figures 2 and 3), and Plate 5 (Sand Distribution Model).

The stratigraphic column in Figure 5 correlates the glacial geologic units from Part A with the hydrogeologic units of Part B. The naming convention for the buried sand and gravel aquifers in this atlas was based on the underlying till unit described in Part A. Part A descriptions are generally classified 1) *sand and gravel* or 2) *till* or *lake clay*. These are converted into the hydrogeologic descriptions of 1) *aquifer* or 2) *aquitard*.

The Part B units are shown as follows:

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

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

The sand and gravel layers were deposited by meltwater that flowed from successive glacial advances and retreats (Part A, Plate 5, Sand Distribution Model – Introduction):

> *Most of the aquifers within the mapping area consist of sand and gravel beds, which were laid down in meltwater streams that flowed from these glaciers. Buried sand bodies are typically bracketed above and below by low permeability confining layers (aquitards) composed of unsorted sediment (till) deposited directly from the ice or of fine-grained clay- and silt-rich bedded sediment deposited in ponded glacial meltwater. The ice sheets typically covered broad areas of the landscape and deposited widespread layers of till during each ice advance. Some meltwater stream deposits formed large outwash plains beyond the ice front and others were confined to drainages at lower elevations on the evolving land surface.*

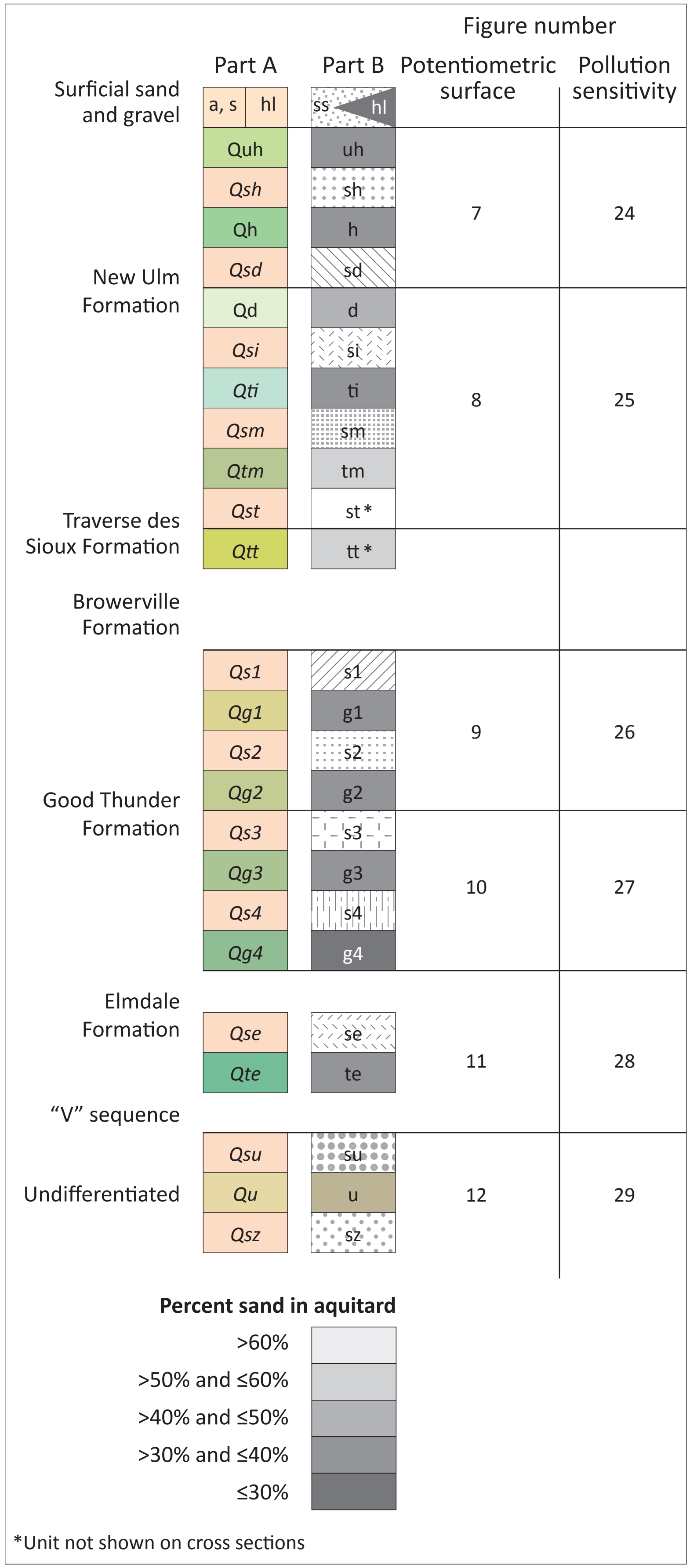


Figure 5. Hydrostratigraphy of Quaternary unconsolidated sediment

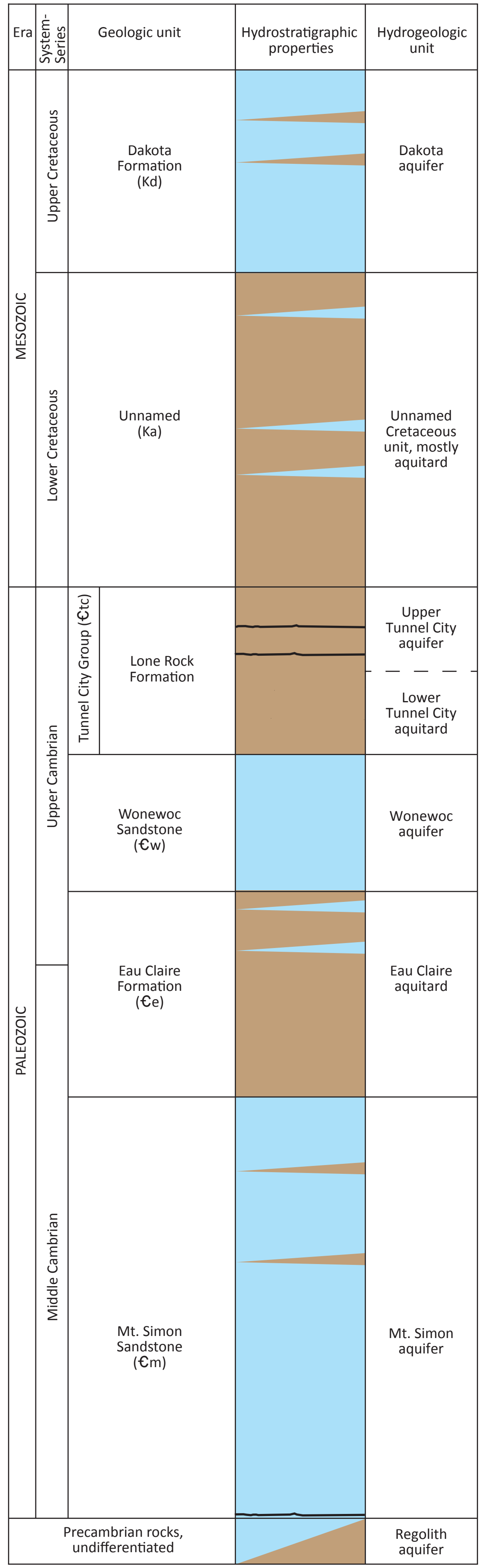
Due to these depositional patterns, the till layers (confining units or aquitards) tend to be laterally extensive, whereas the buried sand layers tend to be more limited in extent. Approximately 62 percent of the wells in the county are completed in buried sand aquifers. Reported water use from this type of aquifer in 2017 was 56 percent, representing the most widespread and generally available source of groundwater.

Bedrock and weathered bedrock

In areas where the buried sand aquifers are absent, well owners need to rely on bedrock and weathered bedrock sources for groundwater (Figure 6).

During the Cretaceous period, the middle portion of the continent was occupied by a shallow sea (Cretaceous interior seaway). Brown County has a geologic record of fine-grained and sandy sediment deposited by this sea in marine and marginal marine settings, from approximately 90 to 113 million years ago. This sediment is patchy and has undergone erosion but is thought to have once covered all of Brown County (Part A, Plate 2, Figure 3).

Two Cretaceous units were mapped, the Dakota Formation (Kd) and an unnamed slightly older Cretaceous formation (Ka). Sandstone layers are more common in the Dakota Formation (Kd) and they can be a significant source of groundwater. Approximately 21 percent of the 1,700 located wells in the county are completed in Cretaceous Dakota sandstone aquifers. Seventeen percent of the permitted water use in 2017 came from the Cretaceous Dakota sandstone aquifer. Some of the sandstone units within the Dakota Formation are shown on cross sections as dotted patterns (Plate 7). These interpretations were created by the DNR for the Part B atlas. Interpretations are based on the assumption that sandstone units found in multiple boreholes can be correlated based on common elevation ranges reported by well drillers from water well records in the CWI. Maps of sandstone units are not shown due to a general lack of lithostratigraphic information such as core or geophysical logs that would be needed to determine stratigraphic equivalency. Given the uncertainties of the data, the extent of Cretaceous sandstone layers shown on the cross sections may not be definitive.



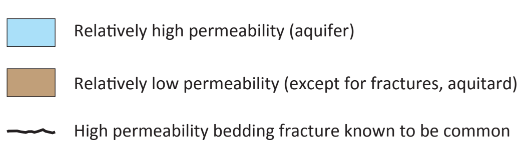


Figure 6. Bedrock stratigraphy and hydrostratigraphy

In areas without buried sand aquifers, well owners need to rely on bedrock sources of groundwater. Sandstone layers in Cretaceous and the Mt. Simon aquifer are a significant source of groundwater. Modified from Part A, Plate 2, Figure 4.

Minor sandstone is present in the stratigraphically lower unnamed Cretaceous unit (Ka). Approximately 1 percent of the 1,700 located wells in the county are completed in this unit. This unit consists mostly of fine-grained aquitard sediment including shale and mudstone. However, layers of sandstone are present and supply water in a few areas in the eastern portion of the county.

Cambrian bedrock of varying thickness (0 to 250 feet) exists in the eastern part of the county, beneath the Cretaceous bedrock. These layers are composed of sandstone, siltstone, shale, and carbonate deposited in shallow seas during the Cambrian Period (approximately 500 million years ago).

The Mt. Simon Sandstone is the thickest part of this layer (up to 150 feet thick) and is overlain by the Eau Claire Formation, the Wonewoc Sandstone, and a portion of the Tunnel City Group in the far eastern part of the county. The Mt. Simon aquifer is used by approximately 4 percent of the located wells in the county and accounted for 6 percent of the total permitted water use in 2017. This aquifer is an important water resource in the New Ulm area and along the Minnesota River valley to the southeast.

A layer of weathered rock known as saprolite (also called regolith) exists beneath the Cretaceous and Cambrian units. The saprolite layer is primarily clay that was originally feldspar crystals in the much older Precambrian bedrock. The layer can include intact clasts of rock. Saprolite covers most of the Precambrian bedrock surface. Based on limited drillhole data, it varies in thickness from a few to several hundred feet. Relict rock clasts and fracturing within the saprolite may create enough porosity and permeability to allow limited groundwater flow and storage within the layer. Less than 1 percent of the located wells in the county are completed in this weathered bedrock layer.

The oldest bedrock of Brown County is a faulted and folded gneissic and granitic rock (Precambrian, local age range is approximately 1.1 to 3.5 billion years). These mostly metamorphic rocks (formed by heat and pressure from other rock types) have interlocking grains and crystals that leave very few spaces for water (porosity) and very few connections for water to flow (permeability). These types of bedrock are not considered aquifers. However, in areas where overlying sand, sandstone, or saprolite aquifers are not available, low-volume wells can be constructed, if the well borehole encounters a fault or fracture that can convey small amounts of water. Less than 1 percent of the located wells in the county are completed in this type of fractured bedrock. Most of these are in the northeastern part of county where the overlying glacial sediment is commonly thin, sand aquifers are limited, and sedimentary bedrock is absent or thin (Part A, Plate 2, Figure 3).

Groundwater flow

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

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

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

Potentiometric surface maps were created using static water-level data from the CWI, measurements made by the DNR staff, and river elevation points (3000-meter spacing) along the major rivers. River elevation points are included where groundwater discharge is likely. The CWI records represent various climatic and seasonal conditions from the 1950s to 2016. This data variability creates some uncertainty in potentiometric surface elevations (MGS and MDH, 2016).

Water level data from the buried sand aquifers were mostly combined into groups of two or three aquifers to create composite potentiometric surface maps that may represent connected hydrologic units. These groups were created by combining data from adjacent stratigraphic units to minimize combinations of aquifers that might result in large potentiometric surface elevation discrepancies.

The sh and sd aquifers (Figure 7) and the si, sm, and st aquifers (Figure 8) have a limited extent and associated water level data. However, a general groundwater flow direction toward the Minnesota River is apparent. Local flow toward the Cottonwood River in the sh and sd aquifers is shown west of New Ulm (Figure 7).

More data are available for the underlying s1 and s2 aquifers (Figure 9) and the s3 and s4 aquifers (Figure 10) in the upper and lower parts of the Good Thunder

Formation, respectively. In these aquifers the dominant groundwater flow directions are toward the Minnesota and Cottonwood rivers.

The se aquifer in the Elmdale Formation (Figure 11) and the undifferentiated (su) sand aquifer (Figure 12) have the same general pattern of flow toward the Minnesota and Cottonwood rivers apparent as in the overlying aquifers.

The Cretaceous Dakota aquifer (Kd), is mostly shown as separate units on the cross sections and appear to be relatively thin and discontinuous across most of the county based on existing data. However, these units are assumed to have local hydraulic connections due to the relatively thin separation of sandstone layers and the possibility of locally thicker portions that were deposited directly on top of the underlying layer. Two possible examples of connected layers are shown on F–F′ (left side, Plate 7). Based on this assumption of some hydraulic connections between the Cretaceous sandstone layers, only one potentiometric surface map was created. This map shows a pattern of flow toward the Minnesota River (Figure 13). The highest groundwater flow gradient for the mapped aquifer is apparent in the southwestern part of the county southwest of the Cottonwood River. This higher gradient is because of the higher topographic relief in the area.

The Paleozoic bedrock has only a limited extent in the eastern part of the county and only the Mt. Simon aquifer is used in the northern portion of this extent (Figure 14). Similar to the overlying aquifers, flow toward the Minnesota River is the dominant direction. Most of the high-volume public wells are in the central New Ulm area within or near the closed contours. This geographic association suggests that a cumulative cone of depression has been created locally by a large amount of groundwater withdrawal from Mt. Simon wells in the area.

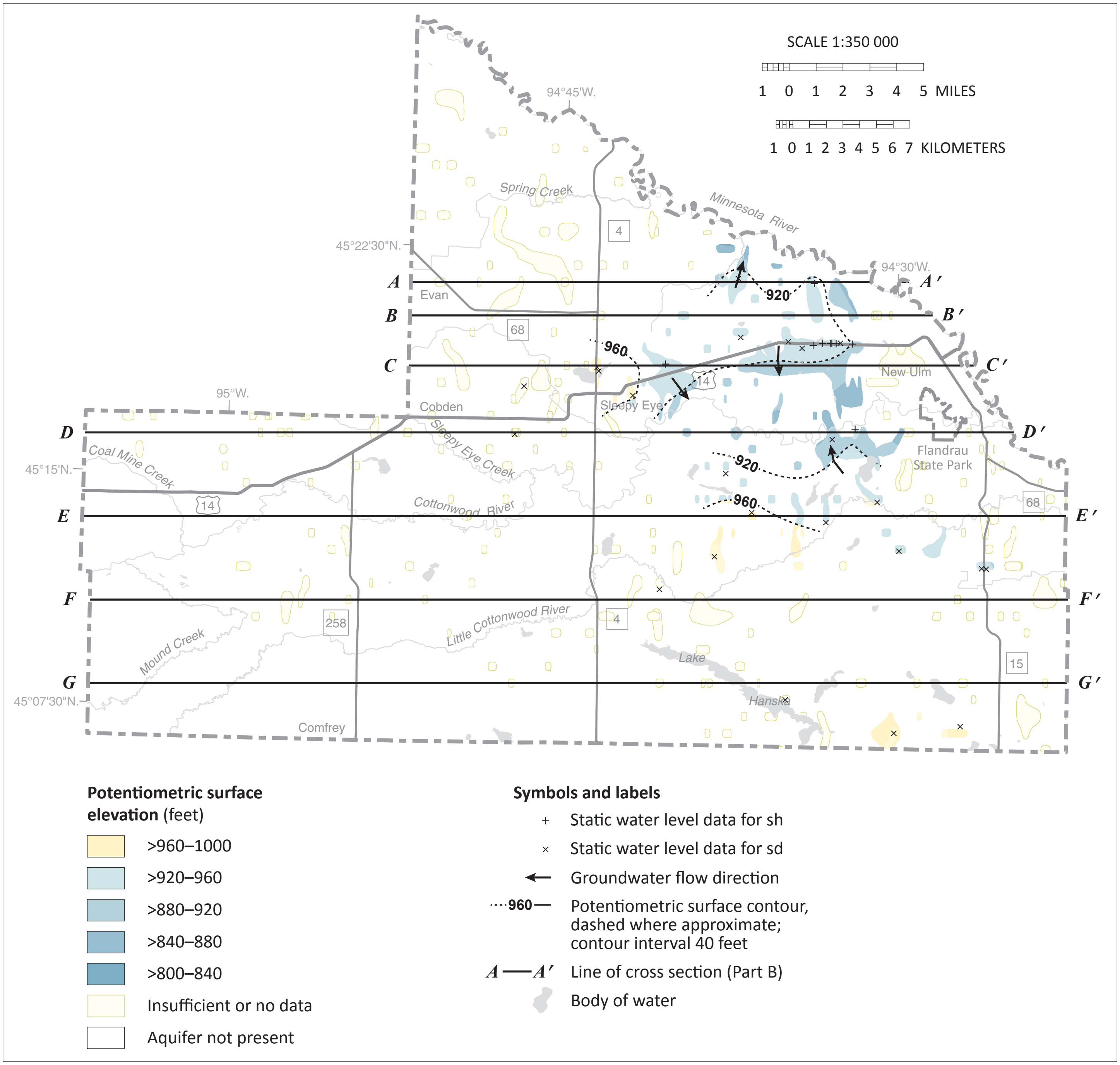


Figure 7. Potentiometric surface of the sh and sd aquifers

Groundwater flow directions are mostly toward the Minnesota and Cottonwood rivers.

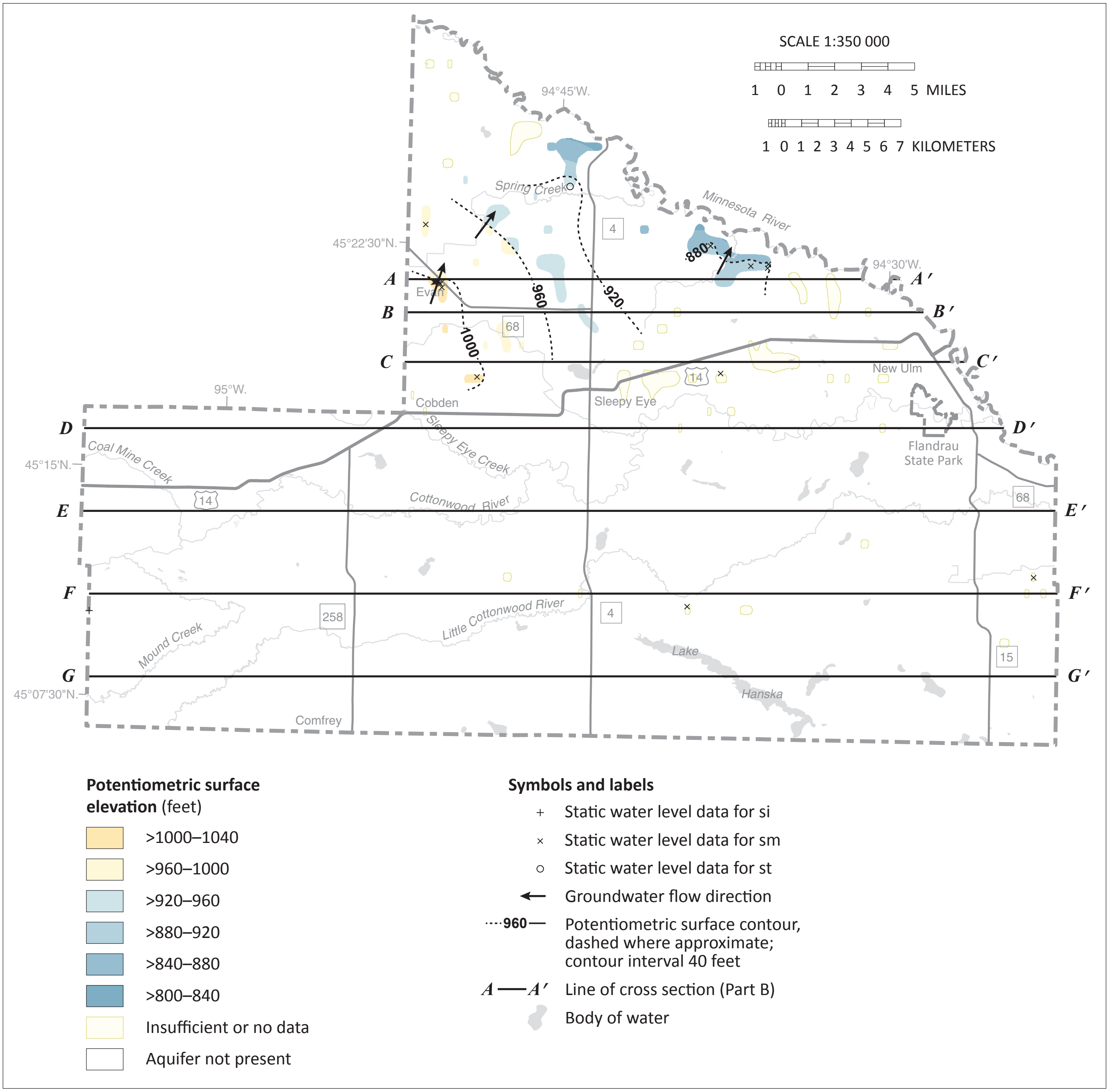


Figure 8. Potentiometric surface of the si, sm, and st aquifers

Limited data indicate groundwater flow directions toward the Minnesota River.

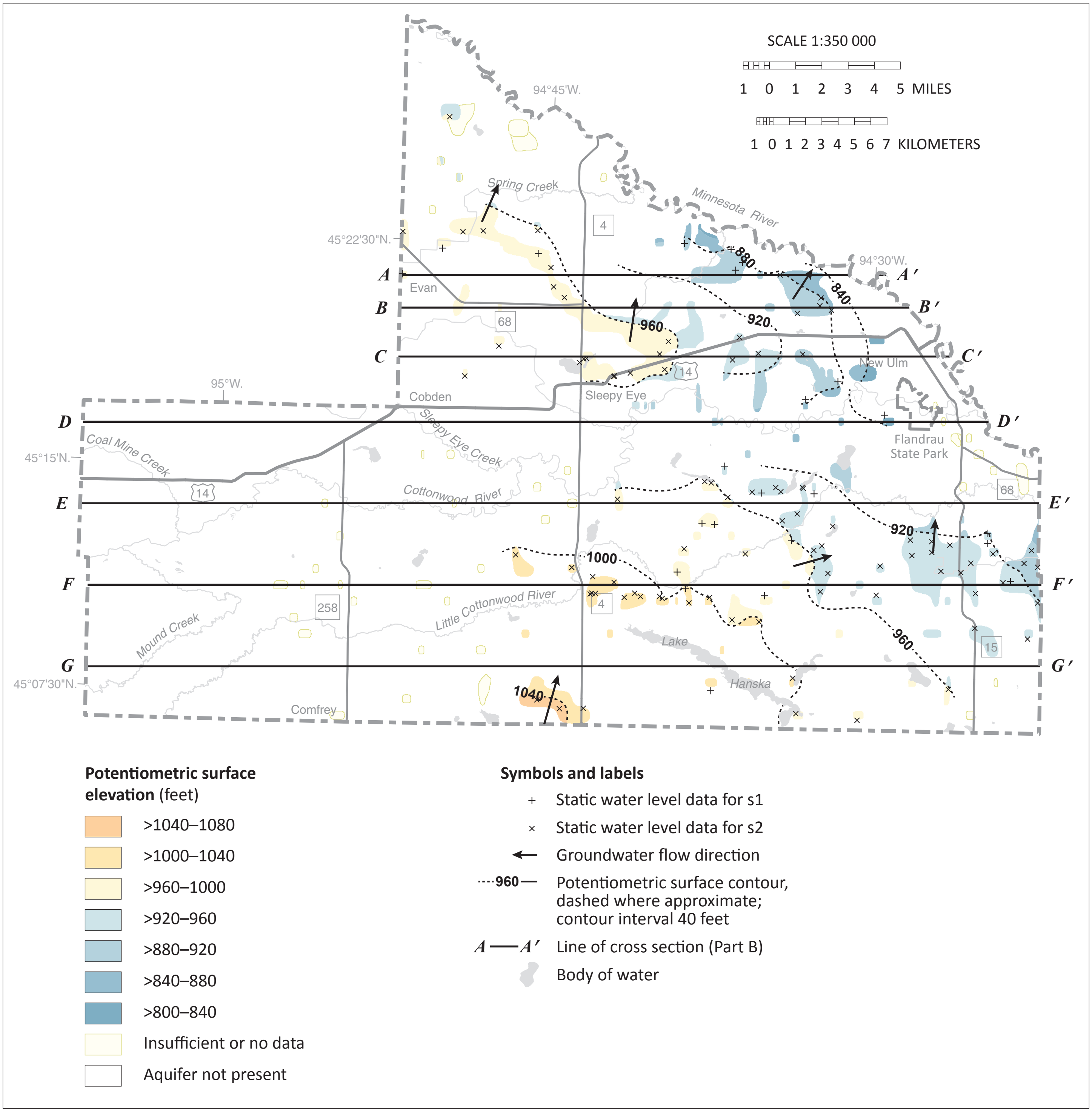


Figure 9. Potentiometric surface of the s1 and s2 aquifers

The dominant groundwater flow directions are toward the Minnesota and Cottonwood rivers.

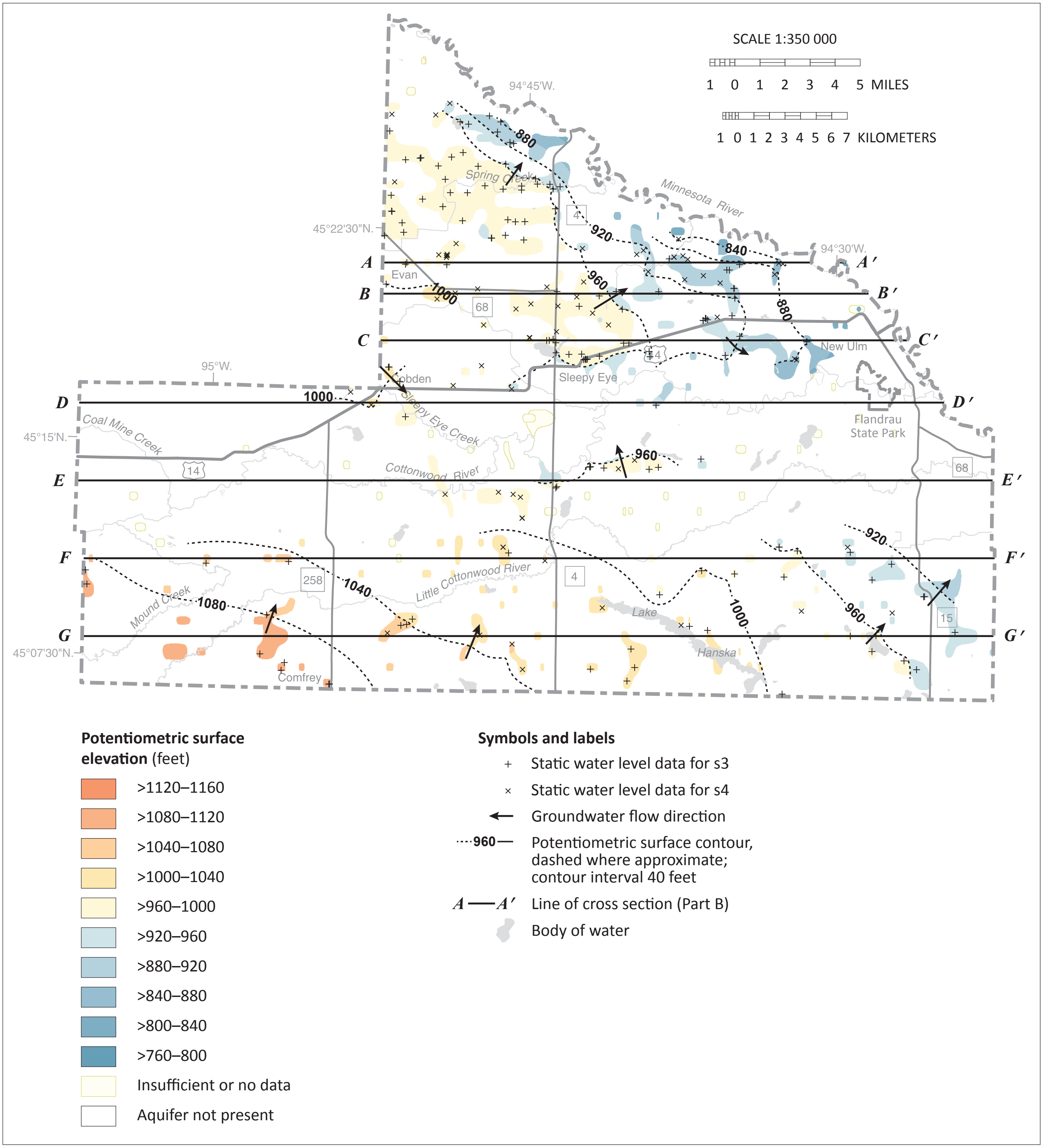


Figure 10. Potentiometric surface of the s3 and s4 aquifers

The dominant groundwater flow directions are toward the Minnesota and Cottonwood rivers.

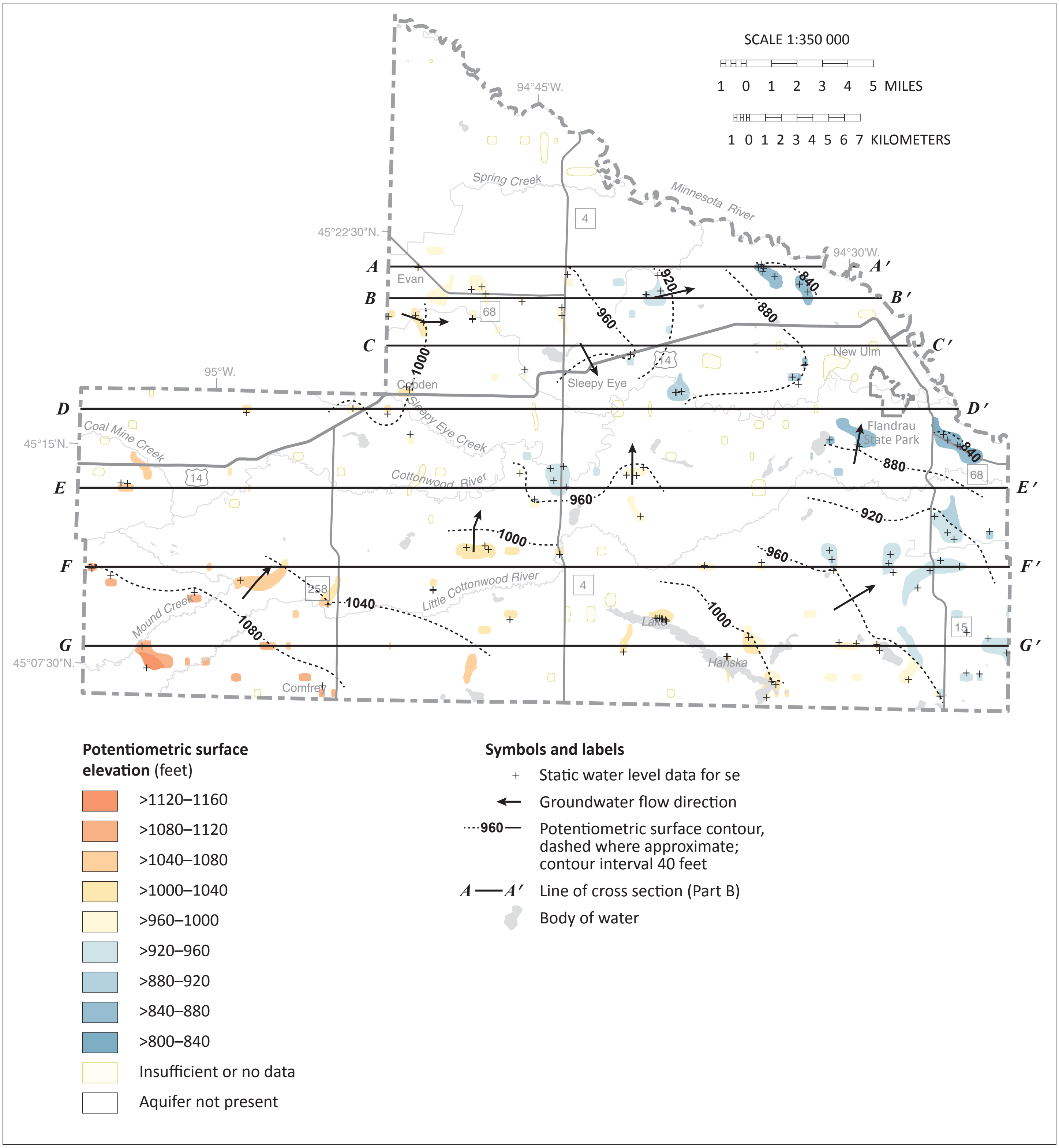


Figure 11. Potentiometric surface of the se aquifer

The dominant groundwater flow directions are toward the Minnesota and Cottonwood rivers.

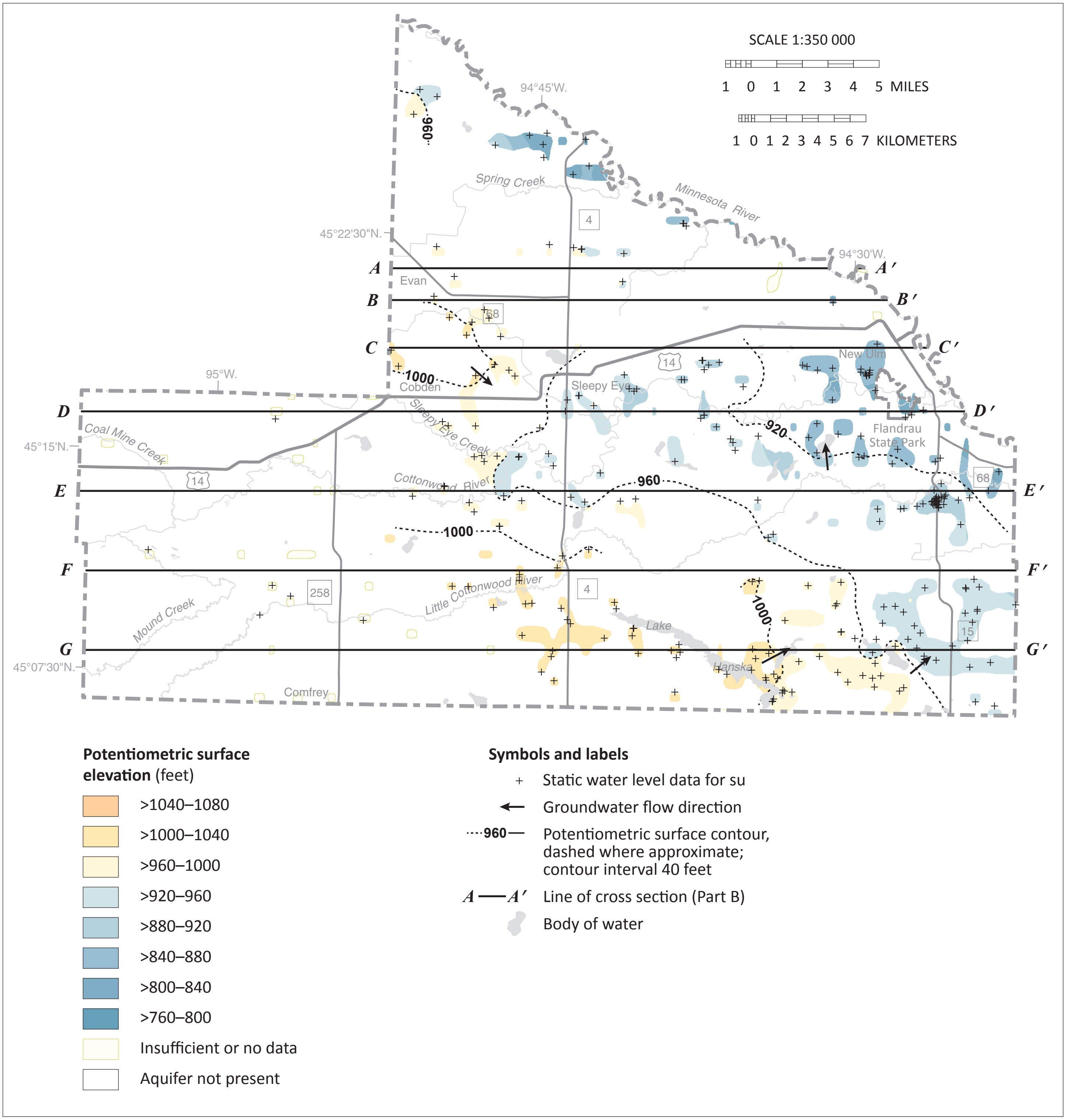


Figure 12. Potentiometric surface of the undifferentiated buried sand aquifer (su)

The undifferentiated sand aquifer has the same pattern of flow toward the Minnesota and Cottonwood rivers as the overlying aquifers.

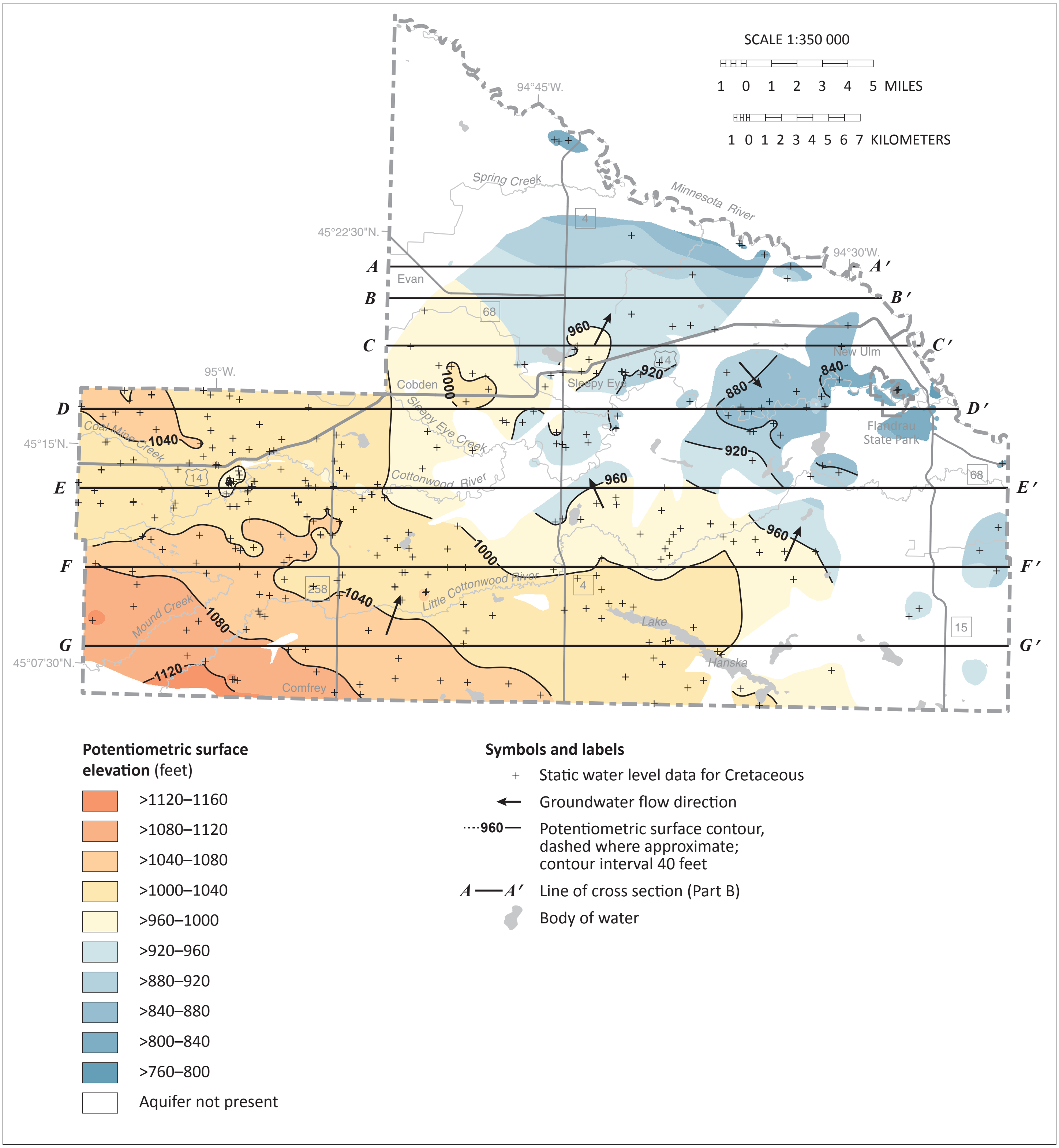
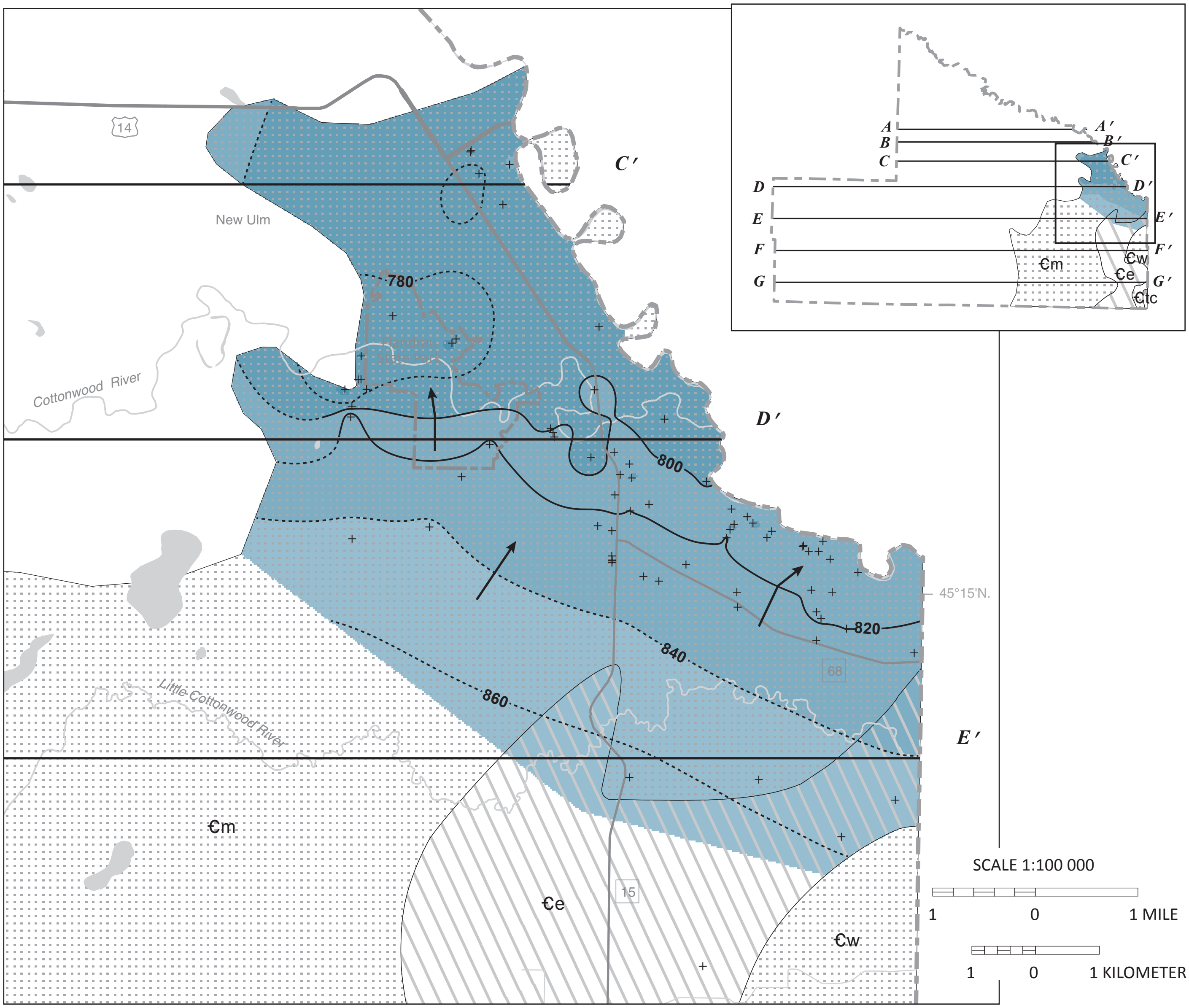


Figure 13. Potentiometric surface of the Cretaceous Dakota sandstone aquifer

The dominant pattern of flow is toward the Minnesota River.



Potentiometric surface elevation (feet)

- >840–880
- >800–840
- >760–800
- >720–760
- Aquifer not present

Symbols and labels

- + Static water level data for Eau Claire–Mt. Simon
- × Static water level data for Mt. Simon
- ← Groundwater flow direction
- ····820— Potentiometric surface contour, dashed where approximate; contour interval 20 feet
- *A*—*A′* Line of cross section (Part B)
- Body of water

Paleozoic bedrock

- Ꞓtc Tunnel City Group
- Ꞓw Wonewoc Sandstone
- Ꞓe Eau Claire Formation
- Ꞓm Mt. Simon Sandstone

Figure 14. Potentiometric surface of the Mt. Simon aquifer

Similar to the overlying aquifers, flow toward the Minnesota River is dominant. Cumulative use from high-volume pumping from public wells appears to have created a cumulative cone of depression in the central New Ulm area.

Water chemistry (Plate 6)

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

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

Water sampling

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

An ideal well-sampling network for the county atlas is distributed evenly across the county, includes populated areas, and targets surface water and groundwater interaction around lakes and larger rivers. The final network sampled depends on willingness of citizens to participate. Approximately 1,000 well owners were contacted for permission to sample. County atlas protocol is to collect samples from approximately 90 of those wells.

Water chemistry data for Brown County included wells sampled for this atlas and regional special studies by the DNR (Berg and Pearson, 2012) along with historical water samples that were incorporated into the interpretations of this report. The total of 127 groundwater samples from wells included: 4 DNR samples collected in 2009, 90 DNR samples collected during the summer of 2017, and 33 Minnesota Department of Health (MDH) samples collected from 1990 to 2017. Additionally, 2 surface-water samples from MDH (2001 to 2002) were included.

Groundwater recharge sources

Chemical changes occur as water moves from precipitation to groundwater. These can help determine whether groundwater was recharged directly from precipitation, lake water, or a mixture of the two. Stable isotopes of oxygen and hydrogen were used for determining groundwater and surface-water interactions. Oxygen and hydrogen each have two main stable isotopes: ^{18}O and ^{16}O, and ^{2}H and ^{1}H. The different masses cause each to evaporate at a different rate, which results in *fractionation*, leaving behind different ratios of heavy to light isotopes. This results in isotopic signatures unique to groundwater with different recharge sources (Kendall and Doctor, 2003).

- A **meteoric (precipitation)** isotopic signature indicates groundwater was recharged from precipitation that infiltrated directly into the ground.
- An **evaporative** isotopic signature indicates groundwater was partially recharged from **surface water,** such as lakes or open-water wetlands. Lighter isotopes evaporate more readily (fractionate), leaving water enriched in heavier isotopes.

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

Definition of delta (δ)

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

Results

County results were compared to the global meteoric water line (Figure 15). The majority of the groundwater samples plot along the meteoric water line, in the center and left portions of the stable isotope graph. This suggests these samples are sourced from precipitation (rain and snow melt) that infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies.

None of the samples had definitive evaporative signatures, with the possible exception of two samples in the northeastern part of the county near the Minnesota River (624259 and 807689). Both of these vintage tritium-age samples were from the relatively deep undifferentiated units (su and sz, respectively). They did not have elevated anthropogenic constituents (chloride or nitrate) and are not downgradient from any large surface-water bodies.

The general lack of evaporative signatures in groundwater samples reflects the lack of large nonflowing surface-water bodies (such as lakes) that generate most of the evaporative water in other parts of the state.

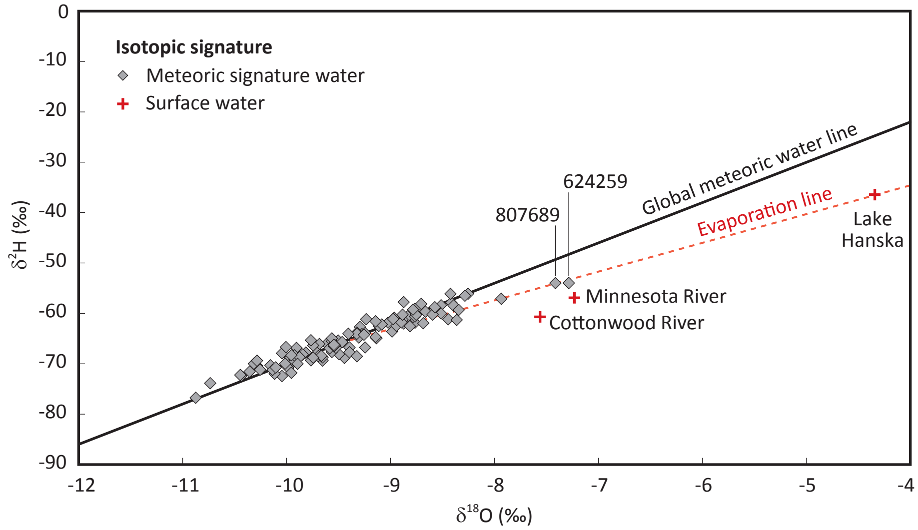


Figure 15. Stable isotope values from water samples

The *meteoric water line* represents precipitation values from rapid infiltration. The global meteoric water line was developed using precipitation samples from around the world and is described by the following equation: $\delta^{2}H = 8.0\ \delta^{18}O + 10.0$ (Craig, 1961).

The *evaporation line* represents groundwater recharge that was partially from surface water sources. None of the groundwater samples collected from this and other studies detected groundwater with evaporative signatures.

Groundwater residence-time indicators

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

Tritium

Groundwater residence time was interpreted from the concentration of tritium. Although tritium is a naturally occurring isotope of hydrogen, atmospheric concentrations greatly increased from atmospheric testing of nuclear weapons between 1953 and 1963 (Alexander and Alexander, 1989). Tritium concentrations were used to estimate groundwater residence time using the known half-life of 12.32 years (Lucas and Unterweger, 2000). The concentrations are presented in tritium units (TU) and are referred to as *tritium age* in the following categories.

- **Cold War era**—water entered the ground from the peak period of atmospheric tritium concentration from nuclear bomb testing, 1958–1959, and 1961–1972 (greater than 15 TU).
- **Recent**—water entered the ground since about 1953 (8 to 15 TU).
- **Mixed**—water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- **Vintage**—water entered the ground before 1953 (less than or equal to 1 TU).

Historical data (sample dates from 1990 to 2016) are used in the residence-time interpretations of this report and are classified according to Table B-2 in Appendix B.

Carbon-14

Selected vintage and mixed tritium-age samples were further sampled for the carbon-14 (^{14}C) isotope to estimate longer residence times. This naturally occurring isotope has a half-life of 5,730 years, and is used to estimate groundwater residence time ranging from 50 to greater than 40,000 years (Alexander and Alexander, 2018).

A total of 10 carbon-14 samples were collected for this study and were combined with 4 samples from previous studies. Carbon-14 residence times ranged from 700 to 30,000 years. These data are described in more detail in the hydrogeologic cross section portion of this report.

Inorganic chemistry of groundwater

Chemicals in groundwater can occur naturally or can come from contamination from anthropogenic sources such as road salts, water softener salts, fertilizers, or animal and human waste. Anthropogenic sources can be indicated from concentrations of chemicals and comparisons to background levels of similar elements; elevated levels can indicate a short groundwater residence time and high sensitivity.

Water quality evaluations describe contaminants that are potentially harmful (either naturally occurring or anthropogenic) or that affect aesthetics such as taste, odor, or discoloration. This atlas uses the following guidelines.

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

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

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

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

Minnesota Department of Health
(MDH, 2012a)

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

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

Minnesota Department of Natural Resources
Groundwater Atlas program

Elevated: values above background conditions for anthropogenic constituents (chloride and nitrate), above method detection limits for naturally occurring arsenic, or greater than or equal to 100 ppb for naturally occurring manganese.

Anthropogenic: caused by human activity.

Naturally occurring: drinking water can be contaminated by natural sources, like heavy metals in rock and soil. Most impurities in natural waters are harmless. However, drinking water containing certain levels of micro-organisms, minerals, naturally-occurring contaminants can be harmful to your health.

Chemical descriptions

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

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

Calcium, magnesium, and sodium cations and bicarbonate anions are dissolved out of the glacial sediment and bedrock by groundwater. The constituents are derived from limestone and dolomite bedrock sources (Hem, 1985) and are common in glacial sediment groundwater aquifers. Sodium is often present in deep aquifers or at mineral interfaces. As groundwater moves through aquifer systems, calcium and magnesium ions in solution are exchanged for sodium ions (Hounslow, 1995).

Sulfate (SMCL 250 ppm) is largely naturally occurring. High concentrations in groundwater can negatively affect taste and may act as a laxative.

Chloride (SMCL 250 ppm; elevated ≥5 ppm; anthropogenic: chloride to bromide ratio ≥250) can occur naturally from deep sources such as residual brine, or it may come from anthropogenic sources such as road salt, water softener salt, and fertilizer (Davis and others, 1998; Panno and others, 2006).

Nitrate-nitrogen (nitrate) (MCL and HRL 10 ppm, elevated ≥1 ppm) can occur naturally at low concentrations but elevated concentrations are typically from fertilizer and animal or human waste. Nitrate concentrations lessen with time (denitrification) when there is little oxygen in the groundwater. In Minnesota, groundwater with long residence time typically has little available oxygen and little to no nitrate (MDH, 1998; Wilson, 2012).

Arsenic (MCL 10 ppb; MCLG 0) is a naturally occurring element that has been linked to negative health effects, including cancer. If arsenic is indicated at any level, the MDH advises domestic well owners to treat drinking water (MDH, 2018a). Current science cannot predict which wells will have high arsenic concentrations, therefore newly constructed drinking-water wells are tested for arsenic (Minnesota Administrative Rules 4725.5650, 2008).

The factors affecting elevated arsenic concentrations in groundwater are not completely understood. There is a strong correlation with glacial sediment derived from rocks northwest of Minnesota (Erickson and Barnes, 2005a). High arsenic concentrations are believed to be caused by naturally occurring, arsenic-bearing minerals associated with small shale particles in these tills. Some of this arsenic was previously released and then adsorbed to surfaces of mineral crystals and other small particles during earlier oxidizing conditions. This surface-adsorbed arsenic (the most chemically available form) is released to groundwater under reducing conditions (Erickson and Barnes, 2005b; Nicholas and others, 2011; Thomas, 2007). Research also indicates that arsenic concentrations increase in wells that have short-screened sections near the boundary of an aquifer and aquitard (Erickson and Barnes, 2005a; McMahon, 2001).

Manganese (HBV 100 ppb; SMCL 50 ppb) is a naturally occurring element beneficial to humans at low levels, but at high levels may harm the nervous system (MDH, 2018b). In addition to health effects, concentrations above the SMCL can cause negative secondary effects such as poor taste, odor, and water discoloration (stained laundry and plumbing fixtures).

Statewide, manganese concentrations were greater than 100 ppb in drinking-water wells for 57 percent of water-table aquifers and 63 percent of buried sand aquifers sampled (MDH, 2012b). Although there are no clear patterns of manganese distribution across most of Minnesota, the MDH has found that southeastern Minnesota tends to have low levels of manganese (below 50 ppb) and southwestern Minnesota tends to have higher levels (some over 1,000 ppb).

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

Results

Sulfate (Plate 6)

Of the 108 samples analyzed for sulfate, 30 exceeded the SMCL. Sulfate minerals are common in the aquitard materials (till and shale) that surround the Quaternary and Cretaceous aquifers (sand and gravel, and sandstone, respectively) throughout western and southwestern Minnesota (Winter, 1974).

Chloride (Figure 16)

Anthropogenic chloride is generally not a significant contaminant in Brown County. Of the 115 well samples analyzed for chloride, 12 were anthropogenic but none equaled or exceed the SMCL. These elevated occurrences were mostly in the northern portion of the county where there are more towns. Affected aquifers included buried sand and Cretaceous units.

Naturally occurring chloride was detected in the deeper buried sand aquifers (s2, s3, s4, and sz), the Cretaceous sandstone aquifers, and the Mt. Simon aquifer, at concentrations ranging from 6 to 23 ppm. The typical pattern for most areas of Minnesota is for chloride to bromide ratios that exceed 250 to match tritium concentrations that equal or exceed 1 tritium unit (recent and mixed tritium age). Exceptions to this pattern are somewhat rare, but prevent a definitive classification of the chloride source as anthropogenic or naturally occurring. Therefore, groundwater samples that don’t follow this pattern are shown as unknown rather than anthropogenic or natural (Figure 16).

Nitrate (Figure 16)

Of the 119 well samples analyzed for nitrate, 4 had elevated concentrations indicative of an anthropogenic source, and 1 was above the MCL with a concentration of 11 ppm. The elevated occurrences of nitrate are in the northern part of the county from the sh, sd, s4, and se buried sand aquifers.

Arsenic (Figure 17)

Elevated concentrations of naturally occurring arsenic are common in the county. Of the 115 samples analyzed for arsenic, 91 exceeded the method detection limits, and 31 of those exceeded the MCL. Those at or above the MCL were mostly in the northern part of the county where the buried sand aquifers are the main source of groundwater. For more information, see MDH, 2018a and MDH, 2018b.

Manganese (Plate 6)

Of the 106 samples analyzed for manganese, 69 were greater than or equal to the HBV. These high values ranged from 111 to 1,850 ppb and were found in most of the mapped aquifers. For more information, see MDH, 2018b and MDH, 2018c.

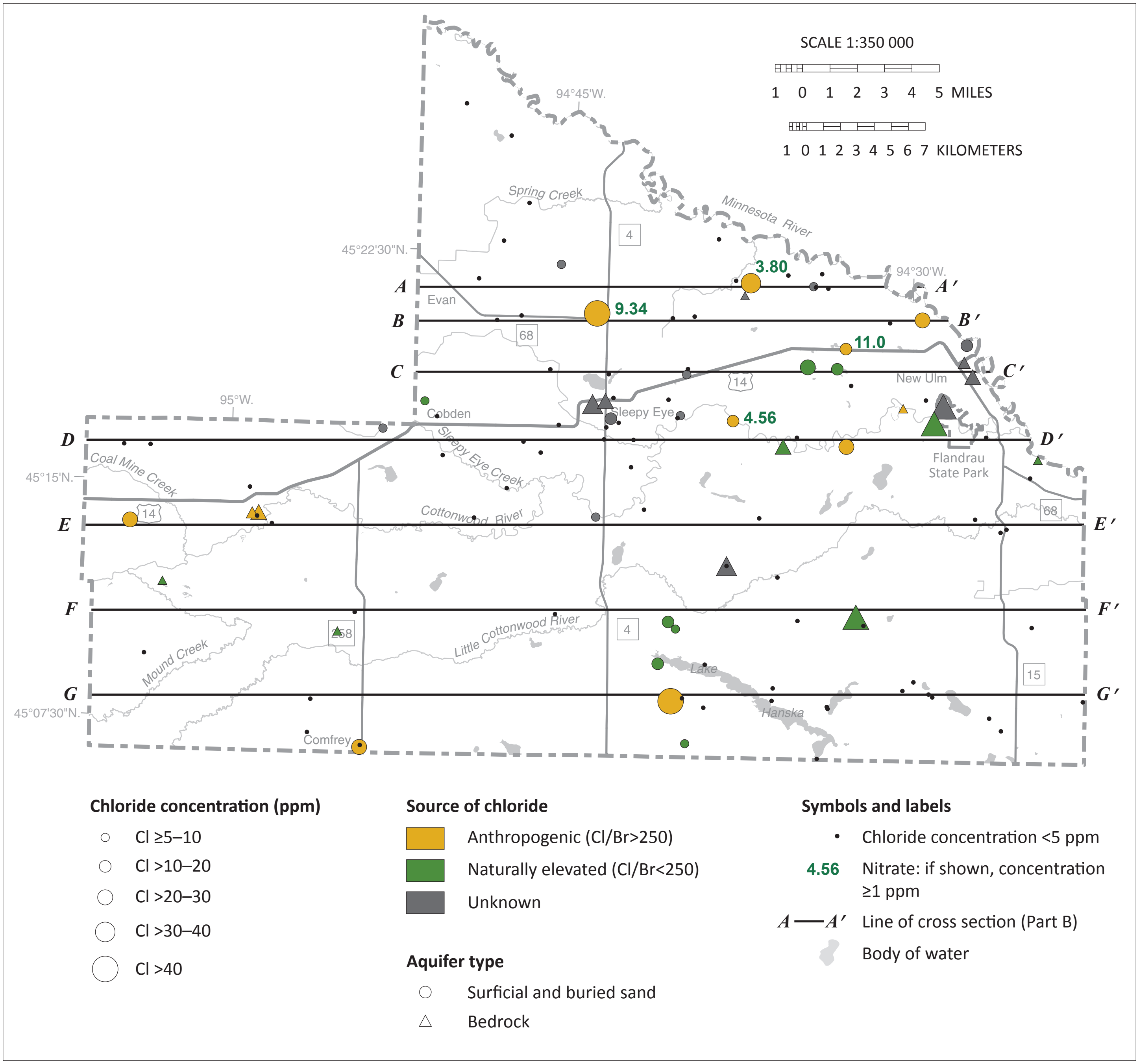


Figure 16. Chloride and elevated nitrate concentrations from groundwater samples

Anthropogenic chloride is generally not a significant contaminant in Brown County. Of the 115 well samples analyzed for chloride, 12 were anthropogenic but none equaled or exceed the SMCL. These elevated occurrences were mostly in the northern portion of the county where there are more towns.

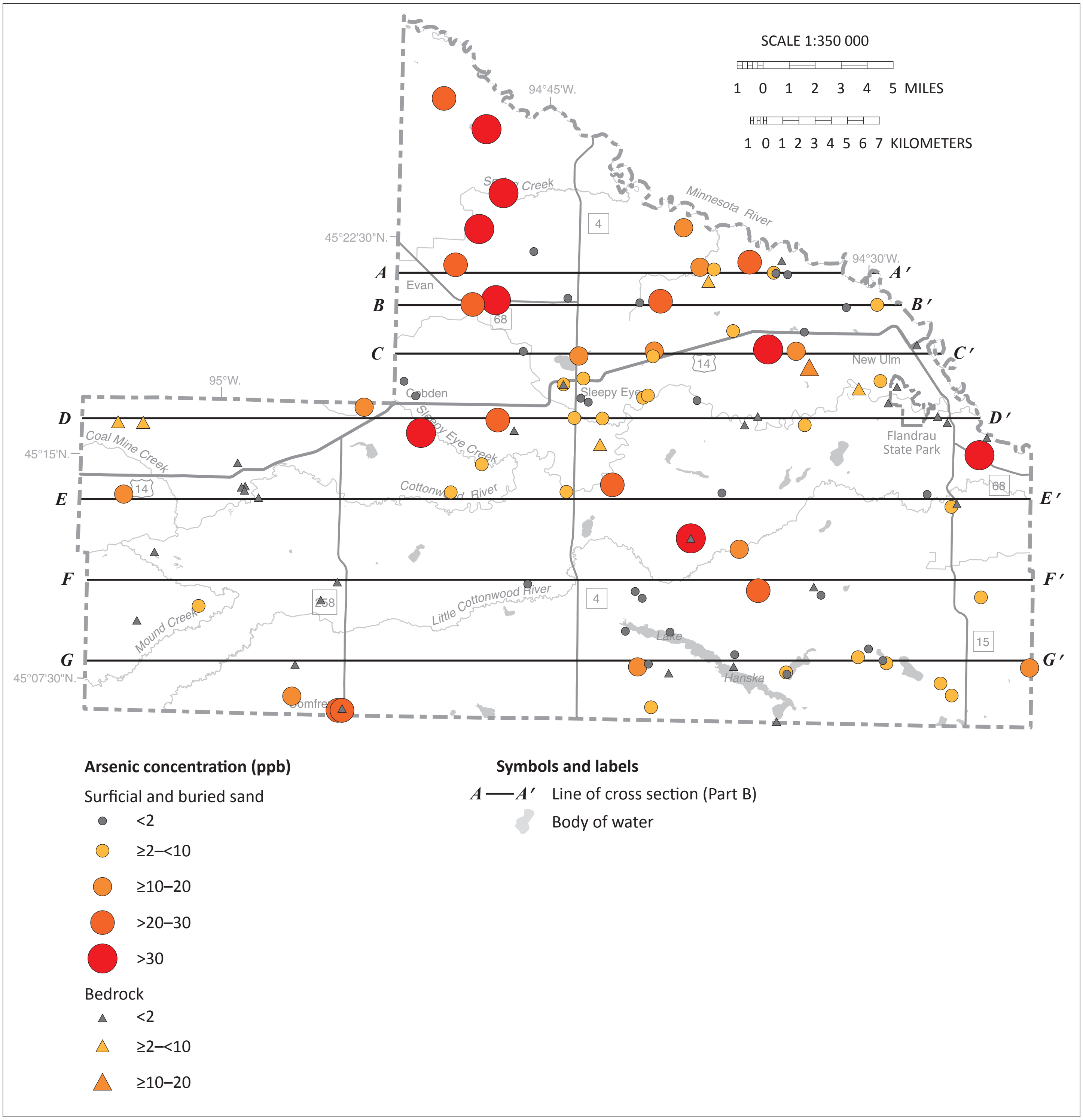


Figure 17. Arsenic concentrations from groundwater samples

Of the 115 samples analyzed for arsenic, 91 exceeded the method detection limits, and 31 of those exceeded the MCL. Those at or above the MCL were mostly in the northeast where the buried sand aquifers are the main source of groundwater.

Piper diagram: major cations and anions

The Piper diagram (Figure 18a) depicts the relative abundance of common dissolved chemicals in water samples. Combining groundwater chemistry data and physical hydrogeologic information, such as groundwater levels and groundwater flow paths, creates a more complete hydrogeologic interpretation. The Piper diagram can reveal information about:

- The source of dissolved chemicals as water travels through the aquifers and aquitards
- Changes in water chemistry as groundwater moves from recharge to discharge areas
- The distribution and mixing of different water types
- Precipitation and solution processes affecting water chemistry

A water type was assigned to the samples by plotting each on a Piper diagram. This graphically represents a water sample relative to the most common ionic constituents in natural waters: calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and nitrate. The relative proportions of these dissolved ions differ depending on the water's original interaction with the atmosphere and any subsequent interactions with anthropogenic sources and geologic material.

The sample points in the figure are color coded according to tritium age to help show chemical relationships.

- The sample points on each triangle (ternary diagram) reflect the relative percentages of the major cations (lower left triangle) and anions (lower right triangle) in DNR samples.
- Lines from the two ternary diagrams can be projected onto the central diamond-shaped field and the intersections plotted to show the overall chemical characteristics of the groundwater.

Results

Graph area 1: calcium and magnesium

The cation triangle (lower left) shows that groundwater with a mixture of calcium and magnesium is common in the county with calcium as the dominant ion. This cation type of water was mostly from the buried sand aquifers but also from a few Cretaceous sandstone, saprolite, and Precambrian aquifers.

Graph area 2: sodium+potassium

A relatively uncommon cation water type was sodium+potassium. This may be caused by a relative lack of samples from the Cretaceous aquifers in the southwestern portion of the county where this type of water is very common, based on the results of the *Groundwater Atlas of Redwood County* (Berg and Baratta, 2019) which is adjacent to the Brown County western border. The location of the three sodium+potassium samples is shown on Figure 18b as larger triangle symbols in the northeastern part of the county.

Graph area 3: bicarbonate to sulfate

The anion triangle (lower right) shows that the buried sand aquifers contain a continuum of bicarbonate to sulfate water types.

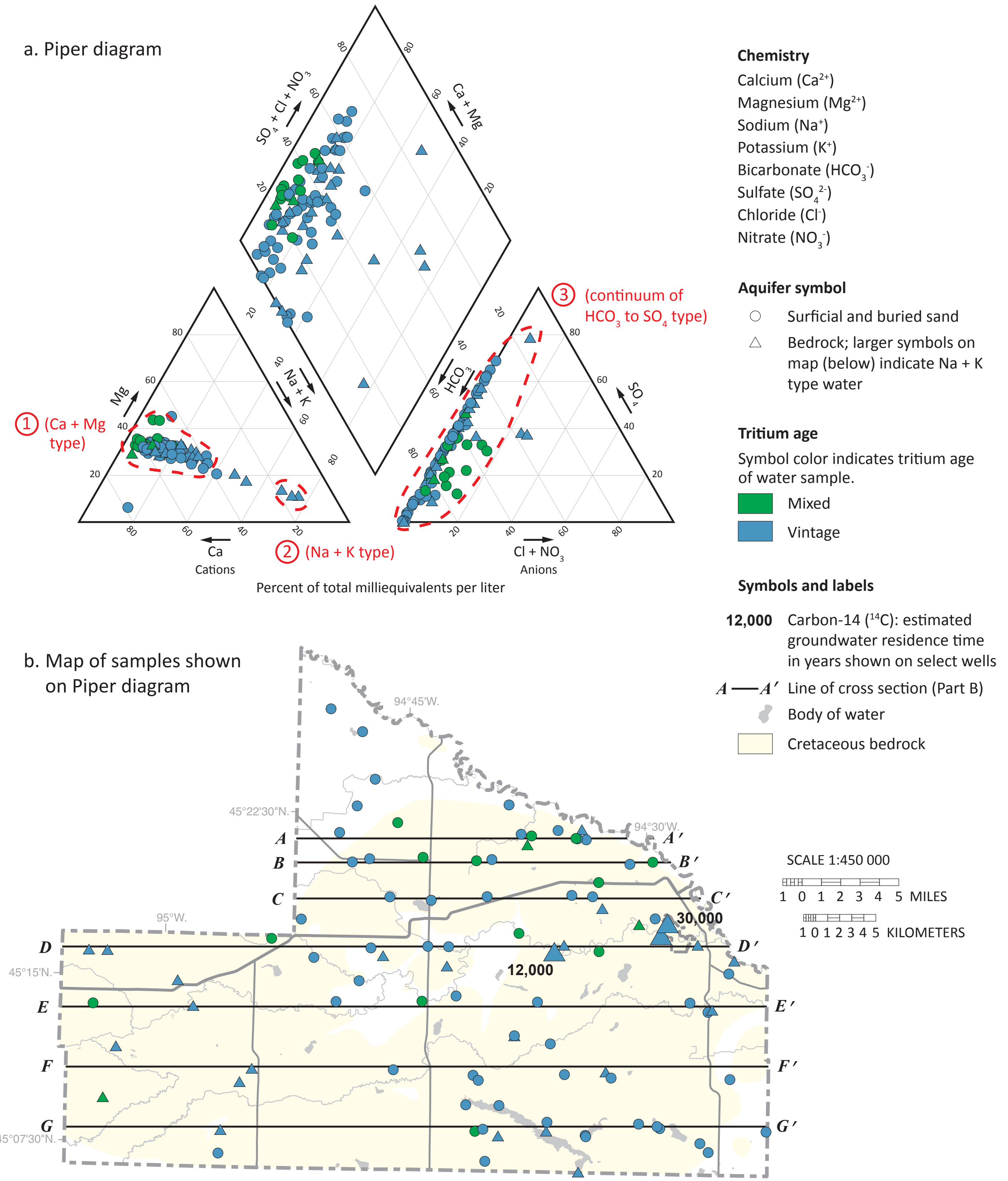


Figure 18. Piper diagram of groundwater samples and tritium age

Comparison of the relative proportions of cations and anions in groundwater from the sampled wells. The cations and anions are shown in the left and right triangles, respectively. The center diamond shows a composite of cations and anions. Common water types include calcium and magnesium type water (1 in the cation triangle) and a broad continuum of bicarbonate to sulfate water (3 in the anion triangle).

Pollution sensitivity

Pollution sensitivity is defined as the potential for groundwater to be contaminated from the land surface because of the properties of the geologic material. Migration of contaminants dissolved in water flowing from the land surface through unsaturated and saturated sediment is a complex process that is typically affected by biological degradation, oxidizing or reducing conditions, and other factors. The methods used to interpret pollution sensitivity included the following general assumptions:

- Flow paths are vertical and downward from the land surface through the soil and underlying sediment to an aquifer.
- A contaminant is assumed to travel at the same rate as water.
- A dissolved contaminant that is moving within water from the surface is not chemically or physically altered over time.

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

The following assumptions were applied in the two models.

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

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

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

Near-surface materials

Methods

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

The transmission rate varies depending on the texture. Coarse-grained materials generally have faster transmission rates than fine-grained materials. The two primary inputs used to estimate transmission rate are the hydrologic soil group and the surficial geologic matrix texture. Attributes of both are used to estimate the time of travel (Table 1) (Natural Resources Conservation Service, 2016; Part A, Plate 3).

The time of travel through near-surface sediment varies from hours to approximately a year (Figure 19).

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

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

Table 1. Transmission rates through unsaturated materials used to assess the pollution sensitivity rating of the near-surface materials

Hydrologic Soil Group (0–3 feet)		Surficial Geologic Texture (3–10 feet)		
Group*	**Transmission rate (in/hr)**	**Classification**	**Transmission rate (in/hr)**	**Surficial geology map unit (Part A, Plate 3)**
A, A/D	1	gravel, sandy gravel, silty gravel	1	Qa, Qi, Qrk, Qs, Qsw, Qt
		sand, silty sand	0.71	Not mapped in the county
B, B/D	0.50	silt, loamy sand	0.50	Qf
		sandy loam, peat	0.28	Qc
C, C/D	0.075	silt loam, loam	0.075	Qtd, Qth, Qwh
		sandy clay loam	0.035	Ql
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Qhl, Qwd
--	--	glacial lake sediment of Lake Agassiz	0.000011	Not present in the county

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

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

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

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

Group C: water transmission is somewhat restricted.

Group D: water movement is restricted or very restricted.

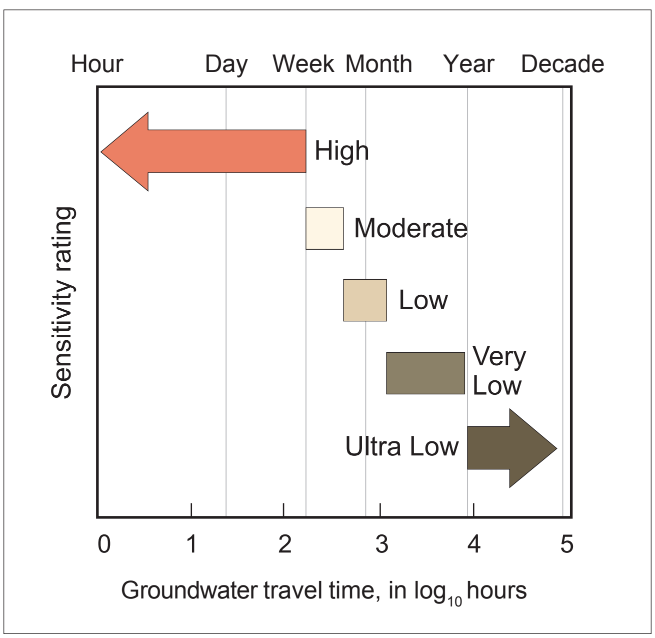


Figure 19. Pollution sensitivity rating for near-surface materials

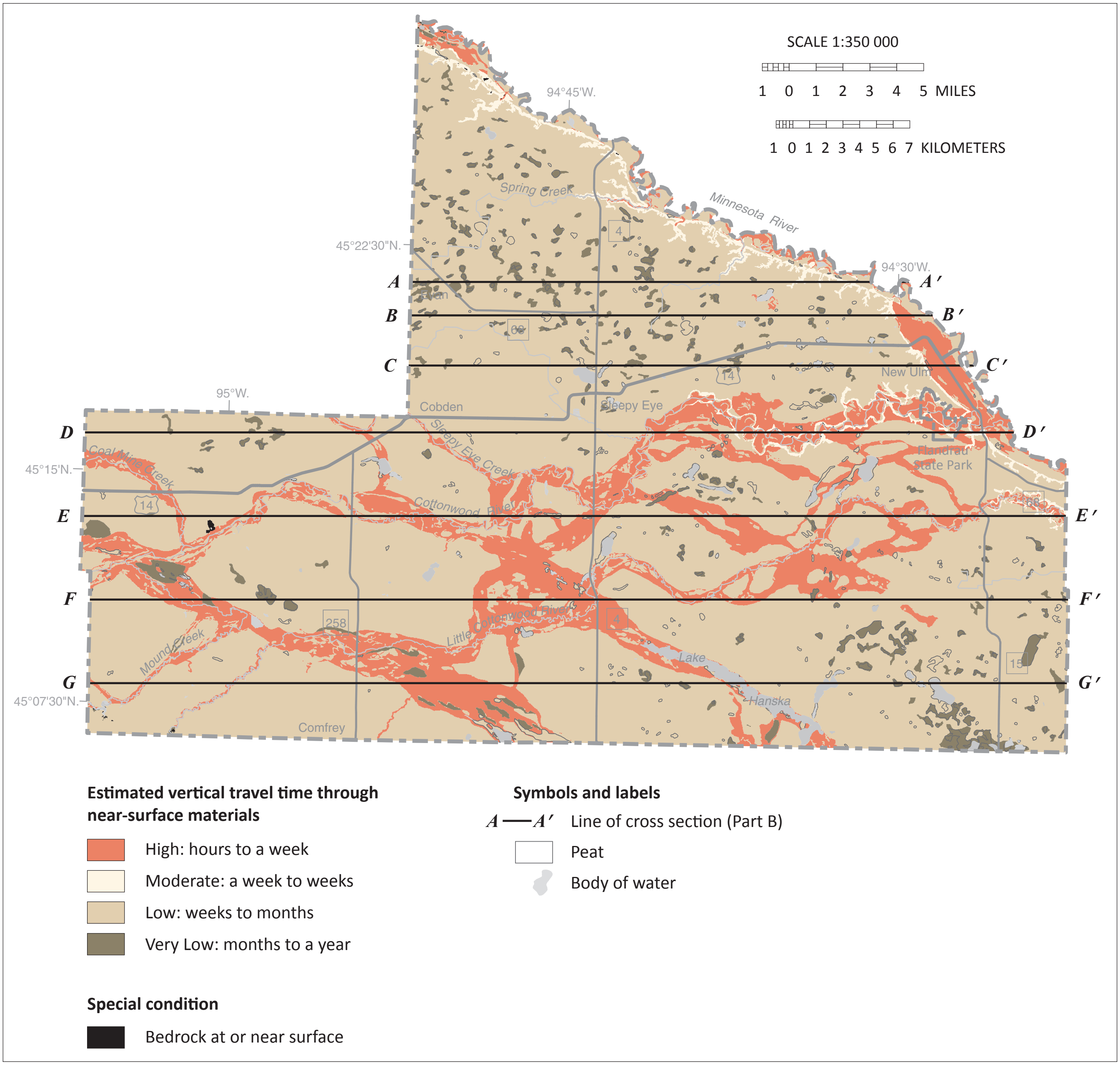


Figure 20. Pollution sensitivity of near-surface materials

Brown County is dominated by low sensitivity for this shallow (10-foot depth) evaluation. High sensitivity exists in areas where alluvium and glacial outwash are at the surface. Most of these high sensitivity areas are occupied by the larger rivers (Minnesota, Cottonwood, and Little Cottonwood) and smaller streams including Sleepy Eye, Coal Mine, and Mound creeks.

Buried sand aquifers and bedrock surface

Methods

The sensitivity rating for the buried sand aquifers and the bedrock surface is based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with ratings of high or very high have relatively short travel times of less than a few years. Areas rated low or very low have estimated travel times of decades or longer (Figure 21).

The DNR developed a pollution sensitivity model that represents how precipitation infiltrates the land surface and recharges portions of deeper aquifers. The central concept is that focused (relatively rapid) recharge occurs where aquifers overlap and are connected by complex pathways. The model assumes that the thickness of fine-grained sediment overlying an aquifer is inversely proportional to the sensitivity of an aquifer. The thicker the fine-grained sediment, the longer it takes for water to move through it (Figure 22).

Geographic Information System (GIS) software is used to calculate cumulative thickness of the fine-grained sediment layers in the county. Thicknesses of 10 feet or less are rated very high sensitivity, thicknesses greater than 40 feet are rated very low, and thicknesses between 10 and 40 are given intermediate ratings.

More details are available in *Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment thickness* (DNR, 2016c).

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

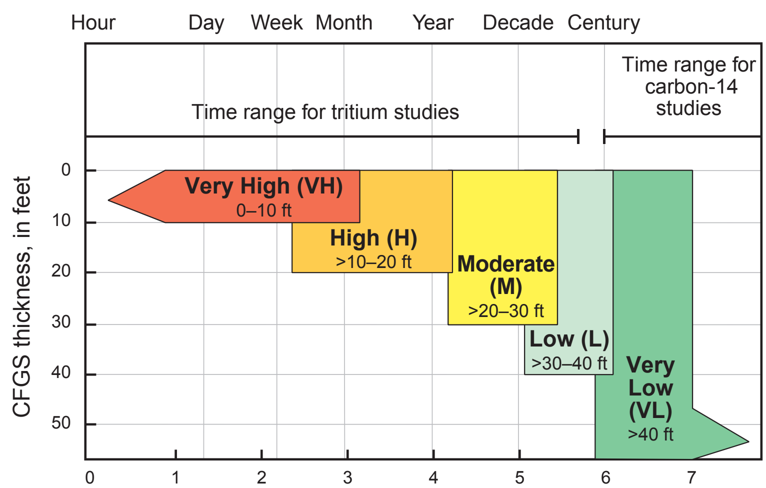


Figure 21. Geologic sensitivity rating for the buried sand aquifers and the bedrock surface

Sensitivity is defined by estimated vertical travel time. The numbers following each rating represent the cumulative fine-grained sediment (CFGS) thickness overlying an aquifer.

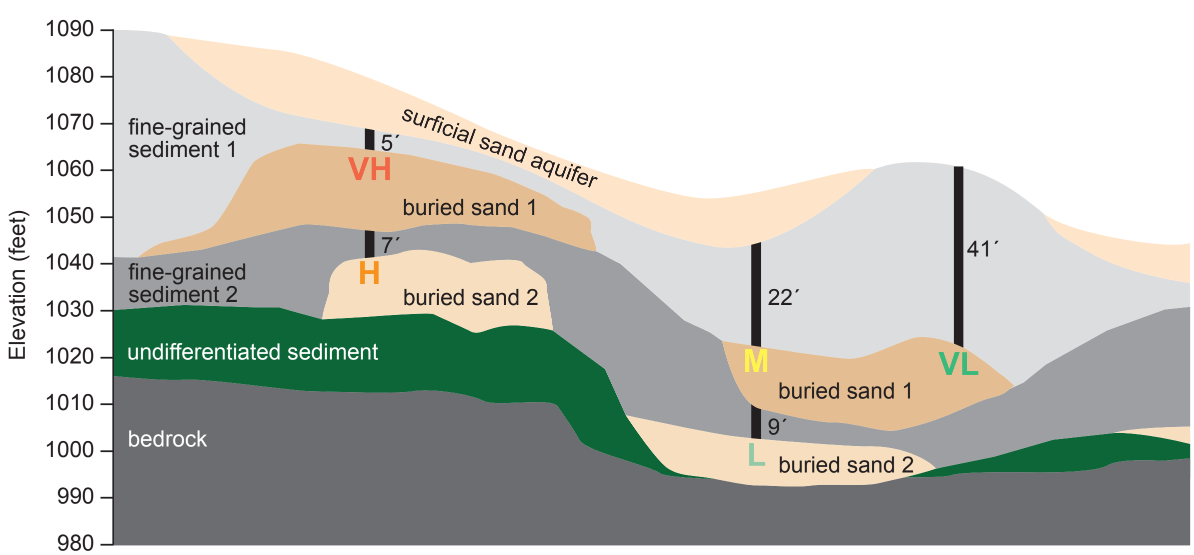


Figure 22. Cross section showing examples of pollution sensitivity ratings

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

Groundwater conditions

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

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

(L) Groundwater flows laterally.

(P) Tritium concentration can be artificially elevated by high-volume pumping.

(U) Groundwater flowpath is unknown.

(D) Groundwater discharges to a surface-water body.

⦿ Groundwater movement is out of cross section.

In general, conditions 1, 2, 3, and the associated tritium-age water (recent and mixed) match the type of vertical groundwater flow and focused recharge that is assumed in the pollution sensitivity model. These conditions provide some validation of the model in areas of moderate to very high sensitivity (Figure 23).

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

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

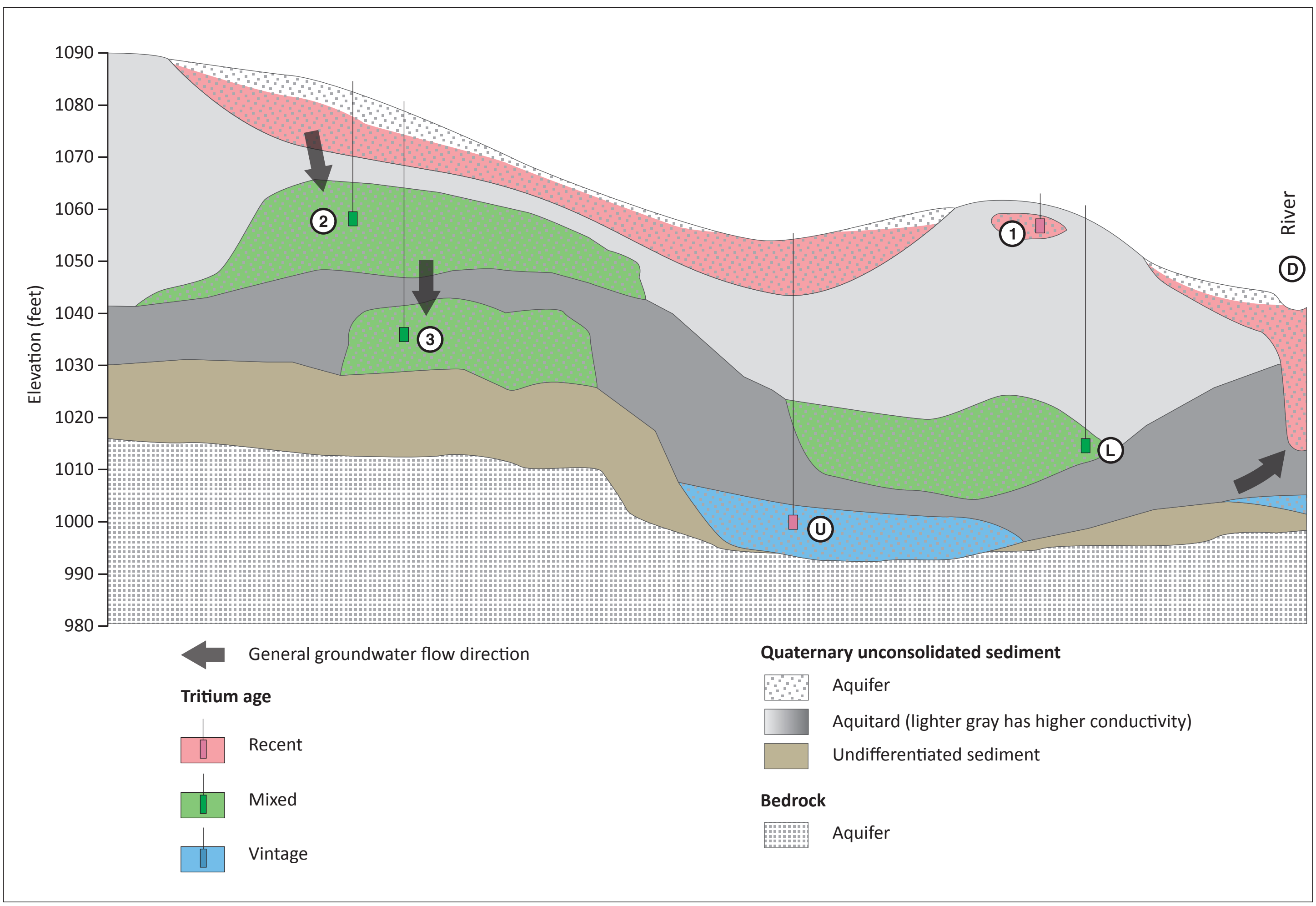


Figure 23. Hypothetical cross section illustrating groundwater conditions

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

Results

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

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

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

The tritium dataset was a combination of sampling efforts by the DNR and the MDH (MDH for several projects since 1988). Descriptions of groundwater chemistry and pollution sensitivity were qualitatively compared to the results of the pollution sensitivity modeling. Tritium detections in groundwater samples from aquifers in areas mapped as very low sensitivity should rarely occur, assuming that flow of recent water to the aquifer is vertical and not altered by nearby pumping or well integrity issues.

sh and sd aquifers (Figure 24)

These units were mapped as limited extent buried sand aquifers at scattered locations. Depths ranged from approximately 10–40 feet (sh) and 10–90 feet (sd). These aquifers are used by approximately 2 percent of the wells in the county. The pollution sensitivity ranged from very low to very high. Most of the very low to low ratings were for the sd aquifer where portions of this aquifer are the deepest.

Of the 5 samples, all were analyzed for tritium, resulting in 3 mixed and 2 vintage tritium age. All of the 3 mixed tritium-age samples also contained anthropogenic chloride (20 to 39 ppm), and 2 contained elevated nitrate (3.8 and 11 ppm). Two of the mixed tritium-age samples west of New Ulm were near moderate to high sensitivity portions of the aquifer. The vintage tritium-age sample between Sleepy Eye and Cobden was in a very low sensitivity part of the aquifer. All of these results are consistent with the pollution sensitivity model.

si, sm, and st aquifers (Figure 25)

The si aquifer was mapped in a small area of the southwest. The sm aquifer was mapped mostly in the northern portion of the county. The st aquifer was mapped as one sand body in the northern part of the county. Depths range from approximately 10–70 feet (si) to 10–110 feet (sm). These aquifers are used by approximately 1 percent of the wells in the county. The pollution sensitivity includes the entire range of ratings from very low to very high. The higher sensitivity is found along the river valleys where they are shallower.

Only one sample was from this group in the sm aquifer northwest of New Ulm. This vintage tritium-age sample contained neither elevated chloride or nitrate. The corresponding pollution sensitivity is very low, which fits the sensitivity model.

s1 and s2 aquifers (Figure 26)

The s1 and s2 aquifers were mostly mapped in the northern and eastern parts of the county. Depths range from approximately 10–120 feet (s1), and 10–140 feet (s2). These aquifers are used by approximately 7 percent of the wells in the county. The pollution sensitivity includes the entire range of ratings from very low to very high. Most of the higher sensitivity areas (moderate to very high) are in the western portions of the s2 aquifer's extent, south of the Cottonwood River where portions of this aquifer are shallower and surficial sand is common.

Of the 12 samples analyzed for tritium, 2 were mixed and 10 were vintage. One vintage tritium-age sample west of Hanska had a carbon-14 residence time of 7,000 years. Of the 12 samples analyzed for nitrate, none had elevated concentrations. Of the 12 samples analyzed for chloride, 4 were elevated but none of them appeared to be from an anthropogenic source.

Both mixed tritium-age samples were in moderate to very high pollution sensitivity areas. All of the vintage tritium-age samples were in low to very low sensitivity areas. All of the tritium and anthropogenic indicators match the pollution sensitivity model.

s3 and s4 aquifers (Figure 27)

The s3 and s4 aquifers are distributed across most of the county. Depths range from approximately 10–120 feet (s3), and 20–160 feet (s4). These aquifers are used by approximately 13 percent of the wells in the county. The pollution sensitivity includes the entire range of ratings from very low to very high. The higher sensitivity ratings for both aquifers are mostly in the southern portion of the county where these aquifers are shallower and surficial sand is common.

Of the 25 samples from these aquifers, 23 were analyzed for tritium with the following results: 1 recent, 5 mixed, and 17 vintage. One of the vintage s3 samples in the northern part of the county had a carbon-14 residence time of approximately 4,000 years. Of the 22 samples analyzed for nitrate, 1 was elevated. Of the 22 samples analyzed for chloride, 8 were elevated and 2 of those were anthropogenic.

Most of the recent and mixed tritium-age samples were found at locations mapped with very low to low sensitivities. The exception was a mixed tritium-age sample west of Cobden that matches the higher sensitivity in that area. This sample likely has tritium from groundwater flowing vertically. At the other recent and mixed-tritium locations lateral flow is likely from a higher sensitivity area (condition L), or the reasons are unknown (condition U). The vintage tritium-age samples were in very low sensitivity areas which is consistent with the pollution sensitivity model.

se aquifer (Figure 28)

The se aquifer was mapped at locations scattered across most of the county. The depth range is approximately 20–170 feet. This aquifer is used by approximately 7 percent of the wells in the county. The pollution sensitivity of this aquifer is mostly very low to low with some areas of moderate to very high in the west and southern portions of the county where aquifers are shallower in the river valleys or surficial sand is more common.

Of the 13 samples, 12 were analyzed for tritium with the following results: 5 mixed and 7 vintage. Of the 11 samples analyzed for nitrate, one sample east of Sleepy Eye was elevated (4.56 ppm). Of the 11 samples analyzed for chloride, 4 were elevated and 3 of those were anthropogenic.

Most of the mixed tritium-age samples were from locations in moderate to very high sensitivity areas. However, for two samples in the southern part of the county the source of tritium and anthropogenic chloride remain unknown (condition U). All of the vintage tritium-age samples were in very low sensitivity areas, which is consistent with the pollution sensitivity model.

su and sz (undifferentiated buried sand) aquifers (Figure 29)

These undifferentiated aquifers were mapped as sand bodies of various sizes across the county. Approximate depths range from 10–220 feet (su) and 10–250 feet (sz). These aquifers are used by approximately 23 percent of the wells in the county. The pollution sensitivity is mostly very low with some higher sensitivity ratings in the Minnesota and Cottonwood river valleys where these aquifers are relatively shallow.

Of the 30 samples, 29 were analyzed for tritium; all but 3 were vintage. Four of the vintage tritium-age samples had carbon-14 residence times of approximately 2,500 to 13,000 years. The 2,500-year sample was near the Cottonwood River valley, just west of New Ulm, and just north of a very high pollution sensitivity area. Of the 27 samples analyzed for nitrate, none were elevated. Of the 26 samples analyzed for chloride, 3 were elevated but none were anthropogenic.

The 3 mixed tritium-age samples were in or near the Cottonwood River valley and two of these samples (east of Sleepy Eye) were near moderate sensitivity areas. The 26 vintage tritium-age samples were in very low sensitivity areas. All of these results are consistent with the pollution sensitivity model.

Bedrock surface (Figure 30)

The type of bedrock at the bedrock surface is variable across the county. Cretaceous shale and sandstone are the dominant bedrock types across most of the county. Exceptions include Precambrian granitic and gneissic rocks in the northern, central, and far southwest portions; and smaller areas of Cambrian rocks in the east. Some portions of the Dakota aquifer are at or near the bedrock surface. The Dakota aquifer is used by approximately 21 percent of the wells in the county.

Depths to the bedrock surface range from typically less than 100 feet in the southwest and areas along the Cottonwood and Minnesota rivers, to depths of greater than 100 feet up to 350 feet in the remainder of the county (Part A, Plate 2, Figure 3, and Plate 5, Depth to Bedrock).

This surface mostly has a very low pollution sensitivity with the exception of areas near the Minnesota and Cottonwood rivers and other areas in the western part of the county where the bedrock surface is shallow. A limited number of bedrock samples are shown on Figure 30 for comparison with the bedrock surface pollution sensitivity. Groundwater samples from wells with open-hole portions that are much deeper than the bedrock surface are likely not representative of bedrock surface pollution sensitivity. Therefore, the only data shown for this comparison are from wells with open-hole sections no deeper than 40 feet below the bedrock surface. Of the 10 wells that met this criteria, all were completed in Dakota aquifers. All 10 were analyzed for tritium; 4 had mixed tritium age and 6 had vintage tritium age. One of the vintage tritium-age samples was west of New Ulm in the Cottonwood River valley and had a carbon-14 residence time of 6,000 years. All 10 samples were analyzed for nitrate and chloride. None were elevated for nitrate; 3 of the 4 elevated chloride samples were anthropogenic, which is consistent with the moderate to very high pollution sensitivity in these areas.

Of the 4 mixed tritium-age samples, 3 of them were near moderate pollution sensitivity areas in the Cottonwood River valley. All the 6 vintage tritium-age samples were in very low pollution sensitivity areas. All of these results are consistent with the pollution sensitivity model.

Deeper bedrock groundwater chemistry (Figure 31)

In general, the groundwater chemistry from samples below the bedrock surface zone indicates relatively isolated and probable very low sensitivity conditions. The samples shown in Figure 31 are from wells with open-hole sections significantly deeper (greater than 40 feet) than the bedrock surface. The aquifers represented on this map include Cretaceous Dakota sandstone, unnamed Cretaceous rocks that are poorly understood (mapped as unit Ka), and the Cambrian Mt. Simon Sandstone. Of the 28 wells that met this criterion, all were analyzed for tritium; 4 had mixed tritium age and 24 had vintage tritium age. Six of the vintage tritium-age samples had approximate carbon-14 residence times of 1,200 to 30,000 years. The two samples with the youngest carbon-14 residence times (1,200 and 2,500 years) were from the upper part of the Dakota aquifer in the western part of the county. The two samples with the oldest carbon-14 ages (13,000 to 30,000 years) were from the deeper Mt. Simon aquifer in the eastern part of the county. All samples were analyzed for nitrate and none were elevated. Of the 26 samples analyzed for chloride, 12 were elevated but none were anthropogenic. These results are consistent with the pollution sensitivity model.

Of the 4 mixed tritium-age samples, 3 were in or near the Cottonwood and Minnesota river valleys and could have been sourced from upgradient higher pollution sensitivity areas (see the eastern ends of cross sections C–C′ and D–D′, Plate 7).

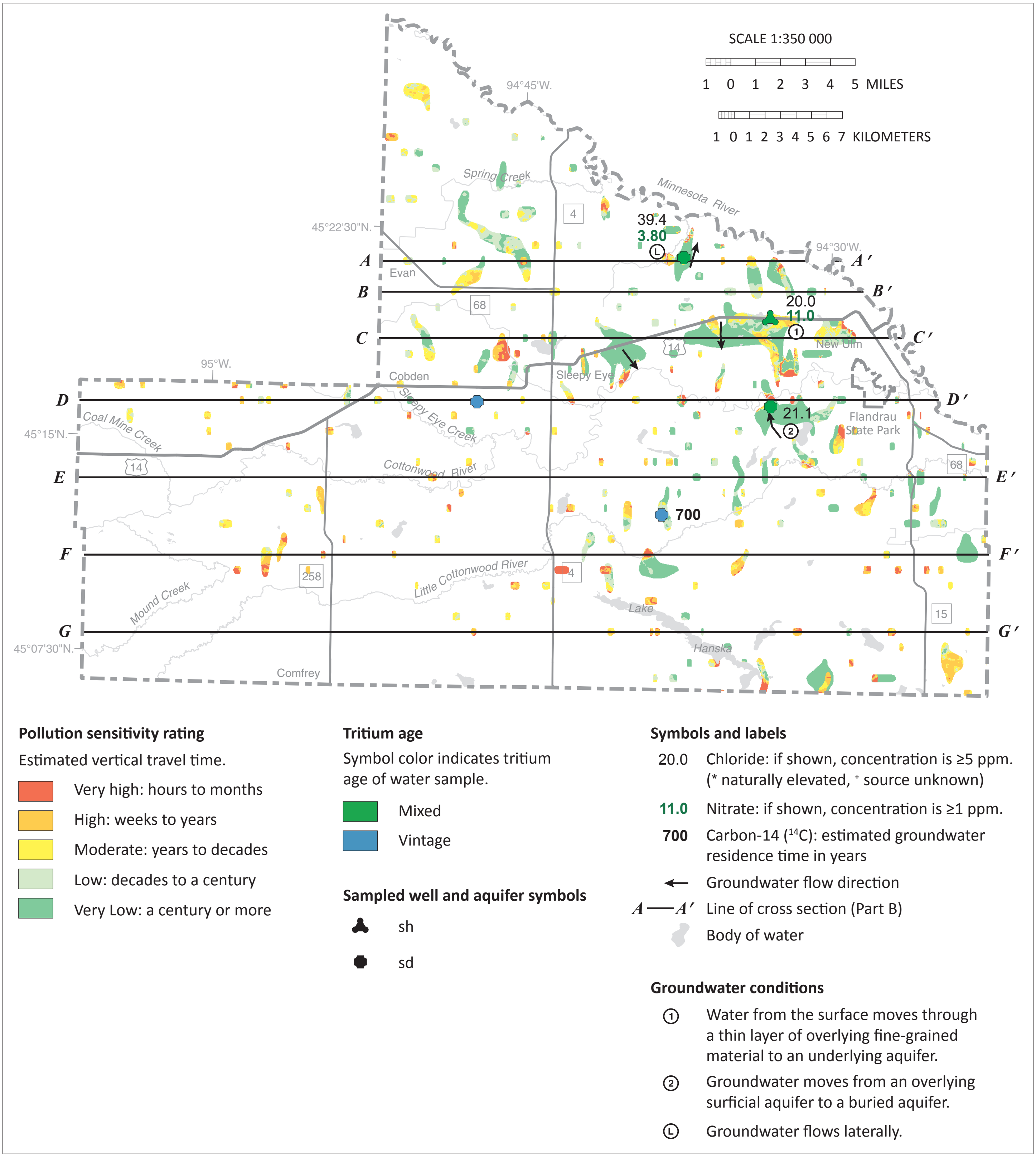


Figure 24. Pollution sensitivity of the sh and sd aquifers and groundwater flow directions

These units were mapped as limited extent buried sand aquifers at scattered locations. The pollution sensitivity ranged from very low to very high.

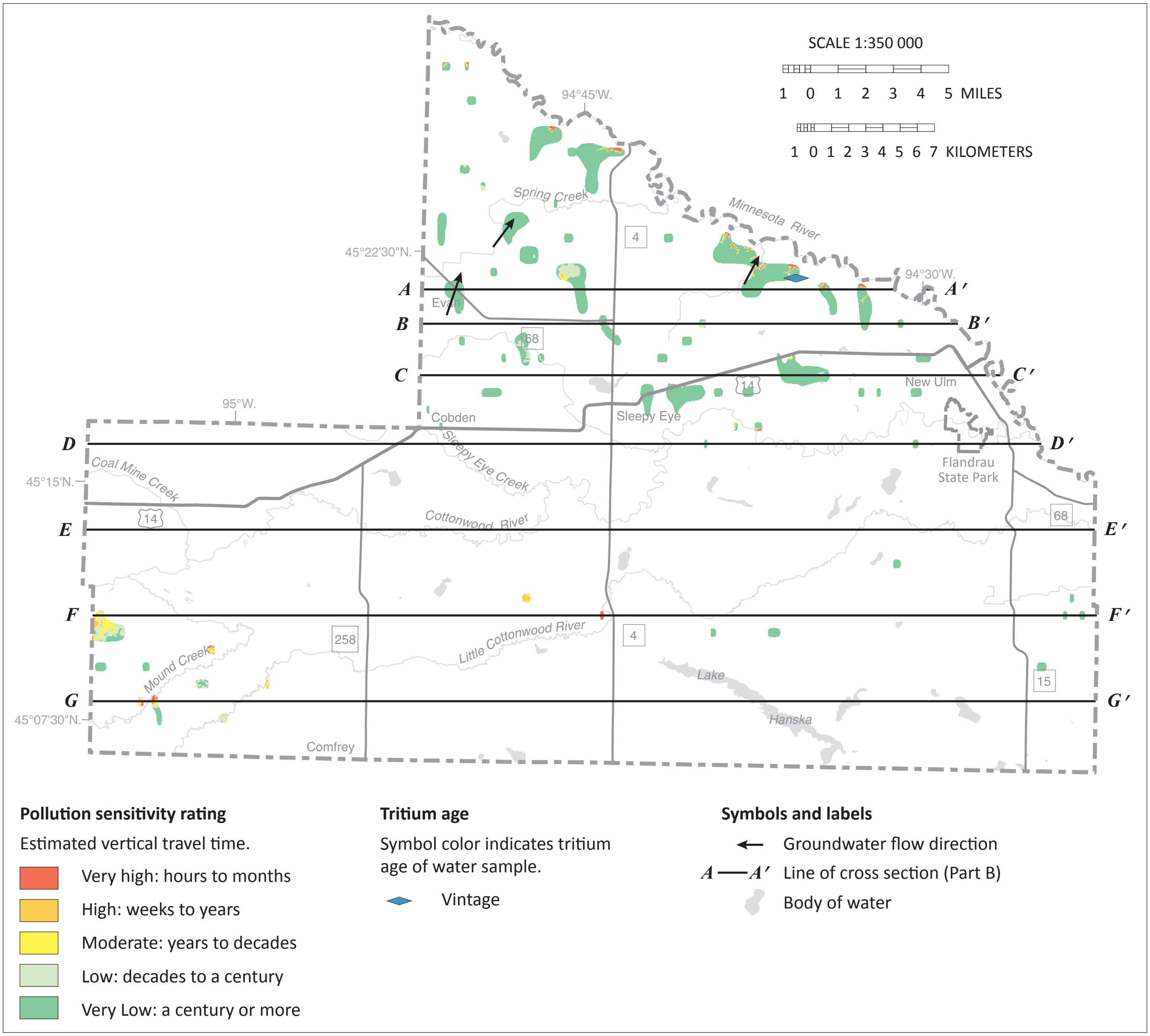


Figure 25. Pollution sensitivity of the si, sm, and st aquifers and groundwater flow directions

The si aquifer was mapped in a small area of the southwest. The sm aquifer was mapped mostly in the northern portion of the county. The st aquifer was mapped as one sand body in the northern part of the county. The pollution sensitivity includes the entire range of ratings from very low to very high. The higher sensitivity ratings in the aquifers are along the river valleys where they are shallower.

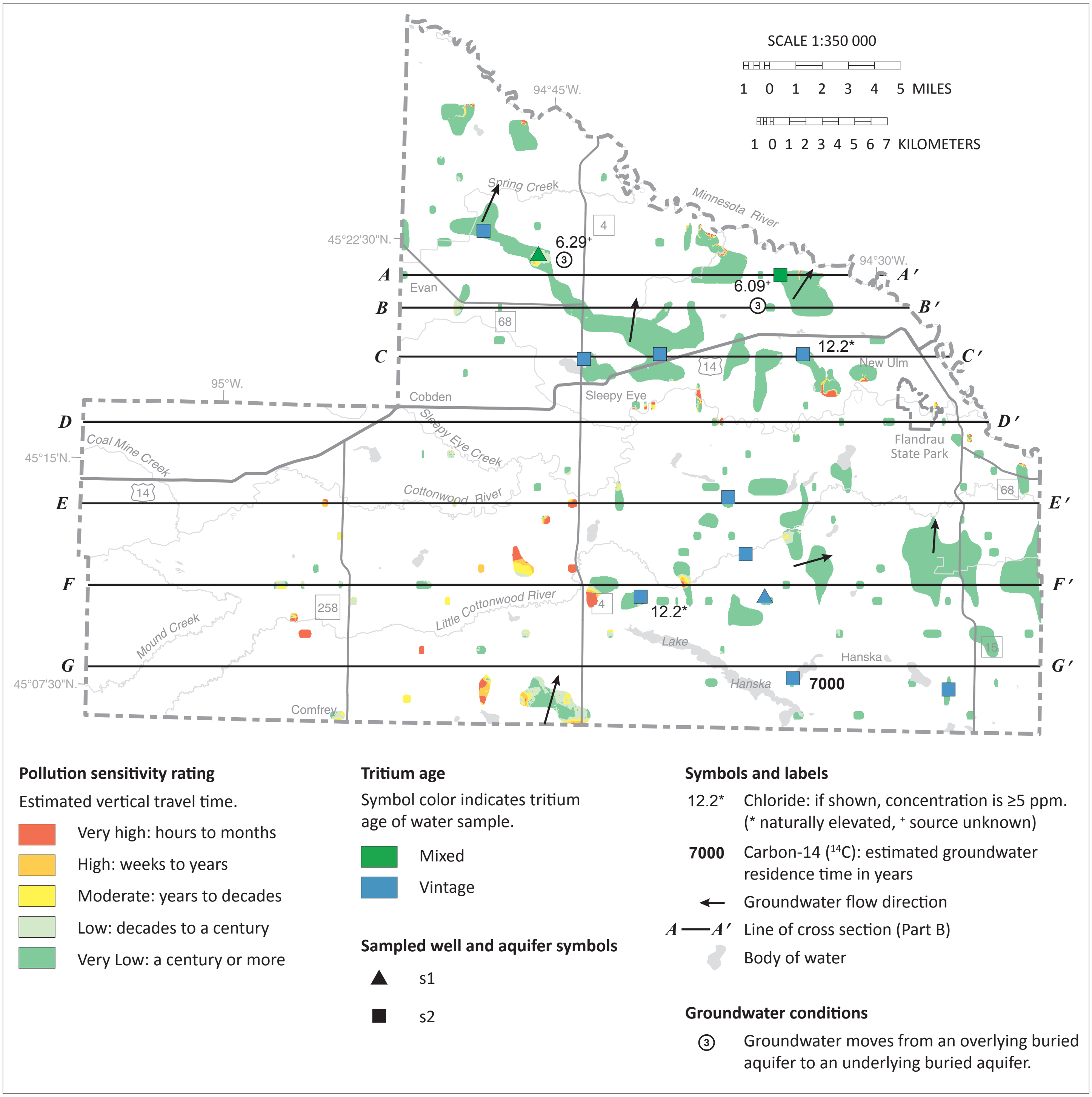
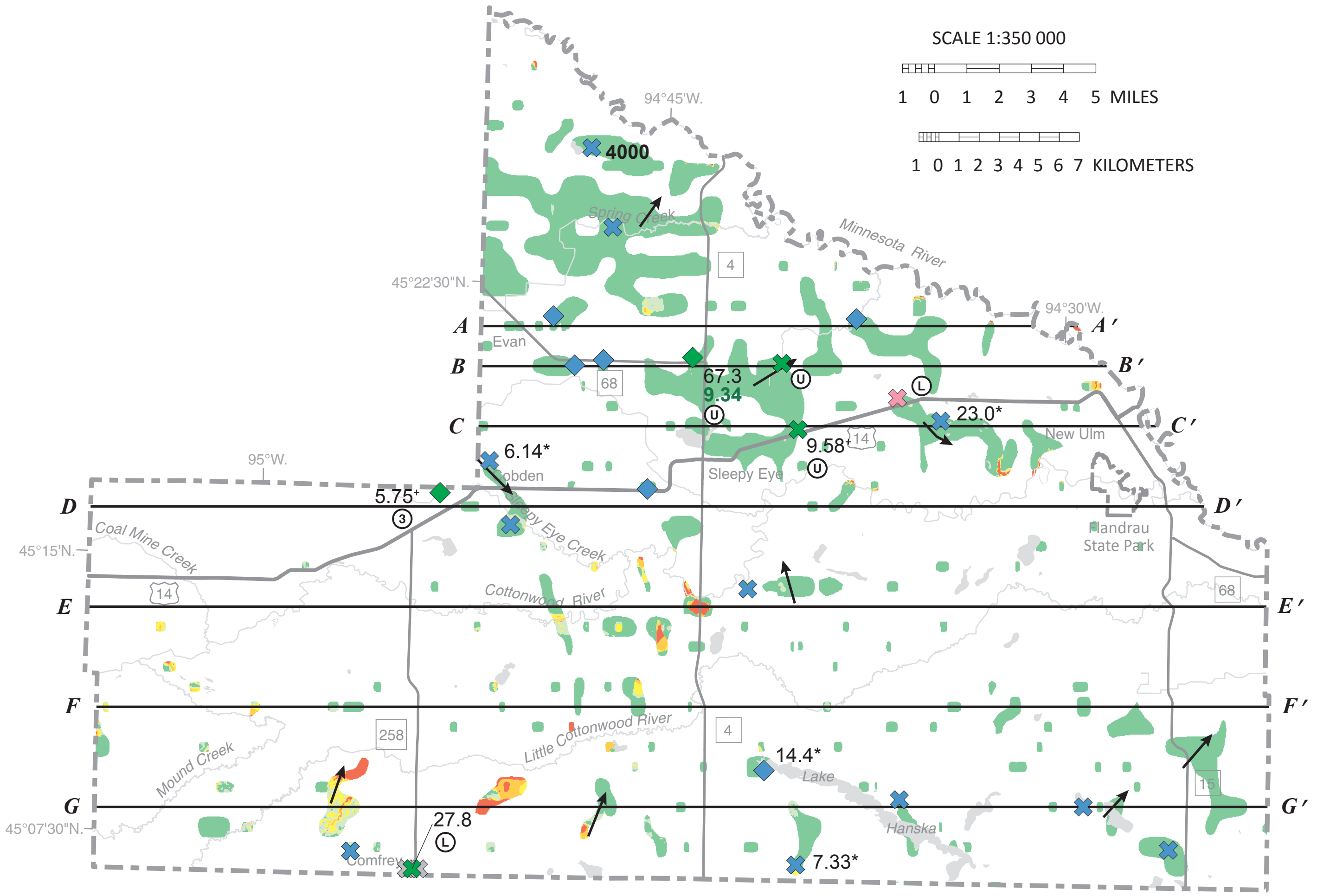


Figure 26. Pollution sensitivity of the s1 and s2 aquifers and groundwater flow directions

The s1 and s2 aquifers were mostly mapped in the northern and eastern parts of the county. The pollution sensitivity includes the entire range of ratings from very low to very high. Most of the higher sensitivity areas (moderate to very high) are in the western portions of the s2 aquifer's extent, south of the Cottonwood River where portions of this aquifer are shallower and surficial sand is common.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Recent
- Mixed
- Vintage
- Not sampled for tritium

Sampled well and aquifer symbols

- ✖ s3
- ◆ s4

Symbols and labels

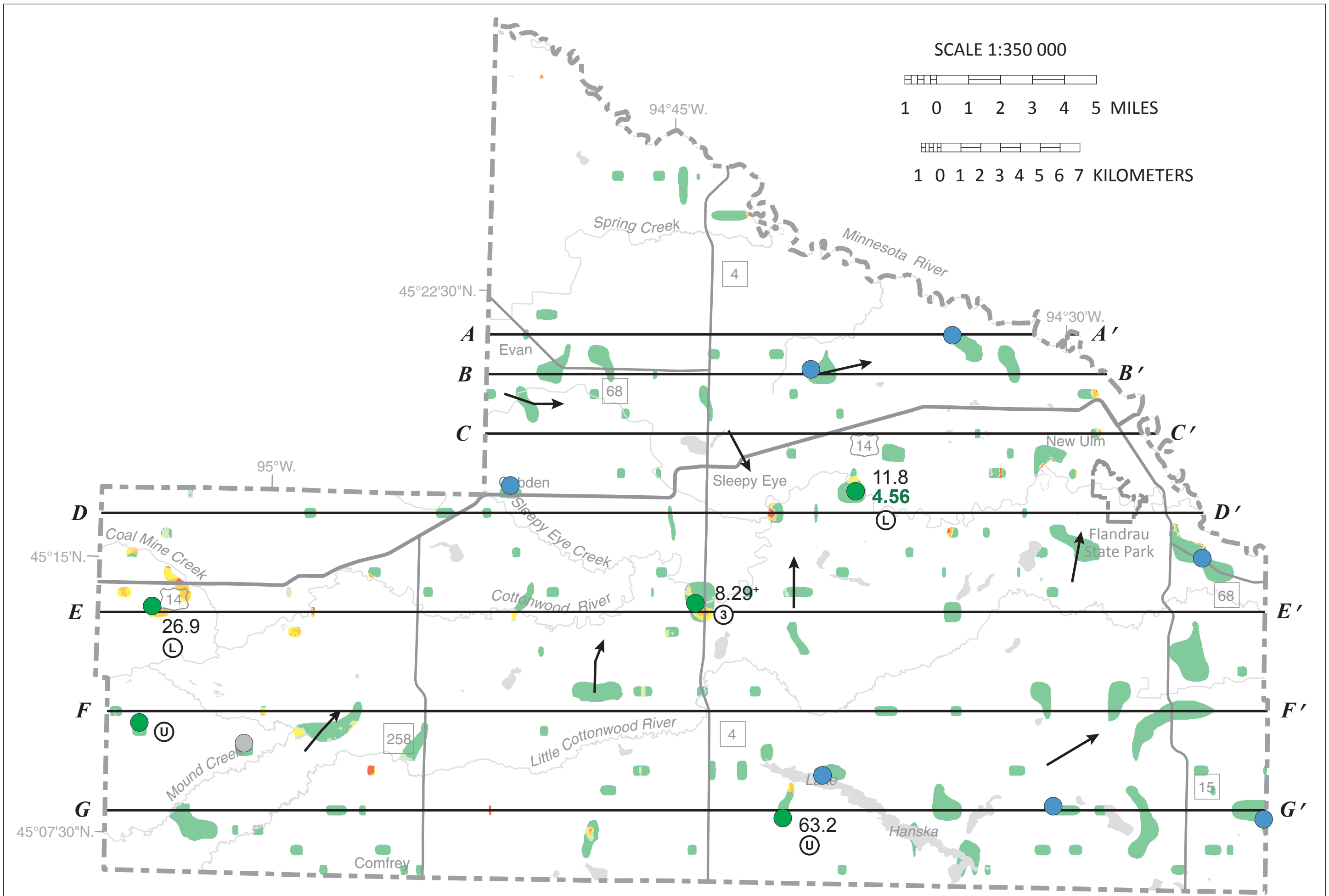
- 67.3 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, + source unknown)
- **9.34** Nitrate: if shown, concentration is ≥1 ppm.
- **4000** Carbon-14 (^{14}C): estimated groundwater residence time in years
- ← Groundwater flow direction
- *A* — *A′* Line of cross section (Part B)
- Body of water

Groundwater conditions

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

Figure 27. Pollution sensitivity of the s3 and s4 aquifers and groundwater flow directions

The s3 and s4 aquifers are distributed across most of the county. The pollution sensitivity includes the entire range of ratings from very low to very high. The higher sensitivity ratings for both aquifers are mostly in the southern portion of the county where these aquifers are shallower and surficial sand is common.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage
- Not sampled for tritium

Symbols and labels

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

Groundwater conditions

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

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

The se aquifer was mapped at locations scattered across most of the county. The pollution sensitivity of this aquifer is mostly very low to low with some areas of moderate to very high in the west and southern portions of the county where aquifers are shallower in the river valleys or surficial sand is more common.

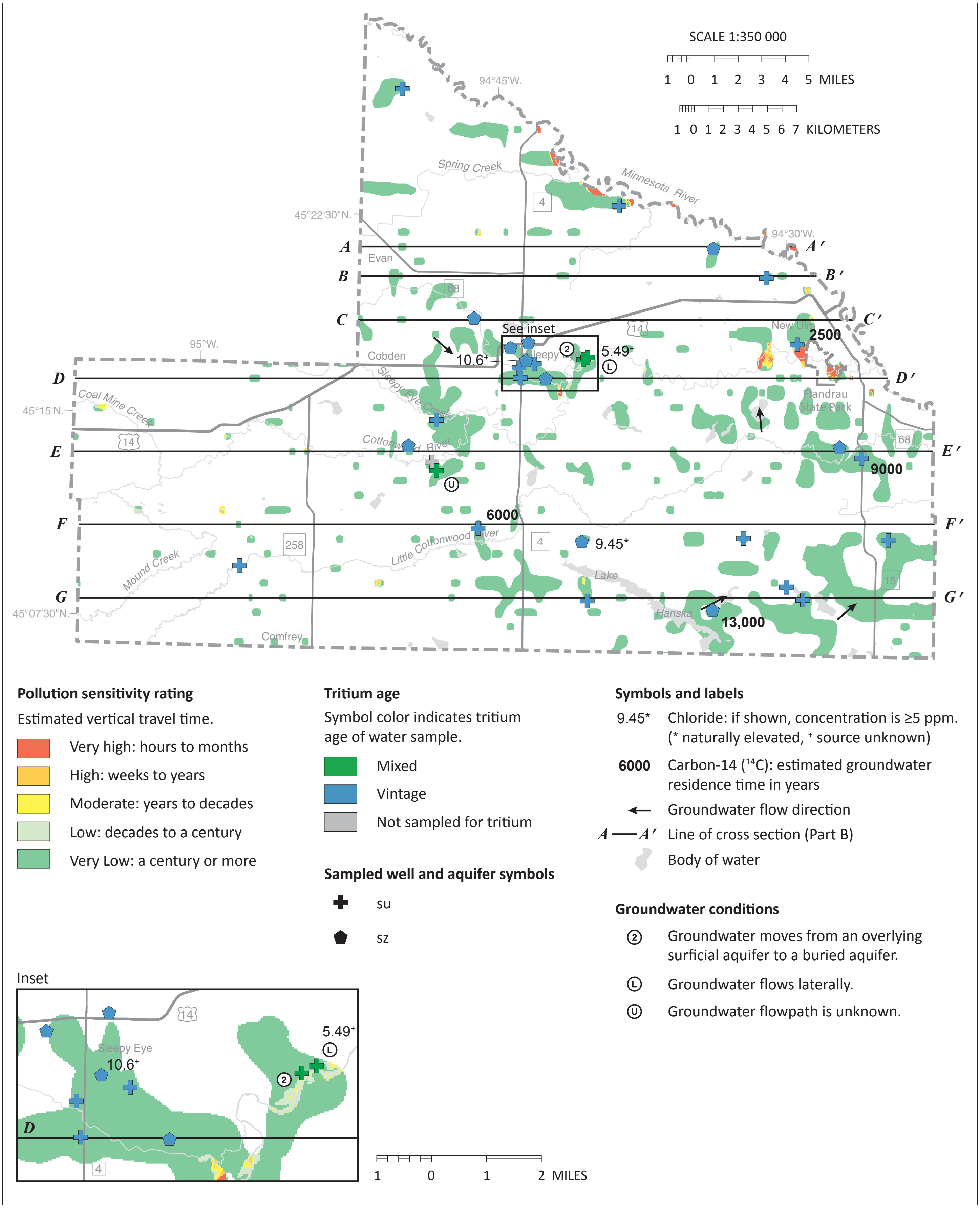
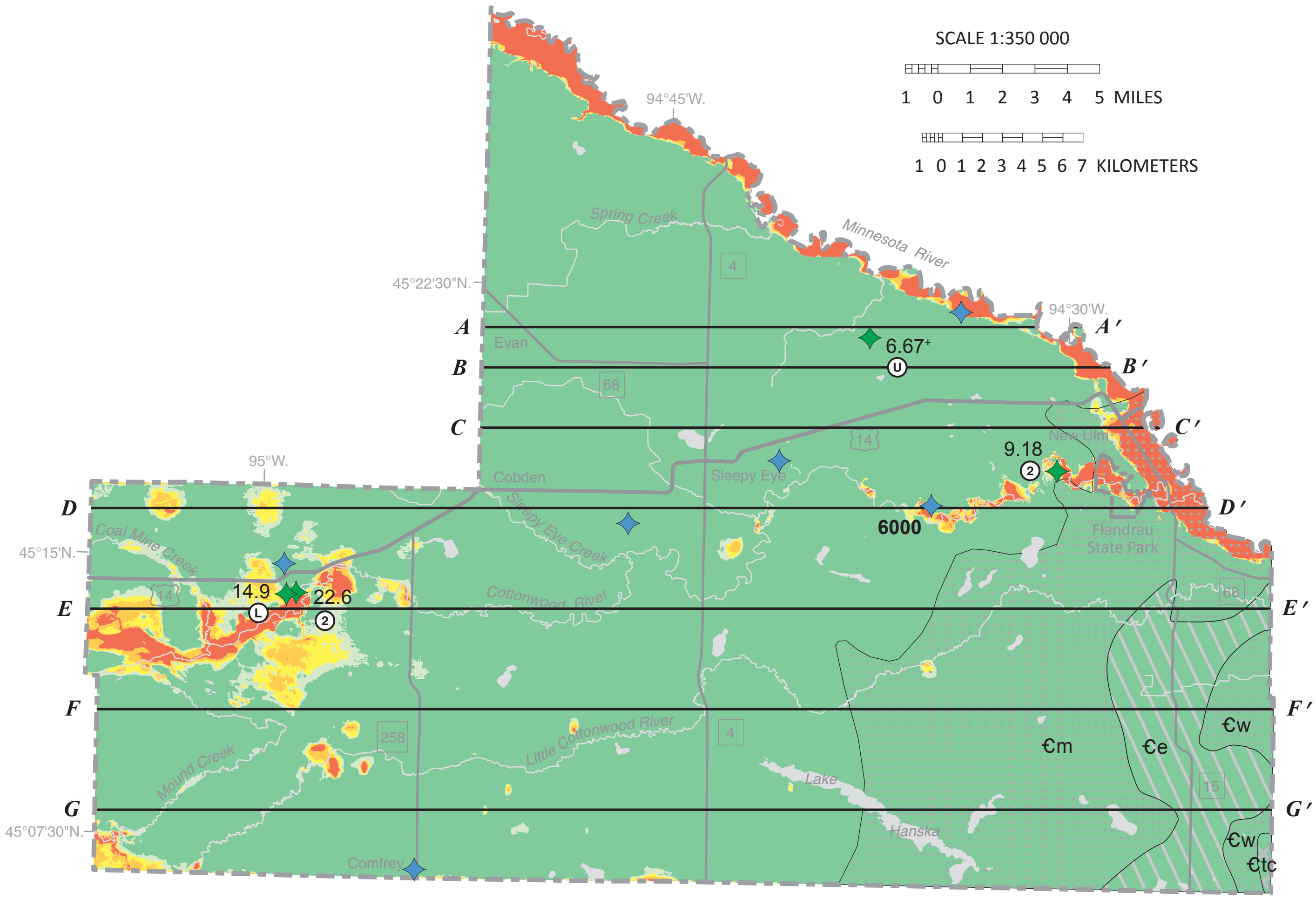


Figure 29. Pollution sensitivity of the su and sz (undifferentiated buried sand) aquifers and groundwater flow directions

These undifferentiated aquifers were mapped as sand bodies of various sizes across the county. The pollution sensitivity is mostly very low with some higher sensitivity ratings in the Minnesota and Cottonwood river valleys where these aquifers are relatively shallow.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage

Symbols and labels

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

6000 Carbon-14 (^{14}C): estimated groundwater residence time in years

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

Body of water

Groundwater conditions

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

L Groundwater flows laterally.

U Groundwater flowpath is unknown.

Paleozoic bedrock

Ꞓtc Tunnel City Group

Ꞓw Wonewoc Sandstone

Ꞓe Eau Claire Formation

Ꞓm Mt. Simon Sandstone

Figure 30. Pollution sensitivity of the bedrock surface

This surface mostly has a very low pollution sensitivity with the exception of areas near the Minnesota and Cottonwood rivers and other areas in the western part of the county where the bedrock surface is shallow.

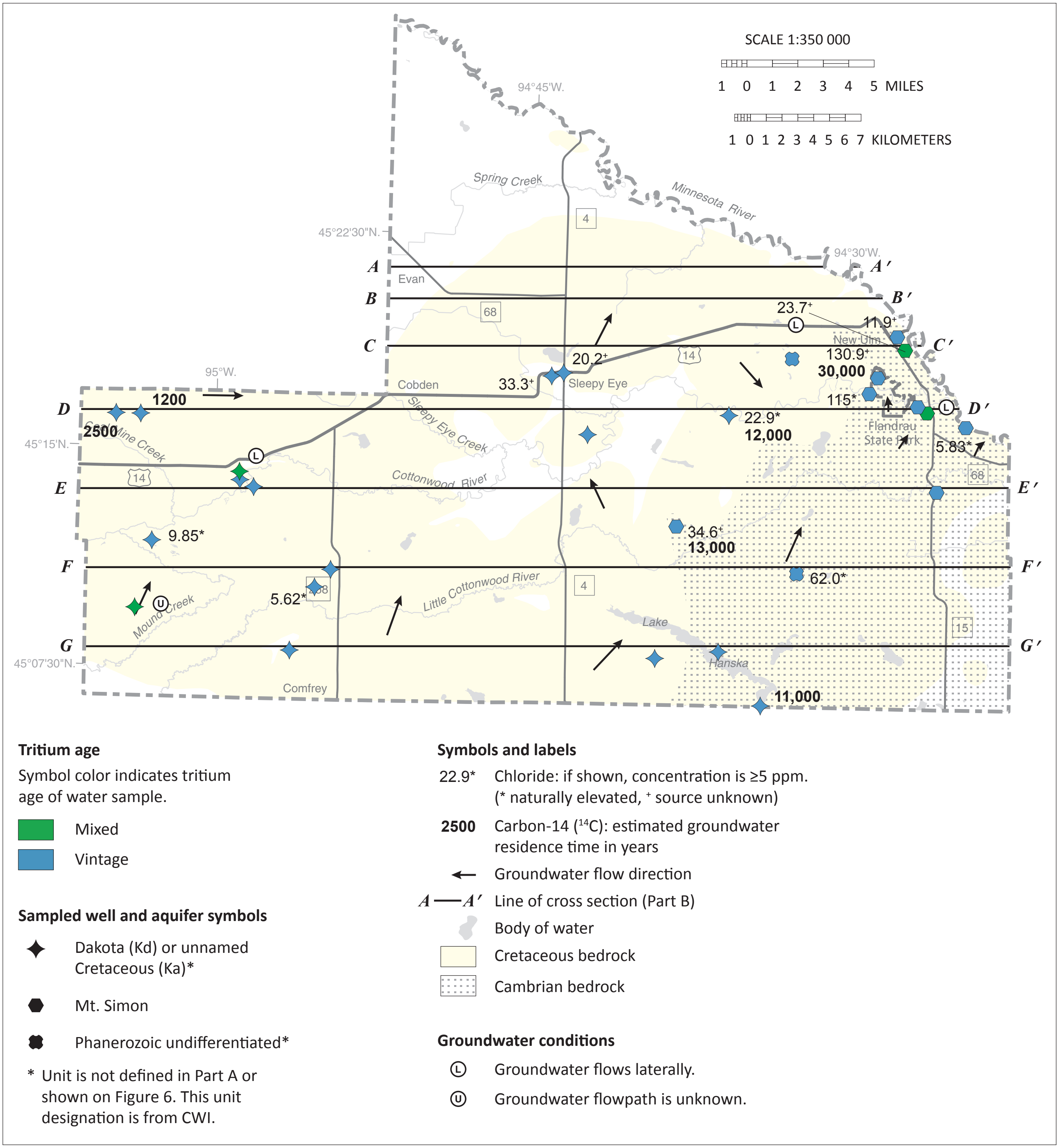


Figure 31. Deeper bedrock groundwater chemistry

In general, the groundwater chemistry from samples below the bedrock surface zone indicates relatively isolated and probable very low sensitivity conditions.

Hydrogeologic cross sections (Plate 7)

The hydrogeologic cross sections shown on Plate 7 illustrate the horizontal and vertical extent of aquifers and aquitards, the relative hydraulic conductivity of aquitards, general groundwater flow direction, areas of groundwater recharge and discharge, and groundwater residence time. The cross sections were chosen to incorporate existing data, to align with groundwater level monitoring wells, and to intersect areas with high-volume municipal pumping.

The 7 cross sections were selected from a set of 44 regularly-spaced (1 kilometer) west-to-east cross sections created by the MGS. The cross sections were constructed in GIS using a combination of well data from CWI and sections of Part A: Bedrock Geology (Plate 2), Surficial Geology (Plate 3), and Quaternary Stratigraphy (Plate 4). The well information for each cross section was projected onto the trace of the cross section from distances no greater than one-half kilometer.

Relative hydraulic conductivity

Hydraulic conductivity is a function of the porosity (volume of pores) and permeability (connectedness of pores) of a sediment or rock layer. Percent sand content in the glacial sediment matrix is a proxy for permeability because coarse grains typically add permeability to sediment. Glacial aquitards with higher sand content are assumed to have higher hydraulic conductivity. This assumption does not account for the occurrence of larger clasts (pebbles, cobble, and boulders), the potential for fine sediment to fill pore spaces, or fractures in the shallow till units.

Glacial sediment layers that act as aquitards (till units) are shown in shades of gray. Lighter shades indicate aquitards with higher relative hydraulic conductivity. The percent sand in each of the aquitards is based on the average matrix texture of each glacial aquitard.

Groundwater flow direction

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

The equipotential contours and flow arrows show that the groundwater flow is initially downward, then laterally toward the rivers. However, smaller discrete groundwater recharge areas are identified in the following section based on occurrences of connected aquifers (focused recharge) and geochemical data such as tritium, chloride, and nitrate.

Groundwater recharge and discharge

Data used to illustrate the extent of the Dakota aquifer were limited mostly to the southwestern portion of the county. Therefore, representations of these sandstone units are similarly limited on the cross sections to the western portions of D–D′ through G–G′. Portions of the cross sections shown without Cretaceous sandstone layers may have sandstone aquifers that are not mapped.

Downward and lateral flow directions are most common across all of these cross sections, except for the area near the Minnesota (A–A′ through D–D′) and Cottonwood rivers (D–D′ and E–E′). In those areas, groundwater flow is likely upward indicating discharge to these major rivers. In many areas recharge to the deeper aquifers can take a very long time. The residence time can be hundreds or thousands of years where focused recharge does not occur through interconnected buried sand aquifers. The carbon-14 relationships shown on the hydrogeologic cross sections are a useful tool for visualizing this very slow type of recharge through aquitards. Carbon-14 residence time values in Brown County range from 700 to 30,000 years.

In some cases, wells sampled for carbon-14 were selected nearby one another in order to compare residence times of nested shallow and deep wells. In a pair of wells northwest of Springfield on the left side of D–D′, the shallower portion of the Dakota aquifer had a residence time of 1,200 years while the nearby deeper portion had 2,500 years. In another pair of wells on the right side of D–D′, the shallower well completed in the Dakota aquifer had a residence time of 6,000 years. This sample is compared to another from the nearby and deeper well in the unnamed Cretaceous unit (Ka) and Precambrian crystalline bedrock with a residence time of 12,000 years. Both of these pairs illustrate very slow groundwater recharge through Cretaceous shale and mudstone aquitards.

Other old residence time results that are not shown as pairs of wells include two samples in the southern part of the county. A sample from the su aquifer on the right side of E–E′ south and east of the Little Cottonwood River had a carbon-14 residence time of 9,000 years. In the south-central portion of the county, also near the Little Cottonwood River (center of F–F′), a sample from the su aquifer had a carbon-14 residence time of 6,000 years. Both of these samples illustrate that nonfocused recharge to buried sand aquifers can be just as slow or slower to the buried sand aquifers through glacial till aquitards as recharge to Cretaceous sandstone aquifers through shale and mudstone aquitards.

Focused recharge through interconnected surficial and buried sand aquifers in the northern part of the county is relatively rare since most of the extensive surficial sand is limited to the southern portion of the county (Figure 2). Examples of focused recharge shown on the cross sections include:

- A–A′ : one sample on the right side of the cross section, east of John's Creek, where a combination of vertical and lateral groundwater flow from John's Creek may be recharging the sd aquifer through hydraulic connections that aren't shown due to sparse well control. This mixed tritium-age sample had an anthropogenic chloride value of 39.4 ppm and an elevated nitrate value of 3.8 ppm.
- E–E′: One mixed tritium-age sample from the se aquifer, near the middle of the cross section and south of Sleepy Eye, appears to have been recharged from the overlying surficial aquifer through multiple overlying buried sand aquifers. Although elevated (8.29 ppm), the chloride concentration from this sample was not clearly anthropogenic and the nitrate was not elevated.

The groundwater discharge to rivers shown on the cross sections is interpreted. Direct evidence of groundwater discharge to rivers in the county is largely beyond the scope of this project. Evidence of groundwater discharge can include hydraulic head or chemical data from multiple wells near rivers showing upward gradients. None of these types of data were available for this project. Examples of interpreted groundwater discharge to the Minnesota River are shown on the right side of A–A′ through D–D′ from possible sources ranging from fractured Precambrian bedrock, the Mt. Simon aquifer, and unnamed Cretaceous unit (Ka). Groundwater flow to the Cottonwood River is shown at multiple locations on the right side of D–D′ and the left side of E–E′.

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

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

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

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

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

The surficial sand aquifers have the highest mean value (49 gpm/ft). The unconsolidated aquifers have a similar range of values. The bedrock aquifers have much lower mean values but may not be representative due to the low number of tests (Table 2).

Transmissivity is an aquifer's capacity to transmit water. It provides a more accurate representation of the aquifer properties than specific capacity because it is from longer-term and larger-scale aquifer tests. It is determined by multiplying the thickness of the aquifer by the hydraulic conductivity of the aquifer material (the rate groundwater flows through a unit cross section).

The highest transmissivity from the general types of aquifers is one test of the surficial sand aquifer (highest mean value at 33,400 ft^2/day). The mean values of the buried sand and Dakota sandstone aquifers are similar at 2,300 and 2,000 ft^2/day, respectively. However, the data lack adequate representation of the Dakota sandstone aquifers with only two test results. The Mt. Simon aquifer had only one test result (500 ft^2/day).

Table 2. Specific capacity and transmissivity of selected wells

Aquifer	Specific capacity (gpm/ft)					Transmissivity (ft^2/day)				
	Casing diam. (in.)	Mean	Min	Max	No. of tests	Casing diam. (in.)	Mean	Min	Max	No. of tests
Unconsolidated										
Surficial sand (water table–QWTA)	12–16	49	20	84	9	16	33,400	--	--	1
Confined buried sand (QBAA)	12–16	27	4	117	11	8–16	2,300	1,300	3,900	9
Bedrock										
Dakota (KRET)	8–12	5	1	11	4	12	2,000	1,500	2,600	2
Mt. Simon (CMTS)	12	1	--	--	1	12	500	--	--	1

Specific capacity data adapted from the CWI
Transmissivity data are from aquifer test data compiled by the DNR
QWTA: Quaternary water-table aquifer; QBAA: Quaternary buried artesian aquifer
Dash means no data

Groundwater level monitoring

The DNR maintains a statewide groundwater level monitoring program for assessing groundwater resources, determining long-term trends, interpreting impacts of pumping and climate, planning for water conservation, evaluating water conflicts, and managing water resources (DNR, 2019a).

Well nests consist of closely spaced wells that are constructed in different aquifers. Long periods of record from multiple aquifers are useful for determining trends and provide insight into how aquifers respond to recharge events, climatic conditions, and pumping stresses (Figure 32).

In 2009, a two-well nest was constructed on the Helget Braulick Wildlife Management Area (WMA). The well nest included a well constructed in a thin portion of the Mt. Simon aquifer (768259) and in a thin portion of a relatively shallow, overlying buried sand aquifer (sd aquifer, 768260). This well nest (well numbers labeled on Figure 33 inset map) was part of a larger project to better define and understand the recharge characteristics of the Mt. Simon aquifer (Berg and Pearson, 2012) and to expand the statewide network of groundwater level monitoring wells into areas that had little or no monitoring.

Figure 32a. Subtle effects of yearly precipitation cycles appear to cause the yearly high and lower water elevations in the shallow sd aquifer shown in Figure 32b.

Figure 32b. The water level of the sd aquifer reached minimum yearly low values during the drier fall and winter periods shown on the precipitation graph.

The Mt. Simon aquifer hydrograph shows a similar yearly pattern of regular high and low water levels. However, the low periods tend to be a few months earlier compared to the sd aquifer hydrograph. The minimum yearly low periods of the Mt. Simon hydrograph match the typical irrigation season (July through September) suggesting that the low water level periods may also be created by pumping from relatively deep irrigation wells in the area.

Figure 32c. A close match is shown in a comparison of the yearly high water-use periods from well 770697 and the yearly low water level periods of the Mt. Simon aquifer hydrograph.

Figure 33 inset map. Of the three high-volume wells in the area, only the well in the Dakota aquifer (770697) is likely to be hydraulically connected to the Mt. Simon aquifer, allowing pumping from the Dakota aquifer to raise and lower water levels in the nearby Mt. Simon observation well (approximately 1.5 miles to the north). A direct hydraulic connection of the Dakota and Mt. Simon aquifers is shown as a possible juxtaposition of the two units right of the center portion of F–F′ near the Dakota well (770697).

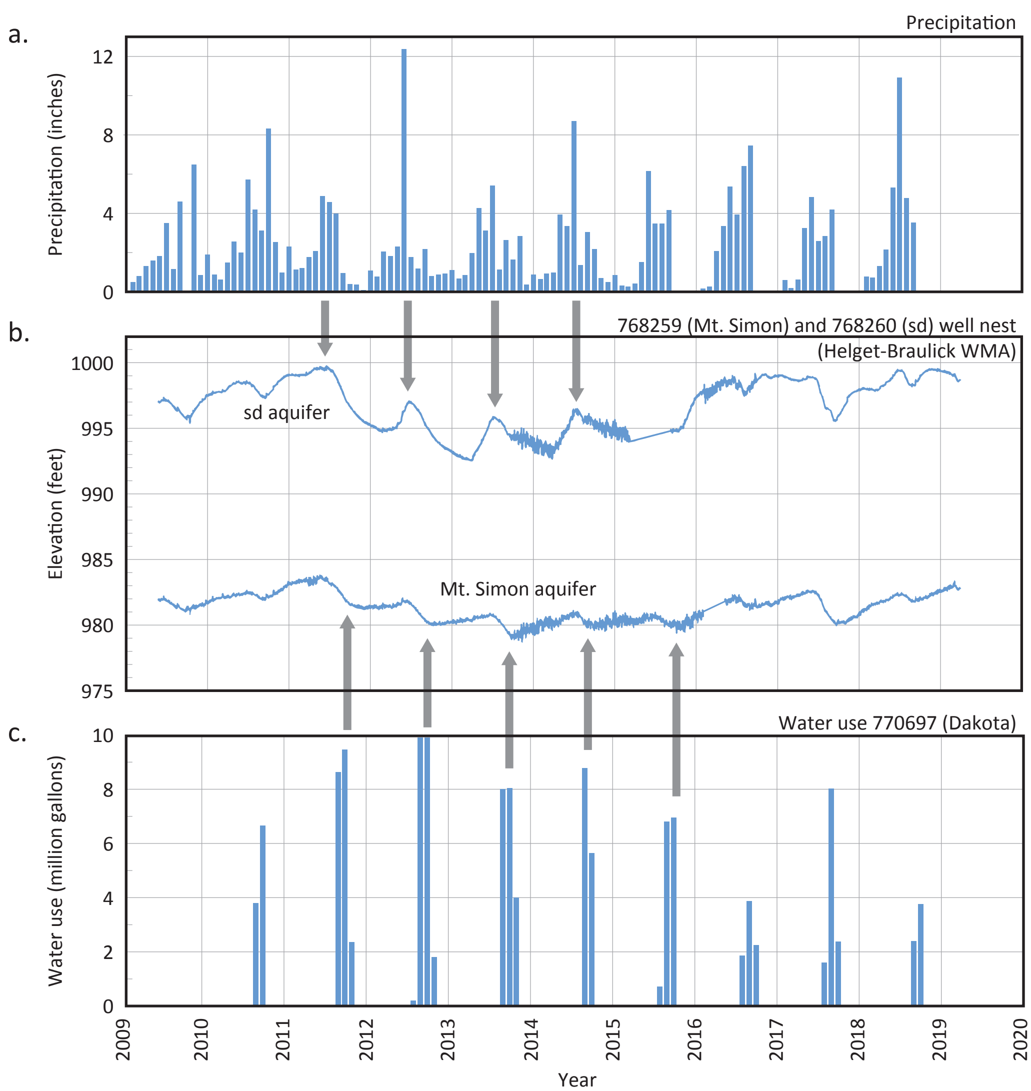


Figure 32. Precipitation, water level, and water use hydrographs

Groundwater use

A water appropriation permit is required from the DNR for groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year. This provides the DNR with the ability to assess which aquifers are being used and for what purpose. Permits require annual water-use reporting. This information is recorded using Minnesota Permitting and Reporting System (MPARS), which helps the DNR track the volume, source aquifer, and type of water use (DNR, 2019b).

Permitted groundwater use (Table 3) is presented by general aquifer type (Figure 33) and by water use type (Figure 34). The highest volume use is from the buried sand aquifers (56 percent), followed by surficial sand (21 percent), and Dakota aquifer (17 percent). The most common permitted water use is for crop irrigation (55 percent) followed by municipal/public water supply (34 percent), food processing (5 percent), and livestock watering (3 percent). By numbers of wells in the county (approximately 1,700), 82 percent are domestic, 4 percent are public supply, and 4 percent are irrigation.

Table 3. Reported 2017 water use from the DNR groundwater permit holders in millions of gallons per year (mgy)

Aquifer	Number of wells	Agricultural crop irrigation	Agricultural/food processing	Golf course irrigation	Livestock watering	Municipal/public water supply	Total (mgy)	Total (percent)
Quaternary								
Surficial sand (water table)	21	242	--	--	--	--	242	21
Buried sand	63	371	25	11	25	216	648	56
Bedrock								
Dakota	17	29	34	10	15	104	192	17
Mt. Simon	2	--	--	--	--	75	75	6
Total (mgy)	--	642	59	21	40	395	1157	
Total (percent)	--	55	5	2	3	34		

Data from MPARS; mgy, million gallons per year; dash marks (--) indicate no use in those categories]

Percentage might not equal 100 due to rounding.

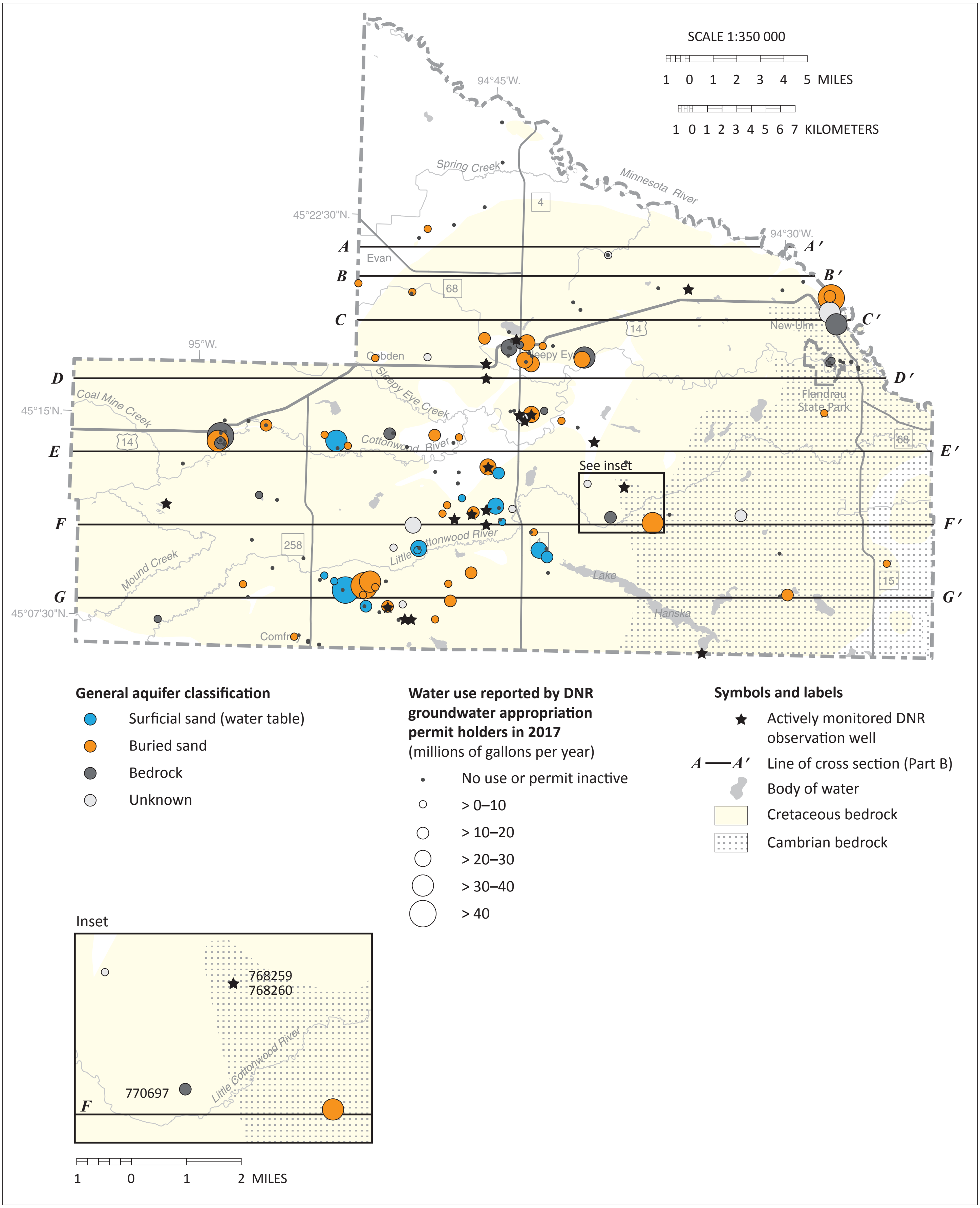


Figure 33. Groundwater use shown by general aquifer classification of the DNR appropriation permit holders

Surficial and buried sand aquifers are the most used types of aquifers for high-volume use.

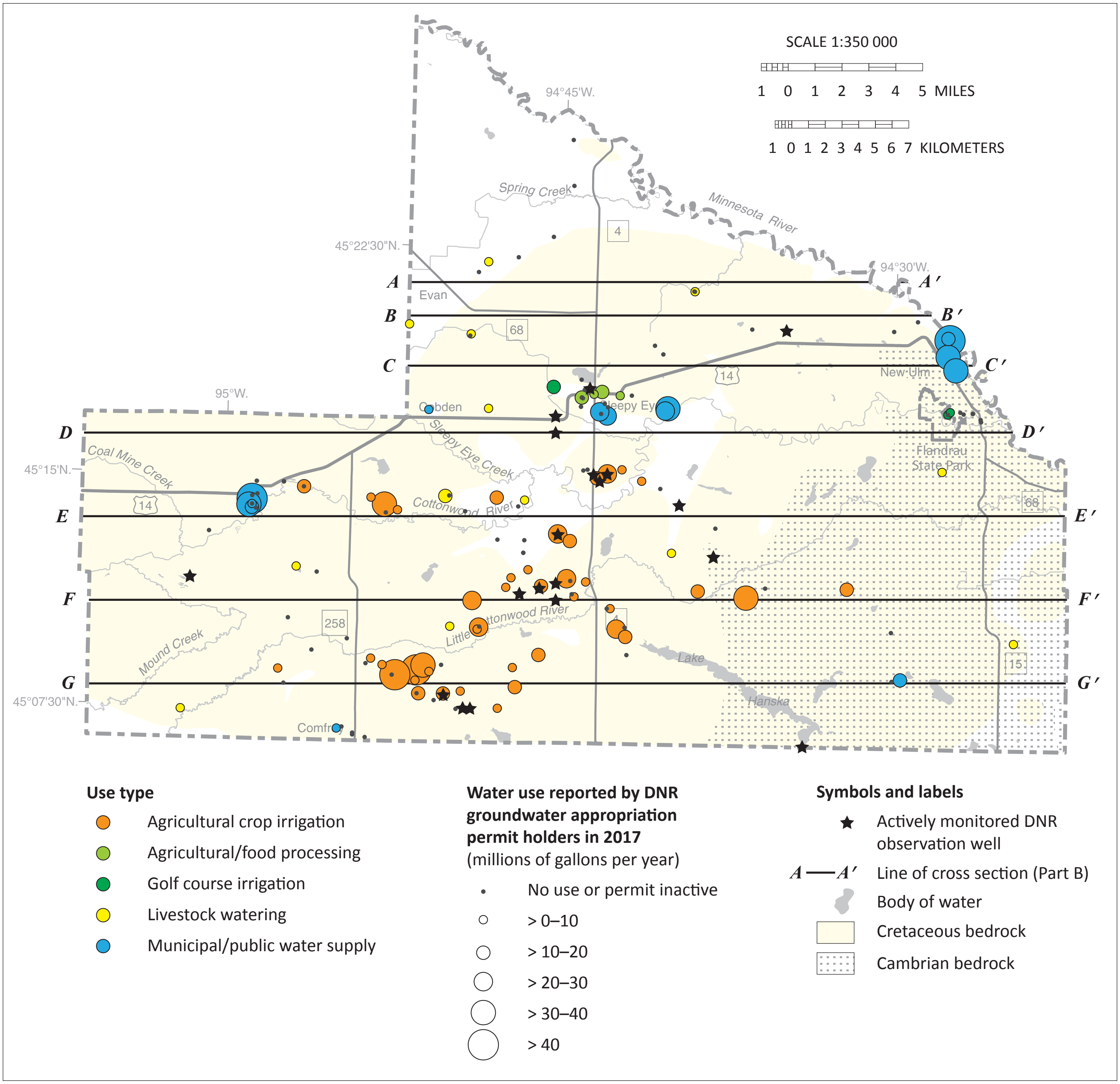


Figure 34. Groundwater use shown by use type of the DNR appropriation permit holders

Irrigation is the most common type of groundwater use in the central portion of the county, followed by municipal and public water supply in the New Ulm, Springfield, Sleepy Eye, Comfry, and Hanska areas.

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Glossary

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

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

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

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

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

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

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

carbon-14 (^{14}C)—a radioactive isotope of carbon that has a half-life of 5,730 years. It is used to identify groundwater that entered the ground from less than 50 to greater than 40,000 years before present.

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

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

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

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

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

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

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

groundwater level monitoring well—a well that is used to monitor the water level of groundwater. It is usually not used as a water source.

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

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

hydraulic—relating to water movement.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

stable isotope—chemical isotopes that are not radioactive.

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

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

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

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

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

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

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

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

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

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

watershed—the area of land that drains into a specific downstream location.

well nest—two or more wells in close proximity completed in different aquifers.

Appendix A

Groundwater field sample collection protocol

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

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

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

Appendix Table A: Groundwater field sample collection and handling details

Parameter	Tritium	^{18}O Deuterium	Nitrate/Nitrite & Total Phosphorus	F, Cl, SO_4	Metals	Bromide	Alkalinity	^{14}C
Lab	Waterloo	Waterloo	MDA	MDA	MDA	MDH	DNR	UMN
Sample container	500 ml HDPE	60 ml HDPE	250 ml plastic	250 ml plastic	250 ml plastic	125 ml plastic	500 ml plastic	30 gallon barrel
Head space	yes	yes	yes	yes	yes	yes	no	yes
Rinse	no	no	yes*	yes*	yes*	yes*	yes**	no
Filter	no	no	yes	yes	yes	yes	no	yes
Preservative	no	no	5 ml 10% H_2SO_4 (yellow cap)	no	2.5 ml 20% HNO_3 (red cap)	no	no	NH_4OH to pH 8.5
Refrigeration	no	no	yes	yes	yes	yes	yes, if not analyzed onsite	no
Shelf life	long	long	2–3 weeks	2–3 weeks	2–3 weeks	2–3 weeks	24–48 hours	years
Field duplicate	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	none
Field blank	none	none	1 for every 20***	1 for every 20***	1 for every 20***	1 for every 20***	none	none
Storage duplicate	yes	yes	no	no	no	no	no	no

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

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

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

Appendix B

Tritium values from precipitation and surface water

Samples were analyzed for enriched tritium by the University of Waterloo Environmental Isotope Laboratory for determination of recent tritium values. Samples came from precipitation composites collected at a Minnesota DNR MNgage climatology monitoring station in Maplewood (Twin Cities metropolitan area). Precipitation samples were composited over the course of 30-day periods between the seasons of spring and fall over the years 2012 through 2018.

For more information, contact the following.

County Atlas program page
(mndnr.gov/groundwatermapping)
Weather station information, MNgage program page
(https://climateapps.dnr.state.mn.us/HIDENsityEdit/HIDENweb.htm)

Appendix Table B-1: MNgage precipitation station enriched tritium results

Sample date range	Tritium (TU)	Analytical error	Sample type
05/21/2012–06/20/2012	8.7	0.7	Precipitation composite
09/30/2012–10/30/2012	6.7	0.7	Precipitation composite
05/09/2014–06/09/2014	7.0	0.7	Precipitation composite
10/01/2014–10/31/2014	6.7	0.7	Precipitation composite
05/01/2015–05/31/2015	5.3	0.6	Precipitation composite
08/17/2016–09/16/2016	8.3	0.8	Precipitation composite
04/01/2017–04/30/2017	8.1	0.7	Precipitation composite
09/06/2017–10/06/2017	6.5	0.6	Precipitation composite
10/03/2018–11/01/2018	3.7	0.5	Precipitation composite

Tritium age of historic groundwater samples

The groundwater atlas uses tritium data to assess the residence time of groundwater, which is then used to evaluate atlas pollution sensitivity models and recharge conditions of the aquifer. Data from other studies prior to the DNR project sample period (historic data) are used to inform our understanding of groundwater residence time where we lack current data.

The residence time is classified for the date or year the sample was collected. Historic tritium unit values change over time because of tritium's relatively short half-life of 12.32 years (Lucas and Unterweger, 2000). Historic data are classified according to Table B-2. For example, a sample collected in 2009 that had 9 TU is mixed tritium age. A sample collected in 2016 that had 9 TU is recent tritium age.

The Cold War era classification is a special case and implies that groundwater sampled for this atlas infiltrated into the ground in the 1960s. The Cold War era classification is only assigned to samples collected contemporaneously with this atlas (in 2017). All historic data (pre-2017) classified in earlier reports as *Cold War era* is now classified as *recent* tritium age.

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

	Sampling periods for tritium		
Tritium age	**2017**	**2013–2016**	**2012 or before**
Cold War era	>15 TU	NA	NA
Recent	≥8 to 15 TU	≥8 TU	≥10 TU
Mixed	>1 to <8 TU	>1 and <8 TU	>1 and <10 TU
Vintage	≤1 TU	≤1 TU	≤1 TU

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This information is available in alternative format on request.

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