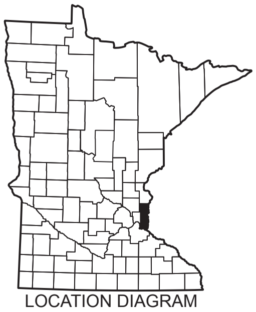
Groundwater Atlas of Washington County, Minnesota

County Atlas Series C-39, Part B



Report

To accompany these atlas components:

Plate 7, Water Chemistry

Plate 8, Hydrogeologic Cross Sections, A–A′ through G–G′

Plate 9, Hydrogeologic Cross Sections, H–H′ through L–L′

DEPARTMENT OF NATURAL RESOURCES

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County Atlas Program

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

Part A Geology was produced by the Minnesota Geological Survey (MGS) in 2016 and contains the following: Plate 1, Data-base Map; Plate 2, Bedrock Geology; Plate 3, Surficial Geology; Plate 4, Quaternary Stratigraphy; Plate 5, Sand Distribution Model; Plate 6, Bedrock Topography and Depth to Bedrock.

Part B Groundwater was produced by the Minnesota Department of Natural Resources (DNR), who expanded on the Part A information after its completion. The Part B components are described in the introduction of this report.

Explanations of the history and purpose of the program, atlas applications, map sales, user guides, and descriptions of the Part A and Part B components are available online.

Part A, Geology, MGS (http://www.mngs.umn.edu/county_atlas/countyatlas.htm)

Part B, Groundwater, DNR (mndnr.gov/groundwatermapping)

Technical Reference

Maps were compiled and generated in a geographic information system. Digital data products are available from the DNR County Atlas Program page (mndnr.gov/groundwatermapping).

Maps were prepared from DNR and other publicly available information. 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 MGS, Washington County Geologic Atlas, 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 gallon per day per foot = 0.1337 foot^2 per day

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

Report Contents

Report Figures

Report Tables

Plates (folded inserts)

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Groundwater Atlas of Washington County, Minnesota

By James A. Berg

Introduction

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

The purpose of this atlas is to illustrate the groundwater 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 decisions that take into account aquifer sensitivity, water quality, and sustainability.

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

Physical setting

Washington County is in the northern continental United States and is characterized with a cool, subhumid climate with a large temperature difference between summer and winter seasons. Average summer temperatures are approximately 70 degrees Fahrenheit June through August, and winter temperatures are approximately 18 degrees Fahrenheit December through February (NOAA, 2018). Average annual precipitation is approximately 32 inches, placing it in the upper statewide range of 20 to 36 inches.

The county is located in east-central Minnesota (Figure 1) with land use that is a mix of agricultural/rural, small towns, and suburban. The western portion is part of the Twin Cities metropolitan area. The population in 2017 was approximately 256,000 (U.S. Census Bureau, 2018).

It lies within the watersheds of the Mississippi (Twin Cities portion) and the Lower St. Croix rivers (Figure 2). The St. Croix River forms the eastern border and the Mississippi River forms the southern and southwestern border. With the exception of deeper aquifers, most of the county groundwater recharges within county boundaries because of the higher land surface elevations in the central portion of the county and the generally permeable nature of surficial deposits and shallow bedrock.

A wide range of geomorphic terrains include a relatively flat glacial lake plain in the northwest, hilly terrain in the center, and deeply incised river valleys in the east and southeast. Lakes are an important recreational and habitat resource in the northern two-thirds of the county.

Geology and physical hydrogeology (page 5)

This section 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).

The county is underlain by several buried sand and bedrock aquifers, making it one of the best areas in the state for groundwater availability. However, with the exception of the northwestern portion of the county, these aquifers tend to be well connected to the surface creating interaction between groundwater and surface water that increase the potential for pollution sensitivity. Two unique bedrock features have a major affect on aquitard integrity and contaminant transport: a large bedrock valley in the central and southern part and an upward faulted (horst) bedrock area in the southern part.

The water table (pages 5–7) in the eastern portion of the county flows east toward the St. Croix River, south toward the Mississippi River in the southern portion of the county, and west along the Ramsey and Anoka county boundaries. Local water-table flow is toward the major tributaries, ravines and lakes.

Water-table depths are classified into three major zones: 1) The northwest area with relatively shallow (0–20 feet) and uniform depths, 2) the center area with variable depths ranging from 0–40 feet over relatively short distances, and 3) the bluff and ravine areas in the east and southeast that are also variable with deep water tables (greater than 50 feet) resulting from high topographic relief and proximity to the major groundwater discharge areas of the Mississippi and St. Croix rivers.

Buried sand and bedrock aquifers (pages 9–24) show groundwater flow patterns resulting from the proximity of the county to two major river valleys: the Mississippi and St. Croix rivers. In general, groundwater flows outward in all directions from the center to the county borders.

Water chemistry (pages 25–33, plate 7)

Water chemistry 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.

Surface-water connections to groundwater were detected in the northeastern and central portions of the county from a relatively large number of groundwater samples. The evaporative isotopic signatures indicate a partial lake water source to aquifers. The stronger groundwater connections were associated with Big Marine, Otter (adjoining Anoka and Ramsey counties), Sunset, and White Bear lakes. Big Marine and White Bear are examples of deeper lakes with hydraulic connections to a range of underlying aquifers, from relatively shallow buried sand aquifers to the deeper Prairie du Chien and Jordan aquifers.

Chloride is a significant contaminant and is relatively widespread across the county in most of the aquifers. **Nitrate** was found relatively widespread across the county in both urban and rural settings. **Arsenic** is not a significant concern because Washington County does not have the type of geology that results in high concentrations of arsenic in groundwater. **Manganese** concentrations were generally found to be lower than the statewide averages for water-table and buried sand aquifers.

Carbon-14 residence times in bedrock aquifers reflected the wide range of groundwater conditions in the county, ranging from less than 100 to 25,000 years.

Pollution sensitivity (pages 34–53)

The pollution sensitivity of an aquifer is estimated based on the time it takes water to flow through various types and thicknesses of soils and geologic materials. Pollutants are assumed to travel with water at the same speed. The ratings are modeled with different methods for the 1) near surface materials and 2) the 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 34–36) ratings of the three general surficial geology areas can be broadly grouped as follows:

1. The northwest has fine-grained loamy New Ulm till with continuous areas of low sensitivity.
2. The St. Croix moraine occupies the majority of the county, from the northwest border ending on a diagonal line from St. Paul Park to Bayport. It has fine and coarse-grained sediment types with sensitivity ratings that range from low to high, and contains a few areas of karst.
3. The southeast contains shallow bedrock and sandy glacial sediment, has primarily high sensitivity, and contains areas of karst.

Buried sand and gravel aquifers (pages 37–48): All together, the large number of wells in these aquifers represent approximately 25 percent of all water use in the county. The highly variable geology results in pollution sensitivity ratings that range from very low to very high for each aquifer. The stratigraphically lower aquifers with higher sensitivity areas tend to be in the east and southeast.

Bedrock aquifers (pages 49–53): Thirty percent of the wells in the county were completed in the top of the bedrock. This shallow zone is used by wells from the top to the bottom of the bedrock stratigraphic section. The Prairie du Chien is the most commonly used, followed by the Jordan and Upper Tunnel City aquifers, and combinations of the St. Peter–Prairie du Chien aquifers and Prairie du Chien–Jordan aquifers. The pollution sensitivity of the bedrock aquifers varies widely across the county.

- The northwestern part has typically very low pollution sensitivity.
- The St. Croix moraine area is a complex mosaic of very low to very high pollution sensitivity.
- The St. Croix River valley and the southern part of the county commonly have extensive areas of very high sensitivity because of thin and/or sandy overlying unconsolidated sediment.
- Much of the Jordan aquifer is sensitive to contamination due to complicated groundwater pathways and lateral groundwater movement entering at the surface and flowing through hydraulically connected combinations of aquifers.

Hydrogeologic cross sections (page 54, plates 8 and 9)

Hydrogeologic cross sections illustrate important variations and patterns of groundwater flow direction and gradient, residence time, distribution of chemicals, and groundwater to surface-water connections. In addition, Washington County has some prominent geologic features such as deep and long buried bedrock valleys and a highly faulted southern zone that have major influences on hydrogeologic characteristics.

Aquifer characteristics and groundwater use (pages 55–64)

Aquifer characteristics and groundwater use 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.

Water use: The majority of the permitted water use is for municipal and other public water supply. This is drawn mainly from the Jordan aquifer, and to a lesser extent the Mt. Simon or Mt. Simon–Hinckley, or combinations of the Prairie du Chien and Jordan. The other most common categories are multiple use, industrial processing, and pollution containment.

Groundwater level monitoring and surface water connections: Four lakes and 1 stream were evaluated for groundwater to surface-water connections. Forest Lake appears to have a limited connection to groundwater. This lake appears to be underlain by relatively loamy New Ulm till limiting the amount of groundwater and lake-water seepage.

Big Marine, Oneka, and White Bear lakes have strong groundwater connections. These lakes are apparently underlain by sand aquifers and sandy loam aquitards and have a small watershed/lake area ratio. Big Marine and White Bear lakes have both flow through and discharge characteristics. A comparison of the lake and groundwater hydrographs supports a groundwater-dominated classification for all three lakes.

Brown's Creek is known to have shallow groundwater inflow due to its typically cool temperatures and ability to support trout. The downstream portion of the creek is fed by shallow buried sand and bedrock aquifers.

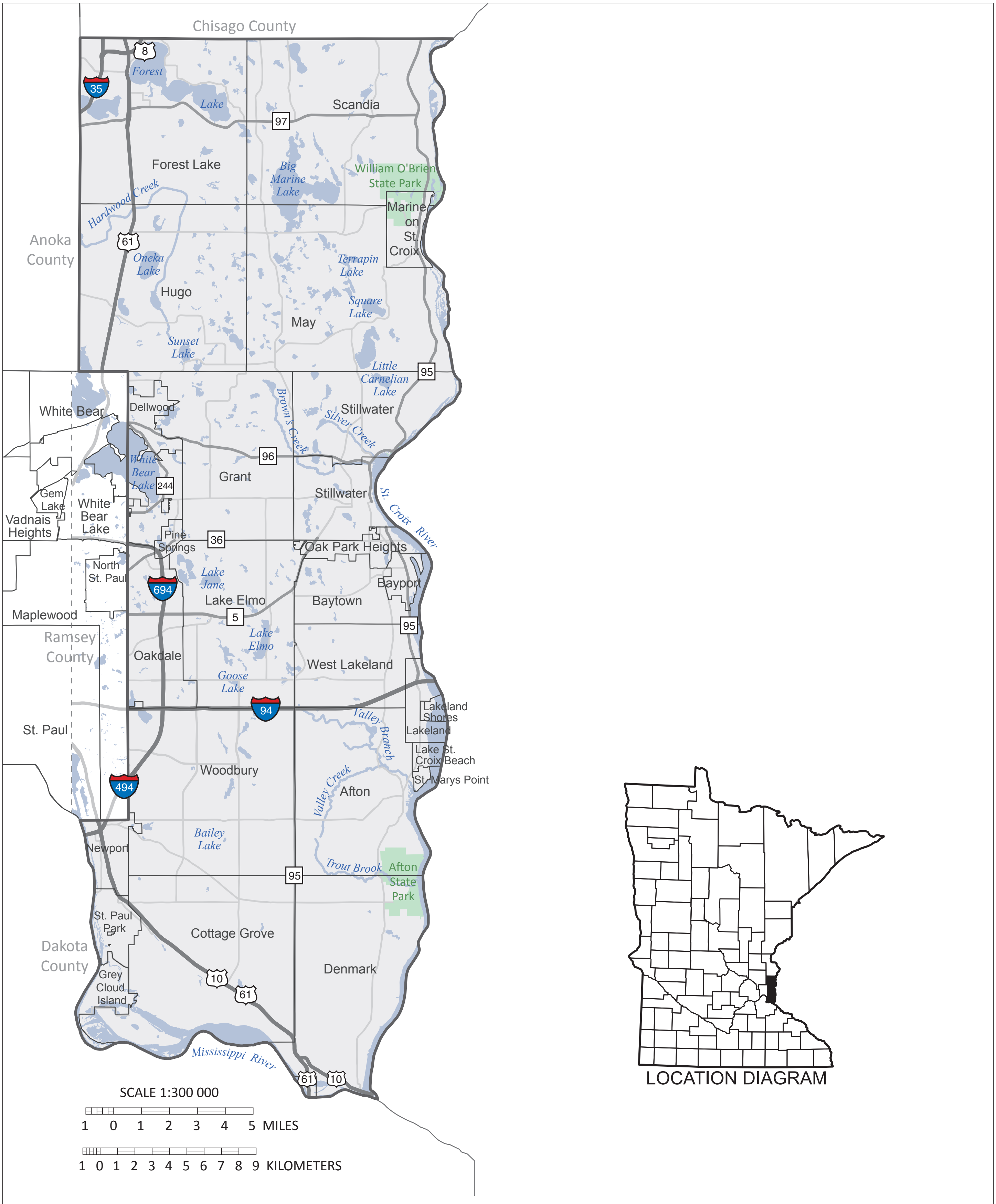


Figure 1. Washington County, Minnesota

Geology and physical hydrogeology

Surficial aquifers

The origin of the topography and surficial deposits of the county can be traced back to the advance and retreat of glacial ice that deposited fine-grained and coarse-grained sediments (Part A, Plate 3). The fine-grained sediments include a mixture of sand, silt, clay, and gravel referred to as diamicton or till. Coarser-grained sediments include glacial outwash that is commonly composed of sand and gravel, and shoreline or deltaic deposits of glacial lakes commonly composed of fine sand. When the glaciers eventually melted, large proglacial lakes formed and discharged enormous volumes of water and sediment through the present-day Mississippi and St. Croix river valleys.

The complex distribution of surficial sand and gravel is one of the most important geologic features controlling groundwater availability and the pollution sensitivity of underlying aquifers. Three major glacial events set the stage for the distribution of coarse and fine-grained sediment in this area.

The first event was an advance and retreat of Superior lobe glaciers from the northeast (Part A, Plate 3, Figure 2). These glacial episodes created the **St. Croix moraine** that dominates the topography of the central portion of the county. This moraine is an area of thick glacial sediment and higher land elevations that were created as the edge of the glacier stagnated in and around the current Twin Cities metropolitan area. The farthest extent of the Superior lobe advance (the Superior lobe ice margin) is mapped as an irregular diagonal line from St. Paul Park to the City of Bayport (Part A, Plate 3). To the southeast of that margin, surficial aquifers of Superior outwash origin are thin or unsaturated.

The second major event, the Des Moines lobe glaciation, advanced into the region from the northwest and into the county from the southwest as the Grantsburg sublobe. This sublobe advanced to the northeast over the St. Croix moraine, across the northwestern corner of present-day Washington County, and into Wisconsin. As this sublobe retreated, water from the melting glacial ice was trapped within the surrounding highlands of the St. Croix moraine, creating glacial Lake Anoka. Very fine to medium-grained sand accumulated in this glacial lake creating the sandy portion of the New Brighton Formation in the northwestern part of the county.

In the third event, the final melting of glacial ice caused the release of glacial meltwater from glacial Lake Agassiz in the western part of the state and glacial Lake Duluth in the east, releasing massive amounts of water to flow through the present-day Mississippi and St. Croix river valleys (Part A, Plate 3, Figure 4). The draining of these lakes deposited thick layers of sand and gravel in the form of terrace deposits along the Mississippi and St. Croix river valleys.

Water table

The water table is the surface between the unsaturated and saturated zones where water pressure equals atmospheric pressure. It occurs in aquifer and aquitard sediment across the entire county. The water table is shown in the figures as a static surface, but actually fluctuates over time (Figures 2 and 3).

The water table is generally a subdued expression of the surface topography. Flow is generally from local high elevation areas; through the underlying aquifers; then to streams, lakes, and wetlands.

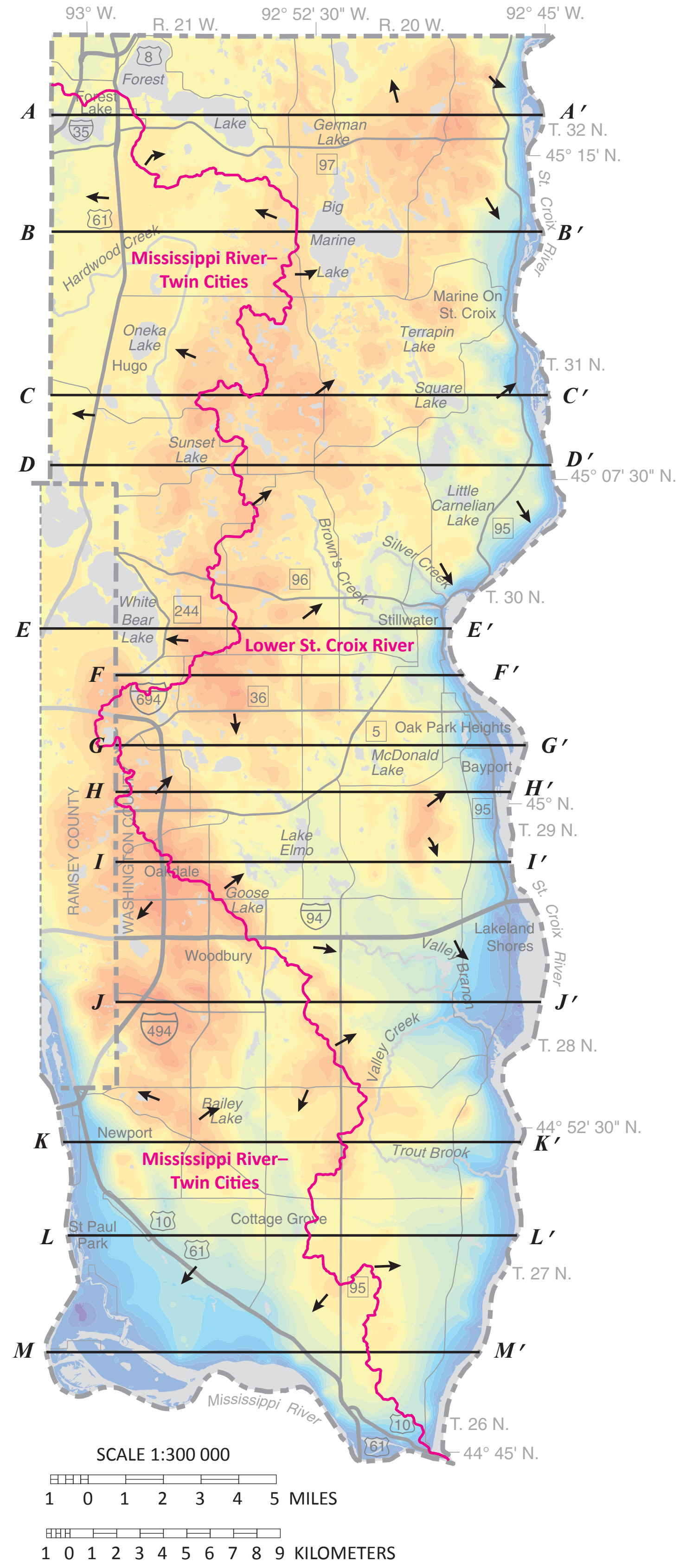
The water-table maps provide guidance for many applications, but additional site-specific information should be used to refine this information at local scales. Certain conditions affect the fluctuation of the water table and can create locally different results from the maps created for this atlas.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

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

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



Water-table elevation (feet)

🟧 >1050–1075
🟧 >1025–1050
🟧 >1000–1025
🟧 >975–1000
🟧 >950–975
🟨 >925–950
🟨 >900–925
🟩 >875–900
🟩 >850–875
🟩 >825–850
🟩 >800–825
🟦 >775–800
🟦 >750–775
🟦 >725–750
🟦 >700–725
🟦 >675–700
🟪 >650–675
🟪 >625–650

Symbols and labels

— Surface watershed boundary
← Groundwater flow direction
B —— *B′* Line of cross section (Part B)
Body of water

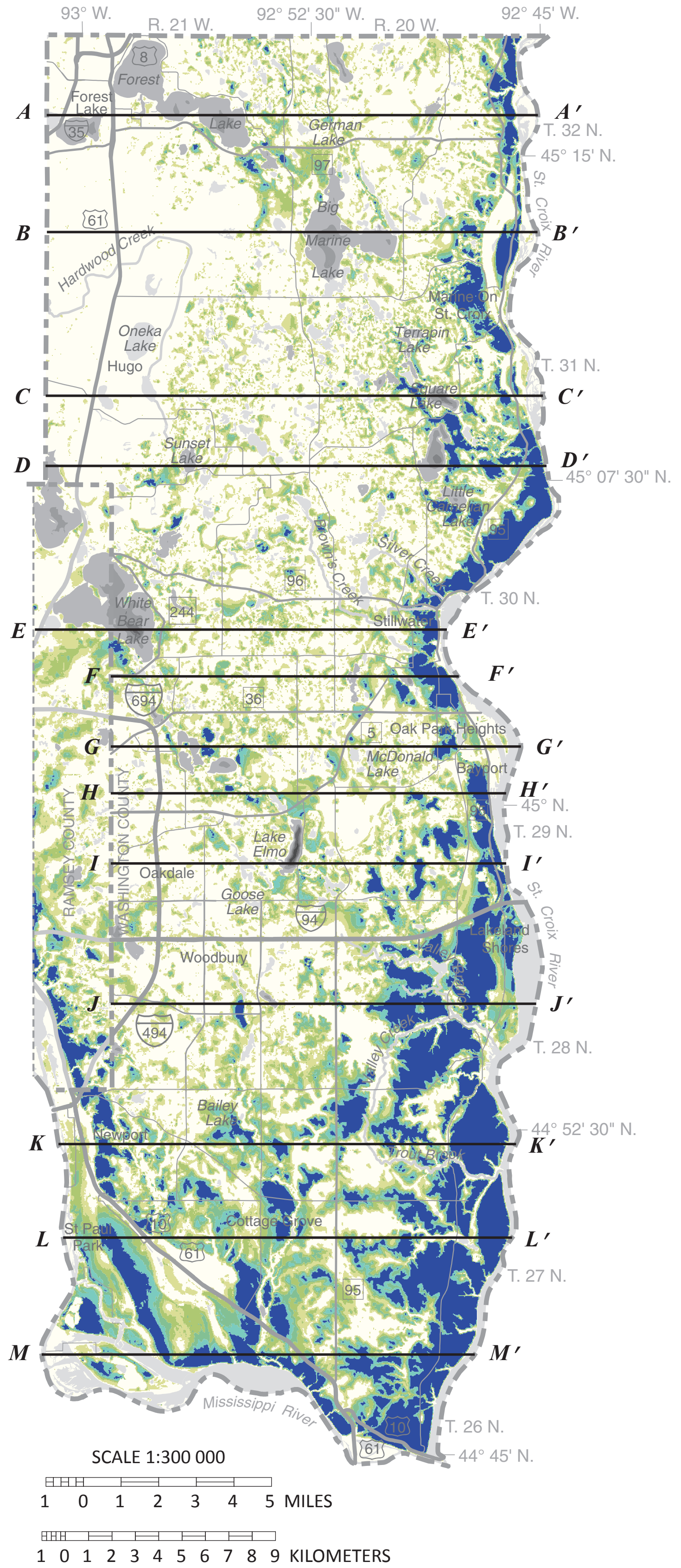
Figure 2. Water-table elevation and groundwater flow directions

Water-table elevations in the county cover a wide range of values. High elevations exist along the Mississippi–St. Croix watershed divide and portions of the northeast and southwest.

The lower elevations are along major rivers (Mississippi and St. Croix) and associated tributaries of the St. Croix River including Brown's Creek, Valley Creek, and Trout Brook.

The Cottage Grove ravine in the eastern parts of Cottage Grove and Woodbury is a large area of low water-table elevation that is not drained by a perennial stream.

The main groundwater flow directions are from the center to the east toward the St. Croix River, south or southwest toward the Mississippi River, or west toward Ramsey and Anoka counties. Local water-table flow is toward the major tributaries, lakes and other surface-water features.



Depth to water table (feet)

Depth of selected lakes (feet)

Symbols and labels

Figure 3. Depth to water table

Water-table depths in the county are split into three major zones:

1. The northwestern portion includes western Hugo and Forest Lake. This zone has relatively shallow and uniform depths to the water table (0 to 20 feet). The area was eroded by the advance of the Grantsburg sublobe, covered by the deposition of the New Ulm Formation, and then received deposition of lake sediments from glacial Lake Anoka.
2. The central portion extends from the eastern part of Hugo and Forest Lake south to the Superior lobe glacial margin. It has a hummocky and variable topography from the deposition of the St. Croix moraine. The water-table depths in the area are similarly variable with depths ranging from 0 to 40 feet over relatively short distances.
3. The bluff and ravine areas are approximately 1 to 3 miles from the St. Croix and Mississippi rivers and include areas south of the Superior lobe glacial margin. The high topographic relief creates large areas with a deep water table (greater than 50 feet) and are the major groundwater discharge areas.

Buried aquifers

Sand and gravel

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

The stratigraphic column in Figure 4 correlates the Part A geologic units with Part B hydrogeologic units of the glacial sequence. Part A geologic descriptions are generally classified as sand and gravel or till/lake clay. These are converted into the hydrogeologic descriptions of aquifer or aquitard, respectively.

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).
- Units of **undifferentiated sediment** are shown in **brown**.

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

Figure 4. Hydrostratigraphy of Quaternary unconsolidated sediment

*Note that two tills have the same names as two aquifers (sc and sl). These are differentiated on the cross sections by colored patterns for aquifers and solid grays for aquitards.

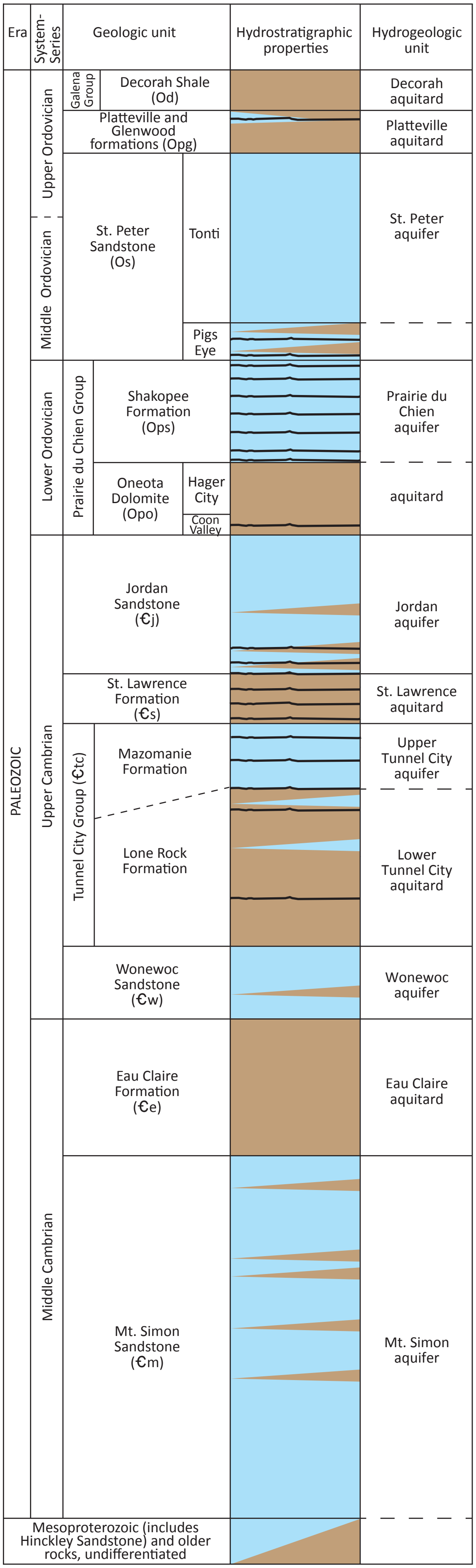
Bedrock aquifers

The bedrock formations of Washington County are part of regionally extensive, gently dipping layers of sandstone, shale, and carbonate rock that range from 30 to 280 feet in thickness (Figure 5 and Part A, Plate 2, Figure 1). These sedimentary rocks were originally deposited in mostly shallow marine settings during the Paleozoic era (Part A, Plate 2). Portions of these rocks endured periods of weathering while at or near the surface that affected the hydraulic properties. Cambrian-aged formations are primarily siliciclastic (sandstones and siltstones) and include in ascending order (oldest to youngest) the Mt. Simon Sandstone, Eau Claire Formation, Wonewoc Sandstone, Tunnel City Group (Lone Rock and Mazomanie formations), St. Lawrence Formation, and Jordan Sandstone. On the cross sections (Plates 8 and 9) the contact between the upper and lower Tunnel City Group is approximate. The Mazomanie Formation (Upper Tunnel City aquifer) is shown as 100 feet thick in the northern part of the county and thins to approximately 25 feet thick in the southern part (Part A, Plate 2).

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

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

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



🟦 Relatively high permeability (aquifer)

🟫 Relatively low permeability (except for fractures, aquitard)

〰 High permeability bedding fracture known to be common

— — Well often includes parts of immediately underlying units

Figure 5. Bedrock stratigraphy and hydrostratigraphy

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

Potentiometric surfaces

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 groundwater-level elevation maps show changes in water levels similar to how topographic maps show changes in 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. The 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 County Well Index (CWI), measurements made by DNR staff, and river elevation points along the major rivers and streams. The CWI records represent various climatic and seasonal conditions from the 1950s to 2016. This data variability creates some uncertainty in potentiometric surface elevations. River and stream elevation points are included because these features can be groundwater discharge locations.

At least three characteristic flow patterns are evident in the potentiometric surface maps for buried sand and bedrock (Figures 6 through 19).

1. In the north and northwest groundwater tends to flow northwest and westerly toward the Rice Creek Chain of Lakes (Anoka County) and northerly toward the south-central Chisago County lakes. These types of flow pathways are shown for the mapped buried sand aquifers (Figures 6 through 12), with the exception of the sp aquifer. In addition, in the northern portion of the Upper Tunnel City aquifer groundwater flows to the north (Figure 17).
2. In the eastern part of the county, easterly flow is shown for all of the aquifers (Figures 8 through 19) with the exception of the upper two buried sand aquifers (sl and sc).
3. In the southern part of the county southerly flow toward the Mississippi River is shown for the Prairie du Chien, Jordan, and Upper Tunnel City aquifers (Figures 15 through 17) and southwest for the St. Peter, Prairie du Chien, and Jordan aquifers (Figures 14 through 16).

Figure 6. Potentiometric surface of the sl aquifer

Groundwater flow diverges westerly toward the Rice Creek Chain of Lakes (Anoka County) and northerly toward the south-central Chisago County lakes.

Figure 7. Potentiometric surface of the sc aquifer

Similar to the overlying sl aquifer, groundwater flow diverges west toward the Rice Creek Chain of Lakes (Anoka County) and northerly toward the south-central Chisago County lakes. In addition, local flow is southwest toward Bald Eagle and White Bear lakes.

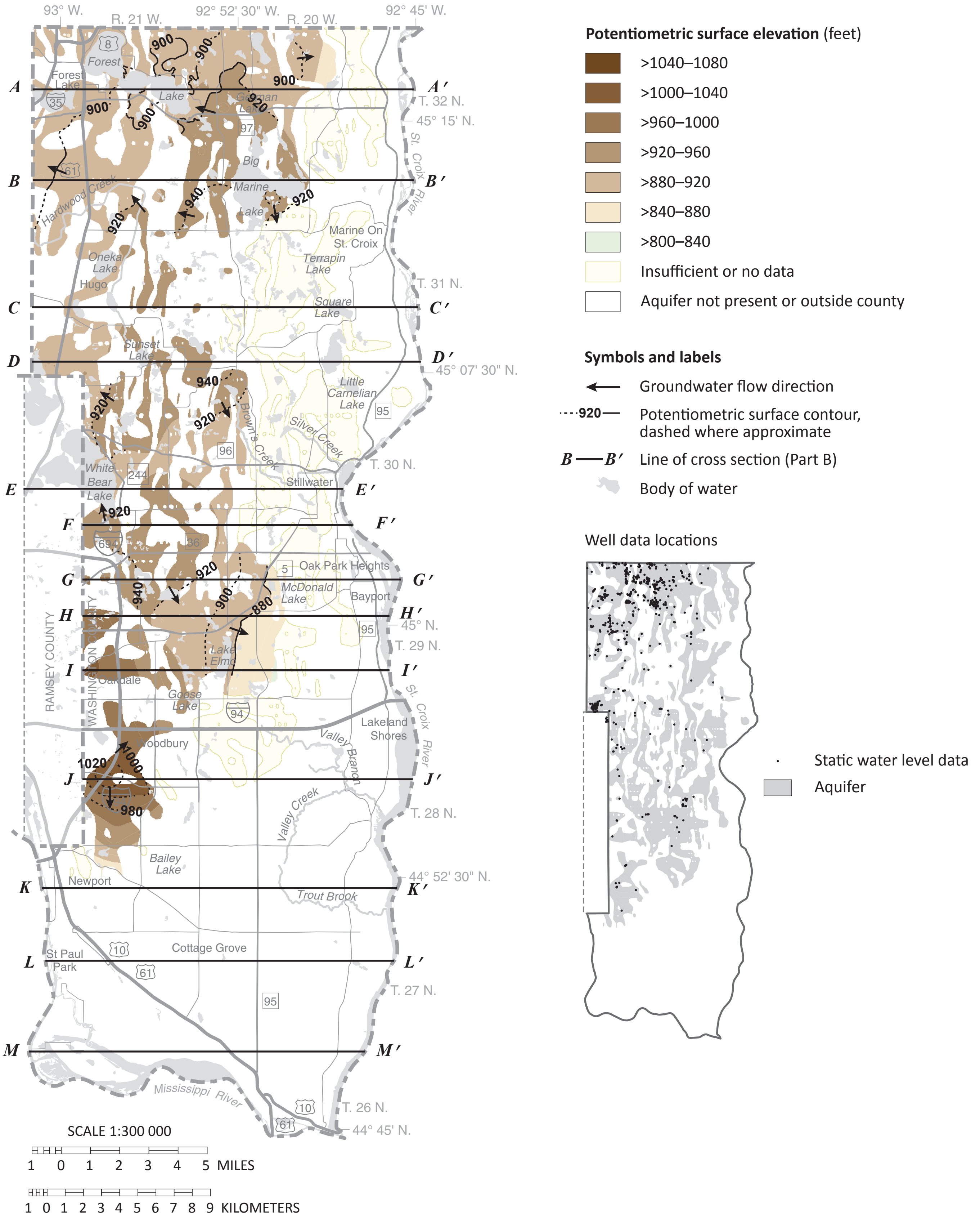


Figure 8. Potentiometric surface of the se aquifer

Groundwater flow radiates in all directions from an elongated high area that extends from southern Woodbury to west of Big Marine Lake.

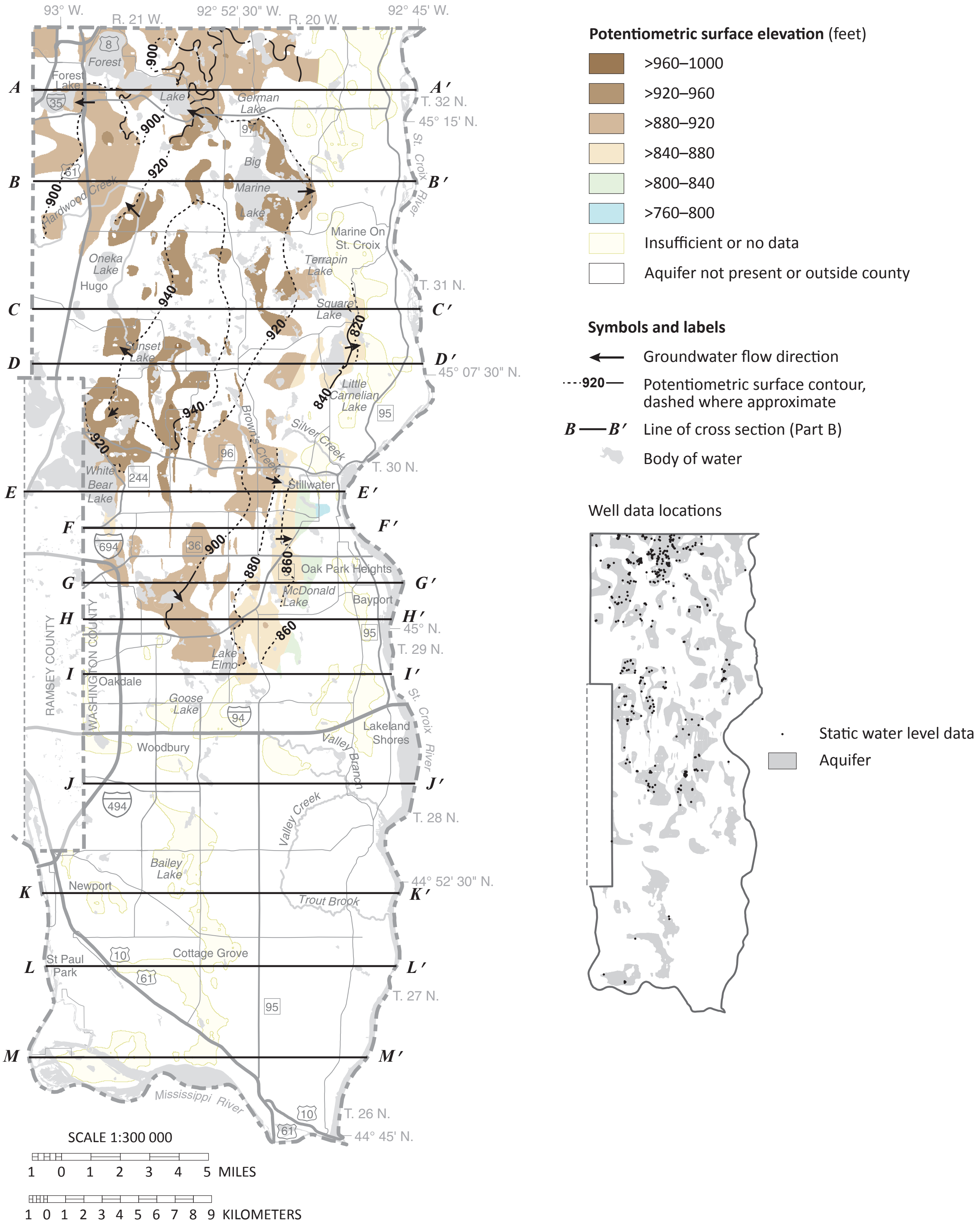


Figure 9. Potentiometric surface of the s1 aquifer

Groundwater flow radiates in all directions from an elongated high area that extends from east of White Bear Lake north to west of Big Marine Lake.

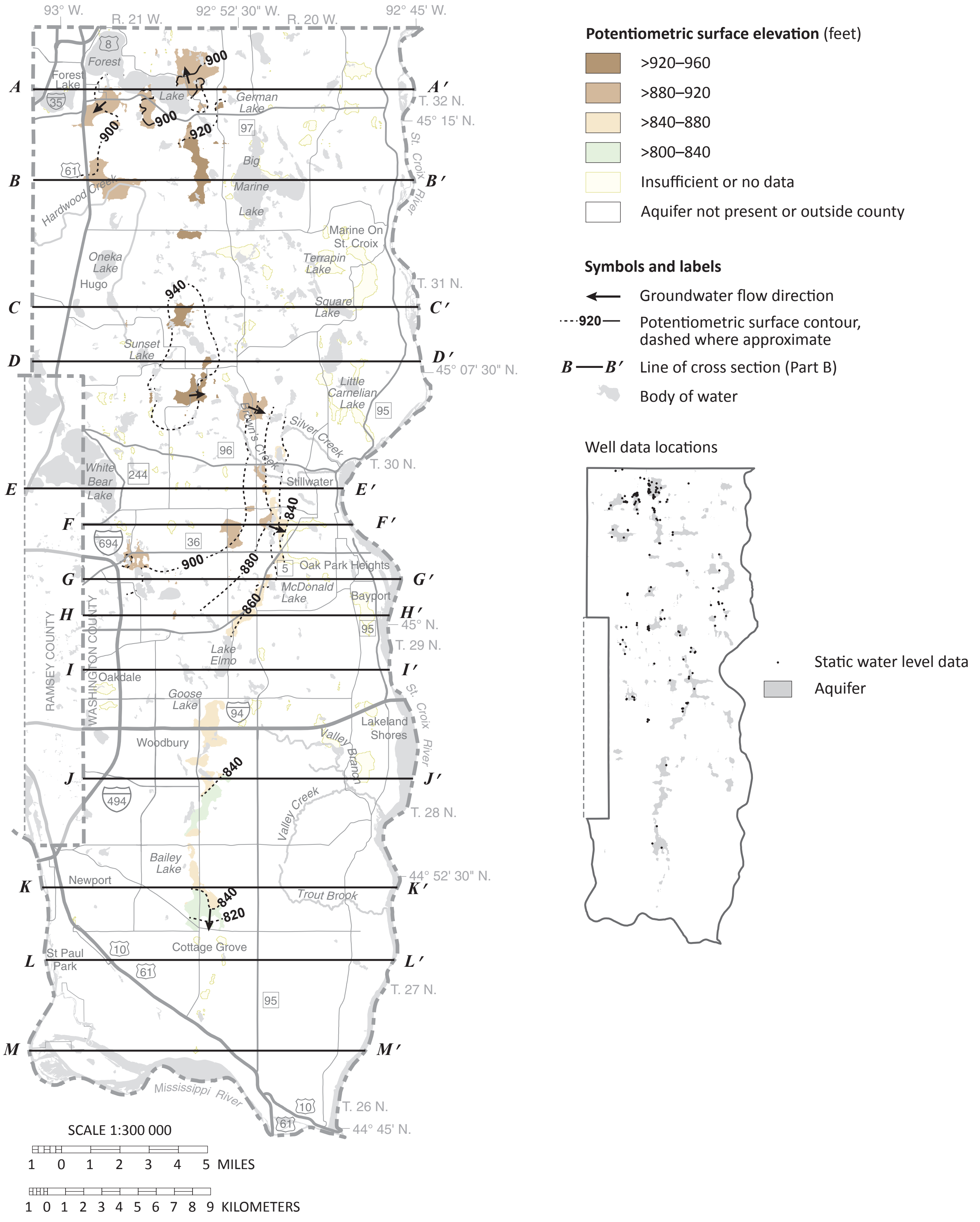


Figure 10. Potentiometric surface of the s2 aquifer

The main groundwater flow directions are northwest and east.

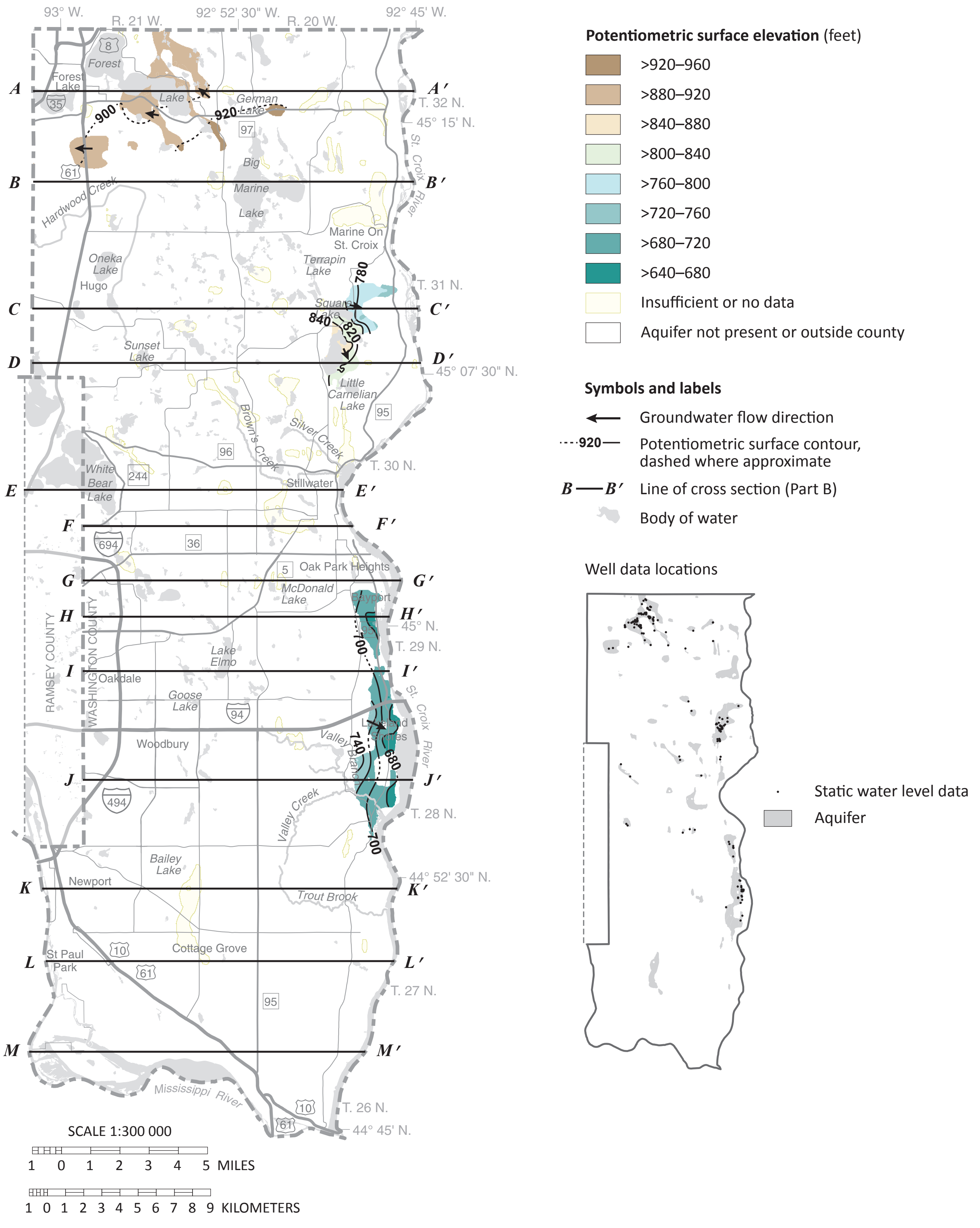


Figure 11. Potentiometric surface of the sx aquifer

Similar to the overlying s2 aquifer, the main groundwater flow directions are northwest and east.

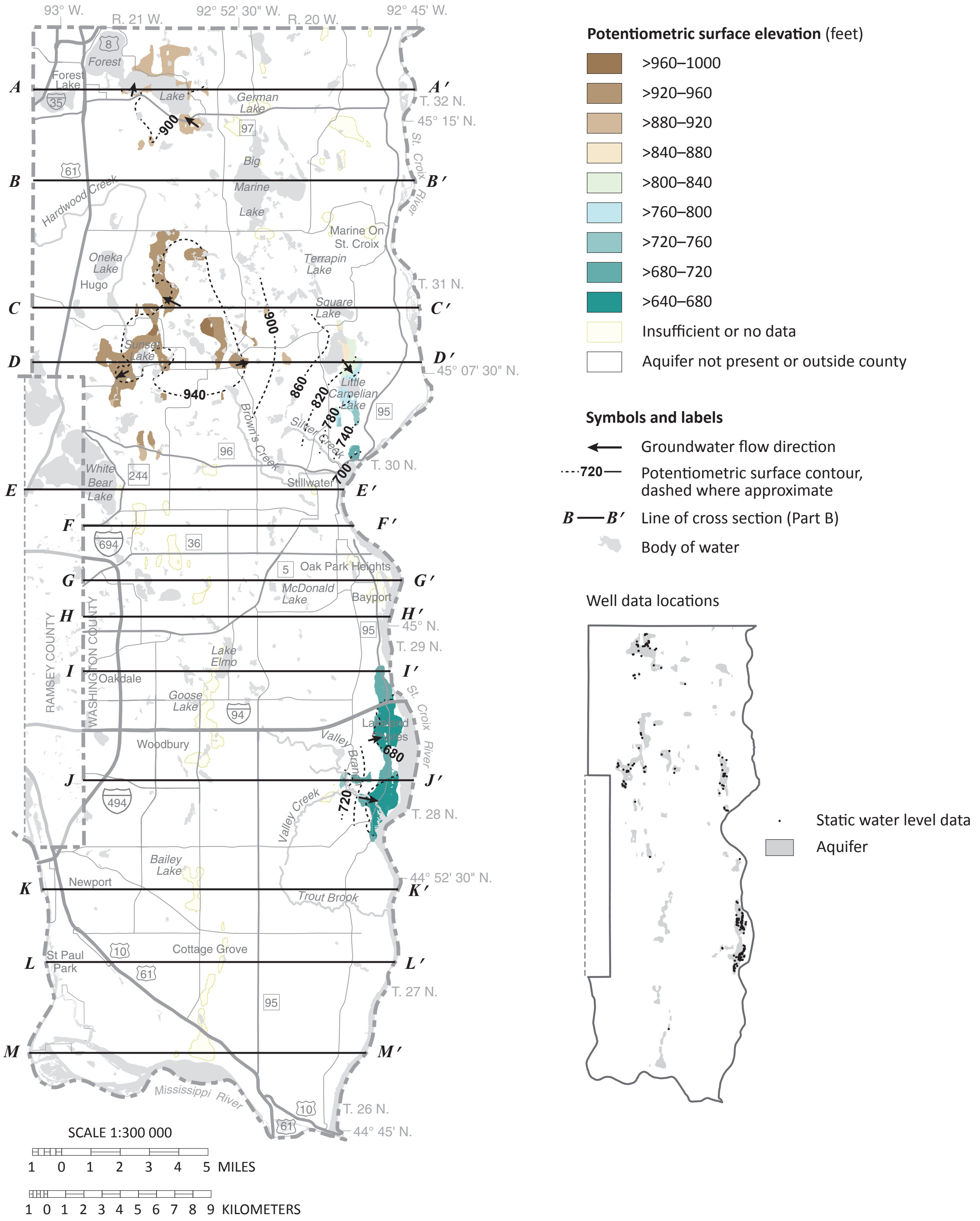


Figure 12. Potentiometric surface of the s3 aquifer

Similar to the overlying s2 and sx aquifers, the main groundwater flow directions are northwest and east.

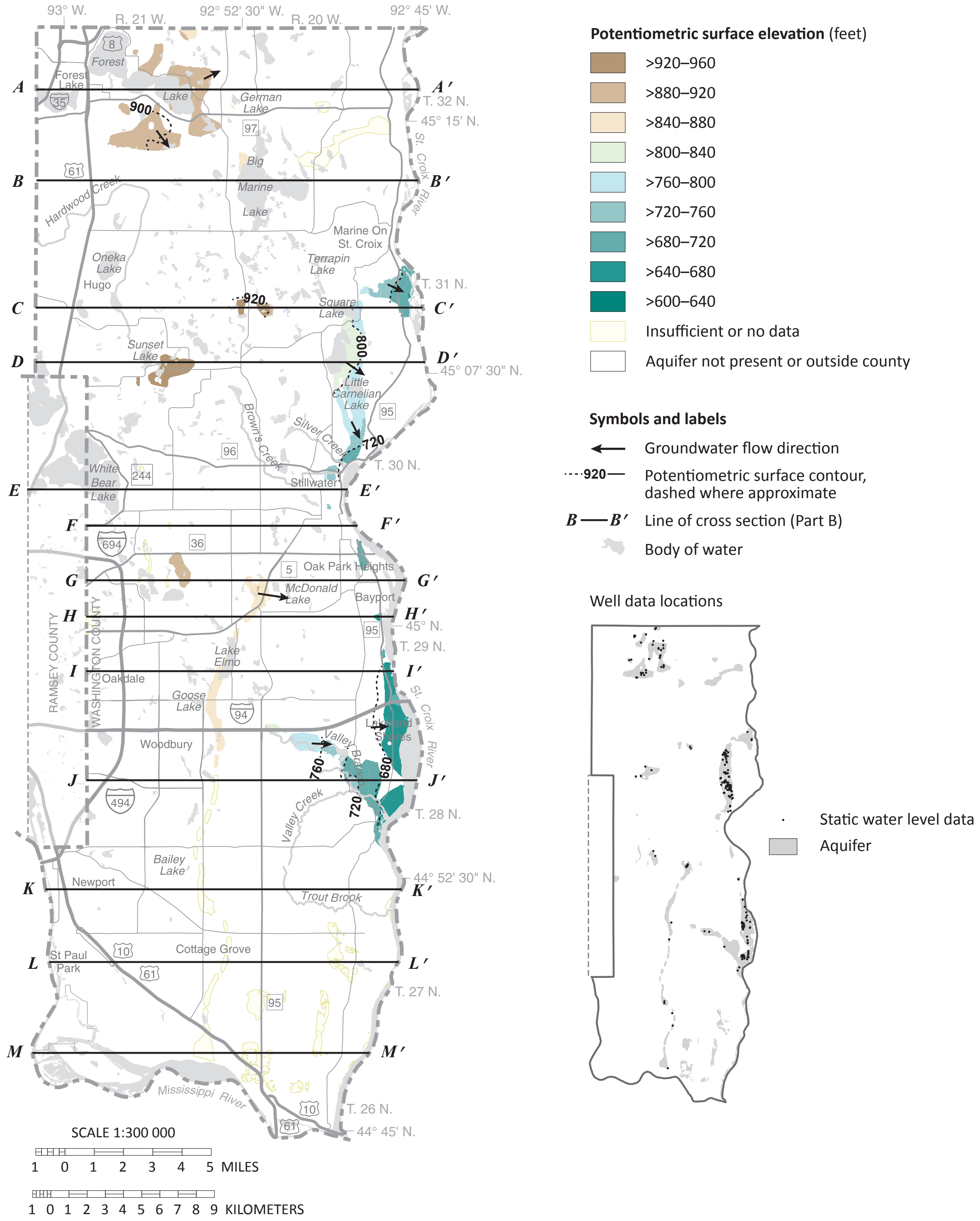


Figure 13. Potentiometric surface of the sp aquifer

The main groundwater flow direction is east.

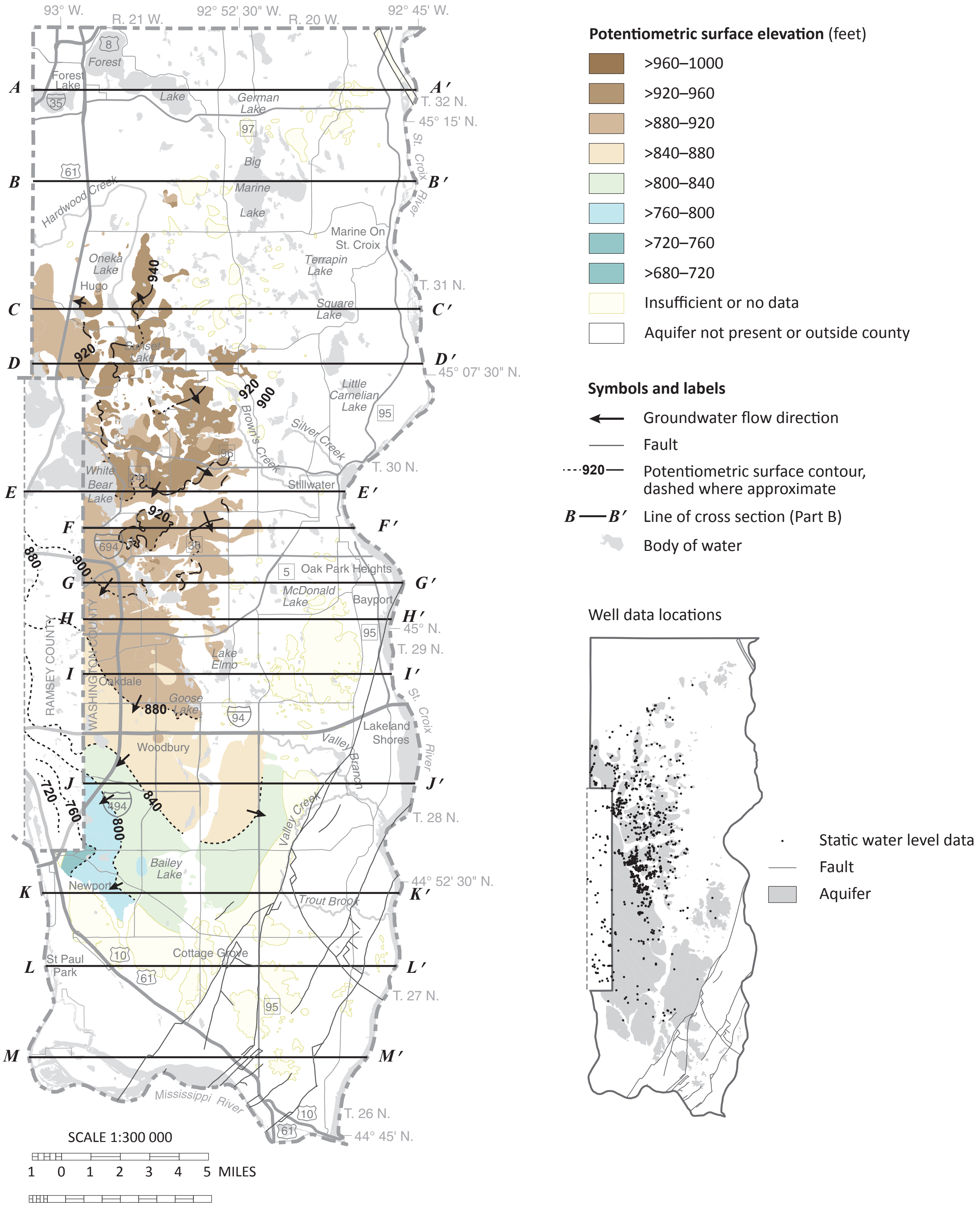


Figure 14. Potentiometric surface of the St. Peter aquifer

Groundwater flows in all directions from an elongated north-south high area in the west-central portion of the county.

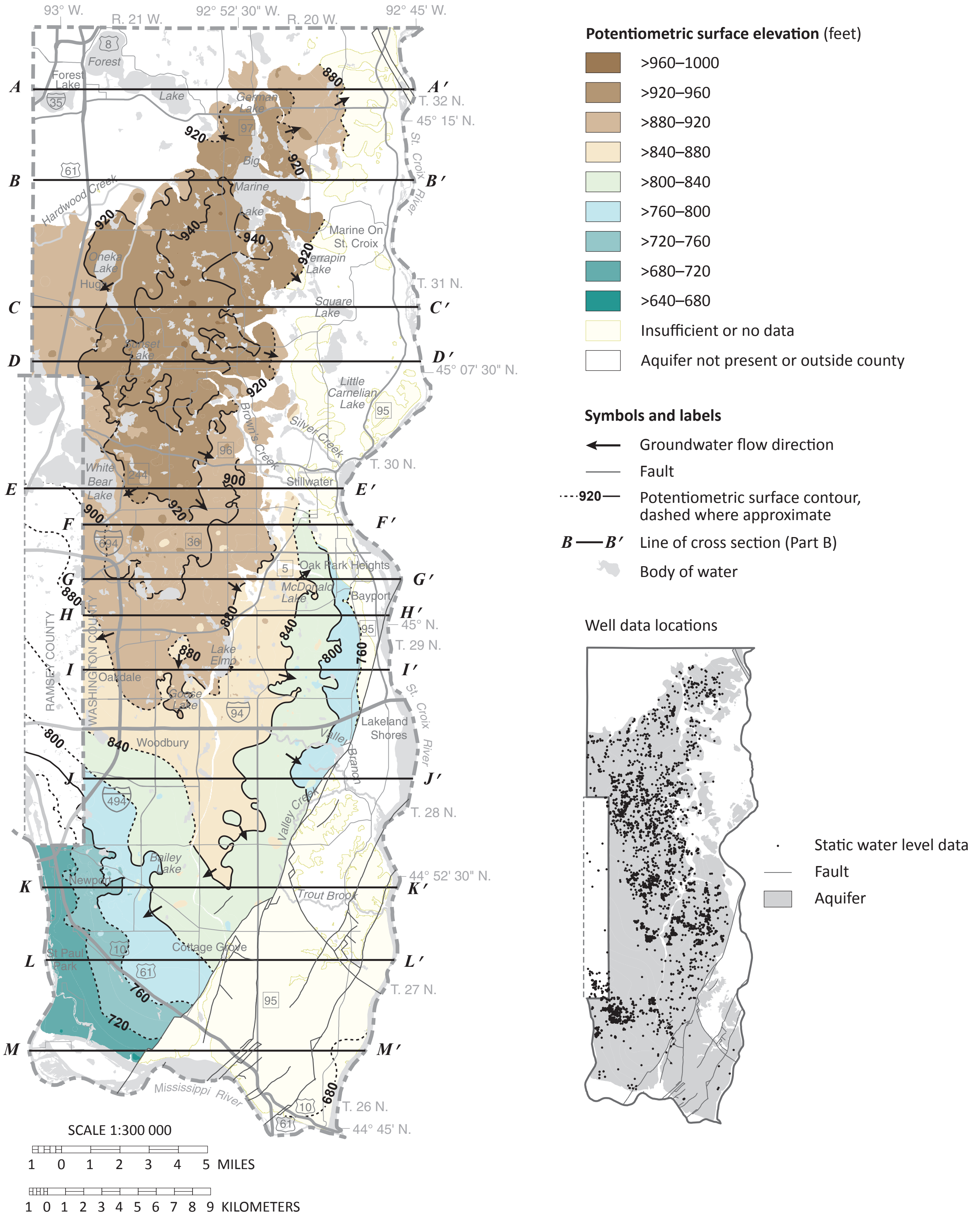


Figure 15. Potentiometric surface of the Prairie du Chien aquifer

Groundwater flows in all directions from an elongated north-south high area in the west-central portion of the county.

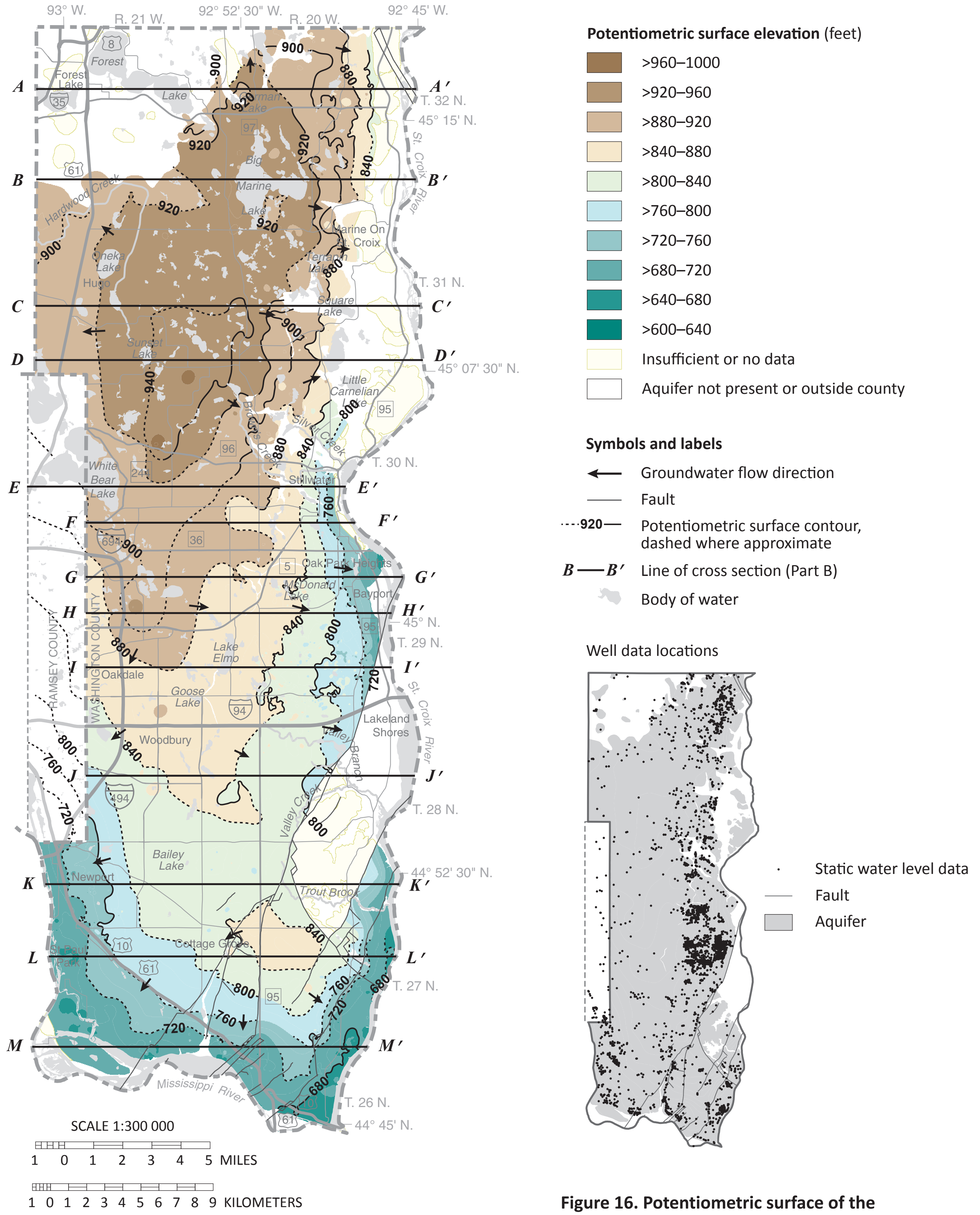


Figure 16. Potentiometric surface of the Jordan aquifer

Groundwater flows in all directions from an elongated north-south high area in the west-central portion of the county. Groundwater flow directions in the southeastern part of the county are complex due to faulting.

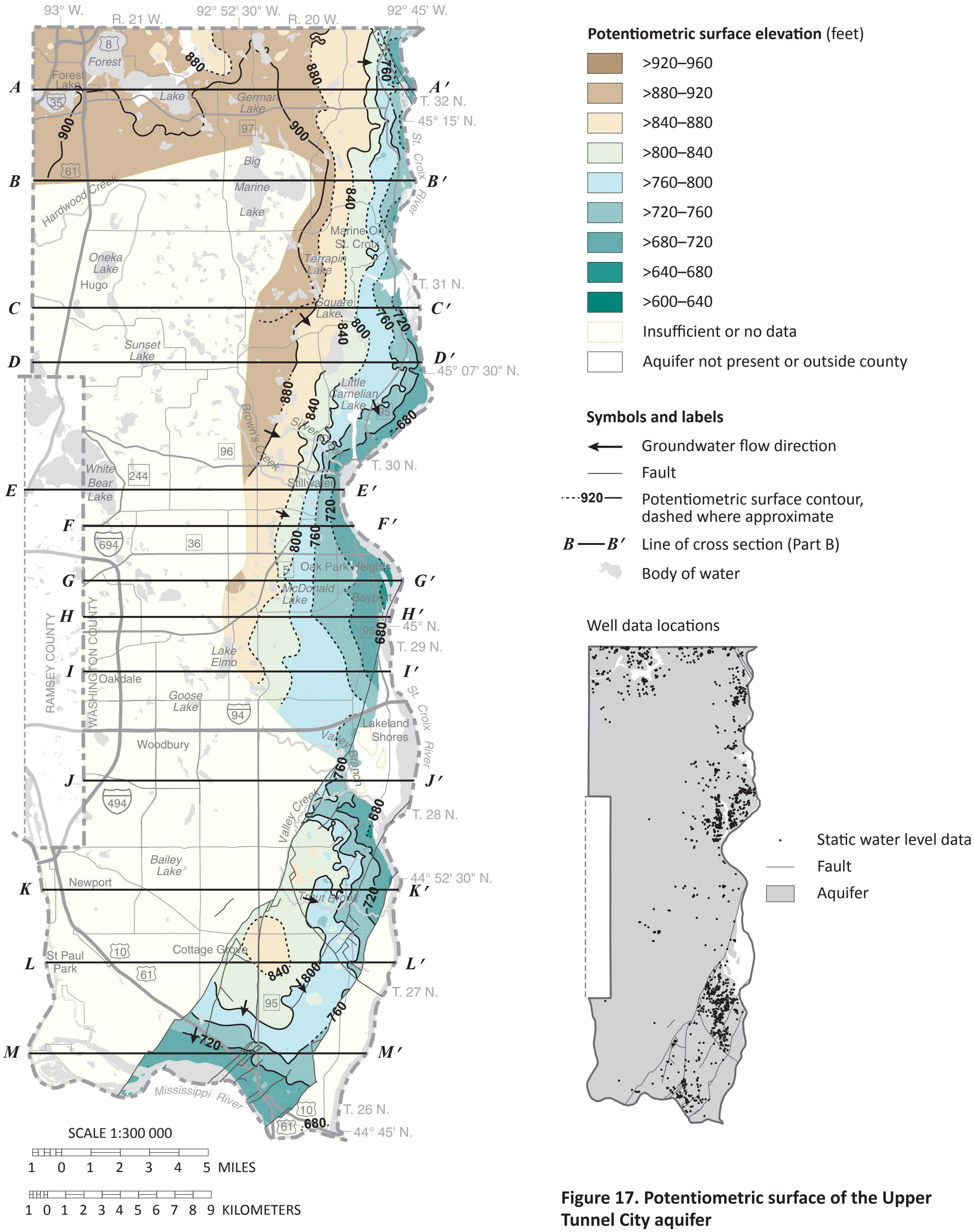


Figure 17. Potentiometric surface of the Upper Tunnel City aquifer

Groundwater flows in all directions from a broad high area in the northern portion of the county. In the southeastern faulted area, groundwater flows southwest and northeast.

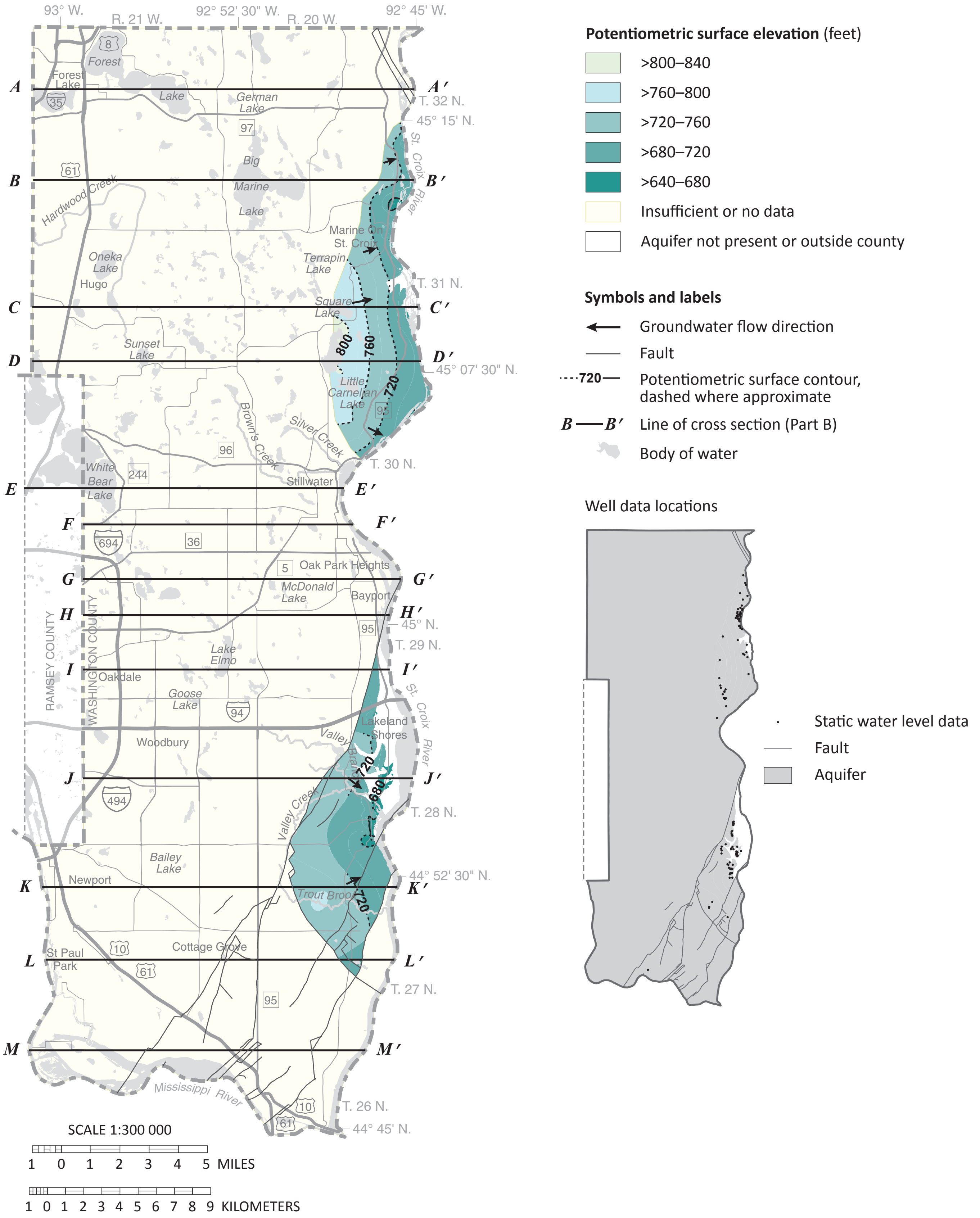


Figure 18. Potentiometric surface of the Wonewoc aquifer

Groundwater flow is east toward the St. Croix River.

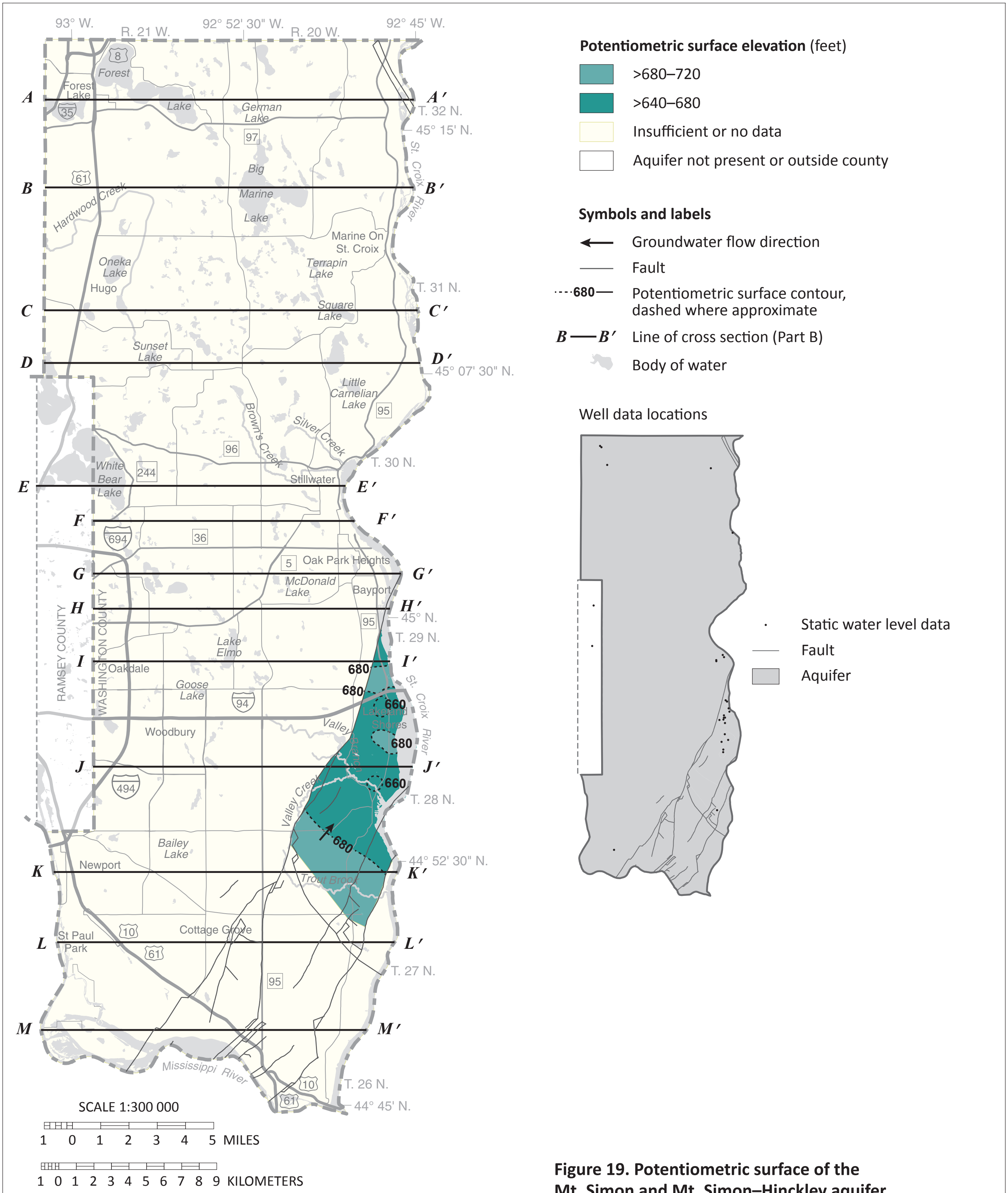


Figure 19. Potentiometric surface of the Mt. Simon and Mt. Simon–Hinckley aquifer

Local groundwater flow in this small faulted portion of the county appears to be controlled more by local pumping than by regional groundwater flow directions.

Water chemistry (Plate 7)

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

- Groundwater **recharged** 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 **chemical elements** can indicate areas where groundwater consumption is a potential concern to human health.

Water sampling

Wells were selected based on their aquifer characteristics and distribution and were collected according to the protocols outlined in Appendix A. Chemical data from well-water samples were used along with physical measurements (static water level and aquifer tests) to understand water movement.

An ideal well-sampling network for the atlas is evenly distributed across the county, includes populated areas, and targets surface water and groundwater interaction around lakes and larger rivers. Approximately 1000 well owners were contacted and approximately 30 percent gave permission for sampling.

The water chemistry data set used for Washington County included 90 wells sampled for this atlas by DNR along with many historical water samples that were incorporated into the interpretations of this report (Plate 7). The total of 355 groundwater samples from wells included: 90 DNR, 191 Minnesota Department of Health (MDH), 37 US Geological Survey (USGS), 5 USGS and MDH, 9 Minnesota Pollution Control Agency (MPCA), 2 MGS, 2 University of Minnesota, and 19 Emmons and Oliver Resources (EOR). Other samples included: 15 lake samples USGS or MDH, 1 river sample from MDH, and 10 spring samples from the University of Minnesota.

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 (Kendall and Doctor, 2003). Oxygen and hydrogen each have two main stable isotopes: ^{18}O and ^{16}O, and ^{2}H and ^{1}H. The different mass of the isotopes causes each to evaporate at different rates, 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.

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

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

Definition of delta (δ)

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

Recharge results

County results are compared to the global meteoric water line, which was developed from precipitation data from around the world (Craig, 1961). The majority of the Washington County groundwater samples plot along the meteoric water line, in the center and left portions of the stable isotope graph (Figure 20). This suggests sources from precipitation (rain and snow melt) infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies for these samples. A relatively large number of samples (30) had evaporative signatures throughout the county and adjoining areas to the west. The very southern and northwest portions did not match this trend. Lakes in the northwest are more hydraulically isolated from underlying aquifers by the relative low permeability of the New Ulm till (Qnt) in that part of the county. The lack of evaporative signature water in the south is probably due to the lack of surface-water bodies in that area.

Water samples with evaporative signatures were further divided based on higher or lower evaporative signatures (Figures 20 and 21). In addition, the approximate extent of the evaporative signature areas are shown using data in all aquifers. The stronger evaporative signatures were associated with Big Marine, Otter (Anoka and Ramsey counties), White Bear (Ramsey and Washington counties), and Sunset lakes. The areas around the larger lakes were intensively sampled for stable isotopes through the combination of DNR, MDH, and USGS projects. Big Marine and White Bear are examples of deeper lakes with hydraulic connections to a range of underlying aquifers from relatively shallow buried sand aquifers to the deeper Jordan aquifer. On the other hand, Forest and Bald Eagle are shallower lakes that are relatively isolated from underlying aquifers due to the underlying New Ulm till.

The presence of evaporative signatures in groundwater samples does not provide any information regarding the timing of that groundwater movement. Minnesota lakes have existed for a very long time from a human cultural and life span point of view. The lake water in underlying aquifers can be very old according to samples that were analyzed for both stable isotopes and residence time indicators including tritium and carbon-14 (Berg, 2011).

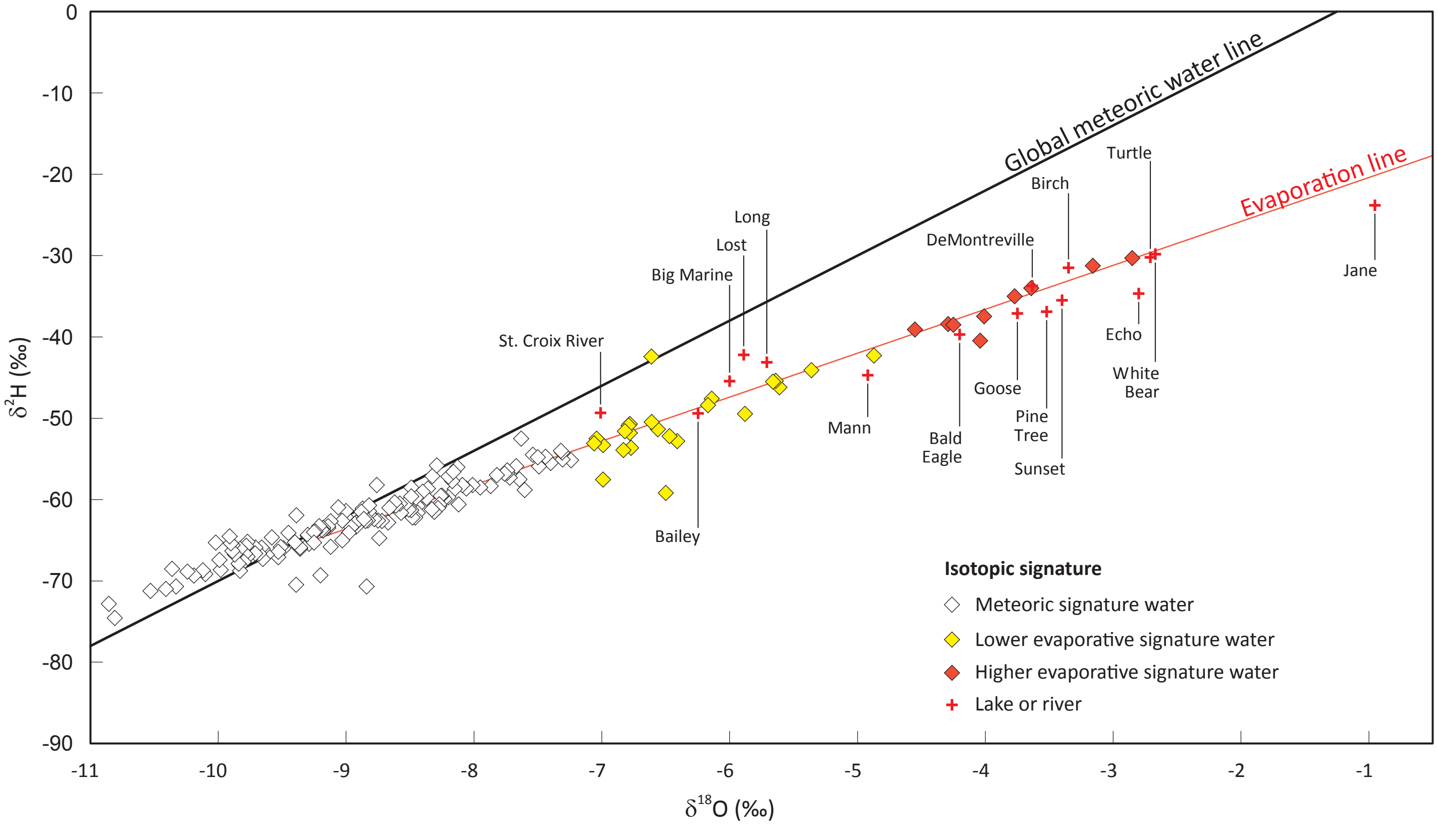


Figure 20. Graph of stable isotope values from water samples

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

The evaporation line represents groundwater recharged partially from surface water. The approximate extent of the evaporative signature groundwater is shown on Figure 21.

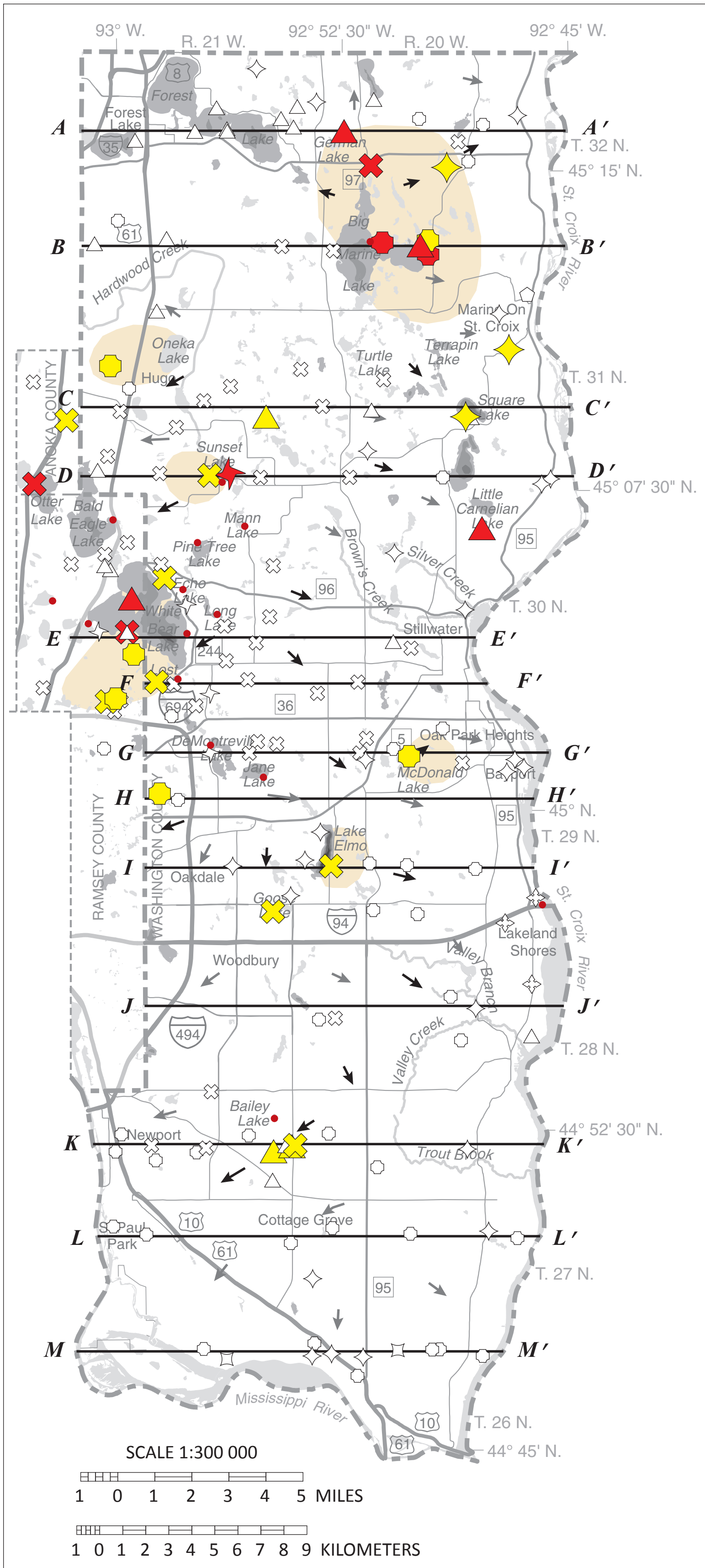


Figure 21. Stable isotope characteristics of groundwater samples

Most groundwater samples collected in the county originated as direct infiltration of precipitation. However, many samples from the central and northeastern part of the county have evaporative signatures indicating some of the water in these samples is recharged from nearby lakes.

Samples with an evaporative signature are shown with larger symbols.

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 (^3H) measured in the samples. Although tritium is a naturally occurring isotope of hydrogen, atmospheric concentrations greatly increased from atmospheric testing of nuclear weapons between 1953 and 1963 (e.g., 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).

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 can be used to estimate groundwater residence time ranging from 100 to greater than 40,000 years (Alexander and Alexander, 1989).

A total of 10 samples were collected for this study and were combined with 12 samples from previous studies. Carbon-14 residence times ranged from less than 100 years to 25,000 years. These data are reviewed in more detail in the hydrogeologic cross section descriptions on Plate 8 and 9.

Inorganic chemistry of groundwater

Water begins dissolving minerals in the soil, sediment, and bedrock as soon as precipitation infiltrates the soil layer and becomes groundwater. Water chemistry is used to characterize changes as water moves deeper. Water quality evaluations describe contaminants that are potentially harmful (natural or anthropogenic) or that affect aesthetics (hardness, taste, odor, color). The following guidelines are used in this atlas.

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 which has been promulgated under rule.

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

Results of water sample analysis are presented for inorganic chemistry, including the major cations and major anions, reported in units of parts per million (ppm).

Trace elements such as arsenic and manganese are typically reported in units of parts per billion (ppb). The following chemicals are naturally occurring. Some are harmful at elevated levels and some can be elevated by anthropogenic activities.

- **Calcium, magnesium, and sodium cations and bicarbonate anions** are dissolved out of the glacial sediment and bedrock by groundwater. The calcium, magnesium, and bicarbonate constituents are derived from limestone and dolomite bedrock sources (Hem, 1985) and are common in groundwater in glacial sediment aquifers. Sodium is often present in deep aquifers or at mineral interfaces. As groundwater moves through aquifer systems, calcium and magnesium ions are exchanged for sodium ions (Hounslow, 1995).
- **Sulfate** is largely naturally occurring. High concentrations in groundwater can negatively affect taste and may act as a laxative (SMCL 250 ppm).
- **Chloride** can occur naturally from deep sources such as residual brine, or it may come from road salts, water softener salts, and fertilizers (SMCL 250 ppm). Chloride is considered elevated if concentrations are greater than or equal to 5 ppm. It is considered anthropogenic if chloride/bromide ratios are greater than or equal to 250 (Davis and others, 1998; Panno and others, 2006).
- **Nitrate-nitrogen (nitrate)** can occur naturally at low concentrations but elevated concentrations (greater than or equal to 1 ppm) are typically from fertilizer and animal or human waste (MDH, 1998; Wilson, 2012). 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. The MCL and HRL for nitrate is 10 ppm.
- **Arsenic** is a naturally occurring element that has been linked to negative health effects, including cancer. The MDH advises domestic well owners to treat drinking water if arsenic values equal or exceed method reporting limits (MDH, 2018a). Current science cannot predict which wells will have high arsenic concentrations, therefore newly constructed wells are tested for arsenic if they are used for drinking water (Minnesota Administrative Rules 4725.5650, 2008). The EPA MCL is 10 ppb; the MCLG is zero.

  The factors affecting elevated arsenic concentrations in groundwater are not completely understood. There is a strong correlation with glacial sediments derived from rocks northwest of Minnesota, from the Riding Mountain provenance (Erickson and Barnes, 2005a). High arsenic concentrations are caused by naturally occurring arsenic-bearing minerals that are 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 are increased in wells that have short-screened sections near the boundary of an aquifer and aquitard (Erickson and Barnes, 2005a; McMahon, 2001).
- **Manganese** is a naturally occurring element that is beneficial to humans at low levels, but high levels may harm the nervous system. The HBV for manganese is 100 ppb (MDH, 2018b). In addition to health effects, elevated manganese concentrations (greater than 50 ppb) can cause negative secondary effects such as poor taste, odor, and water discoloration (stained laundry and plumbing fixtures).

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

Results

Chemicals in groundwater can occur naturally or can originate 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.

Chloride (Figure 22)

Chloride is a significant contaminant in Washington County. Of a total 254 well and spring samples analyzed for chloride, 165 (65 percent) had concentrations greater than or equal to 5 ppm (includes 11 unknown source due to lack of bromide data). These elevated occurrences were relatively widespread across the county in the ss aquifer and most of the buried sand aquifers (se, s1, s2, sp, and su). Elevated chloride was also found in bedrock aquifers including: St. Peter, Prairie du Chien, Jordan, St. Lawrence, Upper Tunnel City, and Upper Tunnel City–Wonewoc. Five elevated chloride samples may be from upward migration from deep natural sources through faulted and fractured bedrock since these samples were collected in the southeastern faulted area.

Nitrate (Figure 23)

Of the 261 well and spring samples analyzed for nitrate, 95 (36 percent) had elevated concentrations (greater than or equal to 1 ppm). Only 7 of the 261 (3 percent) were at or above the MCL of 10 ppm. The elevated occurrences of nitrate are relatively widespread across the county in the ss, s1, s3, sp, and su buried sand aquifers and in bedrock aquifers including: St. Peter, Prairie du Chien, Jordan, St. Lawrence, Upper Tunnel City, and Upper Tunnel City–Wonewoc. Samples with elevated nitrate concentrations occurred in urban and rural settings.

In 2014–2015 the Minnesota Department of Agriculture conducted a well sampling project for nitrates in the southern two townships of the county (Cottage Grove and Denmark). Of the 441 wells sampled, 15 percent had values greater than or equal to the 10 ppm MCL (MDA, 2017).

Arsenic

In general, Washington County does not have the type of geology that results in high concentrations of arsenic in groundwater. Of the 165 samples analyzed for arsenic, 82 (50 percent) exceeded the method detection limits (0.1 and 1 ppb). However, only one of those samples exceeded the MCL (10 ppb) and 24 were considered elevated (greater than or equal to 2 ppb) as labeled on Plate 7.

Manganese

Of the 197 samples analyzed for manganese in the county, 43 (22 percent) were greater than or equal to the HBV of 100 ppb (Plate 7). 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).

Piper diagram: major cations and anions (Figure 24)

The Piper diagram graphically represents groundwater types or chemical trends based on the relative amounts of major chemical constituents. Unique geology and hydrogeology of the county groundwater may require special consideration or treatment because of relative concentrations of dissolved ions. This water classification method also provides corroborating information for pollution sensitivity conditions by the spatial distribution of groundwater-type characteristic of hydraulically isolated or open recharge conditions.

The sample points in the figure are color coded according to tritium age to help reveal relationships between residence time and chemical composition.

- 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.
- The lines from the two ternary diagrams are projected onto the central diamond-shaped field and the intersections are plotted to show the overall chemical characteristics of the groundwater.

The cation triangle shows that groundwater with a mixture of calcium and magnesium is common in the county (Figure 24a). The anion triangle shows that bicarbonate water is also common. Overall, the general type of water that is prevalent in the county is calcium+magnesium bicarbonate.

However, many of the samples shown on the anion triangle are also slightly shifted toward the chloride+nitrate corner. These shifted samples are also predominately mixed tritium age. This association suggests that most of the additional chloride and nitrate in these samples is anthropogenic. The mixed tritium-age samples are found throughout the county in the unconsolidated and bedrock aquifers. The vintage tritium-age samples (also bicarbonate dominant water) are mostly limited to the most protected (least sensitive) hydrogeologic settings such as buried sand aquifers beneath the New Ulm Formation in the north and the lower bedrock aquifers in the south.

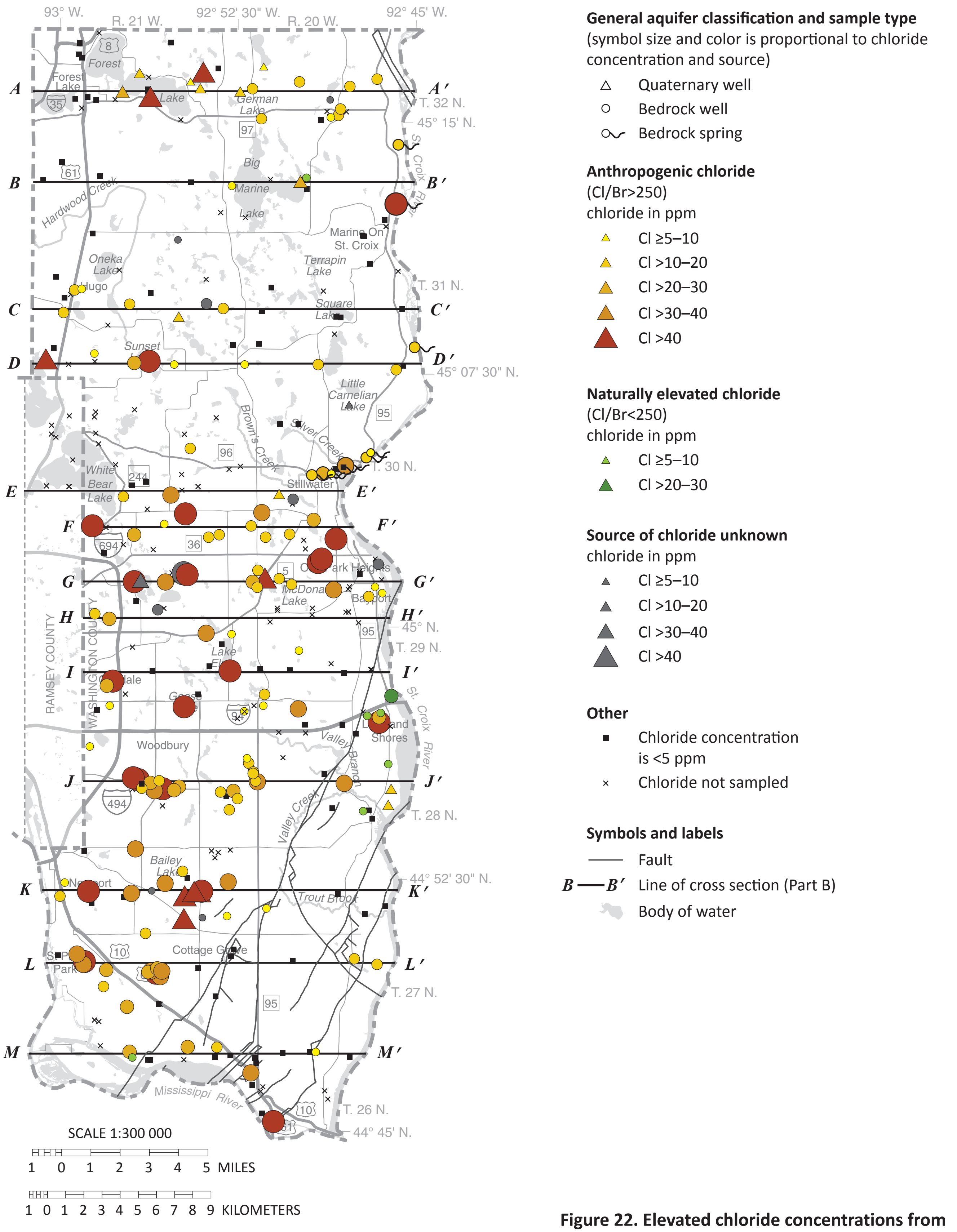


Figure 22. Elevated chloride concentrations from groundwater samples

Chloride is a significant contaminant in Washington County with 165 of 254 groundwater samples (65 percent) greater than or equal to 5 ppm.

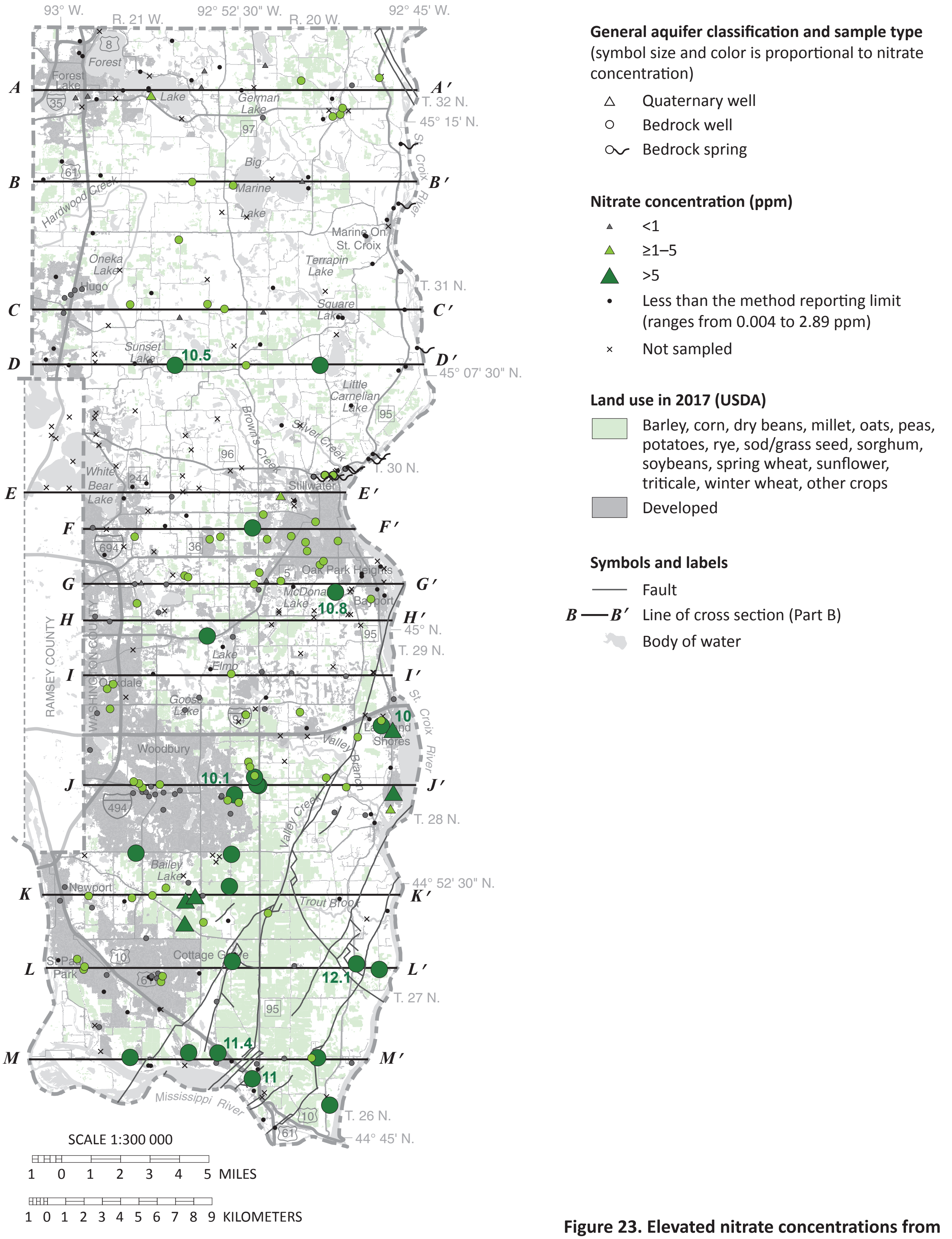
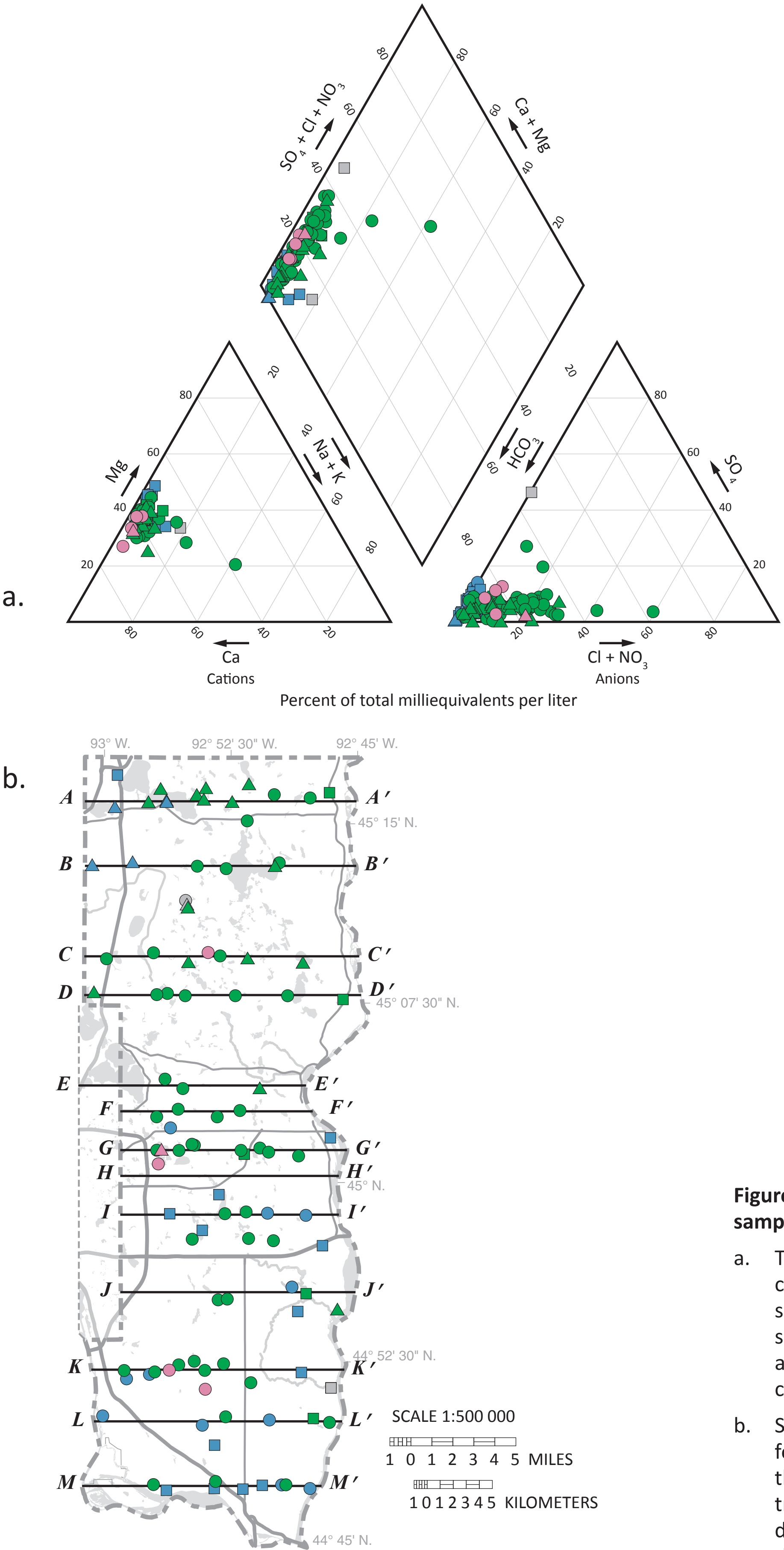


Figure 23. Elevated nitrate concentrations from groundwater samples

Elevated occurrences of nitrate are relatively widespread across the county, but only 3 percent were above the MCL of 10 ppm.



Chemistry

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

Aquifer symbol

△ Buried sand
○ Upper bedrock (St. Peter, Prairie du Chien, Jordan)
□ Lower bedrock (Upper Tunnel City, Wonewoc, Mt. Simon)

Tritium age

Symbol color indicates tritium age of water sample.

🟪 Recent
🟩 Mixed
🟦 Vintage
⬜ Not sampled for tritium

Figure 24. Piper diagram of groundwater samples from the DNR and MDH

a. The most common water type is calcium+magnesium bicarbonate with some of the mixed tritium-age samples shifted toward the chloride+nitrate anion end point due to anthropogenic contamination from the surface.

b. Samples with mixed tritium age are found throughout the county in all of the general aquifer types. The vintage tritium-age samples (also bicarbonate dominant water) are mostly limited to the most protected (least sensitive) hydrogeologic settings.

Pollution sensitivity

Pollution sensitivity maps were generated on a county scale to assist citizens and local government in protecting and managing groundwater resources. Pollution sensitivity is defined as the potential for groundwater to be contaminated because of the properties of the hydrogeologic material. Migration of contaminants dissolved in water flowing through unsaturated and saturated sediment is a complex process that is commonly 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 contaminant that is dissolved and moving within water from the surface is not chemically or physically altered over time.

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.

Two models were used to estimate the pollution sensitivity, based on the different properties of the aquifer materials and the thickness of the geologic layers.

The following assumptions were applied.

- **Near-surface materials** (to a depth of 10 feet): 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**: This method assumes that 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 central concept for both types of pollution sensitivity maps is the relative rate of groundwater movement. This is described as infiltration in the unsaturated zone, and recharge in the saturated zone. Smith and Westenbroek (2015) found that soil properties and land cover have the largest effect on potential recharge of the water-table aquifer. Their statewide analysis included land cover, soil properties, and daily meteorological information.

Recharge maps can be used as a tool for planning aquifer recharge projects using high-quality water. Areas with high infiltration rates or focused recharge may indicate locations for further investigation.

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 the 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 will vary 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) (USDA-NRCS, 2016; Part A, Plate 3).

The time of travel through near-surface sediment varies from hours to approximately a year (Figure 25).

- 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. These areas are not present in this county.

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

Table 1. Transmission rates used to assess the pollution sensitivity rating of 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	Qco, Qf, Qpo, Qno
		sand, silty sand	0.71	Qbs
B, B/D	0.50	silt, loamy sand	0.50	Qa, Qrc
		sandy loam, peat	0.28	Qp, Qcl, Qct, Ql, Qnl
C, C/D	0.075	silt loam, loam	0.075	Ql, Qnt, Qpe
		sandy clay loam	0.035	not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	not mapped in county
--	--	glacial lake sediments of Lake Agassiz	0.000011	not present in county

Note that peat is not shown on the map due to the scale of the coverage

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

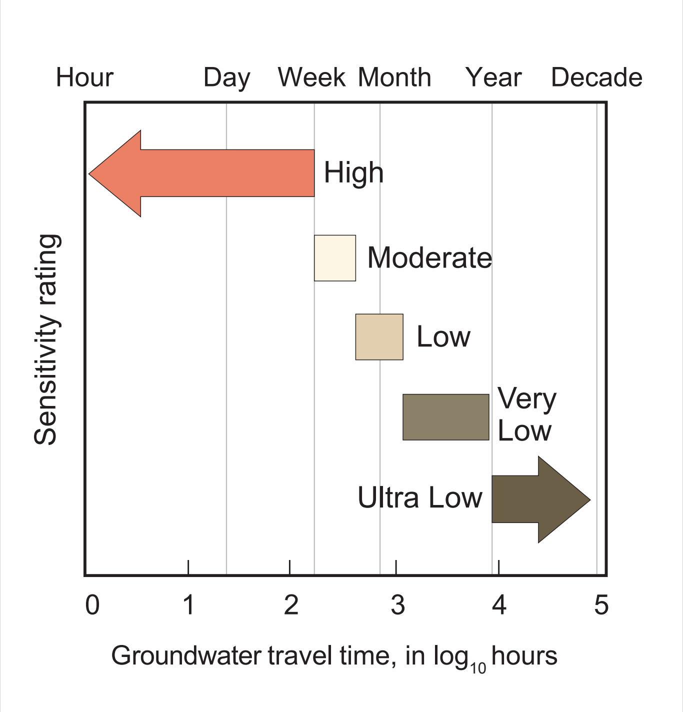
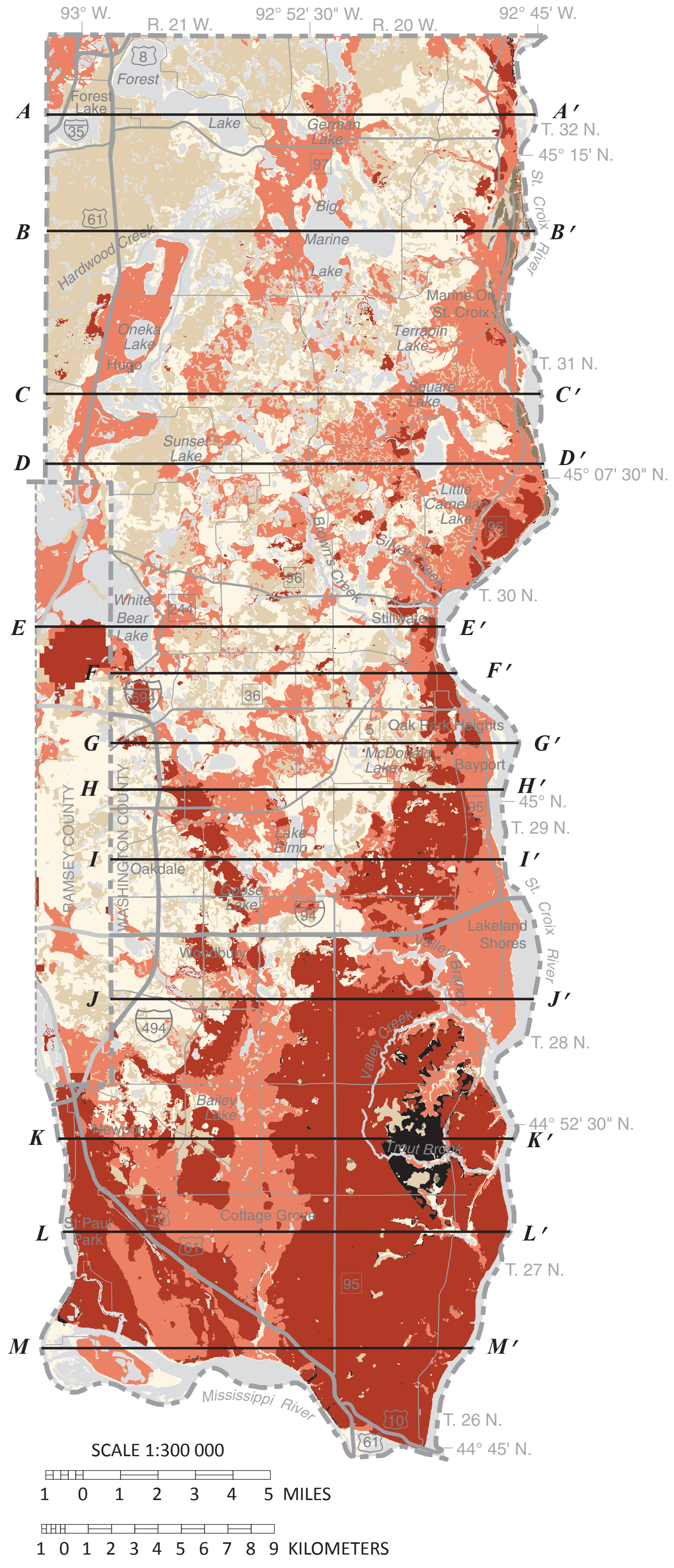


Figure 25. Geologic sensitivity rating for near-surface materials



Estimated vertical travel time through near-surface materials

🟥	High: hours to a week
⬜	Moderate: a week to weeks
🟫	Low: weeks to months
🟫	Very Low: months to a year

Special condition

🟥	Karst
⬛	Bedrock at or near surface

Symbols and labels

B —— *B′*	Line of cross section (Part B)
▨	Body of water

Figure 26. Pollution sensitivity of near-surface materials

Washington County has three groups of sensitivity that generally match three surficial geology areas:

1. **The northwestern portion** has loamy New Ulm till that has mostly low to moderate sensitivity. This contains the largest continuous areas of low sensitivity where the till is commonly at the surface.
2. **The St. Croix moraine** from northwest Woodbury to Scandia has a complex distribution of fine and coarse-grained materials. The resulting sensitivity of this area ranges from low to high with a few areas of karst.
3. **The southeastern portion** has thin and sandy layers of glacial sediment over the bedrock resulting in high and karst sensitivity areas (DNR, 2016c).

   Karst is defined as "terrain with distinctive landforms and hydrology created primarily from the dissolution of soluble rocks." Features such as sinkholes, caves, and springs are common in this type of terrain. The underground drainage through carbonate rock is dominated by rapid conduit flow. Conduits in karst significantly increase groundwater flow rates and contamination risks from pollutants.

   For mapping purposes the karst areas were defined as karst-prone bedrock (carbonate, St. Peter and Hinckley sandstones) within 50 feet of the land surface. The Karst Feature Inventory Points contains surveyed karst features in the southern part of the county and can be downloaded and viewed as a GIS layer (University of Minnesota School of Earth Sciences, 2018). Springs in the county can similarly be found as an online interactive map or as a GIS layer (DNR, 2018c).

Buried sand aquifers and bedrock surface

The sensitivity ratings for the buried sand aquifers and the bedrock surface are based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with 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 27).

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 28).

GIS software was used to calculate cumulative thickness of the sediment layers in the county. Thicknesses of 10 feet or less were rated very high sensitivity, thicknesses greater than 40 feet were rated very low, and thicknesses between 10 and 40 were rated high to low.

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

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

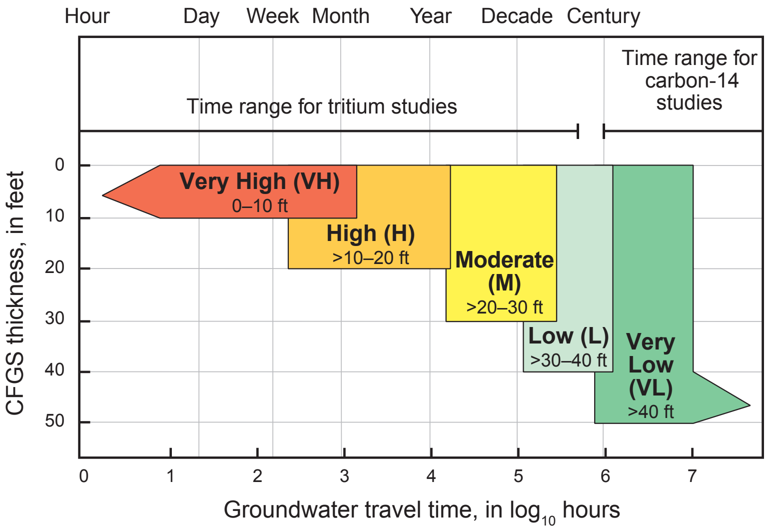


Figure 27. Geologic sensitivity rating for the buried sand aquifers and the bedrock surface

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

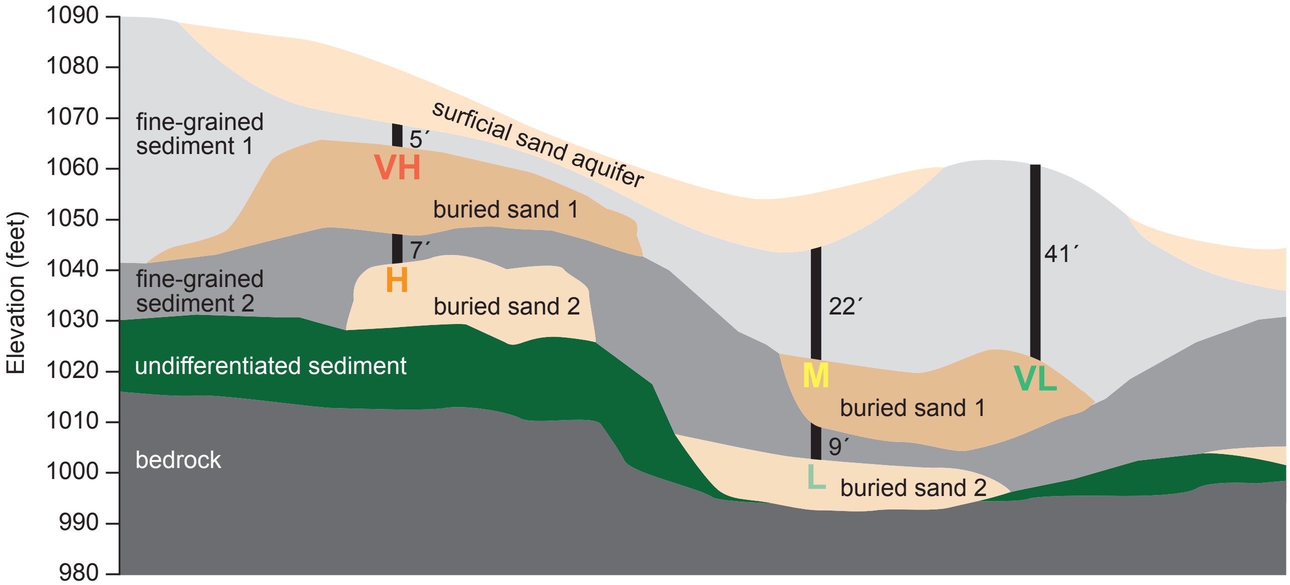


Figure 28. Cross section showing examples of pollution sensitivity ratings
Sensitivity ratings are based on the cumulative thickness of overlying fine-grained sediment. Each vertical black line is labeled with the thickness of fine-grained sediment. The letter at the base of the line indicates the sensitivity 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, chloride and nitrate).

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

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

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

Ⓛ Groundwater flows laterally.

Ⓟ Tritium concentration may be artificially elevated by high capacity pumping.

Ⓤ Groundwater flowpath is unknown.

Ⓓ Groundwater discharges to a surface-water body.

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.

Limitations of the model are represented by conditions L and U. The lateral groundwater flow of condition L often results in recent or mixed tritium-age water in aquifers with low to very low sensitivity. Condition U (unknown) is indicated when 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 plates. Conditions vary across the state and may not be present in every county.

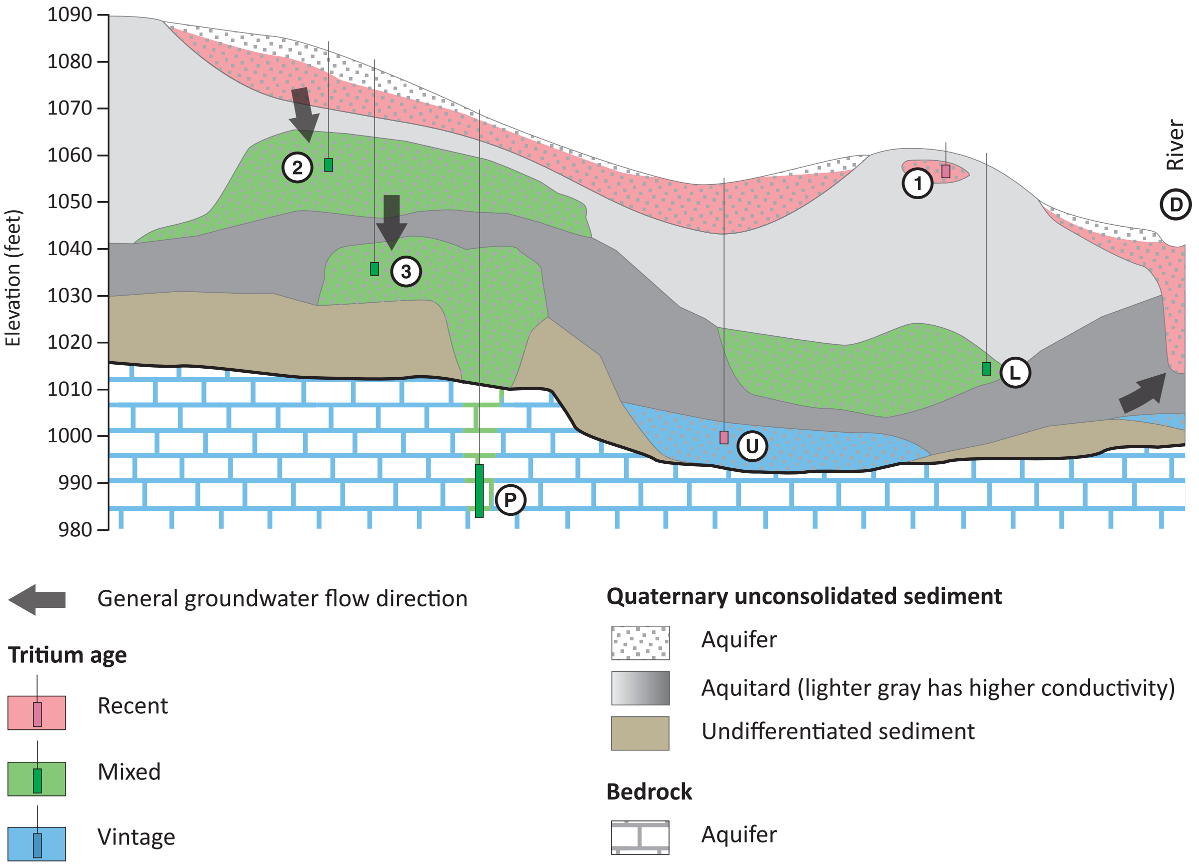


Figure 29. Hypothetical cross section illustrating groundwater conditions

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 highest to lowest, 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 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/bromide ratios are greater than 250.

The tritium dataset is a combination of sampling efforts by the DNR and partners for several projects since 1988. Descriptions of groundwater chemistry and pollution sensitivity are 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 (Figure 27).

The results for Figures 30 through 38 are described in the map captions.

The bedrock descriptions for Figures 39 through 41 are described in more detail in the body text on pages 50 and 51, followed by the map figures and captions.

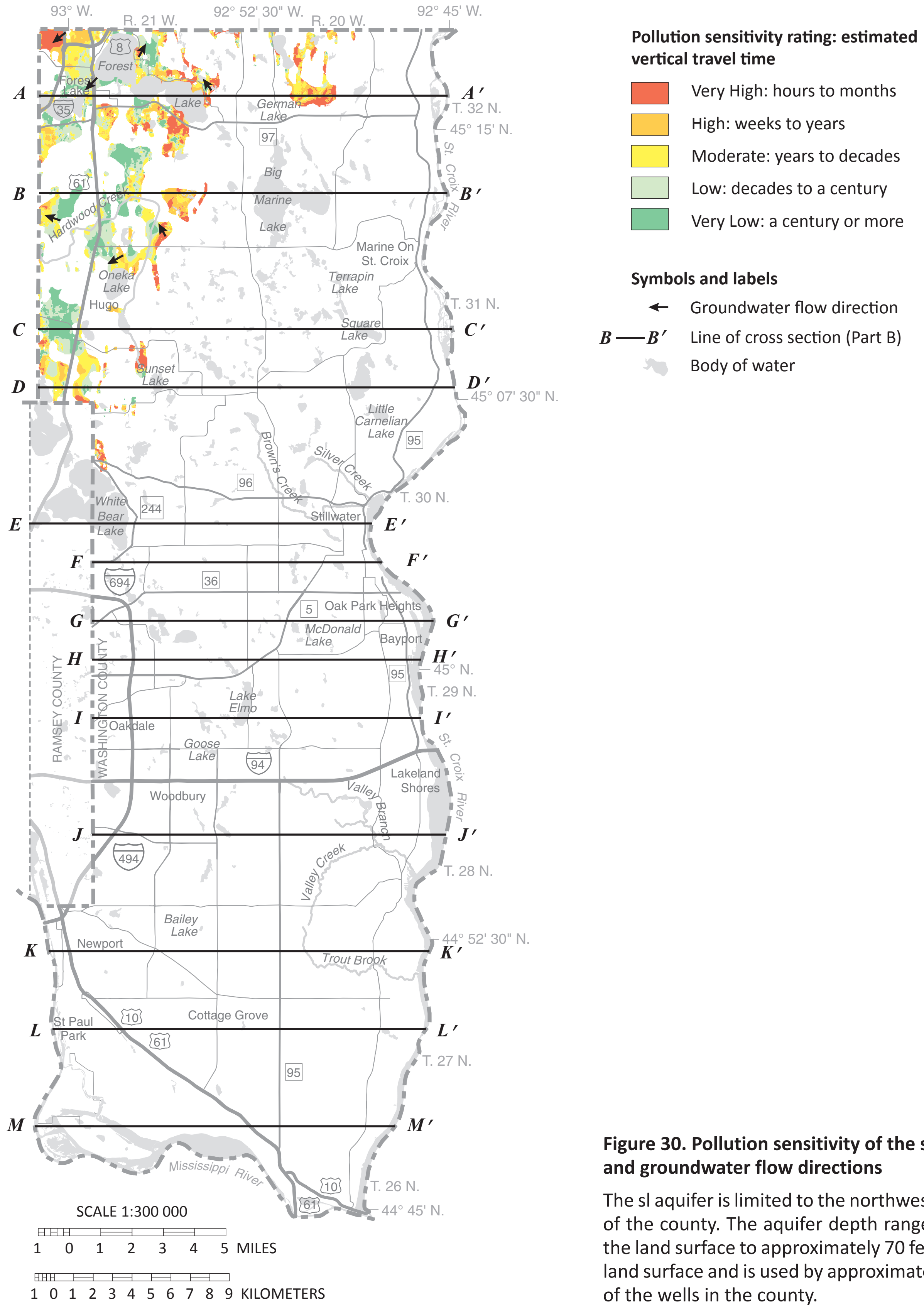


Figure 30. Pollution sensitivity of the sl aquifer and groundwater flow directions

The sl aquifer is limited to the northwestern portion of the county. The aquifer depth ranges from near the land surface to approximately 70 feet below the land surface and is used by approximately 2 percent of the wells in the county.

The pollution sensitivity is commonly very low to moderate due to the overlying New Ulm Formation.

No samples were collected from this aquifer for chemical analysis.

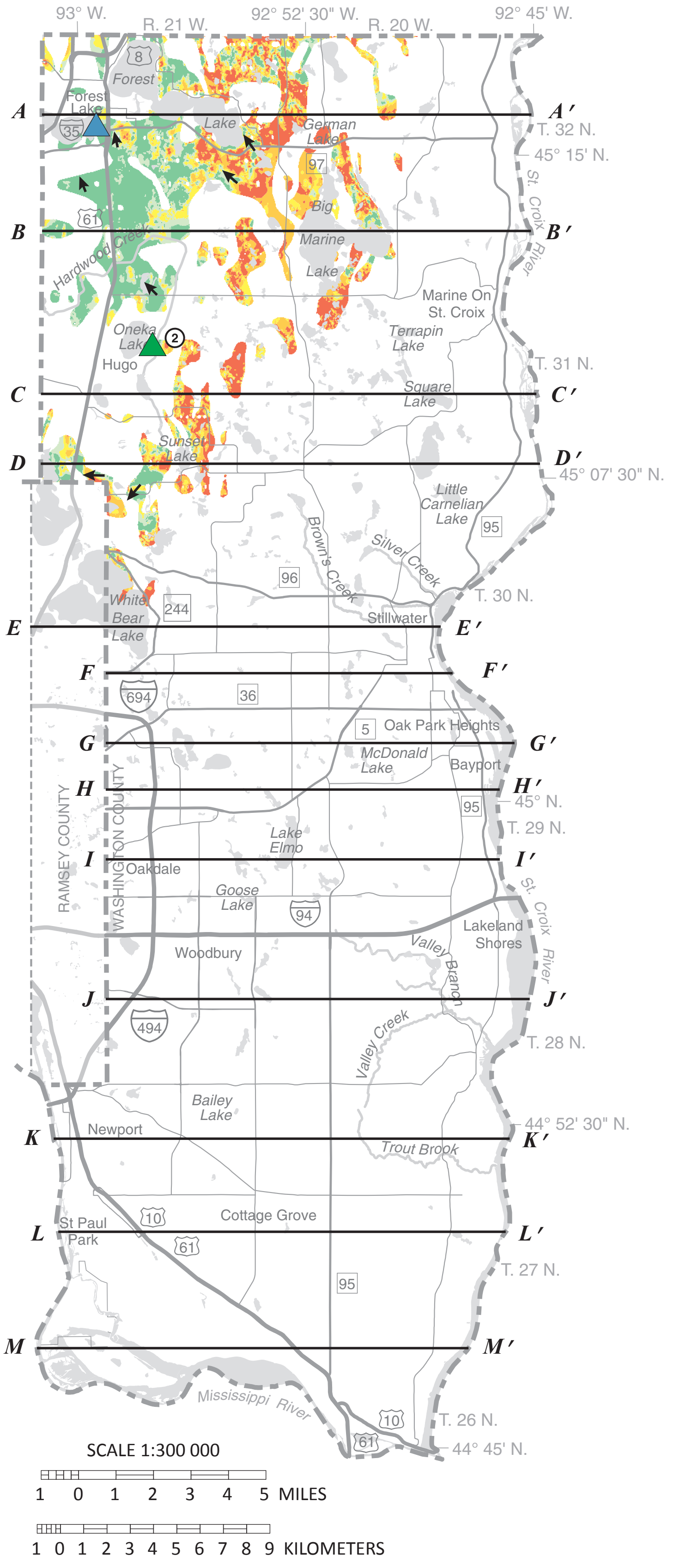
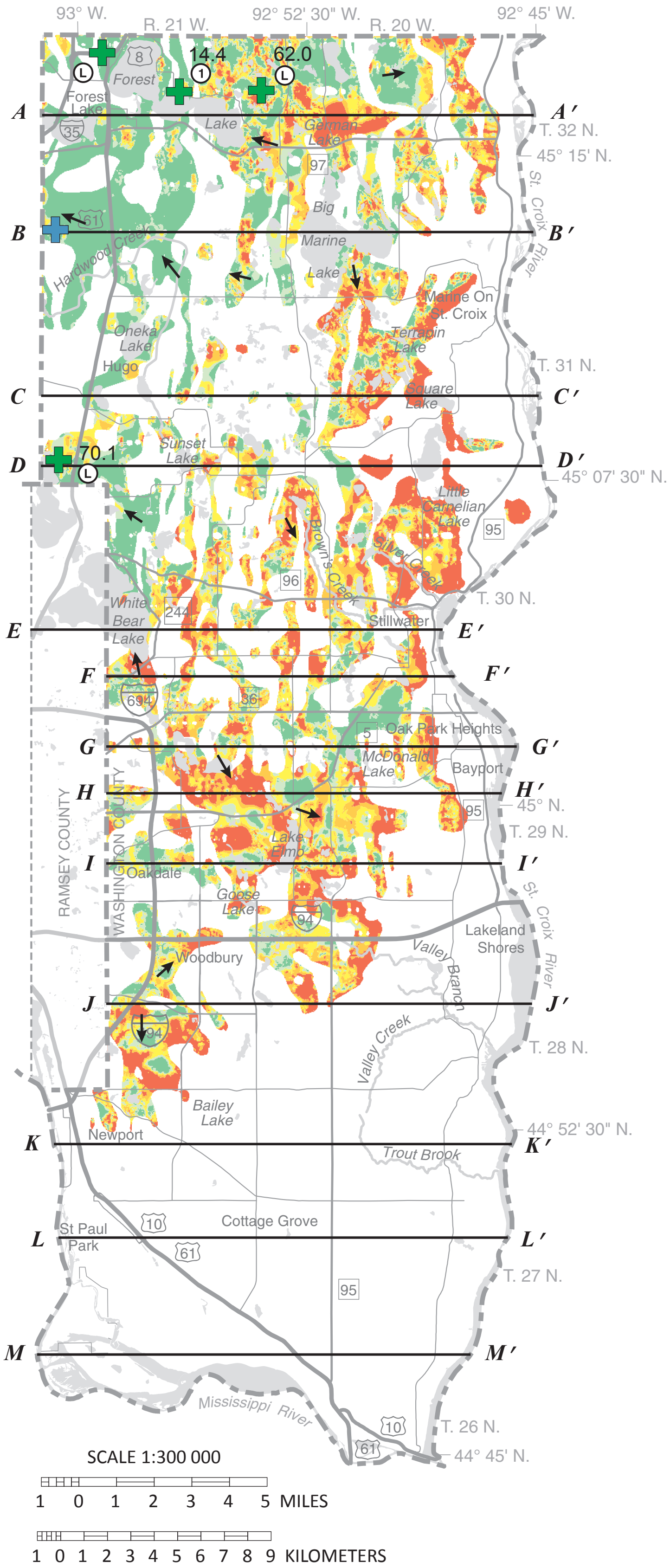


Figure 31. Pollution sensitivity of the sc aquifer and groundwater flow directions

The sc aquifer is limited to the northwestern portion of the county, is located at depths near the surface to approximately 80 feet below the land surface, and is used by approximately 3 percent of the wells in the county.

The pollution sensitivity in the western portion is very low to moderate, and in the eastern portion high to very high. Both samples collected from this aquifer were analyzed for tritium and resulted in 1 mixed and 1 vintage tritium age. The corresponding pollution sensitivity for those sampled areas was moderate and very low, respectively, which fits the sensitivity model.

One sample was analyzed for nitrate and chloride and resulted in no elevated concentrations.



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

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

← Groundwater flow direction

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

Body of water

Groundwater conditions

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

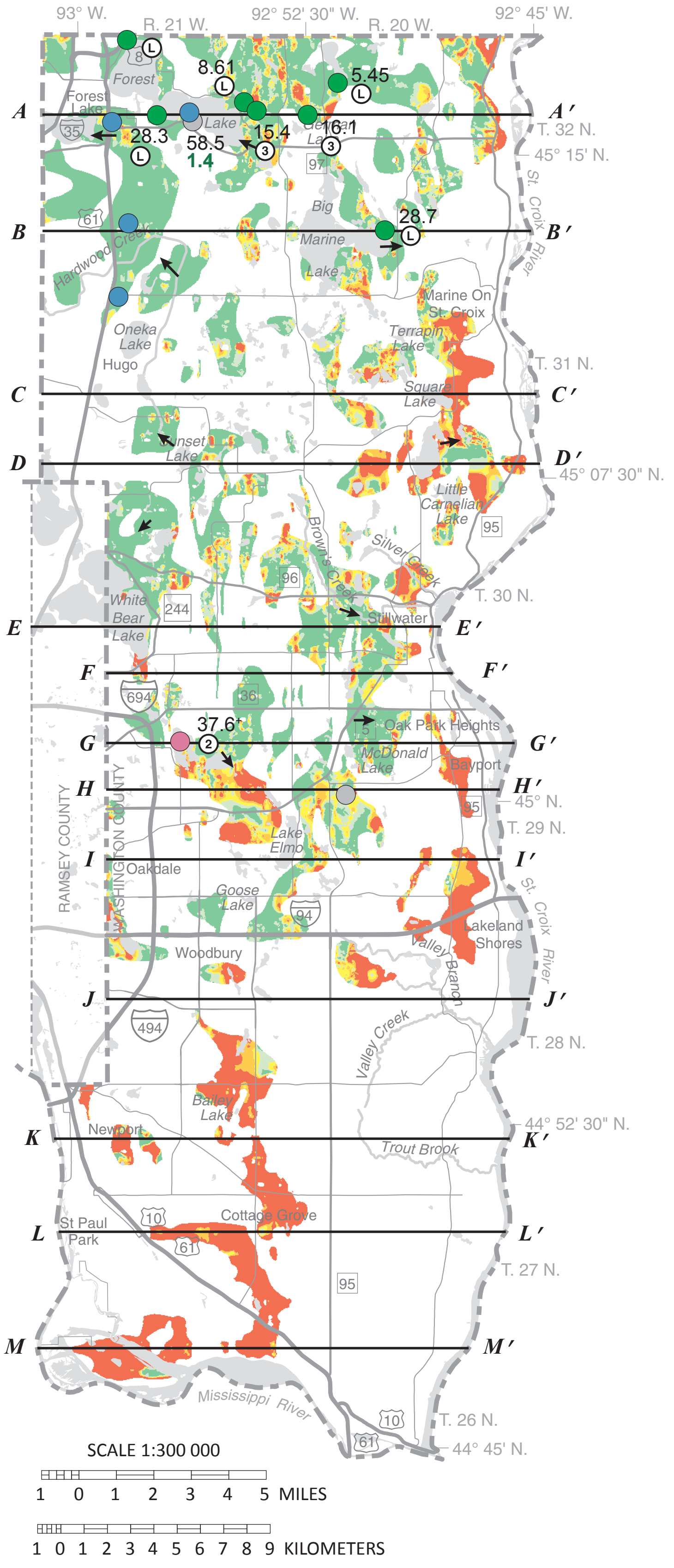
Ⓛ Groundwater flows laterally.

Figure 32. Pollution sensitivity of the se aquifer and groundwater flow directions

The se aquifer spans the northern and central portions of the county extending south to the edge of the St. Croix moraine. It is located at near-surface depths to approximately 80 feet below the land surface and is used by approximately 6 percent of the wells in the county.

The pollution sensitivity is very low in the northwest but mostly moderate to very high in the remainder of its extent. Of the 5 five samples collected from this aquifer. all were tested for tritium resulting in 4 mixed and 1 vintage tritium age. The mixed samples were collected in very low to moderate sensitivity areas; the vintage sample was collected in a very low sensitivity area. These results match the vertical recharge model.

Of the 5 samples analyzed for nitrate, none were elevated. Of the 5 samples analyzed for chloride, 3 were elevated and anthropogenic, possibly due to lateral movement of groundwater (condition L) and recharge through a thin overlying fine grained layer (condition 1).



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.

Symbols and labels

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

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

← Groundwater flow direction

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

Body of water

Groundwater conditions

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

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

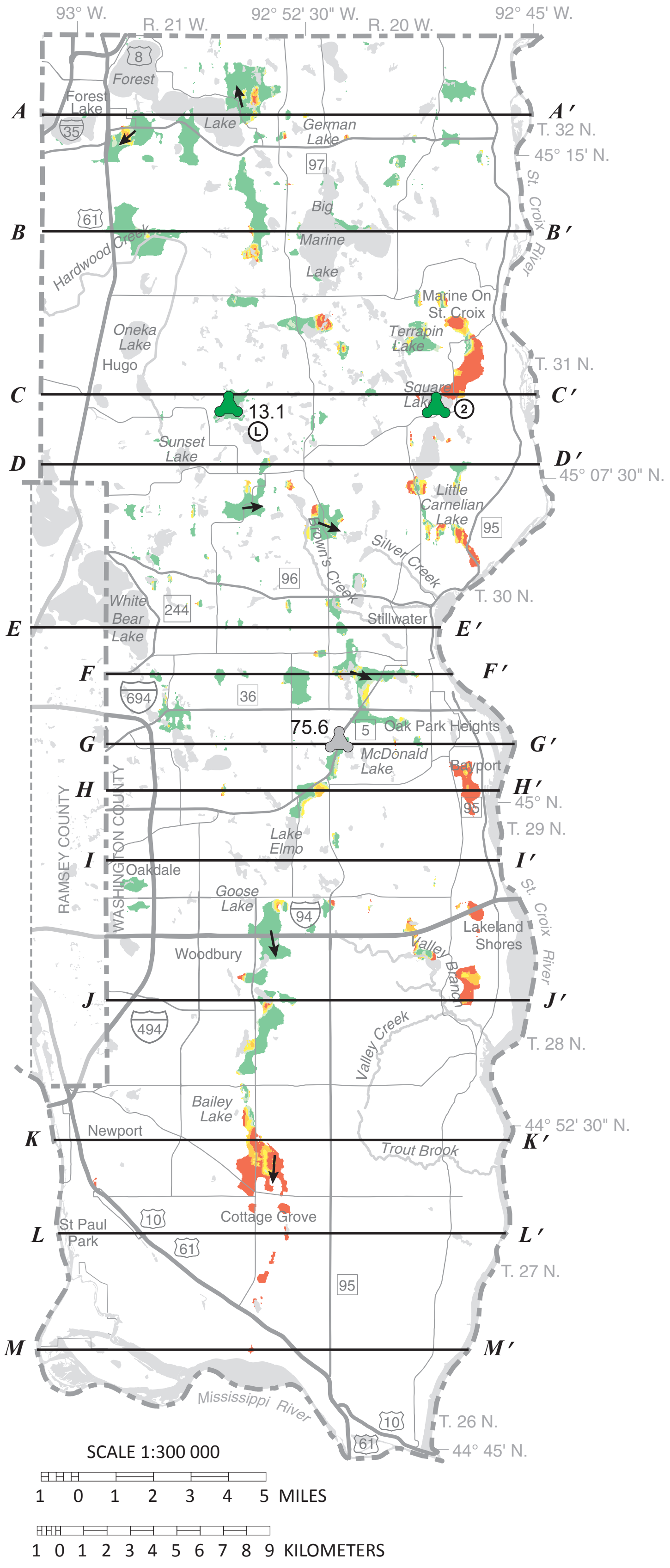
Ⓛ Groundwater flows laterally.

Figure 33. Pollution sensitivity of the s1 aquifer and groundwater flow directions

The s1 aquifer is distributed across most of the county with the exception of the southeast corner. The aquifer is located at near-surface depths to approximately 160 feet below the land surface. It is used by 4 percent of the wells in the county, mostly in the northern portion.

This aquifer has a complex distribution of very low to very high pollution sensitivity in the north and is predominately very high in the south. Of the 14 samples collected from this aquifer, 12 were tested for tritium with the following results: 1 recent, 7 mixed, and 4 vintage tritium ages. Recent and mixed tritium-age samples were found at locations mapped with very low to very high sensitivities. This detection is likely from groundwater flowing vertically (conditions 2 and 3) and laterally (condition L). All of the vintage tritium-age samples were located in very low sensitivity areas which is consistent with the pollution sensitivity model.

Of the 12 samples analyzed for nitrate, 1 was elevated. Of the 12 samples analyzed for chloride, 8 were elevated and 7 of these were anthropogenic.



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
- ▲ Not sampled for tritium.

Symbols and labels

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

← Groundwater flow direction

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

Body of water

Groundwater conditions

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

Ⓛ Groundwater flows laterally.

Figure 34. Pollution sensitivity of the s2 aquifer and groundwater flow directions

The s2 aquifer was mapped in small patches at locations scattered across most of the county. The aquifer is one of several buried sand units inside a buried bedrock valley extending from Stillwater south through Cottage Grove. The aquifer is located at near-surface depths to approximately 200 feet below the land surface. It is used by approximately 2 percent of the wells in the county, mostly in the northern portion.

The pollution sensitivity is mostly very low with the exception of a few scattered areas of moderate to very high sensitivity. Of the 3 samples collected from this aquifer, 2 were analyzed for tritium and both had mixed tritium age. All were collected at locations in very low to low sensitivity areas.

Of the 3 samples analyzed for nitrate, none were elevated. Of the 3 samples analyzed for chloride, 2 were elevated and anthropogenic.

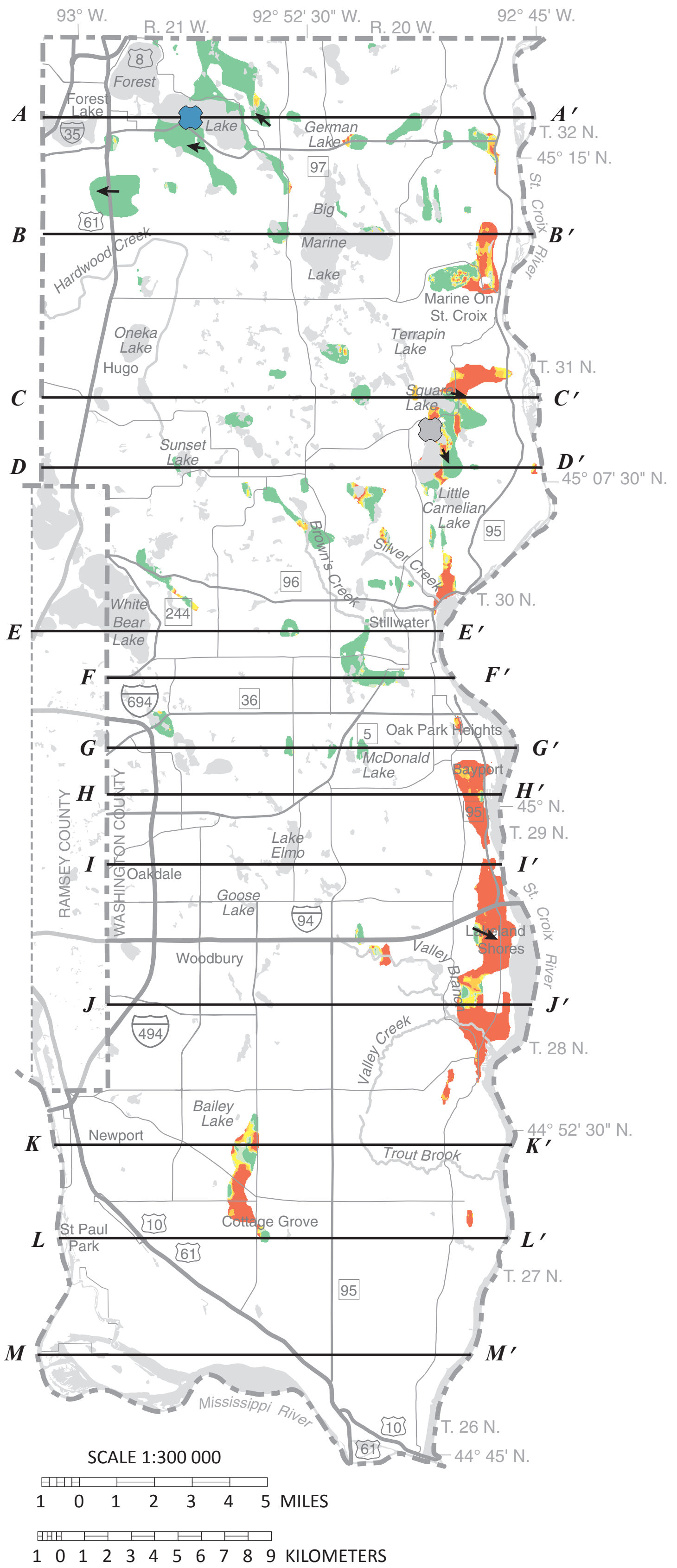


Figure 35. Pollution sensitivity of the sx aquifer and groundwater flow directions

The sx aquifer was mapped in small patches at locations scattered across most of the county. A portion of the aquifer is inside a buried bedrock valley that extends from Stillwater south through Cottage Grove. The aquifer is located at near-surface depths to approximately 230 feet below the land surface. It is used by approximately 2 percent of the wells in the county, mostly in the eastern and northern portions that match its areal extent.

The pollution sensitivity of the sx aquifer is mostly very low in the northern and north-central parts of the county and moderate to very high in the eastern and southern portions. Of the 2 samples collected from this aquifer, 1 was tested for tritium. The sample was vintage and was collected in a very low sensitivity area.

That sample was also analyzed for nitrate and chloride and had no elevated concentrations.

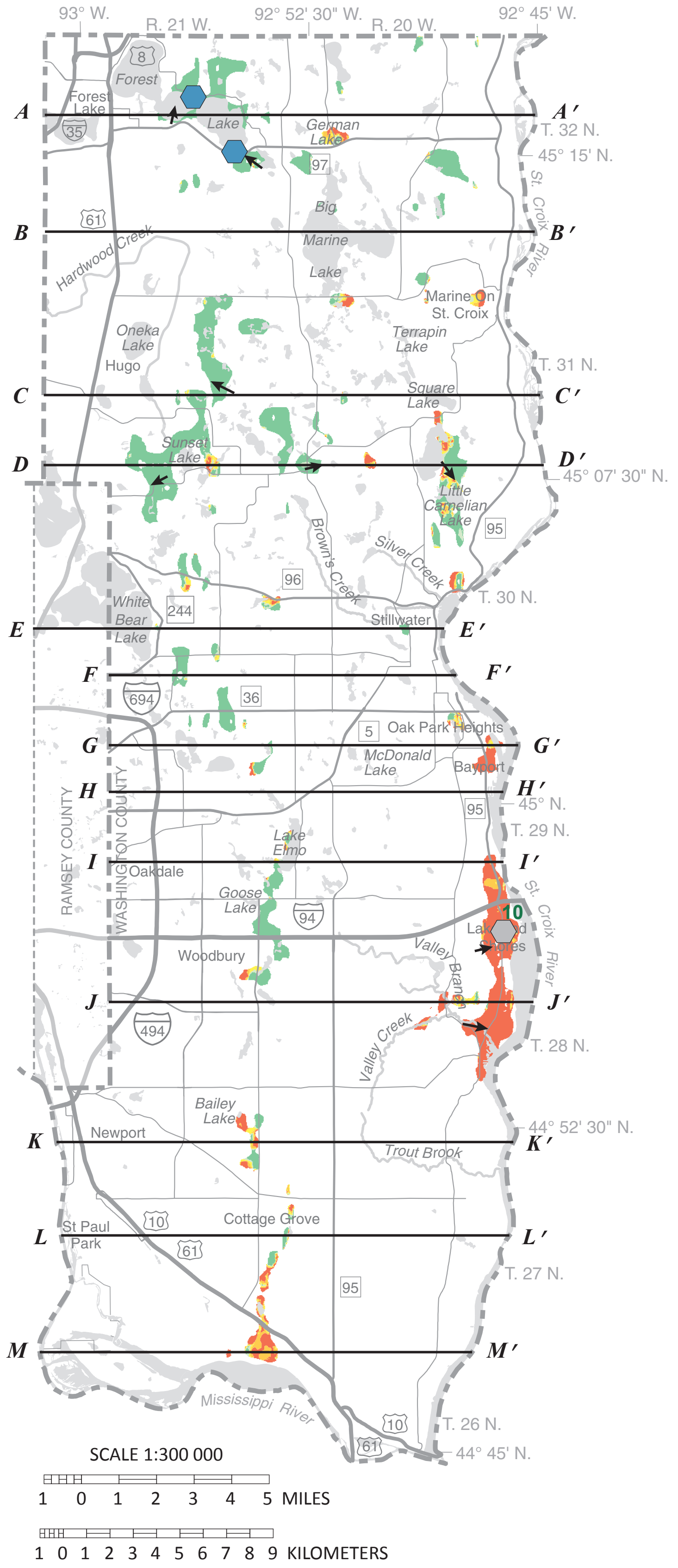
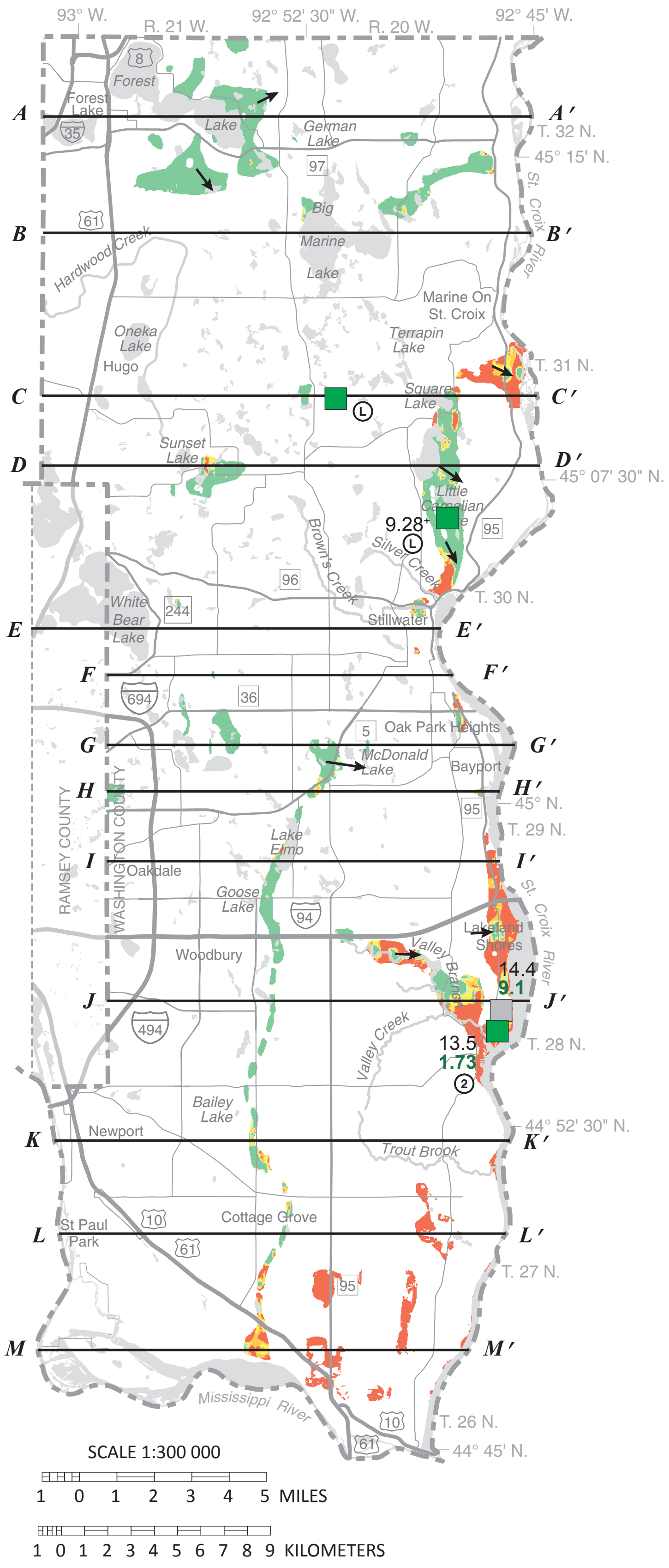


Figure 36. Pollution sensitivity of the s3 aquifer and groundwater flow directions

The s3 aquifer was mapped in small patches at locations scattered across most of the county. Portions of the aquifer are inside a buried bedrock valley that extends from Stillwater south through Cottage Grove. The aquifer is located at near-surface depths to approximately 300 feet below the land surface. It is used by approximately 2 percent of the wells in the county within most of its areal extent in the northern, eastern and southern bedrock valley areas.

The pollution sensitivity of the s3 aquifer is mostly very low in the north and center and moderate to very high in the east and south. Of the 3 samples collected from this aquifer, 2 were tested for tritium age and both were vintage. Both samples were collected at locations in very low sensitivity areas.

One sample was analyzed for nitrate and had an elevated concentration. None of the samples were analyzed for chloride.



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

⬜ Not sampled for tritium.

Symbols and labels

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

Groundwater conditions

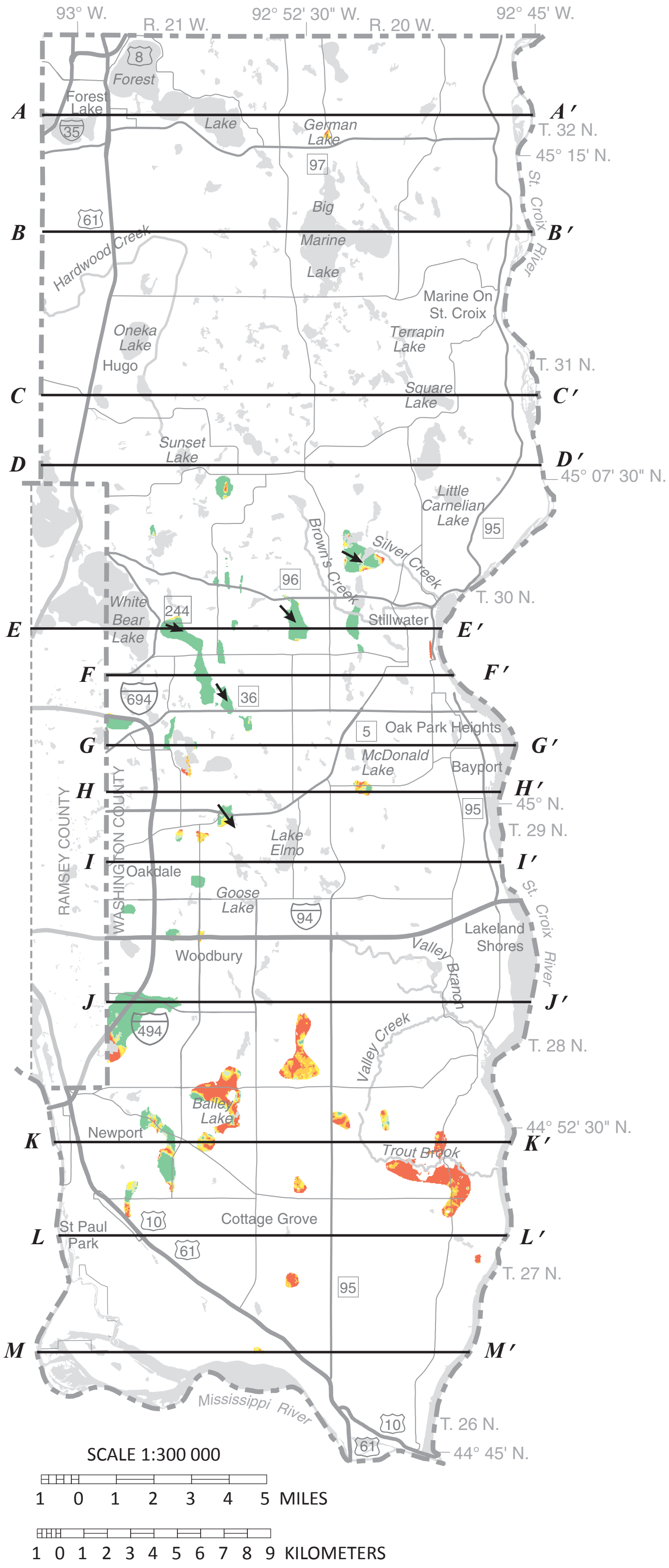
②	Groundwater moves from an overlying surficial aquifer to a buried aquifer.
Ⓛ	Groundwater flows laterally.

Figure 37. Pollution sensitivity of the sp aquifer and groundwater flow directions

The sp aquifer was mapped in small patches at locations scattered across most of the county. The aquifer is almost continuous inside a buried bedrock valley that extends from Stillwater south through Cottage Grove. The sp aquifer is located at near-surface depths to approximately 300 feet below the land surface. It is used by 2 percent of the wells in the county, mostly in the north and eastern areas. It has a patchy areal extent with limited areas mainly in the north, east and the southern bedrock valley.

Pollution sensitivity is commonly very low to low with the exception of higher sensitivity areas in the east and south. Of the 4 samples collected from this aquifer, 3 were tested for tritium age and all 3 were mixed. Two of the samples were collected at locations in very low to moderate sensitivity areas and 1 was in a moderate sensitivity area.

Of the 4 samples analyzed for nitrate, 2 were elevated. Of the 4 samples analyzed for chloride, 3 were elevated and 2 were anthropogenic.



Pollution sensitivity rating: estimated vertical travel time

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

Symbols and labels

← Groundwater flow direction
B —— B′ Line of cross section (Part B)
Body of water

Figure 38. Pollution sensitivity of the sv aquifer and groundwater flow directions

The sv aquifer has patchy distribution in the center and south. The aquifer is located at near surface depths to approximately 200 feet below the land surface and it is used by less than 1 percent of the wells in the county.

The pollution sensitivity is mostly very low in the center and west and high to very high in the southeast.

No samples were collected for chemical analysis.

Bedrock surface (Figure 39)

The depth to bedrock is highly variable in the county. Depths are at or near the land surface in the south but may be 300 to 450 feet in the north, the southern bedrock valley, and the Mississippi River valley. Thirty percent of the wells in the county were completed in the upper bedrock aquifers (casing less than 100 feet into bedrock). This upper bedrock zone is used by wells from the top (St. Peter) to the bottom (Mt. Simon) of the bedrock stratigraphic section. The Prairie du Chien is the most common aquifer used in this shallow zone by number of wells (42 percent); followed by the Jordan (9 percent) and Upper Tunnel City aquifers (9 percent); and combinations of the St. Peter–Prairie du Chien aquifers (6 percent), and Prairie du Chien–Jordan aquifers (6 percent).

The pollution sensitivity of the bedrock surface generally matches the three general geologic areas of the county and the depth to bedrock map (Part A, Plate 6).

1. The northwestern portion where very low pollution sensitivity is typical, where loamy New Ulm till overlies the bedrock surface.
2. The St. Croix moraine area occupies the center in a northeast-southwest diagonal and is a complex mosaic of very low to very high pollution sensitivity. The more sensitive areas are created by the common interconnected surficial and buried sand aquifers.
3. The St. Croix River valley and southern portion of the county commonly have large and extensive areas of very high sensitivity because of thin and/or sandy overlying unconsolidated sediment.

Of the 120 samples collected from this upper bedrock zone, 100 were analyzed for tritium age with the following results: 18 recent, 72 mixed, and 10 vintage. More than half of the recent and mixed tritium-age samples were collected at locations in very low to low sensitivity areas. This association is interpreted at most locations as lateral movement of mixed tritium-age groundwater that was recharged from an upgradient and higher sensitivity location. Another possible factor is leakage through overlying sandy till layers deposited by the Superior lobe.

With the exception of the northwest, recent and mixed tritium-age samples are common throughout the county and could be the result of vertical recharge through interconnected sand units (conditions 2 and 3). Of the 10 vintage tritium-age samples, 6 were in very low pollution sensitivity areas. The other 4 were in very high sensitivity areas but were also near the St. Croix River valley. Therefore, these river valley samples were probably the result of upward, discharging flow of deep and older groundwater. In addition, a groundwater sample collected from the Wonewoc–Eau Claire aquifer on the east side of cross section C–C′ south of Marine on St. Croix probably also had a 5,500 year carbon-14 residence time because of upward flowing old groundwater. Residence times of less than 100 years were found in 1 carbon-14 sample collected from the Prairie du Chien aquifer northwest of Lake Elmo, and two from west of Lakeland Shores (Tunnel City and Eau Claire samples), which is consistent with the high to very high pollution sensitivities of these areas.

Of the 75 samples analyzed for nitrate, 36 were elevated but only 2 exceeded the 10 ppm MCL. Of the 79 samples analyzed for chloride, 60 were elevated (greater than or equal to 5 ppm). Of these, 56 were anthropogenic or unknown, and 4 were from natural brines.

Distribution of conservative chemical tracers in deeper bedrock aquifers (Figures 40 and 41)

The pollution sensitivity model used to create maps of buried sand aquifers and the bedrock surface does not apply to portions of bedrock aquifers that are not at the bedrock surface. However, ample chemical evidence exists that deeper portions of the Jordan and Upper Tunnel City aquifers are sensitive to contaminants from groundwater transport entering at the surface to hydraulically connected combinations of aquifers. Much of the Jordan aquifer is sensitive to contamination through complicated groundwater pathways and lateral groundwater movement.

The distribution of conservative chemical tracers shown in Figures 40 and 41 is based on what we know of groundwater flow directions and geologic features that allow recharge through faults, buried valleys and interconnected sand. The mapped areas are based on the possible extent of detected tritium, perfluorobutyrate (PFBA), or elevated anthropogenic chloride from available data. Some areas may actually be larger or smaller if more data were available. Since these areas are based where we have chemistry data the areas shown in these figures may not match the interpreted tritium-age conditions of the cross sections.

Figure 40 shows portions of the Jordan aquifer that contain tritium, and anthropogenic indicator data described in the previous sections. An additional anthropogenic indicator—**perfluorobutyrate (PFBA)**—is added to this evaluation since it is a conservative tracer like chloride, and large amounts of PFBA data have been collected by MDH since 2006 in southern Washington County. PFBA is one of several per- and polyfluoroalkyl substances (PFAS; formerly referred to as PFCs) found in the groundwater in Washington County. Substances containing PFAS manufactured by the 3M Corporation were disposed at 4 locations in the southern part of the county from the late 1940s to the early 1970s. Similar to chloride, PFAS was not distributed everywhere at the surface. Therefore, detection of PFAS in groundwater samples indicates higher pollution sensitivity but the absence of PFAS does not necessarily indicate lower sensitivity. For this evaluation, PFBA was used since it is the most soluble and mobile of the PFAS, and thus the most widespread in Washington County. Numerous public and private wells that were completed in PFAS contaminated aquifers are no longer used due to ongoing health risk concerns.

A large portion of the Jordan aquifer in the Oakdale area (west-central portion of the county) is sensitive because of lateral groundwater movement of recharge water that enters the aquifer through upgradient moderate to very high sensitivity areas at the bedrock surface. In the east-central and southwestern portions of the county the area affected by conservative chemical tracers is related to the large bedrock valley in that part of the county (Part A, Plate 6). This bedrock valley provides a pathway for downward and lateral migration of near-surface contamination to the Prairie du Chien and Jordan aquifers (Yingling, 2015). The groundwater flow direction in the northern part of the buried valley area is easterly. In the eastern part of Woodbury and south into Cottage Grove the buried valley is approximately in the same location as the Jordan aquifer groundwater divide so contaminants entering the buried valley could flow to the west and east. In the area west and southwest of Bayport along the trace of cross section H–H′ no conservative tracer data were available. However, the presence of detected tritium is inferred for this area based on extensive sampling for a trichloroethylene (TCE) release near the center of cross section H–H′ (MPCA, 2018).

Additional groundwater samples with recent or mixed tritium and detected PFBA from the Jordan aquifer are shown in the southeastern portion of the county in the faulted area. Multiple factors may influence the distribution pattern of these chemicals including karst features in the overlying Prairie du Chien formations, enhanced fracture flow because of extensive faults in the area, and indirect effects of faulting that created groundwater flow pathways through juxtaposition of aquifers and pumping.

A similar map was made for the Upper Tunnel City aquifer, and combinations of the St. Lawrence and Upper Tunnel City (Figure 41). Affected areas are shown in the central part of the county with a combination of tritium and PFBA data. Similar to the overlying Jordan aquifer, a sensitive part of the Upper Tunnel City aquifer was identified in the south-central part of the county with a combination of tritium and PFBA data.

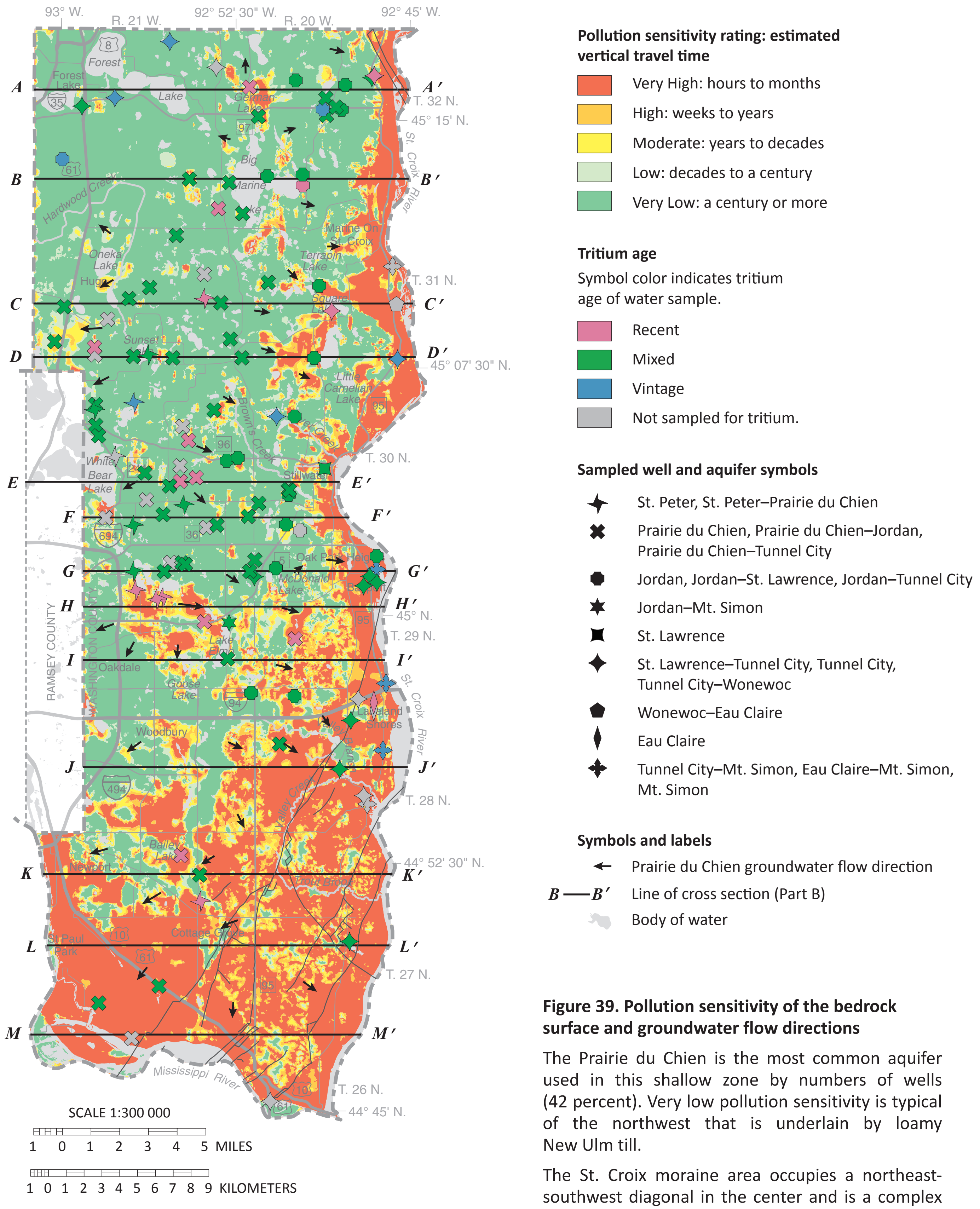


Figure 39. Pollution sensitivity of the bedrock surface and groundwater flow directions

The Prairie du Chien is the most common aquifer used in this shallow zone by numbers of wells (42 percent). Very low pollution sensitivity is typical of the northwest that is underlain by loamy New Ulm till.

The St. Croix moraine area occupies a northeast-southwest diagonal in the center and is a complex mosaic of very low to very high pollution sensitivity.

The St. Croix River valley and southern portion of the county commonly have extensive areas of very high sensitivity because of thin and/or sandy overlying unconsolidated sediment.

See Plate 7 for chemistry labeling.

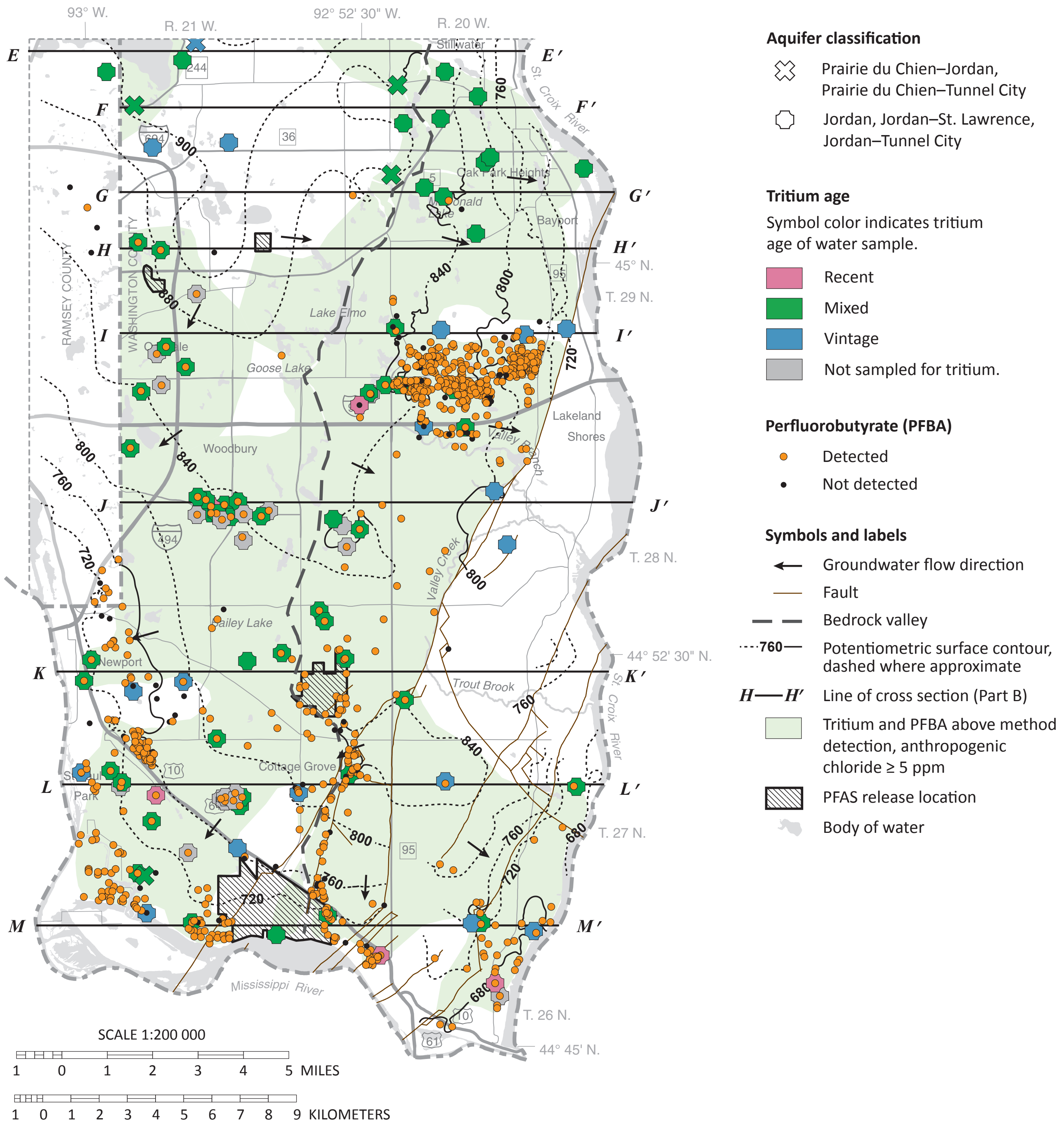


Figure 40. Distribution of conservative chemical tracers in the Jordan aquifer

Much of the Jordan aquifer is sensitive to contamination through complicated groundwater pathways and lateral groundwater movement.

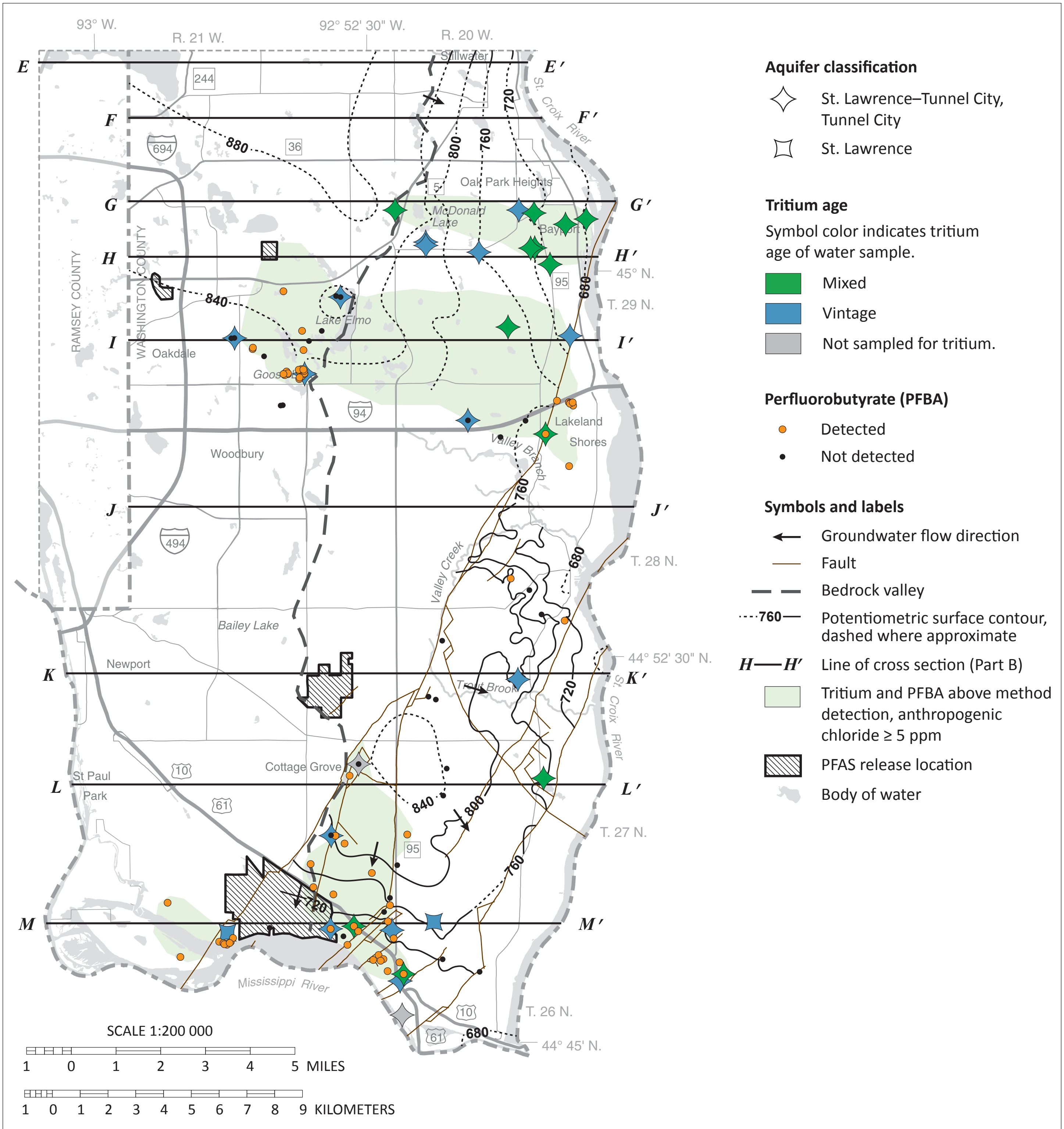


Figure 41. Distribution of conservative chemical tracers in the Upper Tunnel City aquifer

Portions of the Upper Tunnel City aquifer are sensitive to contamination through complicated groundwater pathways and lateral groundwater movement.

Hydrogeologic cross sections (Plates 8 and 9)

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

Thirteen cross sections were selected from a set of 63 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 the following 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 on Plates 8 and 9. Lighter shades indicate higher relative hydraulic conductivity. The percent sand 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 larger creeks and rivers. Groundwater recharge zones exist across broad areas of the county. However, smaller discrete groundwater recharge areas are identified in the following section based on occurrences of connected aquifers and geochemical data such as tritium, chloride, and nitrate.

Groundwater recharge and discharge overview

The description of the hydrogeologic cross sections is organized into three groups. Each group has similar characteristics as relevant to the topics of aquifer recharge and pollution sensitivity:

- Northern cross sections: A–A′, B–B′, C–C′, D–D′
- Central cross sections: E–E′, F–F′, G–G′, H–H′
- Southern cross sections: I–I′, J–J′, K–K′, L–L′, M–M′

Downward and lateral flow directions are most common across all of these cross sections, except for the area near the St. Croix and the Mississippi river valleys as shown on the southern cross sections. In those areas, groundwater flow is upward indicting discharge to these major rivers. Residence time indicators in these areas show vintage and older carbon-14 ages reflecting the upward movement of deep groundwater. Carbon-14 residence time values range from less than 100 to 25,000 years (carbon-14 inset map).

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 air lifting), 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.

Most of the specific capacity data listed are for bedrock aquifers. The highest mean values include the combined Prairie du Chien and Jordan aquifers (184 gpm/ft) and combinations of the Tunnel City Group which includes the Mazomanie sandstone (CTCW, 52 gpm/ft; CTCM, 40 gpm/ft; and OPCT, 35 gpm/ft). The Jordan aquifer had the most tests (46) with a mean value of 21 gpm/ft.

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 calculated from longer-term and larger-scale aquifer tests. Transmissivity 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).

Most of the aquifer tests were also from the Jordan aquifer, which had a mean transmissivity value of 6,020 ft^2/day, similar to the values of the other aquifers with available data.

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 aquifers										
Water table	-	-	-	-	-	-	-	-	-	-
Unconfined buried sand	-	-	-	-	-	-	-	-	-	-
Confined buried sand	18	42	-	-	1	-	-	-	-	-
Bedrock aquifers										
Prairie du Chien (OPDC)	8–12	19	10	33	4	-	-	-	-	-
Prairie du Chien–Jordan (OPDJ)	10–24	184	13	1,042	8	-	-	-	-	-
Prairie du Chien–Tunnel City (OPCT)	16	35	-	-	1	-	-	-	-	-
Jordan (CJDN)	8–24	21	3	87	46	10–24	6,020	1,640	25,200	14
Jordan–St. Lawrence (CJSL)	12	31	-	-	1	-	-	-	-	-
Jordan–Tunnel City (CJTC)	8	16	-	-	1	-	-	-	-	-
Tunnel City (CTCG)	8	7	-	-	1	-	-	-	-	-
Tunnel City–Wonewoc (CTCW)	8–10	52	6	97	2	-	-	-	-	-
Tunnel City–Eau Claire (CTCE)	8	18	-	-	1	-	-	-	-	-
Tunnel City–Mt. Simon (CTCM)	12–16	40	25	50	3	16	7,670	-	-	1
Wonewoc–Eau Claire (CWEC)	8	3	2	4	2	-	-	-	-	-
Wonewoc–Mt. Simon (CWMS)	16	15	-	-	1	-	-	-	-	-
Mt. Simon (CMTS)	14–18	16	13	20	4	10–18	4,450	2,370	6,720	3
Mt. Simon–Hinckley (CMSH)	12	8	7	9	2	-	-	-	-	-

Specific capacity data adapted from CWI
Transmissivity data are from aquifer test data compiled by the DNR
-, no data

Groundwater level monitoring

The DNR maintains a statewide groundwater level monitoring program (DNR, 2018a) 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. When combined with DNR lake level and precipitation monitoring data, some of the common trends during periods of drought and above average rainfall can be evaluated. The nature of groundwater connections with surface water is important for anticipating possible problems because of cumulative groundwater use, the effects of a changing climate, or both. While a thorough examination of these issues is beyond the scope of this report, some relatively simple tools and tests can be used to assess the strength of connections between groundwater and surface water. One of these tests has already been summarized using stable isotopes and evaporative signatures (Figures 20 and 21). Characteristics of lakes with strong groundwater connections are illustrated with examples of watershed/lake area ratios and hydrograph comparisons.

The following examples include 4 lakes and 1 stream with the following data.

- Precipitation
- Lake level or stream flow volume
- Water level data from a nearby DNR observation well in one of the upper buried sand or bedrock aquifers
- Stable isotope data from a groundwater sample collected from a nearby well indicating an evaporative signature (no sample available for Brown's Creek)

Lakes with strong groundwater connections are commonly in closed-basin settings where the surrounding watershed is relatively small compared to the size of the lake (watershed/lake area ratio, Table 3). With no inflowing streams, these lakes are dependent on groundwater inflow and direct precipitation. A higher ratio indicates that a greater volume of surface runoff will reach the lake.

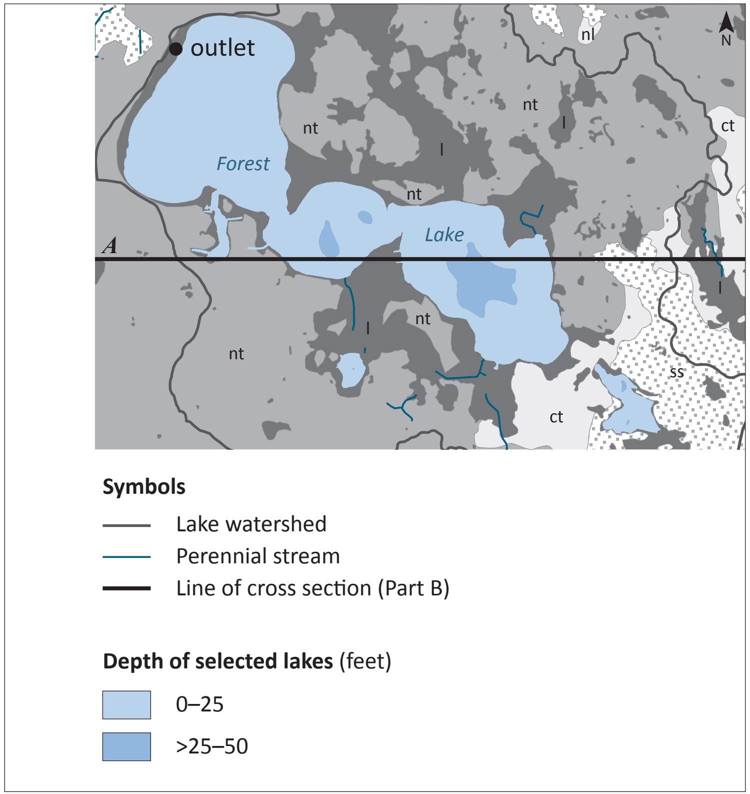
These types of lakes sometimes have a high fluctuation range caused by short-term climate changes (precipitation and evaporation). These short-term changes not only alter the net amount of direct precipitation to the lake but also affect the elevation of the regional water table and other underlying potentiometric surfaces. The altered potentiometric surfaces of underlying aquifers create yet another unseen mechanism that indirectly affects lake-water levels by increasing or decreasing the hydraulic gradient between the lake and underlying aquifers. A high gradient leads to more lake water leakage and a low gradient leads to less.

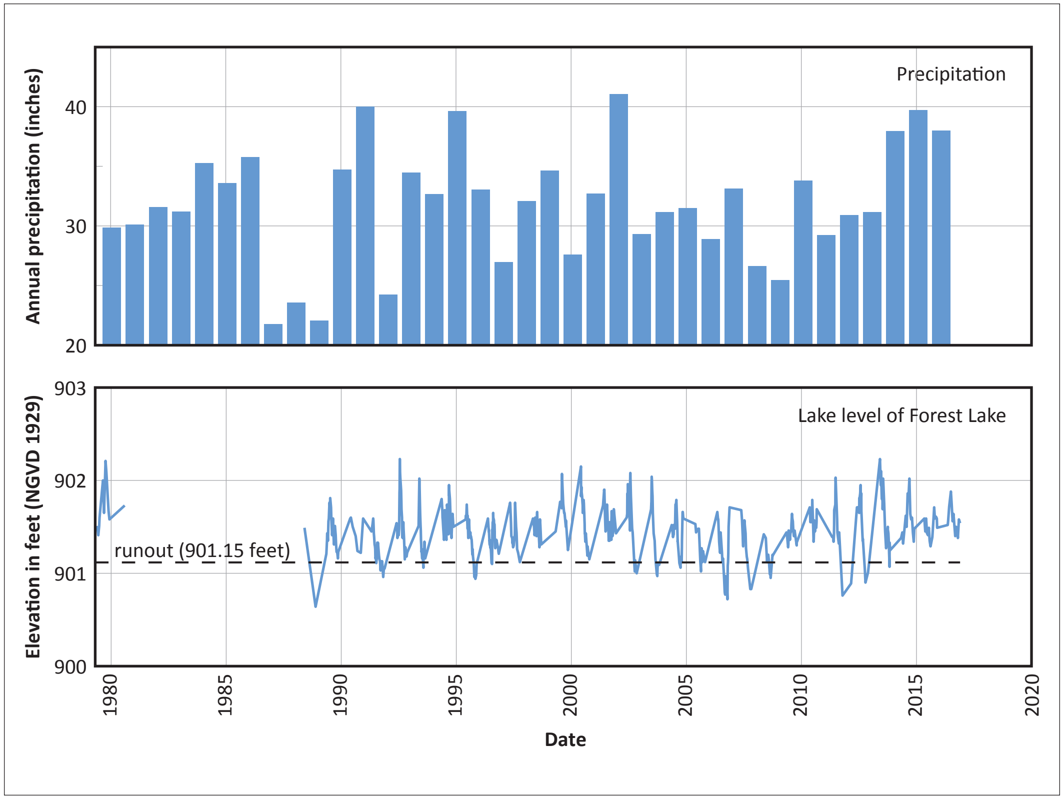
Other studies have further classified lakes based on the nature of the surface water/groundwater connection mainly based on the suspected groundwater inflow and outflow (Emmons and Oliver Resources, 2003; Barr Engineering, 2010). For example in **flow-through** lakes the groundwater flows into the lake from the upgradient side and leaves on the downgradient. **Recharge lakes** are predominantly precipitation fed, but discharge lake water to the underlying aquifer. Most of the examples included in this section represent combinations of these tendencies.

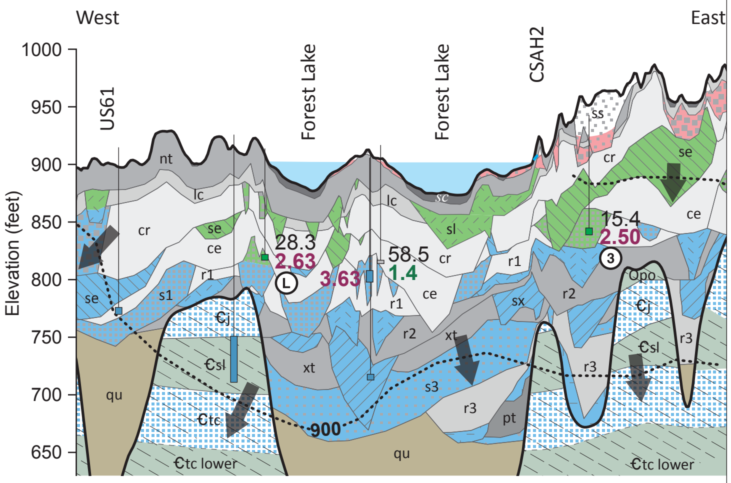
Table 3. Characteristics of selected lakes

Lake name	Forest	Big Marine	Oneka	White Bear
DNR lake number	82015900	82005200	82014000	82016700
Lake area (acres)	2,271	1,689	358	2,433
Watershed area (acres)	10,724	7,818	785	7,629
Watershed/lake area ratio	4.7	4.6	2.2	3.1
Current elevation outflow (ft NGVD 29)	905.6	940.6*	931.0	924.1*
Elevation range (ft)	2.8	7.1	4.3	7.9
Period of record	1965–2018	1961–2018	1971–2018	1924–2018
Stream inflow	perennial	no	no	no
Stream outflow	perennial	yes	intermittent	intermittent

*Elevation of outflow changed during period of record







From Plate 8, cross section A–A′.

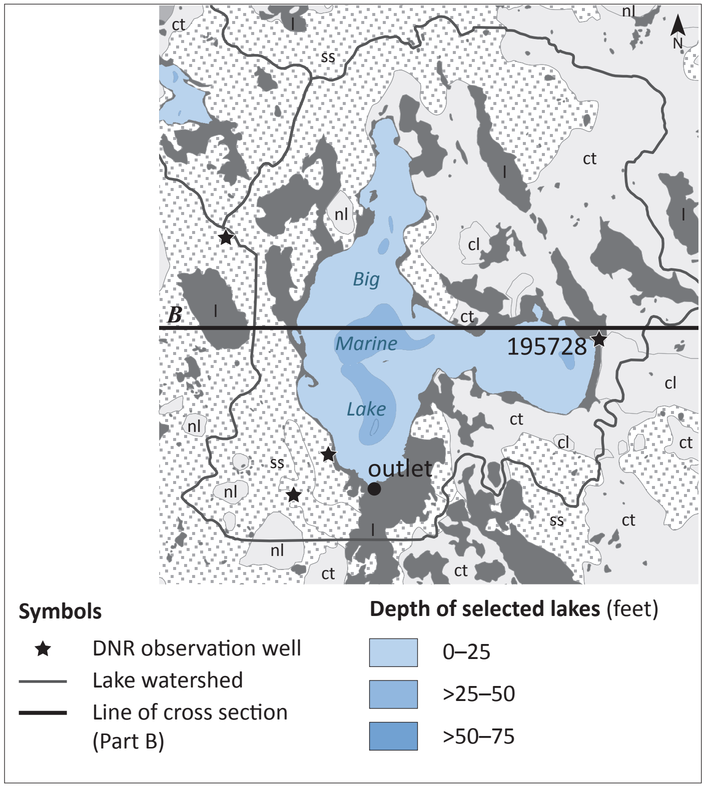
Figure 42. Forest Lake: limited groundwater connection

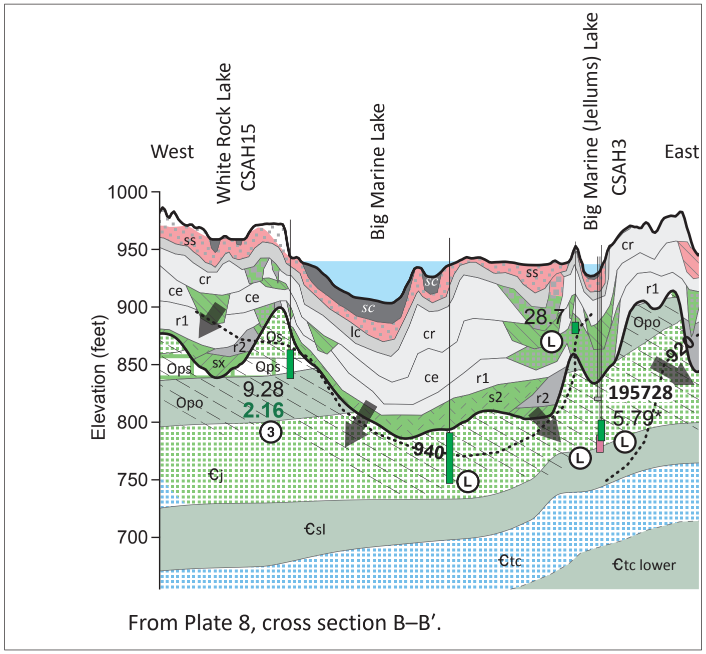
Upper left: Lakes with a small watershed/lake area ratio are usually connected to groundwater, but this lake is an exception with limited connection.

Lower left: The limitation is likely because the lake is underlain by an effective aquitard of loamy sediment, the **nt** (New Ulm till), one of the more effective aquitards in the region.

Corroborating chemical evidence (Figure 21) shows the lack of evaporative signature water in the downgradient buried sand aquifers.

Above: Significant surface water inflow and outflow limits the fluctuation of water levels to approximately 3 feet for the period of record since 1965 (Table 3).





From Plate 8, cross section B–B′.

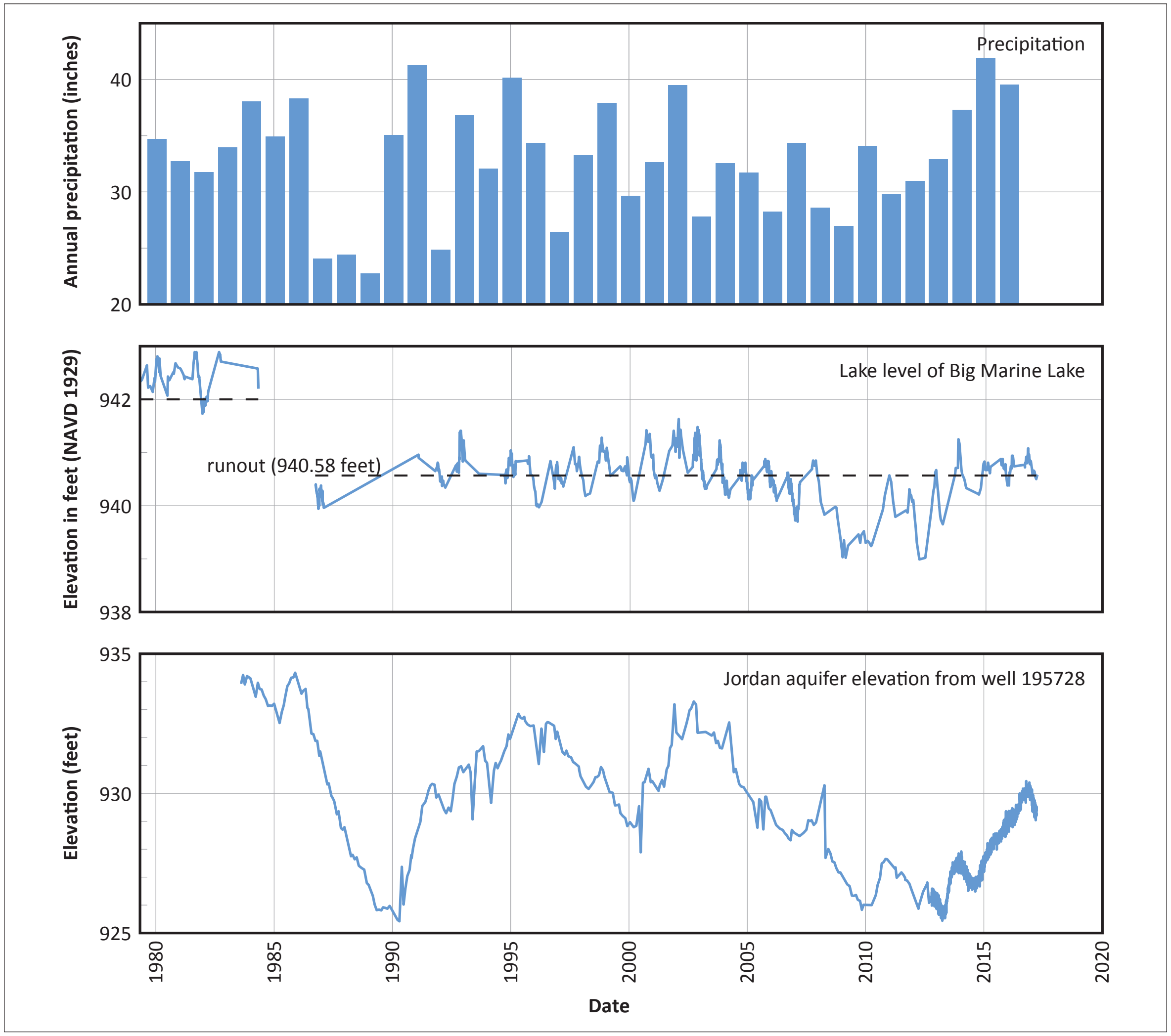


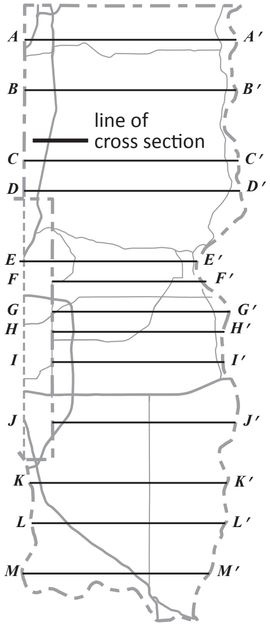
Figure 43. Big Marine Lake: groundwater flow dominated

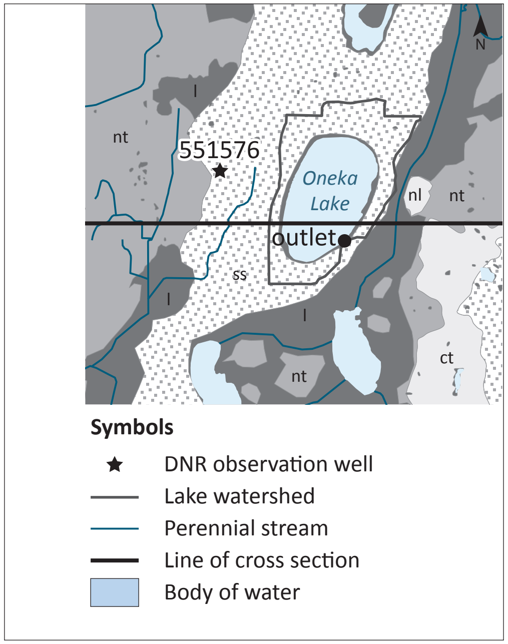
Upper left: Prior to 1984, Big Marine Lake did not have an engineered outlet and the lake was entirely land locked. The lowest land surface surrounding the lake that controlled lake levels was at approximately 942 feet (Brown, 1985). This elevation flooded homes in the area so a weir was installed in 1984 with a lower runout elevation of 940.58 feet (DNR, 1994). The lake has a small watershed/lake area ratio.

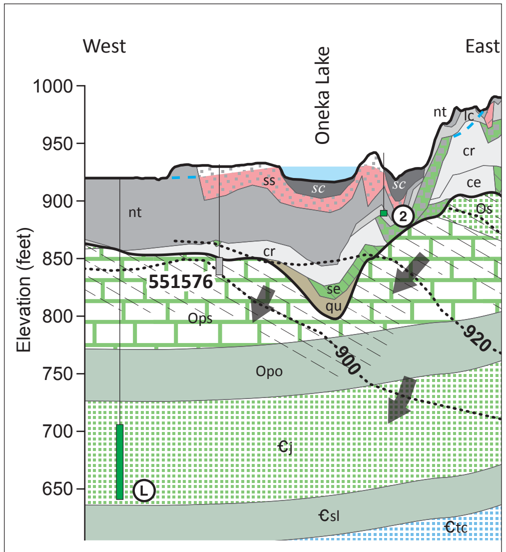
Lower left: Big Marine Lake is apparently underlain by sand aquifers (ss) and aquitards (sc). Previous studies classified this lake as flow through.

The chemical and potentiometric information suggest both flow through and discharge conditions.

Above: Two low precipitation periods are reflected in the lake and water levels from the Jordan aquifer (1987–1989 and 2003–2012). These periods resulted in a drop in groundwater levels of approximately 6 feet from the 932–934 feet peak levels of the intervening years. The corresponding lake-level drop during the later period was approximately 2.5 feet from the peak in 2002. Only limited lake-level data were available during the earlier drought period.







Line of cross section.
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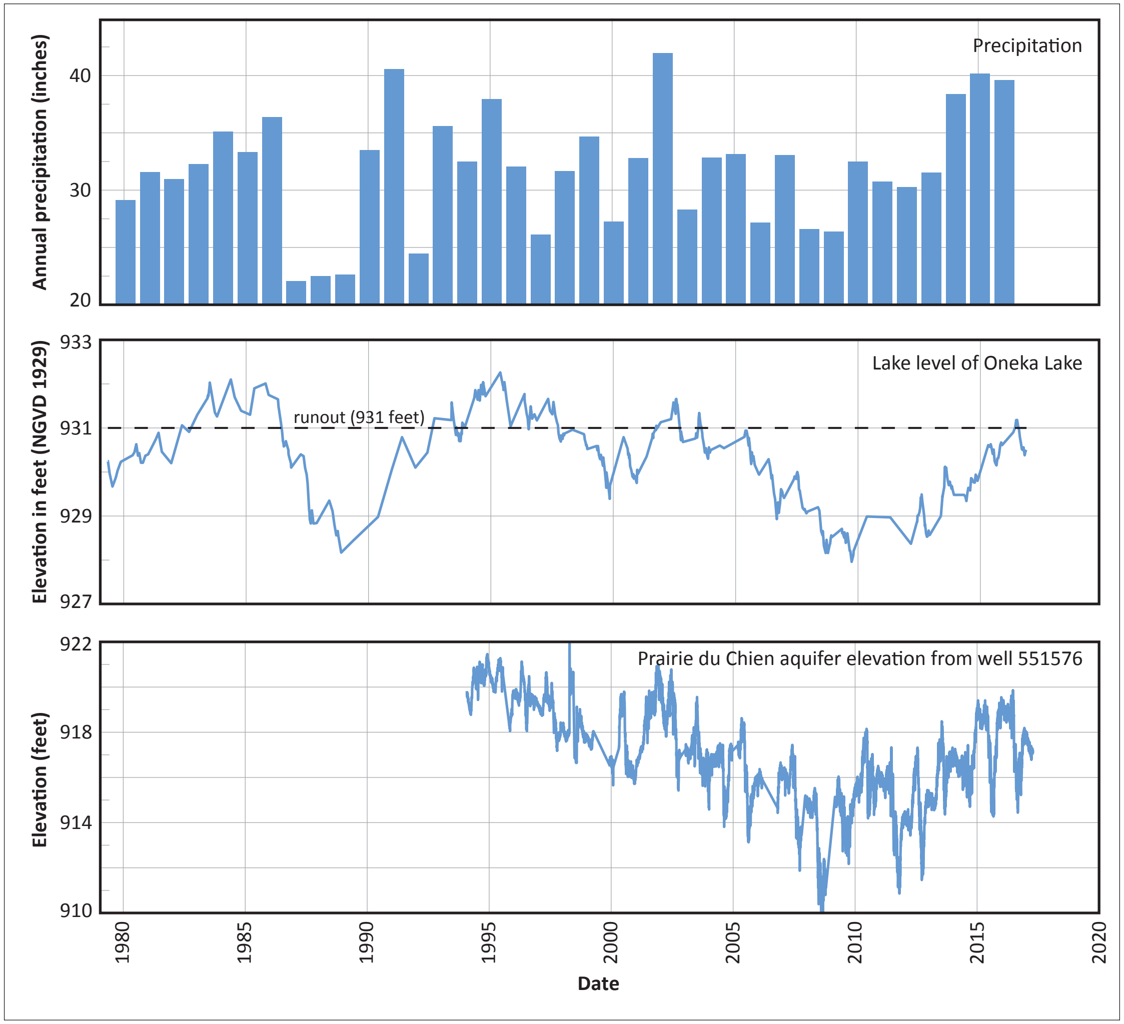
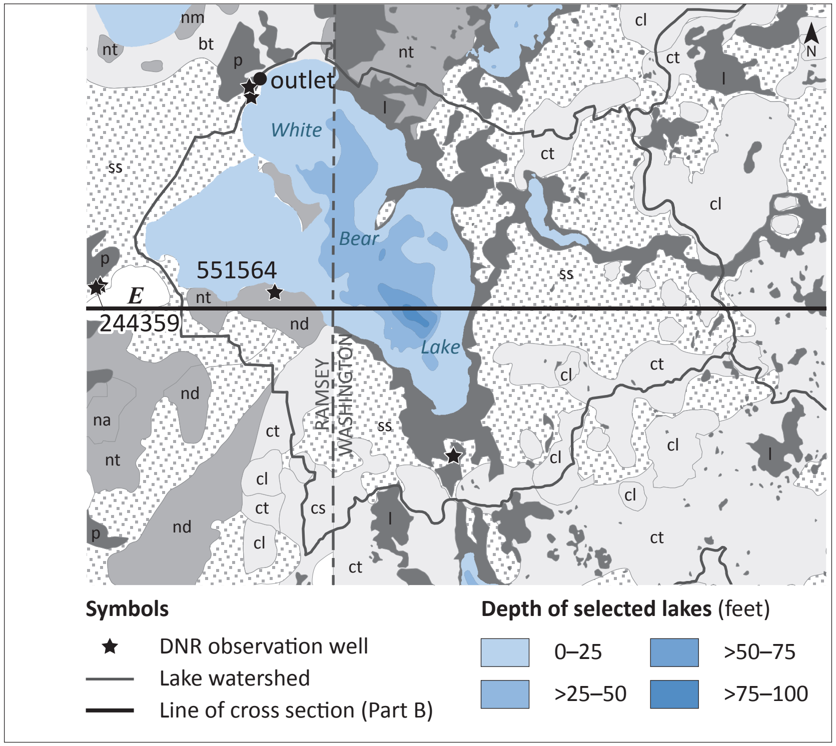


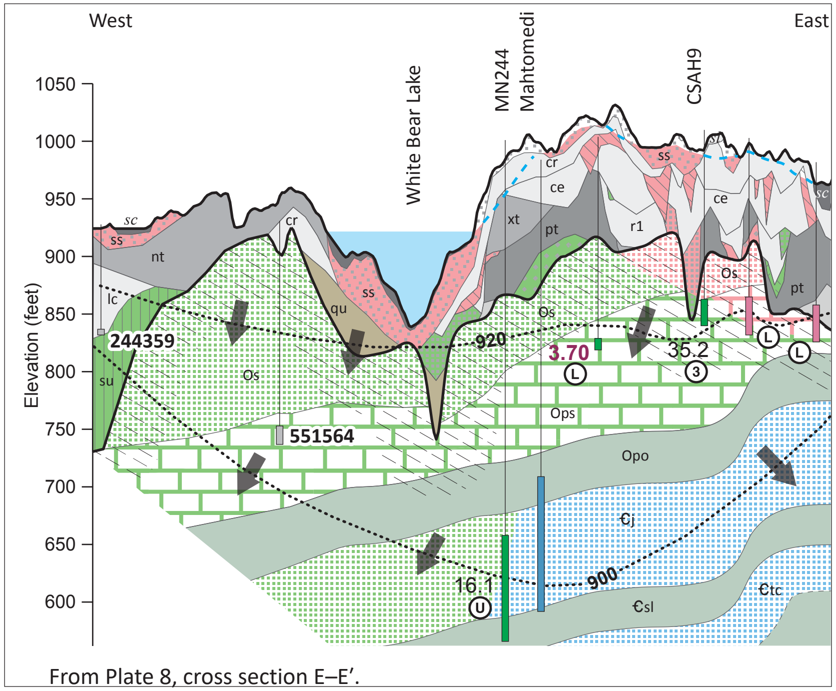
Figure 44. Oneka Lake: recharge lake (also groundwater flow dominated)

Upper left: Similar to Big Marine Lake, Oneka Lake has a small watershed/lake area ratio.

Lower left: The lake is apparently underlain by surficial sand (ss) and glacial till (nt). Previous studies have classified this lake as a recharge lake.

Above: The lake and Prairie du Chien aquifer levels have similar trends that match the higher and lower periods of precipitation. During the 1987–1989 drought, the lake level dropped approximately 4 feet. No water levels were recorded from the downgradient Prairie du Chien observation well during this period, but the low precipitation period from 2003–2013 is reflected in a low water-level trend in this aquifer.





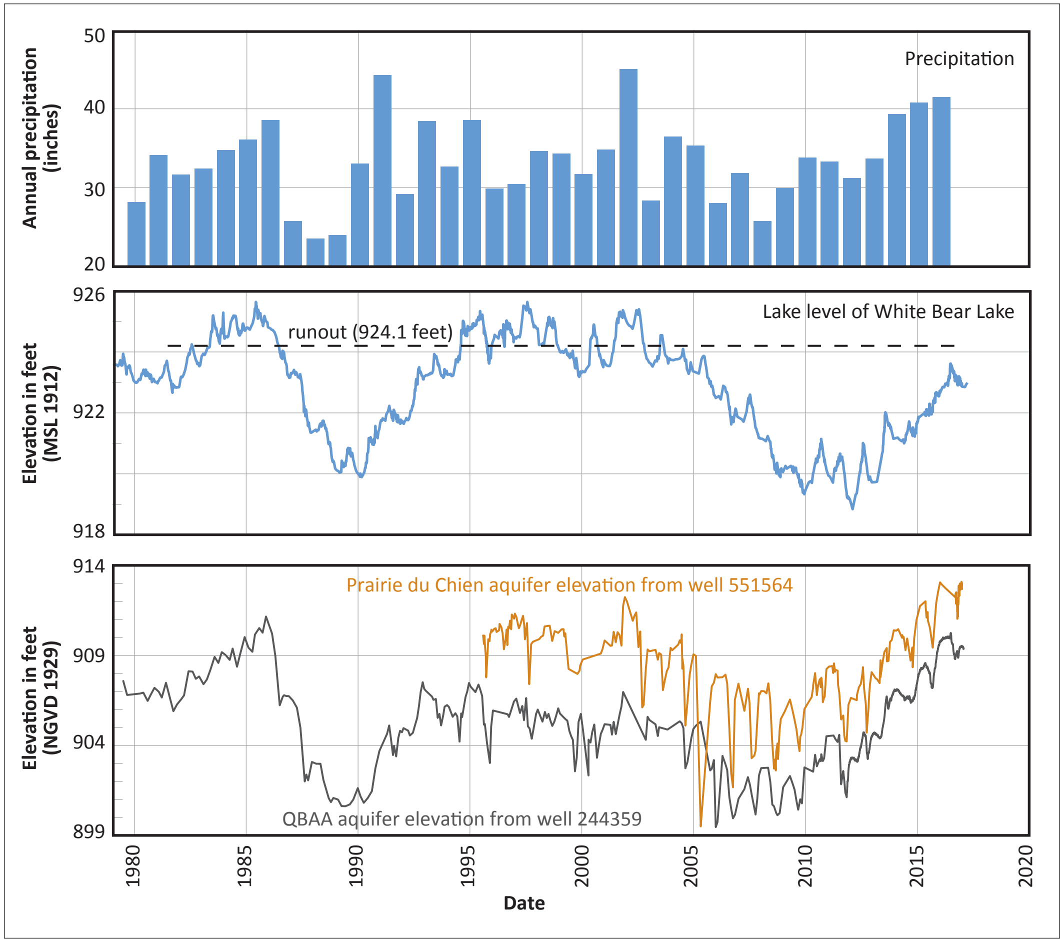


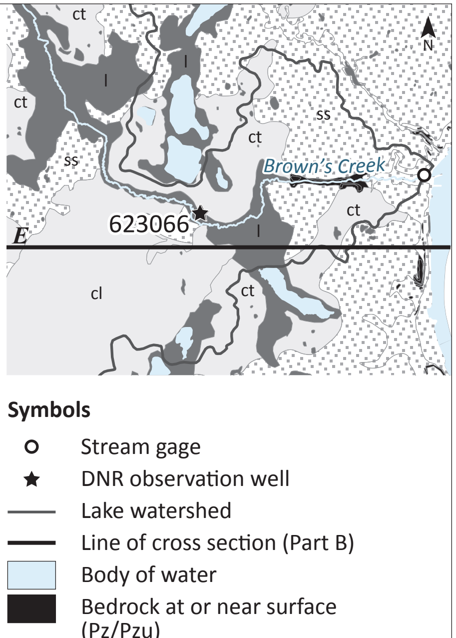
Figure 45. White Bear Lake: groundwater flow dominated

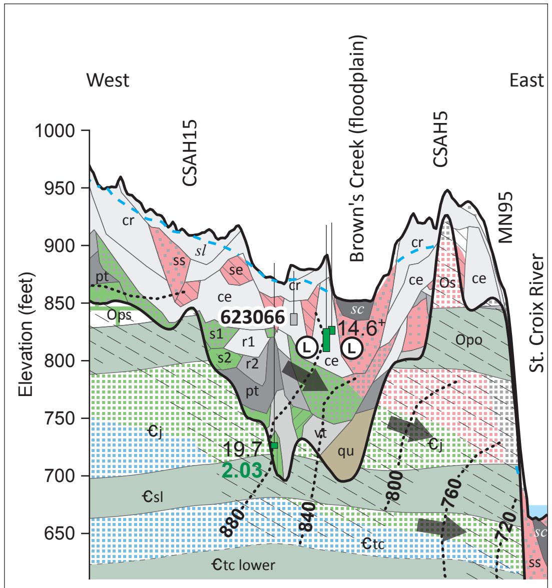
Upper left: White Bear Lake also has a small watershed/lake area ratio. Previous studies classified this lake as flow through.

Lower left: White Bear Lake has hydraulic connections to the underlying bedrock aquifers: St. Peter (Os) and Prairie du Chien (Ops). There may be less than 50 feet of glacial sediment between the bedrock surface and the deepest portion of the lake (approximately 80 feet deep on the south end). The chemical and potentiometric information suggest that this lake has both flow through and discharge tendencies.

Above: Short-term climate changes produced similar responses for the lake and aquifers. During the mid to late 1980's drought, the lake level dropped approximately 5 feet and the shallow buried sand aquifer (QBAA) dropped approximately 10 feet from the peak water level in 1985. During the low precipitation period from 2003–2013 the lake dropped approximately 5 feet. The aquifers declined approximately 7 (QBAA) and 5 (Prairie du Chien) feet. The high seasonal variability of the aquifers was probably due to increased groundwater pumping in the summers (Jones, 2013).

Higher rainfall returned in 2014 and by 2017, the water level in the Prairie du Chien aquifer was the highest ever recorded since observation well 551564 was installed in 1996. White Bear Lake levels returned to near outlet elevations, similar to Big Marine and Oneka lakes.





From Plate 8, cross section E–E′.

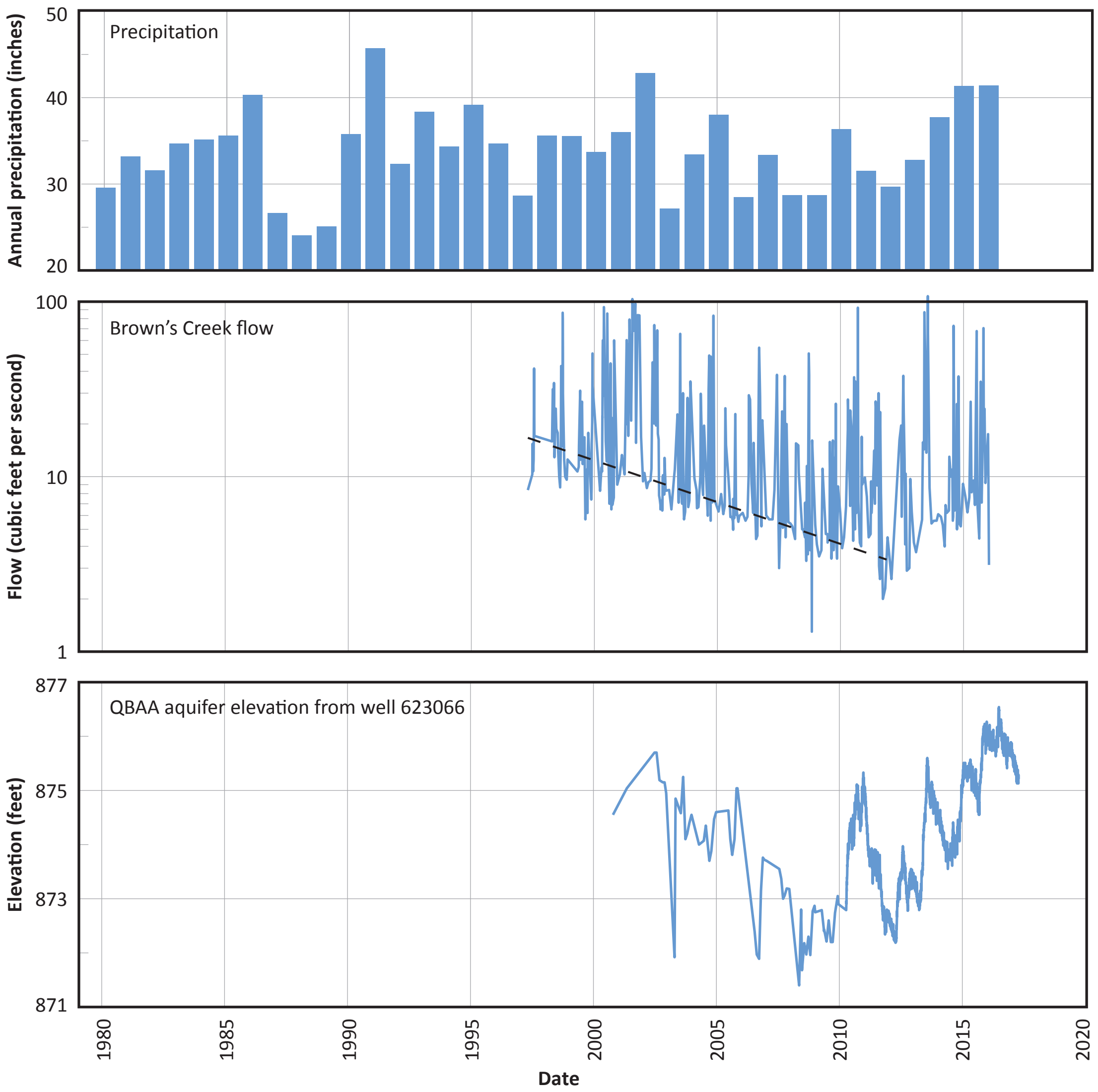


Figure 46. Brown's Creek: trout stream with shallow groundwater inflow

Upper left: Brown's Creek is known to have shallow groundwater inflow indicated by its typically cool temperatures and ability to support trout in approximately the last mile of the stream. The creek is one of the few remaining designated trout streams in the Twin Cities metropolitan area. Located in a small watershed, the creek originates from wetland areas in the northern portion of the watershed and flows through a mixed-use landscape including rural and urban areas.

Lower left: The creek is fed by shallow sand (ss) and bedrock aquifers: Prairie du Chien (Ops) and Jordan (Ꞓj).

Above: During the low precipitation period of 2003–2013, the creek flow volume and the shallow buried sand aquifer water levels declined. Creek base flow volumes dropped from a peak of approximately 9 cubic feet per second (cfs) in 2003 to a low of approximately 3 cfs in 2012 (Metropolitan Council, 2018). Water levels in the shallow buried sand aquifer declined approximately 5 feet in 2008 and 2012. Higher precipitation in 2014 caused stream flow volumes to return to the higher values of 9 to 10 cfs and the aquifer water levels to peak at 876 feet, the highest since the observation well was installed in 2000.

Groundwater use

A water-use 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. Permits require annual water-use reporting. This information is recorded using Minnesota Permitting and Reporting System (DNR, 2018b), which helps the DNR track the volume, source aquifer, and type of water use. Permitted groundwater use is presented as follows.

- Data for Washington County is represented in Table 4 by both aquifer type and water use.
- Data for the greater North and East Metro Groundwater Management Area (GWMA) is represented in Figure 47 by general aquifer type and in Figure 48 by water use. This area includes Washington County and was chosen to include wells outside the western borders because the water use is relevant to policy and legal issues for White Bear and other lakes in the area (DNR, 2015).

Most of the large capacity groundwater use across the greater GWMA area is from bedrock aquifers. Use from surficial sand and buried aquifers is relatively rare and limited to a few scattered locations. In Washington County the most commonly used aquifers are the Jordan and Jordan–St. Lawrence, followed by the Prairie du Chien and Prairie du Chien–Jordan.

The most common type of water use across the GWMA and the county is water supply. In Washington County the second and third most common categories are multiple uses and special categories. The highest volume for multiple uses occurs in southern Cottage Grove near the Mississippi River.

Table 4. Reported 2016 water use in Washington County

Aquifer	Number of wells	Agricultural irrigation	Industrial processing	Non-crop irrigation	Power generation	Special categories (primarily pollution containment)	Water supply	Multiple uses	Total (mgy)	Total (percent)*
Quaternary aquifers/										
Water table	26	-	34	-	-	49	-	546	629	6
Buried sand	14	-	-	1	-	4	-	454	459	4
Bedrock aquifers										
Platteville	1	-	-	-	-	-	-	1	1	<1
St. Peter	1	-	-	-	-	-	1	-	2	<1
Prairie du Chien	48	82	2	62	-	975	22	-	1,143	10
Prairie du Chien–Jordan	34	58	-	38	-	399	301	202	998	9
Prairie du Chien–St. Lawrence	12	-	-	-	-	-	38	516	554	5
Jordan, Jordan–St. Lawrence	86	240	-	46	-	-	6,040	-	6,326	57
Jordan–Tunnel City	2	-	-	-	-	1	-	5	6	<1
St. Lawrence–Mt. Simon	3	-	-	-	-	-	21	-	21	<1
Tunnel City	7	12	-	-	-	-	47	-	59	1
Tunnel City–Wonewoc, Tunnel City–Eau Claire	14	-	-	20	-	-	-	93	113	1
Tunnel City–Mt. Simon	3	-	124	13	-	-	-	-	137	1
Wonewoc	1	-	-	-	-	-	61	-	61	1
Wonewoc–Mt. Simon, Eau Claire–Mt. Simon	4	-	36	-	-	-	212	-	248	2
Mt. Simon, Mt. Simon–Hinckley	6	-	-	-	52	-	366	-	418	4
Unknown	10	5	4	-	-	-	-	-	9	<1
Total (mgy)		397	200	180	52	1,428	7,109	1,817	11,184	
Total (percent)*		4	2	2	<1	13	64	16		

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

*Percentage may not equal 100 due to rounding.

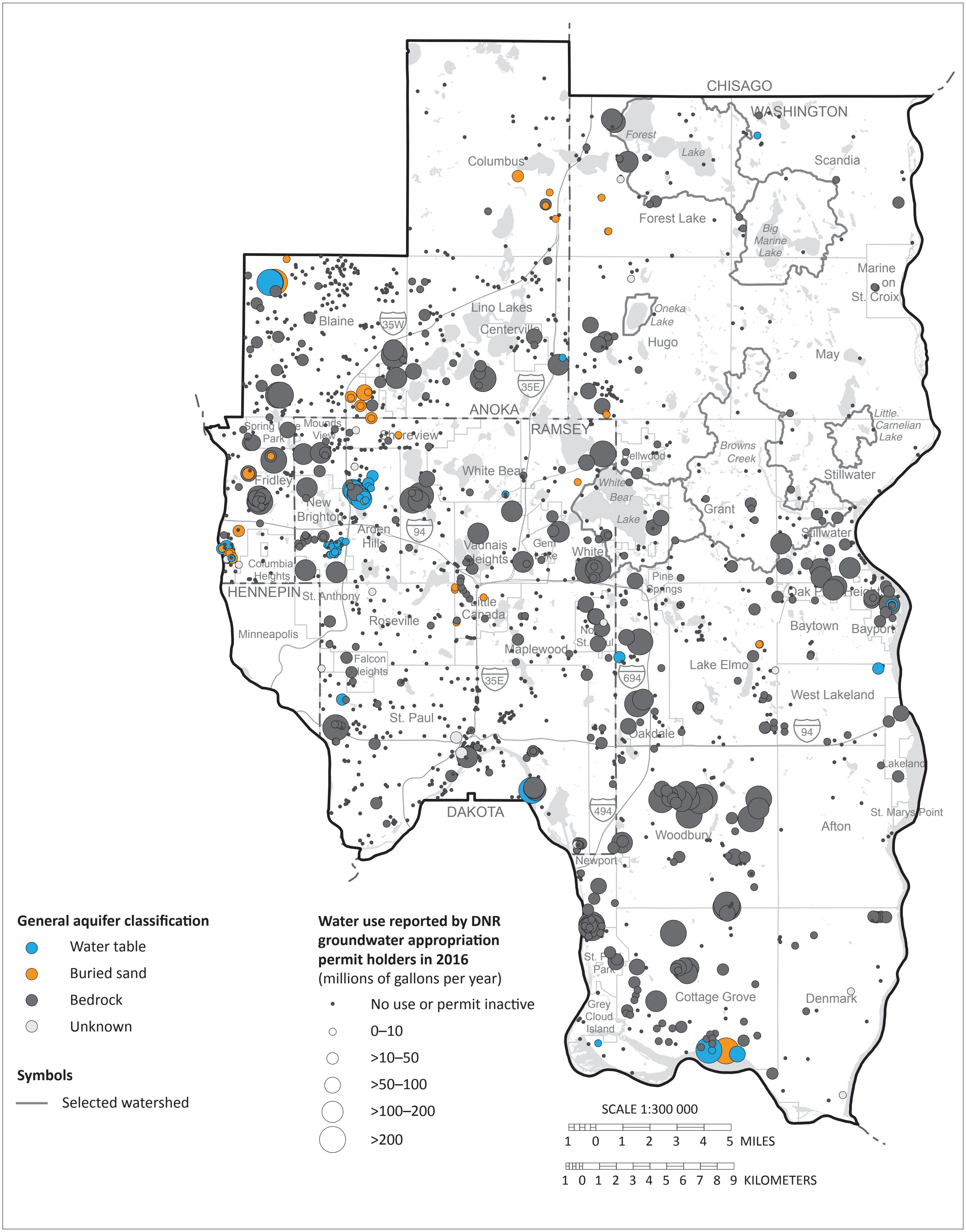


Figure 47. General aquifer classification of DNR appropriation permit holders in the North and East Metro Groundwater Management Area.

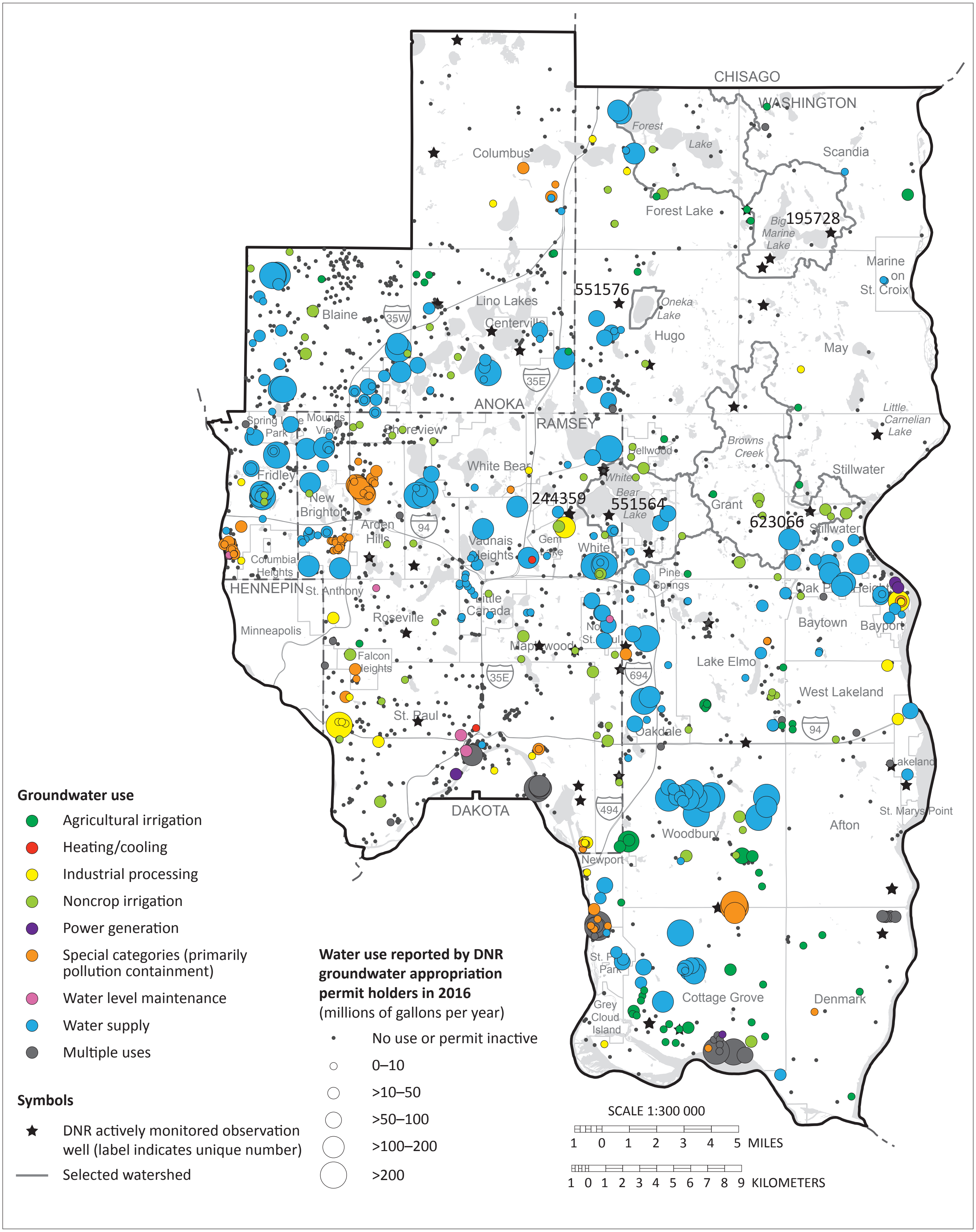


Figure 48. Groundwater use of DNR appropriation permit holders in the North and East Metro Groundwater Management Area.

References

Alexander, S.C., and Alexander, E.C., Jr., 1989, Residence times of Minnesota groundwaters: Minnesota Academy of Sciences Journal, v. 55, no. 1, p. 48–52.

Barr Engineering, 2010 (June), Evaluation of groundwater and surface-water interaction–guidance for resource assessment: Twin Cities Metropolitan Area, Minnesota, prepared for the Metropolitan Council.

Berg, James A., 2011, Geologic atlas of Carlton County, Minnesota: Minnesota Department of Natural Resources, County Atlas Series C-19, Part B, 4 pls.

Brown, R.G., 1985, Hydrologic factors affecting lake-level fluctuations in Big Marine Lake, Washington County, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 85-4176.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702–1703.

Davis, S.N., Whittemore, D.O., and Fabrryka-Martin, J., 1998, Uses of chloride/bromide ratios in studies of potable water: Ground Water, March–April, v. 36, no. 2, p. 338–350.

DNR, 1994 (April), Big Marine Lake (82–36) Washington County, hydrologic study: Minnesota Department of Natural Resources and Carnelian–Marine Watershed District.

DNR, 2015 (November), North & East Metro Groundwater Management Area Plan: Minnesota Department of Natural Resources.

DNR, 2016a, Methods for estimating water-table elevation and depth to water table: Minnesota Department of Natural Resources, County Geologic Atlas program, GW-04.

DNR, 2016b, Methods to estimate near-surface pollution sensitivity: Minnesota Department of Natural Resources, County Geologic Atlas program, GW-03.

DNR, 2016c, Minnesota regions prone to surface karst feature development: Minnesota Department of Natural Resources, County Geologic Atlas program, GW-01.

DNR, 2016d, Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment (CFGS) thickness: Minnesota Department of Natural Resources, County Geologic Atlas program, GW-02.

DNR, 2018a, Cooperative groundwater monitoring database: Minnesota Department of Natural Resources, data for Washington County wells, accessed June 2018.

DNR, 2018b, Minnesota Permitting and Reporting System (MPARS): Minnesota Department of Natural Resources, data for Washington, Ramsey, Anoka, and Hennepin counties, accessed June 2018.

DNR, 2018c, Minnesota Spring Inventory: Minnesota Department of Natural Resources, statewide dataset of springs.

Emmons and Oliver Resources, 2003, Integrating groundwater and surface water management, northern Washington County.

EPA, 2017 (July), National primary drinking water regulations–inorganic chemicals: U.S. Environmental Protection Agency website.

EPA, 2017 (March), Secondary drinking water standards–guidance for nuisance chemicals: U.S. Environmental Protection Agency website.

Erickson, M.L., and Barnes, R.J., 2005a, Glacial sediment causing regional-scale elevated arsenic in drinking water: Ground Water, November–December, v. 43, no. 6, p. 796–805.

Erickson, M.L., and Barnes, R.J., 2005b, Well characteristics influencing arsenic concentrations in ground water: Water Research, v. 39, p. 4029–4039.

Geologic Sensitivity Workgroup, 1991, Criteria and guidelines for assessing geologic sensitivity of ground water resources in Minnesota: Minnesota Department of Natural Resources, 122 p.

Hem, J.D., 1985 [1986, 1989], Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water Supply Paper 2254, 272 p., [U.S. Government Printing Office 1985, reprinted in 1986 and 1989, ISBN 85-600603].

Hounslow, A.W., 1995, Water quality data–analysis and interpretation: CRC Press, p. 71–128.

Jones, P.M., Trost, J.J., Rosenberry, D.O., Jackson, P.R., Bode, J.A., and O’Grady, R.M., 2013, Groundwater and surface-water interactions near White Bear Lake, Minnesota, through 2011: U.S. Geological Survey, Scientific Investigations Report 2013-5044, 73 p.

Kendall, C., and Doctor, D., 2003, Stable isotope applications in hydrologic studies, *in* Holland, H.D., and Turekian, K.K., eds., Surface and ground water, weathering, and soils: Amsterdam, The Netherlands, Elsevier, Inc., Treatise on Geochemistry, 1st edition, v. 5.11, p. 319–364, ISBN 978-0-08-043751-4.

Lucas, L.L., and Unterweger, M.P., 2000, Comprehensive review and critical evaluation of the half-life of tritium: Journal of Research of the National Institute of Standards and Technology, v. 105, p. 541–549.

McMahon, P.B., 2001, Aquifer/aquitard interfaces–mixing zones that enhance biogeochemical reactions: Hydrogeology Journal, v. 9, p. 34–43.

MDA, 2017, Washington County–final overview of nitrate levels in private wells (2014–2015): Minnesota Department of Agriculture.

MDH, 1998, Guidance for mapping nitrates in Minnesota groundwater: Minnesota Department of Health, revised January 10, 2003 [available upon request from the County Geologic Atlas program].

MDH, 2012a, Human health-based water guidance table: Minnesota Department of Health website under Environmental Health.

MDH, 2012b, Initial assessment of manganese in Minnesota groundwater: Minnesota Department of Health, Internal Memorandum, September 5, 2012, p. 4–5.

MDH, 2018a, Arsenic in well water: Minnesota Department of Health, document ID# 52971.

MDH, 2018b March, Manganese and drinking water: Minnesota Department of Health, Health Risk Assessment Unit Information Sheet.

Metropolitan Council, 2018, Environmental information and management systems database: Browns Creek at Dellwood Rd, accessed June 2018.

Minnesota Administrative Rules 4725.5650, 2008, Water quality samples from newly constructed potable water-supply well: Office of the Revisor of Statutes, State of Minnesota.

MPCA, 2018, Baytown township groundwater contamination site: Minnesota Pollution Control Agency web page, accessed December 2018.

Nicholas, S.L., Toner, B.M., Erickson, M.L., Knaeble, A.R., Woodruff, L.G., and Meyer, G.N., 2011, Speciation and mineralogy of arsenic in glacial sediments and their effect on arsenic concentrations in groundwater [abs.]: Geological Society of America, Abstracts with Programs [digital version], v. 43, no. 5.

NOAA, 2018, Climate at a glance: National Oceanic and Atmospheric Administration, U.S. Time Series Precipitation, data for State/Region–Minnesota, Climate Division–CD 5 Central, accessed August 28, 2018.

Panno, S.V., Hackley, K.C., Hwang, H.H., Greenberg, S.E., Krapac, I.G., Landsberger, S., and O'Kelly, D.J., 2006, Characterization and identification of Na-Cl sources in ground water: Ground Water, March–April, v. 44, no. 2, p. 176–187.

Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., and Alexander, S.C., 2006, Hydrostratigraphic characterization of intergranular and secondary porosity in part of the Cambrian sandstone aquifer system of the cratonic interior of North America–improving predictability of hydrogeologic properties: Sedimentary Geology, v. 184, p. 281–304.

Smith, E.A., and Westenbroek, S.M., 2015, Potential groundwater recharge for the state of Minnesota using the soil-water-balance model, 1996–2010: U.S. Geological Survey, Scientific Investigations Report 2015-5038, 85 p.

Thomas, M.A., 2007, The association of arsenic with redox conditions, depth, and ground-water age in the glacial aquifer system: U.S. Geological Survey, Scientific Investigations Report 2007-5036, 26 p.

University of Minnesota School of Earth Sciences, 2018: Karst feature inventory points: available from the Minnesota Department of Natural Resources on the Minnesota Geospatial Commons website.

U.S. Census Bureau, 2018, QuickFacts: data for Washington County, accessed June 2018.

USDA-NRCS, 2009, Hydrologic soil groups: U.S. Department of Agriculture–Natural Resources Conservation Service, National Engineering Handbook, Chapter 7, Part 630, Hydrology.

USDA-NRCS, 2016, Web soil survey geographic database (SSURGO): U.S. Department of Agriculture, Natural Resources Conservation Service, data for Washington County, Minnesota, accessed April 2016.

Wilson, J.T., 2012, Water-quality assessment of the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Scientific Investigations Report 2011-5229, 154 p.

Yingling, V., 2015, Karst influence in the creation of a PFC megaplume, *in* Doctor, D.H., Land, L., and Stephenson J.B. (eds.), Sinkholes and the engineering and environmental impacts of karst: Proceedings of the Fourteenth Multidisciplinary Conference, published by the National Cave and Karst Research Institute, Carlsbad, NM.

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).

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

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

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

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

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

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

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

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

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

horst—a raised fault block that is bounded by normal faults.

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.

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 (≥1 ppm) is primarily from human waste, animal waste, and fertilizer sources.

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

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.

provenance—the place of origin of a glacier.

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

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

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

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

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.

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.

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 field parameters such as temperature, conductivity, dissolved oxygen, and pH had stabilized. 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 (U of M), and/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.

For additional information, contact the County Atlas program.

Appendix Table A-1: 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	U of M
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 sample water prior to collecting the sample (FILTERED if sample is filtered). 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 2017.

For additional tritium information, contact the DNR Groundwater Atlas Program (county.groundwater.atlas.dnr@state.mn.us).

For additional weather station information, contact the MNgage program. (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

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 time 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 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 to <8 TU	>1 to <10 TU
Vintage	≤1 TU	≤1 TU	≤1 TU

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