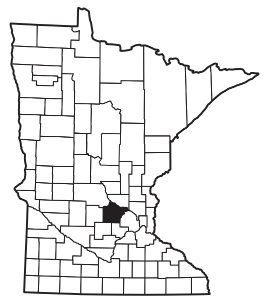
Geologic Atlas of Wright County, Minnesota

County Atlas Series C-30



Part B, Hydrogeology

Report

To accompany these atlas components:

Plate 7, Water Chemistry

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

Plate 9, Hydrogeologic Cross Sections, D–D′ through G–G′

DEPARTMENT OF NATURAL RESOURCES

St. Paul

2018

mndnr.gov/groundwatermapping

Recommended Citation

Barry, J.D., 2018, Geologic Atlas of Wright County, Minnesota (Part B): Minnesota Department of Natural Resources, County Atlas Series C-30, Report and Plates 7–9.

County Geologic Atlas Program

The Minnesota County Geologic 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 2013. It 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 Hydrogeology 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, and descriptions of the Part A and Part B components are available online:

Part A (mngs.umn.edu/county_atlas/countyatlas.htm)

Part B (mndnr.gov/groundwatermapping)

Technical Reference

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

Maps were prepared from DNR and other publicly available information. Every reasonable effort has been made to ensure the accuracy of the factual data on which the report and map interpretations were based. However, the DNR does not warrant the accuracy, completeness, or any implied uses of these data. Users may wish to verify critical information. Sources include both the references here and information on file in the offices of the MGS and the DNR. Every effort has been made to ensure the interpretations conform to sound geologic and cartographic principles. These maps should not be used to establish legal title, boundaries, or locations of improvements.

Base maps were modified from MGS, Wright County Geologic Atlas, Part A, 2013. Universal Transverse Mercator projection, zone 15, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion Factors

1 inch per hour = 7.056 x 10^{-6} meters 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 (separate inserts)

Acknowledgments

The author would like to thank the following people from the DNR for their help in reviewing this report and providing helpful suggestions: Jim Berg, Nick Evans, Holly Johnson, Ruth MacDonald, Todd Petersen, and Paul Putzier. The author also thanks the following people for assistance with fieldwork: Vanessa Baratta, Nic Borchardt, Randy Bradt, Holly Johnson, and Ruth MacDonald; Pete Boulay assisted with precipitation isotope sample collection; and Joe Stewig assisted with lake water isotope sampling. Scott Alexander from the University of Minnesota assisted with the collection and interpretation of the carbon-14 results of this report.

Additional technical review was provided by Melinda Erickson, United States Geological Survey; Al Knaeble, Minnesota Geological Survey; Sharon Kroening, Minnesota Pollution Control Agency; Mike MacDonald, Minnesota Department of Agriculture; Julia Steenberg, Minnesota Geological Survey; Bill Stephens, Wright County Environmental Health; Bob Tipping, Minnesota Geological Survey; and John Woodside, Minnesota Department of Health.

Geologic Atlas of Wright County, Minnesota, Part B

By John D. Barry

Introduction

This report and the accompanying plates are Part B of the Wright County Geologic Atlas. Part B describes the hydrogeology and is produced by the Minnesota Department of Natural Resources (DNR). It builds on the geology described in Part A of the atlas, which was previously published by the Minnesota Geological Survey (MGS).

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

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 buried sand and gravel aquifers and bedrock aquifers. The following describes the sections incorporated into this atlas.

Physical setting and climate describes the location of the county, summarizes the county's average temperature and precipitation, and lays the framework for how these influence groundwater recharge.

Geology and physical hydrogeology describes characteristics of the 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).

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.

Pollution sensitivity is modeled for the following:

1) The sensitivity of *near-surface materials* is an estimate of the time it takes for water to infiltrate the land surface to a depth of 10 feet. This model is based on hydrologic soil groups and surficial geologic matrix textures.

2) The *sensitivity of buried sand and gravel aquifers and the bedrock surface* is based on the cumulative thickness of fine-grained sediment (aquitard material) overlying an aquifer or the bedrock surface. The pollution sensitivity ratings are compared to tritium and carbon-14 data for residence time, and to inorganic chemistry constituents. These comparisons are used to evaluate the model results.

Hydrogeologic cross sections illustrate groundwater flow, residence time, and distribution of chemicals. Cross sections help define areas of interest, such as locations of important groundwater recharge, discharge, and sensitivity to pollution.

Aquifer characteristics and groundwater use summarize specific capacity tests, aquifer tests, and water-use records for each aquifer, where available. DNR groundwater level monitoring data is also used to characterize aquifer recharge in the county.

A Geologic Atlas User's Guide is available from the MGS for additional information on the history and purposes of the County Geologic Atlas program, various atlas applications, and descriptions of the Part A components (Setterholm, 2014).

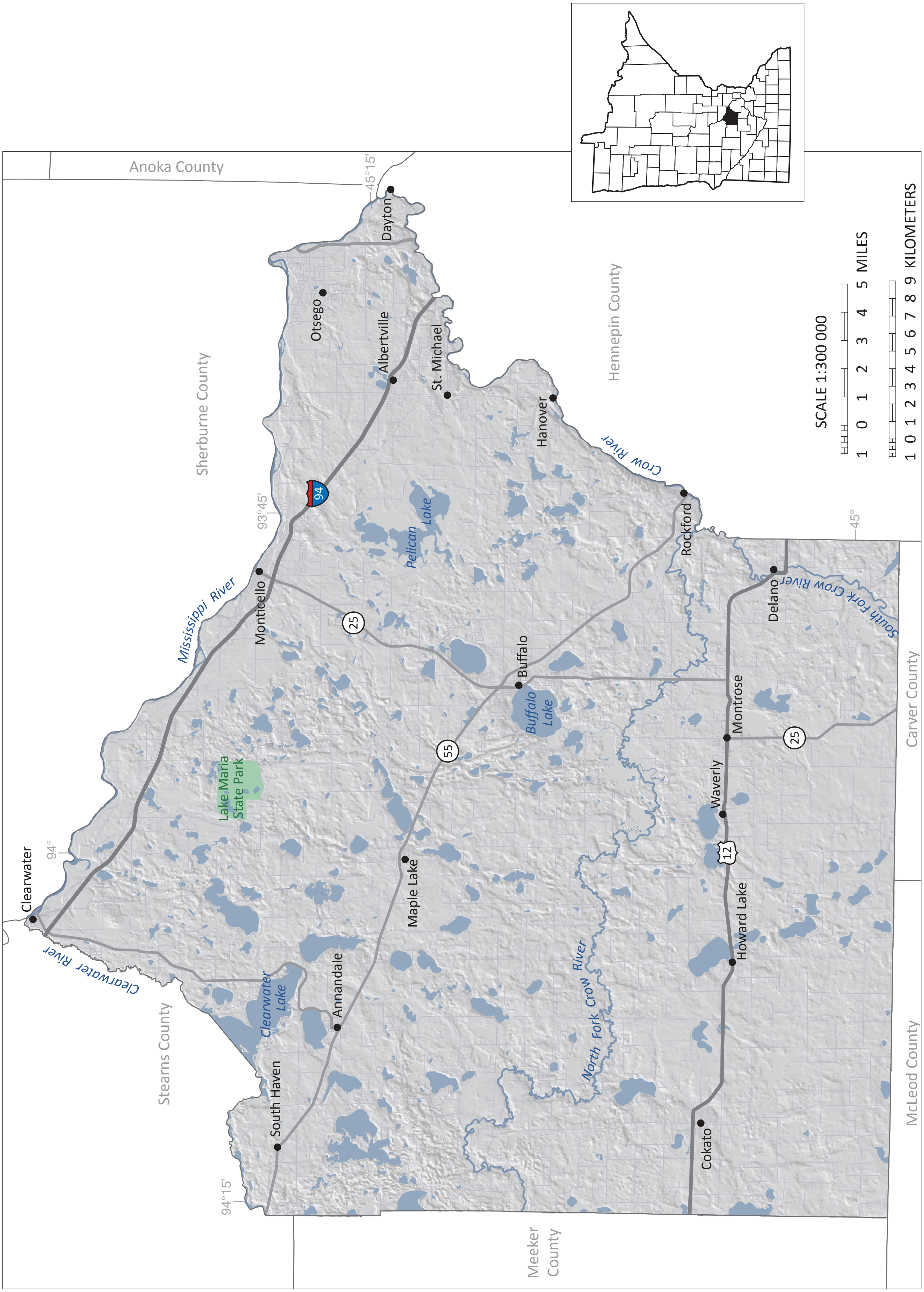


Figure 1. Wright County, Minnesota

Physical setting and climate

Wright County is located in south-central Minnesota and is characterized by varied landforms with hummocky terrain and numerous lakes and wetlands. The landscape was primarily shaped by processes during the most recent glacial period.

The county is bordered by three river systems. The Clearwater River forms the northwestern border, the Mississippi River forms the northeastern border, and the Crow River forms roughly two-thirds of the eastern border. The North Fork Crow River crosses the entire county from Meeker County in the west to the confluence with the South Fork Crow River in Rockford. Surface-water flow is influenced by elevation and landform and drains toward three separate subbasin-level surface watersheds (Figure 4) which ultimately flow southeast to the Mississippi River basin. Detailed explanations that illustrate how the landforms were shaped by glacial processes are available in Part A, Plate 3.

Minnesota is a headwaters state where surface water and shallow groundwater systems are replenished solely by precipitation. Because of this, water levels and availability fluctuate with wet and dry years. Water levels in deeply buried aquifer systems often don't track directly with precipitation, as water takes longer to travel to these systems. Water that doesn't percolate underground leaves the state by a network of rivers that flow north into the Red River basin, east to the Great Lakes basin, southwest to the Missouri River basin, or southeast to the Mississippi River basin.

Wright County is characterized as a cool subhumid climate with a large temperature differential between summer and winter. Summers are relatively short with an average temperature of approximately 69 degrees Fahrenheit (°F) (NOAA, 2017). The typical growing season is approximately 150 days from May to October with an average daily air temperature over 45°F (Figure 2). Evaporation increases dramatically during the growing season through plant uptake and transpiration, reducing the amount of precipitation that ultimately becomes groundwater.

Average winter temperatures are typically below freezing and the ground is frequently covered with snow from November through March. The soil frost depth often ranges from 3 to more than 5 feet for approximately 4 to 5 months of the year, limiting the amount of precipitation that can infiltrate and become groundwater during the winter.

Average annual precipitation is approximately 29 inches, falling in the middle of the statewide range of 20 to 36 inches. Most precipitation occurs in June, July, and August (MCWG, 1981–2010). Only a small fraction of this precipitation eventually becomes groundwater because of evaporation, transpiration, and overland runoff to streams and wetlands.

The majority of groundwater recharge occurs in the spring, when snowmelt and precipitation infiltrate the land surface prior to the growing season. Hydrographs from groundwater level monitoring wells illustrate this pattern and are presented in the discussion of groundwater level response in the "Aquifer characteristics and groundwater use" section of this atlas (p. 56–57).

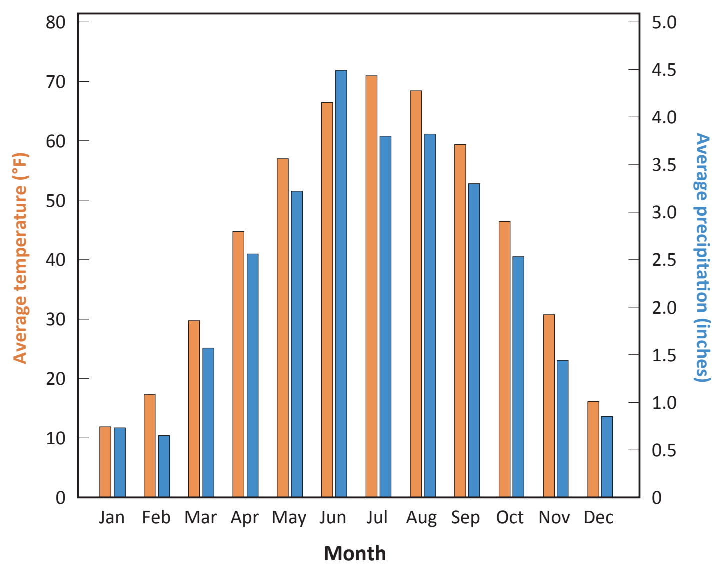


Figure 2. Average temperature and precipitation
Minnesota Climate Division 5, which includes Wright County (1971–2000, 30-year record; NOAA, 2017).

Geology and physical hydrogeology

Surficial aquifers

The surficial geology of Wright County is dominated by New Ulm Formation sediments that were deposited by glacial ice of the Des Moines Lobe (Part A, Plate 3). These sediments are primarily fine grained in texture (clay and silt) and are depicted with a brown hue in Figure 3. The coarse-grained sand and gravel deposits depicted with a light tan hue in Figure 3 are where the Des Moines lobe reworked earlier Superior lobe deposits in what is now northern Wright County. The term *texture* qualitatively refers to the physical size of soil particles, ranging from coarse grained, such as sand and gravel, to fine grained, such as silt and clay.

Additional coarse-grained terrace deposits occur along the modern-day Mississippi River and within the main valleys of the North Fork Crow, South Fork Crow, and Crow rivers. Where saturated, these coarse-grained sediments make up the surficial sand and gravel aquifer, which will be referred to as the *surficial sand aquifer* for the rest of this atlas. The texture of these surficial deposits influences the rate and amount of precipitation that infiltrates from the land surface downward and eventually becomes groundwater. A detailed explanation of the county's glacial history and how it relates to present-day surficial geologic deposits is available in Part A, Plate 3 of this atlas.

Water table

The water table is the surface between the unsaturated and saturated zones where the water pressure equals atmospheric pressure. The water table occurs in both aquifer and aquitard sediment across the entire county. The water table is shown as a static surface in this atlas but actually varies with time (Figure 4 and 5).

Water-table elevation was estimated in this atlas using several sources of data as described in *Methods for estimating water-table elevation and depth to water table* (DNR, 2016a). The primary data sources used to estimate the water table were the following:

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

Figure 4 shows the approximate elevation of the water table throughout the county. The water table is generally a subdued expression of the surface topography. In Wright County it is highest in the northwest and southwest; it is lowest along the northeastern and southeastern borders and within the main valley of the North Fork Crow River near Rockford. At county scale, groundwater flow is from water-table elevation highs to regional discharge areas, such as the Mississippi, North Fork Crow, South Fork Crow, and Crow rivers. At more localized scales, groundwater flow in the water-table aquifer is from local highs to river tributaries, lakes, and wetlands.

The stippled area shown in Figure 3 and 4 show areas where the surficial sand aquifer is present. These are areas where the aquifer has sufficient saturated thickness and yield to provide a reliable source of water. Countywide, less than 7 percent of permitted wells are constructed in the surficial sand aquifer, with the majority of these wells located in the stippled area. Less than 1 percent of permitted wells (approximately 70), use the surficial sand aquifer for nondomestic use, such as irrigation or monitoring.

Many wells completed in the surficial sand aquifer are not in the database (A. O'Hare, Wright SWCD, written commun., 2017). These drive point wells are less than 30 feet deep and use the water-table aquifer for domestic use. Their number and distribution is unknown. Drive point wells are colloquially known as "sand points."

The water-table maps provide useful baseline information for applications, such as water resource protection, planning, modeling, and site investigations, but additional site-specific information, such as soil borings should be used to refine information at local scales. Certain conditions affect the fluctuation of the water table and can create locally different results from the maps in this atlas. These conditions include seasonal weather conditions, extent and composition of surficial geology units, land-use practices, vegetation composition and distribution, and pumping of large capacity wells.

Depth to water table was derived by subtracting the water-table elevation from the land-surface elevation (DNR, 2016a).

Shallow water-table conditions (0–10 feet) are common in the county (Figure 5). Exceptions are areas where coarse-grained outwash deposits form topographic highs, such as around Annandale and Monticello, or areas along the valley edges of the county's larger river systems.

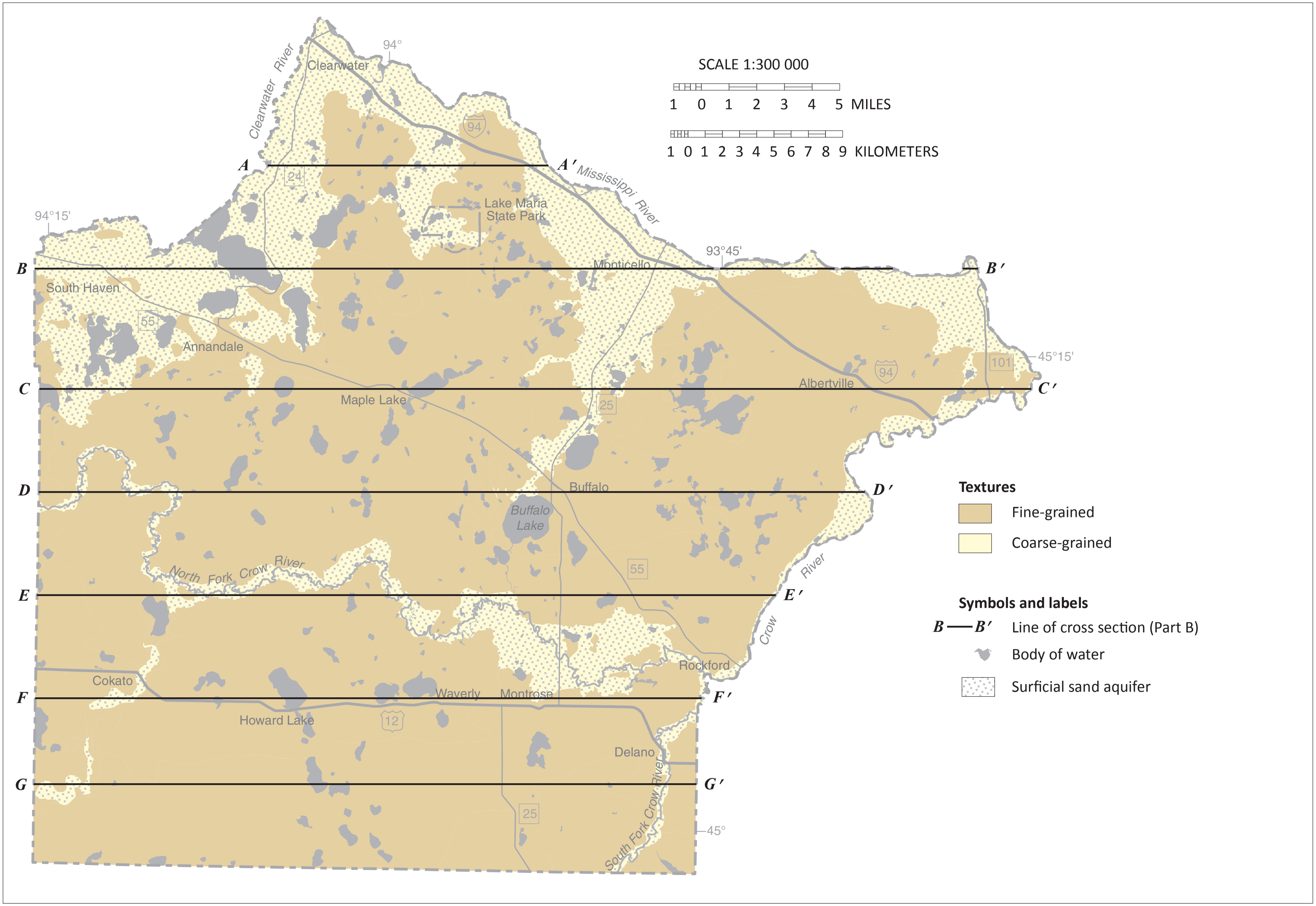


Figure 3. Generalized surficial geologic units
Fine-grained deposits, such as clay and silt are present at the surface in the majority of the county. Elsewhere, coarse-grained deposits, such as sand and gravel are present. The presence of coarse-textured geologic materials at the surface in part controls the pollution sensitivity of the underlying aquifers (modified from Part A, Plate 3).

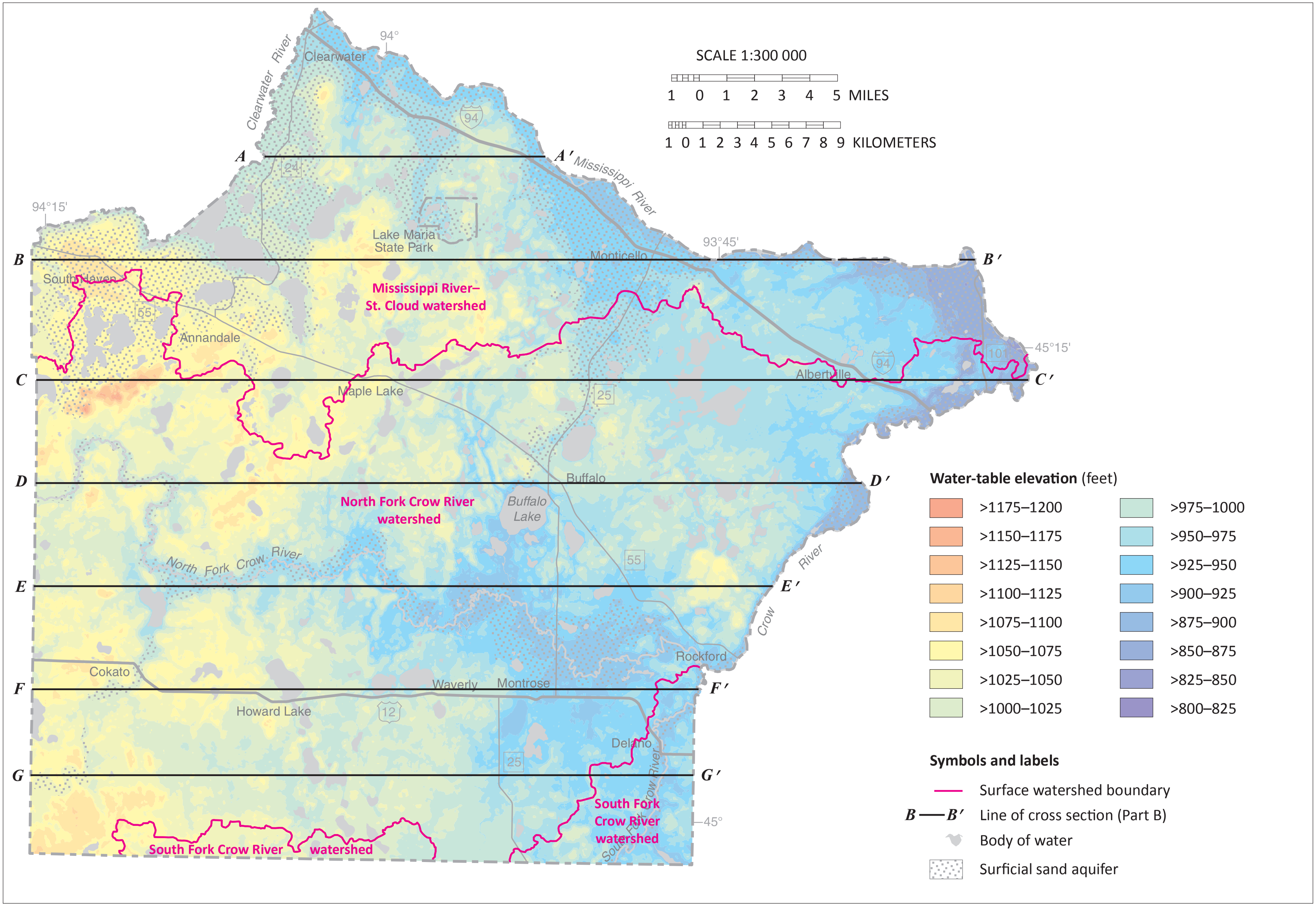


Figure 4. Water-table elevation
The water table is a subdued expression of the county's topography. Groundwater flows from elevation highs toward major rivers and their tributaries. Map modified from Adams, 2016a.

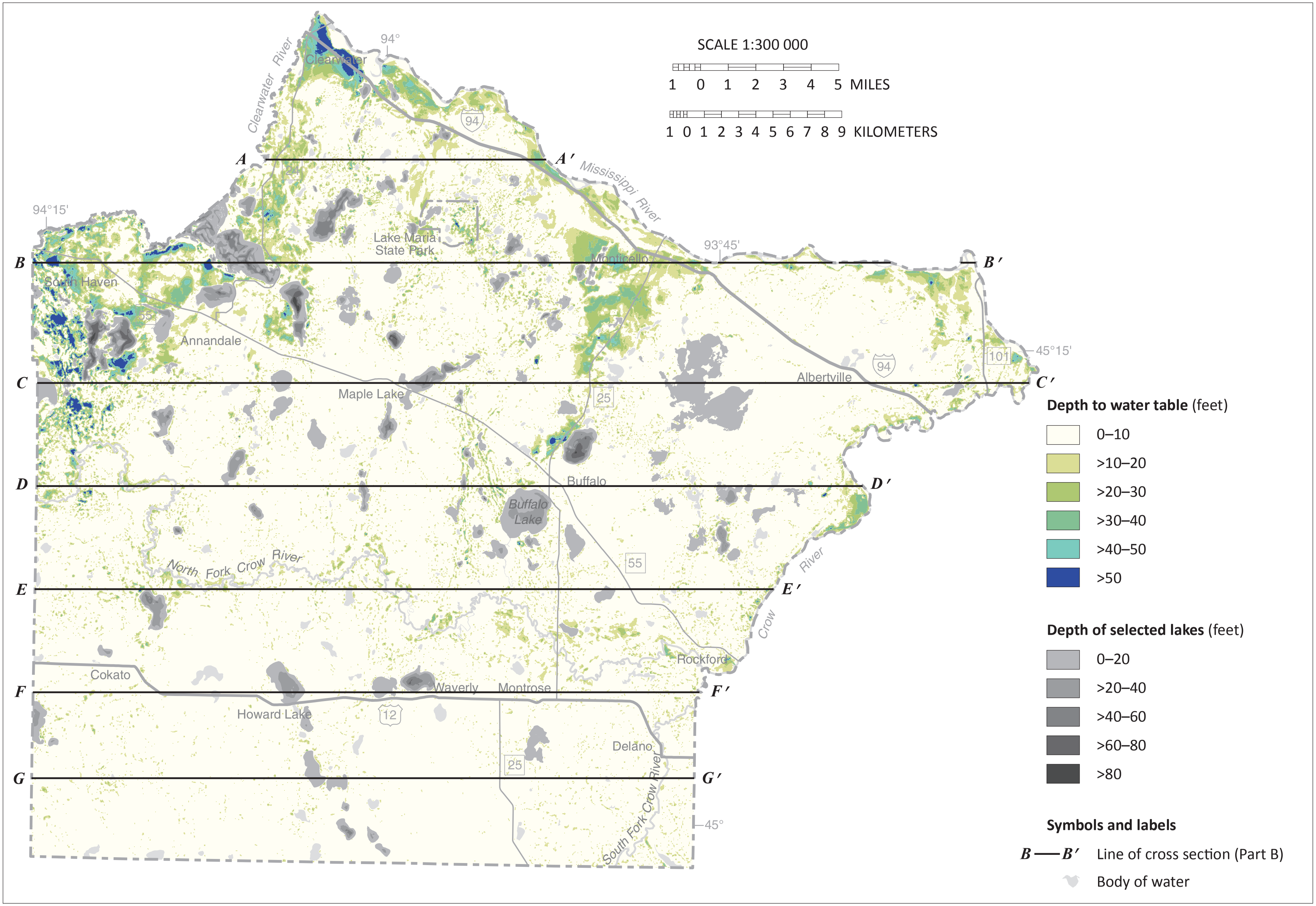


Figure 5. Depth to water table
Shallow water-table conditions are common in the county. Deeper conditions, greater than 10 feet to water table, are present west of the Annandale area and north of Buffalo. Most lakes and wetlands are assumed to be visible expressions of the shallow water table. Map modified from Adams, 2016a.

Buried aquifers

Sand and gravel

Underlying the surficial geologic deposits are alternating layers of older sand and gravel and fine-grained deposits from previous glacial advances. These may form aquifers where saturated. Unconsolidated deposits are up to 500 feet thick in portions of the county (Part A, Plate 6). The stratigraphic column shown in Figure 6 correlates the Part A geologic unit with the Part B unit names and map labels. Unit names are based on the underlying till unit described in Part A; geologic descriptions are generally classified as sand and gravel or till. These are converted into the hydrogeologic descriptions of aquifer or aquitard, respectively.

The Part B units are represented as follows (Figure 6, Plates 8 and 9):

- *Aquifers* are represented 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 portion of the matrix that is less than 2 millimeter grain size.
- Units of *undifferentiated sediment* with an unknown or unnamed texture are shown in *brown*.

The buried sand and gravel aquifers will be referred to as **buried sand aquifers** for the rest of this atlas.

Bedrock

Under the glacial deposits is an assemblage of saturated bedrock units (Part A, Plate 2). The physical and mechanical properties of these rocks dictate their ability to make good aquifers. In general, the county's best bedrock aquifers are from the Paleozoic era sedimentary rocks and the underlying Mesoproterozoic sedimentary rocks. Those in Wright County are on the edge of an extensive basin across southeast Minnesota of gently dipping layers of sandstone, shale, and carbonate rock (Part A, Plate 2).

The older metamorphic and igneous rocks underlying the county typically do not have properties conducive for aquifer use, but there may be limited use where these rocks have endured extended weathering (Runkel and others, 2006). The weathering process also enhanced permeability in sedimentary rocks, which can be beneficial in aquifers but can undermine the protective character of an aquitard.

The younger-aged Mesozoic era sedimentary aquifers are used to a lesser extent across the county. Where present, the uppermost coarse-grained layers are more conducive for storage and transmittal of groundwater.

Figure 7 categorizes generalized hydrostratigraphic attributes of the bedrock aquifers and aquitards based on their relative permeability (Part A, Plate 2). Layers assigned as aquifers are permeable and easily transmit water through porous media, fractures, or conduits as in sandstone aquifers, such as the Jordan, Wonewoc, Mt. Simon, and underlying Mesoproterozoic aquifers (Runkel and others, 2003). Layers assigned as aquitards have lower permeabilities that vertically restrict flow, but still can yield quantities of water sufficient for domestic well use through high permeability bedding plane fractures, such as the St. Lawrence Formation (Runkel and others, 2014). Although the St. Lawrence Formation acts as an aquitard on a regional level in the Twin Cities Metropolitan area, it is primarily eroded away in Wright County and offers little protection to underlying aquifers. Groundwater movement in the Upper Tunnel City aquifer mainly moves through enlarged fractures or macropores (Runkel and others, 2006).

Potentiometric surfaces

Potentiometric surfaces show the direction of groundwater flow. In confined aquifers, pressure causes water in a well to rise above the aquifer. The levels are measured and contoured to create a map of the *potentiometric surface* for each aquifer. These groundwater 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. Flow directions are shown on the maps and hydrogeologic cross sections.

Groundwater flows from *recharge* areas through aquifers 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 through deeper aquifers and aquitards can take centuries to millennia to travel tens of miles. In aquitards vertical flow is typically slow; horizontal flow through the same aquitard may be more rapid.

When combined with other information, high elevation areas on the potentiometric surface can indicate important recharge areas. River valleys are typically low elevation groundwater discharge areas.

Potentiometric surface maps (Figures 8–21) were created from static water-level data from CWI, measurements made by DNR staff, and river elevation points along major rivers and streams. The CWI records represent water levels affected by various climatic and seasonal conditions over four decades ending in 2014. This data variability creates some uncertainty in potentiometric surface elevations. Major river and stream elevation points were included in the processing because these features are typically groundwater discharge locations for the relatively shallow buried sand aquifers.

Potentiometric surfaces shown for aquifers located below the scs aquifer are less certain than the others because of the limited numbers of wells in these units.

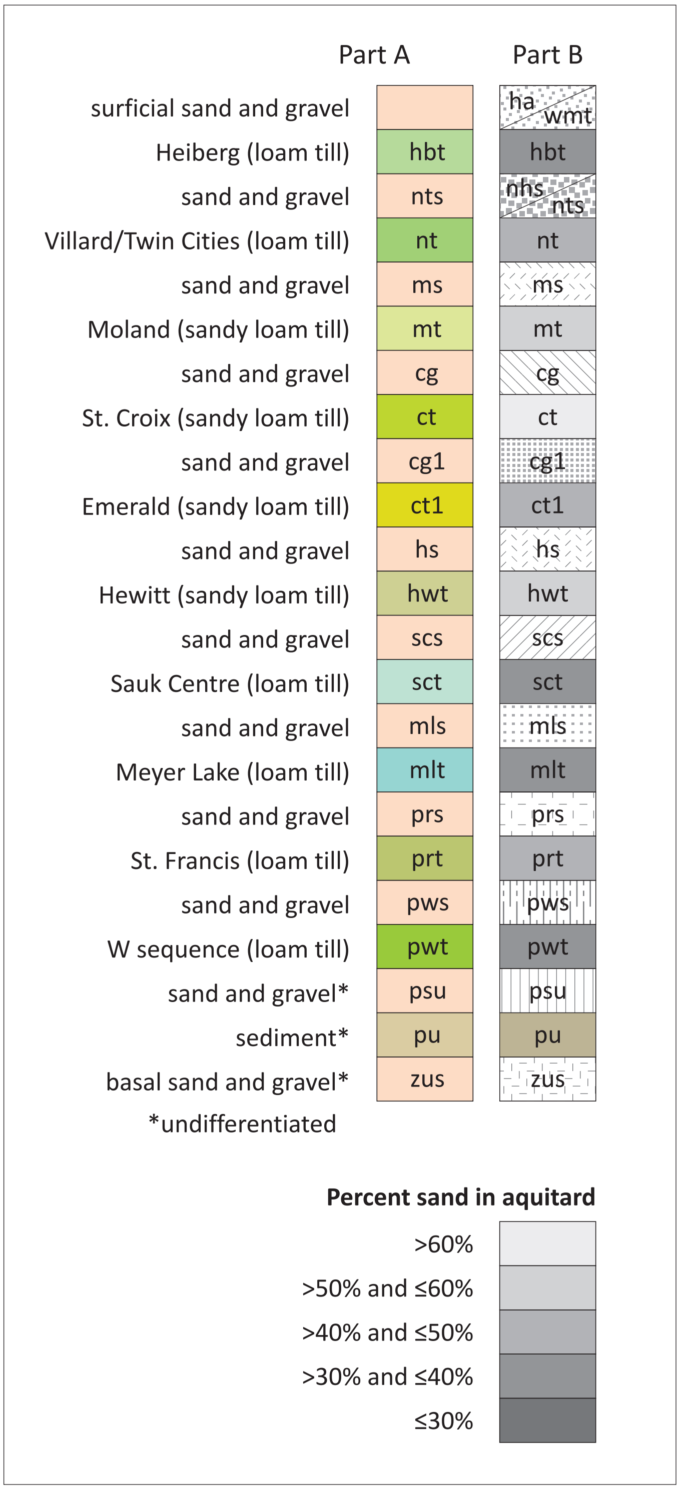


Figure 6. Hydrostratigraphy of unconsolidated sediment

Correlation of Part A and B unit names and map labels as described on page 8.

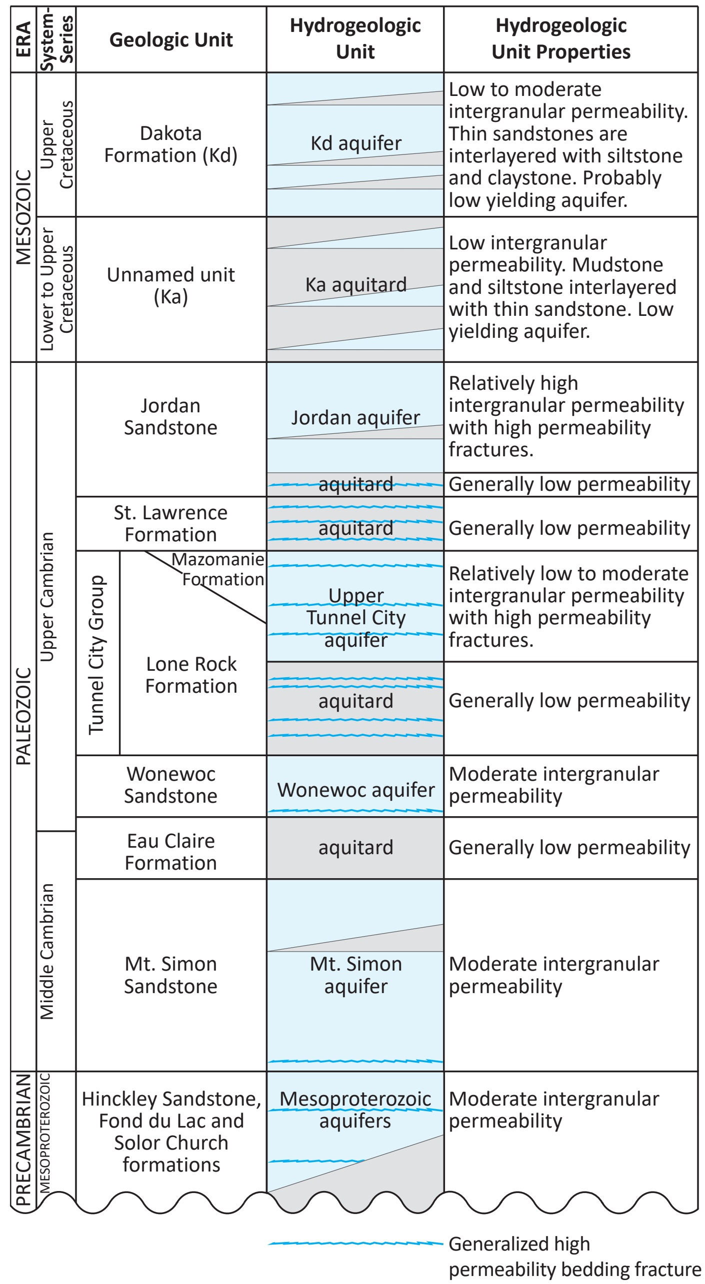


Figure 7. Bedrock stratigraphy and hydrostratigraphy
Geologic stratigraphic units and correlated hydrogeologic units. Generalized hydrogeologic units are shown as aquifers (blue) and aquitards (gray). Figure not to scale.

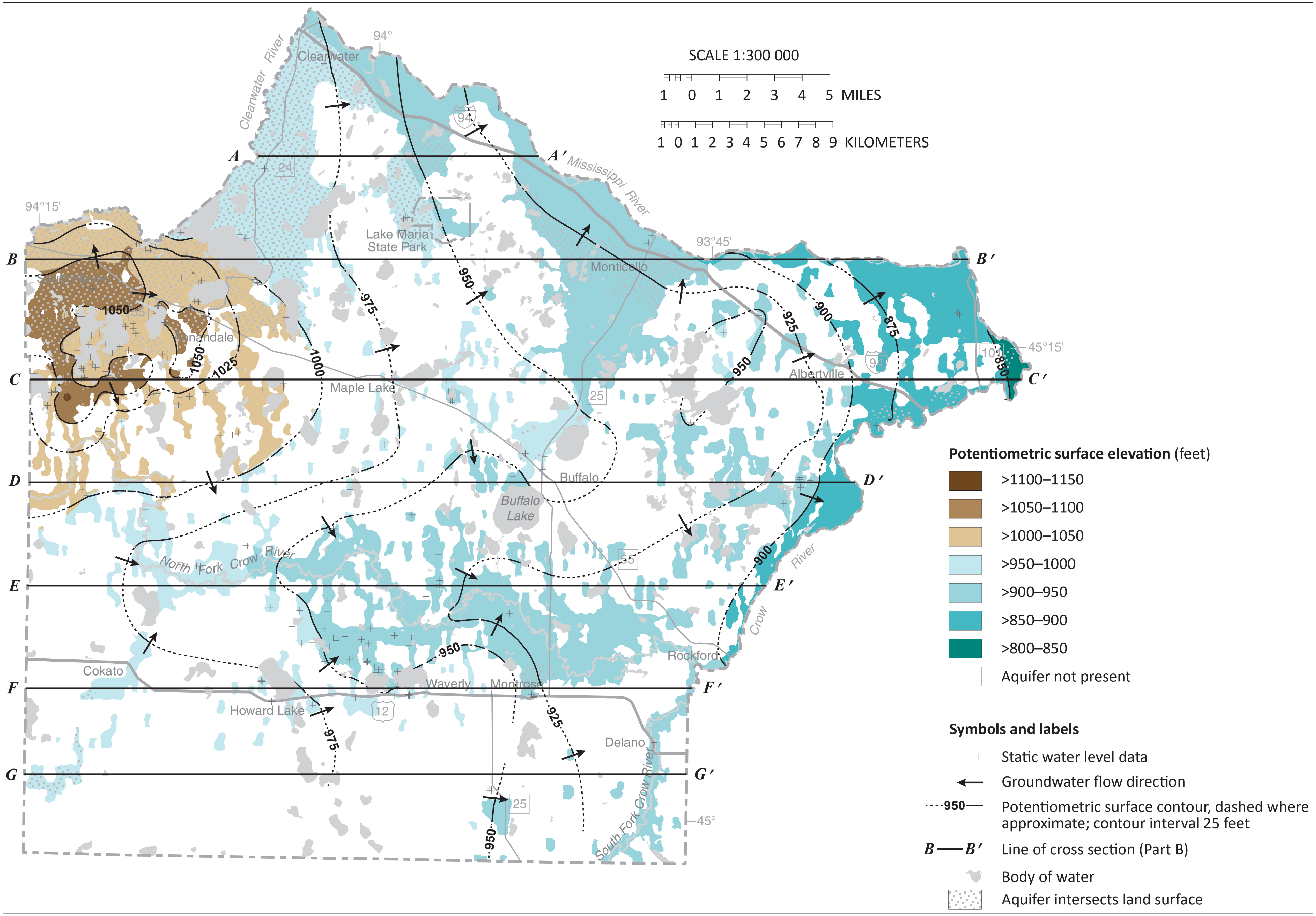


Figure 8. Potentiometric surface of the nts buried sand aquifer
The nts is present as both a surficial sand aquifer (stipple pattern) and a sand aquifer buried by Heiberg loam till. Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

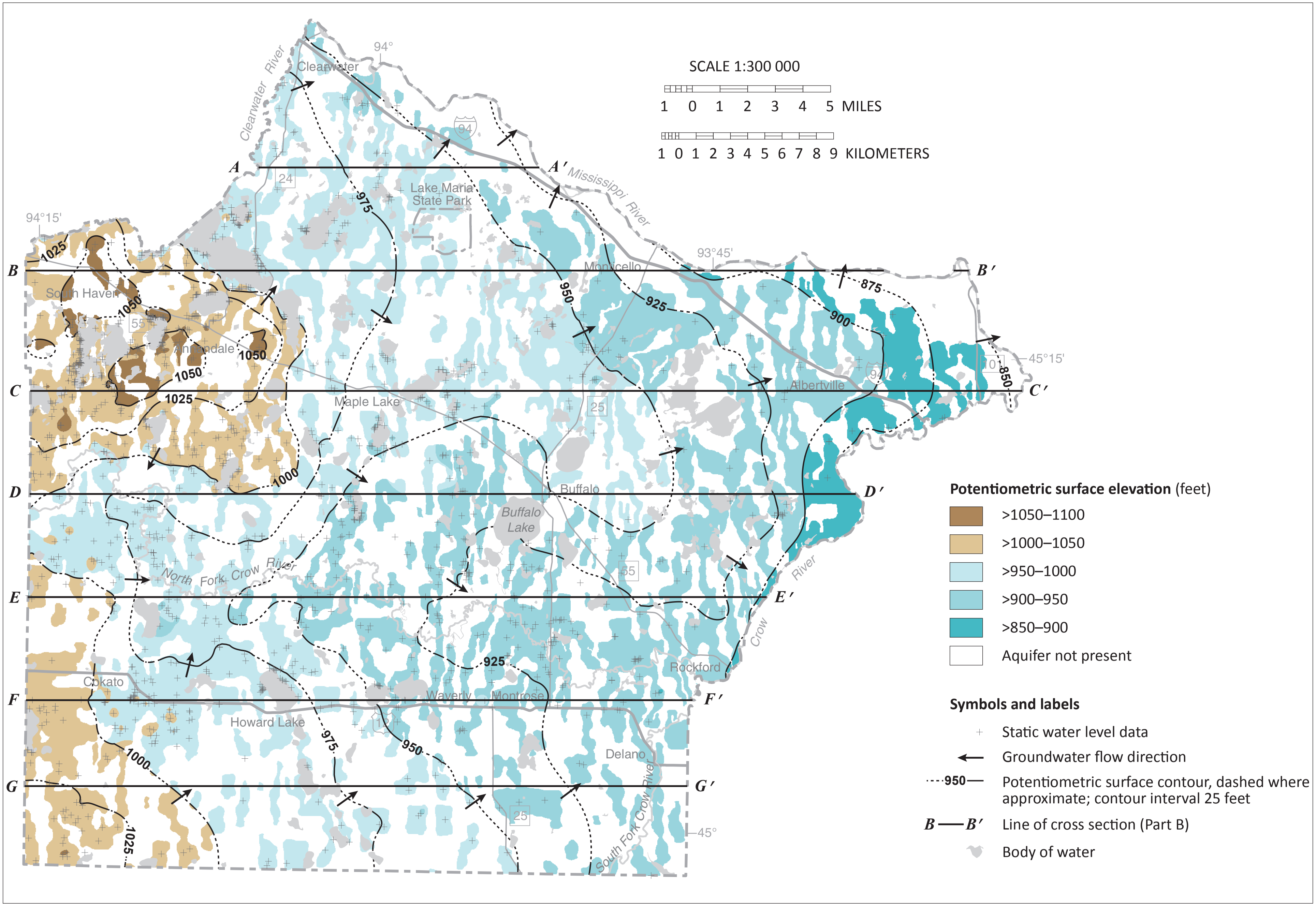


Figure 9. Potentiometric surface of the ms buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

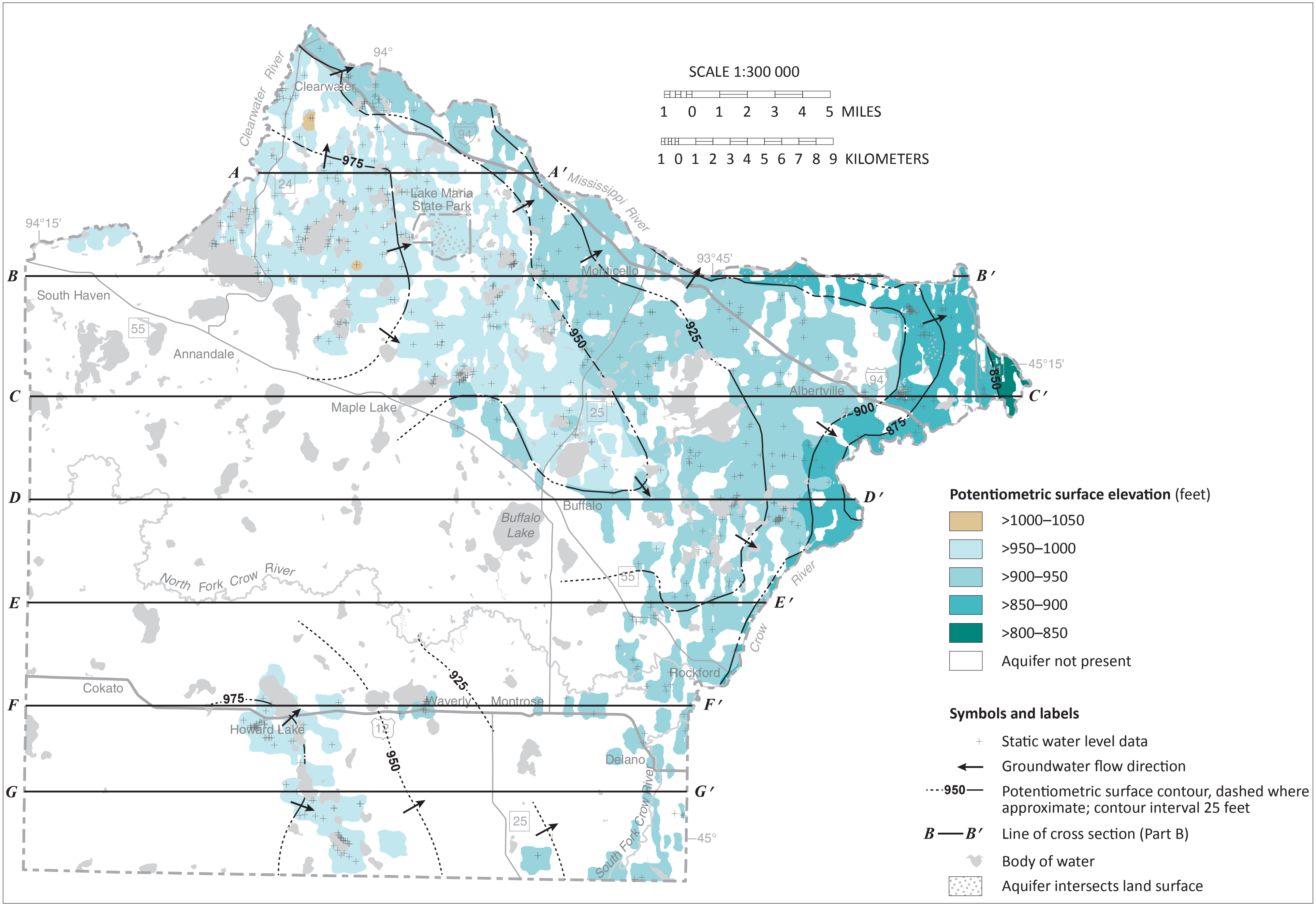


Figure 10. Potentiometric surface of the cg buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

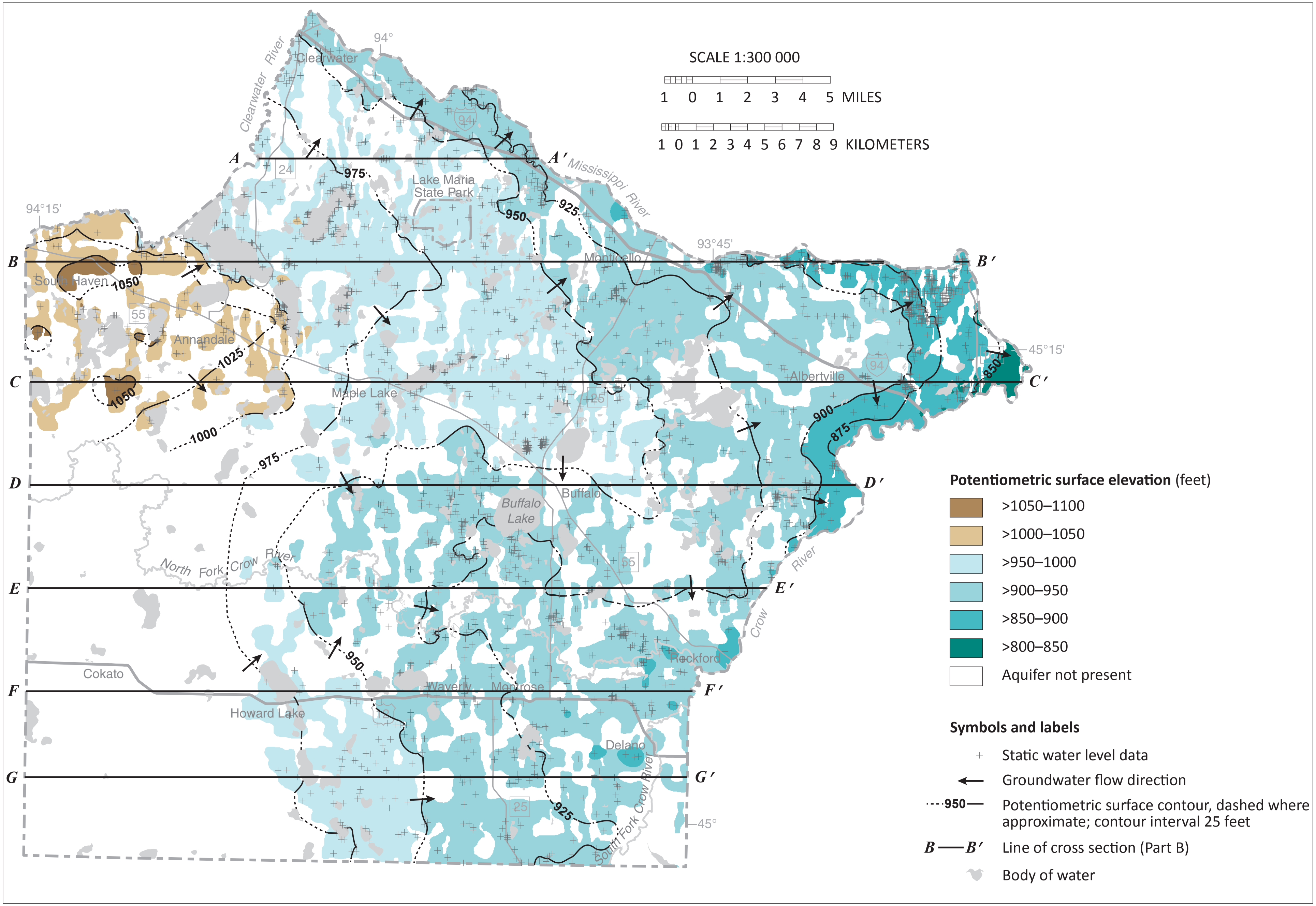


Figure 11. Potentiometric surface of the cg1 buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

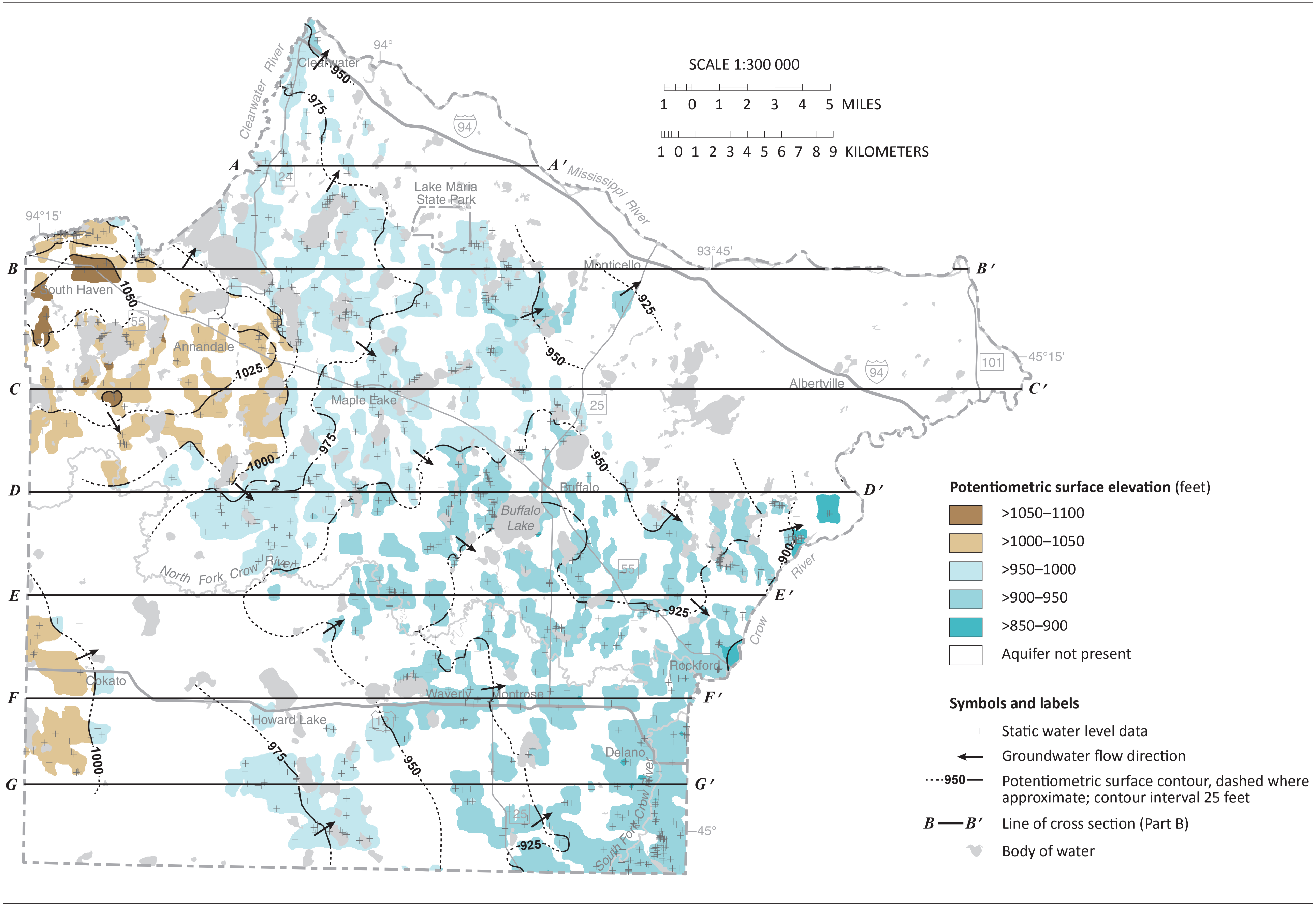


Figure 12. Potentiometric surface of the hs buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

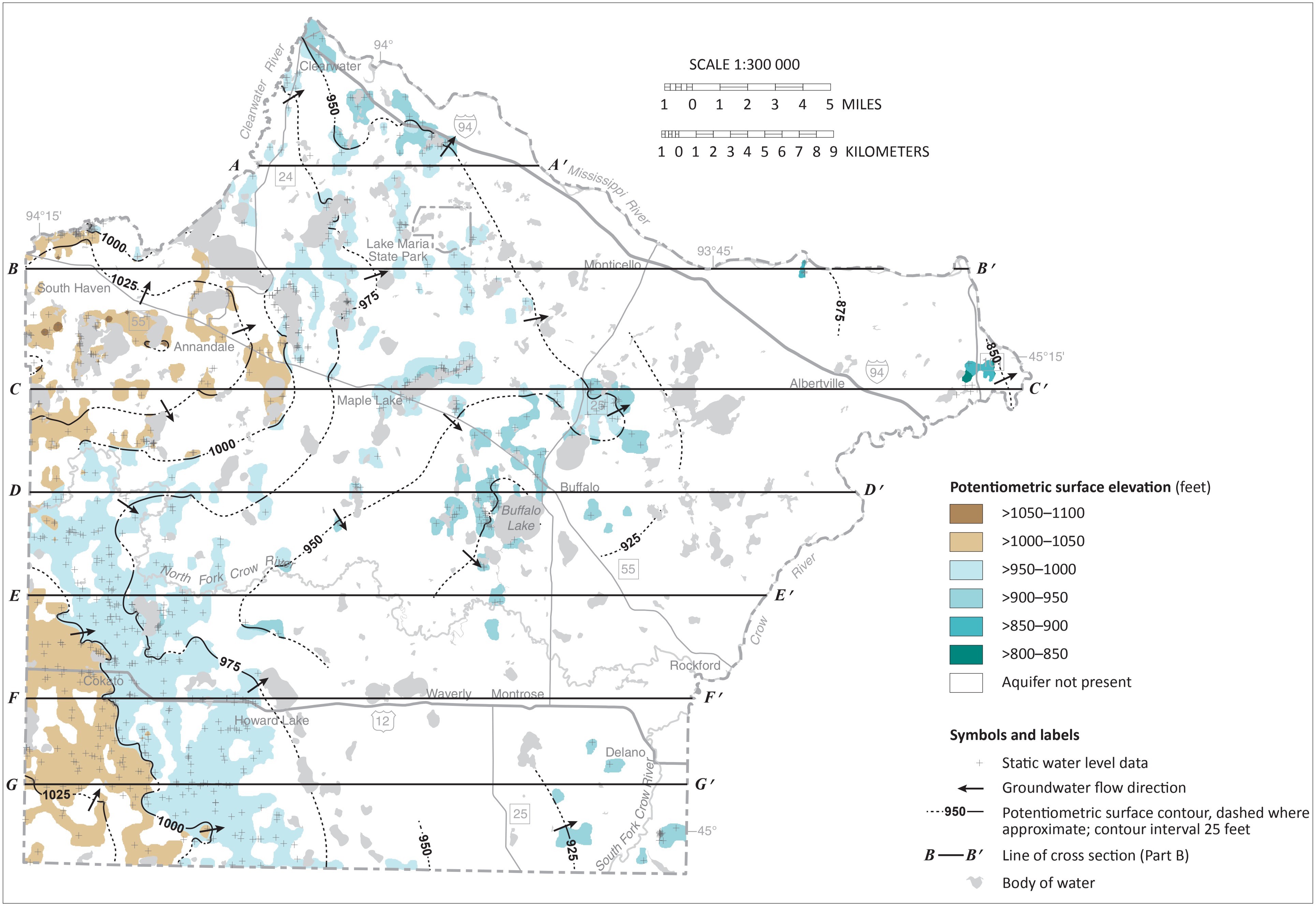


Figure 13. Potentiometric surface of the scs buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

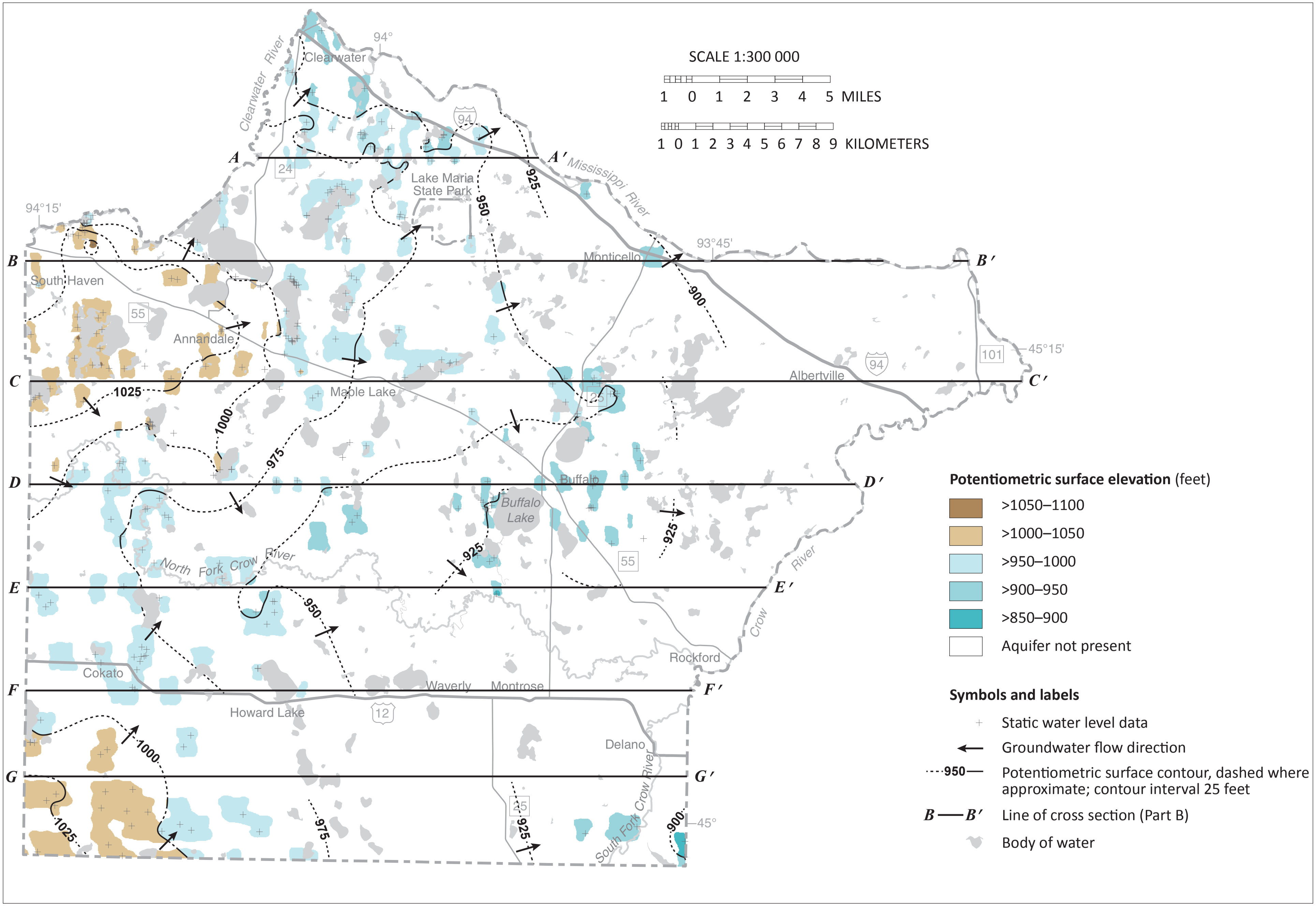


Figure 14. Potentiometric surface of the mls buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

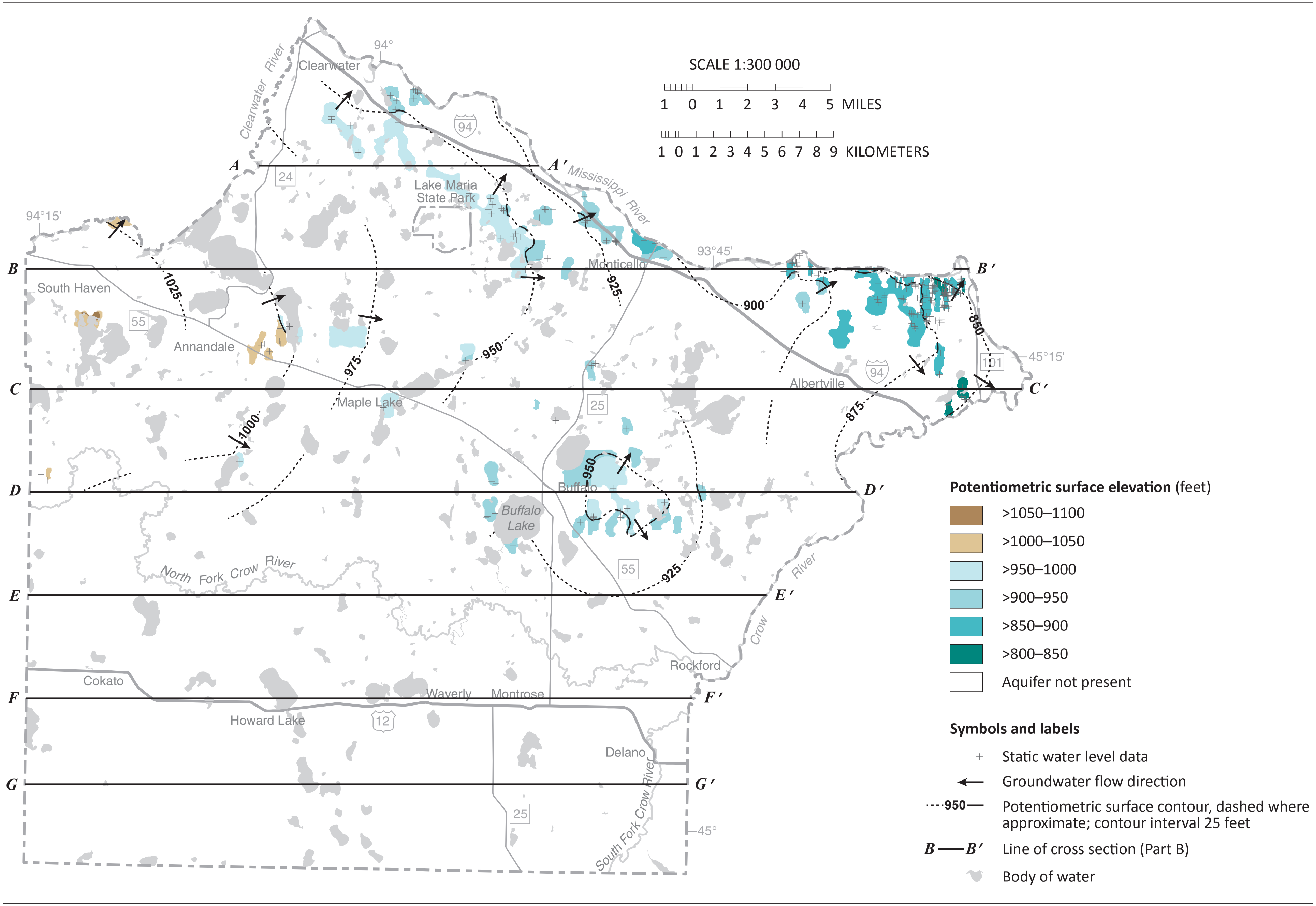


Figure 15. Potentiometric surface of the prs buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

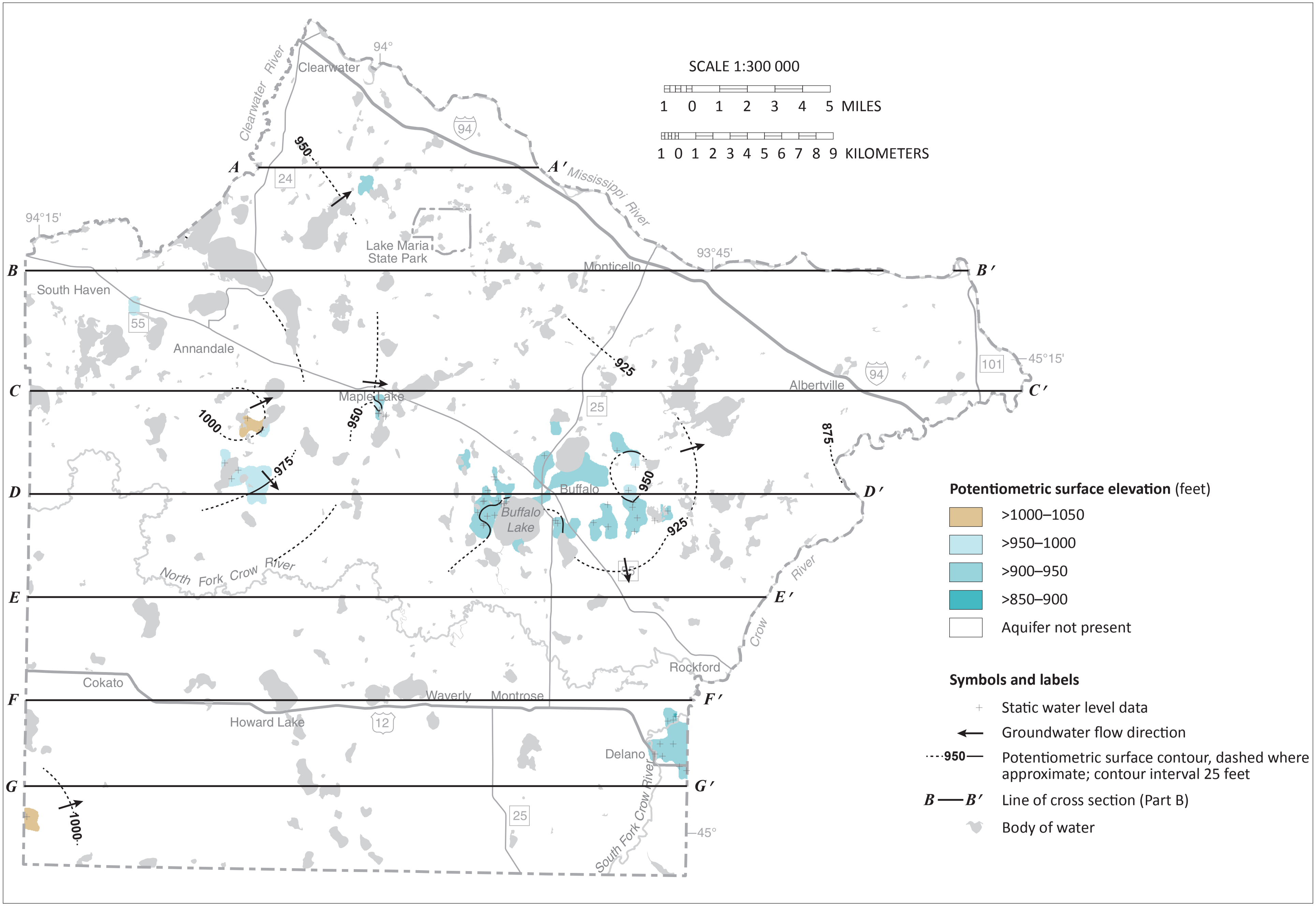


Figure 16. Potentiometric surface of the pws buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

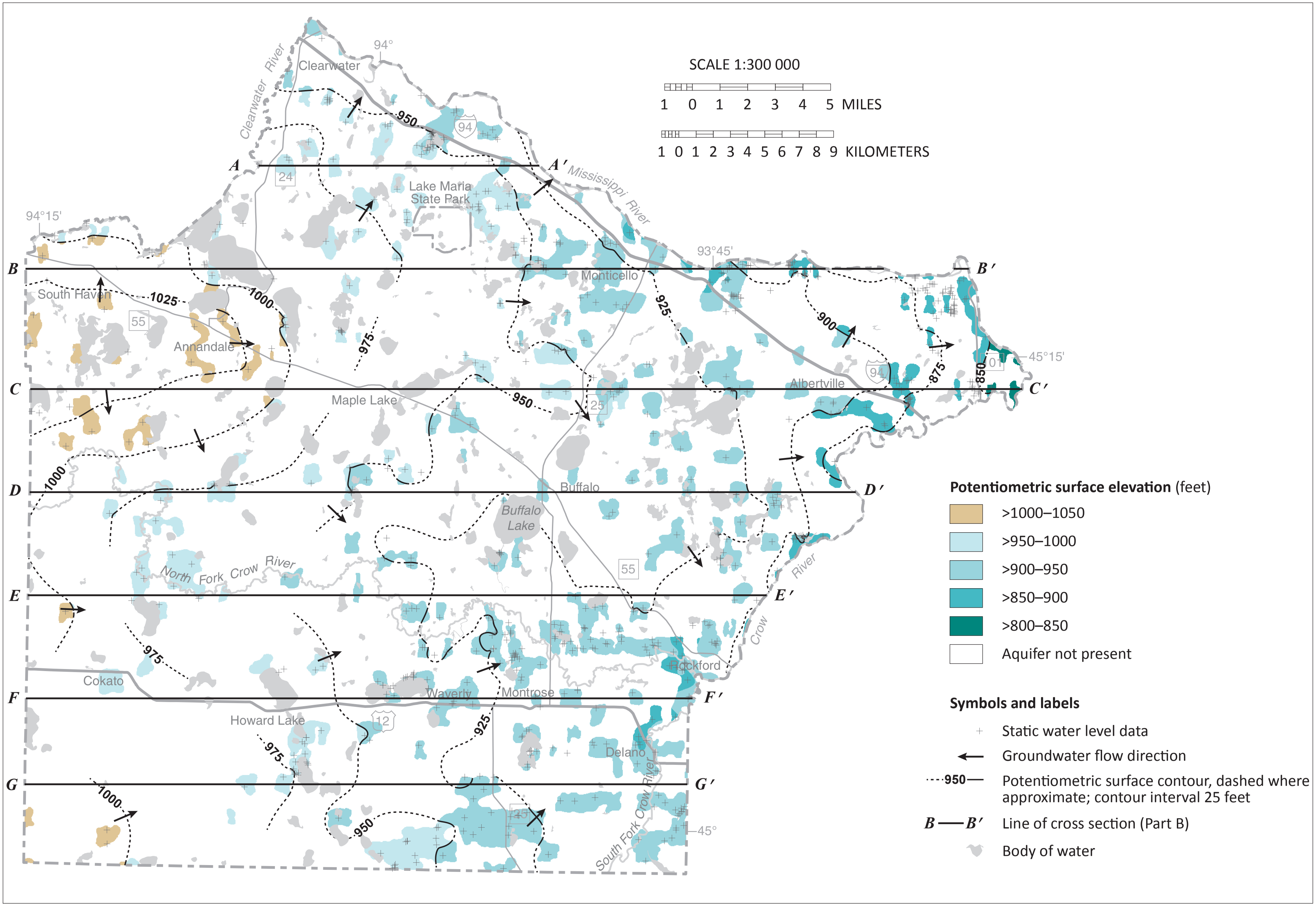


Figure 17. Potentiometric surface of the psu buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

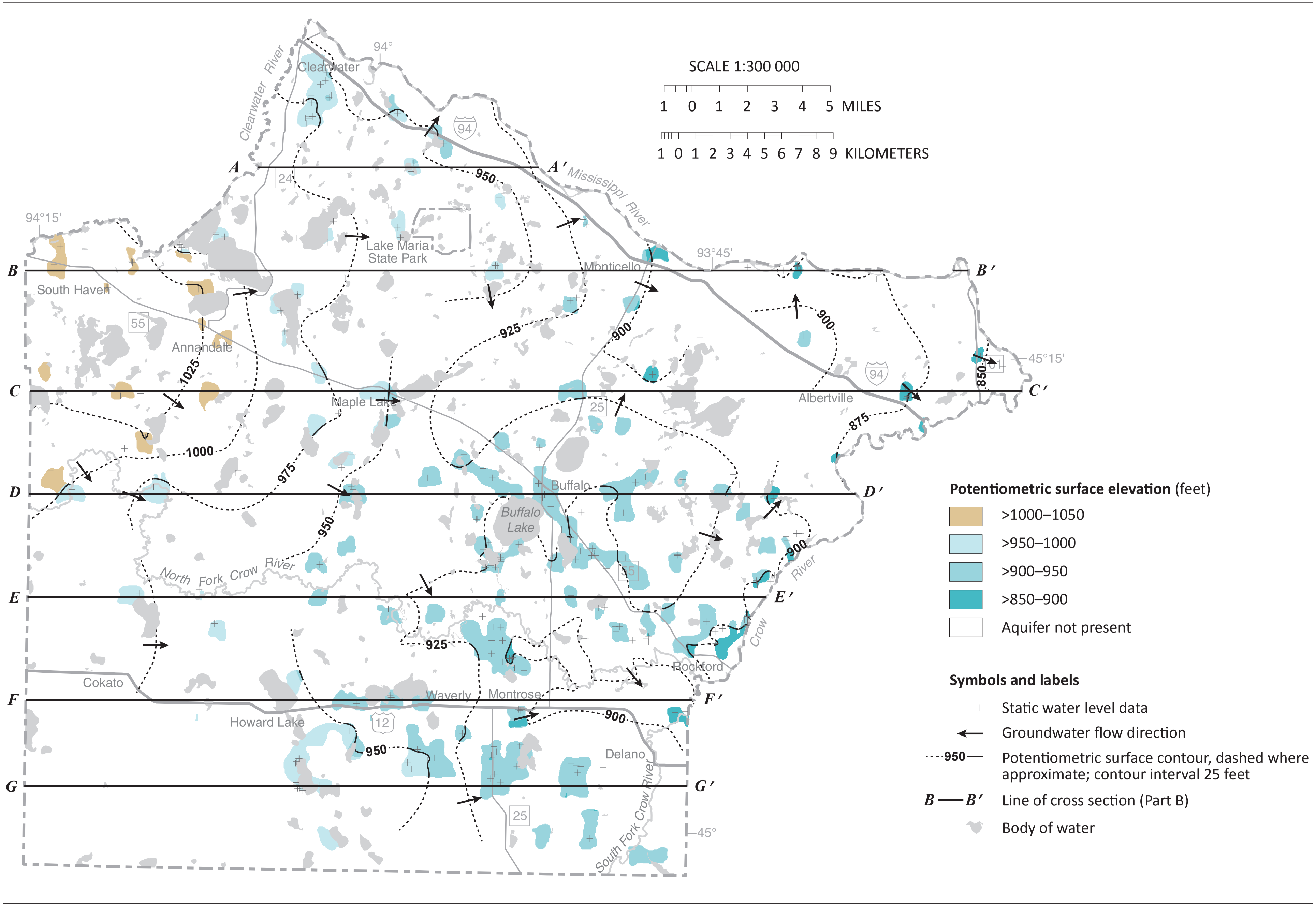


Figure 18. Potentiometric surface of the zus buried sand aquifer
Groundwater flow at the county scale is primarily eastward toward the Mississippi and Crow rivers. Township scale flow varies in direction, with gradients toward the Clearwater River, North Fork Crow River, and smaller tributary streams. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

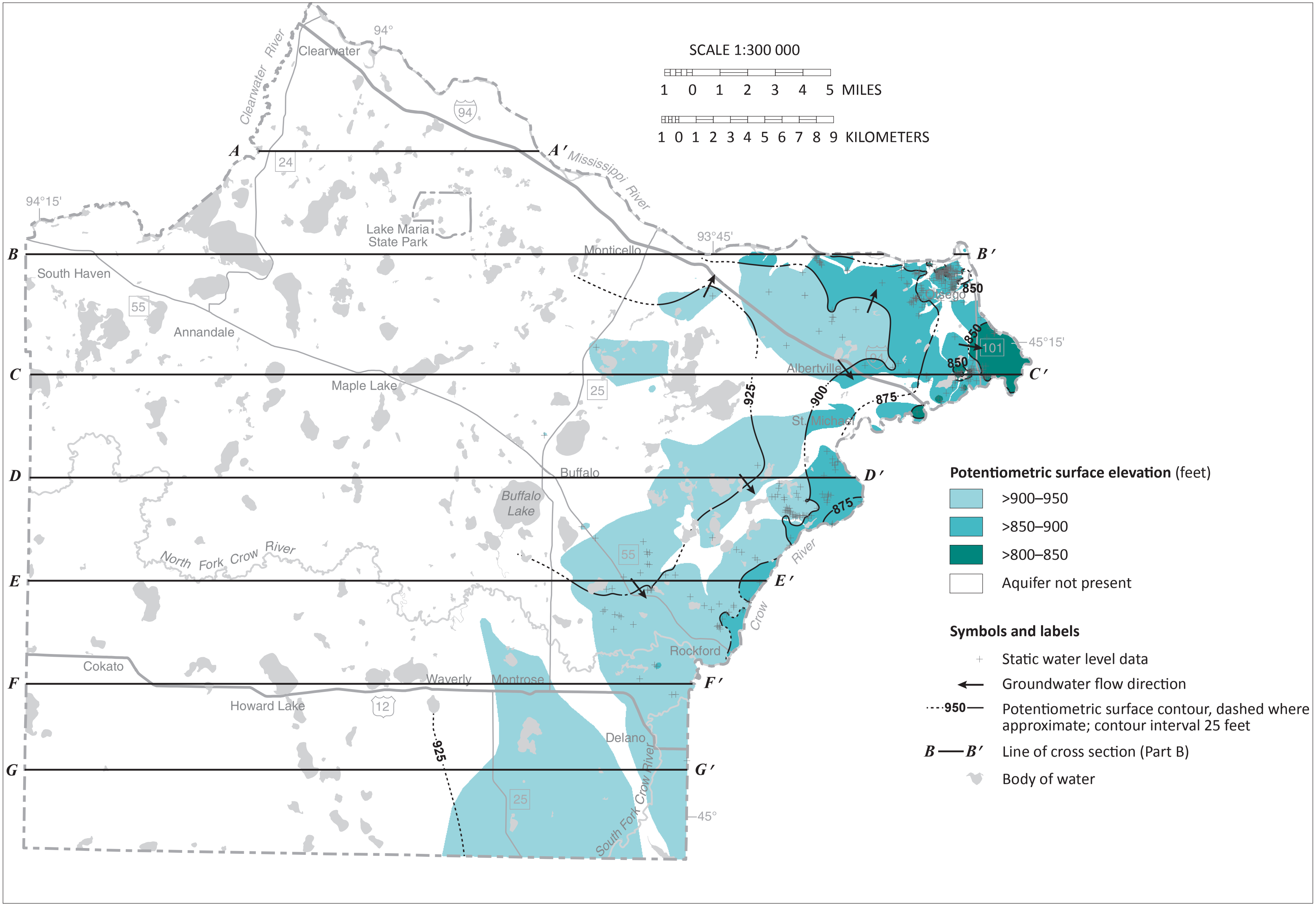


Figure 19. Potentiometric surface of the Upper Tunnel City aquifer
The Upper Tunnel City aquifer is present in the eastern part of the county and is primarily used near of Otsego and St. Michaels. Additional use occurs in Rockford Township between the cities of Rockford and Buffalo. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

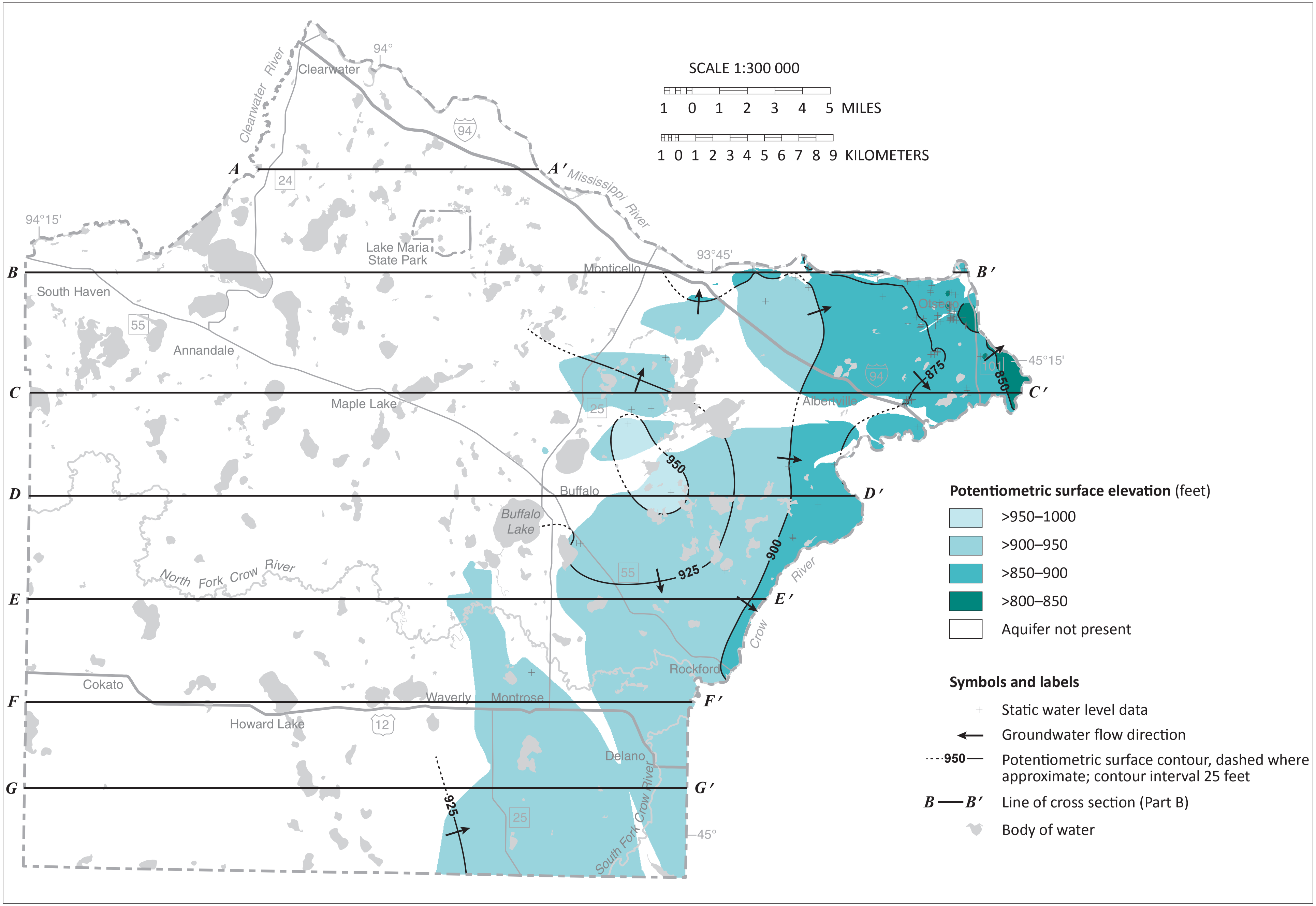


Figure 20. Potentiometric surface of the Wonewoc aquifer
The Wonewoc aquifer is present in the eastern part of the county and is primarily used near Otsego. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

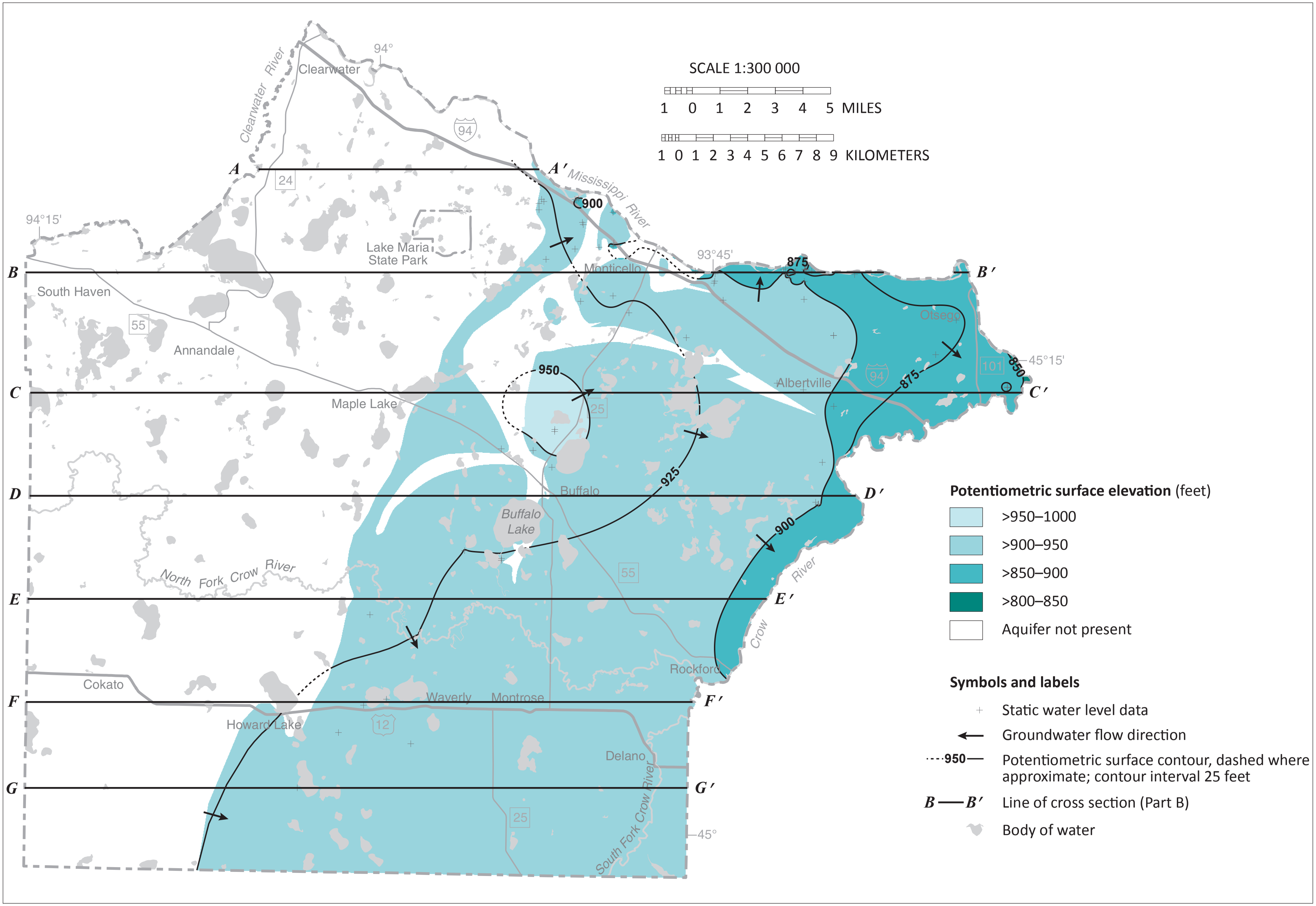


Figure 21. Potentiometric surface of the Mt. Simon aquifer

The Mt. Simon aquifer is present in the eastern part of the county and is primarily used near Monticello and Otsego. Potentiometric surfaces do not extend outside the area of the aquifer, but are shown as dashed contours to facilitate understanding of groundwater flow direction.

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 by interpreting data of the isotopes of hydrogen and oxygen.
- Groundwater residence time is estimated from tritium and carbon-14 isotopes. Tritium identifies water that has moved into the subsurface since the 1950s. Carbon-14 is used to determine groundwater residence times of centuries to millennia.
- The occurrence of some naturally occurring trace elements can indicate areas where groundwater consumption may adversely affect human health.

Water sampling

To better understand groundwater movement and pollution sensitivity in the county, samples were collected from wells in aquifers most important for domestic water supply. Wells were selected for sampling based on their aquifer characteristics and distribution. All water samples 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 a county atlas is evenly distributed across the county, includes populated areas, and targets surface water and groundwater interaction near lakes and larger rivers. However, the final well-sampling network distribution was dependent on citizen willingness to participate. Approximately 1,000 well owners were contacted to determine if they were willing to participate. Approximately 30 percent gave permission for sampling. The DNR collected water samples and standard field parameters from 90 wells and 16 lakes. The sampling approach targeted wells distributed along seven east-west cross sections in the county at a variety of depths.

The analytical results from these samples were combined with the results from a number of wells sampled by the Minnesota Department of Health (MDH) and Minnesota Pollution Control Agency (MPCA). Results from the MDH came from two separate databases: Minnesota Drinking Water Information System (MNDWIS), a compliance monitoring database which emphasizes treated water, and a noncompliance chemistry database (WCHEM). Results from the MPCA came from data collected as part of the Ground Water Monitoring and Assessment Program (GWMAP).

Groundwater recharge sources

As water moves from precipitation to groundwater, chemical changes occur that can be used to 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 them to evaporate at different rates, which results in *fractionation*, leaving behind different ratios of heavy to light isotopes. This results in isotopic signatures that are unique to groundwater with different recharge sources.

- Groundwater infiltrated directly from *precipitation* exhibits a *meteoric* isotopic signature. It infiltrates directly into the ground, leaving the isotopic ratio unchanged.
- Groundwater recharged from *surface water,* such as lakes or open-water wetlands, exhibits an *evaporative* isotopic signature. It has been subjected to fractionation where lighter isotopes evaporated, leaving a ratio favoring heavier isotopes.

To identify the source of a groundwater sample (precipitation or surface water), oxygen and hydrogen isotopic data were plotted against each other (Figure 22). The x-axis represents the oxygen isotope value ($\delta^{18}O$) and the y-axis represents the hydrogen isotope value ($\delta^{2}H$). The measured ratio in the sample is divided by the ratio in a standard (Vienna Standard Mean Ocean Water [VSMOW]).

Definition of delta (δ)
The stable isotope composition of oxygen and hydrogen are reported as δ values. δ (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 Rx represents the ratio of the sample, and Rs represents the ratio in VSMOW. Delta values are reported in units of parts per thousand (⁰/₀₀ or permil) relative to VSMOW.

Wright County samples plotted on a stable isotope graph fall near the intersection of the meteoric water line and the evaporation line, with a significant portion trending along the evaporation line.

Wells with a characteristic evaporative signature are located throughout the northern and eastern regions of the county where there is a prevalence of geologic deposits with coarse-grained textures coupled with a large number of lakes and open water wetlands. These data demonstrate the connectivity of area lakes to the groundwater system, and highlight their importance in providing groundwater recharge to aquifers in this area, including deep bedrock aquifers. Well locations symbolized in red in Figure 23 and encased in red circles in Plate 7 represent groundwater samples with at least 50 percent of the maximum evaporative lake signature.

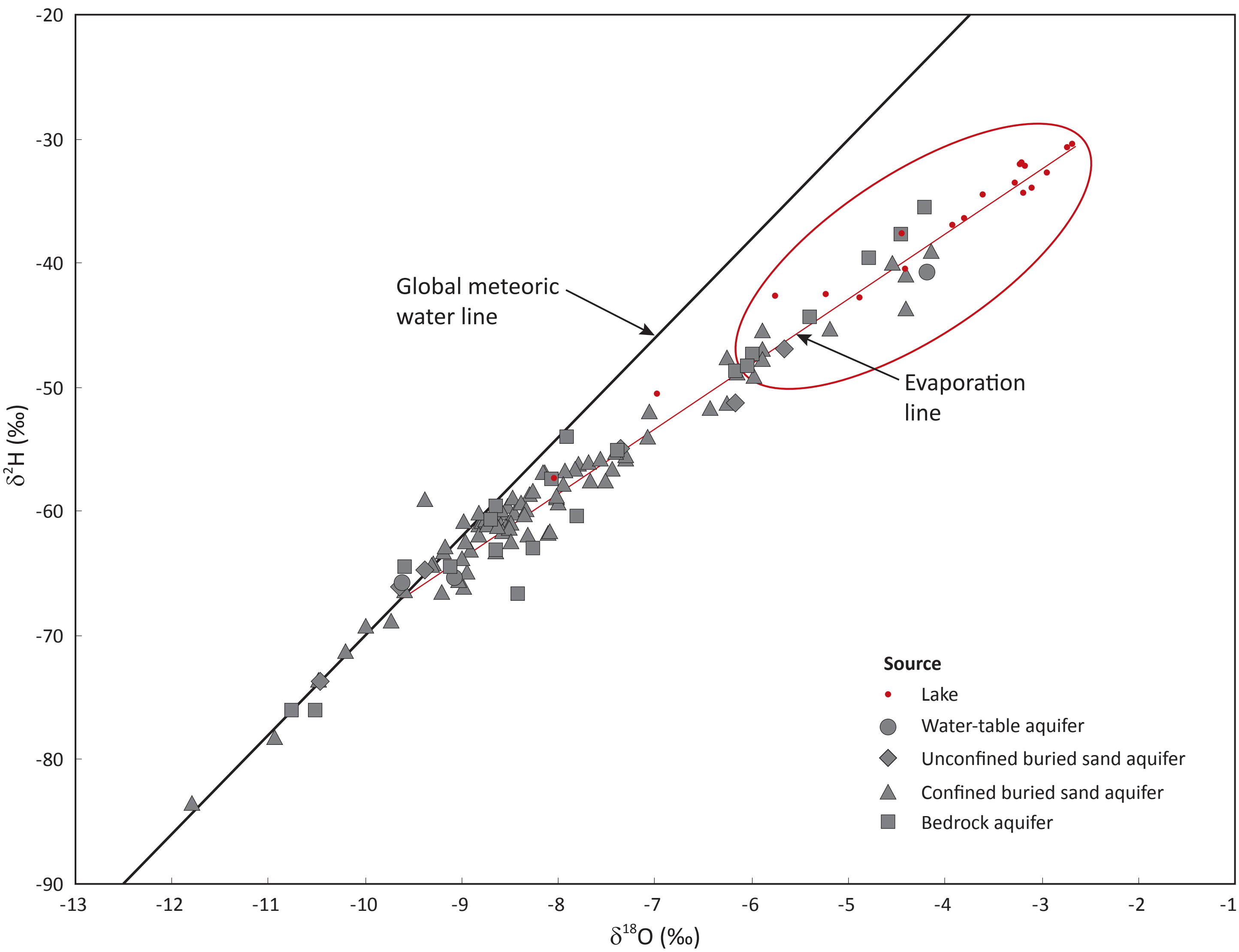


Figure 22. Graph of stable isotope values from groundwater samples

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

Groundwater that was partially recharged from surface water plots along an **evaporation line**. Samples with at least 50 percent of the maximum evaporative lake signature are shown in the oval. The local evaporation line is described by the following equation: $\delta^2H = 5.2\ \delta^{18}O - 16.9$.

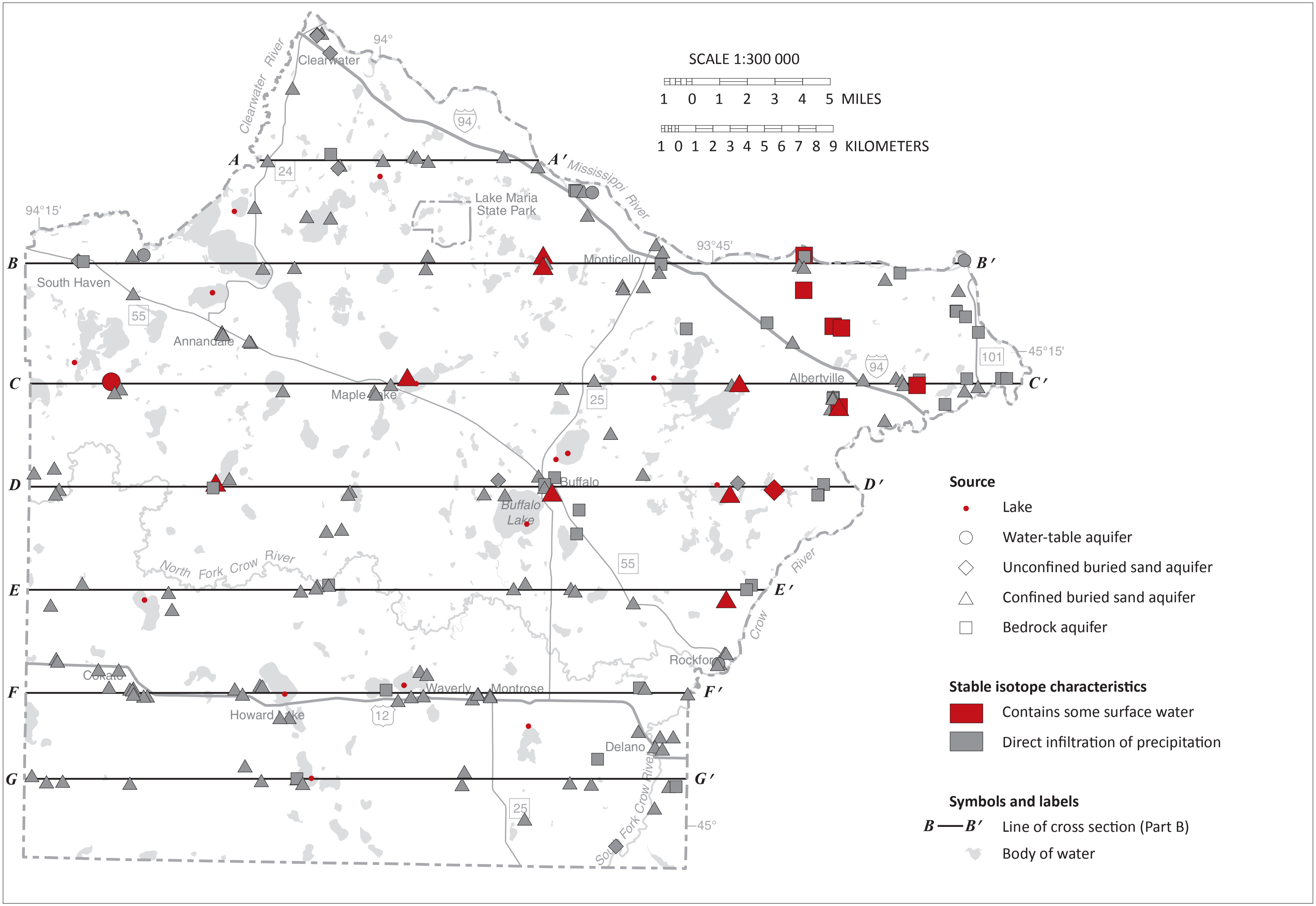


Figure 23. Distribution of groundwater stable isotopic signature
The majority of the groundwater samples collected within Wright County originated from direct infiltration of precipitation (samples that plot near the Global meteoric water line in Figure 22). A subset of samples (that plot along the shallower sloped evaporation line in Figure 22) represent groundwater partially recharged by infiltrated water from lakes and open-water wetlands. Groundwater samples with at least 50 percent of the maximum evaporative signature are shown in red with an enhanced symbol size and are distributed throughout the northern and eastern portions of the county.

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 times generally suggest high recharge rates and/or short travel paths; long residence times suggest low recharge rates and/or long travel paths. In this atlas, the residence time of groundwater was estimated using isotopic analysis of the radioactive elements tritium and carbon-14.

Tritium

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

Tritium concentrations and other groundwater chemistry (such as nitrate and chloride values) were compared with estimated pollution sensitivity. The interpretations were used in maps for pollution sensitivity and the hydrogeologic cross sections. 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).

The breakpoint for recent tritium age is based on the results of two lake water samples from this project and 4 years of data (2012–2016) from a climate monitoring station in the Twin Cities (Appendix B).

Carbon-14

Residence time can be estimated for selected vintage and mixed tritium-age samples using the carbon-14 (^{14}C) isotope. This naturally occurring isotope has a half-life of 5,730 years, and is used to estimate groundwater residence time ranging from 100 to 35,000 years (Alexander and Alexander, 1989). Samples with a carbon-14 residence time of less than 100 years are labeled in this atlas as *recent.*

Inorganic chemistry of groundwater

As soon as precipitation infiltrates the soil layer and becomes groundwater, the water begins dissolving minerals in the soil, sediment, and bedrock. It also may transport pollutants. Inorganic chemical analysis of samples is used to characterize changes in chemistry as water moves deeper. Water quality describes contaminants that are potentially harmful to humans (natural or manmade) and aesthetics (hardness, taste, odor, color). The following guidelines from U.S. Environmental Protection Agency are used in this atlas (EPA, July 2017; EPA, March 2017).

- **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.

This report includes analyses of water samples for inorganic chemistry, including major cations and anions generally found in parts per million (ppm), and select elements that are typically found in trace amounts of parts per billion (ppb).

Several major cations and anions commonly found in groundwater are listed below with brief descriptions about their sources and characteristics.

- **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, 1989) 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 at low concentrations in groundwater but elevated concentrations (≥5 ppm) may come from road salts, water softener salts, and fertilizers (SMCL 250 ppm).
- **Nitrate-nitrogen (nitrate)** can occur naturally at low concentrations but elevated concentrations (≥1 ppm) are typically from fertilizer and animal or human waste (MDH, 1998). The MCL for nitrate is 10 ppm. Nitrate concentrations lessen with time (denitrification) when there is little oxygen in groundwater. In Minnesota, groundwater with a long residence time typically has little available oxygen and low to no nitrate.

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

Results

Plotting sample chemistry using a Piper diagram allows hydrologists to assign a water type to a sample. This graphically represents a water sample relative to the most common ionic constituents in natural waters. The relative proportions of dissolved ions differ depending on the water's interaction with the atmosphere, the aquifer, and subsequent interactions with anthropogenic sources (if present).

Figure 24 is a Piper diagram of groundwater samples analyzed as part of this report. Positively charged major ions (cations) are shown in the lower left ternary diagram and negatively charged major ions (anions) are shown in the lower right. The analytical results of each sample are represented by one point in the cation portion and one point in the anion portion. These points are projected to the diamond-shaped portion to assign a hydrogeochemical classification.

The bulk of the Wright County water samples are characterized as calcium bicarbonate, which is typical for central and southern Minnesota. The outlined arrow in Figure 24 highlights waters with long travel times determined through tritium and carbon-14 analysis. Along the path of this arrow, as groundwater residence time generally increases, calcium and magnesium ions are exchanged with sodium and potassium ions. A small subset of samples are of the sodium + potassium chloride type, which is consistent with waters that may have interacted with brine associated with Cretaceous seas (Olcott, 1992). Additional information and analysis using chloride and nitrate can be found in the section on pollution sensitivity.

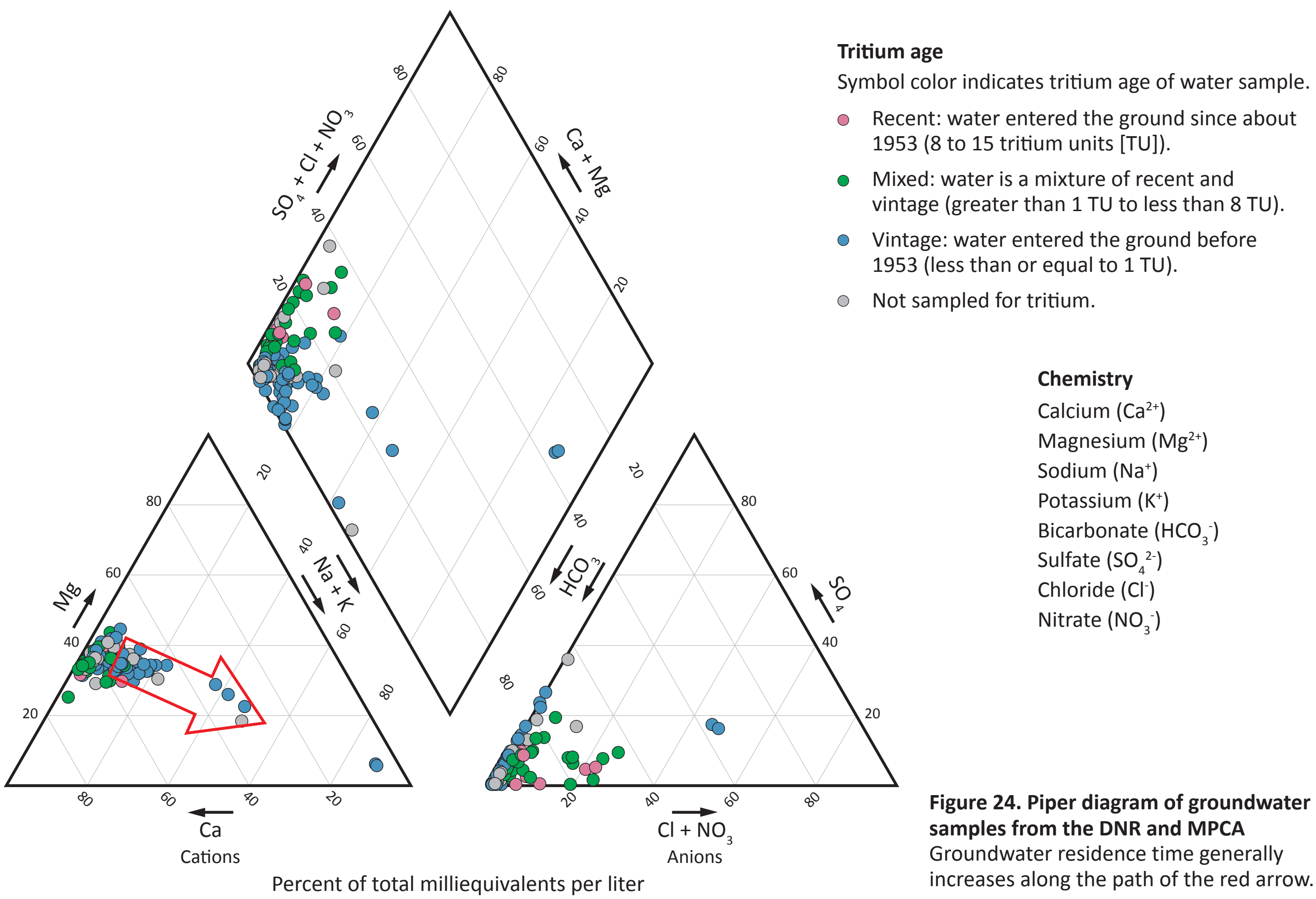


Figure 24. Piper diagram of groundwater samples from the DNR and MPCA
Groundwater residence time generally increases along the path of the red arrow.

Naturally occurring elements of health concern

Some chemicals present in water may be naturally occurring, but elevated concentrations can potentially pose a risk to human health.

Arsenic

Arsenic is a naturally occurring element in Minnesota groundwater. The MDH advises domestic well owners to treat drinking water if arsenic is detected at any concentration (MDH, 2018). For more information search “Arsenic in Drinking Water” on the MDH website.

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 MCLG for arsenic is zero; the MCL is 10 ppb.

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 believed to be caused by naturally-occuring 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 aquitard and aquifer (Erickson and Barnes, 2005a; McMahon, 2001).

The Riding Mountain provenance tills in Wright County have higher average relative percentage of Cretaceous shale deposits than the tills associated with other glacial advances, pointing to these tills as a possible arsenic reservoir (Part A, Plate 4, Table 1). Elevated arsenic (≥2 ppb) is common in the county and is likely due to the origin of the till units that lie at the surface and serve as aquitards for the buried sand aquifers. A total of 168 groundwater samples were analyzed for arsenic, collected from water-table, buried sand, and bedrock aquifers. Of these, 105 samples were elevated; 51 were greater than or equal to the MCL of 10 ppb (Figure 25). The majority of elevated arsenic samples were collected from buried sand aquifers. However, six samples from bedrock aquifers had elevated arsenic levels, likely from recharge from overlying buried sand aquifers.

Manganese

Manganese is a naturally occurring element in groundwater across Minnesota. Low levels of manganese are beneficial to humans, but high levels may harm the nervous system. In addition to health effects, elevated manganese concentrations (>50 ppb) can cause negative secondary effects, such as poor taste, odor, and water discoloration (stained laundry and plumbing fixtures). For more information search “Manganese in Drinking Water” on the MDH website.

There are currently no MCLs for manganese, but the MDH has determined the following guidance values as Risk Assessment Advice (RAA): 100 ppb for infants (<1 year old), 300 ppb for children and adults (MDH, 2012a). RAAs are advice from studies or newer methodologies that have not been formally adopted as a rule.

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 high levels (some over 1,000 ppb) (MDH, 2017).

A total of 156 groundwater samples were analyzed for manganese, collected from the water-table, buried sand, and bedrock aquifers. Of these 140 samples were greater than or equal to the RAA for infants (100 ppb), 77 were greater than or equal to the RAA for children and adults (300 ppb), and 146 exceeded the SMCL (50 ppb).

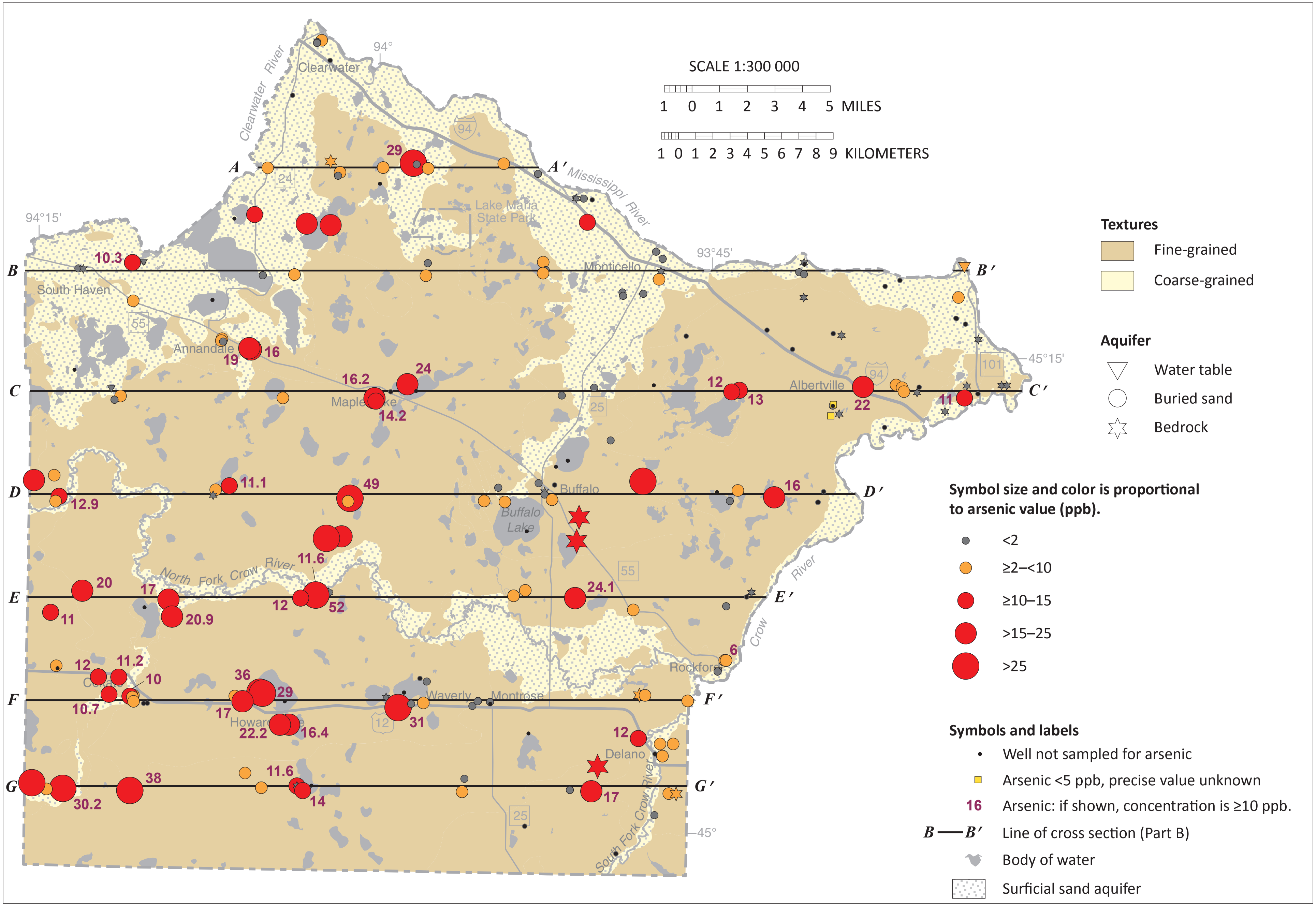


Figure 25. Groundwater arsenic values
Arsenic concentrations that equaled or exceeded federal drinking water standards (10 ppb) were found in approximately 25 percent of sampled wells.

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 through unsaturated and saturated sediment is a complex process that is 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. The following assumptions 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**: 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. 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.

Chemical indicators of pollution sensitivity

The pollution sensitivity model results were authenticated by comparing to select chemistry from water samples from the mapped aquifers. The following can indicate anthropogenic sources of contamination and moderate to high pollution sensitivity.

- Recent and mixed tritium age indicates that at least a portion of the groundwater has been recharged since the 1950s.
- Nitrate concentrations ≥1 ppm are greater than background conditions (MDH, 1998; Wilson, 2012).
- Chloride concentrations ≥5 ppm with high chloride/bromide ratios are greater than background conditions. Although elevated chloride is commonly human caused it can also occur naturally, likely from a deep natural source, such as residual brine. The chloride source can be distinguished using chloride/bromide ratios. In general ratios below 300 are likely from natural sources. (Davis and others, 1998; Panno and others, 2006).

Near-surface materials

Methods

The pollution sensitivity of near-surface materials is an estimate of the time it takes for water to infiltrate the land surface, travel through the unsaturated zone, and reach the water table, which is assumed to be 10 feet below land surface. The first 3 feet of the unsaturated zone is assumed to be soil and 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. In general, coarse-grained materials 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). Further details of how the near-surface pollution sensitivity map was created are available in *Methods to Estimate Near-Surface Pollution Sensitivity* (DNR, 2016b).

The time of travel through near-surface materials varies from hours to approximately a year (Figure 26).

- Areas with a relatively short time of travel (hours to a week) are rated high sensitivity.
- Areas with a longer time of travel (weeks to a year) are rated low or very low.
- Areas with travel times of more than a year are rated ultra low, but are not present in Wright county.

Results

Low sensitivity, associated with loam and silt loam, is prevalent throughout the majority of the county (Figure 27). Elsewhere, high sensitivity, associated with sand and gravel, exists in the northern and eastern portions of the county and within the main valleys of the North Fork Crow, South Fork Crow, and Crow rivers. Smaller areas of moderate sensitivity exist around Lake Maria State Park in the northern portion of the county. No water chemistry was collected from shallow water-table aquifers.

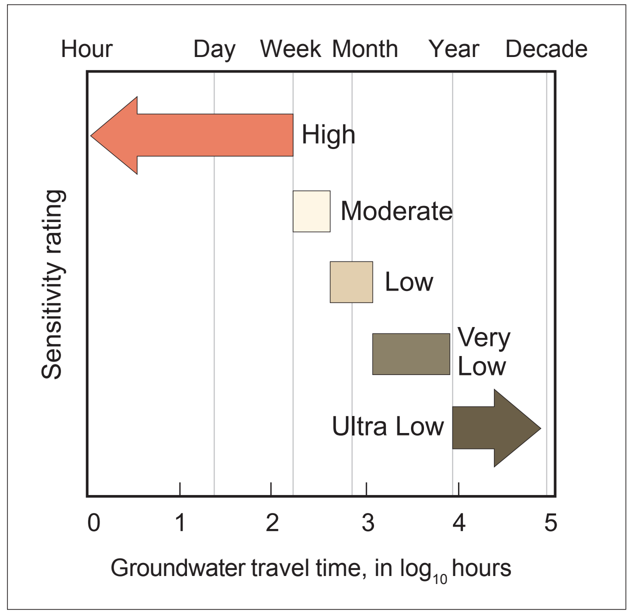


Figure 26. Geologic sensitivity rating for near-surface materials

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 (Plate 3)**
A, A/D	1	gravel, sandy gravel, silty gravel	1	cg, ng, tco, wmt
		sand, silty sand	0.71	Not mapped in county
B, B/D	0.5	silt, loamy sand	0.50	Not mapped in county
		sandy loam, peat	0.28	ct
C, C/D	0.075	silt loam, loam	0.075	ht, htw, nlc, nls, tct, vt, vtw
		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 used as an overlay on the map due to variable and typically unknown thicknesses.
*The Natural Resources Conservation Service (NRCS) defines hydrologic soil groups primarily based on texture and the occurrence of low permeability layers (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.

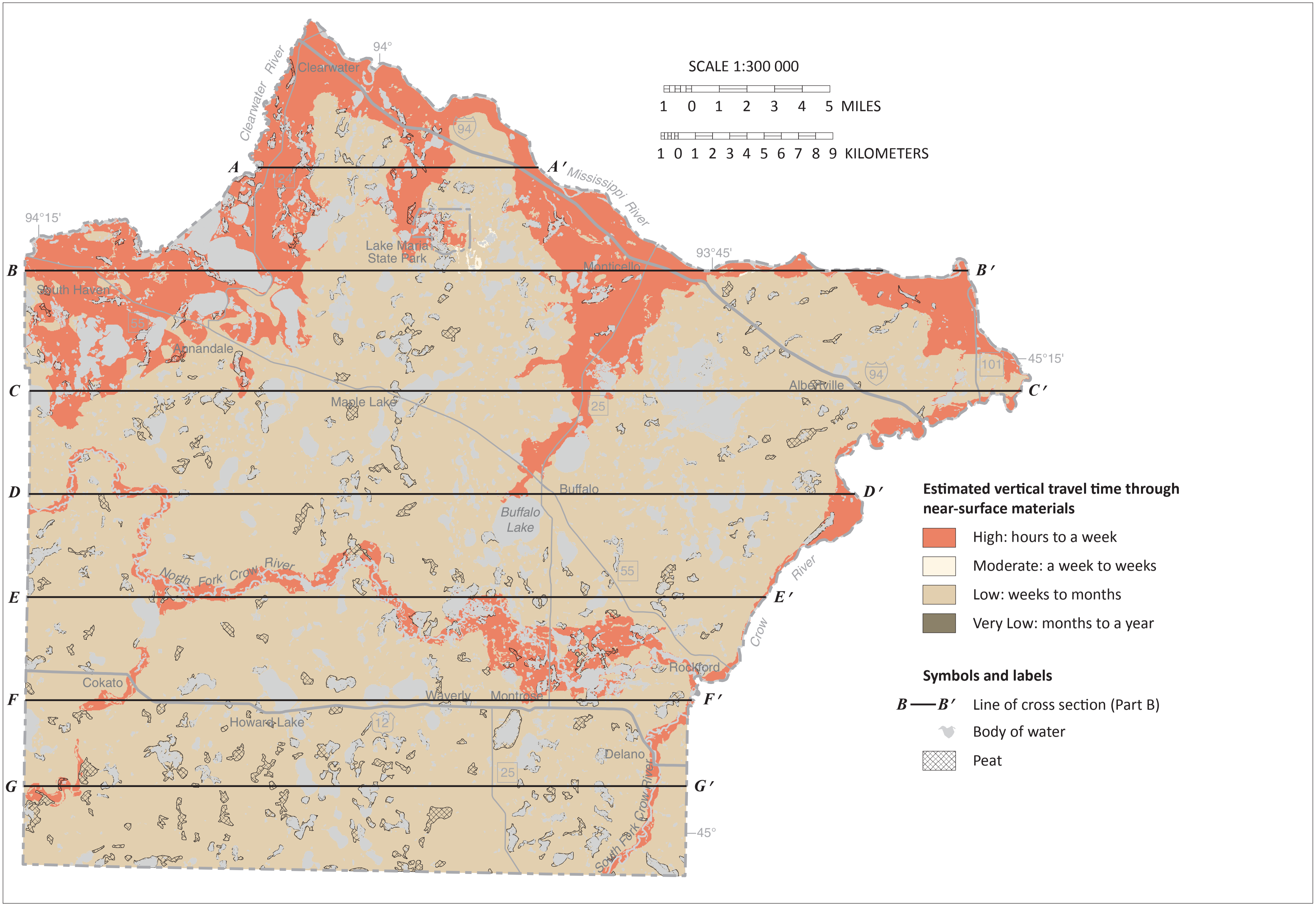


Figure 27. Pollution sensitivity of near-surface materials
Estimated vertical travel time to an assumed 10-foot deep water table. Map modified from Adams, 2016b.

Buried sand aquifer and bedrock surface

Methods

The sensitivity rating for the buried sand aquifers and the bedrock surface is based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with ratings of high or very high have relatively short travel times of less than a few years. Areas rated low or very low have estimated travel times of decades or longer (Figure 28).

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 29).

GIS software was used to calculate cumulative thickness of the sediment layers based on digital elevation models of sand and till distribution developed by Knaeble and others (2013), and the bedrock surface developed by Steenberg and Chandler (2013). Thicknesses of 10 feet or less were rated very high sensitivity, thicknesses greater than 40 feet were rated very low, and intermediate thicknesses had intermediate sensitivity ratings. More details are available in *Procedure for buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment (CFGS) thickness* (DNR, 2016c).

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

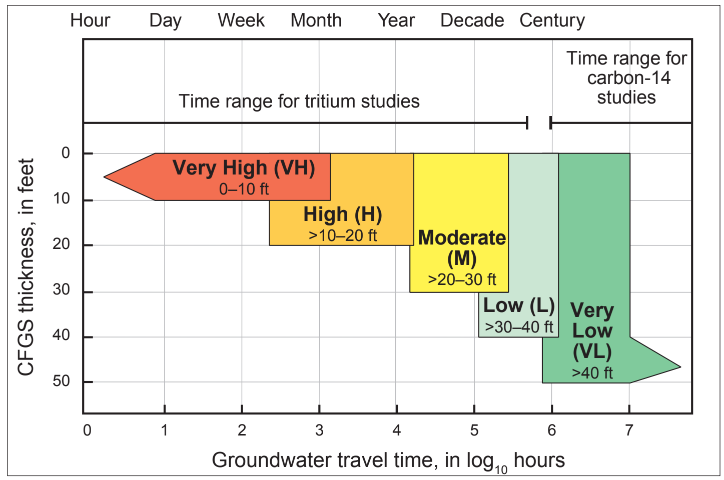


Figure 28. Geologic sensitivity rating for the buried sand aquifers and the bedrock surface
Sensitivity is defined by vertical travel time. The numbers following each rating represent the *cumulative fine-grained sediment* (CFGS) thickness overlying an aquifer.

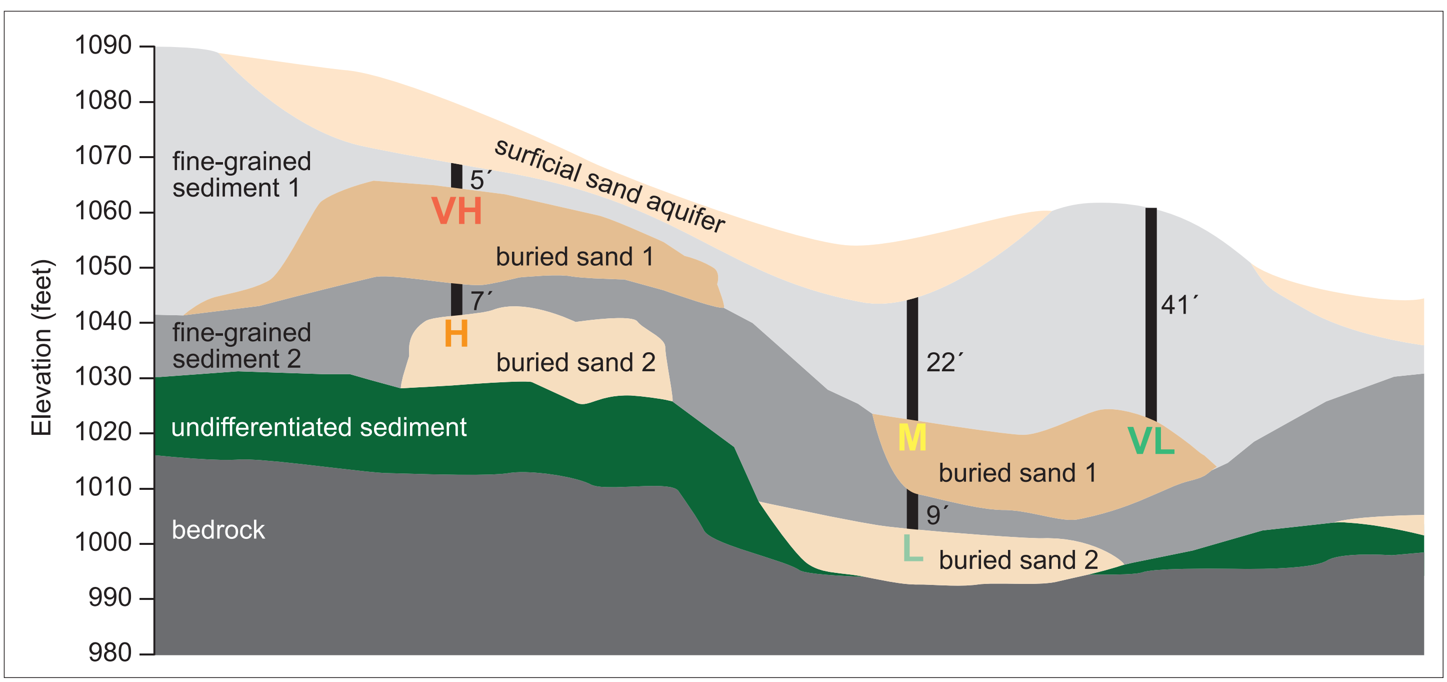


Figure 29. Cross section showing examples of pollution sensitivity ratings
Sensitivity ratings are based on the cumulative thickness of overlying fine-grained sediment. Each vertical black line is labeled with the thickness of fine-grained sediment. The letter at the base of the line indicates the sensitivity rating.

Groundwater conditions

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

- (1) Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
- (2) Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- (3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- (L) Groundwater flows laterally.
- (P) Tritium concentration may be artificially elevated by high capacity pumping.
- (U) Groundwater flowpath is unknown.
- (D) 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. Lateral flow of groundwater often results in recent or mixed tritium-age water in aquifers with low to very low sensitivity (condition L). The model can't always predict the origin of recent or mixed tritium-age water in deep, isolated, or protected settings (condition U).

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

Groundwater flow interpretations

Interpretations of groundwater flow and groundwater conditions are shown on the cross sections by coupling geologic texture, pollution sensitivity, estimated groundwater residence time, groundwater chemistry, equipotential lines, groundwater flow direction, and groundwater recharge and discharge areas.

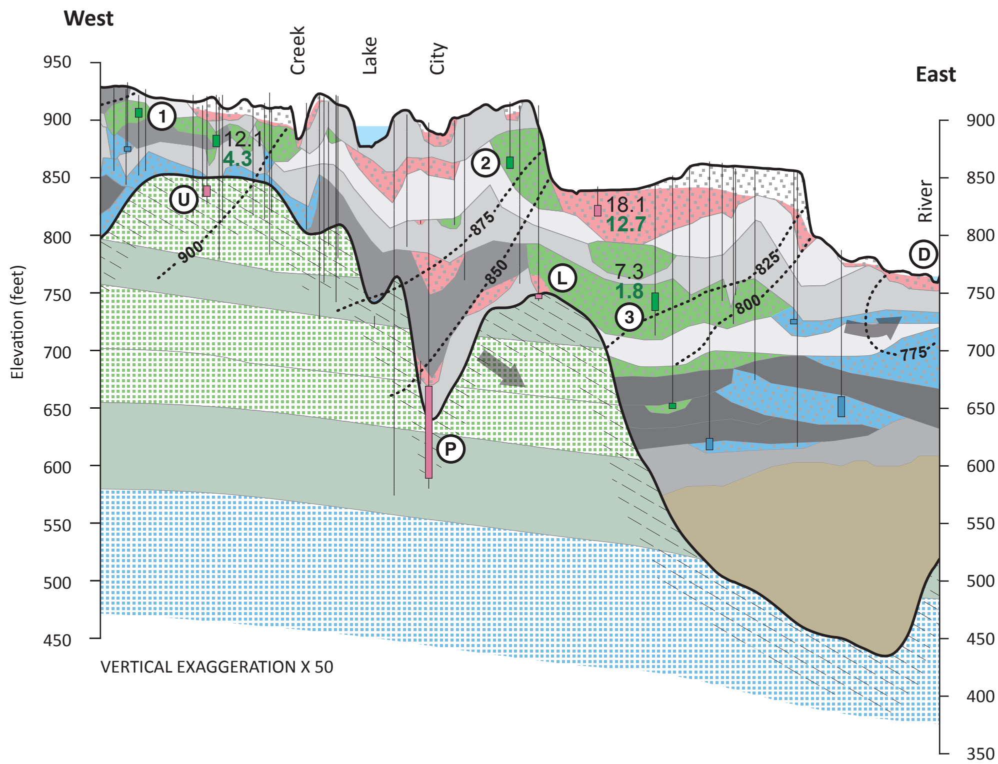
Figure 30 is a hypothetical cross section that integrate data elements used to understand groundwater flow. In this figure, sandy geologic materials (lighter grays) dominate the land surface, increasing recharge potential and near-surface pollution sensitivity in these areas. Moderately sandy till is present at the land surface in the central region of the cross section, which lessens groundwater recharge.

In the extreme western portion of the cross section, the till at the land surface has limited sand content, which decreases both groundwater recharge and pollution sensitivity. Groundwater residence time determined using tritium concentration varies widely across the cross section.

The hypothetical conditions described below appear from west to east in Figure 30.

- Condition 1: water moves through a thin layer of overlying fine-grained material to an underlying aquifer.
- Condition U: recent tritium-age water at this well is found below aquifers with vintage and mixed tritium-age signatures, therefore the groundwater flow path is unknown.
- Condition P: near the City, recent tritium-age water is found at a depth greater than should occur in a natural state. High-volume groundwater pumping in this area has likely steepened gradients bringing recent tritium-age water to this depth.
- Condition 2: east of the City, groundwater moves from an overlying surficial aquifer to an underlying buried aquifer.
- Condition L: recent tritium-age water is likely from lateral flow from an upgradient source.
- Condition 3: focused recharge from interconnected sands imparts a mixed tritium-age signature on the well that is additionally reflected in elevated levels of chloride and nitrate.
- Condition D: regional groundwater flow is both vertically downward and east toward the River. Groundwater discharges to the river system.

Groundwater conditions for Wright County are presented on Plates 7–9; groundwater flow interpretations are described on Plates 8 and 9.



Groundwater conditions

- (1) Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
- (2) Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- (3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- (L) Groundwater flows laterally.
- (P) Tritium concentrations may be artificially elevated by high capacity pumping.
- (U) Groundwater flowpath is unknown.
- (D) Groundwater discharges to a surface-water body.

Symbols and labels

- 7.3 Chloride: if shown, concentration is ≥5 ppm.
- 4.3 Nitrate: if shown, concentration is ≥1 ppm.
- General groundwater flow direction
- ···· 825 ···· Approximate equipotential contour
- Geologic contact
- Land or bedrock surface

Tritium age

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

- Recent
- Mixed
- Vintage

Quaternary unconsolidated sediment

- Aquifer (interpreted tritium age is indicated by background color)
- Aquitard (grouped by texture ranging from highest [light gray] to lowest sand content [dark gray] indicating relative hydraulic conductivity)
- Undifferentiated sediment

Bedrock

- Aquifer (interpreted tritium age is indicated by pattern color)
- Aquitard

Figure 30. Hypothetical cross section illustrating groundwater conditions

Results

These results describe the buried aquifers in stratigraphic order from shallowest to deepest, and include the depth, thickness, spatial distribution, and pollution sensitivity. This information is compared with the tritium age of groundwater and the presence or absence of anthropogenic chemical indicators. Higher sensitivity is associated with the following:

- Recent or mixed tritium age.
- Nitrate concentrations ≥1 ppm
- Chloride concentrations ≥5 ppm with chloride/bromide ratios ≥250.

nts aquifer (Figure 31)

Sensitivity: The nts aquifer is used by approximately 3 percent of wells in the county and has a wide extent over the northern and central portions. In the north, large areas of the aquifer intersect the land surface. The majority of the aquifer is located between the land surface and 35 feet, with a mean depth of 18 feet. Its proximity to the land surface and lack of a thick overlying till results in an overall very high pollution sensitivity. The buried portions of the aquifer are predominately overlain by till (hbt) of the Heiberg Member of the New Ulm Formation. The loamy texture of the hbt provides a protective layer where the thickness is adequate.

Chemistry: 1 groundwater sample was collected from this aquifer in a confined condition. The sample had a mixed tritium age which is consistent with the highly variable sensitivity of the aquifer near the well. The sample had elevated chloride and recent (<100) carbon-14 residence time.

ms aquifer (Figure 32)

Sensitivity: The ms aquifer is used by approximately 13 percent of wells in the county and has a widespread areal extent. The aquifer is located at depths between 15 and 90 feet below the land surface, with a mean depth of 52 feet. Sensitivity is variable due to its varying proximity to the land surface, intermittent connections to the overlying nts aquifer, and wide range of depth. It varies from moderate to very high sensitivity in large areas where the aquifer is near the overlying nts aquifer. The sensitivity is very low elsewhere in the county, where overlying till provides more protection. The overlying till (nt) of the Villard Member of the New Ulm Formation has a predominately sandy loam to loam texture that provides a protective layer where the thickness is adequate.

Chemistry: 20 groundwater samples were collected from this aquifer. Of these, 16 were analyzed for tritium: 10 had mixed tritium age and 6 had vintage tritium age. The mixed tritium-age samples were generally located in areas mapped with high to very high sensitivity, or downgradient of such areas. All of the vintage tritium-age samples were located in areas mapped as very low sensitivity. Of the 17 samples tested for chloride, 8 had elevated concentrations. Of the 18 samples tested for nitrate, none were elevated.

cg aquifer (Figure 33)

Sensitivity: The cg aquifer is used by approximately 7 percent of wells in the county. It has limited areal extent, predominately occurring in the north and northeastern portions of the county and intermittently in the south-central portion. The aquifer is at the land surface in a few places in the northeastern portion of the county. Elsewhere its depth is between 20 and 90 feet, with a mean depth of 58 feet. Large portions have moderate to very high pollution sensitivity due to its proximity to the land surface and direct connections to the overlying ms aquifer. The sensitivity rating is very low where protection is provided by the aquifer's depth and the relatively thick sandy loam till (mt) of the overlying Moland Member of the New Ulm Formation.

Chemistry: 12 groundwater samples were collected from this aquifer. Of these, 11 were tested for tritium: 3 had recent tritium age, 5 had mixed tritium age, and 3 had vintage tritium age. In general, the recent and mixed tritium-age samples were located in areas mapped with high to very high sensitivity, or downgradient of such areas. The 3 vintage tritium-age samples were collected in south central Wright County where the aquifer is mapped as having very low sensitivity. A groundwater residence time of 2,000 years was determined using carbon-14 analysis for a well in an area mapped as very low sensitivity. Of the 12 samples analyzed for chloride, 5 had elevated concentrations. Of the 12 samples analyzed for nitrate, 1 was elevated (3.4 ppm). This sample also had elevated chloride (59 ppm) with a chloride/bromide ratio of 1,218 that suggests anthropogenic influences.

cg1 aquifer (Figure 34)

*Sensitiv*ity: The cg1 aquifer is used by approximately 26 percent of wells in the county and has widespread areal extent, except in the southwestern portion. It is located at depths between 50 and 140 feet below the land surface, with a mean depth of 85 feet. Large portions of the aquifer have very low sensitivity. Elsewhere the sensitivity increases from moderate to very high where the aquifer is connected with overlying sands. In these locations, the overlying sandy loam till (ct) of the Cromwell Formation, St. Croix phase, is absent or discontinuous.

Chemistry: 36 groundwater samples were collected from this aquifer. Of these, 26 were analyzed for tritium: 1 had recent tritium age, 19 had mixed tritium age, and 6 had vintage tritium age. In general, samples with recent and mixed tritium age were from wells located in areas mapped with high to very high sensitivity, or downgradient of such areas. The 6 vintage tritium-age samples were spread throughout the central and eastern border of the county where the mapped sensitivity ranges from very low to moderate. A vintage tritium-age sample collected near Albertville was from a part of the aquifer that was likely influenced by old regional groundwater flow that was discharging to the Mississippi River. Elsewhere, a groundwater residence time of 3,000 years was determined using carbon-14 analysis for a well located in an area mapped as very low sensitivity. Of the 32 samples analyzed for chloride, 16 had elevated concentrations. Of the 33 samples analyzed for nitrate, 5 were elevated.

hs aquifer (Figure 35)

Sensitivity: The hs aquifer is used by approximately 12 percent of wells in the county. It has moderate areal extent, primarily in the central portion of the county. The majority of the aquifer is located between 70 and 160 feet below the land surface, with a mean depth of 107 feet. Large portions of the aquifer have very low pollution sensitivity, except in the South Haven, Clearwater, Lake Maria, and Rockford areas. In these areas, the sensitivity increases from moderate to very high where the aquifer is connected to overlying sands. Here the sandy loam tills (ct and ct1, respectively) of the overlying Cromwell Formation, St. Croix and Emerald phases are absent or discontinuous.

Chemistry: 23 groundwater samples were collected from this aquifer. Of these, 17 were analyzed for tritium: 5 had mixed tritium age and 12 had vintage tritium age. In general, mixed tritium-age samples were located in areas mapped with high to very high sensitivity, or downgradient of such areas. There was not a clear reason for the mixed tritium-age sample from a well southwest of Delano. The 12 vintage tritium-age samples were spread throughout the central and southeastern portions of the county where the mapped sensitivity was very low. Of the 17 samples analyzed for chloride, 4 had elevated concentrations. Of the 19 samples tested for nitrate, 2 were elevated.

scs aquifer (Figure 36)

Sensitivity: The scs aquifer is used by approximately 9 percent of wells in the county. It has fragmented areal extent in the northern and central portions of the county, but is relatively laterally continuous in the southwestern portions. The aquifer is located at depths between 60 and 150 feet, with a mean depth of 105 feet. Large portions have very low sensitivity with fragmentary areas having moderate to very high sensitivity. In these areas, the sandy loam till (hwt) of the overlying Hewitt Formation is absent or discontinuous.

Chemistry: 24 groundwater samples were collected from this aquifer. Of these, 22 were analyzed for tritium: 4 had recent tritium age, 3 had mixed tritium age, and 15 had vintage tritium age. In general, mixed tritium-age samples were located in areas mapped with high to very high sensitivity, or downgradient of such areas. Three recent tritium-age samples were located near Annandale where the mapped sensitivity is very low. This cluster of recent values is anomalous for this area. One possible explanation is that buried sand layers may be present that were not mapped in the overlying MGS buried sand extent and thickness information (Part A, Plate 5). Note that a mixed tritium-age sample was collected in this area in the overlying aquifer. Another explanation is that high-volume municipal groundwater pumping may be steepening the groundwater flow gradients in the area bringing recent tritium-age water to greater depths. A recent tritium-age sample was collected near Lake Maria State Park that was close to a mixed tritium-age sample and areas mapped as high to very high sensitivity. In this location, it appears the areal extent of the scs aquifer and likely pathways to overlying aquifers was not accurately represented in the model. The 15 vintage tritium-age samples were spread throughout the aquifer but were primarily located in the southwestern area near Cokato and Howard Lake. Modeled carbon-14 residence time for the aquifer ranged between 500 and 5,000 years, which was consistent with the modeled pollution sensitivities near the collected samples. Of the 18 samples analyzed for chloride, 4 had elevated concentrations. Of the 20 samples analyzed for nitrate, 1 was elevated.

mls aquifer (Figure 37)

Sensitivity: The mls aquifer is used by approximately 3 percent of wells in the county. It has a limited areal extent and is fragmentary where present. The majority of the aquifer is located at depths between 85 and 180 feet, with a mean depth of 135 feet. The majority of the aquifer has very low sensitivity, with limited areas of moderate to very high sensitivity. In these areas, the overlying loam till (sct) of the Sauk Centre Member of the Lake Henry Formation (Winnipeg provenance) is absent or discontinuous.

Chemistry: 8 groundwater samples were collected from this aquifer. Of these, 6 were analyzed for tritium: 2 had mixed tritium age and 4 had vintage tritium age. One mixed tritium-age sample was from a well north of Buffalo in an area mapped with sensitivity ranging from very low to very high. The other mixed tritium-age sample was near Annandale where the mapped sensitivity was very low, but recent and mixed tritium was found in overlying aquifers (see scs). Four vintage tritium-age samples were spread throughout the aquifer in areas mapped with very low sensitivity. Three were near Cokato and one was north of Lake Maria State Park. Of the 8 samples analyzed for chloride, 2 had elevated concentrations. Of the 8 samples tested for nitrate, none were elevated.

prs aquifer (Figure 38)

Sensitivity: The prs aquifer is used by approximately 3 percent of wells in the county. It has limited areal extent in the northern and northeastern portions of the county and is fragmentary around Buffalo and Maple Lake. The aquifer is located at depths between 85 and 140 feet, with a mean depth of 116 feet. The majority of the aquifer has very low sensitivity, however parts of the aquifer located north of Monticello and northeast of Albertville range from very low to very high sensitivity. In these areas, the loam till (mlt) of the overlying Meyer Lake Member of the Lake Henry Formation (Winnipeg provenance) is absent or discontinuous, which increases the sensitivity of the aquifer.

Chemistry: 3 groundwater samples were collected from this aquifer. Of these, 2 were tested for tritium: each had a mixed tritium age. The samples were located in areas with mapped sensitivity ranging from very low to moderate. These wells were located downgradient and were near areas with higher mapped sensitivities. Of the 2 samples analyzed for chloride, 1 had elevated concentrations. Of the 2 samples analyzed for nitrate, none were elevated.

pws aquifer (Figure 39)

Sensitivity: The pws aquifer is used by less than 1 percent of wells in the county. It has limited areal extent in the central portion of the county. The majority of the aquifer is located at depths between 115 and 220 feet, with a mean depth of 155 feet. The aquifer has very low sensitivity, with a limited area near Delano having moderate sensitivity. In this area, the loam till (prt) of the overlying pre-Wisconsinan Superior provenance is thin and discontinuous.

Chemistry: 3 groundwater samples were collected from this aquifer and analyzed for tritium. Two near Delano had vintage tritium age and one near Buffalo had recent tritium age. The recent tritium-age sample was located in an area that was primarily mapped as very low sensitivity, but also had moderate to high sensitivity mapped within 500 meters. Of the 3 samples analyzed for chloride, 1 had an elevated concentration. Of the 3 samples analyzed for nitrate, none were elevated.

psu aquifer (Figure 40)

*Sensitivi*ty: The psu aquifer is used by approximately 8 percent of wells in the county. It has wide areal extent, but is primarily present as discontinuous bodies. The majority of the aquifer is located at depths between 80 and 200 feet, with a mean depth of 140 feet. The aquifer has very low sensitivity, except in areas near Rockford, Monticello, and Clearwater where it ranges from moderate to very high. In these areas, the loam till (pwt) of the overlying mixed Rainy and Winnipeg provenance is thin and discontinuous, resulting in higher sensitivity.

Chemistry: 18 groundwater samples were collected from this aquifer. All were analyzed for tritium: 6 had mixed tritium age and 12 had vintage tritium age. In general, the mixed tritium-age samples in the northeastern area were located either near or downgradient of areas with higher sensitivities. Elsewhere, the pollution sensitivity model did not neatly predict the elevated tritium values. The 12 vintage tritium-age samples were spread throughout the aquifer. Carbon-14 residence time for a sample in the aquifer was 2,000 years, which was consistent with the modeled pollution sensitivity. Of the 14 samples analyzed for chloride, 1 had an elevated concentration. Of the 14 samples analyzed for nitrate, none were elevated.

zus aquifer (Figure 41)

Sensitivity: The zus aquifer is used by approximately 3 percent of wells in the county. It has wide areal extent but is primarily present as discontinuous bodies. The aquifer is located at depths between 160 and 280 feet, with a mean depth of 210 feet. It has very low sensitivity, except for limited moderate sensitivity near the Crow River northeast of Rockford and a small area near Clearwater. In these areas, there is limited information on the overlying sediment texture and provenance. The overlying undifferentiated sediments (pu) may include sand and gravel deposits that are not explicitly incorporated into the pollution sensitivity model.

Chemistry: 13 groundwater samples were collected from this aquifer. All samples were analyzed for tritium: 3 had mixed tritium age and 10 had vintage tritium age. The pollution sensitivity model did not precisely predict the elevated tritium values of the 3 mixed tritium ages. The

10 vintage tritium-age samples were spread throughout the aquifer. Carbon-14 residence time for the zus aquifer ranged between 1,700 and 1,800 years, which was consistent with the very low pollution sensitivity calculated for the aquifer.

Of the 13 samples analyzed for chloride, 1 had an elevated concentration. Of the 13 samples analyzed for nitrate, none were elevated.

Bedrock surface (Figure 42)

Sensitivity: Bedrock aquifers are used by approximately 13 percent of wells in the county, with most of these located in the eastern portion. Wells completed in bedrock aquifers vary widely in depth, ranging from 65 feet to 1,038 feet below the land surface. In general, the top of the bedrock surface has very low sensitivity, except for moderate to high sensitivity regions along the edges of river valleys. In these areas, sand and gravel terrace deposits overlie the bedrock surface with few intervening till layers to provide protection.

The bedrock surface represents the boundary from overlying unconsolidated sediments (sand, gravel, silt, clay) to underlying sedimentary and crystalline bedrock. Generally, the bedrock surface of Wright County can be differentiated into three primary groups, two of which are water bearing. One group consists of Cretaceous sandstones, siltstones, and mudstones that are primarily located in the southwestern and south-central areas of the county and in a large area near South Haven in the northwest (Steenberg and Chandler, 2013). These deposits are water-bearing, especially in the more predominately sandy Dakota Formation. Another group consists of aquifers and aquitards that are Upper Cambrian through Mesoproterozoic in age (Figure 7). This group is present in the central and eastern portions of the county. The final generalized group consists of low permeability igneous and metamorphic crystalline rock of Precambrian age. Although wells can be completed in crystalline rock, they typically have lower yield than wells completed in sedimentary bedrock aquifers.

Chemistry: 42 groundwater samples were collected from bedrock aquifers. Of these, 35 were analyzed for tritium: 2 had recent tritium age, 6 had mixed tritium age, and 27 had vintage tritium age. One recent tritium-age sample was collected north of Monticello where the modeled sensitivity was high to very high. The other occurred east of Albertville where the modeled sensitivity was very low. It is unclear why this sample had a recent tritium age. In general, the mixed tritium-age samples were near high volume pumping. In these areas, recent tritium-age water may have been brought to deeper than expected depths or was located downgradient of areas with higher sensitivities. The 27 vintage tritium-age samples are spread throughout the county and fit well with the estimated sensitivity. Calculated carbon-14 residence time ranges from recent (<100 years) to 19,000 years, which is consistent with the modeled pollution sensitivity. The recent carbon-14 residence time has a vintage tritium age, suggesting that the residence time is greater than 65 years. Of the 30 samples tested for chloride, 3 had elevated concentrations. Of the 32 samples tested for nitrate, 1 was elevated.

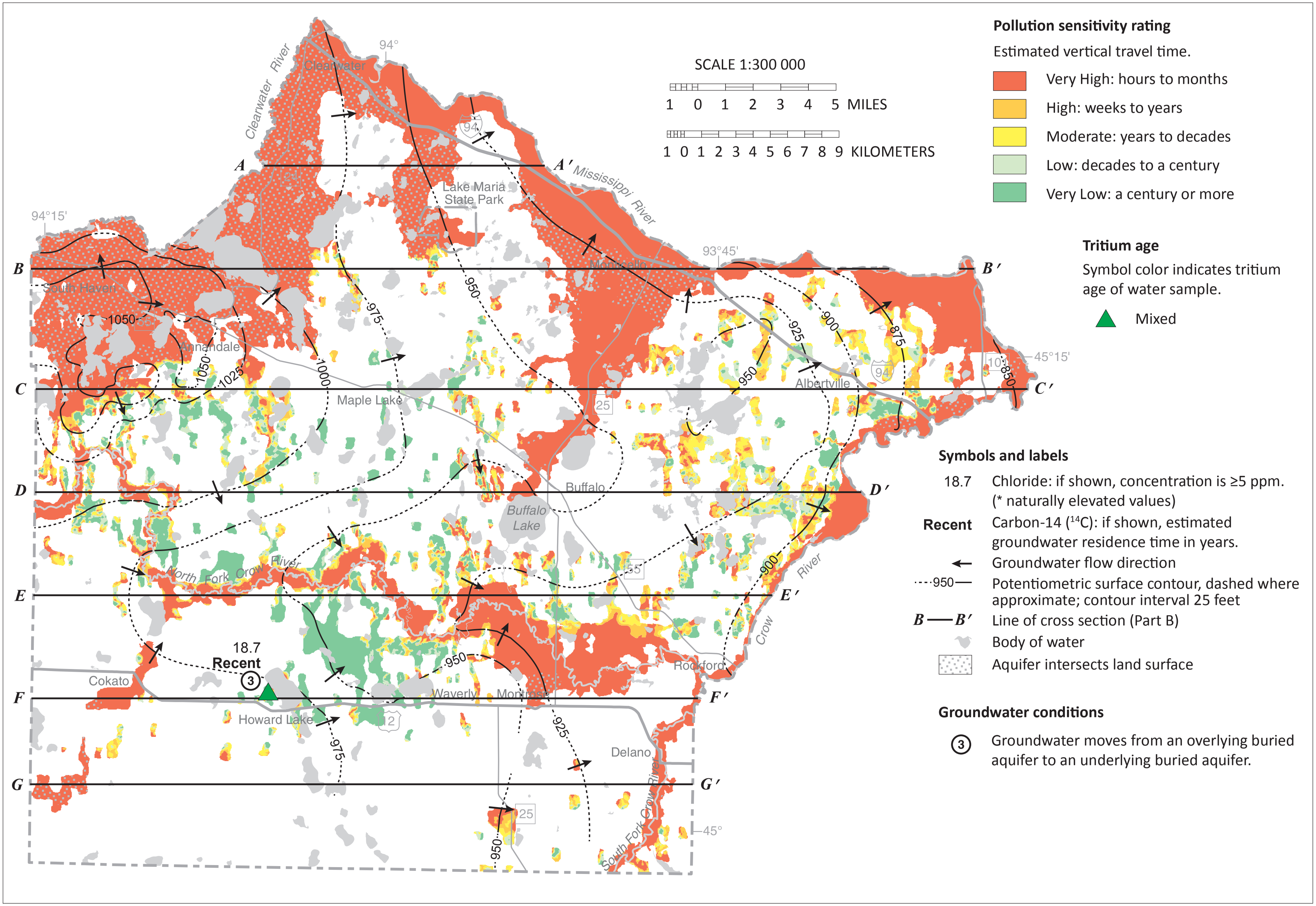
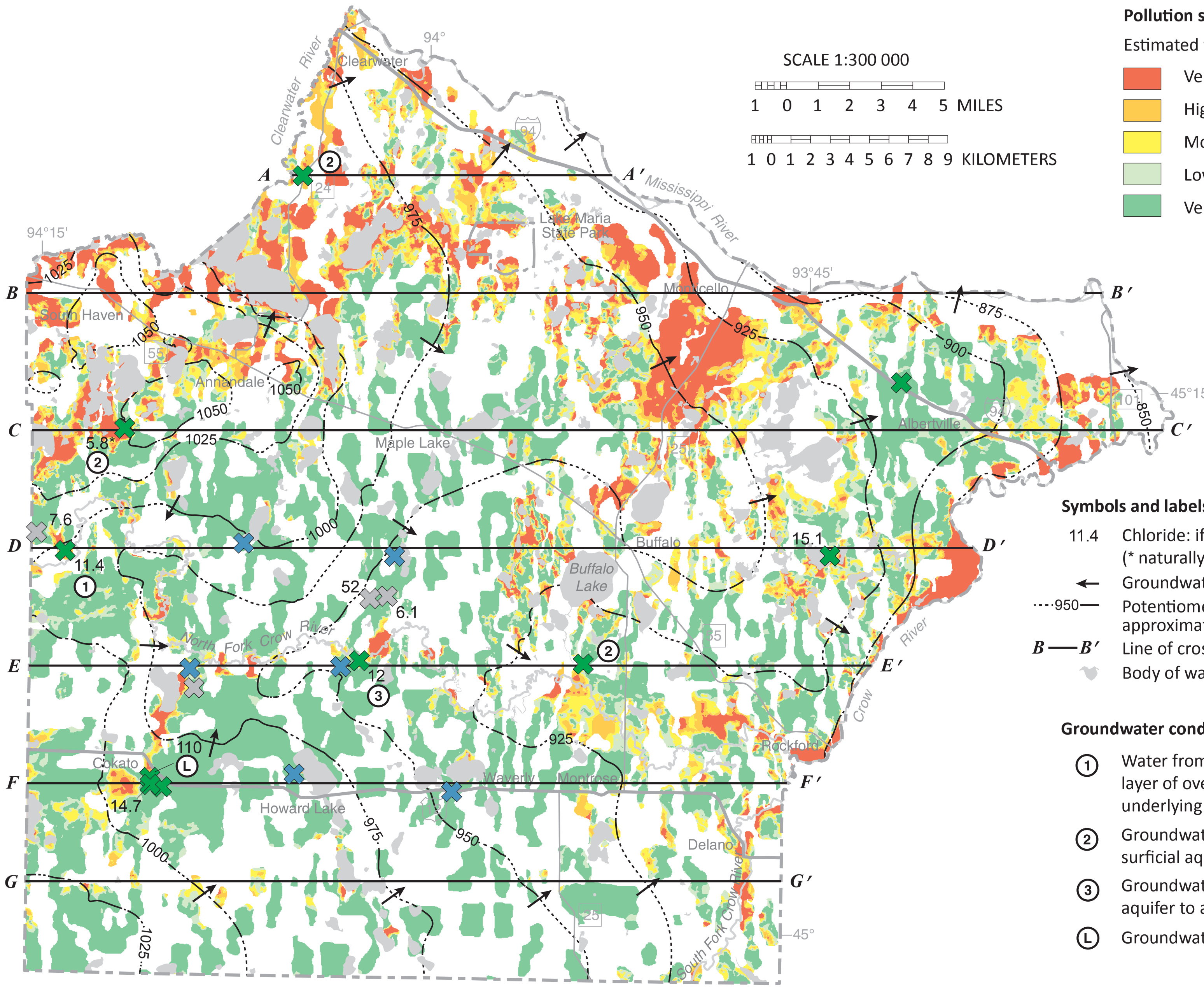


Figure 31. Pollution sensitivity of the nts aquifer and groundwater flow directions
The majority of the nts aquifer has a very high pollution sensitivity, due to its proximity to the land surface and lack of a thick overlying till.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage
- Not sampled for tritium.

Symbols and labels

- 11.4 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated values)
- Groundwater flow direction
- 950 Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- 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.
2. Groundwater moves from an overlying surficial aquifer to a buried aquifer.
3. Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.

L. Groundwater flows laterally.

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

The ms aquifer's sensitivity ranges from very high to very low due to its variable proximity to the land surface, intermittent connections to the overlying nts aquifer, and wide ranging depth below the land surface.

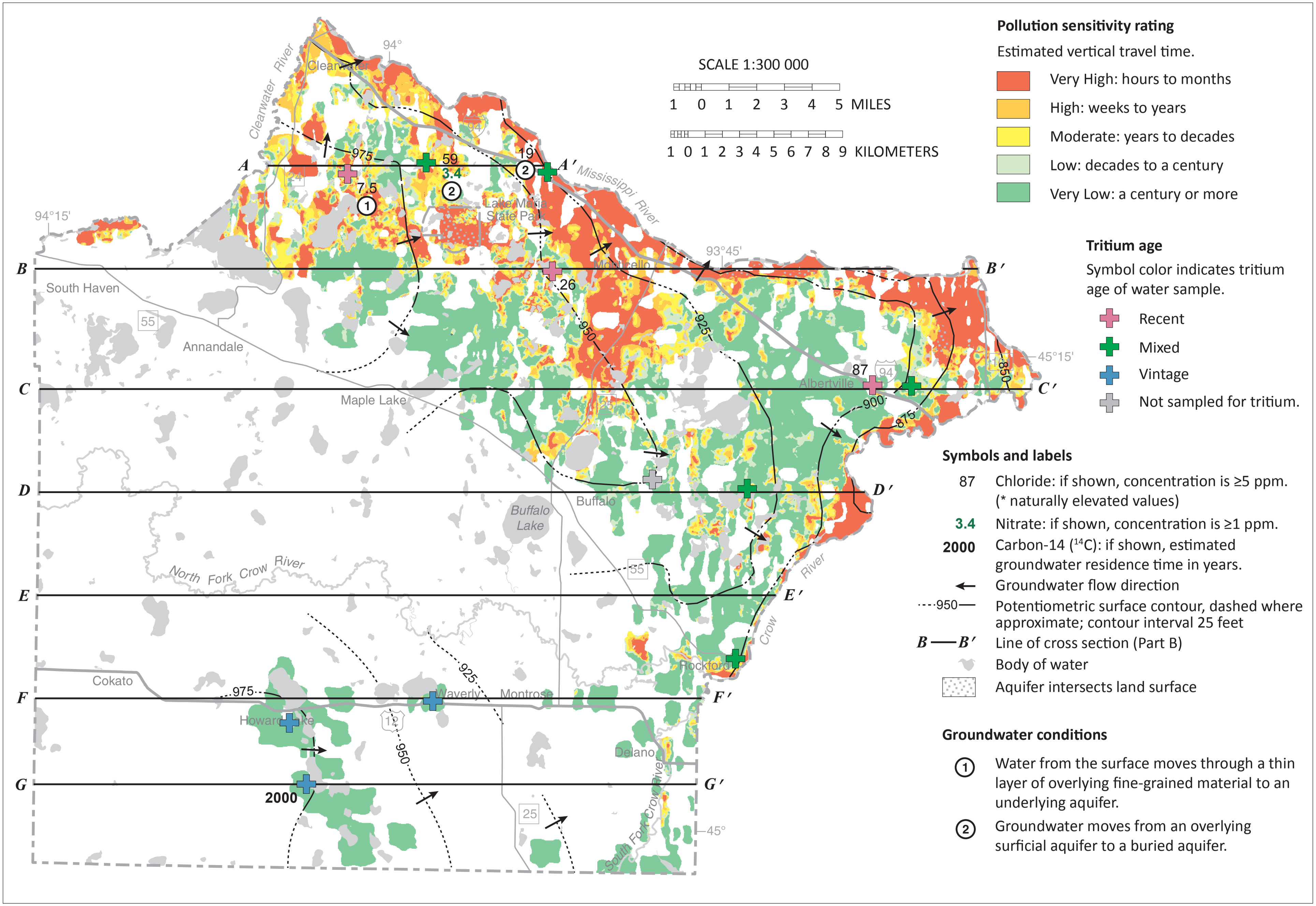


Figure 33. Pollution sensitivity of the cg aquifer and groundwater flow directions
Large portions of the cg aquifer have moderate to very high pollution sensitivity due to its proximity to the land surface and direct connections to the overlying ms aquifer.

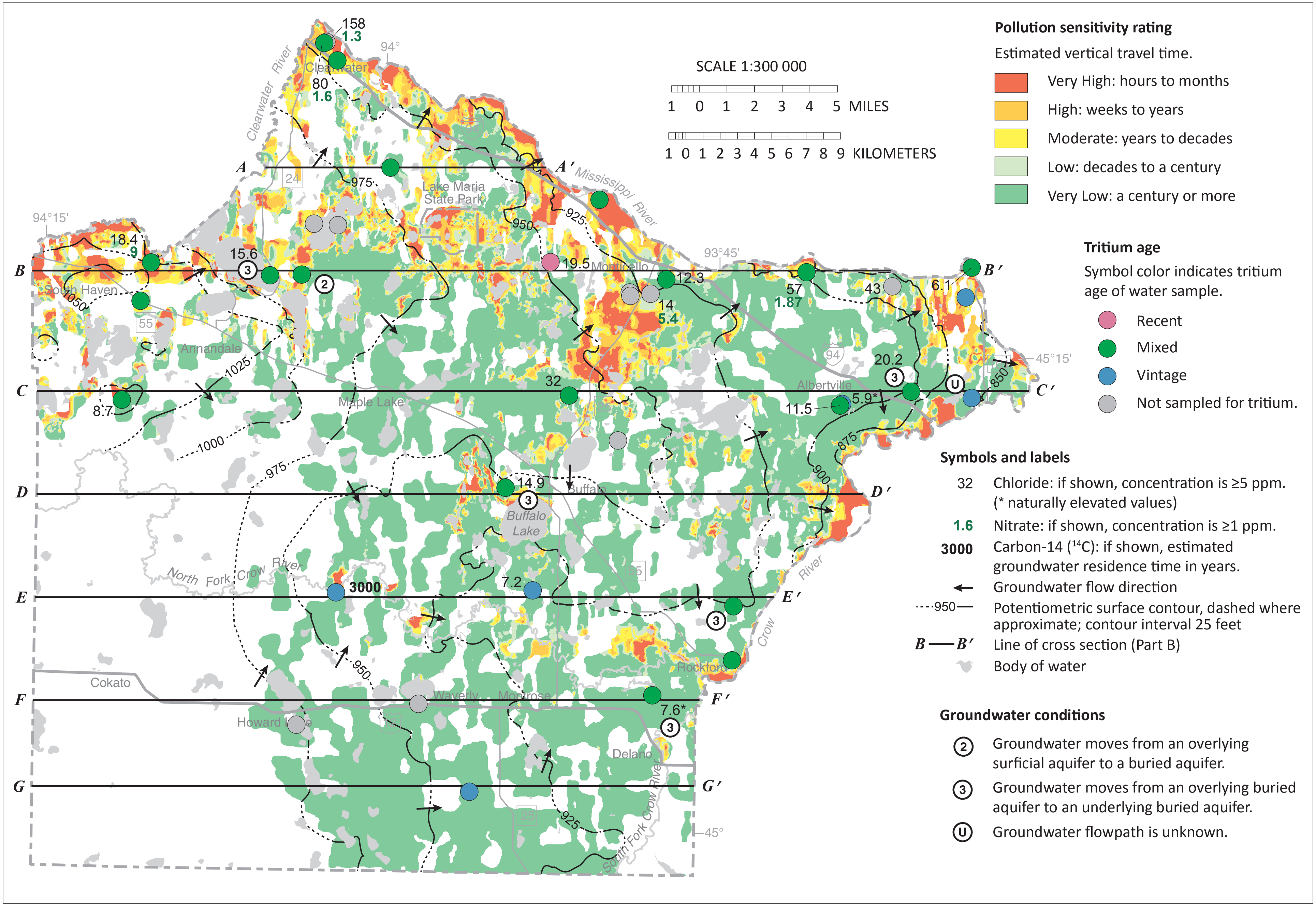


Figure 34. Pollution sensitivity of the cg1 aquifer and groundwater flow directions
Large portions of the cg1 aquifer have very low sensitivity, however, sensitivity increases to very high in areas where the aquifer is connected to overlying sands.

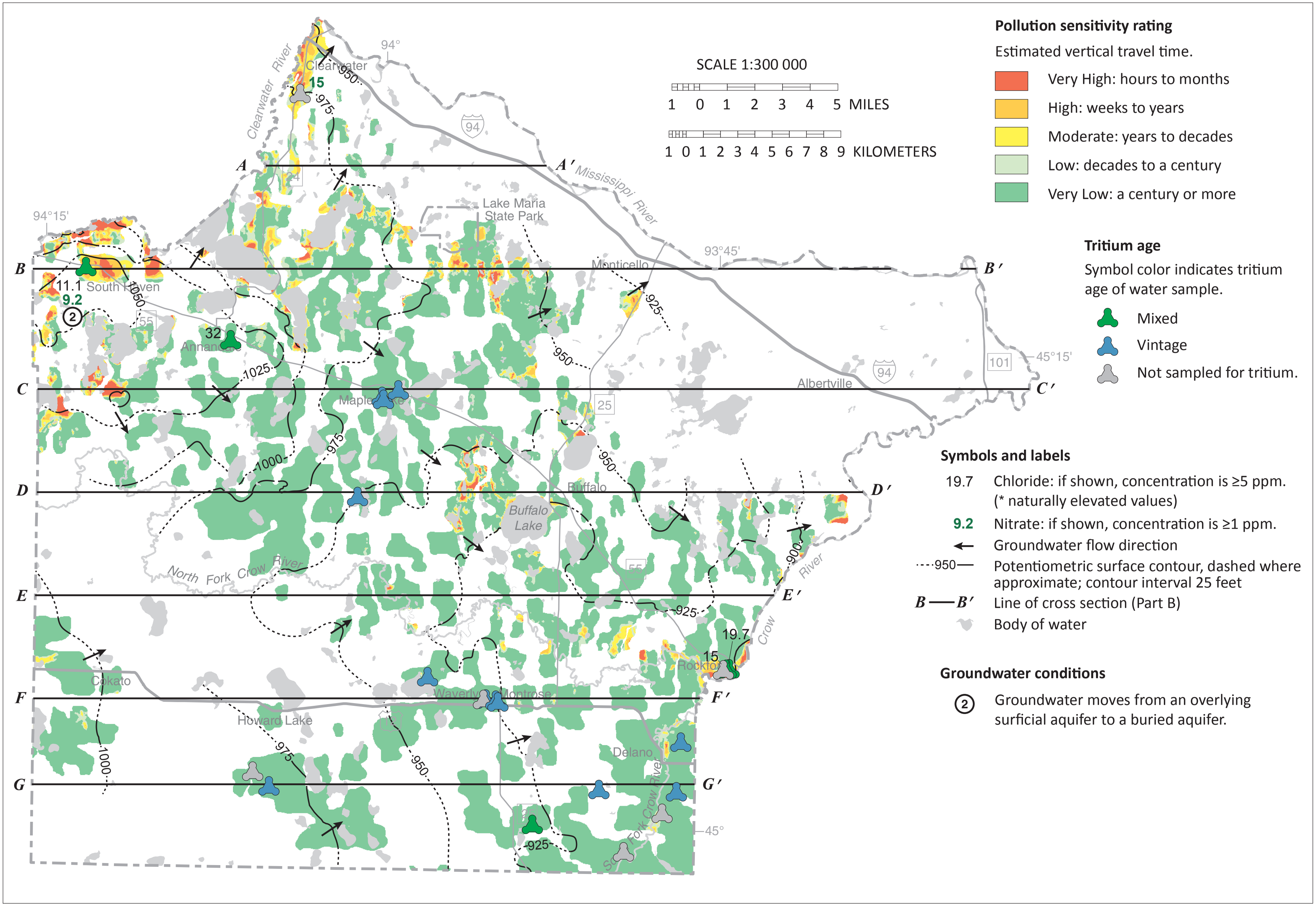


Figure 35. Pollution sensitivity of the hs aquifer and groundwater flow directions
The majority of the hs aquifer has very low pollution sensitivity, except in the South Haven, Clearwater, Lake Maria, and Rockford areas where it is less protected by overlying till.

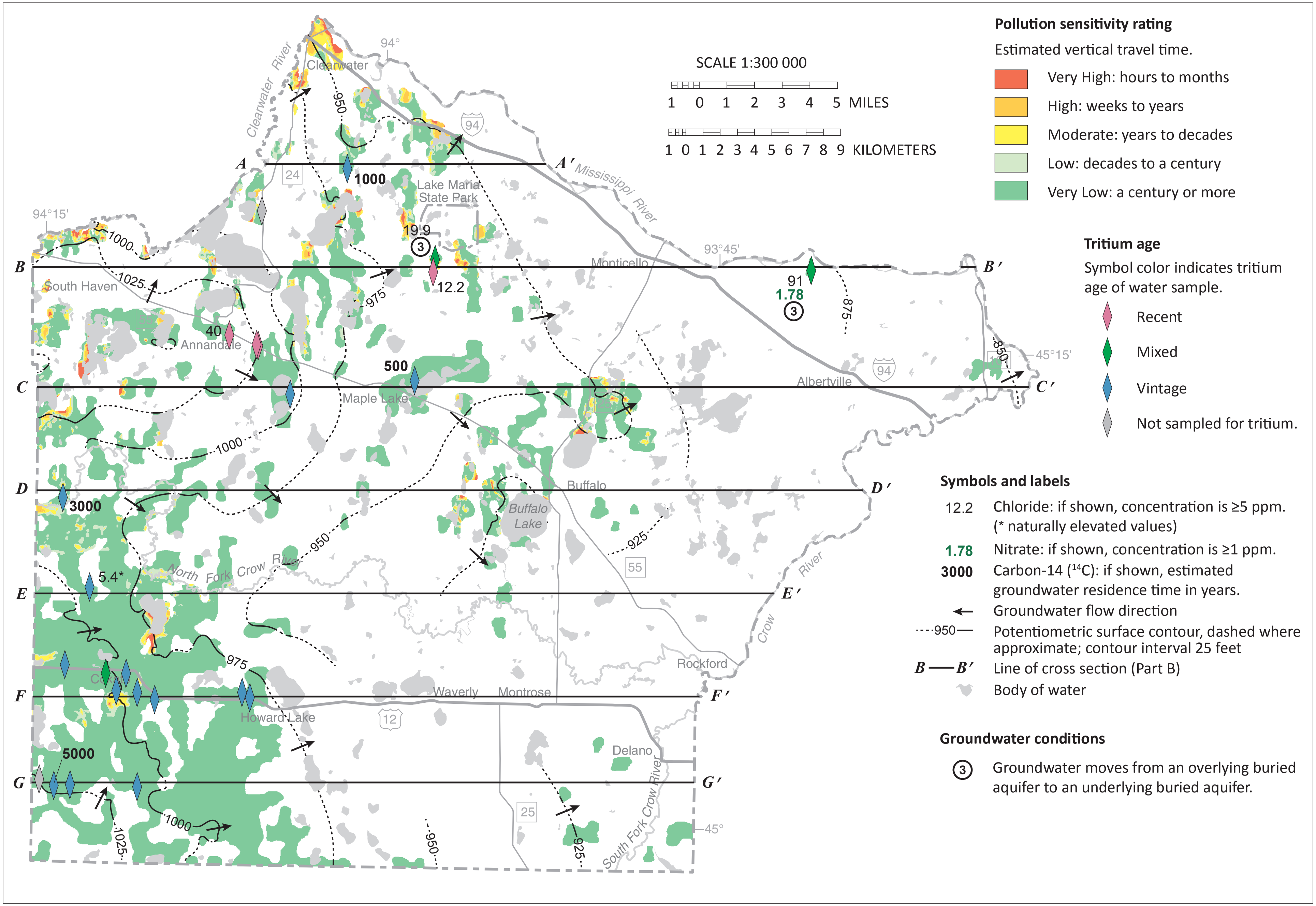


Figure 36. Pollution sensitivity of the scs aquifer and groundwater flow directions
The majority of the scs aquifer has very low sensitivity, with fragmentary areas having moderate to very high sensitivity.

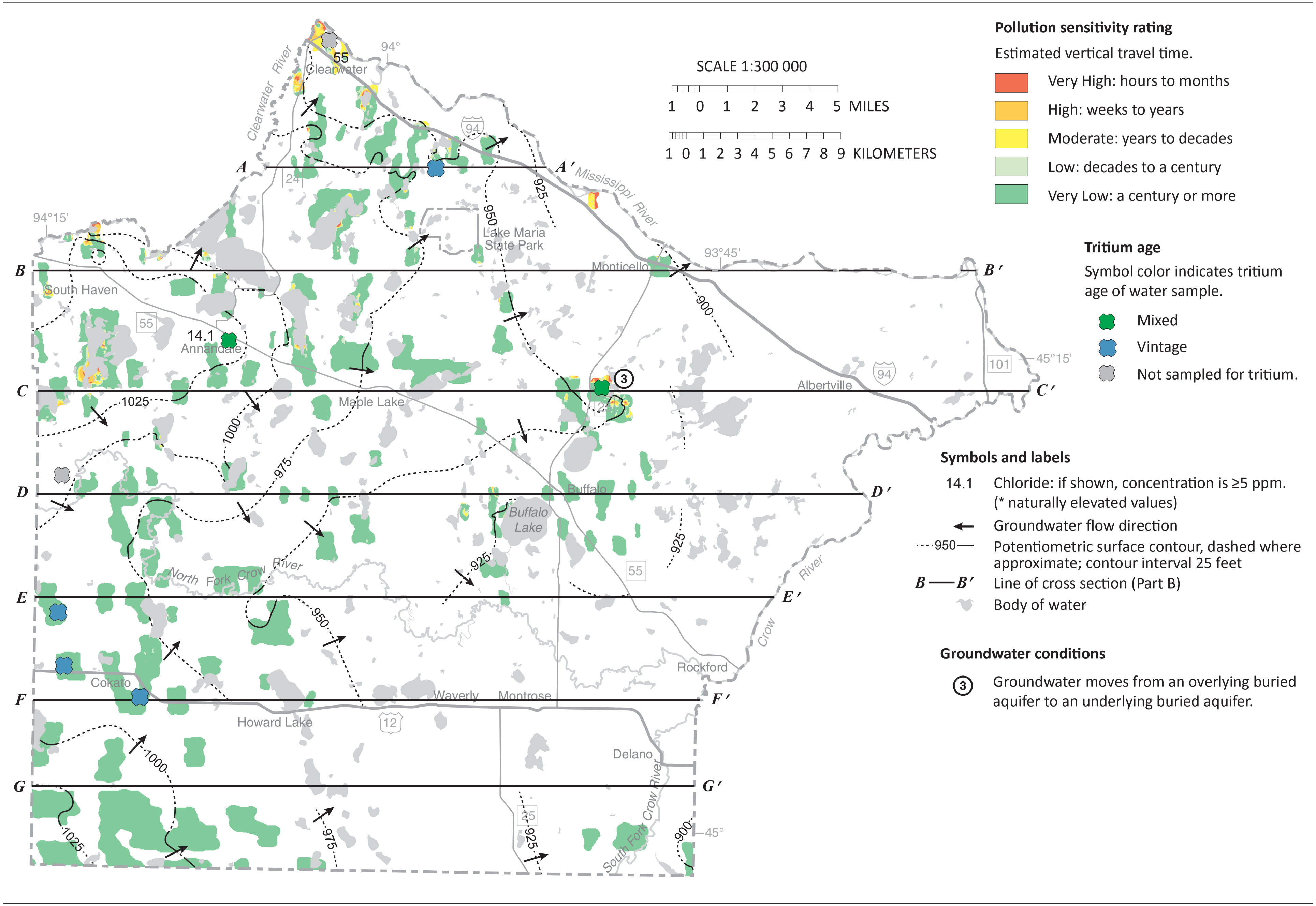


Figure 37. Pollution sensitivity of the mls aquifer and groundwater flow directions
The mls aquifer primarily has very low sensitivity, with more sensitive areas occurring where overlying till is absent or discontinuous.

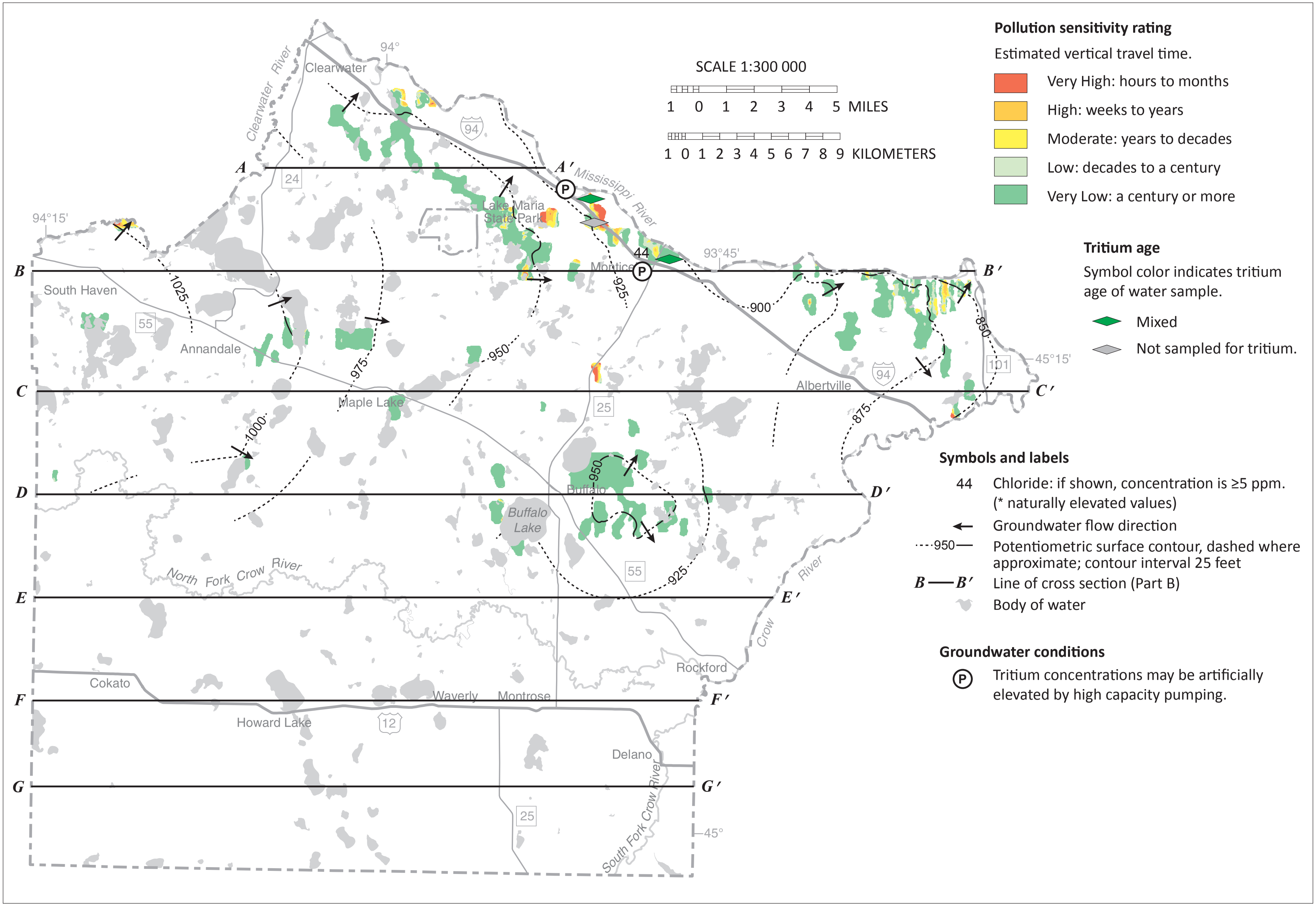


Figure 38. Pollution sensitivity of the prs aquifer and groundwater flow directions
The prs aquifer primarily has very low sensitivity, except in areas located near Monticello and Albertville where it ranges from very low to very high.

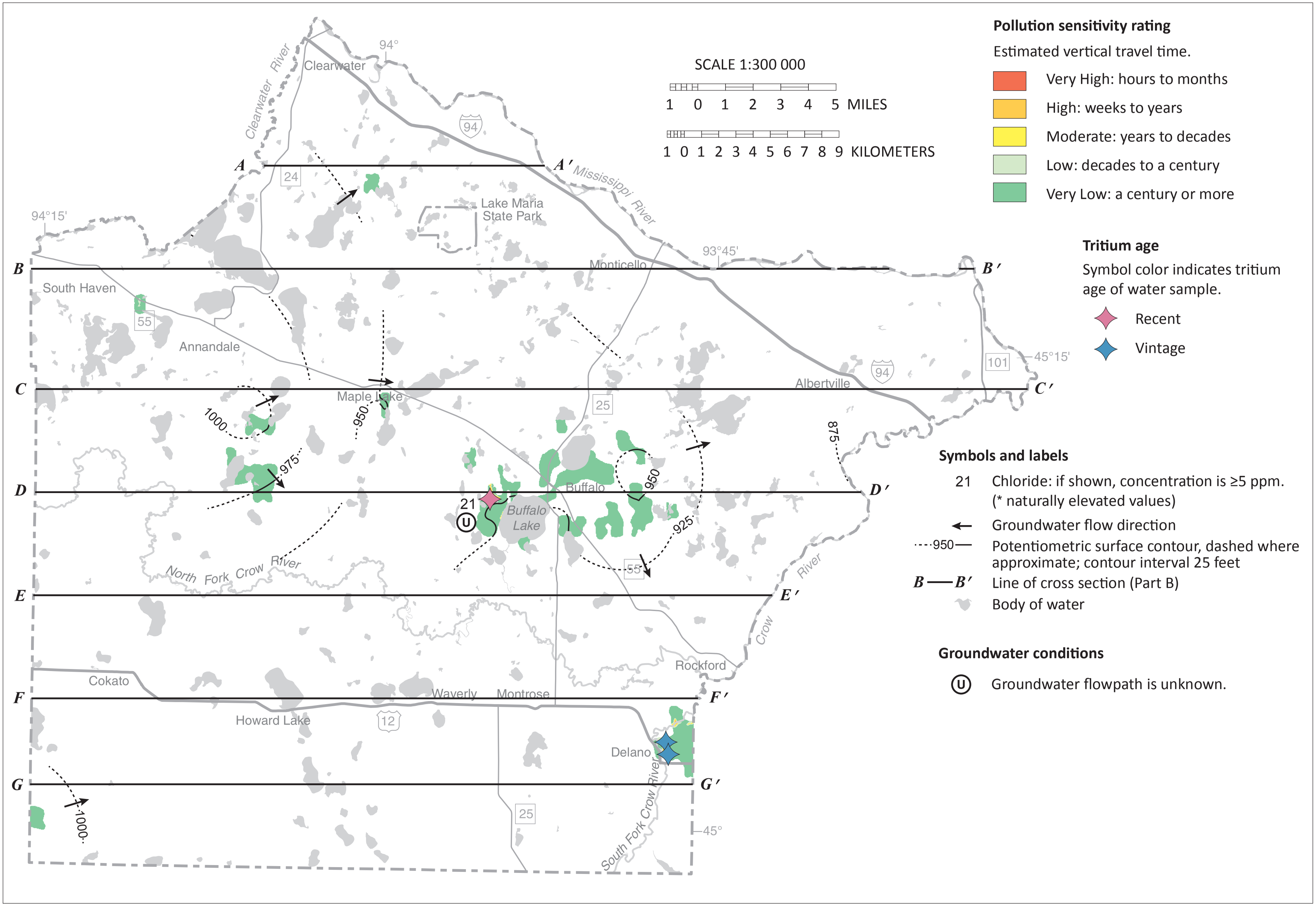


Figure 39. Pollution sensitivity of the pws aquifer and groundwater flow directions
The pws aquifer has very low sensitivity, except in a small area near Delano that has moderate sensitivity.

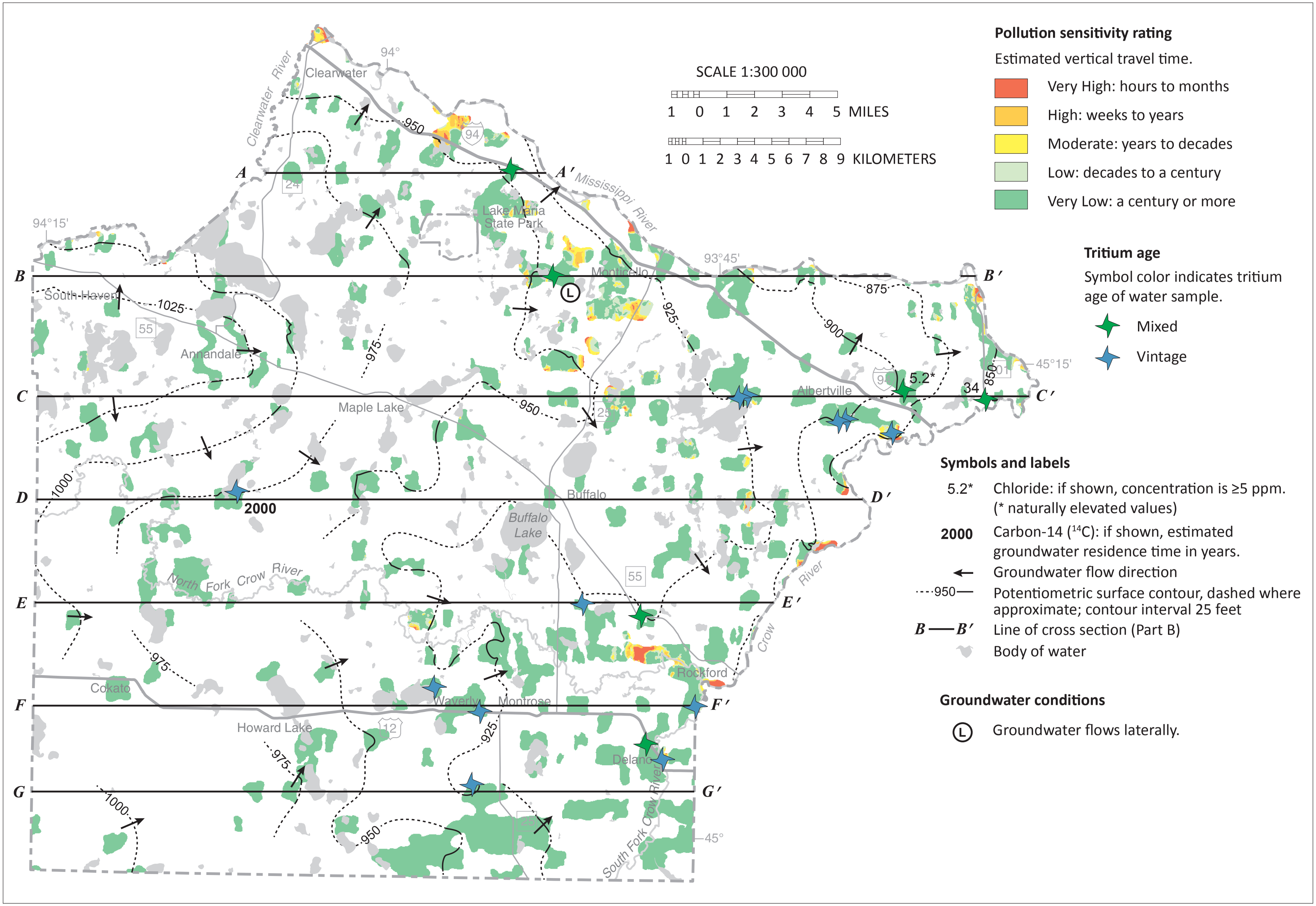


Figure 40. Pollution sensitivity of the psu aquifer and groundwater flow directions
The psu aquifer has very low sensitivity, except in areas near Rockford, Monticello, and Clearwater where the sensitivity ranges from moderate to very high.

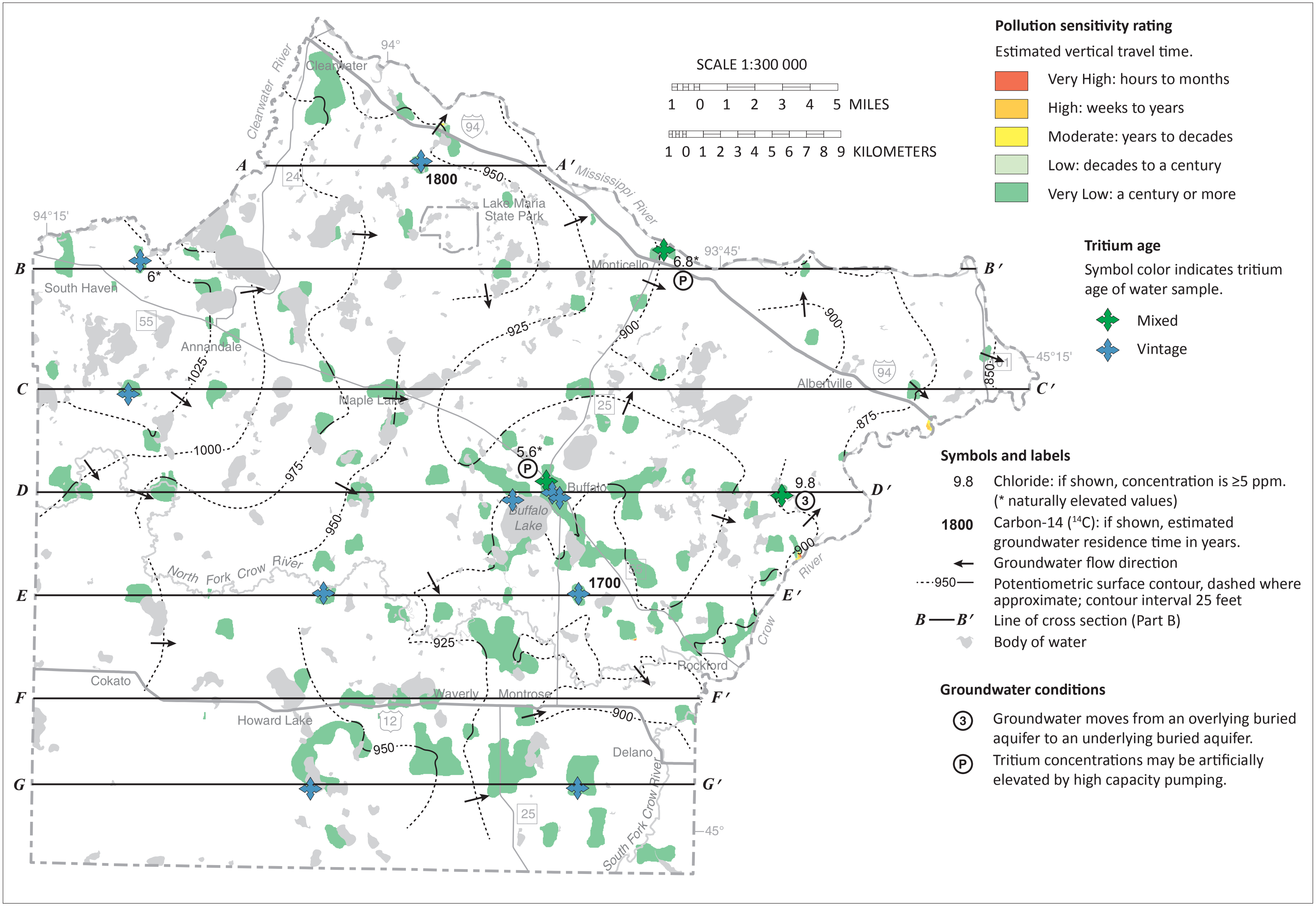


Figure 41. Pollution sensitivity of the zus aquifer and groundwater flow directions
The zus aquifer primarily has very low sensitivity, except for limited moderate sensitivity near river valleys.

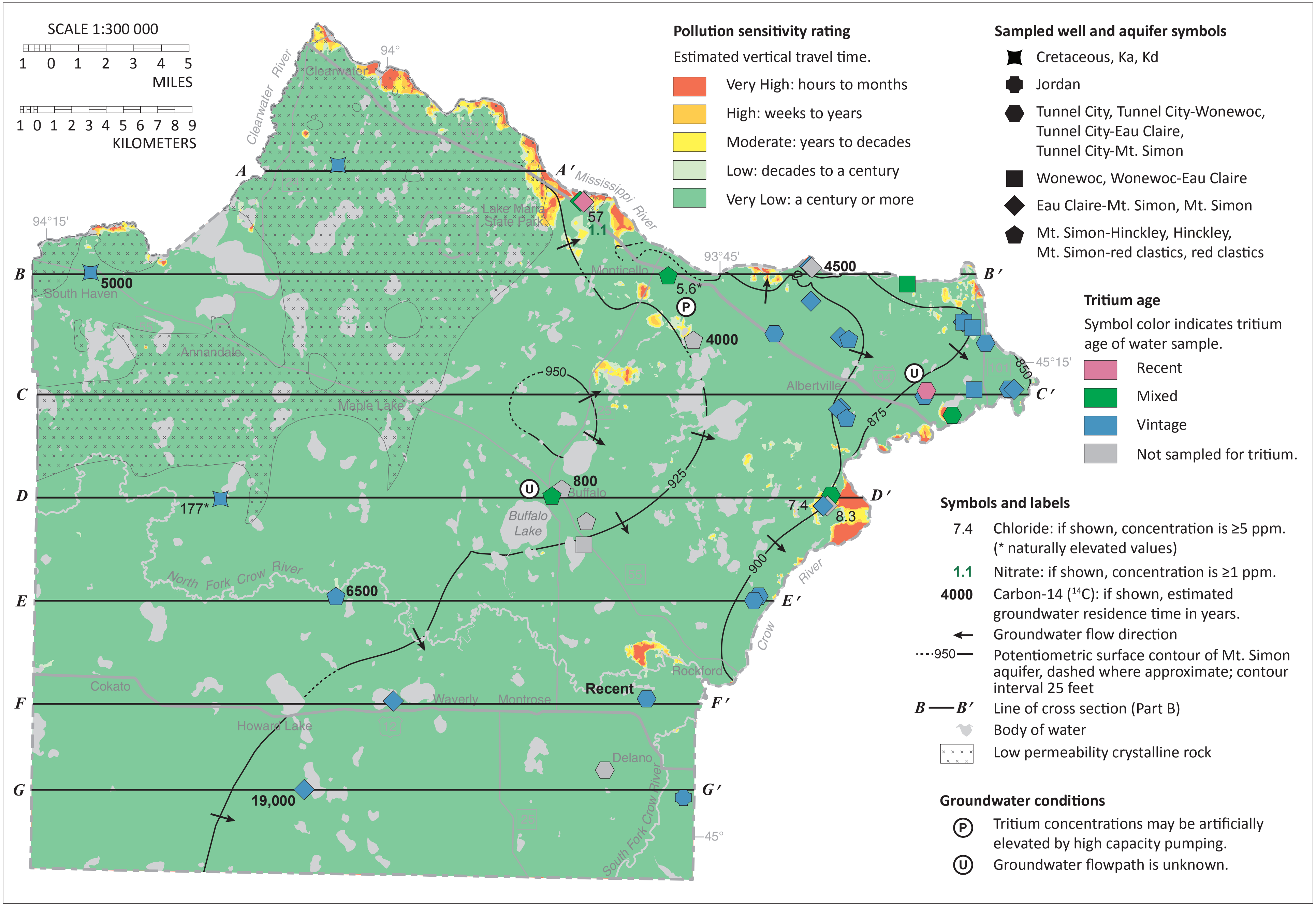


Figure 42. Pollution sensitivity of the bedrock surface and groundwater flow directions
The top of bedrock surface primarily has very low sensitivity, except for moderate to very high sensitivity regions that predominately occur along the edges of river valleys.

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 collected by the MDH, to align with groundwater level monitoring wells, and to intersect areas with high volume municipal pumping.

The seven cross sections were selected from a set of 50 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 a 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), compaction from overlying ice and sediment, 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 as shades of gray on Plates 8 and 9. Lighter shades indicate aquitards with higher relative hydraulic conductivity. The percent sand in each of the aquitards is based on the average matrix texture of each glacial aquitard or till (Part A, Plate 4, Table 1).

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 groundwater flow direction, recharge zones, and discharge zones.

Groundwater recharge and discharge

Precipitation is the source of recharge to the glacial sediments covering the county, which then provide recharge to deep aquifers. Important recharge areas exist primarily in the north and east of the county where sandy surficial sediment allows for higher infiltration. In other regions recharge is limited because the less permeable surficial geologic units have higher clay and silt content.

Recharge to the surficial aquifers ranges from 1.5 to 10.5 inches per year (Smith and Westenbroek, 2015). Recharge to the buried sand aquifers and bedrock aquifers is generally less than 1 percent of average precipitation, or roughly 0.3 inches per year (Delin and Falteisek, 2007). This estimate is dependent upon the matrix texture and thickness of the glacial sediment. Recharge rates are also influenced by high-volume groundwater appropriation centers, which have the potential to locally steepen groundwater gradients and increase recharge.

The Mississippi River is the major groundwater discharge feature for the buried sand and bedrock aquifers of the county. Groundwater is also discharged to other surface-water bodies, such as the Clearwater, North Fork Crow, and South Fork Crow rivers, and some wetlands and lakes. Stable isotopic data collected for this atlas demonstrates that lakes and open water wetlands serve an important recharge function in the northern portion of the county (Figure 22 and 23).

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.

The specific capacity values of 48 wells in Wright County met these conditions: 1 in the water-table aquifer, 1 in an unconfined buried sand aquifer, 22 in confined buried sand aquifers, and 24 in bedrock aquifers (Table 2 and Figure 43). The highest mean specific capacity of 150 gpm/ft was calculated for a bedrock well completed with an open hole across the St. Lawrence Formation through the Eau Claire Formation (the Upper Tunnel City and Wonewoc aquifers) (Table 2).

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

A number of consulting firms and state agencies have completed aquifer tests in Wright County, but the documentation is insufficient to include the results in this report. Transmissivity values for nine aquifer tests with robust documentation are shown in Table 2. These tests include 7 buried sand aquifers and 2 bedrock aquifers. Transmissivity for the buried sand aquifers averaged 21,900 ft^2/day, and ranged from 5,800 ft^2/day to 49,200 ft^2/day. Transmissivity for the bedrock aquifers averaged 37,500 ft^2/day, and ranged from 28,600 ft^2/day to 46,300 ft^2/day.

Table 2. Specific capacity and transmissivity of selected wells

Aquifer	Specific capacity (gpm/ft)					Transmissivity (ft^2/day)				
	Casing diam. (in.)	Mean	Min	Max	Number of tests	Casing diam. (in.)	Mean	Min	Max	Number of tests
Unconsolidated aquifers										
Water table	8	13	13	13	1	--	--	--	--	--
Unconfined buried sand	10	32	32	32	1	--	--	--	--	--
Confined buried sand	8–20	32	3	102	22	6–20	21,900	5,800	49,200	7
Bedrock aquifers										
Cretaceous undifferentiated	8	0.3	0.3	0.3	1	--	--	--	--	--
St. Lawrence–Wonewoc	10	32	32	32	1	--	--	--	--	--
St. Lawrence–Eau Claire	10	150	150	150	1	--	--	--	--	--
Tunnel City–Wonewoc	12	6	4	8	2	--	--	--	--	--
Tunnel City–Eau Claire	12	5	5	5	1	--	--	--	--	--
Tunnel City–Mt. Simon	10	75	75	75	1	--	--	--	--	--
Wonewoc–Mt. Simon	8	8	8	8	1	--	--	--	--	--
Wonewoc	18	9	7	11	2	--	--	--	--	--
Eau Claire–Mt. Simon	8	20	20	20	1	12	37,500	28,600	46,300	2
Mt. Simon	8–24	16	2	26	4	--	--	--	--	--
Mt. Simon–Hinckley	14–20	25	2	57	3	--	--	--	--	--
Mt. Simon–Fond du Lac	12	8	8	8	1	--	--	--	--	--
Mt. Simon–red clastics	8–18	10	2	21	3	--	--	--	--	--
Hinckley	10	5	5	5	1	--	--	--	--	--
Hinckley–Fond du Lac	12	17	17	17	1	*	--	--	--	--

Specific capacity data adapted from the CWI; gpm/ft, gallons per minute per foot.
Transmissivity data are from aquifer test data compiled by the DNR; ft^2/day, --, no data.

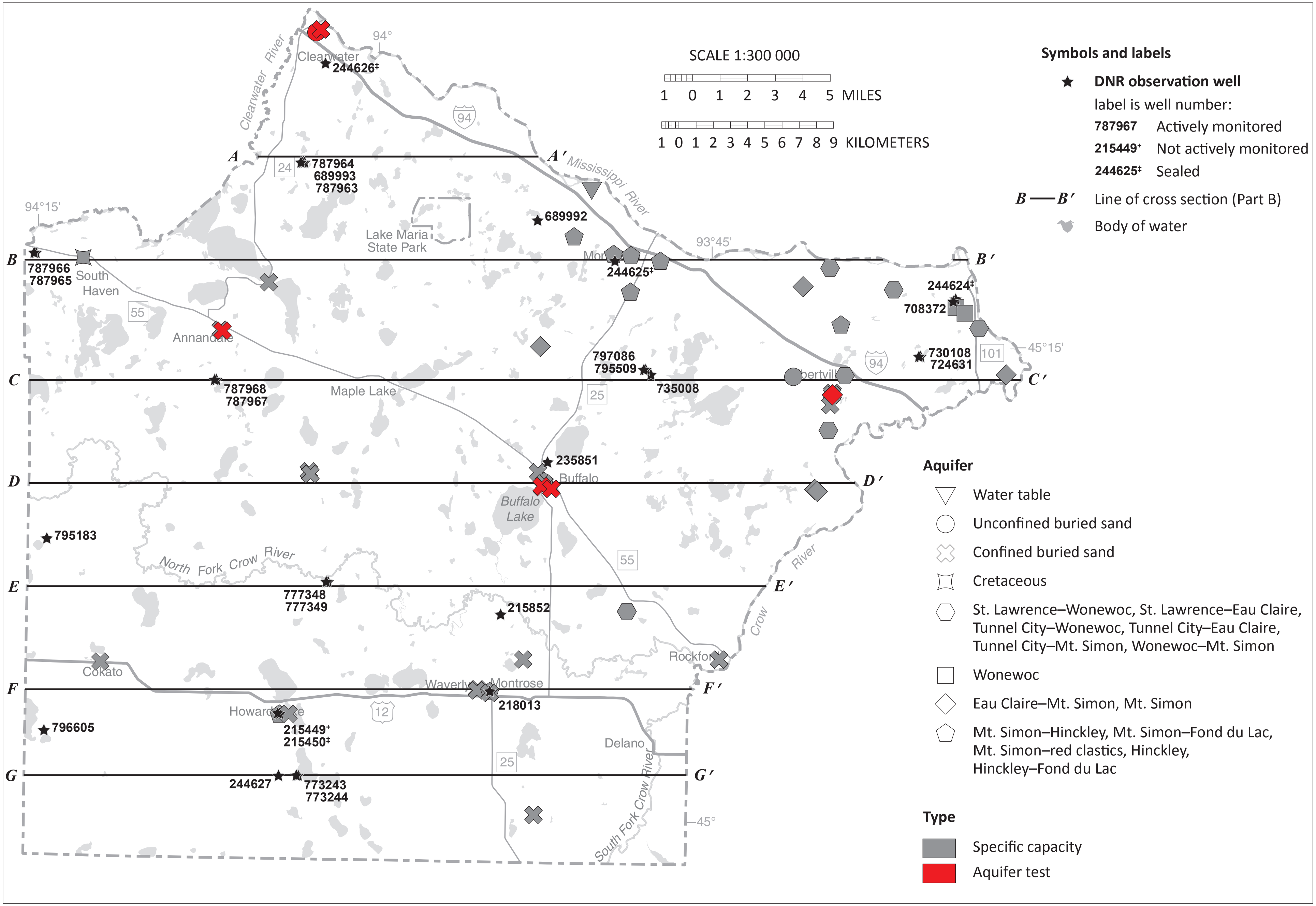


Figure 43. Well locations included in the aquifer characteristics summary

Groundwater level monitoring

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

Well nests consist of closely spaced wells that are constructed in different aquifers. Long periods of record from multiple aquifers are useful for determining trends and provide insight into how aquifers respond to recharge events, climatic conditions, and pumping stresses. The hydrographs shown in Figure 44 and 45 were produced from data retrieved from the DNR's Cooperative Groundwater Monitoring (2017) program.

Figure 44 shows the groundwater elevation hydrographs of four monitoring wells from two nests located north and south of Howard Lake. Groundwater elevation in Figure 44 and 45 is compared to daily precipitation collected at National Weather Service Reporting Station 212500 located in Elk River, MN.

- Well 773243 is constructed to a depth of 118 feet in the cg aquifer and shows annual groundwater elevation increasing in response to snowmelt and precipitation followed by declines over the winter months.
- Well 777349 is constructed to a depth of 142 feet in the cg1 aquifer and shows responses similar to well 777243.
- Well 773244 is constructed to a depth of 530 feet in the Mt. Simon aquifer and shows muted responses to annual precipitation.
- Well 777348 is constructed to a depth of 450 feet in the Hinckley aquifer and also shows muted responses to annual precipitation.

Groundwater elevation differences for these aquifers show the hydraulic gradient is downward from the cg and cg1 aquifers to the Mt. Simon. These data also show that the Hinckley aquifer in this area of the county has greater pressure head than the overlying Mt. Simon aquifer.

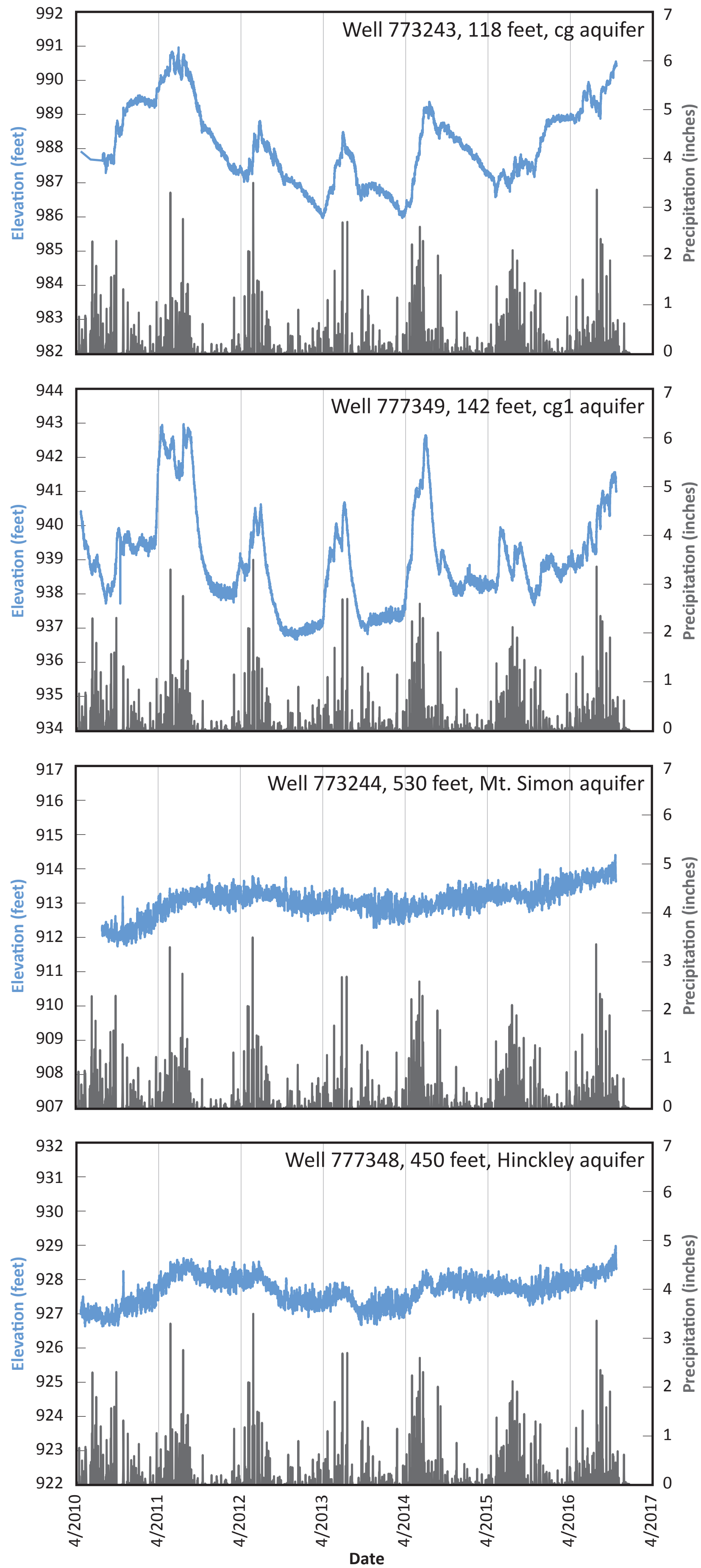


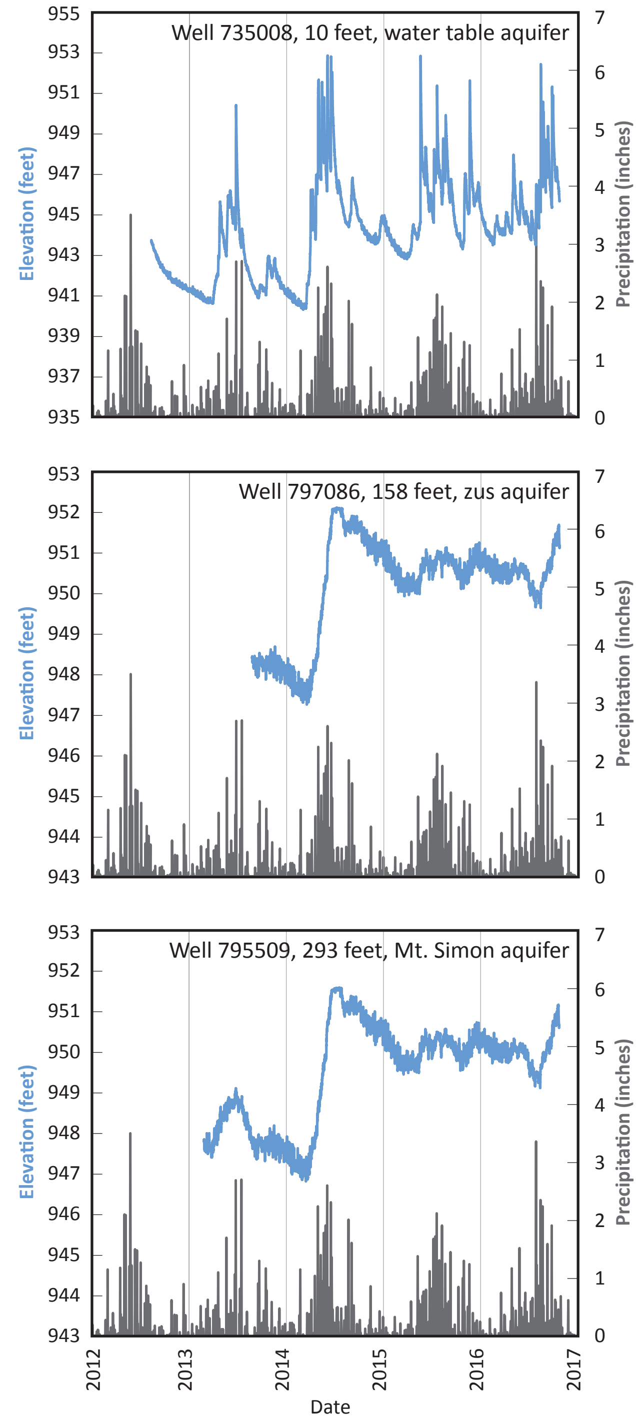
Figure 44. (Right) Hydrographs of groundwater-level monitoring wells north and south of Howard Lake

Figure 45 shows the groundwater elevation hydrographs of three monitoring wells located in northeast Buffalo Township near the west side of Pelican Lake.

- Well 735008 is constructed to a depth of 10 feet in the water table and shows rapid annual responses to precipitation events that decline in winter months.
- Well 797086 is constructed to a depth of 158 feet in the zus aquifer and shows annual groundwater elevation increases in response to snowmelt and precipitation that are more muted than those in the water-table aquifer.
- Well 795509 is constructed to a depth of 293 feet in the Mt. Simon aquifer and shows muted responses to annual precipitation similar to the zus aquifer.

Groundwater elevation differences for these aquifers show there is little vertical hydraulic gradient in this area between the water-table aquifer, the zus aquifer, and the Mt. Simon aquifer.

Figure 45. (Right) Hydrographs of groundwater-level monitoring wells near Pelican Lake.



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. This provides the DNR with the ability to assess which aquifers are being used and for what purpose. Permits require annual water-use reporting. This information is recorded using Minnesota Permitting and Reporting System (MPARS), which helps the DNR track the volume, source aquifer, and type of water use.

Reported water use of large capacity users for 2015 is categorized in Table 3 and in Figure 46 and 47 by type of water use and aquifer type (MPARS, 2015). Municipal and public water supply dominates permitted groundwater use with approximately 77 percent of the total usage. The majority is extracted from buried sand aquifers. In general, high-volume use is centered near large cities, such as Albertville, Monticello, and Buffalo. The second largest (11 percent) is crop irrigation. Over half of this water comes from buried sand aquifers and primarily occurs in the northern portion of the county where coarse-textured soils do not readily retain moisture. The third largest use category (4 percent) is golf course irrigation, which is distributed fairly evenly from Quaternary and bedrock aquifers. These three water uses collectively made up 92 percent of the permitted water used in 2015.

There are no reporting requirements in Minnesota for well owners that use less than 10,000 gallons per day or 1 million gallons per year, but the CWI maintains data for well use type and aquifer type for these wells. This report included nearly 10,000 wells in the analysis. The majority of wells are used for domestic use (94 percent), followed by public supply (2 percent), and irrigation (1 percent). Of the wells with identified aquifers, most are completed in the buried sand aquifers (73 percent), followed by bedrock aquifers (13 percent), and finally surficial sand aquifers (7 percent).

Table 3. Reported 2015 water use from DNR groundwater permit holders

	Use category												
Aquifer	Number of wells	Municipal/public water supply	Crop irrigation (agricultural, orchard, vineyard, nursery)	Golf course irrigation	Food processing	Lake level maintenance	Livestock watering	Landscaping/athletic fields	Water supply (private, campground, wayside, rest area)	Sand and gravel washing	Other uses (heating/cooling, power generation, dust control)	Total (mgy)	Total (percent of 2015 water use)
Quaternary aquifers													
Water table	32	185.3	135	15.6	--	--	--	5.6	2.7	26.1	--	370.3	9.75%
Buried sand	121	1879.3	255.7	52.4	93.6	--	42.6	20.4	27.2	--	0.7	2371.9	62.5%
Bedrock aquifers													
Cretaceous	1	4.5	--	--	--	--	--	--	--	--	--	4.5	0.1%
Upper Paleozoic[1]	3	--	--	--	--	55.1	--	--	--	--	7.9	63	1.7%
Lower Paleozoic[2]	14	457	30.4	76	--	3.4	--	1.3	--	--	--	568.1	15.0%
Mesoproterozoic[3]	2	17.7	2.6	--	--	--	--	--	--	--	--	20.3	0.5%
Multiple[4]	10	366.3	--	--	--	--	--	12.8	--	--	20.2	399.3	10.5%
Total (mgy)	--	2910.1	423.7	144	93.6	58.5	42.6	40.1	29.9	26.1	28.8	3797.4	--
Total (percent)	--	77%	11%	4%	2%	2%	1%	1%	1%	>1%	>1%	--	100% [5]
Highest annual use by permit 2011–2015	--	3541.3	748.1	243.1	104.5	69.8	56.6	40.1	36.1	29.9	41.7	--	--

Data from MPARS; mgy, million gallons per year; dash marks (--) indicate no use in those categories]
1. Upper Paleozoic aquifers includes Jordan and Upper Tunnel City
2. Lower Paleozoic aquifers includes Wonewoc and Mt. Simon
3. Mesoproterozoic aquifers include the Hinckley and Hinckley–Fond Du Lac
4. Multiple aquifer wells extract water from more than one Paleozoic or Mesoproterozoic aquifer
5. Percentage may not equal 100 due to rounding.

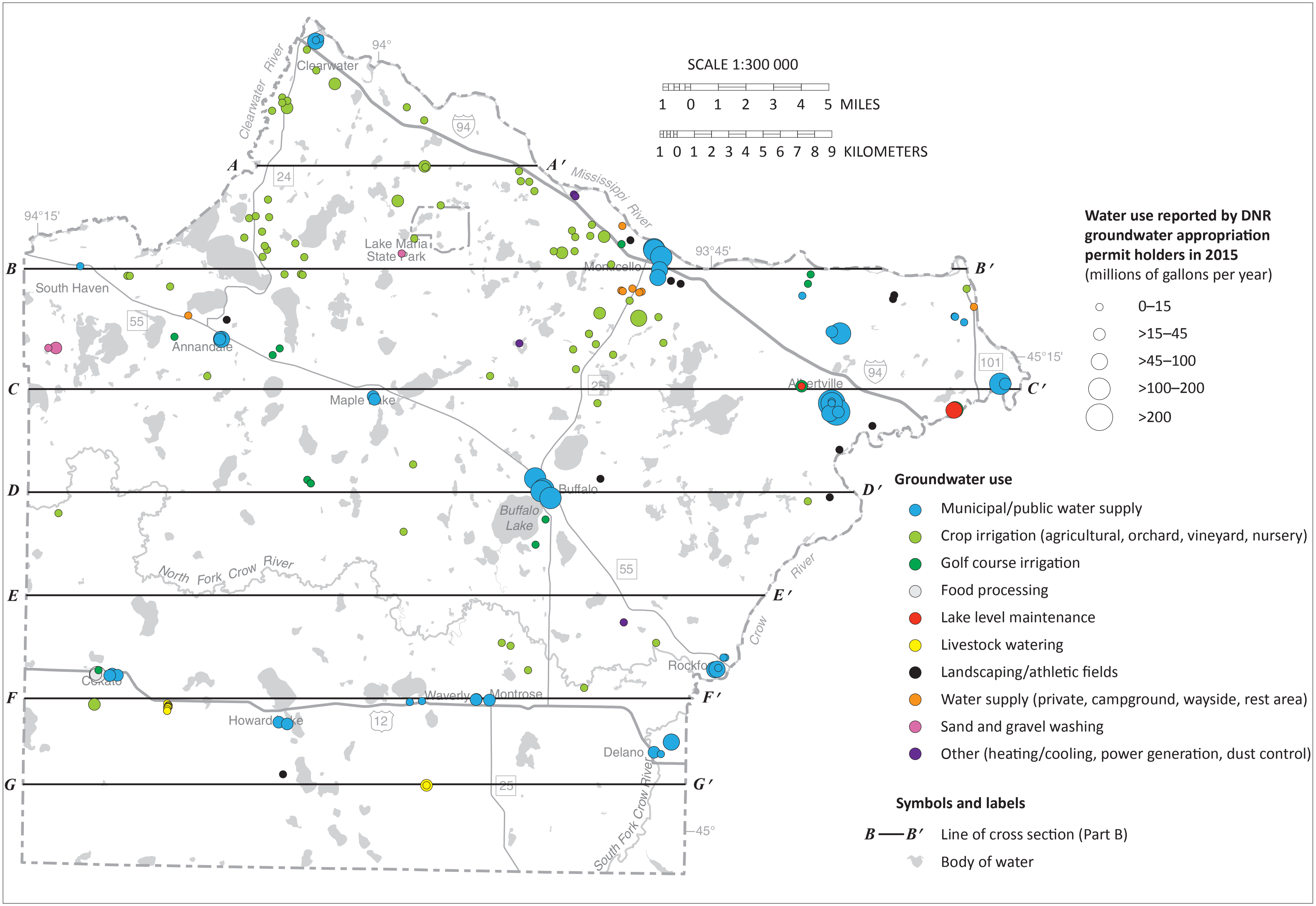


Figure 46. Distribution of groundwater appropriation permits for 2015 by volume reported and use category
Municipal and public water supply accounts for the largest permitted groundwater use in Wright County.

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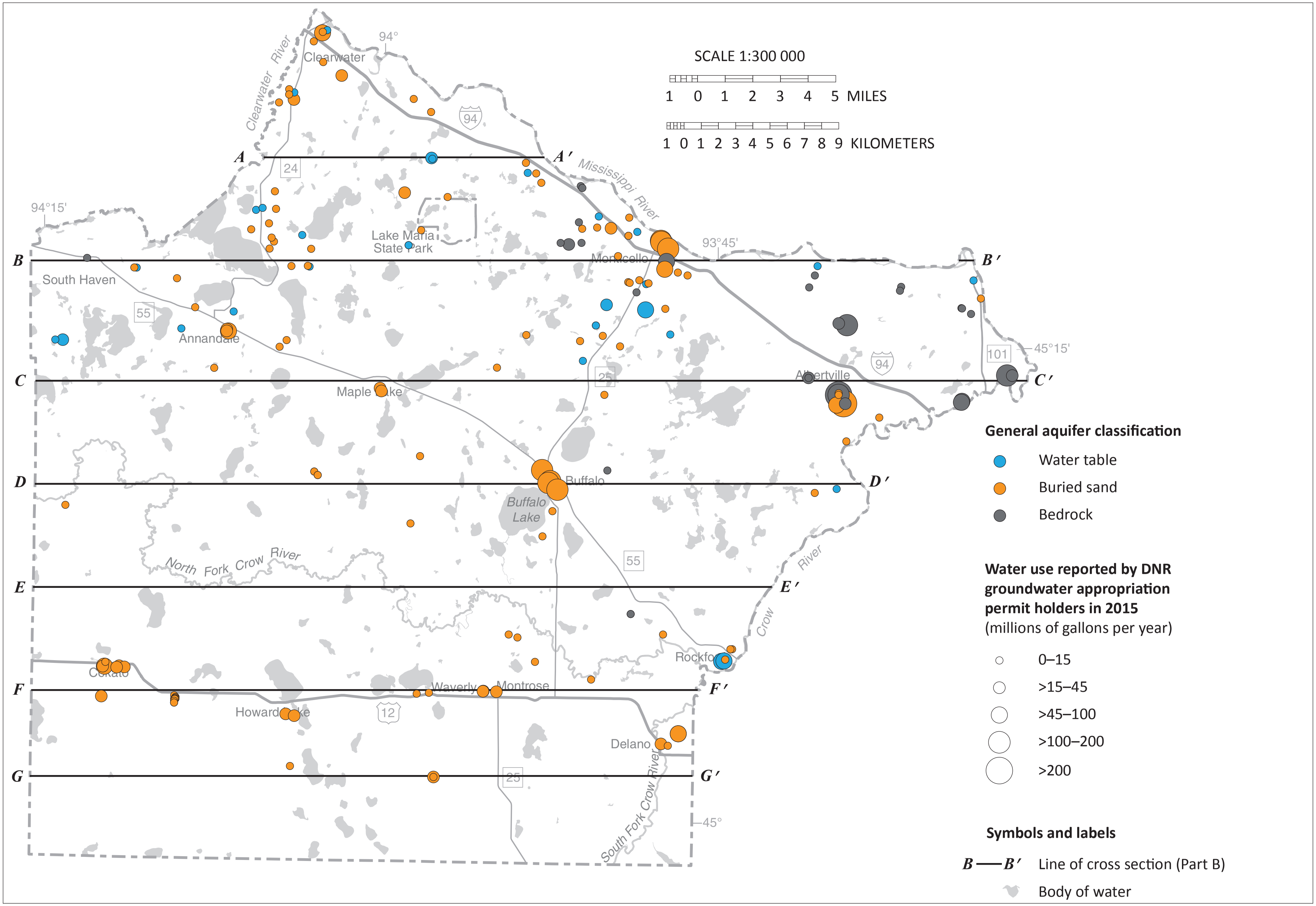

Figure 47. Distribution of groundwater appropriation permits by general aquifer classification
The majority of water used in the county is from buried sand aquifers.

Summary

The **climate** of Wright County is characterized as a cool subhumid climate, which is strongly influenced by its position within the northern continental United States. There is a large temperature differential between summer and winter, with winter temperatures typically below freezing from November through March, and short summers with an average temperature of approximately 69 degrees Fahrenheit. Soil frost at depth frequently limits the amount of precipitation that can infiltrate into the soil column and become groundwater during the winter months. Average annual precipitation is approximately 29 inches, with most falling in June, July, and August.

The **water table** is a subdued expression of surface topography. Its elevation is highest in the northwestern and southwestern portions of the county and lowest along the northeastern and southeastern borders within river valleys. The depth to water table map shows that the water table is within 10 feet of the surface across most of the county, except in areas where there are topographic highs from glacial deposits and within valley edges. At county scale, groundwater flow is from water-table elevation highs to regional discharge areas including the Mississippi, North Fork Crow, South Fork Crow, and Crow rivers. At more localized scales, water-table flow is from local highs to river tributaries, lakes, and wetlands.

Potentiometric surface maps, compiled mostly from static water level data in Wright County, indicate a pattern of generalized groundwater flow toward the Mississippi River valley and larger perennial tributaries, such as the North Fork Crow and South Fork Crow rivers. Potentiometric surfaces of the deeper buried sand aquifers and bedrock aquifers indicate regional groundwater flow to the southeast.

Water chemistry was used to determine areas where influences from human activities were evident in groundwater, to identify areas where naturally occurring elements of concern are elevated, such as arsenic and manganese, and to determine the relative residence time of groundwater using isotopes of tritium and carbon. Elevated levels of nitrate and chloride and recent tritium-age waters were present in the northern portions of the county. Groundwater residence time varies throughout the county, but vintage tritium age is typically found at depths greater than 200 feet below the land surface. Calculated carbon-14 residence time for samples with vintage tritium age ranges between 500 and 19,000 years. Elevated levels of naturally occurring arsenic and manganese are common in the county.

Groundwater recharge sources were differentiated through stable isotope analysis. Samples plotted along both the global meteoric water line and a local evaporation line indicate that a portion of groundwater recharge is through surface waters, such as lakes and open water wetlands.

Pollution sensitivity of aquifers varied widely throughout the county dependent on the depth of the aquifer and the overlying geologic materials. In general, buried aquifers located close to the land surface have higher sensitivities than those located at greater depths. The pollution sensitivity of the bedrock surface is mostly very low, but has areas that are rated high to very high in small areas located near river valleys.

Permitted **groundwater use** is dominated by municipal and public water supply, which accounts for approximately 77 percent of the water used. The majority is extracted from buried sand aquifers. High volume use is centered near large cities, including Albertville, Monticello, and Buffalo. Crop irrigation is the second most common use category (11 percent) and primarily occurs in the northern portion of the county where coarse-textured soils do not readily retain moisture. The third most common use category (4 percent) is golf course irrigation, which is distributed almost evenly from Quaternary and bedrock aquifers. These three water uses collectively made up 92 percent of the permitted water used in 2015.

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Glossary

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

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

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

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

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

equipotential 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 certain quantity of a mixture (solid, liquid, solute, suspension, or isotope) is divided into a number of smaller quantities (fractions) in which the composition varies according to a gradient. Fractions are collected based on differences in a specific property of the individual components. 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.

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 fluid 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 have a different number of neutrons.

LiDAR—an acronym for *Light Detection and Ranging*. It defines a surveying technique used to develop land surface elevation models.

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

observation well—a well that is used to monitor the water level of groundwater.

Paleozoic—an era of geologic time from approximately 542 to 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.

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

stable isotope—chemical isotopes that are not radioactive.

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

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

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

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

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

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

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

Appendix A

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

Samples were analyzed by DNR staff; the University of Minnesota, Department of Earth Sciences Laboratory (U of M); 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.

Groundwater field sample collection and handling details

Parameter	Enriched Tritium	^{18}O ^{2}H	Cations	Anions	Trace constituents	Alkalinity	^{14}C
Lab	Waterloo	Waterloo	U of M	U of M	U of M	DNR Staff	U of M
Sample container	500 ml HDPE	60 ml HDPE	15 ml Fisherbrand BLUE cap	50 ml Argos BLACK bottle***	15 ml Sarstedt RED cap	500 ml plastic	30 gallon barrel
Head space	yes	yes	yes	yes	yes	NO	yes
Rinse	no	no	yes*	yes*	yes*	yes**	no
Filter	no	no	yes	yes	yes	no	yes
Preservative	no	no	1 drop 6N HCl	no	5 drops 15N HNO_3	no	NH4OH added to adjust pH
Refrigeration	no	no	yes	yes	yes	Yes, if not analyzed onsite	no
Shelf life	long	long	2–3 weeks	2–3 weeks	2–3 weeks	24–48 hours	years
Field duplicate	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	none	none
Field blank	none	none	1 for every 20****	1 for every 20****	1 for every 20****	none	none
Storage duplicate	yes	yes	no	no	no	no	no

*Sample bottle was rinsed three times with sample water prior to collecting the sample (filtered water if sample was filtered). Rinsing process was filling the bottle with sample water and then pouring the contents out over the cap.

**Rinsed the bottle three times with sample water prior to collecting the sample. Bottle was filled by submerging with cap in hand, and sealed submerged to ensure no remnant bubbles.

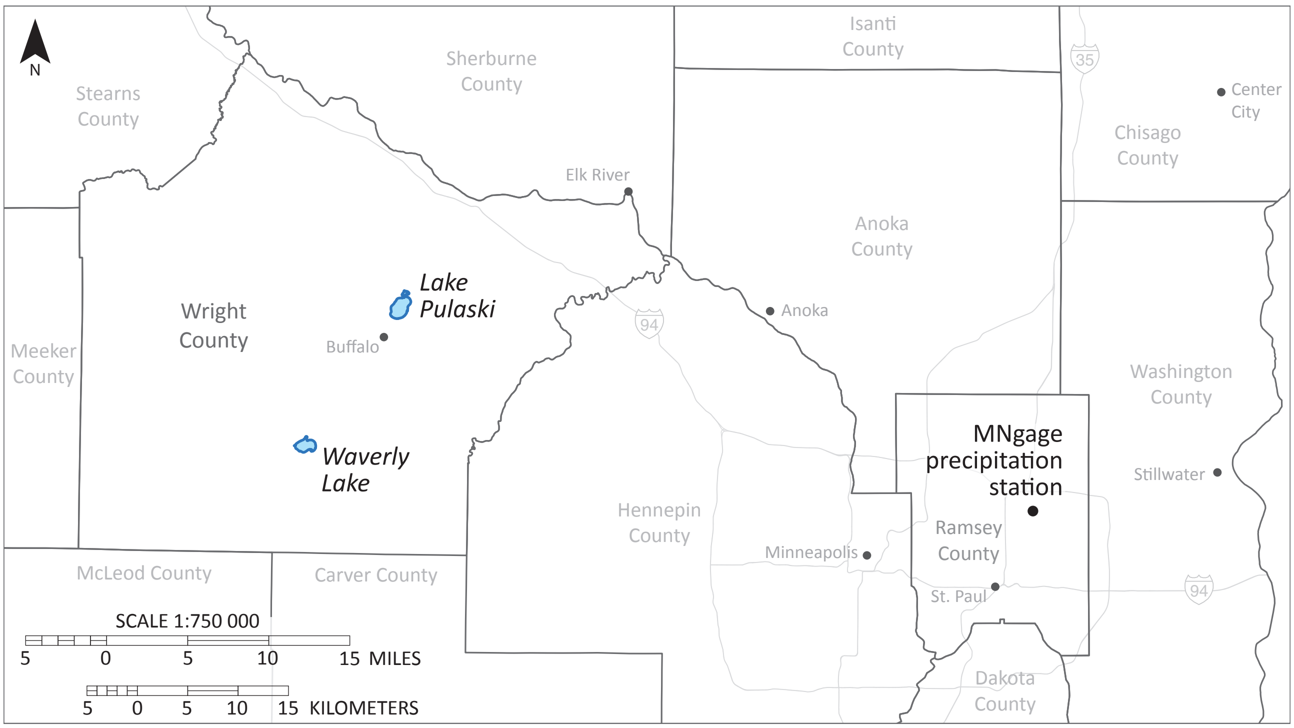
*** 50 ml anion bottle was filled, unless filtering was very difficult. All bottles were filled to at least 1/3 full.

****Deionized (DI) water was used for field blanks. DI water was poured into the back of filtering syringes when the plunger was removed. Bottles were filled by forcing water through filter.

Appendix B

Samples were analyzed for enriched tritium by the University of Waterloo Environmental Isotope Laboratory for determination of recent tritium values. Samples came from two main sources: precipitation composites collected at a Minnesota DNR MNgage climatology monitoring station in Maplewood, and lake water samples collected from two lakes in Wright County. Precipitation samples were composited over the course of 30-day periods between the seasons of spring and fall over the years 2012 through 2016. Lake water samples were collected from a boat in the limnetic zone using a one-meter length integrated sampler (groundwater bailer).

Location of Wright County lakes sampled for tritium and MNgage precipitation station



MNgage precipitation station enriched tritium results

Sample Date Range	Tritium	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

Wright County lake water enriched tritium results

Sample Date	Sample Location	Tritium	Analytical Error	Sample Type
09/05/2014	Waverly Lake	7.4	0.7	Limnetic Zone
09/17/2014	Lake Pulaski	7.8	0.7	Limnetic Zone

For additional tritium information, visit the County Geologic Atlas program page (mndnr.gov/groundwatermapping).

For additional weather station information, visit the MNgage page (climateapps.dnr.state.mn.us/HIDENsityEdit/HIDENweb.htm).

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ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

Prepared and published with the support of the following:

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

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

CLEAN WATER LAND & LEGACY AMENDMENT