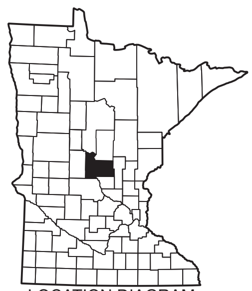
Groundwater Atlas of Morrison County, Minnesota

County Atlas Series C-31, Part B



LOCATION DIAGRAM

Report

To accompany these atlas components:

Plate 6, Water Chemistry

Plate 7, Hydrogeologic Cross Sections, A–A′ through D–D′

Plate 8, Hydrogeologic Cross Sections, E–E′ through H–H′

DEPARTMENT OF
NATURAL RESOURCES

St. Paul
2019

mndnr.gov/groundwatermapping

Recommended Citation

Baratta, V.M., 2019, Groundwater Atlas of Morrison County, Minnesota: Minnesota Department of Natural Resources, County Atlas Series C-31, Part B.

County Atlas Program

The Minnesota County Geologic Atlas series has been produced since 1982. Recent atlases are produced in two parts. Explanations of the history and purpose of the program, atlas applications, user guides, map sales, and descriptions of the Part A and Part B components are available online.

Part A Geology was produced by the Minnesota Geological Survey (MGS) in 2014 and contains the following: Plate 1, Data-Base Map; Plate 2, Bedrock Geology; Plate 3, Surficial Geology; Plate 4, Quaternary Stratigraphy; Plate 5, Bedrock Topography, Depth to Bedrock, and Sand Distribution Model.

Information is available on the Minnesota Geological Survey page (cse.umn.edu/mgs/county-geologic-atlas).

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

Information is available on the DNR Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

Technical Reference

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

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

These bases were modified from MGS, Morrison County Geologic Atlas, Part A, 2014. Universal Transverse Mercator projection, zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion Factors

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

1 part per million = 1 milligram per liter

1 part per billion = 1 microgram per liter

1 milligram per liter = 1000 micrograms per liter

1 gallon per day per foot = 0.1337 $foot^2$ per day

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

Report Contents

Report Figures

Report Tables

Plates (accompanying folded inserts)

Acknowledgments

Guidance and technical assistance was provided by a number of colleagues during the production of this report. Assistance with field data collection was completed by Randy Bradt and Rachel Lindgren. Thoughtful insight, guidance, and technical review was provided by John Barry, Todd Petersen, Paul Putzier, Jim Berg, Ruth MacDonald, and Holly Johnson.

Special thanks also to the following people for taking time to review this report and for providing helpful suggestions: Mike MacDonald, Minnesota Department of Agriculture; Barb Lusardi, Minnesota Geological Survey; Glen Champion, Minnesota Department of Natural Resources; and Mindy Erickson, United States Geological Survey. Editing was done by Ruth MacDonald, Holly Johnson, and Ann Essling. An additional thank you goes to Scott Alexander from the University of Minnesota for his assistance with the collection and interpretation of the carbon-14 results for this report.

Groundwater Atlas of Morrison County, Minnesota

by Vanessa M. Baratta

Executive summary

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

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

This **report** details the methods, results, and interpretations for the county. **Plate 6** illustrates the water chemistry; **Plates 7 and 8** use hydrogeologic cross sections to show groundwater flow directions and residence time within the aquifers. This summary gives an outline of the detailed sections that follow.

Morrison County is located in central Minnesota, with the Mississippi River flowing from north to south through the west-central part of the county. The county is approximately 1,150 square miles, with 3 percent covered by open water. Portions of five major watersheds are present in the county, with almost 90 percent of the water flowing into the Mississippi River.

The geology and physical hydrogeology (pages 4–11) is made up of multiple layers of sands and fine-grained materials that were deposited by glaciers through time. Buried sand and gravel units across the county are abundant and are in many places connected to the land surface without an intervening fine-grained layer. In both the unconfined and buried aquifers water is primarily flowing toward the Mississippi River. Precambrian bedrock beneath the glacial layers are not often used as a water resource due to its limited porosity and permeability.

Water chemistry (pages 12–21) provides information about the water source, flow path, travel time, and residence time of groundwater. For this study, chemistry data from 99 wells and 10 lakes was collected and combined with historic chemistry data from the Minnesota Department of Health (MDH).

- The primary **groundwater recharge source** is precipitation. There were also two wells that showed some recharge from lakes. Both samples were collected from the northwestern portion of the county where there are shallow glacial sediments with coarse-grained textures coupled with a large number of lakes and open water wetlands.
- **Groundwater residence time,** based on radioactive isotope data, indicated that much of the groundwater was recharged as precipitation within the last 60 years (approximately 80 percent of collected samples). This indicates that there is a relatively short residence time from the surface to groundwater resources. The remaining 20 percent of samples collected from buried sand and gravel aquifers has been in the ground more than 60 years. Ten samples were analyzed for carbon-14 and had residence times that ranged from approximately 350 to 8,000 years, indicating that there is some groundwater that is more protected, or less sensitive to land use.
- **Chloride** and **nitrate** concentrations elevated due to anthropogenic sources help identify areas where groundwater is flowing from the surface into buried aquifers. Across the county there was a significant amount of anthropogenically sourced chloride (60 percent of sampled wells) and nitrate (20 percent of sampled wells). The elevated nitrate concentrations were found in areas where there is sandy surficial sediment overlying buried aquifers. The high percentages of elevated chloride and nitrate indicate that there is a relatively short travel time from the surface to the buried water resources in these areas.
- **Arsenic** and **manganese** are geologically sourced (naturally occurring) groundwater chemicals that could be potentially harmful to human health. Approximately 5 percent of the wells analyzed had arsenic concentrations that exceeded health standards and approximately 70 percent exceeded the health standards for manganese. There do not appear to be spatial trends to the elevated values of either chemical.

The **pollution sensitivity** (pages 22–45) of an aquifer is estimated based on the time it takes water to flow through various types and thicknesses of soils and geologic materials.

Pollutants are assumed to travel with water at the same rate. The sensitivity is modeled with different methods for 1) the near-surface materials and 2) the buried sand and gravel aquifers and the bedrock surface. The model results are evaluated by comparing the pollution sensitivity ratings of the buried aquifers to isotopes, such as tritium and carbon-14 for residence time, and to inorganic chemicals for contamination.

- **Near-surface sensitivity** (pages 22–24) in the county ranges from low to high. Lower sensitivity areas are present in the eastern and west-central portion of the county, where fine-grained sediments are at the surface. High sensitivity areas are located along the river valleys and in areas with very sandy surficial sediment.
- **Buried sand and gravel aquifer sensitivity** (pages 25–45) varied widely across the county depending on the depth of the aquifer, thickness of overlying fine-grained materials, and proximity to major rivers and streams. Throughout all the buried sand and gravel aquifers there are areas of very high pollution sensitivity along the Mississippi River and some of the larger tributaries flowing into it. Areas of very low pollution sensitivity are present in the uplands between the rivers. However, chemistry data indicates that water is still moving relatively quickly through these areas.

Hydrogeologic cross sections (pages 46–47, Plates 7–8) illustrate groundwater flow, residence time, and the distribution of chemicals in the subsurface. Cross sections help define areas of interest such as locations of important groundwater recharge, discharge, and increased sensitivity to pollution. Groundwater flows downward and laterally toward the Mississippi River and some of its major tributaries that receive discharge as base flow. Groundwater recharge occurs across the entire county, because there are aquifers or sandy tills at the surface. There are some areas where sandy surficial sediment is in contact with buried aquifers, allowing for greater recharge to the buried aquifers in these areas. In the last 60 years, water has recharged to depths ranging from less than 50 to 165 feet.

Aquifer characteristics and groundwater use (pages 47–54) summarize specific capacity tests, aquifer tests, water-use records, and groundwater-level monitoring data, where available. These data help hydrogeologists plan for new well installations to meet requirements for a given use.

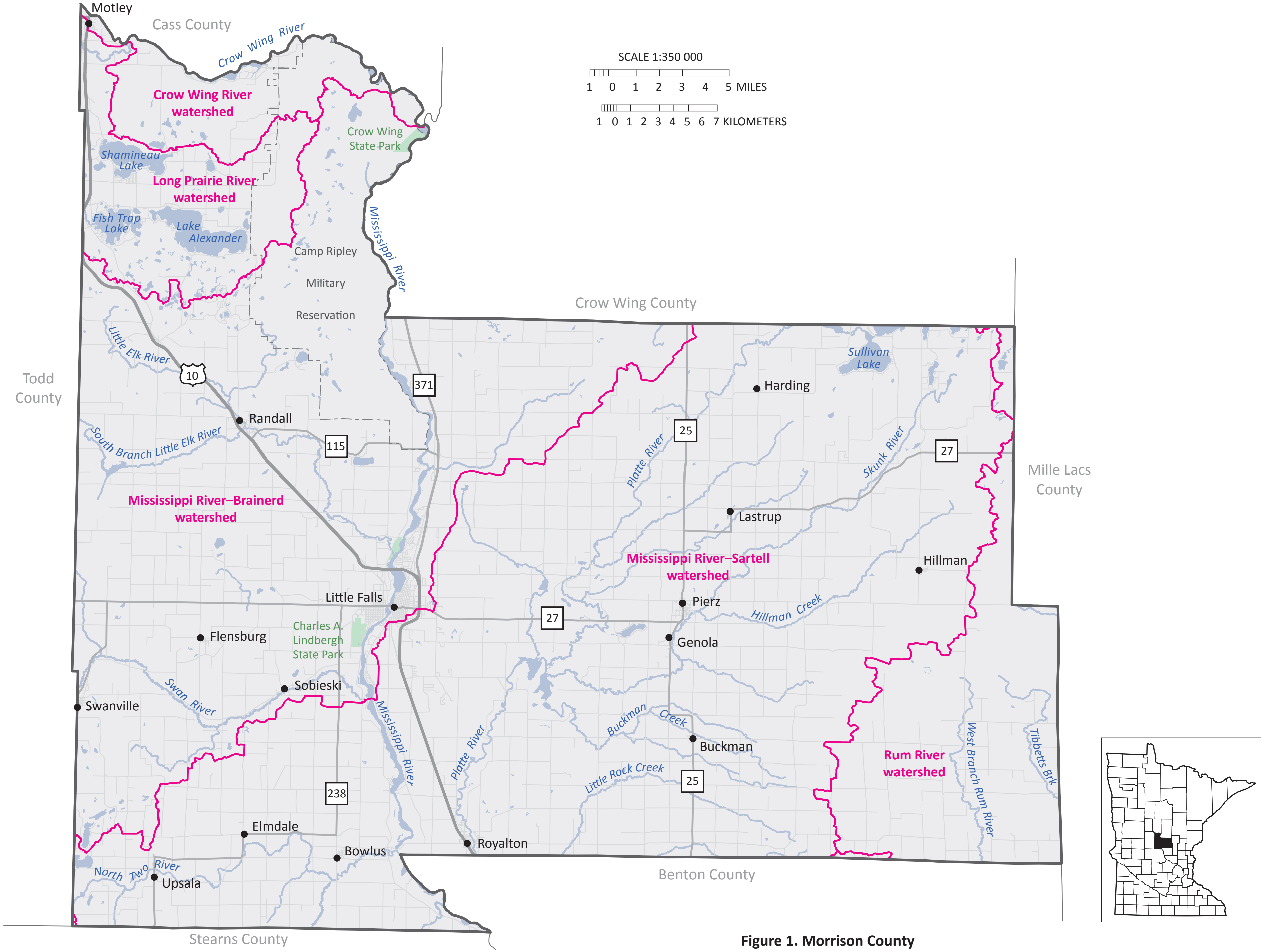


Figure 1. Morrison County
Magenta lines indicate watershed boundaries.

Geology and physical hydrogeology

Morrison County is located in central Minnesota, with the Mississippi River flowing from north to south through the west-central part of the county (Figure 1). The county is approximately 1,150 square miles, with approximately 3 percent covered by open water. The estimated population was 33,170 as of July 2018 (United States Census Bureau, 2018). There are three primary topographic regions across the county. The west and east have rolling hills that are oriented in the direction of ice flows that crossed the land surface during previous glacial time periods. The central topography is dominated by the Mississippi River valley, steep at the valley edges and flatter throughout the flood plain. The third topographic region is in the northwestern corner, where there is a ridge of sand, gravel, and till that is part of the St. Croix Moraine. For detailed explanations that illustrate how the landforms were shaped by glacial processes, see Part A, Plate 3.

Portions of five major watersheds are present in the county (Figure 1). Two drain directly to the Mississippi River (83 percent of the county). The remaining three drain to the Rum (9 percent), Long Prairie (5 percent), and Crow Wing (3 percent) rivers. Water in the northwestern corner flows through the Long Prairie and Crow Wing rivers into the Mississippi River along the northern border of the county. Water in the eastern part of the county flows toward the Rum River in neighboring Mille Lacs County.

Morrison County is in the northern continental United States where there is a large temperature difference between summer and winter. Summers are relatively cool with an average temperature of approximately 67 degrees Fahrenheit. The winter average temperature is approximately 13 degrees Fahrenheit. (NOAA, 2018) Average annual precipitation is approximately 28 inches, placing it in the middle of the statewide range of 20 to 36 inches.

Surficial aquifers

Glacial sediment forms the land surface over most of Morrison County. Surficial sand is mapped over 48 percent of the county and much of it is hydraulically connected to buried sand aquifers (Figure 2). Thicknesses of these sand deposits can be greater than 100 feet in the northwest and central portions of the county. Where saturated, these coarse-grained sediments are aquifers. The texture of these surficial deposits influences the rate and amount of precipitation that infiltrate 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 the atmospheric pressure. It occurs in both aquifer and aquitard sediment across the entire county. The water table in the figures is shown as a static surface but fluctuates through time.

Surficial sand and gravel aquifers are present below the water table where there is sufficient saturated thickness and yield to install a well and economically pump groundwater.

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

- The elevation of surface-water bodies (for example, rivers, perennial streams, lakes, and wetlands)
- Static water levels in surficial sand wells obtained from well records in the County Well Index database (MGS and MDH, 2016)*
- Estimates of wet soil conditions from the Natural Resources Conservation Service (NRCS) county soil survey (Natural Resources Conservation Service, 2016)*

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

Depth to water table is derived by subtracting the water-table elevation from the land-surface elevation (Figure 4). For more details, see *Methods for estimating water-table elevation and depth to water table* (DNR, 2016a).

The water-table maps provide guidance for many applications, but additional site-specific information 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 that were created using this procedure. These include, but are not limited to: seasonal weather conditions, extent and composition of surficial geology units, land-use practices, vegetation composition and distribution, and pumping of large-capacity wells. There are limited data along the high-relief Mississippi River valley in the northwestern portion of the county. The resulting water-table elevation in those locations can be variable and is poorly constrained.

The water table is generally a subdued expression of the surface topography. Groundwater flow is primarily toward the Mississippi River, which is a regional discharge zone. The water-table elevation also shows evidence of localized groundwater flow into many of the tributaries of the Mississippi River. Some of the more prominent examples are along Hillman Creek, Tibbetts Brook, and the Swan, Platte, Skunk, and Little Elk rivers. The water table is estimated to be within 10 feet of the land surface across a large part of the county with greater depths in areas where the surficial sediment has greater amounts of sand and the topography is elevated. Sandier sediment is present in the county's northwest corner along the Mississippi River valley, some smaller river valleys, and in the east, where sandy drumlins were deposited (deeper water table) with some fine-grained deposits between them (shallower water table).

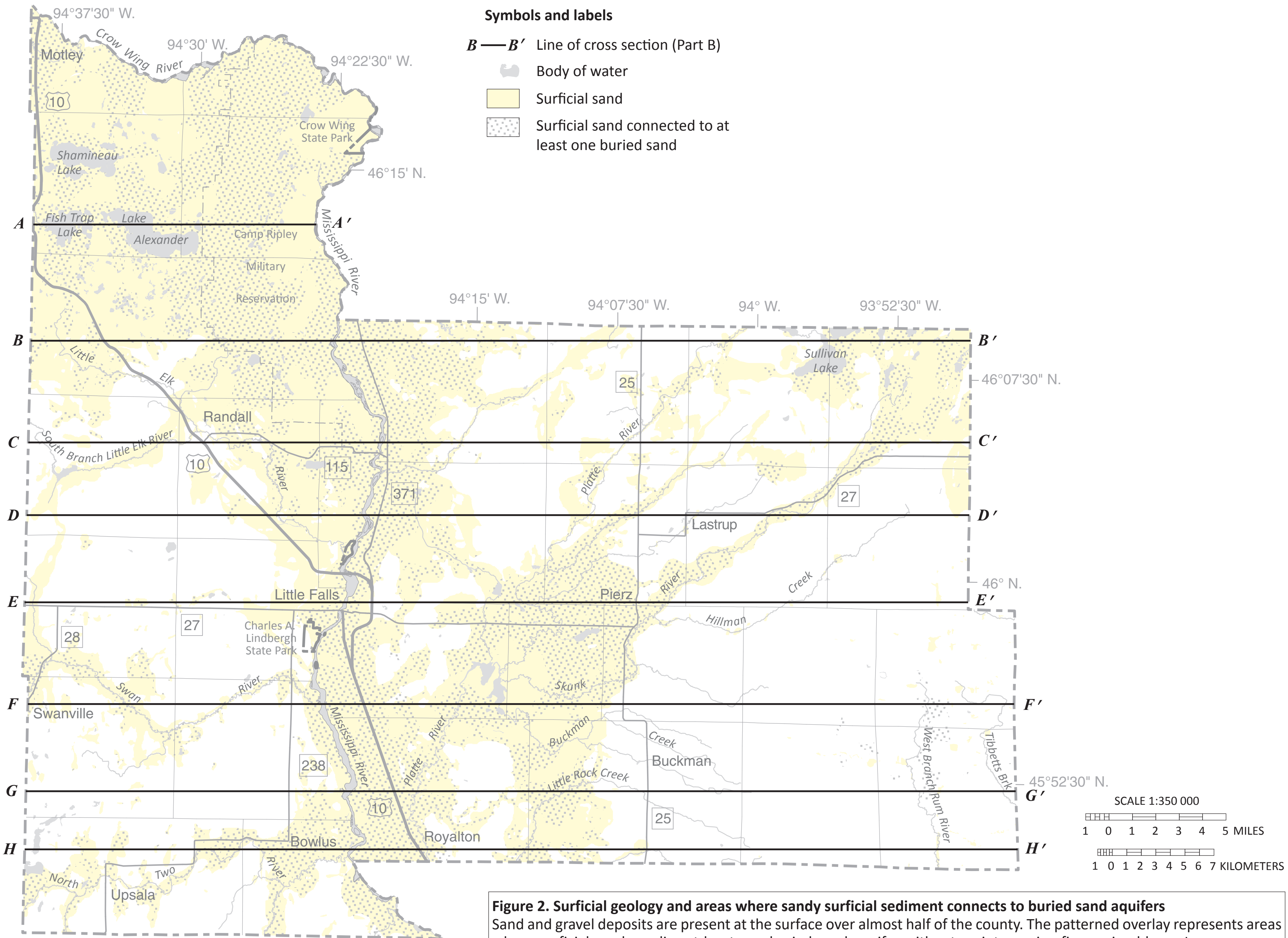


Figure 2. Surficial geology and areas where sandy surficial sediment connects to buried sand aquifers
Sand and gravel deposits are present at the surface over almost half of the county. The patterned overlay represents areas where surficial sand overlies at least one buried sand aquifer without an intervening fine-grained layer. In some areas, sand extends all the way to the bedrock surface.

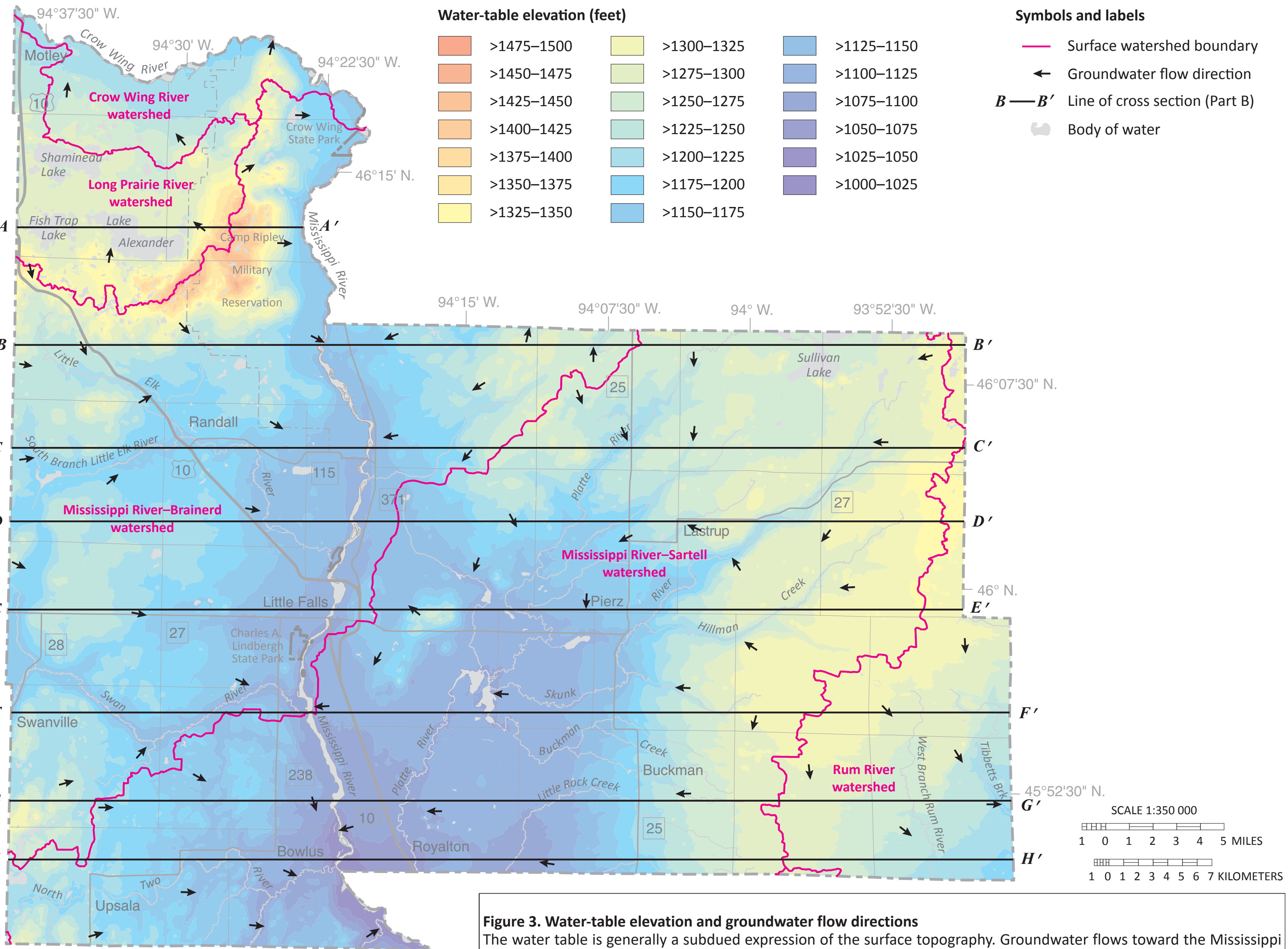


Figure 3. Water-table elevation and groundwater flow directions
The water table is generally a subdued expression of the surface topography. Groundwater flows toward the Mississippi River and many of the tributaries that flow into it.

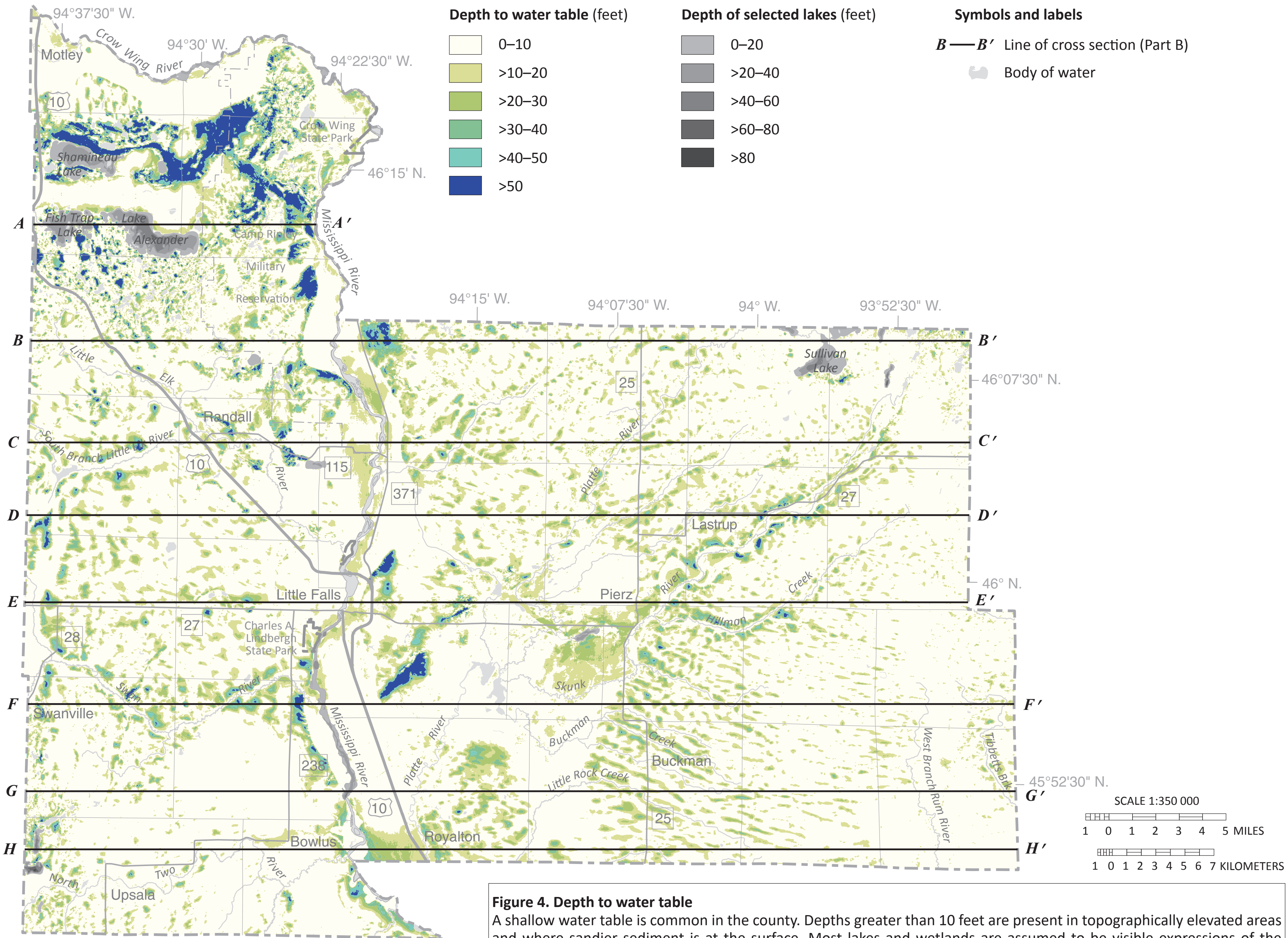


Figure 4. Depth to water table

A shallow water table is common in the county. Depths greater than 10 feet are present in topographically elevated areas and where sandier sediment is at the surface. Most lakes and wetlands are assumed to be visible expressions of the shallow water table. In the southeast, linear features with a deeper water table indicate sandy drumlins are at the surface.

Buried aquifers

Sand and gravel

Beneath the surficial geologic deposits are alternating layers of older sand, gravel, and fine-grained deposits from previous glacial advances. These unconsolidated glacial sediments are primarily within 200 feet of the land surface, with a few areas thicker than 350 feet within buried bedrock valleys (central and southwest) and extensive moraine deposits (northwest) (Part A, Plate 5). The buried sand and gravel aquifers were primarily deposited by meltwater from glaciers. The aquifers vary in lateral extent and thickness, with individual thicknesses rarely exceeding 60 feet. The naming convention for the buried sand and gravel aquifers in this atlas is based on the underlying till described in Part A.

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

The Part B units are shown as follows:

- Aquifers are shown with patterns. An additional pattern is used to indicate areas where sand extends from the surface into buried sand and gravel aquifers without an intervening fine-grained layer.
- Aquitards are shown as shades of gray, representing the relative hydraulic conductivity. Lighter shades represent units with more sand, implying a higher hydraulic conductivity. The shades of gray are based on the average sand content of the aquitard, which is determined from the matrix texture (portion that is less than 2 millimeter grain size).

Percent sand in aquitard

>60%	
>50% and ≤60%	
>40% and ≤50%	
>30% and ≤40%	
≤30%	

- Units of undifferentiated sediment are shown in brown.

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

	Part A	Part B
surficial sand and gravel*		ss*
fine-grained surface sediment	sc	sc
New Ulm (loam till)	nt	nt†
Mille Lacs	mt	mt
Independence 1 (sandy loam till)	it	it†
sand and gravel	is2	is2
Independence 2 (sandy loam till)	it2	it2
sand and gravel	is3	is3
Independence 3 (sandy loam till)	it3	it3
Cromwell 1 (sandy loam till)	ct1	ct1
sand and gravel	is4	is4
Independence 4 (sandy loam till)	it4	it4
sand and gravel	cs2	cs2
Cromwell 2 (sandy loam till)	ct2	ct2
sand and gravel	is5	is5
Independence 5 (sandy loam till)	it5	it5
sand and gravel	is6	is6†
Independence 6 (sandy loam till)	it6	it6
sand and gravel	cs3	cs3
Cromwell 3 (sandy loam till)	ct3	ct3
sand and gravel	hs	hs
Hewitt (sandy loam till)	ht	ht
sand and gravel	brs	brs
Browerville (loam till)	bt	bt
sand and gravel	scs	scs
Sauk Centre (loam till)	sct	sct
sand and gravel	fs1	fs1
St. Francis 1 (loam till)	ft1	ft1
sand and gravel	mls	mls
Meyer Lake (loam till)	mlt	mlt
sand and gravel	fs2	fs2
St. Francis 2 (loam till)	ft2	ft2
sand and gravel	ebs	ebs
Eagle Bend (clay till)	ebt	ebt
sand and gravel	es	es
Elmdale (loam till)	et	et
sand and gravel	vs	vs
unnamed (loam till)	vt	vt
sand and gravel	suu	suu
unknown units	ups	ups

Hydraulically connected combinations of surficial sand and buried sand layers

*Defined by one or a combination of the map units: ns, ou, ms, mst, il, is, ist, cl, cs, cst, hss, hst, cs1.
†Unit not shown on cross sections.

Figure 5. Hydrostratigraphy of Quaternary unconsolidated sediment
Correlation of Part A and B unit names (aquifers and aquitards) map labels.

Groundwater flow

The fine-grained sediment deposited across the majority of the county has a high percentage of sand and gravel. This results in groundwater moving from the surface into buried sand aquifers relatively quickly. The connectivity between these units, along with a shallow depth to bedrock in some areas, results in a groundwater flow system that displays similar groundwater levels throughout all the buried sand aquifers. Chemistry and aquifer test data discussed later in this report indicate that the tills in the county are leaky, and groundwater is moving in the same directions at all depths.

A groundwater flow map was created by contouring water levels measured in wells completed in both surficial and unconsolidated buried sand aquifers across the county (Figure 6). The resulting groundwater flow map shows changes in water levels similar to how topographic maps show changes in land-surface elevations. These are used to determine groundwater flow. As groundwater moves from higher to lower elevations, it flows perpendicular to the elevation contours, as shown on the map.

Groundwater flows from recharge areas through the aquifer to discharge locations. Flow into, through, and out of shallow aquifers can take days to weeks to travel distances of up to a mile. Flow in deeper aquifers can take centuries to millennia to travel dozens of miles. When combined with other information, high elevation areas on the groundwater flow map can indicate important recharge areas or a groundwater divide. River valleys are typical examples of low elevation discharge areas.

The groundwater flow map was created using static water-level data from the County Well Index (CWI) database (MGS and MDH, 2016), measurements made by the DNR staff, and river elevation points every 5 kilometer along the Mississippi River. The CWI records represent various climatic and seasonal conditions from 1949 through 2016. This data variability creates some uncertainty in groundwater elevations. River elevation points are included because the Mississippi River is a major groundwater discharge location for the majority of the county.

Groundwater across Morrison County primarily flows toward the Mississippi River and many of the tributaries that flow into it. The flow contours indicate discharge to the Mississippi, Crow Wing, Platte, Skunk, Little Elk, South Branch Little Elk, and Swan rivers. There is a high point on the groundwater flow map in the southeast that is displaying a groundwater divide. Groundwater to the west of the high point flows toward the Mississippi River. Groundwater to the east flows toward the Rum River in neighboring Mille Lacs County.

Bedrock water resources

Morrison County is underlain by Precambrian bedrock that is covered by glacial sediment, with some scattered bedrock outcrops primarily along rivers and streams. The Precambrian bedrock has little or no primary porosity, which limits its use as an aquifer. These rocks generally do not function as an aquifer except where secondary porosity has developed by fracturing or leaching. Well yield is variable and often poor as evidenced by greater well-screen lengths and long sections of open hole in many of these wells.

Wells drilled into the bedrock in the county are primarily in areas where the bedrock is less than 150 feet below the land surface. These wells are effectively serving as cisterns, as evidenced by the following:

- Over 80 percent of the bedrock wells have an open hole length of 50 feet or greater.
- 75 percent have casing diameters of 6 inches or greater.
- Limited specific capacity data (well diameters of 6–8 inches) indicate values of less than 1 gpm/ft, which is significantly lower than the unconsolidated aquifers (Aquifer specific capacity and transmissivity, page 47).

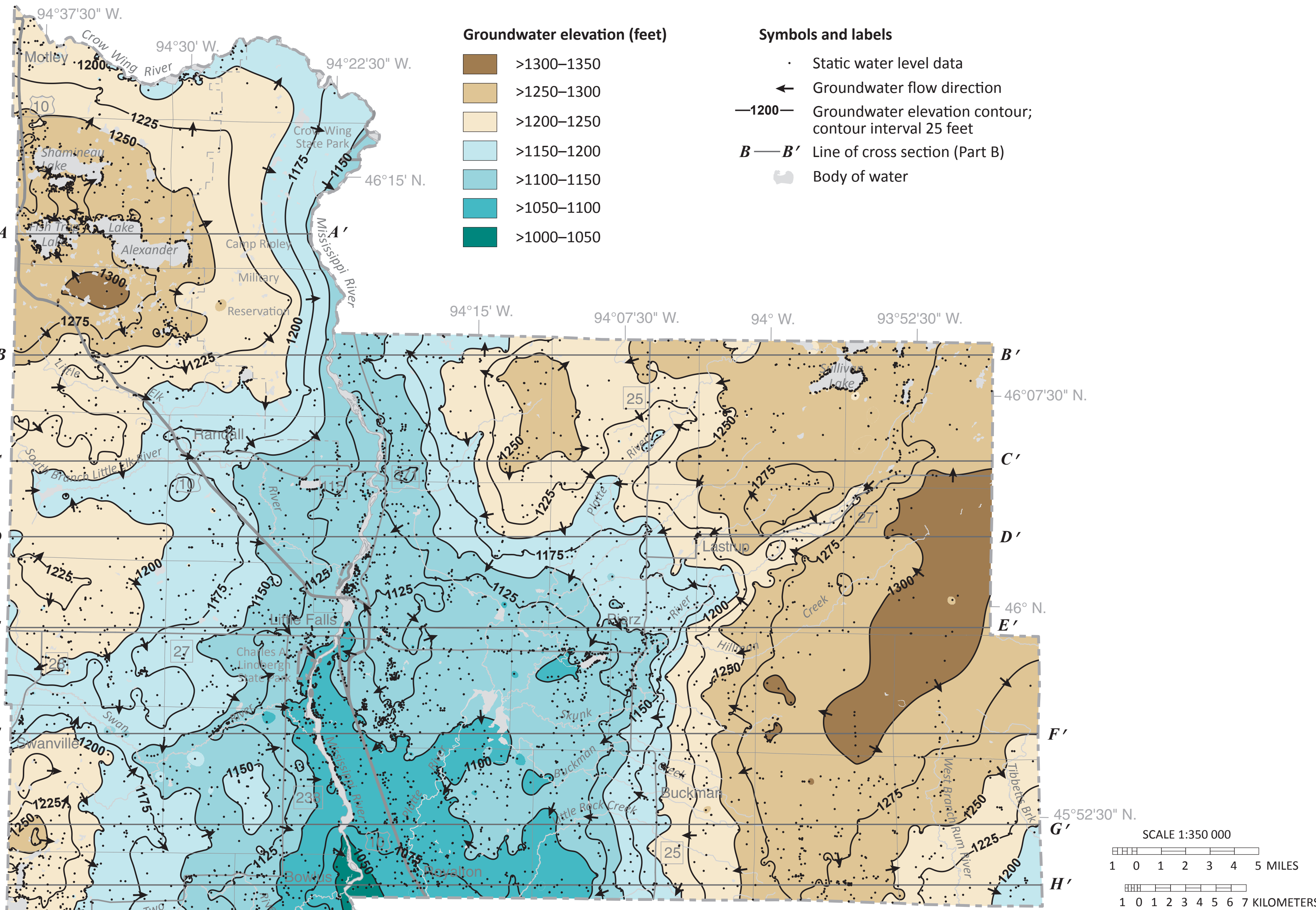


Figure 6. Groundwater flow map of the surficial and buried unconsolidated aquifers

Groundwater across most of the county is flowing toward the Mississippi River, except in the southeast corner of the county where water is flowing eastward toward the Rum River in neighboring Mille Lacs County. Localized flow is toward some of the tributary rivers of the Mississippi River, including the Crow Wing, Skunk, Platte, Little Elk, and Swan rivers.

Water chemistry (Plate 6)

The types of dissolved elements and compounds in groundwater provide information about the recharge areas, the geologic layers that the water has flowed through, and approximately how long the water has been underground (residence time). All groundwater originated as precipitation or surface water that seeped 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 distribution of select chemicals can indicate areas where groundwater consumption is a potential concern to human health.

Water sampling

To better understand water 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 1000 well owners were contacted to determine if they were willing to participate, and of these, 30 percent gave permission for sampling. The DNR collected water samples and standard field parameters from 99 wells and 10 lake samples. All significant aquifers (that have more than 1 percent of drilled wells) were sampled during this investigation. Sampling was distributed across the county for this study including the populated area near Little Falls.

The analytical results from these samples were combined with the results from wells and surface waters sampled by the MDH. Results from the MDH came from two separate databases: Minnesota Drinking Water Information System (MNDWIS), a compliance monitoring database that emphasizes treated water, and a noncompliance chemistry database (WCHEM).

Groundwater recharge sources

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

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

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

Definition of delta (δ)

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

$\delta\ (^{0}/_{00}) = (R_x/R_s-1)*1000$ where:

R represents the ratio of the heavy to light isotope, $^{18}O/^{16}O$ or $^{2}H/^{1}H$;

R_x represents the ratio of the sample;

R_s represents the ratio in VSMOW.

Delta values are reported in units of parts per thousand ($^{0}/_{00}$ or permil) relative to VSMOW.

County results were compared to the global meteoric water line that was developed from worldwide precipitation data (Craig, 1961). The results were compared to a local evaporation line. This line was established from stable isotope values collected at 10 lakes as part of this study and historic surface-water samples collected by the MDH. Samples plotted on a stable isotope graph fall near the intersection of the meteoric water line and the evaporation line, indicating that the groundwater was recharged by precipitation infiltrating from the surface (Figure 7). Only two samples plotted as greater than 50 percent of the maximum evaporative signature for area lakes (Pine Lake). These wells have a characteristic evaporative signature in the northwestern region of the county. In this region there is a prevalence of sandy geologic deposits with a large number of lakes and open water wetlands (Plate 6).

Well 467530 is located between Lake Alexander and Mud Lake (near the northeast corner of Lake Alexander). The stable isotope value in this sample plotted high along the evaporation line near the sample collected from Lake Alexander. This indicates water probably flows out of Lake Alexander toward Mud Lake. Located northeast of Randall south of Round Lake, well 684894 had an evaporative signature halfway between meteoric and the evaporative signature of Round Lake. This implies that the water from the well includes lake water recharging the aquifer. Well locations with a red 'E' on the figures and plates of this report represent groundwater samples with an evaporative signature.

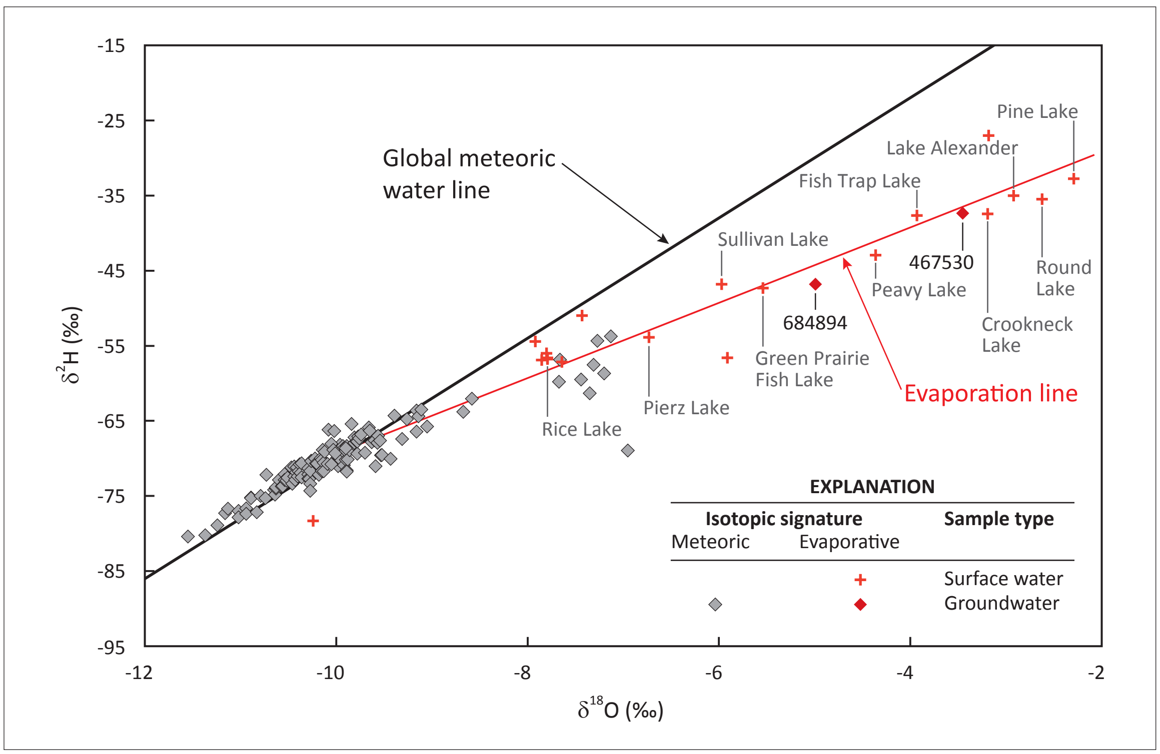


Figure 7. Stable isotope values from water samples

The global meteoric water line (GMWL) represents precipitation values. The GMWL was developed using precipitation samples from around the world and is described by the following equation: $\delta^2H = 8.0\ \delta^{18}O + 10.0$. Groundwater from direct infiltration of precipitation generally plots along or close to the global meteoric water line.

Meteoric waters that undergo evaporation are increasingly enriched in the heavier isotopes (fractionation) resulting in divergence away from and below the GMWL, along the evaporation line. Lake water samples collected by the DNR and historic surface water samples collected by the MDH were used to develop the local evaporation line. The evaporation line represents isotopic fractionation due to evaporation and is described by the following equation: $\delta^2H = 5.01\delta^{18}O - 19.18$. Two wells in Morrison County had an evaporative signature.

Groundwater residence time indicators

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

Tritium

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

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

Historical data (sample dates 1991–1996) are used in the residence time interpretations of this report and are classified according to Table B-2 in Appendix B.

In Morrison County, 130 well samples were analyzed for tritium. Of those:

- 27 had a recent tritium age
- 76 had a mixed tritium age
- 27 had a vintage tritium age

Almost 80 percent of the samples have a recent or mixed tritium age, indicating a relatively short residence time from the surface to the aquifers tested. Five surface-water samples were analyzed for tritium, and all had a mixed tritium age.

Carbon-14

Select vintage tritium-age samples were further sampled for the carbon-14 (^{14}C) isotope to estimate longer residence times. This naturally occurring isotope has a half-life of 5,730 years and is used to estimate groundwater residence time ranging from 100 to greater than 40,000 years (Alexander and Alexander, 1989).

Ten wells in Morrison County were sampled for carbon-14 analysis and had residence times varying from 350 to 8,000 years. The samples indicate that water from deeper depths typically have a longer residence time.

Inorganic chemistry of groundwater

Water begins dissolving minerals in the soil, sediment, and bedrock as soon as precipitation infiltrates the soil layer and becomes groundwater. Its chemistry changes as water moves along its flow paths. Water quality evaluations describe contaminants that are potentially harmful (natural or anthropogenic) or that affect aesthetics. The following guidelines are used in this atlas.

U.S. Environmental Protection Agency

(EPA, 2017 July and EPA, 2017 March)

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

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

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

Minnesota Department of Health

(MDH, 2012)

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

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

Minnesota Department of Natural Resources-County Groundwater Atlas program

Elevated: values above background conditions

Anthropogenic: caused by human activity

Water sample analyses results for inorganic chemicals include:

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

The following chemicals are geologically sourced (naturally occurring). Some are harmful at elevated levels; some can be elevated by anthropogenic activities.

Chemical descriptions

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

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

Chloride (SMCL 250 ppm, elevated ≥5 ppm, anthropogenic Cl/Br ratio >250) can occur naturally from deep sources such as residual brine, or it may come from an anthropogenic source such as road salts, water softener salts, and fertilizers (Davis and others, 1998; Panno and others, 2006).

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

Arsenic (MCL 10 ppb, MCLG 0) is a naturally occurring element that has been linked to negative health effects, including cancer. The MDH advises domestic well owners to treat drinking water if arsenic values are greater than or equal to the method reporting limits (MDH, 2018a). Current science cannot predict which wells will have high arsenic concentrations, therefore newly constructed wells are tested for arsenic if they are used for drinking water (Minnesota Administrative Rules 4725.5650, 2008).

The factors affecting elevated arsenic concentrations in groundwater are not completely understood.

Across much of southern and western Minnesota there is a strong correlation with glacial sediments derived from rocks northwest of Minnesota (Erickson and Barnes, 2005a). High arsenic concentrations in Morrison County cannot be attributed to these glacial sediments because they are not mapped in this part of the state. Geochemistry is driving the source of arsenic; 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).

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

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

Results

Chloride (Figure 8)

Of the 134 well samples analyzed for chloride, 81 were elevated, and 73 of those had anthropogenic chloride to bromide ratios. Of 8 surface-water samples analyzed for chloride, 7 had elevated chloride with an anthropogenic chloride to bromide ratio.

Nitrate (Figure 9)

Of the 138 well samples analyzed for nitrate, nitrate values greater than 1 ppm were present in 27 samples; 3 of the samples exceeded the HRL. Of 8 surface-water samples, 2 had elevated nitrate values. The groundwater samples with elevated nitrate were collected in areas where surficial sand connects to buried sand aquifers with limited intervening fine-grained till or from shallow wells.

Arsenic (Figure 10)

Of the 126 wells sampled for arsenic, 55 had elevated levels of 2 ppm or greater. These were collected from both surficial and buried sand aquifers. Six of these samples were greater than or equal to the MCL. A similar proportion of elevated arsenic values was found in groundwater samples collected by the MDH in Morrison County from 2008 to 2018 in new private wells (MDH, 2018b). Elevated arsenic occurs across the county. It does not appear to follow any spatial pattern and was present in the majority of the aquifers in the county.

Manganese (Plate 6)

Of the 123 samples tested for manganese, 86 were greater than or equal to the HRL, indicating a natural water quality problem for the majority of well owners. Elevated manganese is widespread. It does not appear to follow any spatial pattern and was present in every aquifer group.

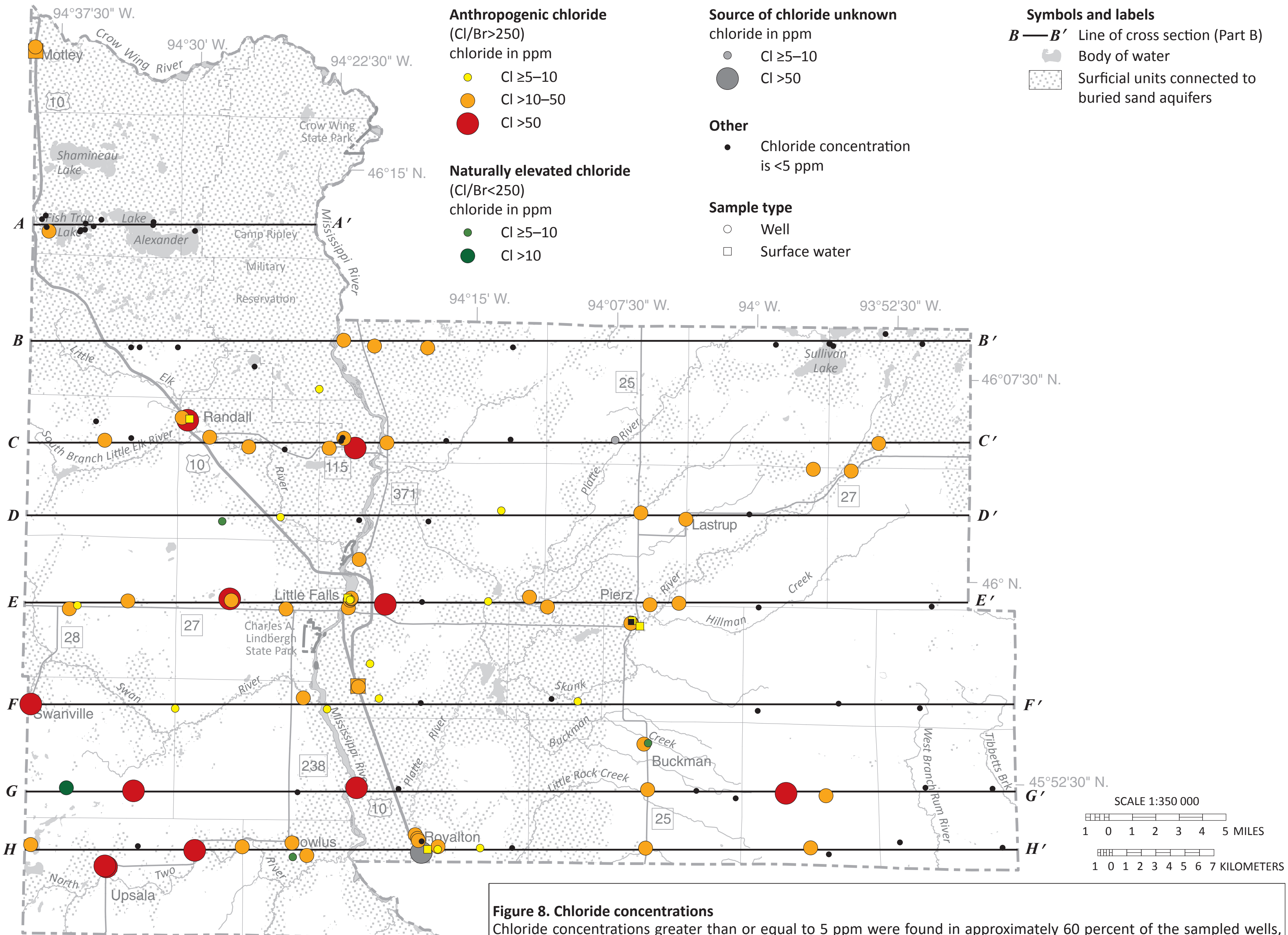


Figure 8. Chloride concentrations

Chloride concentrations greater than or equal to 5 ppm were found in approximately 60 percent of the sampled wells, with the majority of those samples being elevated from an anthropogenic source.

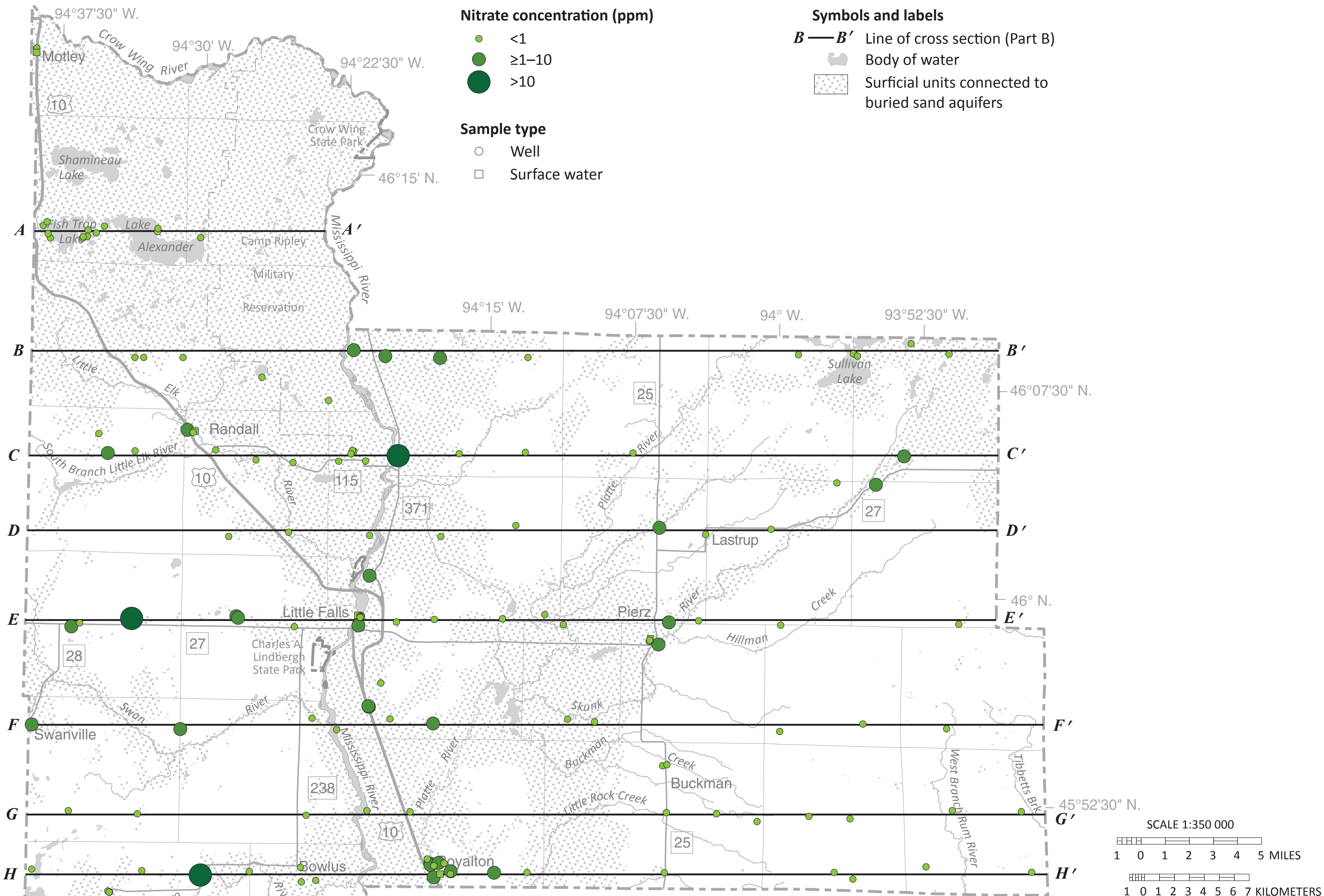


Figure 9. Nitrate concentrations
Nitrate concentrations greater than or equal to 1 ppm were present in approximately 20 percent of the sampled wells, with the majority of the wells located in areas where surficial sand is connected to buried sand aquifers.

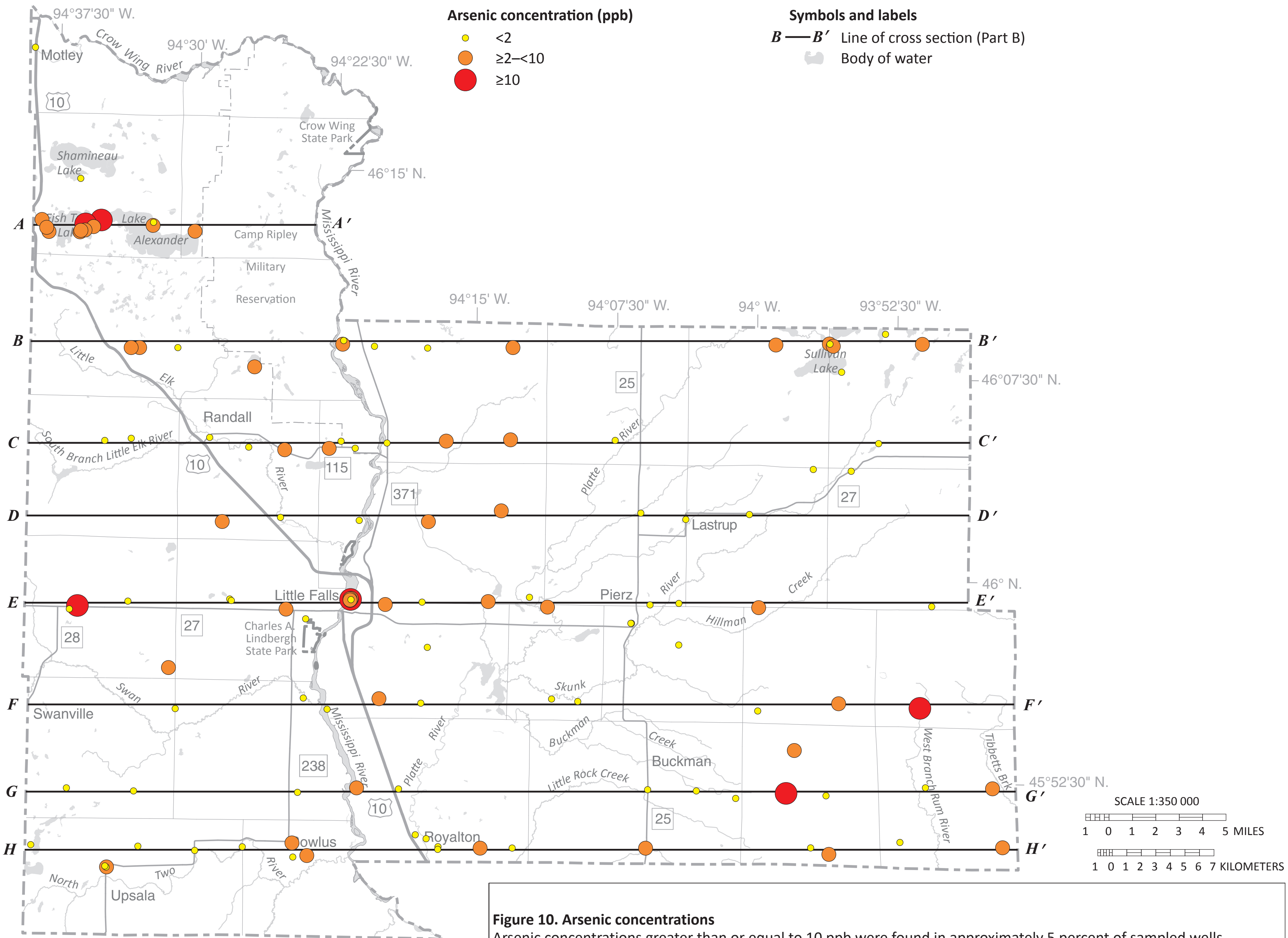


Figure 10. Arsenic concentrations
Arsenic concentrations greater than or equal to 10 ppb were found in approximately 5 percent of sampled wells.

Piper diagram: major cations and anions

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

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

The Piper diagram graphically represents multiple chemistry results. It has three components: a cation triangle, an anion triangle, and a central diamond. Every sample is represented by three data points: one in each triangle and one in the diamond grid.

On both of the ternary diagrams (triangles), major ions are plotted as percentages of milliequivalents per liter (meq/l) of total cations or total anions. The lower left ternary (triangle) diagram compares the major cations: calcium, magnesium, and sodium plus potassium. The lower right ternary diagram compares the major anions: bicarbonate, sulfate, and chloride plus nitrate. The data points in the two ternary diagrams are then projected onto the diamond grid to show the overall chemical characteristics of the groundwater. A water type was assigned to the samples based on where it plots on the diagram. The dashed arrows show an example of this relationship on the Piper diagram in Figure 11.

All the DNR samples collected in Morrison County are plotted on Figure 11 and are color coded according to tritium age to show chemical relationships. The water samples are all classified as calcium bicarbonate type water, which is typical for central and southern Minnesota. The anion triangle on the Piper diagram indicates that the shorter residence time water, indicated by recent and mixed tritium age, has more chloride and nitrate than the vintage tritium-age samples. There are two mixed tritium-age samples that do not cluster with the rest of the data on the cation triangle of the diagram; both were collected from the southeastern corner of the county (Plate 6, eastern end of cross sections G and H). These samples have increased magnesium compared to the other samples, likely due to upwelling of groundwater from the bedrock in this area as it moves toward the Rum River in neighboring Mille Lacs County.

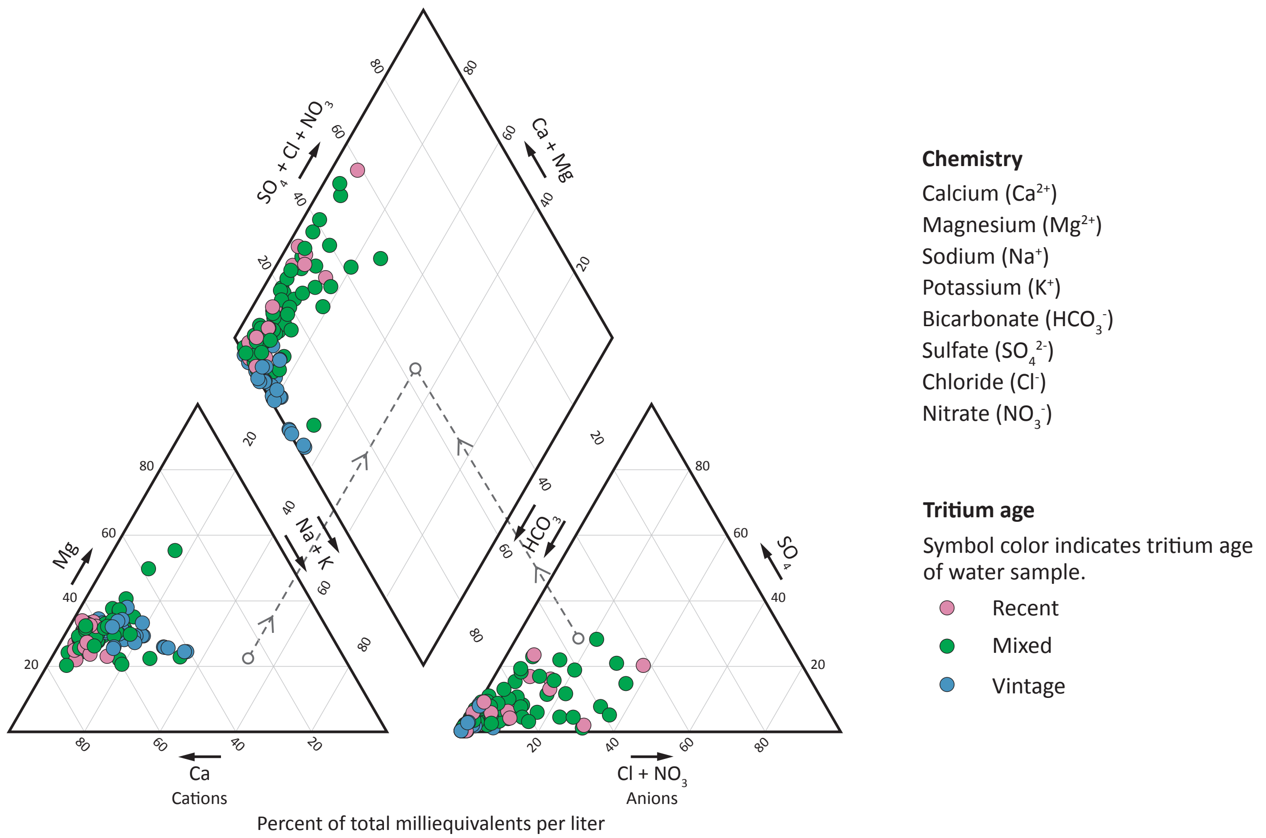


Figure 11. Piper diagram of groundwater samples from the DNR
Comparison of the relative proportions of cations and anions in groundwater from all the sampled wells. The cations and anions are shown in the left and right triangles, respectively. The center diamond shows a composite of cations and anions. The anion triangle indicates that samples with mixed and recent groundwater residence time have an increased amount of chloride and nitrate.

Pollution sensitivity

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

- Flow paths are vertical and downward from the land surface through the soil and underlying sediment to an aquifer.
- A contaminant travels 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 or the thickness of the geologic layers. The following assumptions were applied.

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

The model results are evaluated by comparing select chemistry from mapped aquifers.

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

Near-surface materials

Methods

The pollution sensitivity of near-surface materials is an estimate of the time it takes for water to infiltrate the land surface, travel through the unsaturated zone, and reach the water table, which is assumed to be 10 feet below land surface. The first 3 feet is assumed to be soil 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 of a soil or surficial geologic unit varies 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) (Natural Resources Conservation Service, 2016; Part A, Plate 4).

The time of travel through the near-surface sediment varies from hours to approximately a year.

- Areas with a relatively short travel time (hours to a week) are rated high sensitivity (Figure 12).
- Areas with a longer travel time (weeks to a year) are rated low or very low.
- Areas with travel time of more than a year are rated ultra low, but are not present in the county.

For further details, see *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

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

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

Hydrologic Soil Group (0–3 feet)		Surficial Geologic Texture (3–10 feet)		
Group*	**Transmission rate (in/hr)**	**Classification**	**Transmission rate (in/hr)**	**Surficial geology map unit (Part A, Plate 3)**
A, A/D	1	gravel, sandy gravel, silty gravel	1	Qcg, Qci, Qco, Qhi, Qho, Qig, Qigw, Qii, Qio, Qmi, Qmo, Qno, Qnoc, Qo, Qtl, Qtu, Qtuc
		sand, silty sand	0.71	Qa, Qe
B, B/D	0.50	silt, loamy sand	0.50	Qcl, Qf, Qil
		sandy loam, peat	0.28	Qcb, Qcd, Qcdw, Qch, Qcp, Qct, Qctw, Qit, Qitw, Qmt, Qmtw, Qp
C, C/D	0.075	silt loam, loam	0.075	Qnl, Qz, Qnt
		sandy clay loam	0.035	not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Quf
--	--	glacial lake sediment of Lake Agassiz	0.000011	not present in county

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

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

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

Group C: water transmission is somewhat restricted.

Group D: water movement is restricted or very restricted.

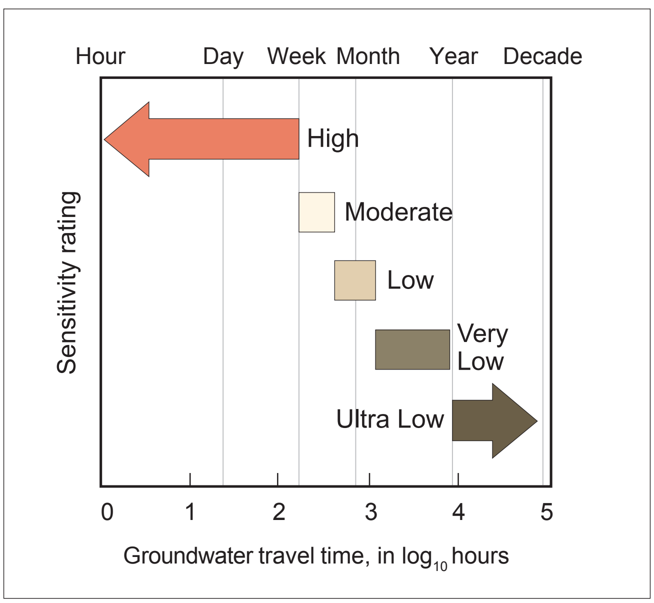


Figure 12. Geologic sensitivity rating for near-surface materials

Results

Slower infiltration rates (very low to low pollution sensitivity) are common in the eastern and west-central portion of the county, where there is fine-grained sediment at the surface (Figure 13). Faster infiltration rates (moderate to high sensitivity) are common in the central, northwest, and southwestern parts of the county. It is also common along river valleys across the county, where sandier surficial geologic units are prevalent.

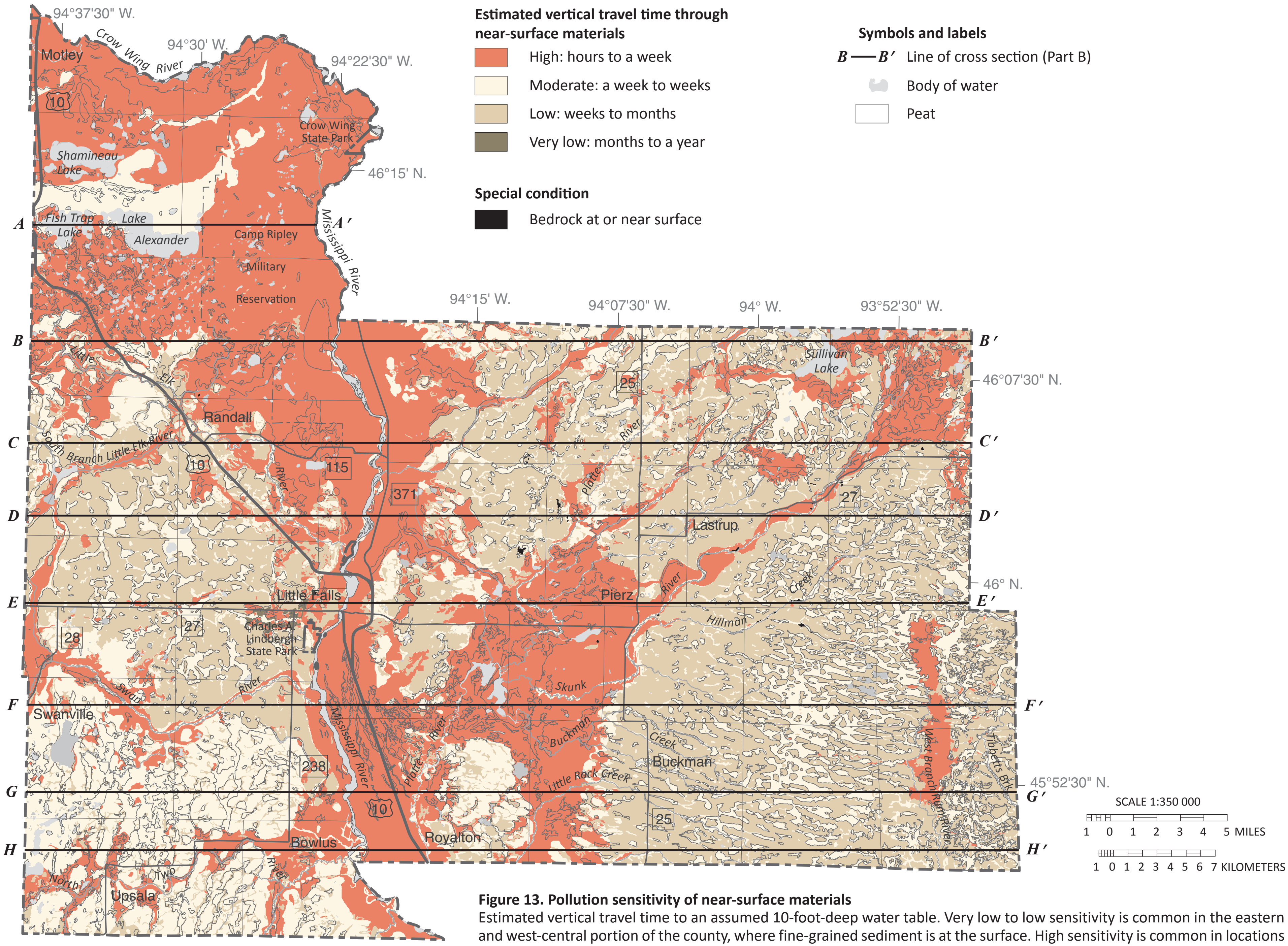


Figure 13. Pollution sensitivity of near-surface materials

Estimated vertical travel time to an assumed 10-foot-deep water table. Very low to low sensitivity is common in the eastern and west-central portion of the county, where fine-grained sediment is at the surface. High sensitivity is common in locations with sandier surficial sediment, especially the northwest and central parts of the county, and along river valleys.

Buried sand aquifers and bedrock surface

Methods

The sensitivity rating for the buried sand aquifers and the bedrock surface is based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with ratings of high or very high have relatively short travel times of less than a few years. Areas rated low or very low have estimated travel times of decades or longer (Figure 14).

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 15).

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

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

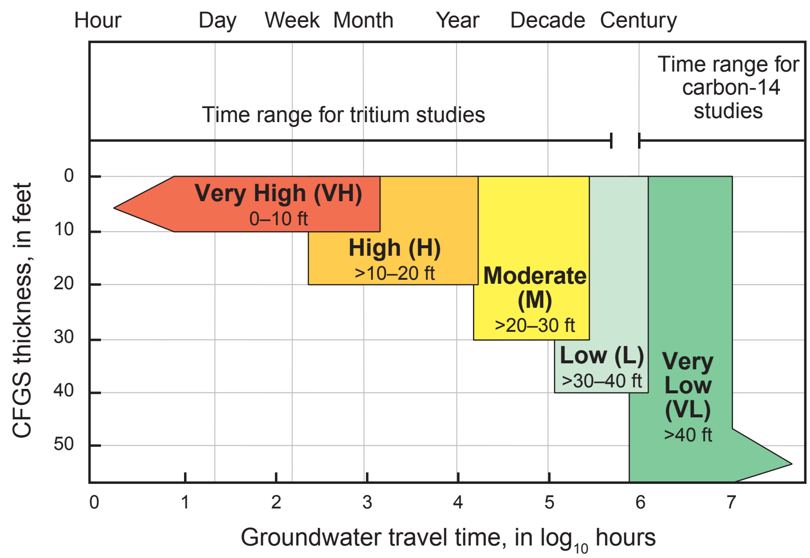


Figure 14. Pollution sensitivity rating for the buried sand aquifers and the bedrock surface
Sensitivity is defined by estimated vertical travel time. The numbers following each rating represent the cumulative fine-grained sediment (CFGS) thickness overlying an aquifer.

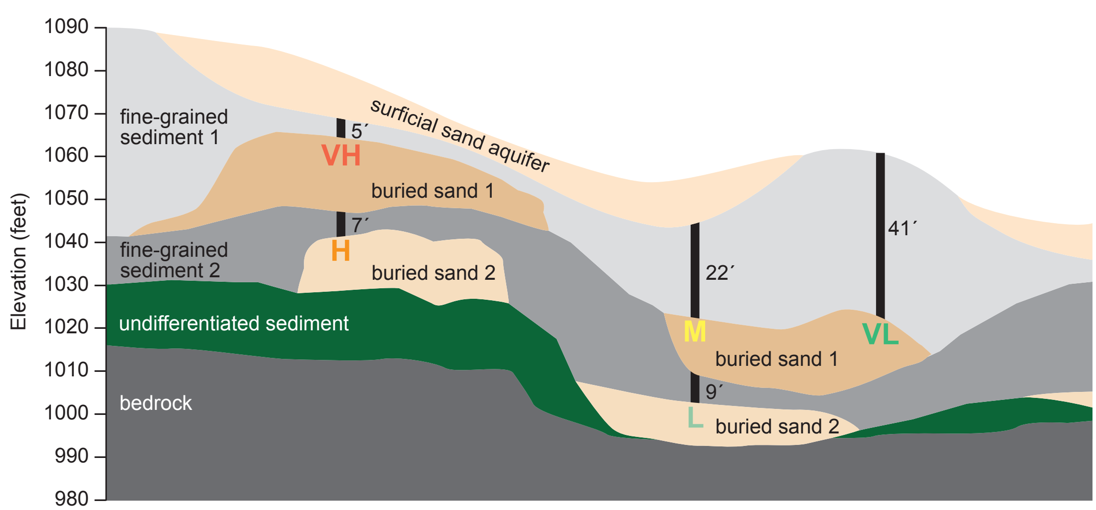


Figure 15. Cross section showing examples of pollution sensitivity ratings
Sensitivity ratings are based on the cumulative thickness of overlying fine-grained sediment. Each vertical black line is labeled with the thickness of fine-grained sediment. The letter at the base of the line indicates the sensitivity 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) (Figure 16).

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.

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

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

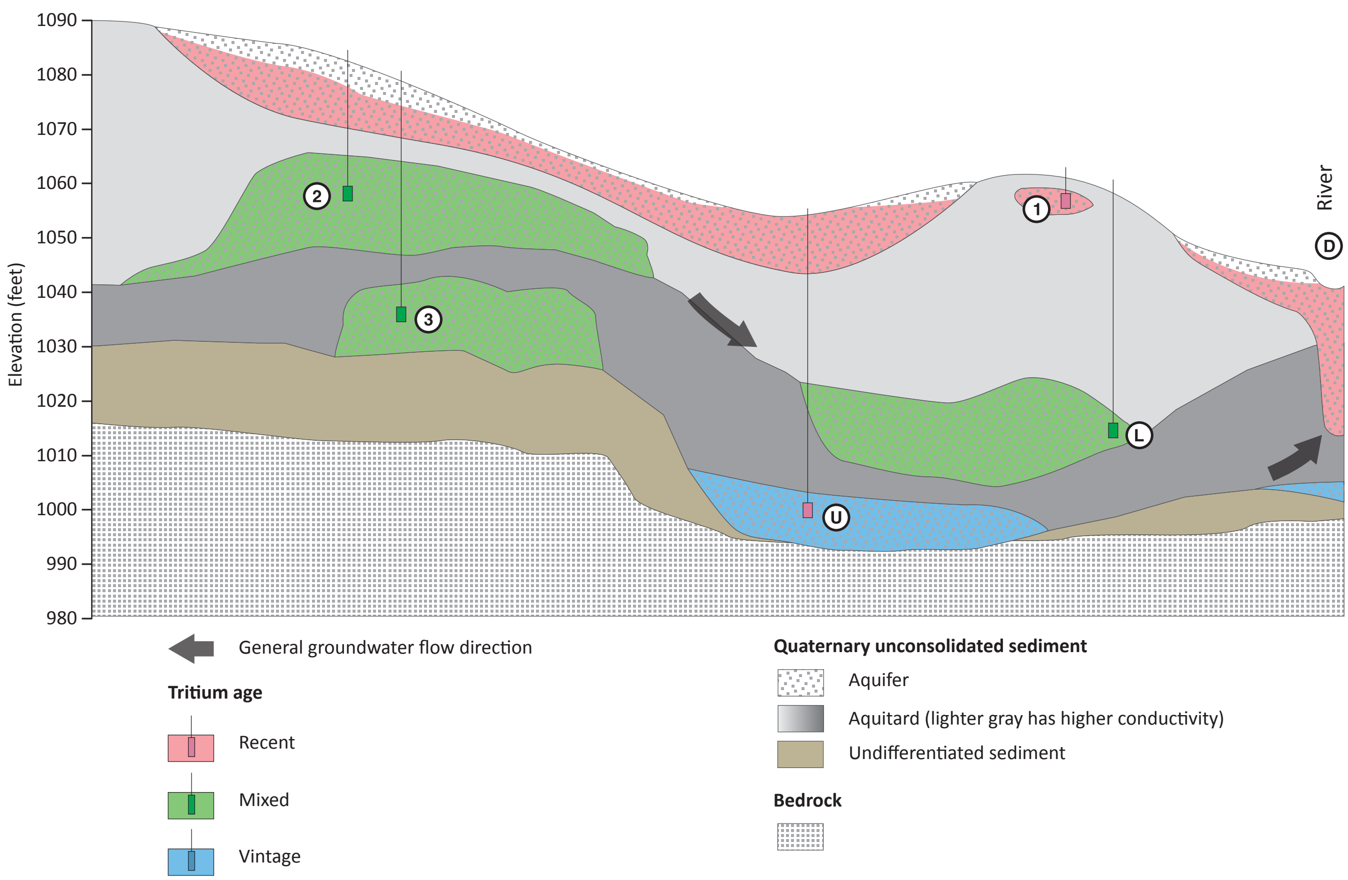


Figure 16. Hypothetical cross section illustrating groundwater conditions
This cross section shows interpretations of why there is tritium present in groundwater samples under five different groundwater conditions.

Results

These results describe the buried aquifers in stratigraphic order from shallowest to deepest, and include the depth, thickness, spatial distribution, and pollution sensitivity. The model results include groundwater flow direction derived from the county groundwater flow map to aid in understanding the groundwater conditions and the distribution of particular chemical constituents.

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

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

is3 **aquifer (Figure 17)**

The *is3* aquifer is part of a large sand deposit in the northern portion of the county near Camp Ripley. The majority of the aquifer ranges in depth from 0 to 270 feet with an average depth of 80 feet. It is used by approximately 1 percent of the county wells. The pollution sensitivity is very high because the aquifer is overlain primarily by other sand deposits without intervening fine-grained sediment.

There were two mixed tritium-age samples collected from this aquifer on the north side of Lake Alexander in an area with limited agriculture or development. This area has very high sensitivity. Neither sample had elevated chloride or nitrate. The samples were recharged through a thin layer of fine-grained sediment from a surficial aquifer.

is4 **aquifer (Figure 18)**

The *is4* aquifer is part of a large sand deposit in the northern portion of the county near Camp Ripley. The majority of the aquifer ranges in depth from 0 to 300 feet, with an average depth of 85 feet. It is used by approximately 1 percent of the county wells. The pollution sensitivity is mostly very high because the aquifer is overlain primarily by other sand deposits without intervening fine-grained sediment. The western and eastern edges of the aquifer have lower sensitivity because it is overlain by fine-grained sediment in these areas.

Of the 2 samples collected, both were analyzed for tritium with the following results: 1 recent and 1 mixed. Neither of the samples had elevated chloride or nitrate. The recent tritium-age sample was collected from a high sensitivity are near Lake Alexander and the mixed tritium-age sample was collected from a low sensitivity area north of Randall. The recent tritium-age sample had stable isotope values that indicate the water was recharged from a lake (probably Lake Alexander). The sample collected north of Randall was most likely recharged directly from precipitation and flowed laterally from the nearby *is3* aquifer.

cs2 **aquifer (Figure 19)**

The *cs2* aquifer is present across the county east of the Mississippi River at depths between 0 and 175 feet. It has an average depth of 30 feet and is used by approximately 6 percent of the county wells. The pollution sensitivity is very high because the aquifer is shallow. There are some areas of low pollution sensitivity where the aquifer is overlain by fine-grained sediment.

Of the 7 total samples collected, all were tested for tritium with the following results: 2 recent, 4 mixed, and 1 vintage. The vintage sample had a carbon-14 residence time of 4,000 years. Of the 6 samples analyzed for nitrate, 1 was elevated. Of the 6 samples analyzed for chloride, 4 were elevated from an anthropogenic source.

The mixed and recent tritium-age samples were collected from low to high sensitivity areas across the county. The samples near higher sensitivity areas were recharged directly from precipitation at the surface or through a thin layer of sandy till. The samples from lower sensitivity areas were recharged from overlying or nearby buried sand aquifers. The vintage tritium-age sample was collected from a very low sensitivity area near Buckman.

is5 **aquifer (Figure 20)**

The *is5* aquifer is part of a large sand deposit that exists in the Camp Ripley area at depths of 0 to 350 feet below the land surface. It has an average depth of 85 feet and is used by approximately 2 percent of the county wells. The central part of the aquifer has very high sensitivity where it is overlain by multiple other aquifers. The western and eastern portions of the aquifer have lower sensitivity because they are overlain by fine-grained sediment.

Of the 4 total samples collected from this aquifer, 3 were analyzed for tritium with the following results: 1 recent, 1 mixed, and 1 vintage. The vintage tritium-age sample had a carbon-14 residence time of 6,500 years. Of the 4 samples analyzed for nitrate, 1 was elevated. Of the 4 samples analyzed for chloride, 2 were elevated from anthropogenic sources.

The mixed and recent tritium-age samples were collected from locations with moderate to very high sensitivity. The sample collected north of Randall had a stable isotope value indicating a recharge connection to a lake, probably Round Lake to the north. The mixed sample was recharged through a stack of sands overlying the aquifer in the Mississippi River valley. The carbon-14 sample was located near the eastern border of the mapped aquifer, which was consistent with the very low sensitivity of that area.

cs3 **aquifer (Figure 21)**

The *cs3* aquifer is present across the central and eastern portions of the county at depths of 0 to 230 feet. It has an average depth of 45 feet and is used by approximately 15 percent of the county wells. The aquifer has moderate and high sensitivity along the river valleys and in the south-central part of the county, between U.S. Highway 10 and Buckman. The aquifer has very low sensitivity between the rivers where the tills have not been eroded.

Of the 21 total samples collected from this aquifer, 20 were tested for tritium with the following results: 5 recent, 11 mixed, and 4 vintage. One vintage sample had a carbon-14 residence time of 350 years. Of 21 samples analyzed for nitrate and chloride, 4 had elevated nitrate. Fourteen had elevated chloride with 12 of those from anthropogenic sources, 1 from a natural source, and 1 from an unknown source.

Mixed and recent tritium-age samples were collected from very low to very high sensitivity areas. The samples collected near higher sensitivity areas were recharged directly from precipitation or from an overlying surficial aquifer. Samples collected from lower sensitivity areas were recharged from overlying or nearby buried aquifers. A sample collected near Buckman did not have a readily identifiable source of recharge. Vintage tritium-age samples were collected from very low to low sensitivity areas. The carbon-14 sample near Sullivan Lake was consistent with the very low sensitivity of that area.

hs **aquifer (Figure 22)**

The *hs* aquifer is present in the western part of the county at depths of 0 to 270 feet. It has an average depth of 40 feet and is used by approximately 5 percent of the county wells. The aquifer has primarily moderate to very high sensitivity because of the shallow depth of the aquifer.

Of the 3 total samples collected from this aquifer, all were tested for tritium age with the following results: 2 mixed and 1 vintage. All were analyzed for nitrate and chloride and both of the mixed samples had elevated chloride and nitrate concentrations, indicating anthropogenic impacts. All were collected at locations of moderate sensitivity. Both of the mixed tritium-age samples were recharged from precipitation moving through a thin layer of till.

brs **aquifer (Figure 23)**

The *brs* aquifer is primarily located in the northwestern corner of the county at depths of 0 to 250 feet below the land surface. It has an average depth of 80 feet and is primarily overlain by sandy till or aquifers. It is used by approximately 3 percent of the county wells. The pollution sensitivity is primarily very high because of the limited amount of fine-grained sediment overlying the aquifer.

One mixed tritium-age sample was collected from a moderately sensitive area west of Fish Trap Lake. It did not have elevated chloride or nitrate. This sample was recharged from the overlying buried *hs* aquifer.

scs **aquifer (Figure 24)**

The *scs* aquifer is located along the western border of the county at depths of 0 to 200 feet. It has an average depth of 55 feet and is used by approximately 2 percent of the county wells. The pollution sensitivity is very low with limited areas of very high sensitivity where the fine-grained sediments are not as extensive.

A total of 3 samples were collected in this aquifer and tested for tritium with the following results: 2 mixed and 1 vintage. All 3 samples were analyzed for nitrate and chloride, and only one had an elevated nitrate concentration and anthropogenic chloride. All these samples were collected from moderately sensitive areas. The mixed tritium-age samples were recharged from precipitation moving through a relatively thin layer of fine-grained sediment or from an overlying surficial aquifer.

fs1 **and** ***fs2*** **aquifers (Figure 25)**

The *fs1* and *fs2* aquifers are primarily located in three corners of the county at depths of 0 to 200 feet. The two aquifers have an average depth of 70–75 feet and are used by approximately 4 percent of the county wells. The extent of the *fs2* aquifer is highlighted with a thin black perimeter in Figure 25. The pollution sensitivity of the aquifers is highest in the southwest and very low to moderate in the other parts of the county where it is present at deeper depths.

A total of 4 samples were collected from these aquifers and tested for tritium with the following results: 1 recent and 3 mixed. All 4 of the samples were analyzed for nitrate and chloride and none had elevated nitrate; 2 had elevated chloride, 1 from an anthropogenic source and 1 from a natural source.

The recent tritium-age sample was collected from a very low sensitivity area between Fish Trap Lake and Lake Alexander and does not have a clear recharge source, which could indicate a well construction issue. The mixed tritium-age samples were collected from very low to moderate sensitivity areas. The samples were recharged laterally or from overlying buried aquifers.

mls aquifer (Figure 26)

The *mls* aquifer is present across the majority of the county at depths of 0 to 375 feet. It has an average depth of 65 feet and is used by approximately 23 percent of the county wells. The pollution sensitivity is moderate to very high along the river valleys and in areas where the aquifer is overlain by other aquifers with limited intervening fine-grained sediments. There is very low pollution sensitivity in upland areas, where fine-grained sediments overly the aquifer.

Of the 37 total samples collected from this aquifer, 33 were tested for tritium age with the following results: 4 recent, 23 mixed, and 6 vintage. Of the 36 samples analyzed for nitrate, 8 were elevated. Of the 34 samples analyzed for chloride, 24 were elevated, 23 of these were anthropogenic and 1 was from a natural source. One vintage sample had a carbon-14 residence time of 950 years.

These samples were collected from areas of very low to very high pollution sensitivity. Samples collected from moderate to high sensitivity areas were primarily recharged from precipitation or an overlying surficial aquifer and samples collected in low sensitivity areas were recharged laterally or from an overlying buried aquifer. The majority of the vintage tritium-age samples were collected from very low sensitivity areas; the carbon-14 sample was collected near Lastrup.

ebs aquifer (Figure 27)

The *ebs* aquifer is located in the western part of the county at depths of 0 to 300 feet. It has an average depth of 85 feet and is used by approximately 8 percent of the county wells. The pollution sensitivity is primarily very low, with higher sensitivity in the river valleys where fine-grained sediment is not present.

Of the 19 total samples collected from this aquifer, 17 were tested for tritium with the following results: 7 recent, 8 mixed, and 2 vintage. The vintage tritium-age samples had carbon-14 residence times of 4,000 years (near Fish Trap Lake) and 6,000 years (near Upsala). Of the 18 samples analyzed for nitrate, 3 were elevated. Of the 17 samples analyzed for chloride, 13 were elevated. Of these, 12 were elevated from an anthropogenic source, and 1 was elevated from a natural source.

These samples were collected from areas of very low to very high pollution sensitivity. Samples collected from moderate to high sensitivity areas were primarily recharged from precipitation or an overlying surficial aquifer and samples collected in low sensitivity areas were recharged laterally or from an overlying buried aquifer.

es aquifer (Figure 28)

The *es* aquifer is present across the majority of the county at depths of 0 to 380 feet. It has an average depth of 95 feet and is used by approximately 15 percent of the wells in the county. The pollution sensitivity of the aquifer is primarily very low, with higher sensitivity in the river valleys where there is less fine-grained sediment.

Of the 19 total samples collected from this aquifer, 17 were tested for tritium with the following results: 2 recent, 7 mixed, and 8 vintage. Two vintage tritium-age samples had carbon-14 residence times of 6,500 years (near Buckman) and 3,500 years (northeast of Little Falls). Of the 18 samples analyzed for nitrate, 3 were elevated. Of the 17 samples analyzed for chloride, 7 were elevated, all from anthropogenic sources.

The mixed and recent tritium-age samples were collected from areas of very low to very high pollution sensitivity. Samples collected from moderate to high sensitivity areas were primarily recharged from precipitation or an overlying surficial aquifer and samples collected in low sensitivity areas were recharged laterally or from an overlying buried aquifer. The majority of the vintage tritium-age samples were collected from very low pollution sensitivity areas.

vs aquifer (Figure 29)

The *vs* aquifer is located in the south-central part of the county at depths of 0 to 220 feet. It has an average depth of 105 feet and is used by approximately 2 percent of the county wells. The aquifer has very high sensitivity in the river valleys where the fine-grained sediment is not present.

Of the 6 total samples collected from this aquifer, 3 were tested for tritium with the following results: 1 recent and 2 mixed. Of the 5 samples analyzed for nitrate, 2 were elevated. Of the 5 samples analyzed for chloride, 2 were elevated from anthropogenic sources and 1 was elevated from an unknown source (likely anthropogenic, but a chloride to bromide ratio could not be calculated).

The recent tritium-age sample was collected in a very high sensitivity area and was recharged from an overlying surficial aquifer. The mixed tritium-age samples were collected from a very low sensitivity area near Royalton, and were recharged laterally or from an overlying buried aquifer.

suu aquifer (Figure 30)

The *suu* aquifer is located across the county at depths of 0 to 320 feet. It has an average depth of 135 feet and is used by approximately 5 percent of the county wells. The aquifer has very low sensitivity except in the river valleys where there is very high sensitivity because there are limited fine-grained sediments overlying the aquifer.

All 10 of the samples collected from this aquifer were tested for tritium with the following results: 1 recent, 6 mixed, and 3 vintage. Two of the vintage samples had carbon-14 residence times of 3,500 years (near Fish Trap Lake) and 8,000 years (near Sullivan Lake). Of the 10 samples analyzed for nitrate, none were elevated. Of the 10 samples analyzed for chloride, 7 had elevated chloride (all the mixed and recent tritium-age samples). Of the elevated values, 5 were from an anthropogenic source and 2 were from natural sources.

The recent and mixed tritium-age samples were collected from areas with very high sensitivity or downgradient from moderate sensitivity areas. Samples collected from high sensitivity areas were recharged from precipitation. Samples collected in low sensitivity areas were recharged laterally or from an overlying buried aquifer. The vintage tritium-age samples were all collected from areas of very low sensitivity.

Bedrock surface (Figure 31)

The bedrock surface is within 270 feet of the land surface across 95 percent of the county and is used by approximately 5 percent of the county wells. In general, the top of the bedrock surface has very low sensitivity, except for moderate to high sensitivity regions along the river valleys where there is less fine-grained sediments. There are some small areas of low sensitivity, outside the river valleys, where the bedrock surface is shallow.

One mixed tritium-age sample was collected from a bedrock well in a very high sensitivity area near Little Falls. The sample did not have elevated chloride or nitrate. It was recharged through a stack of 115 feet of sand overlying the bedrock surface in this region.

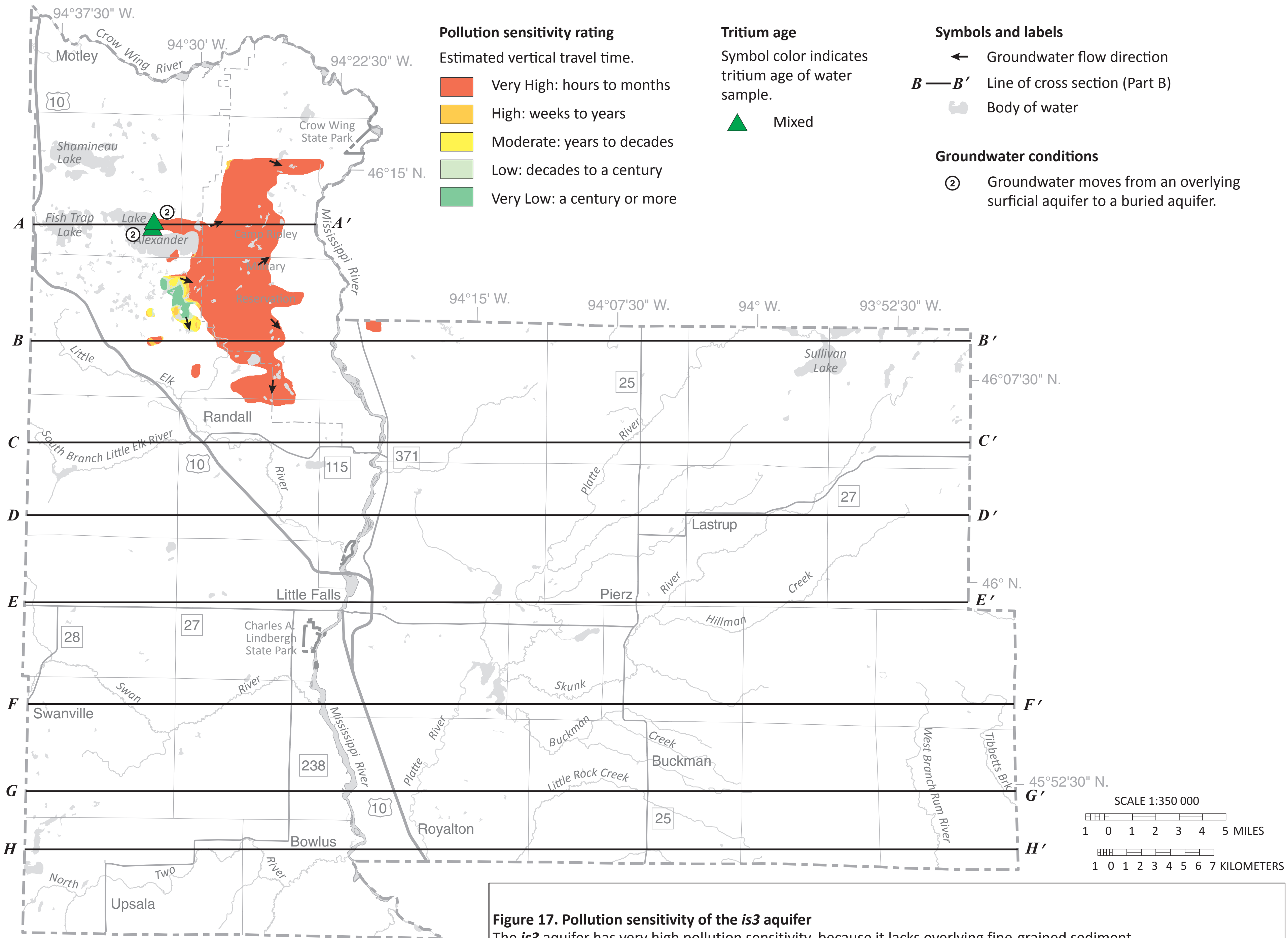


Figure 17. Pollution sensitivity of the *is3* aquifer
The ***is3*** aquifer has very high pollution sensitivity, because it lacks overlying fine-grained sediment.

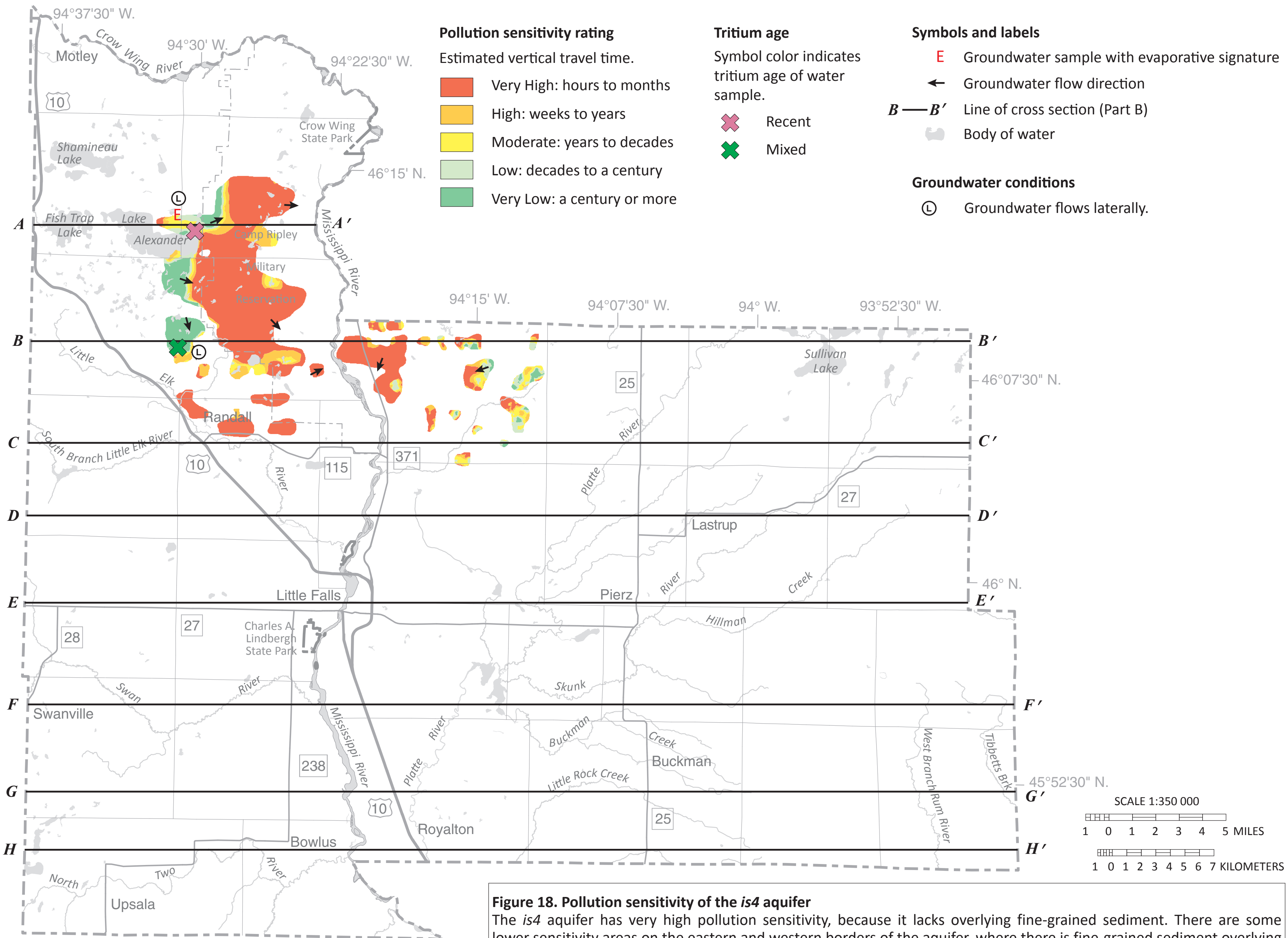


Figure 18. Pollution sensitivity of the *is4* aquifer

The *is4* aquifer has very high pollution sensitivity, because it lacks overlying fine-grained sediment. There are some lower sensitivity areas on the eastern and western borders of the aquifer, where there is fine-grained sediment overlying the aquifer.

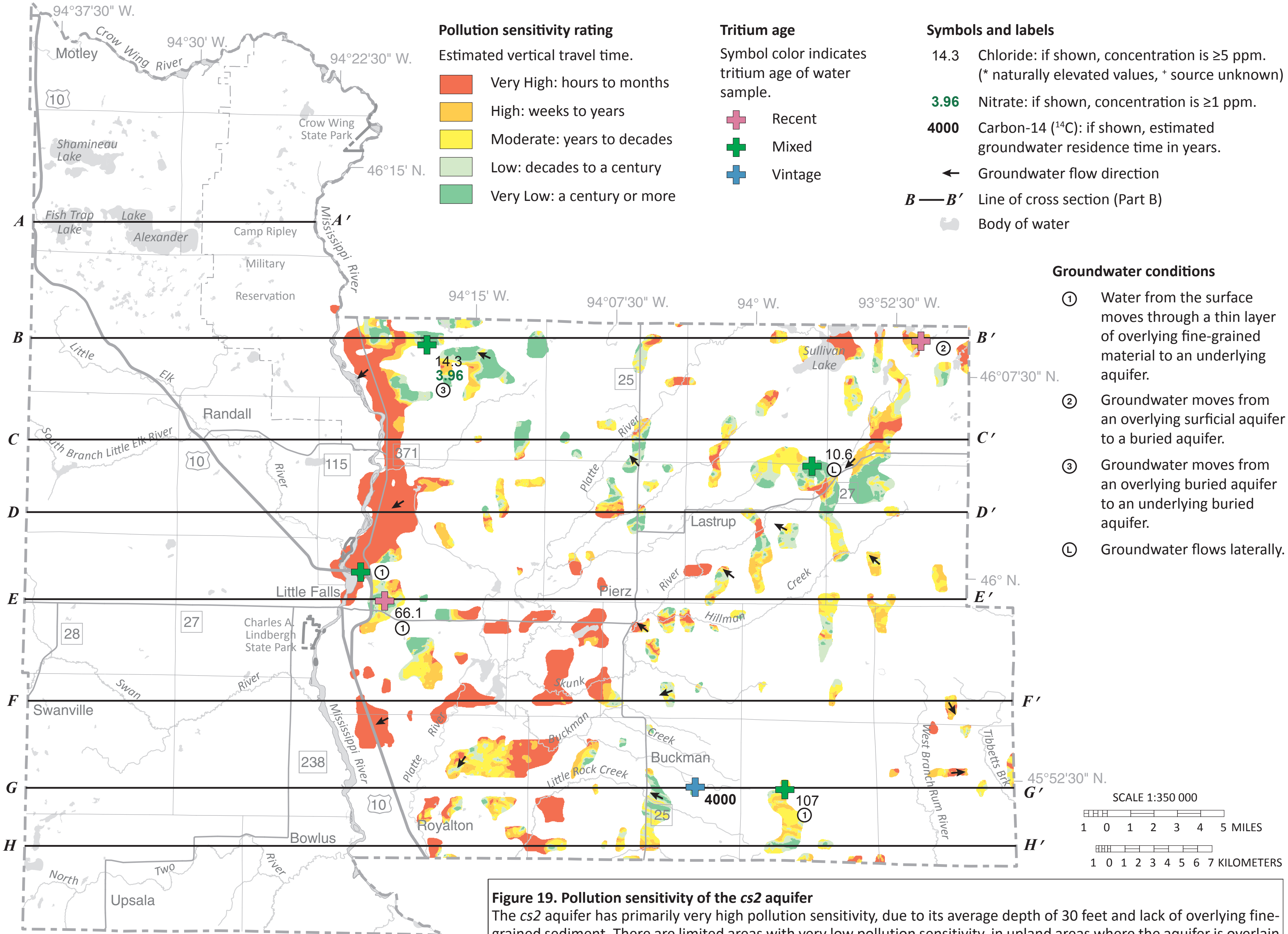


Figure 19. Pollution sensitivity of the *cs2* aquifer
The *cs2* aquifer has primarily very high pollution sensitivity, due to its average depth of 30 feet and lack of overlying fine-grained sediment. There are limited areas with very low pollution sensitivity, in upland areas where the aquifer is overlain by fine-grained sediment.

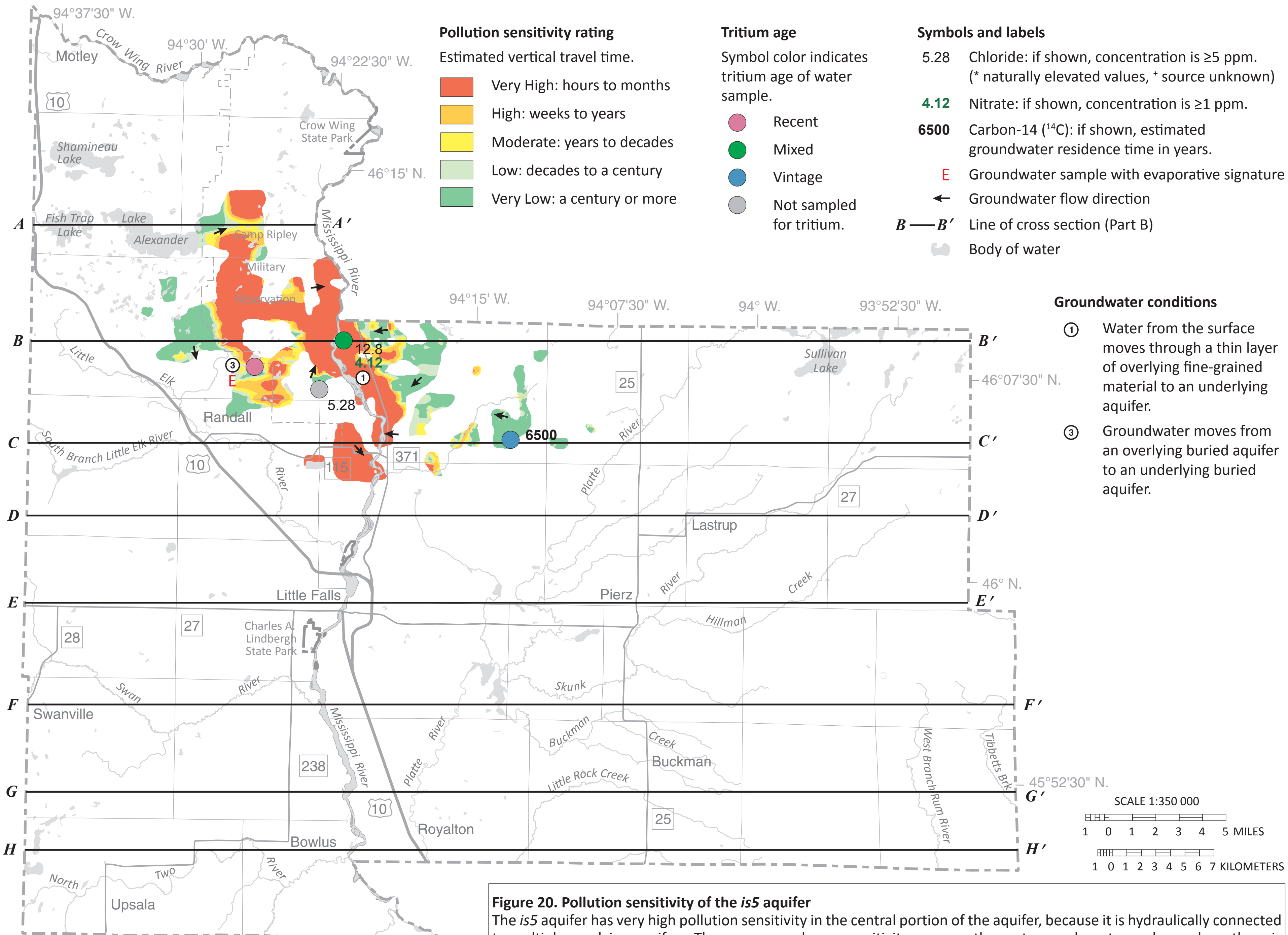


Figure 20. Pollution sensitivity of the *is5* aquifer
The *is5* aquifer has very high pollution sensitivity in the central portion of the aquifer, because it is hydraulically connected to multiple overlying aquifers. There are some lower sensitivity areas on the eastern and western edges, where there is fine-grained sediment overlying the aquifer.

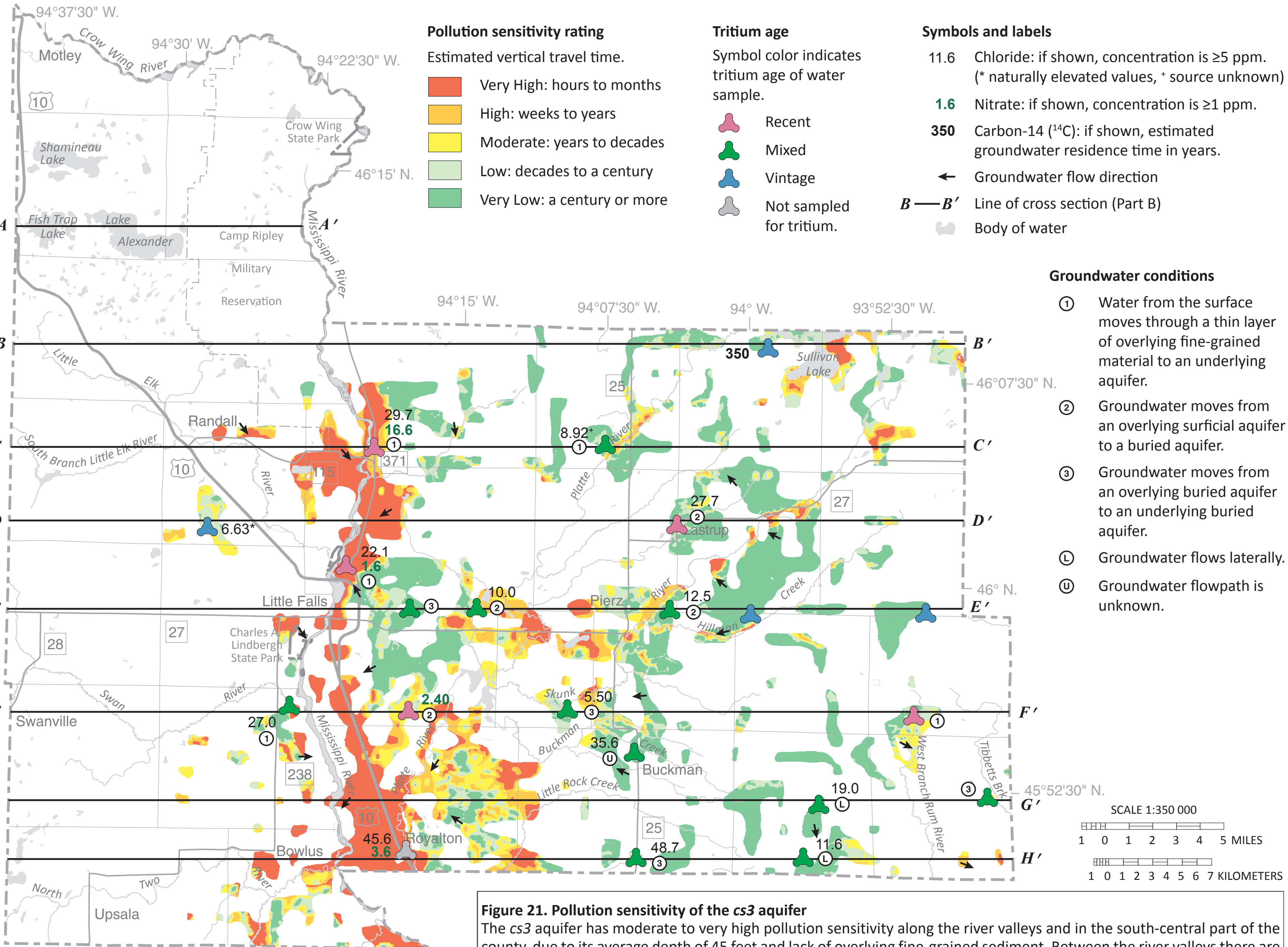


Figure 21. Pollution sensitivity of the *cs3* aquifer

The *cs3* aquifer has moderate to very high pollution sensitivity along the river valleys and in the south-central part of the county, due to its average depth of 45 feet and lack of overlying fine-grained sediment. Between the river valleys there are areas with very low pollution sensitivity, where the aquifer is overlain by fine-grained sediment.

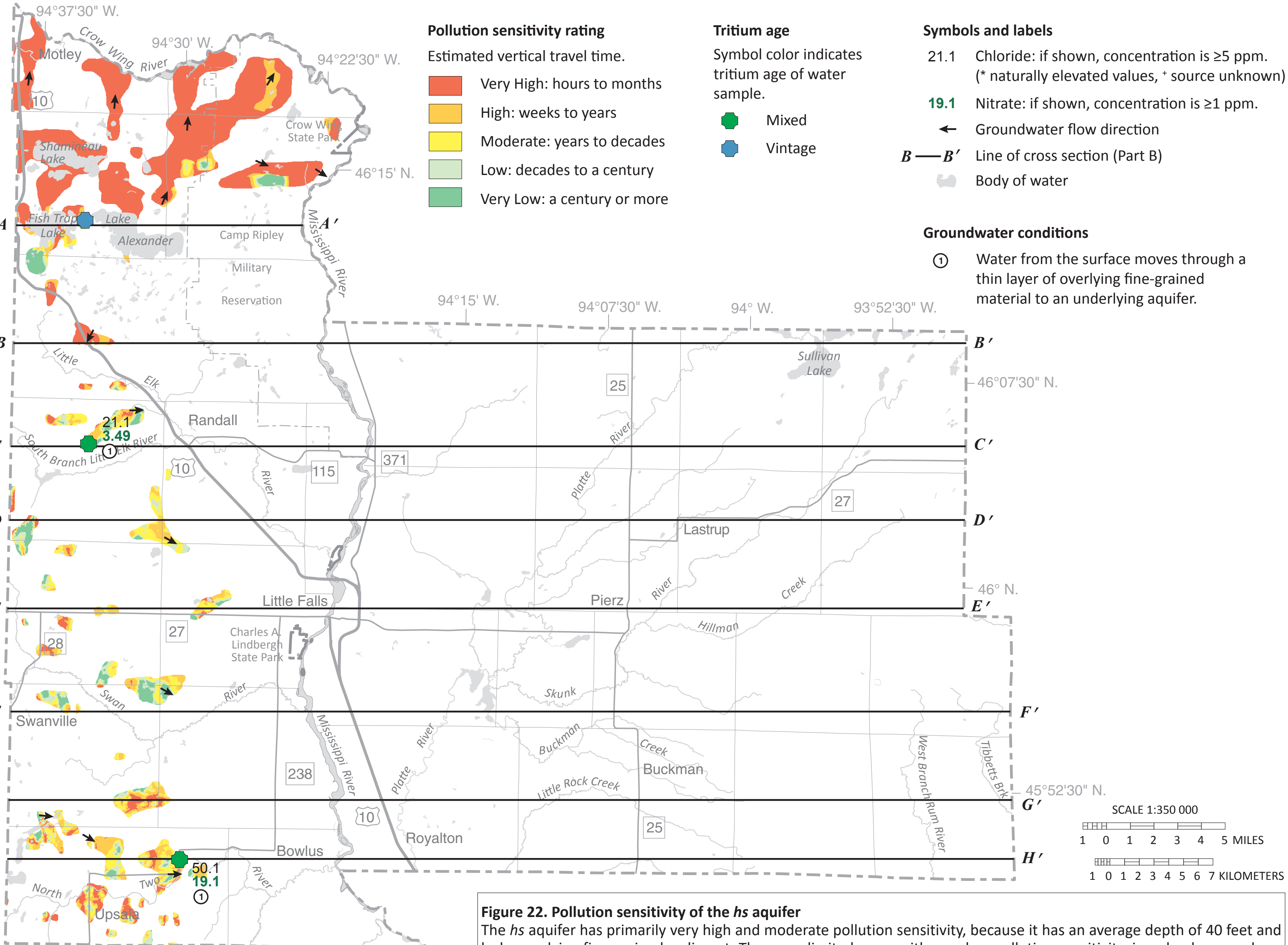


Figure 22. Pollution sensitivity of the *hs* aquifer
The *hs* aquifer has primarily very high and moderate pollution sensitivity, because it has an average depth of 40 feet and lacks overlying fine-grained sediment. There are limited areas with very low pollution sensitivity, in upland areas where the aquifer is overlain by fine-grained sediment.

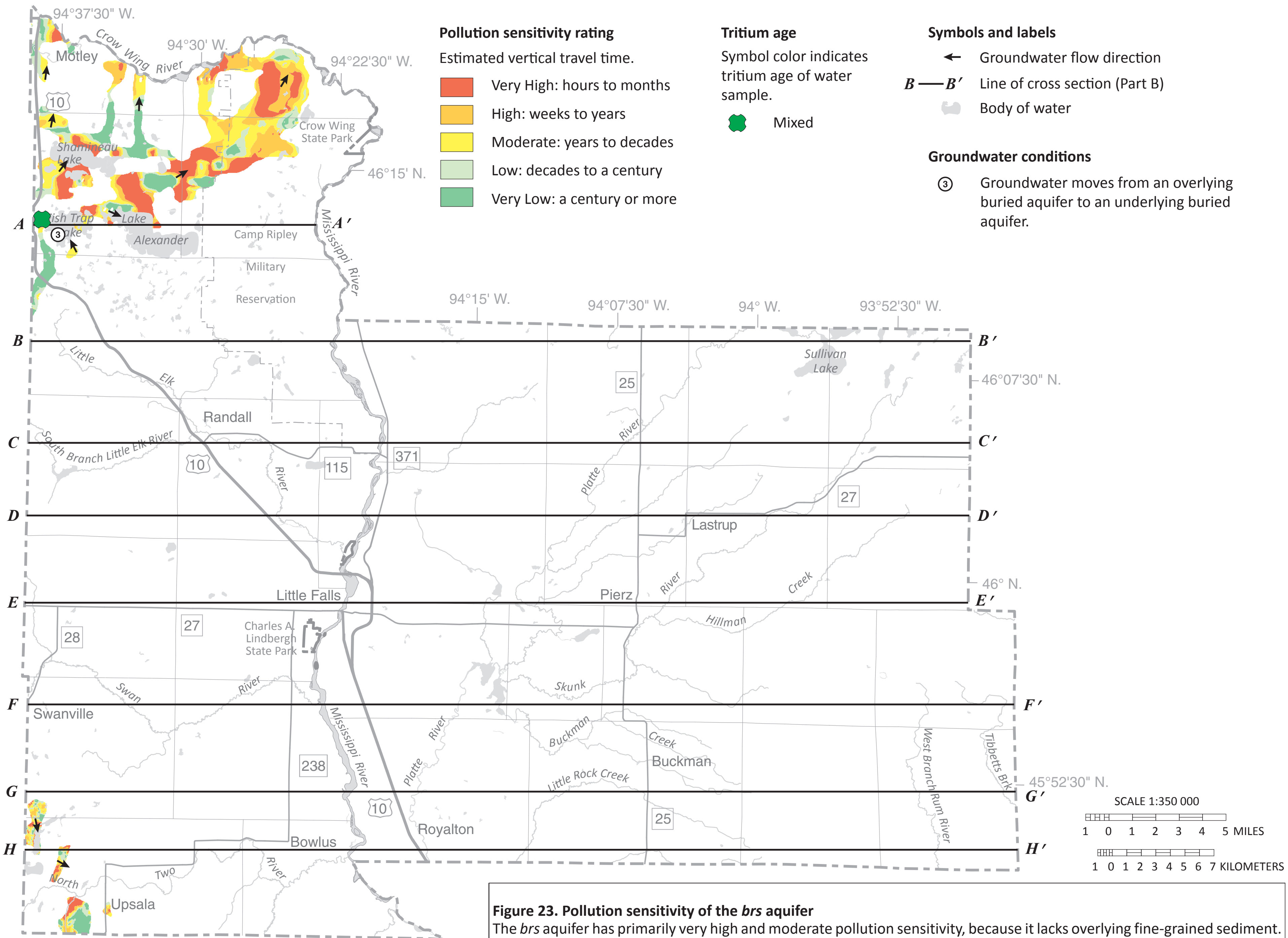


Figure 23. Pollution sensitivity of the *brs* aquifer

The *brs* aquifer has primarily very high and moderate pollution sensitivity, because it lacks overlying fine-grained sediment. There are areas with very low pollution sensitivity, in upland areas where the aquifer is overlain by fine-grained sediment.

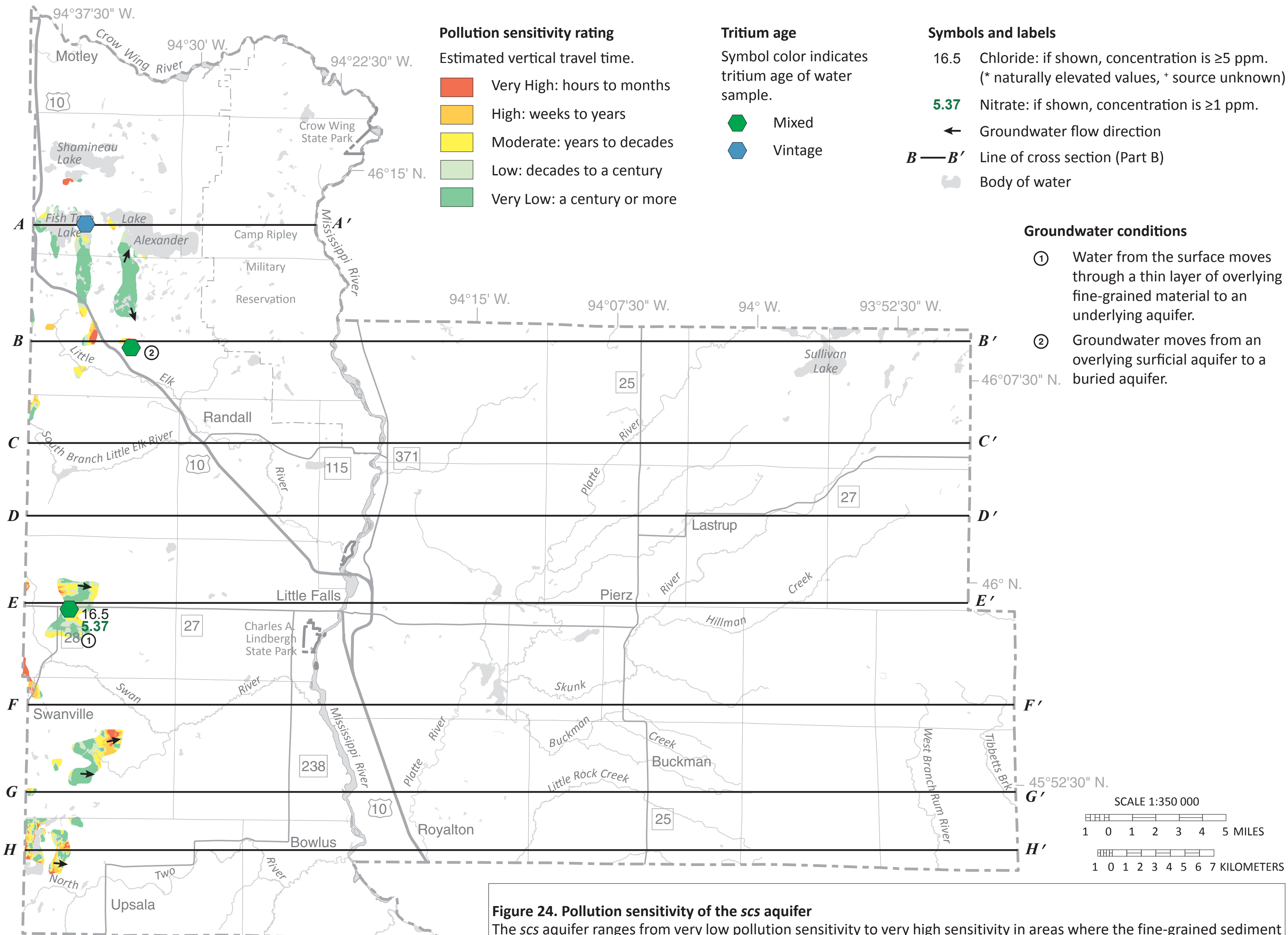


Figure 24. Pollution sensitivity of the *scs* aquifer
The *scs* aquifer ranges from very low pollution sensitivity to very high sensitivity in areas where the fine-grained sediment is not as extensive.

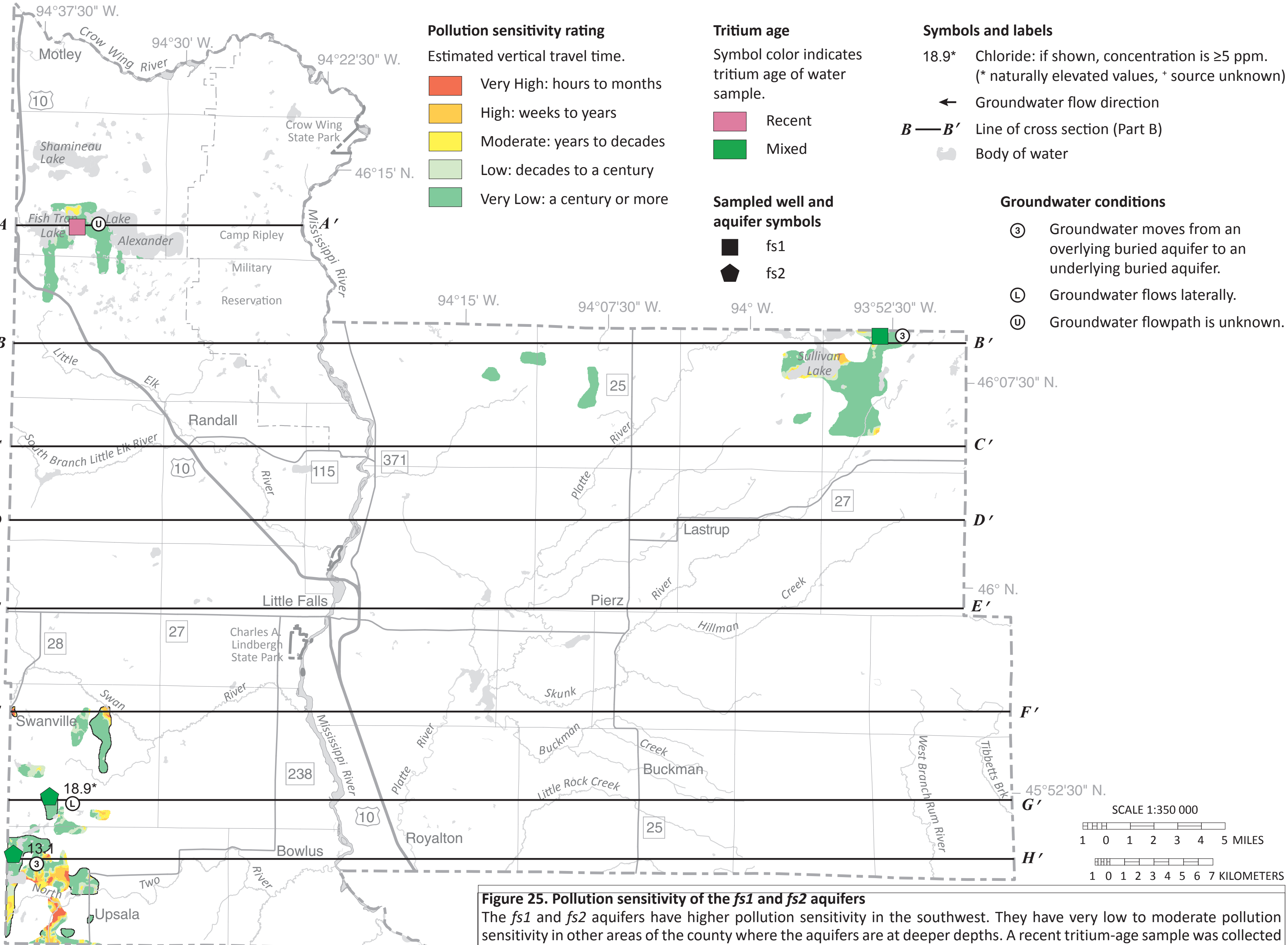


Figure 25. Pollution sensitivity of the *fs1* and *fs2* aquifers

The *fs1* and *fs2* aquifers have higher pollution sensitivity in the southwest. They have very low to moderate pollution sensitivity in other areas of the county where the aquifers are at deeper depths. A recent tritium-age sample was collected from a very low sensitivity area between Fish Trap Lake and Lake Alexander. It does not have a clear recharge source, which could indicate a well construction issue. The *fs2* aquifer is indicated by the black outlined areas on this map.

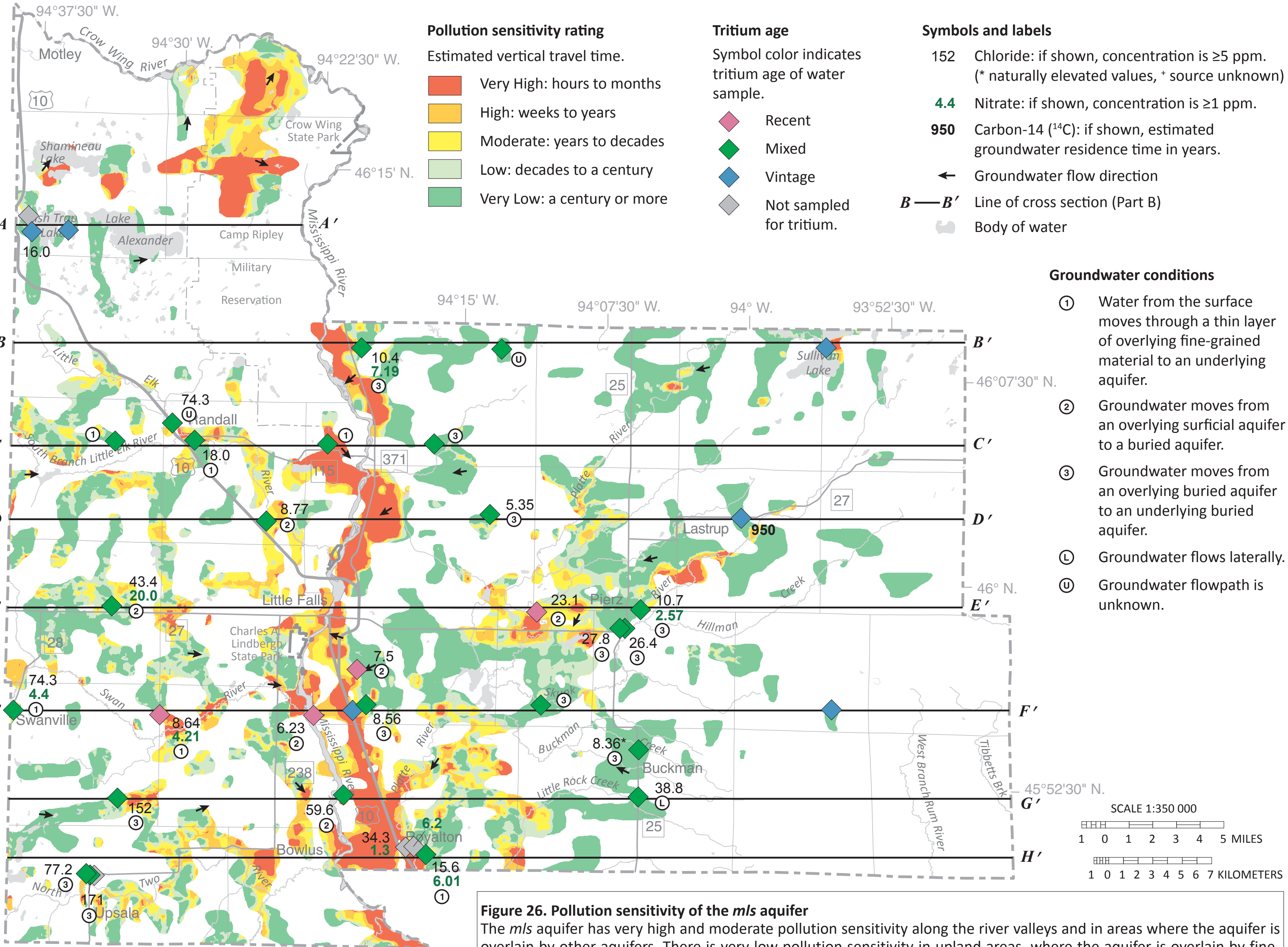


Figure 26. Pollution sensitivity of the *mls* aquifer
The *mls* aquifer has very high and moderate pollution sensitivity along the river valleys and in areas where the aquifer is overlain by other aquifers. There is very low pollution sensitivity in upland areas, where the aquifer is overlain by fine-grained sediment.

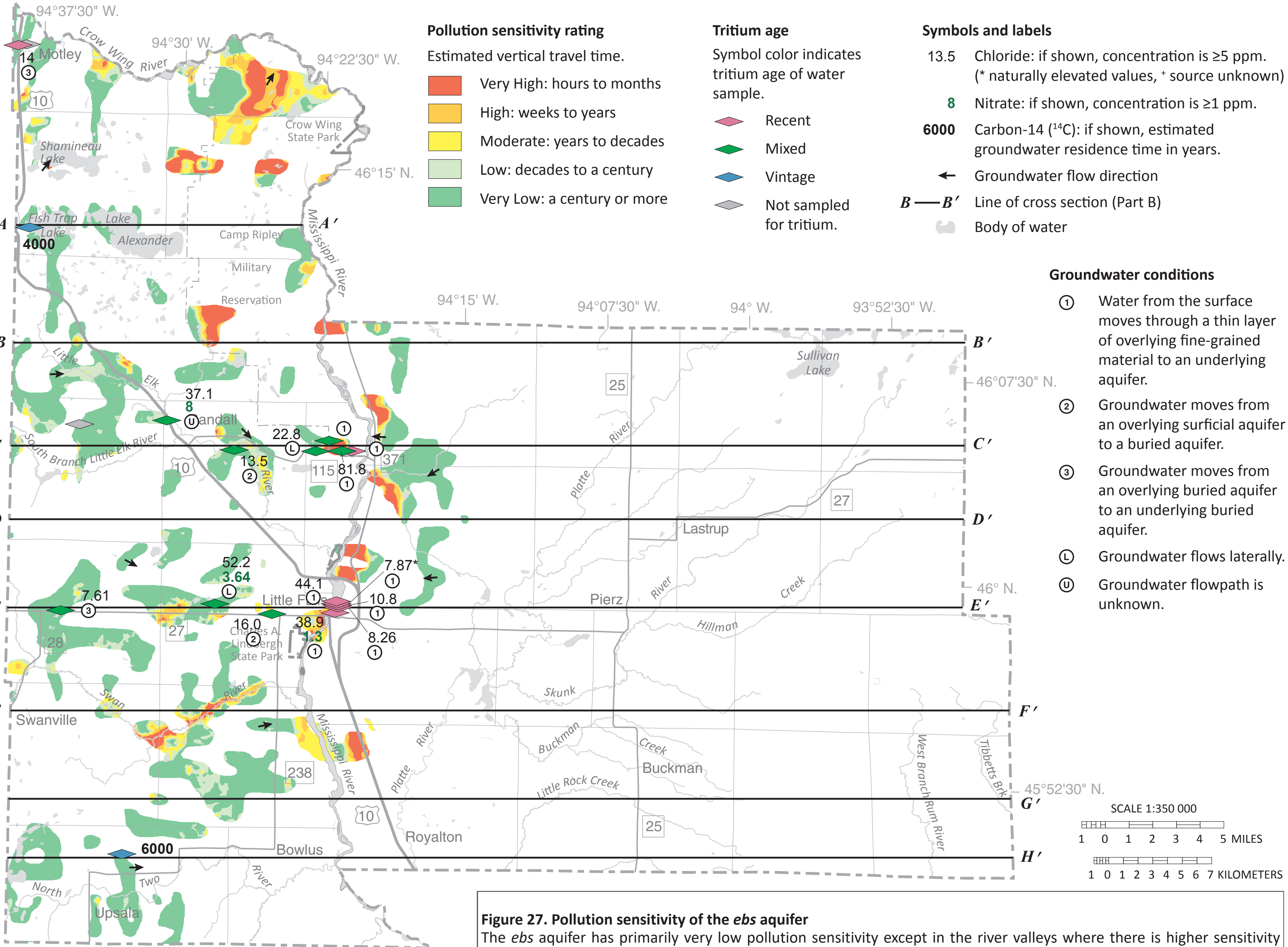


Figure 27. Pollution sensitivity of the *ebs* aquifer
The *ebs* aquifer has primarily very low pollution sensitivity except in the river valleys where there is higher sensitivity because the aquifer is not overlain by fine-grained sediment.

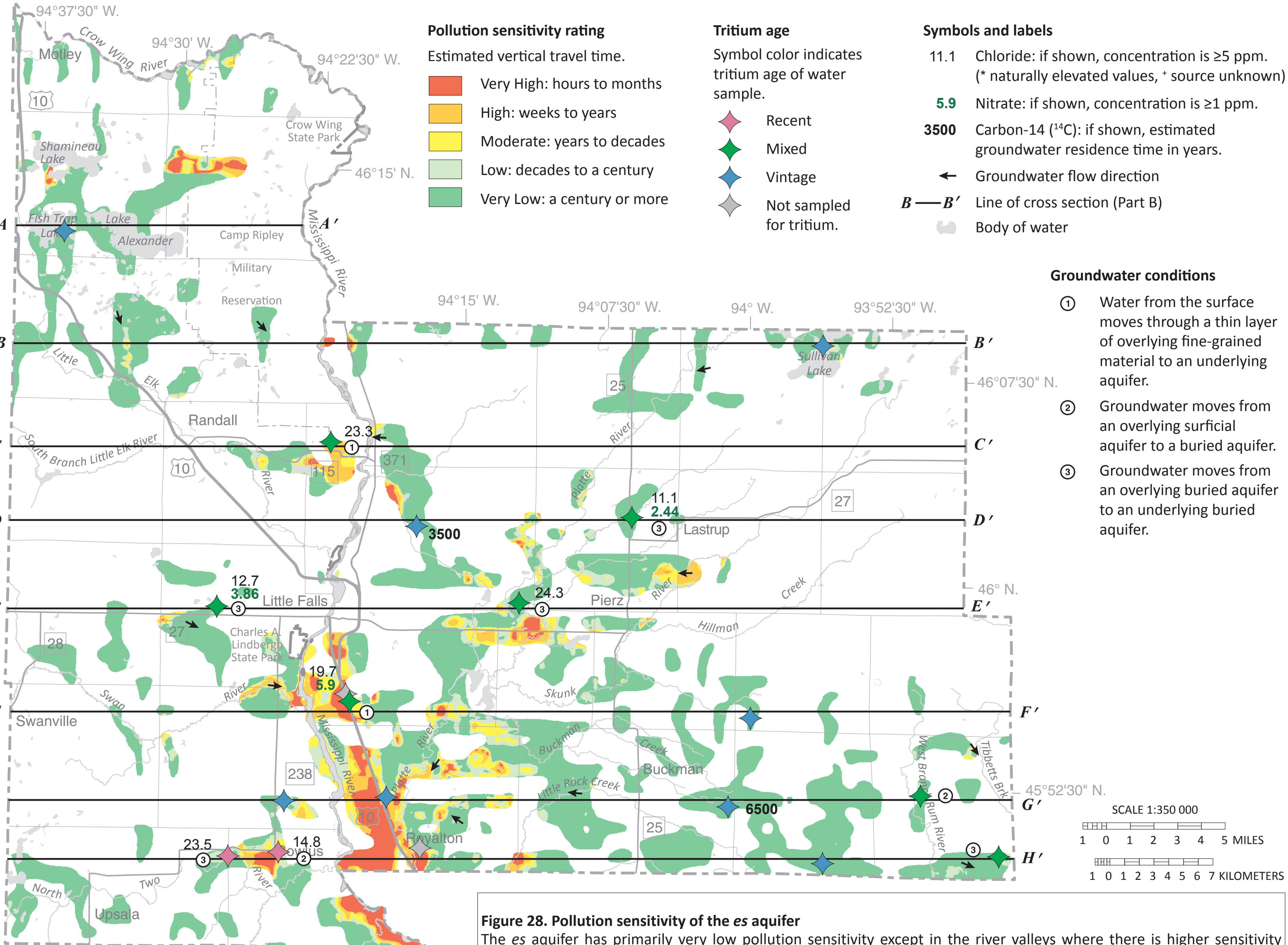


Figure 28. Pollution sensitivity of the *es* aquifer
The *es* aquifer has primarily very low pollution sensitivity except in the river valleys where there is higher sensitivity because the aquifer is not overlain by fine-grained sediment.

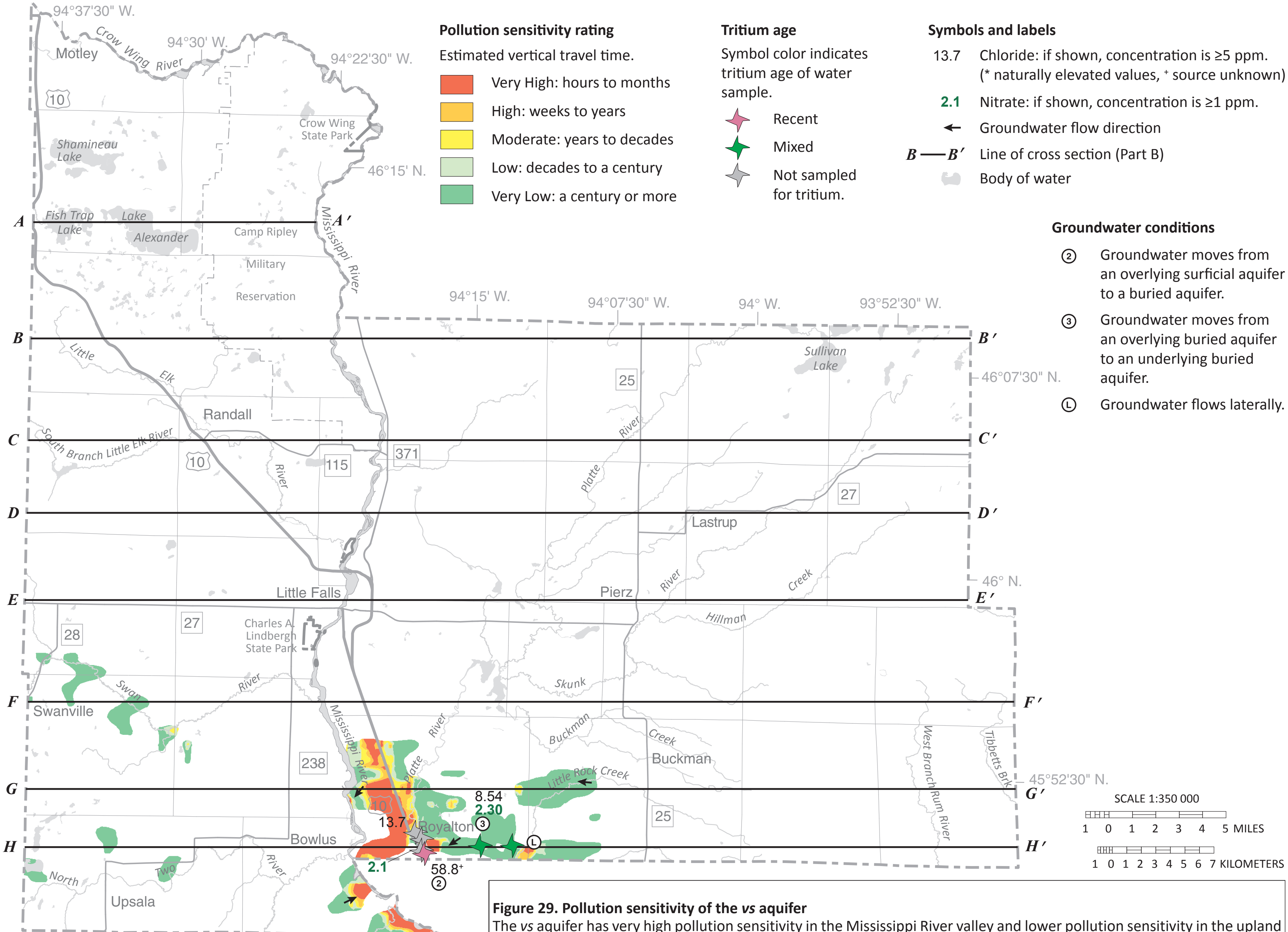


Figure 29. Pollution sensitivity of the *vs* aquifer
The *vs* aquifer has very high pollution sensitivity in the Mississippi River valley and lower pollution sensitivity in the upland areas where the aquifer is overlain by fine-grained sediment.

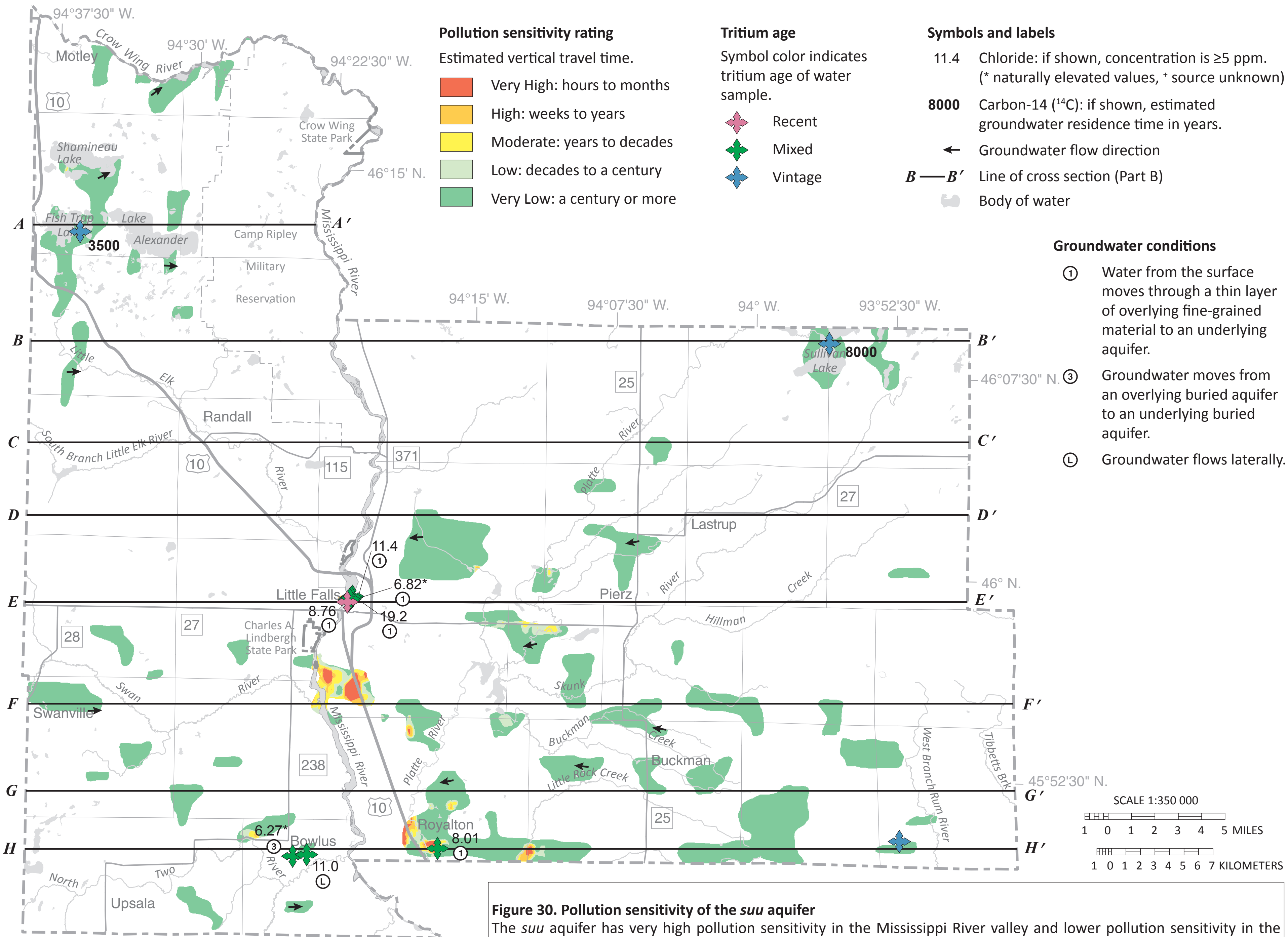


Figure 30. Pollution sensitivity of the *suu* aquifer
The *suu* aquifer has very high pollution sensitivity in the Mississippi River valley and lower pollution sensitivity in the upland areas where the aquifer is overlain by fine-grained sediment.

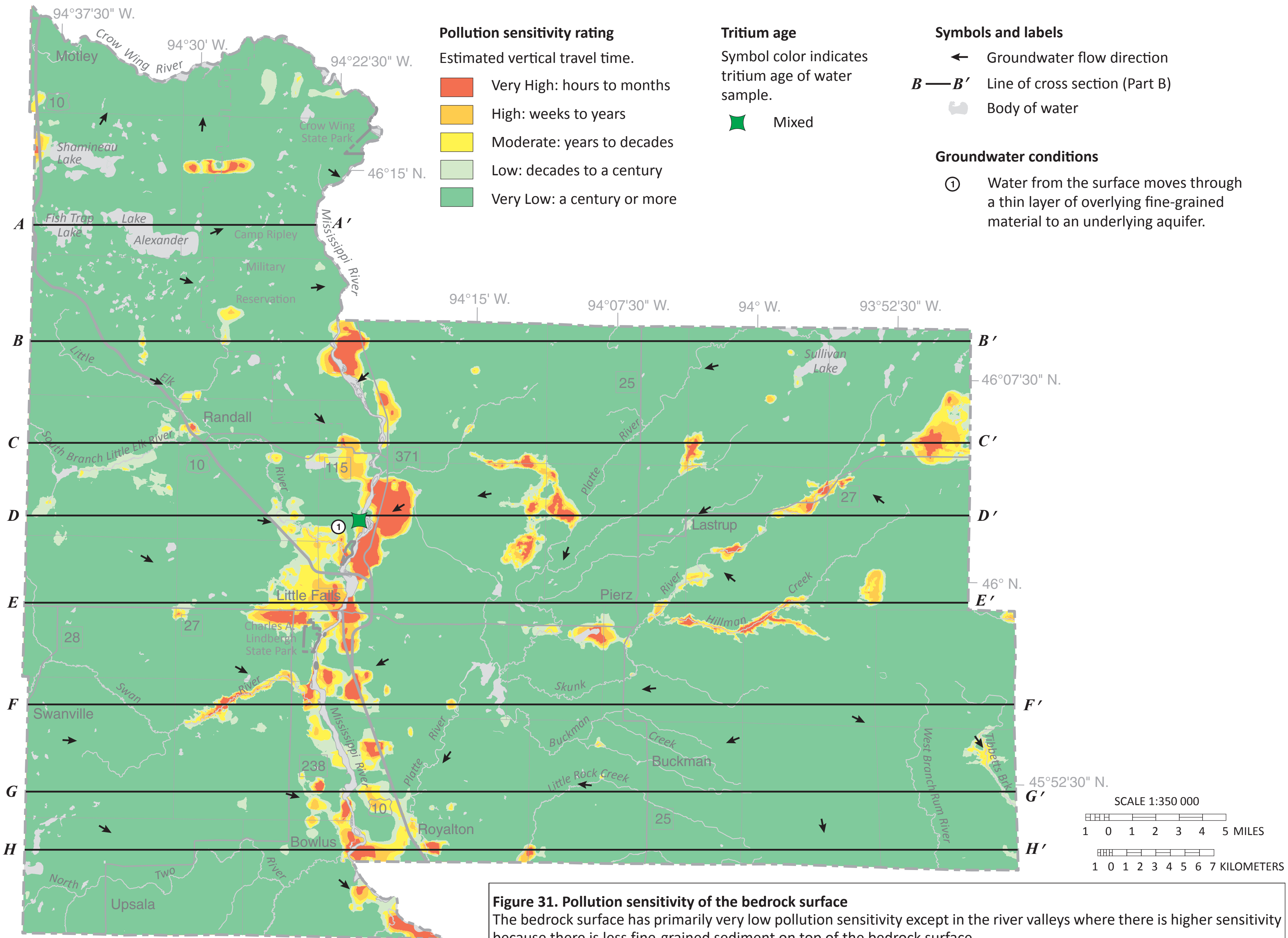


Figure 31. Pollution sensitivity of the bedrock surface
The bedrock surface has primarily very low pollution sensitivity except in the river valleys where there is higher sensitivity because there is less fine-grained sediment on top of the bedrock surface.

Hydrogeologic cross sections (Plates 7 and 8)

The hydrogeologic cross sections shown on Plates 7 and 8 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 nine cross sections were selected from a set of 67 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 a higher hydraulic conductivity. This assumption does not account for the occurrence of larger clasts (pebbles, cobble, and boulders), the potential for fine sediment to fill pore spaces, or fractures in the shallow till units.

Glacial sediment layers that act as aquitards (till units) are shown in shades of gray on Plates 7 and 8. 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 (till) (Part A, Plate 4, Table 2).

High relative hydraulic conductivity is common in many of the sandy till units in Morrison County, resulting in relatively rapid flow of water from the surface to underlying aquifers. Several tills have lower relative hydraulic conductivity, generally found west of the Mississippi River or deeper in the subsurface east of the river.

Groundwater flow direction

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

Morrison County groundwater flow, shown on the cross sections, is primarily moving toward the Mississippi River by entering the surface vertically and then moving laterally to discharge into small streams and the river. The groundwater flow directions shown on the cross sections are consistent with the water table and buried aquifer groundwater flow maps. All these figures indicate groundwater discharge to tributaries that feed the Mississippi River. There are a few areas where the groundwater primarily moves vertically or away from the Mississippi River:

- In the northern part of the county, on the western half of cross section A, there is flow out of the cross section moving toward the Long Prairie River in neighboring Todd County.
- Flow along the eastern edge of cross sections B and C is primarily vertical because of the relatively flat bedrock surface and topography in this area.
- Flow in the center of cross sections C and D, near the Platte River, has a lower flow gradient because of a bedrock valley with steep edges.
- There is a high area with flow moving in opposite directions in the eastern part of the county (along cross sections B through H). This area is a groundwater divide. Groundwater to the west of the divide is moving toward the Mississippi River and groundwater to the east is moving toward the Rum River in neighboring Mille Lacs County.

Groundwater recharge, discharge, and pollution sensitivity

Precipitation is the source of recharge to the glacial sediments covering the county, which then provides recharge to buried aquifers. Recharge occurs across the entire county, because there are aquifers or sandy tills at the surface. There are some areas where sandy surficial units are in contact with buried aquifers, allowing for greater recharge to the buried aquifers in these areas.

Some examples of this are:

- On cross sections A and B where there is a large stack of connected sands under Camp Ripley.
- Near the eastern border of the county on cross sections B and C.
- East of the Mississippi River on cross sections E through H.
- In the Mississippi River valley on all the cross sections.

Recharge can be limited in major discharge areas, where groundwater might be upwelling and sediments are already saturated. Groundwater discharge to the Mississippi River is present along all the cross sections. There is some evidence, based on the water level data, of local discharge to the following tributaries of the Mississippi River:

- Little Elk and Platte rivers on cross sections B, C, and D.
- South Branch Little Elk River on cross section C.
- Skunk River on cross sections C, D, and E.
- Swan River on cross section F.
- Tibbetts Brook on cross sections F and G.
- Little Rock Creek on cross sections G and H.

Areas with higher recharge rates are often areas with higher pollution sensitivity, as is the case in the recharge areas listed above. The chemistry data collected in those areas have more mixed and recent tritium ages and higher chloride and nitrate values from anthropogenic sources. In the last 60 years, groundwater has recharged to depths ranging from less than 50 feet and up to 165 feet.

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 96 wells in Morrison County met these conditions: 1 test in the surficial aquifer and 95 tests in buried aquifers (Figure 32 and Table 2). The highest specific capacity of 87.7 gpm/ft was calculated for a well in the *vs* aquifer, which also has the highest mean specific capacity value (36 gpm/ft) for an aquifer with more than 1 sample.

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).

Data from 13 historic aquifer tests compiled by the DNR and MDH are summarized in Table 2. All the tests were conducted in either unconfined conditions or indicated that the tills overlying the aquifers have leakage, indicating that groundwater readily moves through till in the county. Transmissivity values were summarized for 1 surficial aquifer and 12 buried sand aquifers. The surficial aquifer had a transmissivity value of 27,000 ft^2/day. Buried sand aquifer transmissivity values were variable with average values that ranged from 6,100 to 23,800 ft^2/day. Additional transmissivity data is available for the county, but was not included in this summary due to limited information about the aquifer tests and well construction.

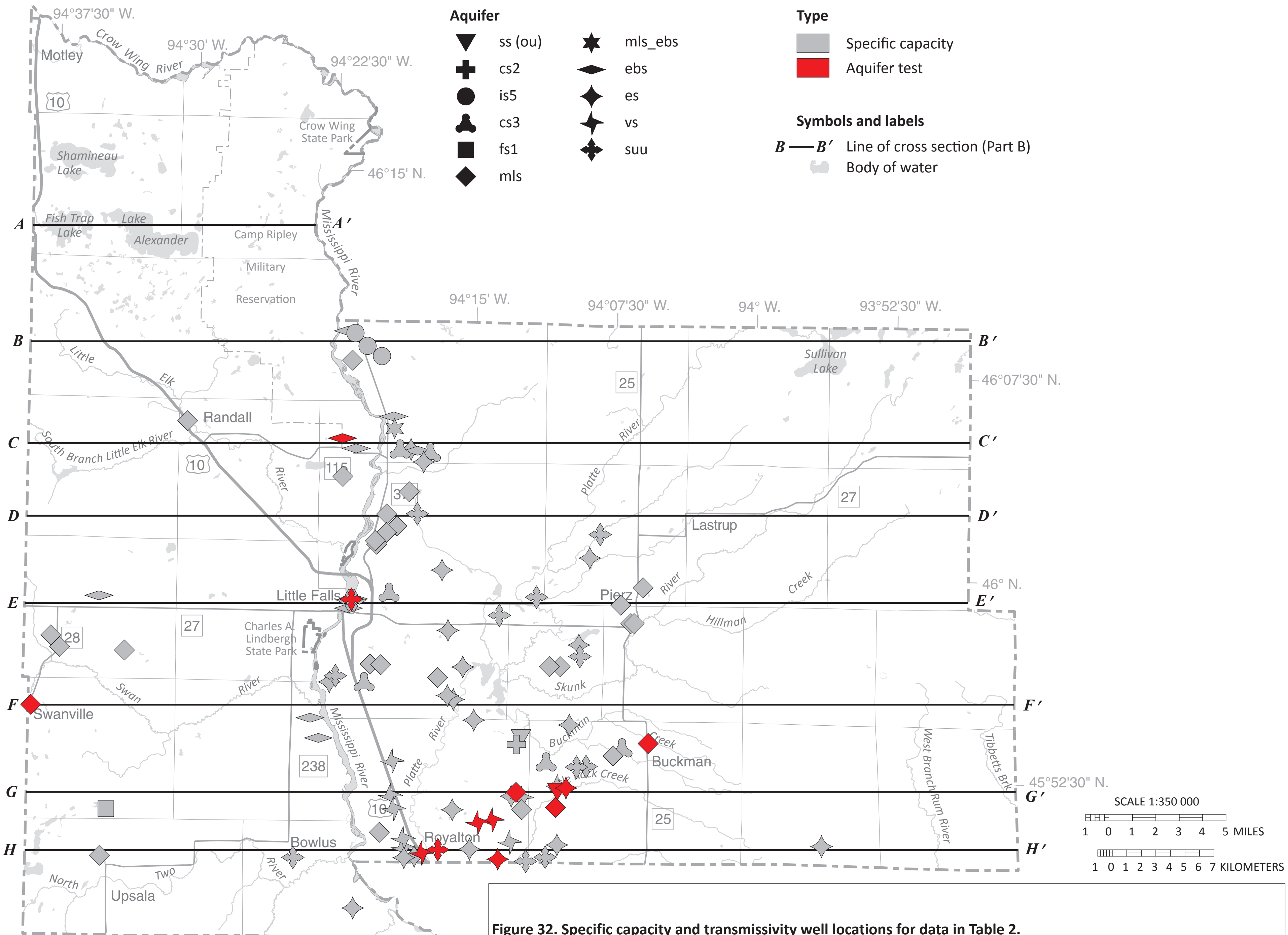


Figure 32. Specific capacity and transmissivity well locations for data in Table 2.

Table 2. Specific capacity and transmissivity of selected wells

Aquifer	Specific capacity (gpm/ft)					Transmissivity (ft^2/day)				
	Casing diam. (in.)	Mean	Min	Max	No. of tests	Casing diam. (in.)	Mean	Min	Max	No. of tests
Surficial aquifer										
ou	12	16.5	--	--	1	12	27,000	--	--	1
Buried sand aquifers										
cs2	12	37.7	--	--	1	--	--	--	--	--
is5	12	18.3	14.5	25	3	--	--	--	--	--
cs3	8–12	23.9	4.4	50	6	--	--	--	--	--
fs1	8	19.6	--	--	1	--	--	--	--	--
mls	8–12	22.2	1	76	27	8–12	16,400	800	56,000	4
mls_ebs	12	25	--	--	1	--	--	--	--	--
ebs	8–18	28.3	6.1	54.7	12	16	11,500	--	--	1
es	8–16	28.5	1.2	63.7	22	12	6,100	2,500	9,700	2
vs	12–16	36	9.6	87.7	9	12–16	10,100	2,000	23,400	3
suu	8–16	25.4	2.9	55.6	13	12	23,800	700	47,000	2

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; --, no data.

Well locations in Figure 32.

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 observation 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.

Two sets of hydrographs (Figures 34 and 35) are shown to illustrate groundwater trends through time and impacts of high capacity pumping in Morrison County. The location of the wells displayed on the hydrographs are highlighted on Figure 33.

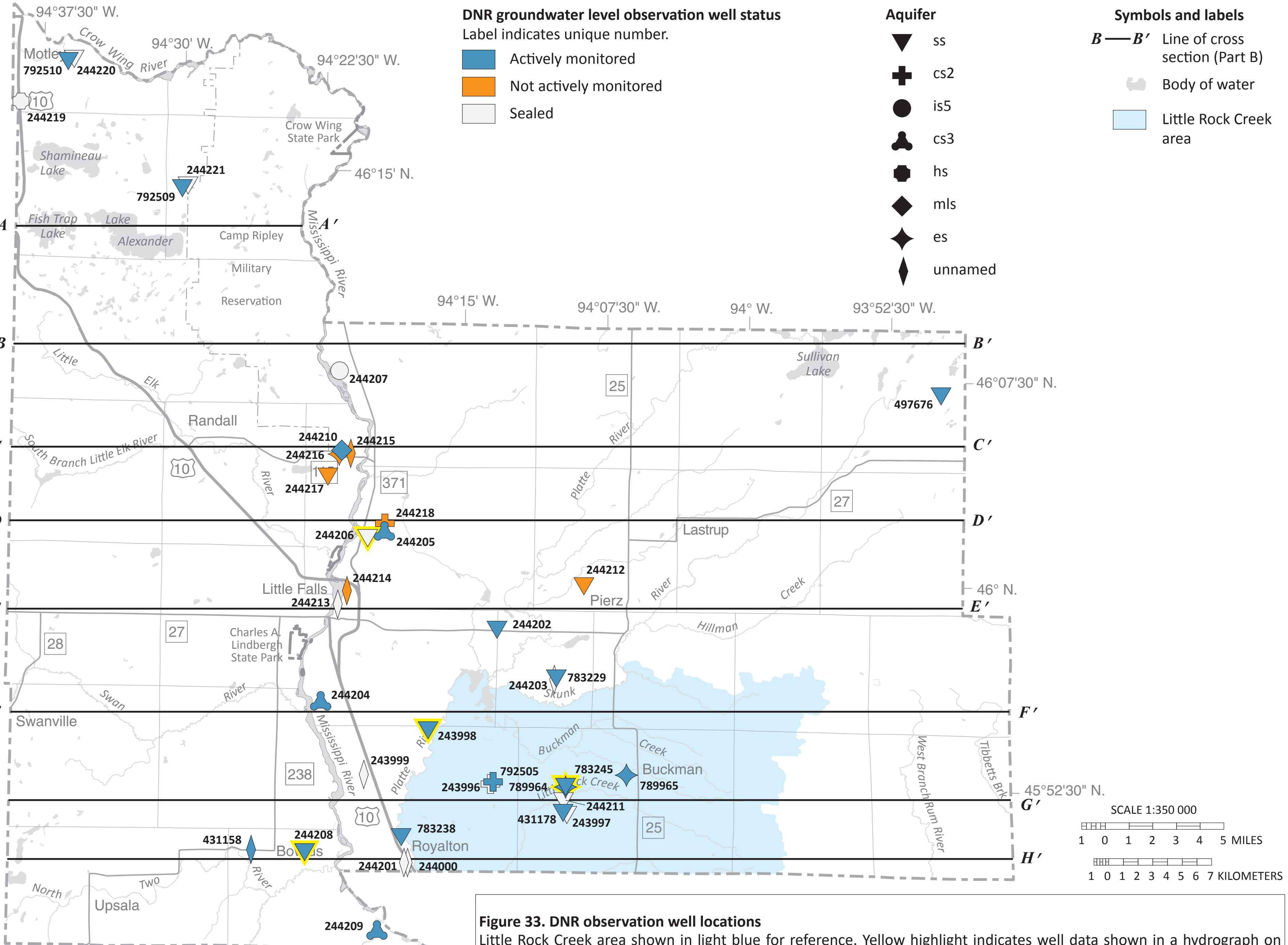


Figure 33. DNR observation well locations
Little Rock Creek area shown in light blue for reference. Yellow highlight indicates well data shown in a hydrograph on Figures 34 and 35.

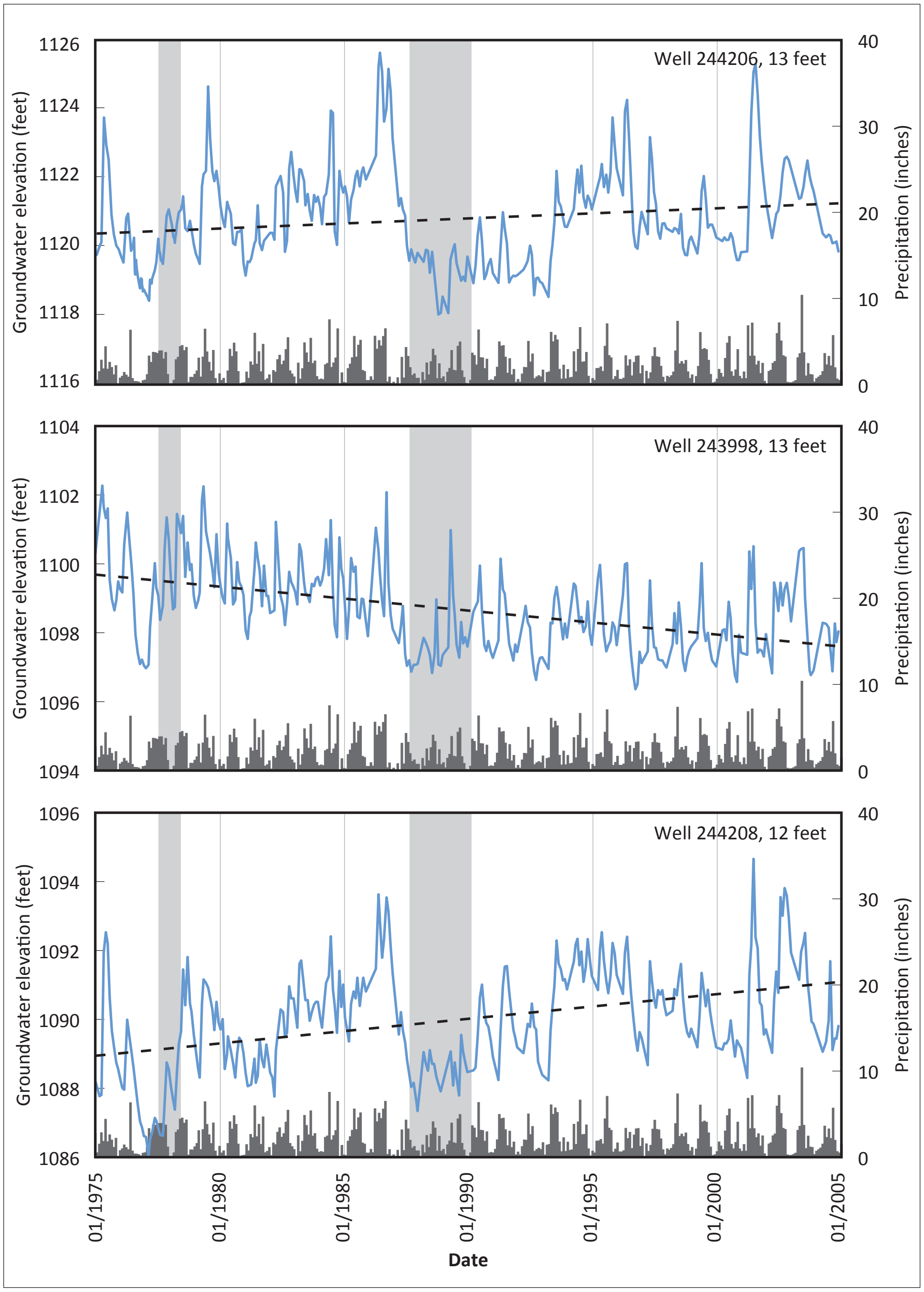


Figure 34. Long term water-table trends

Monthly precipitation from Little Falls plots as vertical bars with values between 0 and 10.36 inches (DNR, 2018c).

Groundwater elevation data (blue line) (DNR, 2018a) are from three separate water-table wells in different parts of the county. The three wells are located at the border of the Little Rock Creek area (243998), north of Little Falls (244206) and on the west side of the Mississippi River (244208) near Bowlus (Figure 33). The dashed line on each hydrograph is a best-fit linear regression of the groundwater elevation data showing the general trend through time. All the wells had 8 or more hand measurements per year during the 1975 to 2005 record.

Gray shaded areas represent times of drought identified by the Palmer Drought Severity Index (Midwestern Regional Climate Center, 2018).

All three of the wells have similar responses to long-term precipitation trends over the last 30 years. Groundwater levels rise in direct response to precipitation percolating below the surface to recharge the water table. Declines in the water-table elevation are the result of evaporation, transpiration, and discharge to surface-water features.

Each well shows a drop in water levels due to the 1987–1989 drought. Both 244206 and 244208 recovered to pre-1988 levels around 1994. Well 243998 dropped in response to the drought but did not recover to pre-drought levels.

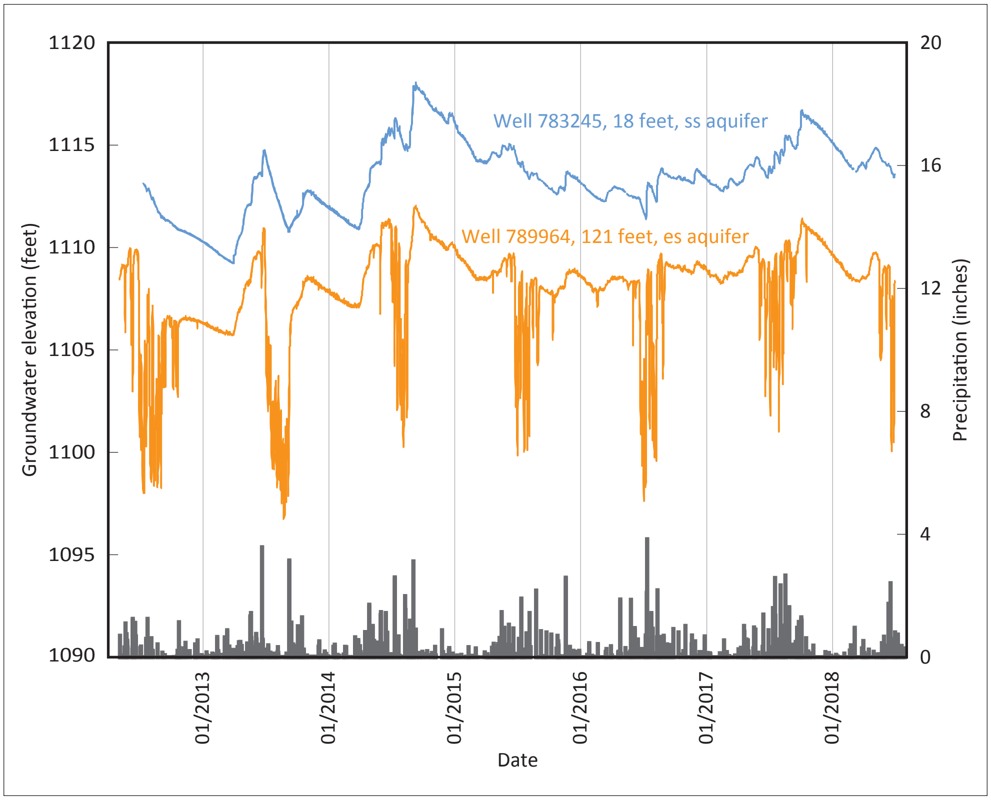


Figure 35. Similar fluctuation to long-term precipitation trends and pumping impacts

Daily precipitation from Little Falls plots as vertical bars with values that range from 0 to 3.84 inches (DNR, 2018c).

Groundwater elevation data (DNR, 2018a) is shown for a well nest in the Little Rock Creek area near Buckman (Figure 33). The shallow water-table well at this location is 18 feet deep and the deeper well is completed in a buried sand aquifer (*es*) at a depth of 121 feet. Both of the wells have hourly water elevation readings collected over a six-year period of record.

Water levels in both of the wells fluctuate in response to daily precipitation, rising in direct response to water infiltration. Declines in the groundwater elevation are the result of evaporation, transpiration, discharge to surface-water features in the shallow well, and pumping. Short-term declines in water level with recovery are present in the deeper well during the summer, when nearby wells are being pumped for irrigation.

The well nest is useful for determining vertical groundwater flow direction. Downward flow is indicated by the decline of groundwater elevation with increasing depth. The well nest displays a connection between the *es* aquifer and the water table. As seasonal pumping takes place from the *es* aquifer in the summer there is a muted response to precipitation that takes place in the water-table aquifer at the same time. The nest shows that while pumping is taking place, the water levels do not have a discernible trend over the relatively short time period.

Groundwater use

A water-use appropriation permit from the DNR is required 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 and regulate which aquifers are being used and for what purpose. Permits require water usage to be reported annually. Information is recorded using Minnesota Department of Natural Resources Permitting and Reporting System (MPARS), which helps the DNR track the volume, source aquifer, and type of water use.

Morrison County reported water use of large capacity users for 2016 is categorized in Table 3 and Figure 36 by type of water use and aquifer type (DNR, 2018b). Agricultural crop irrigation dominates the reported water use with 82 percent of the total usage, primarily from buried sand aquifers. The second largest use category (approximately 12 percent) is municipal and public water supply, primarily from buried sand aquifers (in some areas these buried aquifers are overlain by stacks of sand). These two water uses collectively made up over 94 percent of the permitted water used in 2016.

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. There are a little under 6,000 wells in the county that have an identifiable aquifer. Of those wells, approximately 87 percent are used for domestic use, 7 percent are used for irrigation, and 2 percent are used for public water supplies.

Table 3. Reported 2016 water use from DNR groundwater permit holders

Aquifer	Number of wells	Agricultural crop irrigation	Golf course irrigation	Landscaping/athletic field irrigation	Livestock watering	Municipal/public water supply	Nursery irrigation	Pollution containment	Sand and gravel washing	Total 2016 (mgy)	Total 2016 (percent)*
Surficial aquifer											
ss	7	70	--	--	--	--	6	--	--	76	1.6
Buried sand aquifers											
cs2	11	215	--	--	--	--	--	48	--	263	5.4
is5	4	32	28	--	--	--	--	--	--	60	1.2
cs3	25	347	--	--	--	2	--	--	36	385	7.9
hs	2	6	--	--	--	--	--	--	--	6	0.1
brs	1	12	--	--	--	--	--	--	--	12	0.2
fs1	2	7	--	--	--	--	--	--	--	7	0.1
mls	88	1,177	23		16	62	--	82	--	1,360	27.8
mls_ebs	1	52	--	--	--	--	--	--	--	52	1.1
fs2	2	18	--	--	--	--	--	--	--	18	0.4
ebs	32	192	16	5	8	270	--	--	--	491	10.0
es	81	1,034	--	--	18	10	--	--	--	1,062	21.7
vs	19	326	--	--	--	--	--	--	--	326	6.7
suu	24	431	--	--	--	251	--	--	--	682	13.9
unnamed	6	90	--	--	--	--	--	--	--	90	1.8
Total (mgy)	--	4,009	67	5	42	595	6	130	36	4,890	
Total (percent)*	--	82	1.4	0.1	0.9	12.2	0.1	2.7	0.7		

*Percentage may not equal 100 due to rounding

Dash marks (--) indicate no data in those categories.

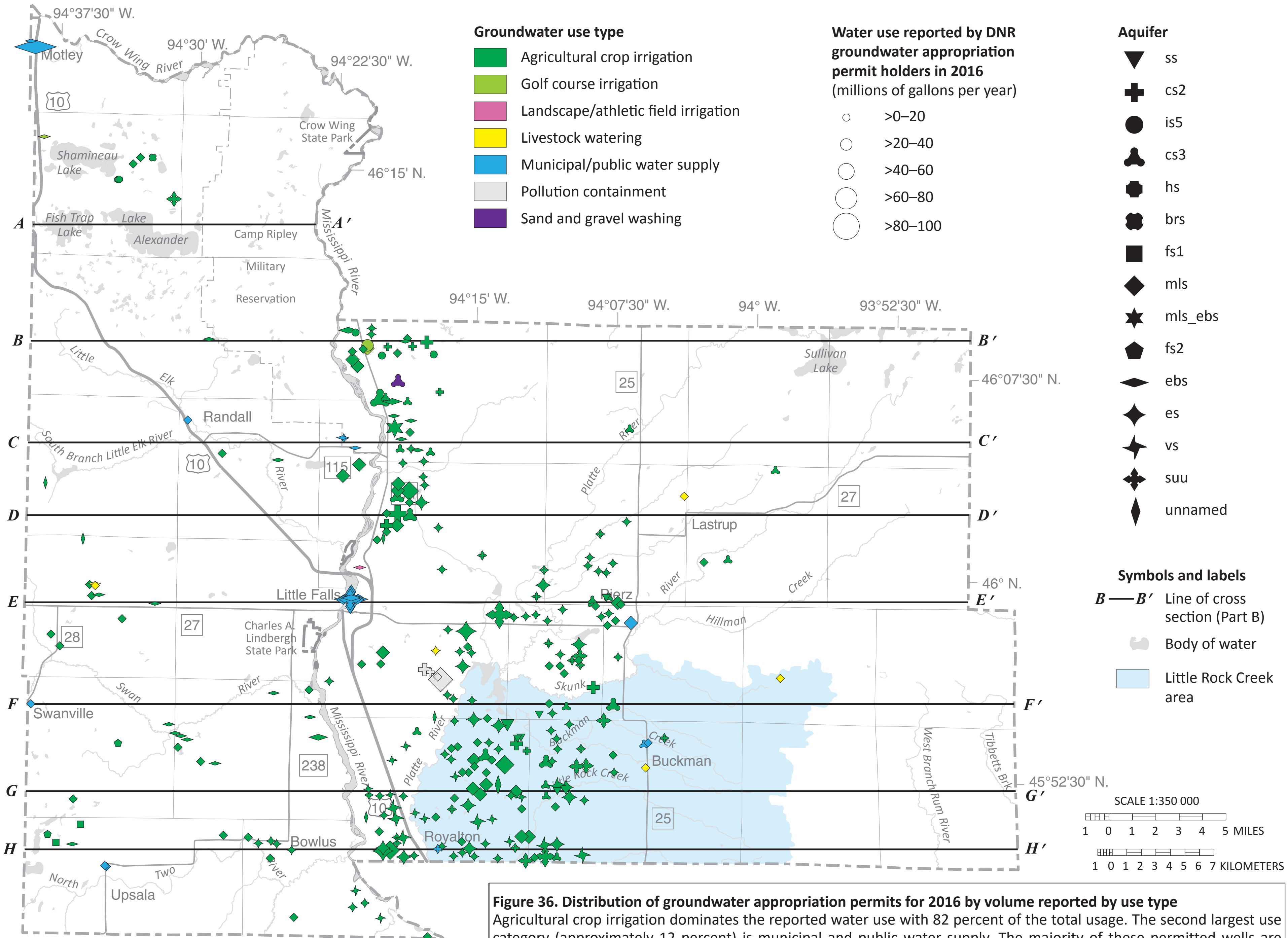


Figure 36. Distribution of groundwater appropriation permits for 2016 by volume reported by use type

Agricultural crop irrigation dominates the reported water use with 82 percent of the total usage. The second largest use category (approximately 12 percent) is municipal and public water supply. The majority of these permitted wells are pulling from sandy areas to the east of the Mississippi River, including the Little Rock Creek area.

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Glossary

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

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

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

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

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

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

buried aquifer—a body of porous and permeable sediment or bedrock which is buried beneath the ground surface by a low permeability layer.

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

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

clast—an individual constituent, grain, or fragment of a sediment or rock, produced by the mechanical or chemical disintegration of a larger rock mass.

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

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

drumlin—An elongated mound or ridge of glacial till built under the margin of glacial ice and shaped by its flow. Its longer axis is parallel to the direction of movement of the ice. It usually has a blunt nose pointing in the direction from which the ice approached and a gentler slope tapering in the other direction.

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

flowpath—the subsurface course that a water molecule follows; the direction of movement of water.

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.

glacial—relating to or derived from a glacier.

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.

hydraulic—relating to water movement.

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

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

hydrograph—a graph showing characteristics of water with respect to time. A stream hydrograph commonly shows rate of flow. A groundwater hydrograph shows water level, head, or water-use volume.

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 each isotope has a different number of neutrons.

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

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

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

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

provenance—the place of origin of a glacier.

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

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

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

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

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

stable isotope—chemical isotopes that are not radioactive.

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

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

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

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.

upgradient—an area that has a higher potentiometric surface (hydraulic head) than a reference point of interest.

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

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

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

Appendix A

Groundwater field sample collection protocol

Groundwater samples were collected from an outside faucet or hydrant. The wells were purged prior to sampling to remove stagnant water from the well bore and plumbing system. Samples were collected after field parameters such as temperature, conductivity, dissolved oxygen, and pH had stabilized. Each was filtered and preserved according to protocols listed below and submitted to laboratories for analysis. Samples were analyzed by the DNR staff; the Minnesota Department of Agriculture (MDA); the Minnesota Department of Health (MDH); the University of Minnesota Department of Earth Sciences Laboratory (U of M); or the University of Waterloo Environmental Isotope Laboratory (Waterloo). The well owners received a copy of the results including some background reference information regarding their meaning.

For additional information, contact the County Groundwater Atlas program.

Appendix Table A. Groundwater field sample collection and handling details

Parameter	**Tritium**	**^{18}O Deuterium**	**Nitrate/ Nitrite & Total Phosphorus**	**F, Cl, SO_4**	**Metals**	**Bromide**	**Alkalinity**	**^{14}C**
Lab	Waterloo	Waterloo	MDA	MDA	MDA	MDH	DNR	U of M
Sample container	500 ml HDPE	60 ml HDPE	250 ml plastic	250 ml plastic	250 ml plastic	125 ml plastic	500 ml plastic	30 gallon barrel
Head space	yes	yes	yes	yes	yes	yes	no	yes
Rinse	no	no	yes*	yes*	yes*	yes*	yes**	no
Filter (micron)	no	no	0.45	0.45	0.45	0.45	no	no
Preservative	no	no	5 ml 10% H_2SO_4 (yellow cap)	no	2.5 ml 20% HNO_3 (red cap)	no	no	NH_4OH to pH 8.5
Refrigeration	no	no	yes	yes	yes	yes	yes, if not analyzed onsite	no
Holding time	long	long	28 days	28 days	6 months	28 days	24–48 hours	years
Field duplicate	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	none
Field blank	none	none	1 for every 20***	1 for every 20***	1 for every 20***	1 for every 20***	none	none
Storage duplicate	yes	yes	no	no	no	no	no	no

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

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

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

Appendix B

Tritium values from precipitation and surface water

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

1. Precipitation composites were collected at the Minnesota DNR MNgage climatology monitoring station MWDM5 in Maplewood (Twin Cities metropolitan area). Samples were composited over the course of 30-day periods between spring and fall over the years 2012 through 2018.
2. A lake-water sample was collected at the Fish Trap Lake surface several feet from shore.

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

For additional weather station information, contact:

- MNgage (climateapps.dnr.state.mn.us/HIDENsityEdit/HIDENweb.htm)

Appendix Table B-1. Enriched tritium results

Sample date range	Tritium (TU)	Analytical error	Sample type
MNgage precipitation station (MWDMS)			
05/21/2012–06/20/2012	8.7	0.7	Precipitation composite
09/30/2012–10/30/2012	6.7	0.7	Precipitation composite
05/09/2014–06/09/2014	7.0	0.7	Precipitation composite
10/01/2014–10/31/2014	6.7	0.7	Precipitation composite
05/01/2015–05/31/2015	5.3	0.6	Precipitation composite
08/17/2016–09/16/2016	8.3	0.8	Precipitation composite
04/01/2017–04/30/2017	8.1	0.7	Precipitation composite
09/06/2017–10/06/2017	6.5	0.6	Precipitation composite
04/17/2018–05/16/2018	11.8	1.2	Precipitation composite
10/03/2018–11/01/2018	3.7	0.5	Precipitation composite
Fish Trap Lake, Morrison County			
10/27/2016	8.3	0.8	Limnetic zone

Tritium age of historic groundwater samples

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

The residence time is classified for the time the sample was collected. Historic tritium unit (TU) values change over time because of tritium's relatively short half-life of 12.32 years (Lucas and Unterweger, 2000). Historic values were converted to coincide with the time of samples collected later for this atlas as shown in Table B-2.

The Cold War era classification is a special case and implies that groundwater sampled for this atlas infiltrated into the ground in the 1960s. The Cold War era classification is only assigned to samples collected contemporaneously with this atlas (in 2015). All historic data (pre-2015) previously classified as Cold War era is now classified as recent tritium age.

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

	Sampling periods for tritium		
Tritium age	**2015**	**2013–2014**	**2012 or before**
Cold War era	>15 TU	NA	NA
Recent	≥8 to 15 TU	≥8 TU	≥10 TU
Mixed	>1 to <8 TU	>1 and <8 TU	>1 and <10 TU
Vintage	≤1 TU	≤1 TU	≤1 TU

DEPARTMENT OF NATURAL RESOURCES

500 Lafayette Road
St. Paul, MN 55155-4025
888-646-6367 or 651-296-6157
mndnr.gov

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

Funding for this project was provided by the following:

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

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

CLEAN WATER LAND & LEGACY AMENDMENT