Groundwater Atlas of Redwood County, Minnesota

County Atlas Series C-36, 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

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County Atlas Program

The Minnesota County 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 components are available online.

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

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

Part B Groundwater was published 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 introduction 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, Redwood County Geologic Atlas, Part A, 2016. Universal Transverse Mercator projection, zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion Factors

1 inch per hour = 7.056×10^{-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

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Groundwater Atlas of Redwood County, Minnesota

by James A. Berg and Vanessa M. Baratta

Executive summary

This report and the accompanying plates are Part B of the **Redwood** County Atlas. It describes the groundwater characteristics of the county and was produced by the Minnesota Department of Natural Resources (DNR). It builds on the geology described in Part A, which was 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 flow of the groundwater within the county. This information can be used to make land-use decisions that take into account aquifer sensitivity, water quality, and sustainability.

This **report** details the methods, results, and interpretations for the county. Plate 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 sets the stage for the detailed sections that follow.

Redwood County is located in southwestern Minnesota (Figure 1) with land use that is a mix of agricultural, rural, and small towns. The population in 2017 was approximately 15,000 (U.S. Census Bureau, 2018). The county lies within two portions of the Minnesota River watershed (Yellow Medicine and Mankato) and the Redwood and Cottonwood river watersheds (Figure 2). The Minnesota River forms the northeastern border of the county.

Redwood County is in the northern continental United States and is characterized as a cool, subhumid climate with a large temperature difference between summer and winter seasons. Average temperatures are approximately 70 degrees Fahrenheit June through August, and 18 degrees Fahrenheit December through February (NOAA, 2018). Average annual precipitation is approximately 28 inches, placing it in the middle of the statewide range of 20 to 36 inches.

Geology and physical hydrogeology (pages 4–16) describes characteristics of geologic units in the county. Aquifers and aquitards are identified by their hydrostratigraphic characteristics and corresponding geologic units from Part A. Groundwater elevation maps give a broad look at the direction of groundwater flow in unconfined conditions (water-table elevation) and confined conditions (potentiometric-surface elevation).

The county comprises three general types of topographic terrain (Plate 3, Figure 1) illustrated by elevation ranges. The low elevation, low topographic relief area of the Minnesota River valley forms the northeastern boundary. The medium elevation range, low topographic relief area in the central part of the county was a highly eroded pathway of multiple glaciations that can be traced northwest into the southern portions of Saskatchewan and Manitoba (Plate 3, Figure 3). This type of terrain covers most of the county. The higher elevation area in the southwest represents the edge of the highly eroded glacial pathway. The land in this area slopes to the northeast away from the less eroded Prairie Coteau region to the southwest.

- **Water table** (pages 4–6) elevations in Redwood County cover a wide range of values with the lowest values in the Minnesota River valley. A broad area of similar values and low gradients exists between the Minnesota River valley and the Cottonwood River, and the highest elevations with higher gradients southwest of the Cottonwood River. Groundwater flow directions are regionally toward the Minnesota River and locally toward the Redwood and Cottonwood rivers and Sleepy Eye Creek. Water-table depths are shallow (0–20 feet) across most of the county. Some deeper water-table conditions likely exist along the Minnesota and Redwood river bluff areas and in the southwestern portion of the county.
- **Buried sand and bedrock aquifers** (pages 7–16) show potential groundwater flow patterns that are similar to groundwater flow in the water table. The groundwater flows to the northeast toward the Minnesota River and locally toward the Redwood and Cottonwood rivers.

Water chemistry (pages 17–25 and Plate 6) provides information about the water source, flow path, travel time, and residence time of groundwater. The groundwater chemistry supports the results of the pollution sensitivity models and is used to identify areas of interest, such as those with high pollution sensitivity or elevated levels of potentially harmful chemicals.

- **Chloride** is generally not a significant contaminant in Redwood County from the buried sand and bedrock aquifers. Seven percent of the collected samples had elevated (greater than or equal to 5 parts per million [ppm]) anthropogenic (human caused) chloride. However, none of those samples equaled or exceeded the secondary drinking water standard.
- **Nitrate** was not commonly found. Only 4 percent of the collected samples had elevated concentrations (greater than or equal to 1 ppm).
- **Arsenic** is a naturally occurring contaminant in the county with 71 percent of collected samples exceeding the method detection limits, and 30 percent exceeding the Maximum Contaminant Limit (MCL) of 10 parts per billion (ppb).
- **Manganese** is a naturally occurring contaminant in the county with 68 percent of collected samples greater than or equal to the Health Based Value (HBV) of 100 ppb. These values above the HBV were found throughout the county and in most of the mapped aquifers.
- **Sulfate** is a naturally occurring groundwater constituent with 70 percent of collected samples exceeding the Secondary Maximum Contaminant Level (SMCL) of 250 ppm.
- **Carbon-14** residence times in aquifers reflected the wide range of groundwater conditions in the county, ranging from less than 50 to greater than 40,000 years.

The **pollution sensitivity** (pages 26–43) of an aquifer is estimated based on the time it takes water to flow through various types and thicknesses of soils and geologic materials. Pollutants are assumed to travel with water at the same speed. The ratings are modeled with different methods for the 1) near surface materials and 2) the buried sand and gravel aquifers and the bedrock surface. The model results are evaluated by comparing the pollution sensitivity ratings to chemical constituents such as tritium (^{3}H) and carbon-14 (^{14}C) data for residence time, and to inorganic chemicals for contamination.

- Near-surface materials (pages 26–28) are primarily very low and low pollution sensitivity, across the entire county. Moderate sensitivity exists in areas where glacial outwash is at the surface near the larger rivers (Minnesota, Redwood, and Cottonwood), and smaller streams including Sleepy Eye Creek.
- Buried sand and gravel aquifers (pages 29–39) exhibit limited areas of moderate to very high pollution sensitivity. Some of these higher sensitivity areas are found in river valleys. Very low to low sensitivity are the most common ratings with the exception of the uppermost buried sand and gravel aquifer.
- Bedrock aquifers (pages 29–33, 40–43) are predominantly Cretaceous sandstone. However, they are typically not at the bedrock surface and are mostly covered by thick glacial till. The bedrock surface mostly has a very low pollution sensitivity with the exception of areas near the Minnesota, Redwood, and Cottonwood rivers and in some areas of the western part of the county where the bedrock surface is shallow.

Hydrogeologic cross sections (pages 44–45, Plates 7 and 8) illustrate important variations and patterns of groundwater flow direction and gradient, residence time, distribution of chemicals, and groundwater to surface-water connections. The cross sections show that the groundwater flow is initially downward, and then laterally toward rivers. In many areas recharge to the deeper aquifers can take a very long time. The residence time can be hundreds or thousands of years where focused recharge does not occur through interconnected buried sand and gravel aquifers.

Aquifer characteristics and groundwater use (pages 46–49) summarizes specific capacity tests, aquifer tests, water use records, and groundwater level monitoring data for each aquifer. These data can be used to characterize aquifer recharge in the county and plan for new well installations. The highest volume use is from the buried sand and gravel aquifers, followed by water table, and then Cretaceous sandstone. The most common water use is for municipal/public water supply followed by livestock watering and industrial processing. There are approximately 1,500 nonregulated wells in the county. By numbers of wells, most well use is for domestic water supply, followed by public water supply. Minor categories include commercial, industrial, and irrigation.

Figure 1. Redwood County, Minnesota

Geology and physical hydrogeology

Surficial aquifers

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

Approximately 11,500 years ago the present-day Minnesota River valley was created by a glacial meltwater river (glacial River Warren) that drained southeastward from glacial Lake Agassiz (northwestern Minnesota and Canada). Thick sand and gravel deposits (current aquifers) associated with this major drainage exist in and near the Minnesota River valley especially in the Redwood Falls area and to the east (map unit Qsw). Other thin sand and gravel outwash deposits include the Qs unit. This unit was deposited by much smaller and narrower meltwater streams across the county. Most of these glacial stream routes are currently occupied by the present-day streams and creeks, including the Redwood and Cottonwood rivers and Sleepy Eye and Dutch creeks. These post-glacial streams and creeks deposited a thinner and generally finer-grained layer of sediment (alluvium, Qa), which is superimposed on, or adjacent to, most of the glacial outwash sediment.

Water table

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

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

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

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

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

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

The water table is generally a subdued expression of surface topography. Groundwater flow is generally from local high elevation areas, through the underlying aquifers and then to streams, lakes, and wetlands. Use of the surficial sand aquifer is limited to 5 percent by number of wells. Water-table elevations in the county cover a wide range of values with the lowest values in the Minnesota River valley. A broad area of similar values and low gradients are characteristic of the area between the Minnesota River valley and the Cottonwood River. The highest elevations, with higher gradients, are southwest of the Cottonwood River. Groundwater flow directions are regionally toward the Minnesota River and locally toward the Redwood and Cottonwood rivers and Sleepy Eye Creek. Water-table depths are shallow (0–20 feet) across most of the county. The water table may be deeper along the Minnesota and Redwood river bluff areas and in the southwestern portion of the county.

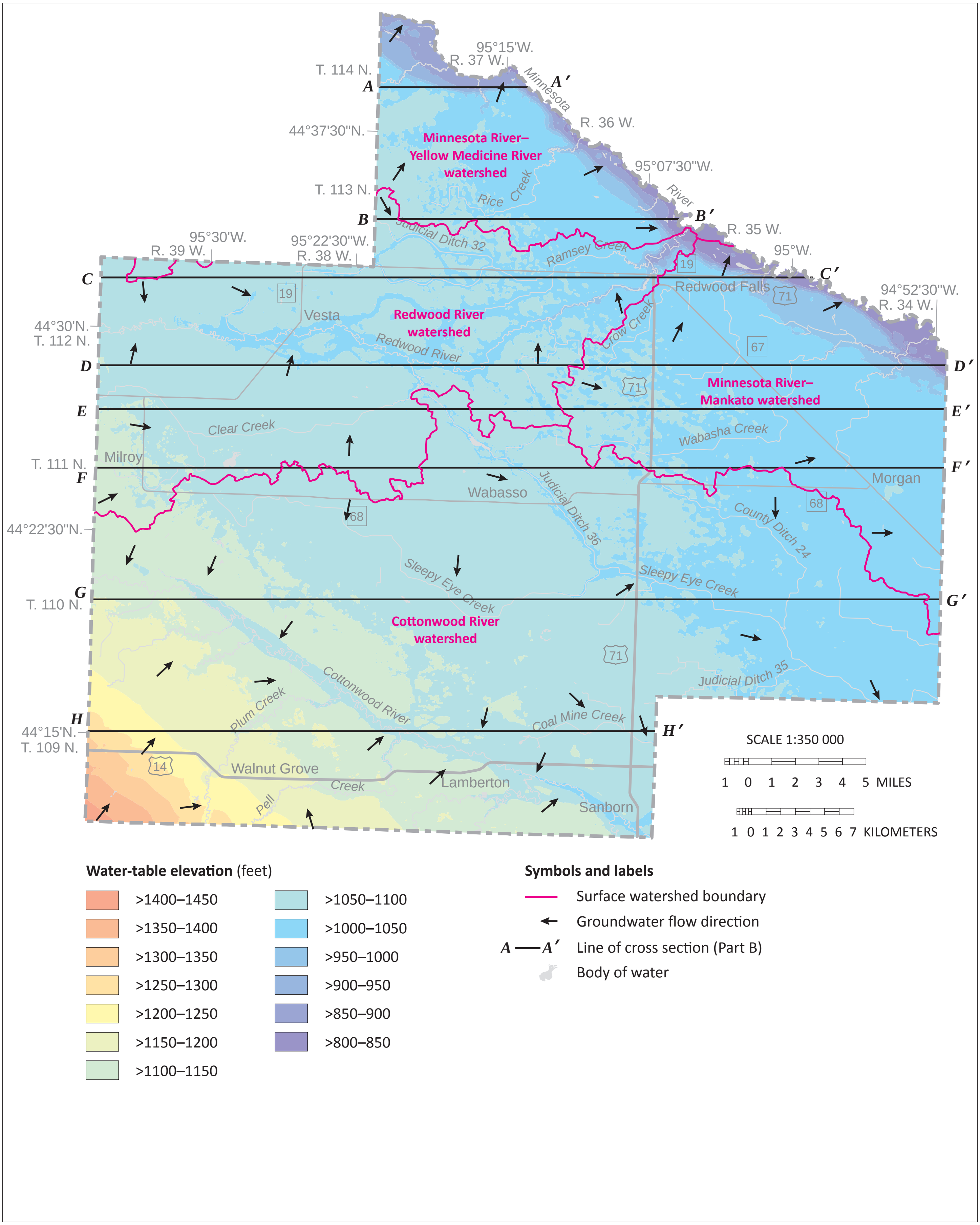


Figure 2. Water-table elevation and groundwater flow directions

Groundwater in the water table flows regionally toward the Minnesota River and locally toward the Redwood and Cottonwood rivers and Sleepy Eye Creek.

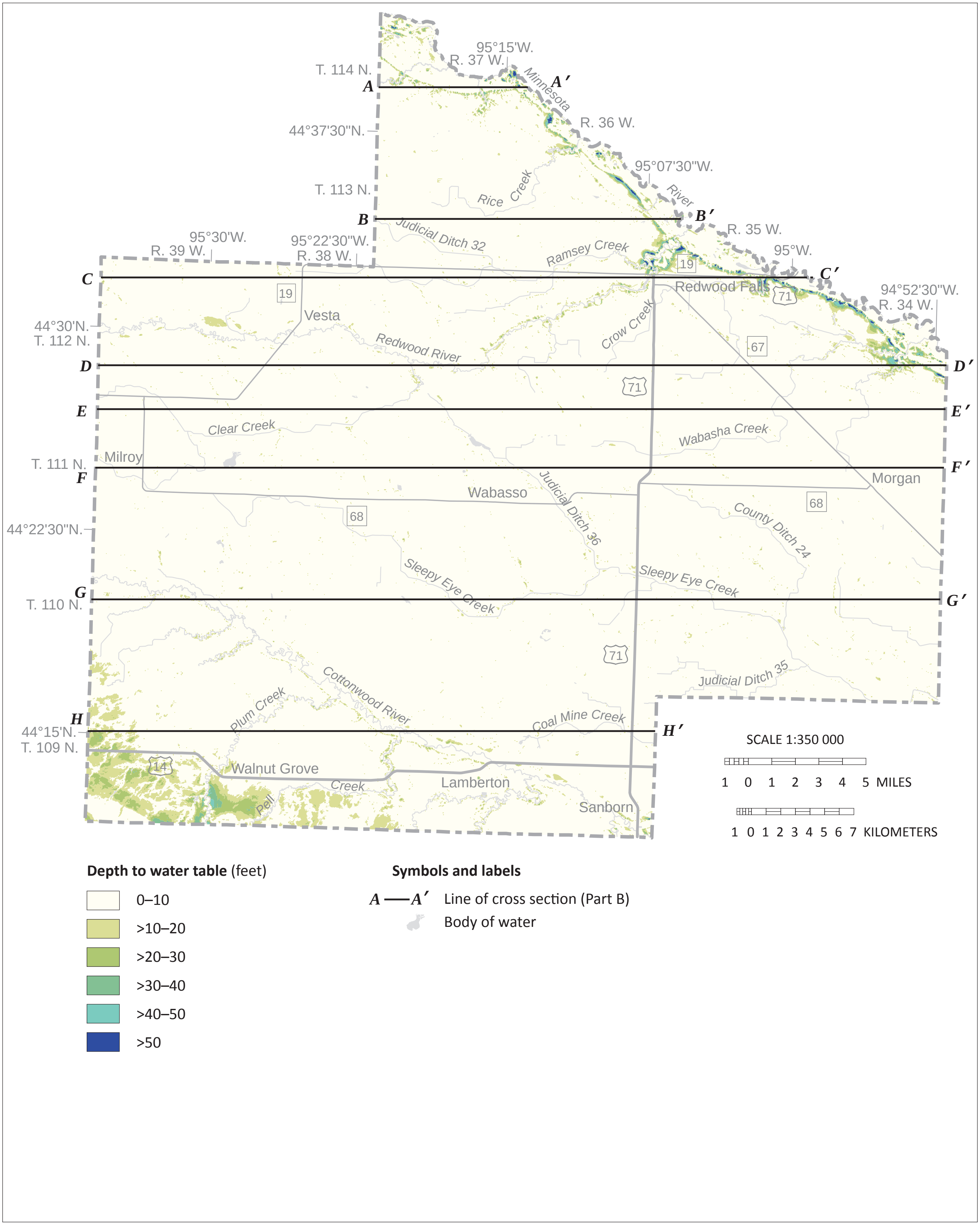


Figure 3. Depth to water table

Water-table depths are shallow (0–20 feet) across most of the county. The water table may be deeper along the Minnesota and Redwood river bluffs and in the southwestern portion of the county.

Buried aquifers

Sand and gravel

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

The sand and gravel beds were deposited by meltwater that flowed from successive glacial advances and retreats. The till layers tend to be more laterally persistent than the sand layers because the ice, from which the till layers originated, was laterally persistent. The naming convention for the buried sand and gravel aquifers in this atlas is based on the underlying till unit described in the associated geologic atlas (Part A). Approximately 55 percent of the wells in the county are completed in buried sand and gravel aquifers.

The stratigraphic column in Figure 4 correlates the glacial geologic units from Part A with the hydrogeologic units of Part B. Part A descriptions 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.
- 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; Plate 4, Table 1).
- Units of undifferentiated sediment are shown in brown.

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

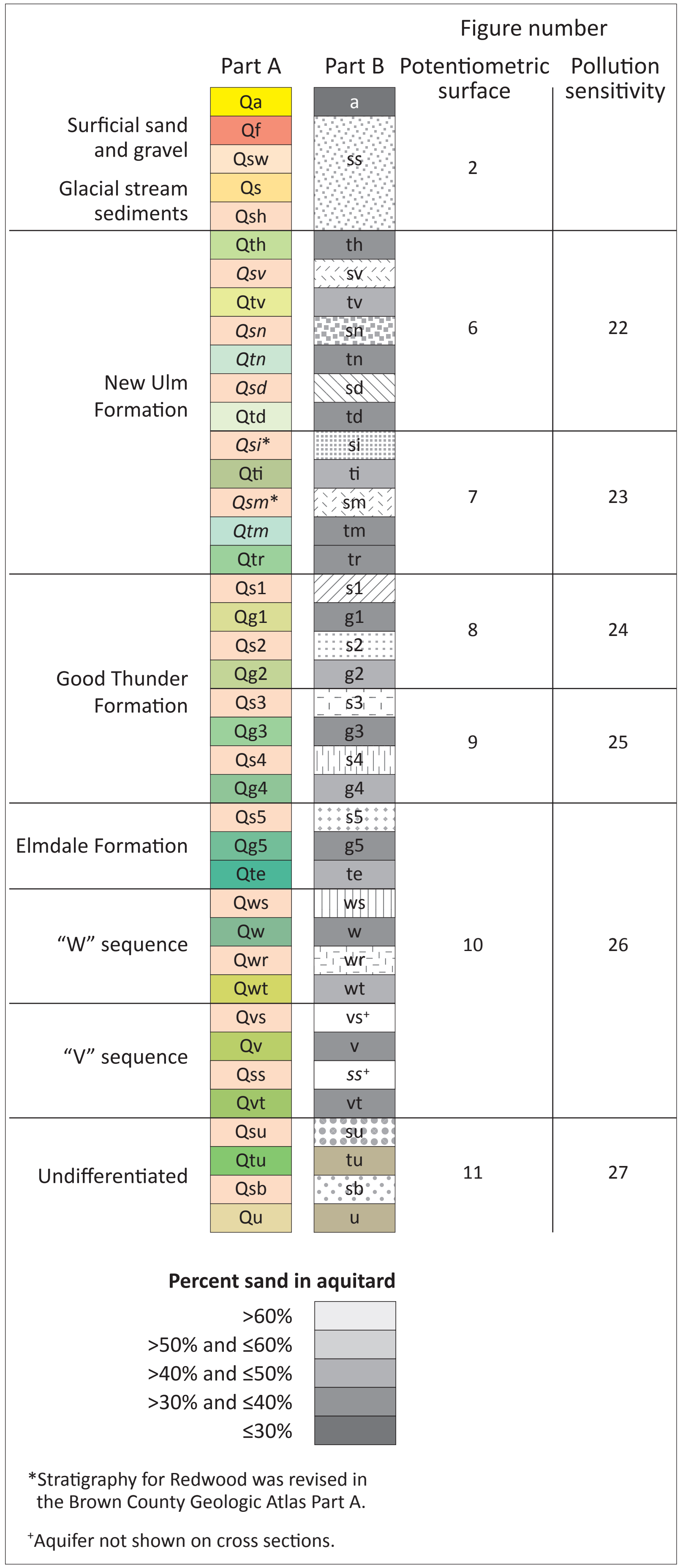


Figure 4. Hydrostratigraphy of Quaternary unconsolidated sediment

*Note that the stratigraphy for Redwood County was revised in the Brown County Geologic Atlas, Part A (Plate 5, Figure 1). The units indicated with an asterisk are shown in a different order compared to the Redwood County Geologic Atlas, Part A (Plate 5, Figure 1).

Bedrock and weathered bedrock

The buried sand aquifers represent the most widespread and generally available source of groundwater. However, in areas where these aquifers are not present, well owners need to rely on bedrock and weathered bedrock sources of groundwater (Figure 5).

During a period from approximately 145 to 65 million years before present, the middle portion of the continent was occupied by a shallow sea (western interior seaway), which deposited fine-grained and sandy sediment in marine and marginal marine settings. The resulting shale, mudstone, and sandstone from this period were deposited across present-day Redwood County but has undergone significant erosion and mostly remains in the southwestern half of the county (Part A, Plate 2, Figure 3).

The sandstone layers are more common in the lower portion of these Cretaceous deposits (below approximately 1,000 feet elevation; Part A, Plate 2) and are a significant source of groundwater. Approximately 19 percent of the 1,500 located wells in the county are completed in Cretaceous bedrock.

The inferred extent of some sandstone units within the Cretaceous bedrock are shown on the southern cross sections (Plate 8). These interpretations are based on the assumption that sandstone units found in multiple boreholes can be correlated based on common elevation ranges reported by well drillers from water well records in the County Well Index (CWI). Maps of sandstone units are not shown due to a general lack of lithostratigraphic information such as core or geophysical logs that would be needed to determine stratigraphic equivalency. Given the uncertainties of the data, the extent of sandstone layers shown on these cross sections does not preclude the possibility of its absence within, or presence outside of the areas shown.

A layer of weathered rock known as saprolite (also called regolith) exists beneath the Cretaceous deposits and covers most of the much older Precambrian bedrock surface. Based on limited drillhole data, saprolite varies in thickness from zero to several hundred feet. The saprolite layer is primarily clay that was originally feldspar crystals in the Precambrian bedrock, and also can include intact clasts of the original bedrock. The relict rock clasts and fracturing within the saprolite may create enough porosity and permeability to allow limited groundwater flow and storage within the layer. Approximately 5 percent of the located wells in the county are completed in this weathered bedrock layer.

The oldest bedrock of Redwood County is a faulted and folded gneissic and granitic rock (Precambrian, approximately 3.2 to 3.6 billion years old). These mostly metamorphic rocks (formed by heat and pressure from other rock types) have interlocking grains and crystals that leave very few spaces for water (porosity) and very few connections for water to flow (permeability). These types of bedrock are not considered aquifers. However, in areas where overlying sand, sandstone, or saprolite aquifers are not available, low capacity wells can be constructed if the well borehole encounters a fault or fracture that can convey small amounts of water. Approximately 6 percent of the 1,500 located wells in the county are completed in this type of fractured bedrock. Most of these are located in the northeastern part of county where the overlying glacial sediment is commonly thin, sand aquifers are limited, and Cretaceous bedrock is absent or thin (Part A, Plate 2, Figure 3).

Groundwater flow

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

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

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

Potentiometric surface maps were created using static water level data from the CWI, measurements made by DNR staff, and river elevation points (3,000-meter spacing) along the major rivers (Redwood, Cottonwood, and Minnesota). The CWI records represent various climatic and seasonal conditions from the 1950s to 2016. This data variability creates some uncertainty in potentiometric surface elevations.

Water level data from the buried sand aquifers were mostly combined into groups of two or three aquifers to create composite potentiometric surface maps to limit the number of maps produced for this atlas while still presenting an appropriate level of detail. These groups were created by combining data from adjacent stratigraphic units to minimize combinations of aquifers that might result in large elevation discrepancies.

The sv, sn, and sd aquifers (Figure 6) and the si and sm aquifers (Figure 7) in the upper and lower parts of the New Ulm Formation, respectively, have a very limited extent and associated water level data. However, a general groundwater flow direction toward the Minnesota River is apparent. Some local flow toward the Redwood River in the sm aquifer also is shown in the Vesta area (Figure 7).

More data are available for the underlying s1 and s2 aquifers (Figure 8) and the s3 and s4 aquifers (Figure 9) in the upper and lower parts of the Good Thunder Formation, respectively. In these aquifers the dominant groundwater flow directions are toward the Minnesota and Redwood rivers.

A more countywide distribution of water level data was available for the s5 and ws aquifers in the Elmdale Formation and "W" sequence, respectively (Figure 10), and the su and sb (undifferentiated buried sand) aquifers (Figure 11). The same general pattern of flow toward the Minnesota and Redwood rivers is apparent as in the overlying aquifers. No water level data were available for the vs and ss aquifers of the "V" sequence.

The Cretaceous sandstone aquifers are shown on cross sections (Plate 8) as relatively thin and discontinuous layers across most of the county based on existing data. However, these layers are assumed to have local hydraulic connections due to the relatively thin separation and the possibility of locally thicker portions that were deposited directly on top of the underlying layers. Based on this assumption of some hydraulic connections between the Cretaceous sandstone layers, only one potentiometric surface map was created.

The potentiometric surface of the Cretaceous sandstone aquifers also shows a pattern of flow toward the Minnesota River (Figure 12). The highest groundwater flow gradient for the mapped aquifers is apparent in the southwestern part of the county southwest of the Cottonwood River. This higher gradient is caused by the higher topographic relief in the area.

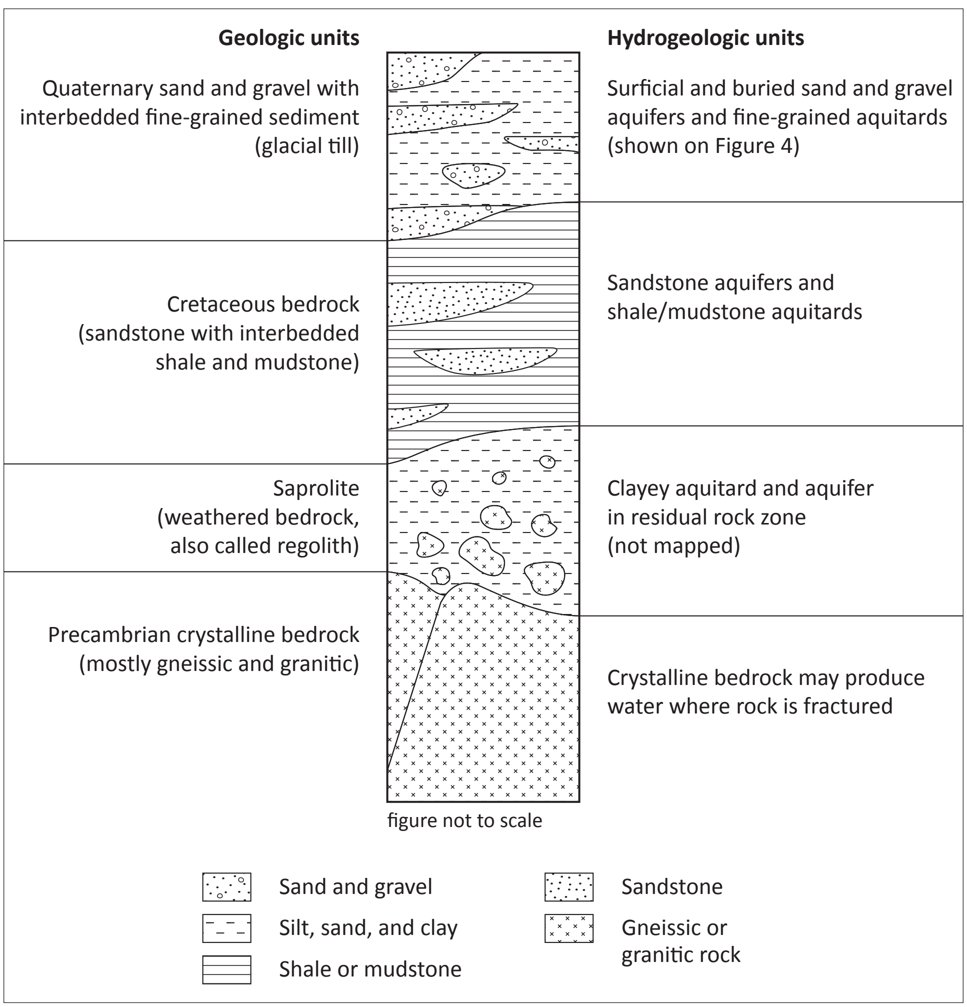


Figure 5. Bedrock stratigraphy and hydrostratigraphy

In areas where buried sand aquifers are not present well owners need to rely on bedrock and weathered bedrock sources of groundwater. Sandstone layers in the lower portion of the Cretaceous bedrock are a significant source of groundwater. Cretaceous bedrock is absent or discontinuous in the northeastern portion of the county.

Beneath the Cretaceous bedrock is a layer of weathered rock known as saprolite. The saprolite layer consists of mostly clay that was originally feldspar crystals within the Precambrian bedrock.

The oldest bedrock of Redwood County (Precambrian, approximately 3.2 to 3.6 billion years old) is a faulted and folded gneissic and granitic rock. Low capacity wells can be completed if the well borehole encounters a fault or fracture in the Precambrian bedrock that can convey small amounts of water.

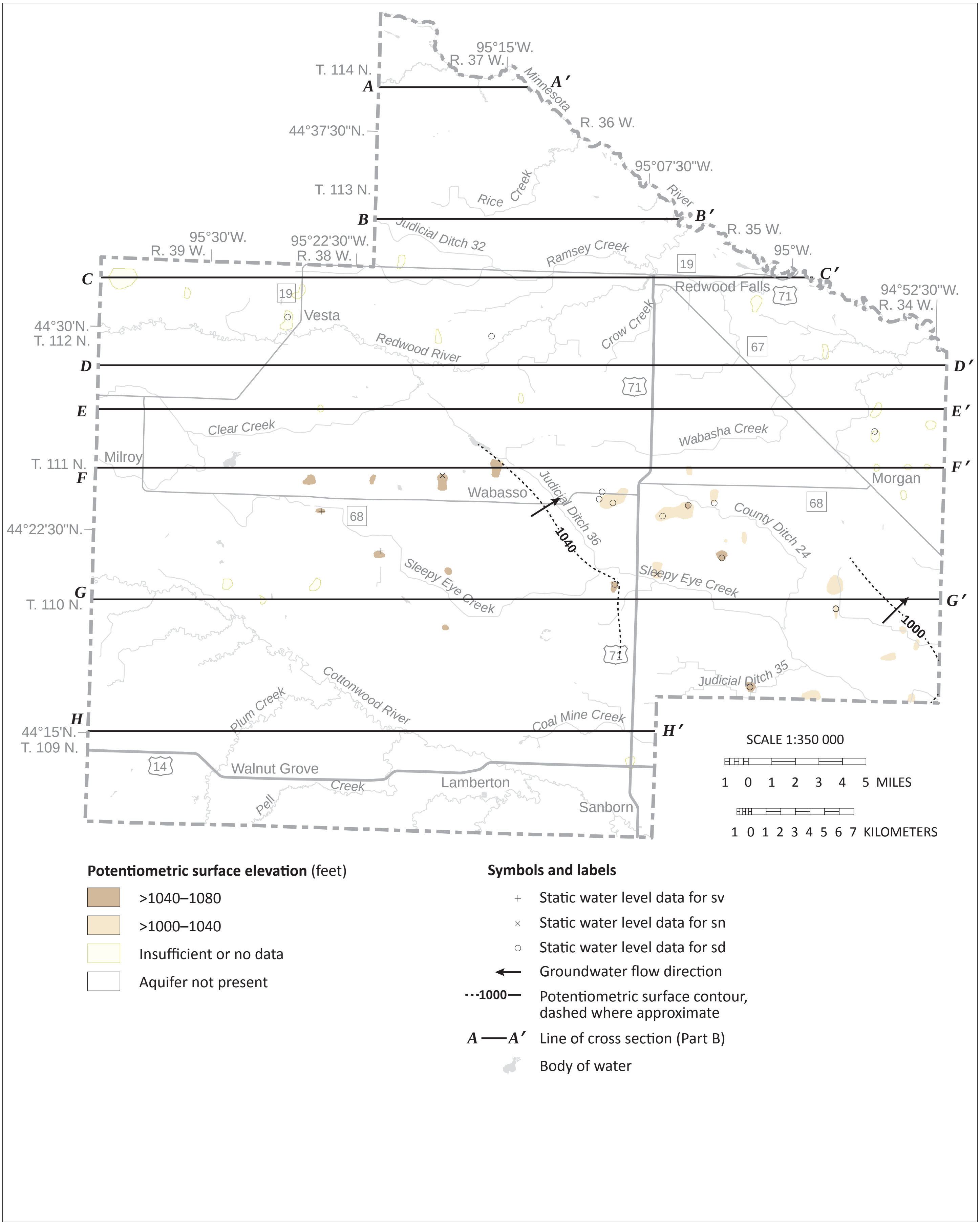


Figure 6. Potentiometric surface of the sv, sn, and sd aquifers

Limited data suggest groundwater flow directions toward the Minnesota River.

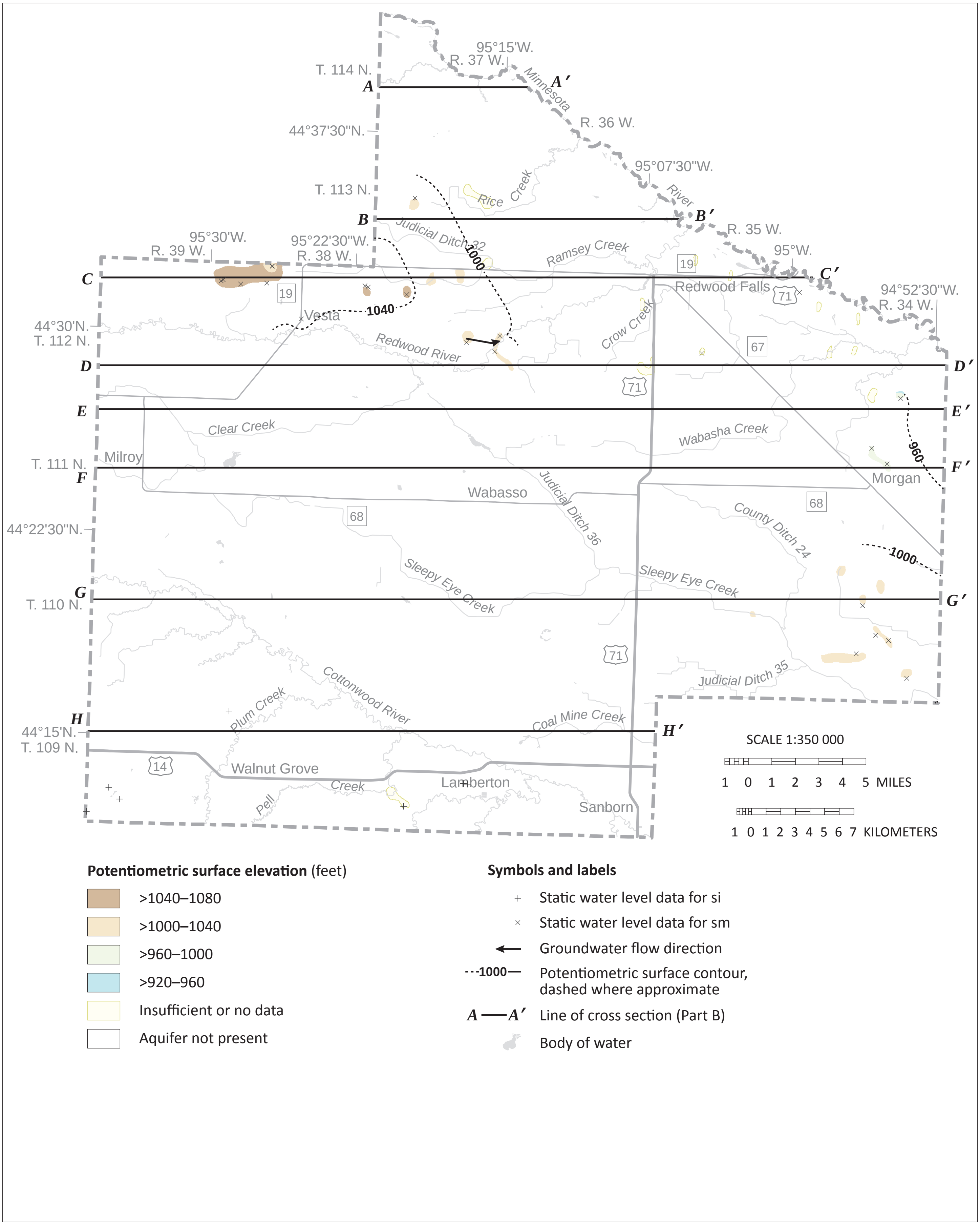


Figure 7. Potentiometric surface of the si and sm aquifers

Limited data suggest groundwater flow directions toward the Minnesota and Redwood rivers.

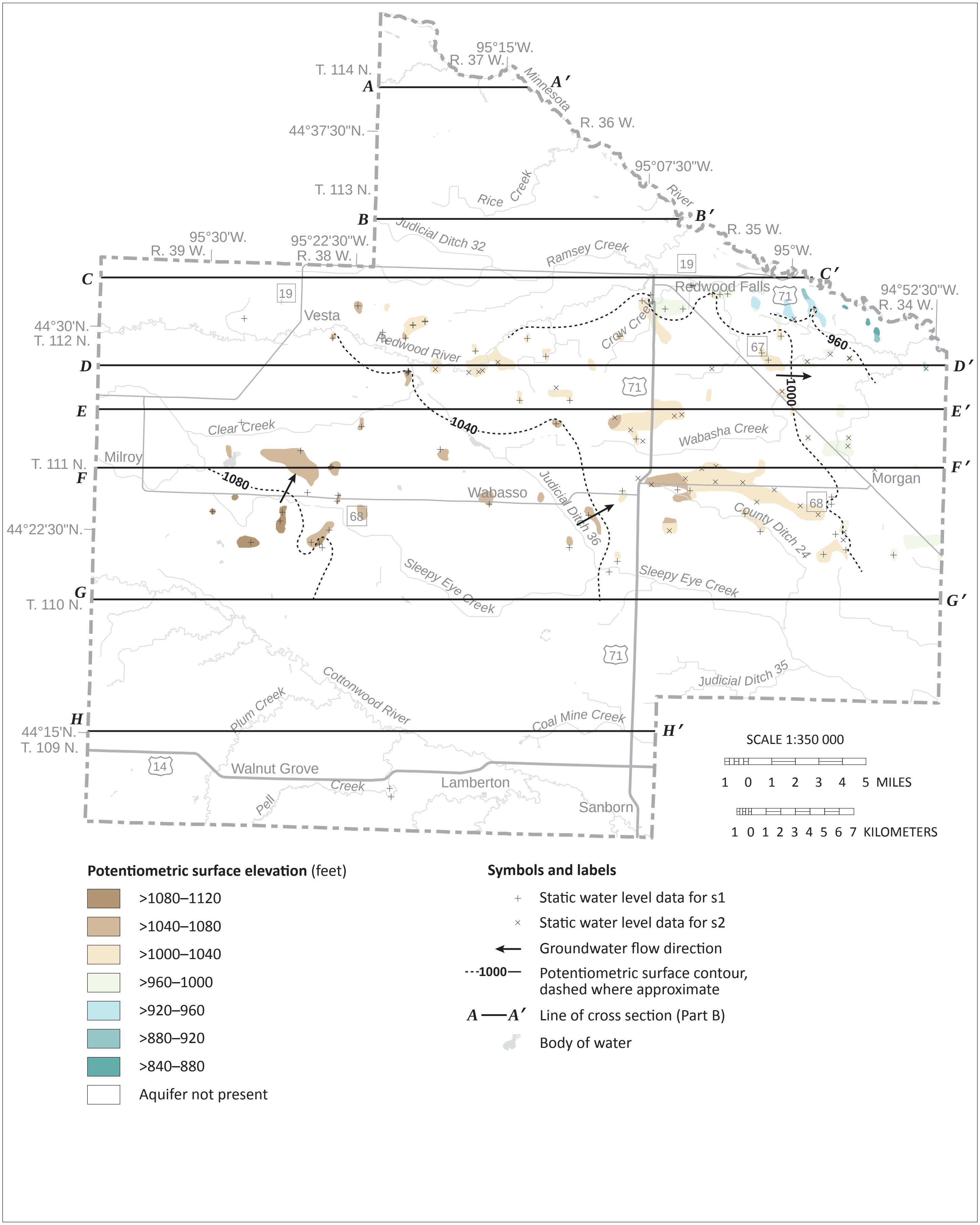


Figure 8. Potentiometric surface of the s1 and s2 aquifers

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

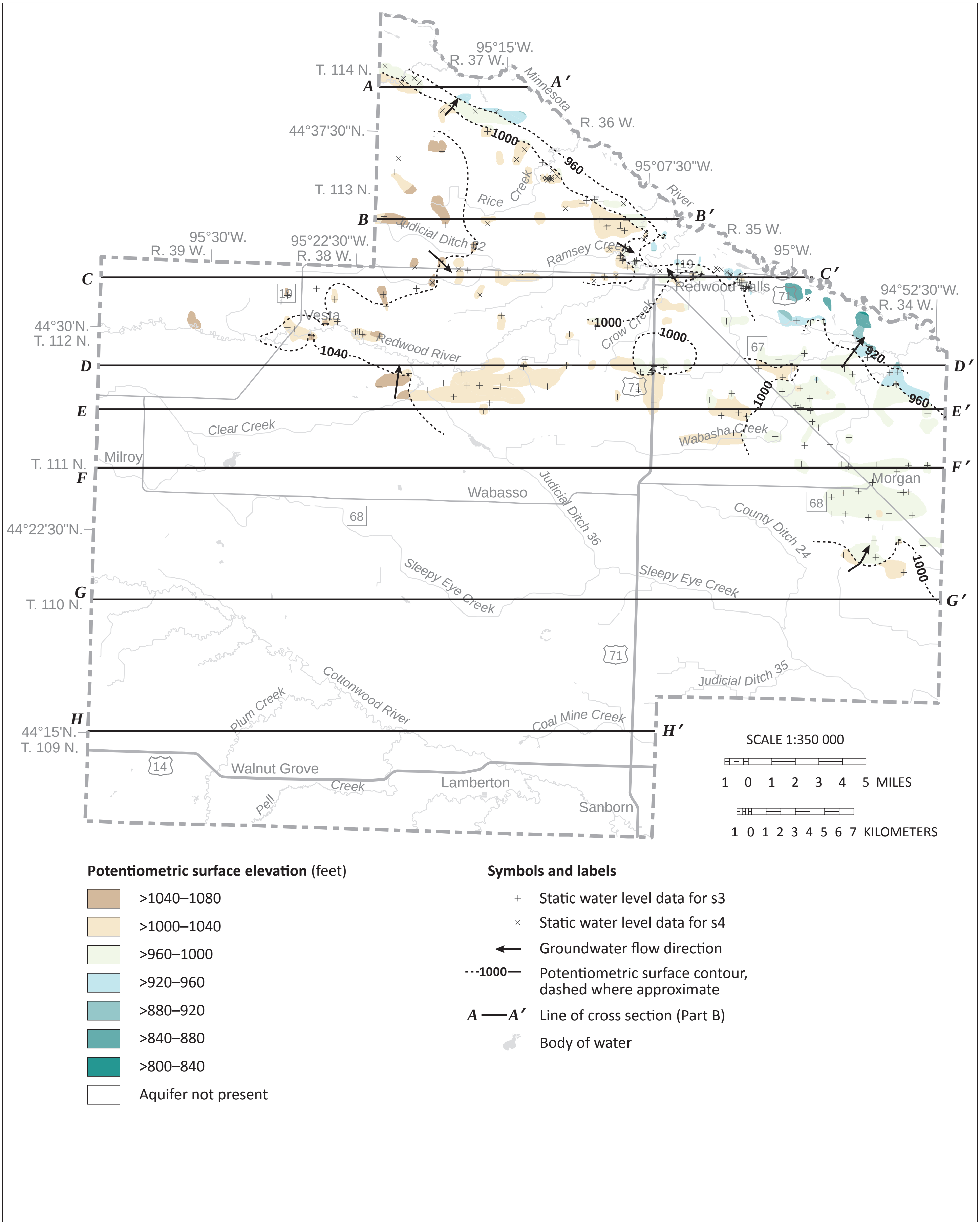


Figure 9. Potentiometric surface of the s3 and s4 aquifers

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

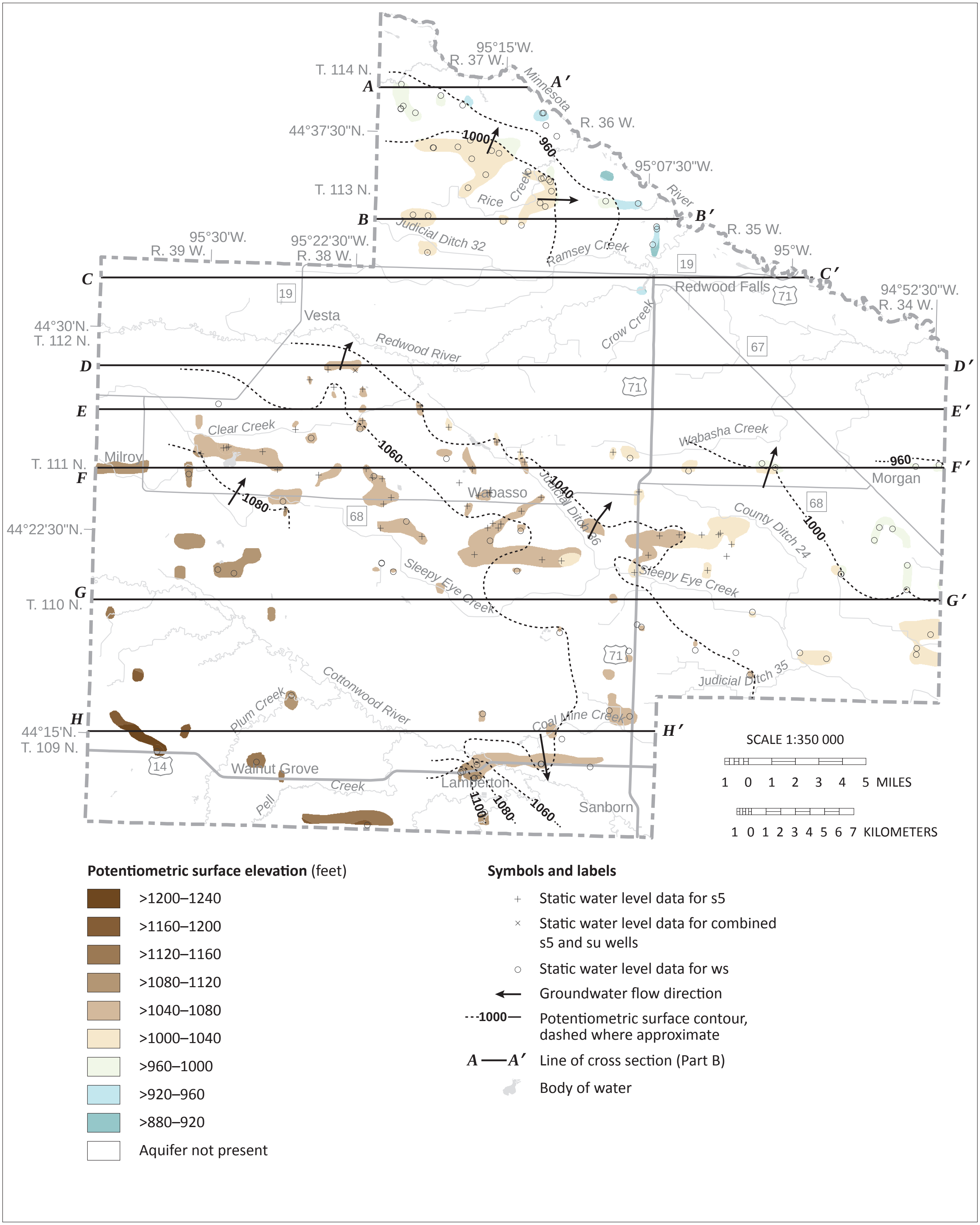


Figure 10. Potentiometric surface of the s5 and ws aquifers

The dominant groundwater flow directions are toward the Minnesota and Redwood rivers. Limited data in the south-central portion of the county show some flow toward the Cottonwood River.

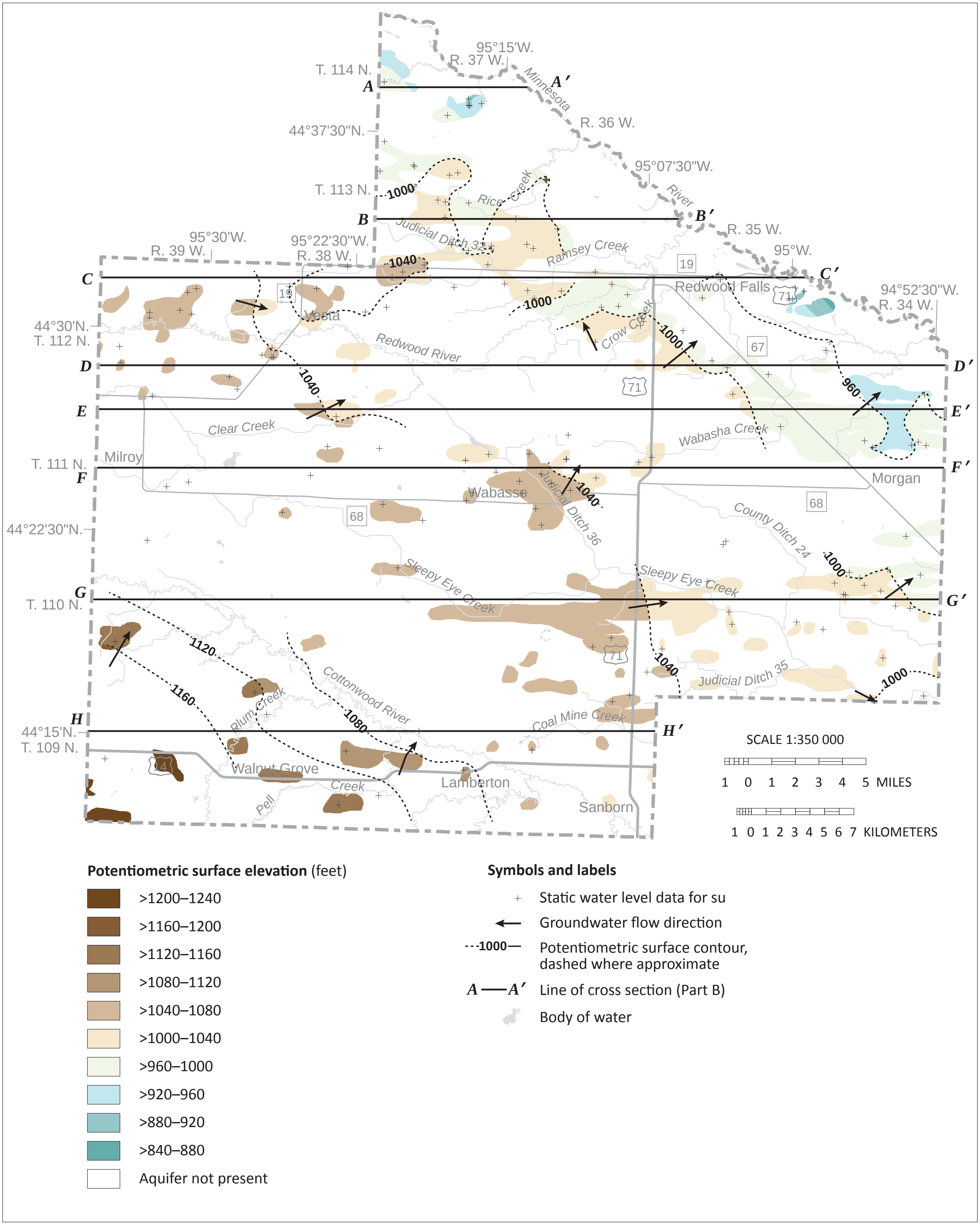


Figure 11. Potentiometric surface of the su and sb (undifferentiated buried sand) aquifers

The undifferentiated sand aquifers have the same pattern of flow toward the Minnesota and Redwood rivers as in the overlying aquifers.

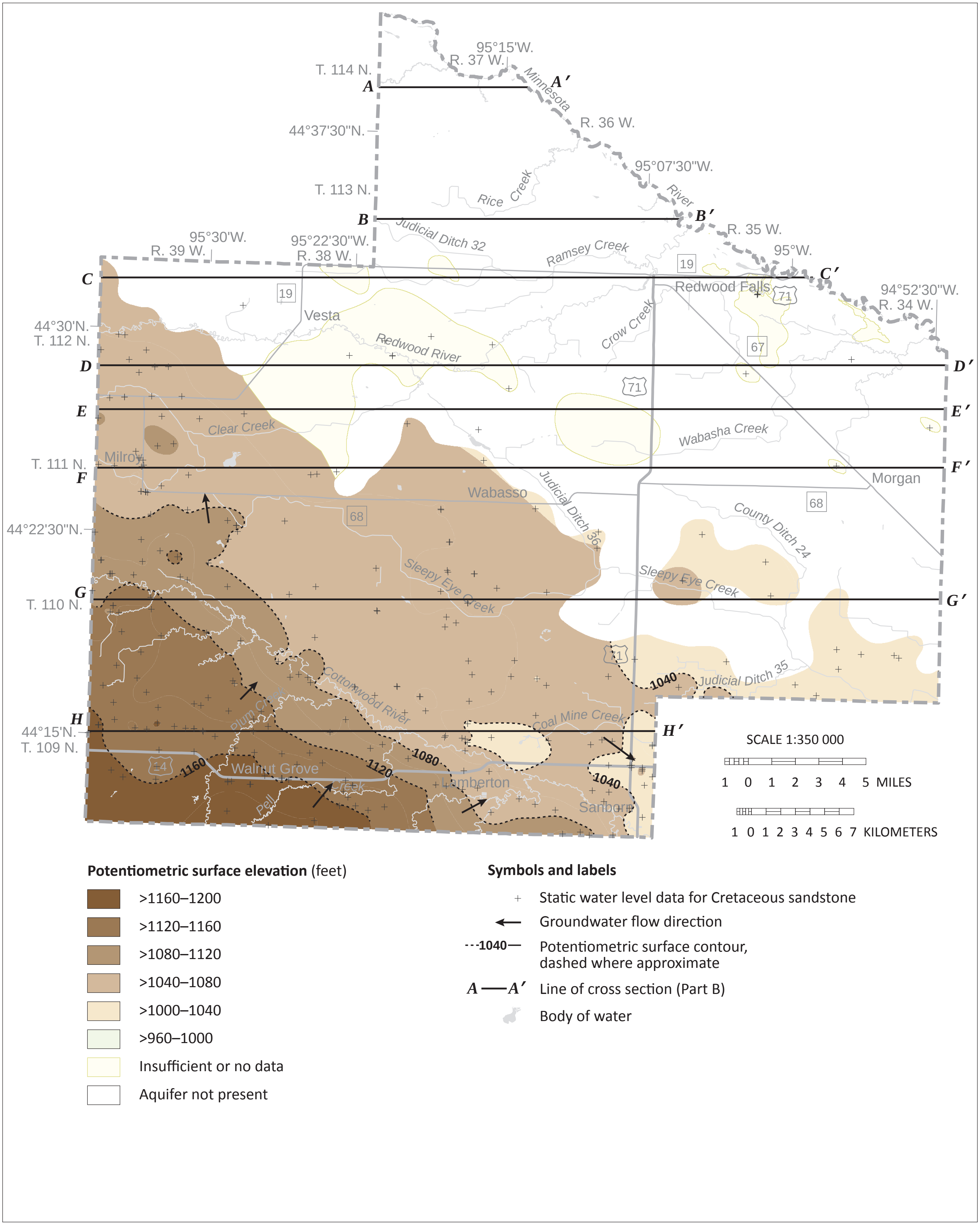


Figure 12. Potentiometric surface of the Cretaceous sandstone aquifers

The potentiometric surface of the Cretaceous sandstone aquifers also shows a pattern of flow toward the Minnesota River. The highest groundwater flow gradient for all the potentiometric surface maps is apparent in the southwestern part of the county southwest of the Cottonwood River.

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

Water sampling

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

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

Water chemistry data for Redwood County included wells sampled for this atlas and regional assessments by the DNR along with historical water samples that were incorporated into the interpretations of this report. The total of 138 groundwater samples from wells included: 101 DNR and 37 Minnesota Department of Health (MDH). Other samples included 4 surface-water samples from MDH.

Groundwater recharge sources

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

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

To help identify the source and recharge pathway of a groundwater sample (precipitation, surface water, or a mixture), oxygen and hydrogen isotopic data were plotted against each other. The x-axis represents the delta⁺ value of oxygen ($\delta^{18}O$) and the y-axis represents the delta⁺ value of hydrogen ($\delta^{2}H$). 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. $\delta\ (^0/_{00}) = (R_x/R_s\text{-}1)*1000$ where R represents the ratio of the heavy to light isotope, $^{18}O/^{16}O$ or $^{2}H/^{1}H$; R_x represents the ratio of the sample and R_s represents the ratio in VSMOW. Delta values are reported in units of parts per thousand ($^0/_{00}$ or permil) relative to VSMOW.

Results

County results are compared to the global meteoric water line, which was developed from precipitation data from around the world (Craig, 1961). The majority of the groundwater samples plot along the meteoric water line, in the center and left portions of the stable isotope graph (Figure 13). This suggests these samples are sourced from precipitation (rain and snow melt) that infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies. None of the samples had definitive evaporative signatures with the possible exception of a sample from well 542995 near the eastern border of the county downgradient from an unnamed perennial drainage ditch. The general lack of evaporative signatures in groundwater samples reflects the lack of large nonflowing surface-water bodies (such as lakes) in the county that generate most of the evaporative water in other parts of the state.

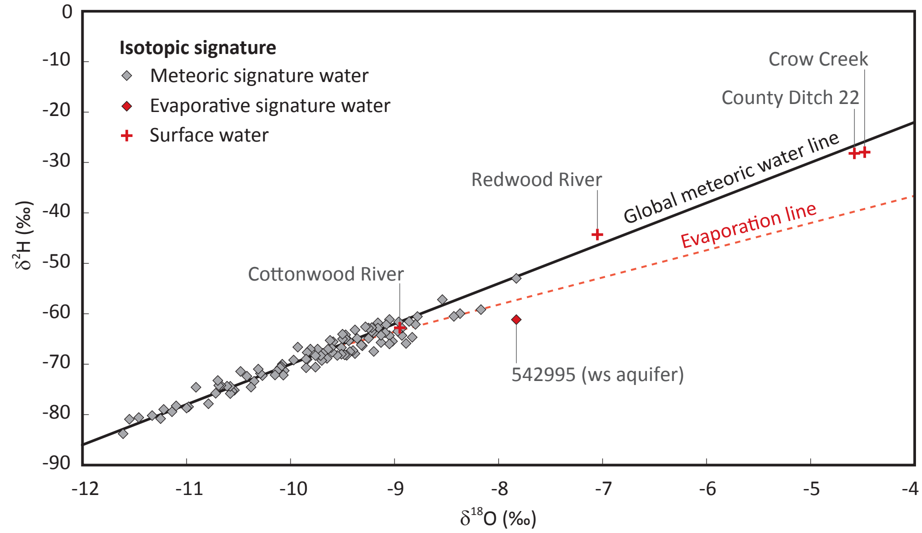


Figure 13. Stable isotope values from water samples

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

The evaporation line represents groundwater recharge that may be partially from surface-water sources.

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. Shorter residence time generally suggests short travel paths and/or high recharge rates; longer residence time suggests long travel paths and/or low recharge rates. The residence time of groundwater was estimated for this atlas using isotopic analysis of the radioactive elements tritium and carbon-14.

Tritium

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

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

Carbon-14

The carbon-14 (^{14}C) isotope was used to estimate the residence time for selected vintage and mixed tritium-age samples. This naturally occurring isotope has a half-life of 5,730 years, and can be used to estimate groundwater residence time ranging from less than 50 to greater than 40,000 years (Alexander and Alexander, in preparation).

A total of 10 samples were collected for this study and were combined with 3 samples from previous studies. Carbon-14 residence times ranged from less than 50 years to greater than 40,000 years. These data are described in more detail in the hydrogeologic cross section portion of this report.

Inorganic chemistry of groundwater

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

Water quality evaluations describe contaminants that are potentially harmful (natural or anthropogenic) or that affect aesthetics. This atlas uses the following guidelines.

U.S. Environmental Protection Agency

(EPA 2017 July, EPA 2017 March)

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

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

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

Minnesota Department of Health

(MDH, 2012a)

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

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

Minnesota Department of Natural Resources, Groundwater Atlas program

Elevated: values above background conditions

Anthropogenic: caused by human activity

Results of water sample analysis are presented for inorganic chemistry, including the major cations and major anions, reported in units of ppm. Trace elements, such as arsenic and manganese, are typically reported in units of ppb. The following chemicals are 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 glacial sediment groundwater aquifers. Sodium is often present in deep aquifers or at mineral interfaces. As groundwater moves through aquifer systems, calcium and magnesium ions in solution are exchanged for sodium ions (Hounslow, 1995).

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

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

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

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

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

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

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

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

Results

Sulfate (Plate 6)

Of the 120 samples analyzed for sulfate, 84 exceeded the SMCL. Minerals that contain sulfur are common in the aquitard materials (till and shale) that enclose the Quaternary and Cretaceous aquifers (sand and gravel, and sandstone, respectively) throughout western and southwestern Minnesota.

Chloride (Figure 14)

Anthropogenic chloride is generally not a significant contaminant in Redwood County. Of the 122 well samples analyzed for chloride, 10 were anthropogenic but none equaled or exceed the SMCL. These elevated occurrences were mostly near towns including Redwood Falls, Delhi, Clements, and Lamberton. Affected aquifers included most of the buried sand aquifers including: sd, s1, s2, s3, s4, ws, and su.

Natural chloride was common in the Cretaceous sandstone aquifers at concentrations ranging from greater than 1 to 114 ppm. Groundwater samples with anthropogenic chloride typically also have tritium detected above the method detection limit since tritium is also an anthropogenic indicator (mixed and recent tritium age). Groundwater samples with natural chloride tend to have a vintage tritium age (tritium below detection limit). Five samples in the northern portion had lower chloride/bromide ratios (165 to 218) suggesting natural chloride, but also had mixed tritium age. These samples probably represent a mixture of both conditions (indicated as “multiple” for multiple chloride sources). Most of these samples are near perennial streams where the upwelling older natural chloride water could mix with the infiltrating younger anthropogenic chloride.

Nitrate (Figure 14)

Of the 124 well samples analyzed for nitrate, 5 had elevated concentrations, and 1 was above the MCL with a concentration of 12.2 ppm. The elevated occurrences of nitrate were located in the north or eastern parts of the county from the sd, s3, and s5 buried sand aquifers.

Arsenic (Figure 15)

Of the 112 samples analyzed for arsenic, 80 exceeded the method detection limits which ranged from less than 0.10 to less than 1 ppb, and 34 of those exceeded the MCL. Those at or above the MCL were mostly located in the northeastern part of the county where the buried sand aquifers are the main source of groundwater. These aquifers included a wide distribution in the stratigraphic section including the surficial sand, sm, s1, s2, s3, s4, s5, sb, ws, wr, su, and Cretaceous sandstone aquifers. The 59 samples with concentrations greater than or equal to 2 ppb are labeled on the water chemistry map (Plate 6).

Manganese (Plate 6)

Of the 119 samples analyzed for manganese, 76 were greater than or equal to the HBV. These elevated values ranged from 106 to 1,960 ppb and were found in most of the mapped aquifers including the surficial sand, sd, sm, s1, s2, s3, s4, s5, sb, ws, wr, vs, su, and Cretaceous sandstone aquifers. The elevated manganese values were found mostly in the buried sand aquifers. Only 3 elevated values were found in Cretaceous groundwater samples.

Piper diagram: major cations and anions

The Piper diagram (Figure 16) graphically represents groundwater types or chemical trends based on the relative amounts of major chemical constituents. It can indicate unique hydrogeology of the county where groundwater may require special consideration or treatment. It also helps corroborate pollution sensitivity conditions by providing information on the distribution of the groundwater-types that are characteristic of conditions that are hydraulically isolated or have focused recharge.

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

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

The cation triangle (lower left) shows that groundwater with a mixture of calcium and magnesium (graph area 1) is common in the county with calcium as the dominant ion (Figure 16a). This cation type of water was mostly from the buried sand aquifers but also from a few Cretaceous sandstone, saprolite, and Precambrian aquifers. Another common cation water type was sodium+potassium (graph area 2). Almost all of the Cretaceous sandstone and Cretaceous saprolite samples were this type but also a large number of buried sand aquifer samples. Three of the Cretaceous sandstone samples of this group had carbon-14 residence times at 35,000 or exceeding the method limit of 40,000 years (Figure 16b).

The anion triangle (lower right) shows that the buried sand aquifers contain a continuum of bicarbonate to sulfate water types (graph area 3). Most of the Cretaceous sandstone and saprolite samples cluster in the sulfate portion of the anion triangle and the sodium+potassium and sulfate portion of the middle graph (graph area 4).

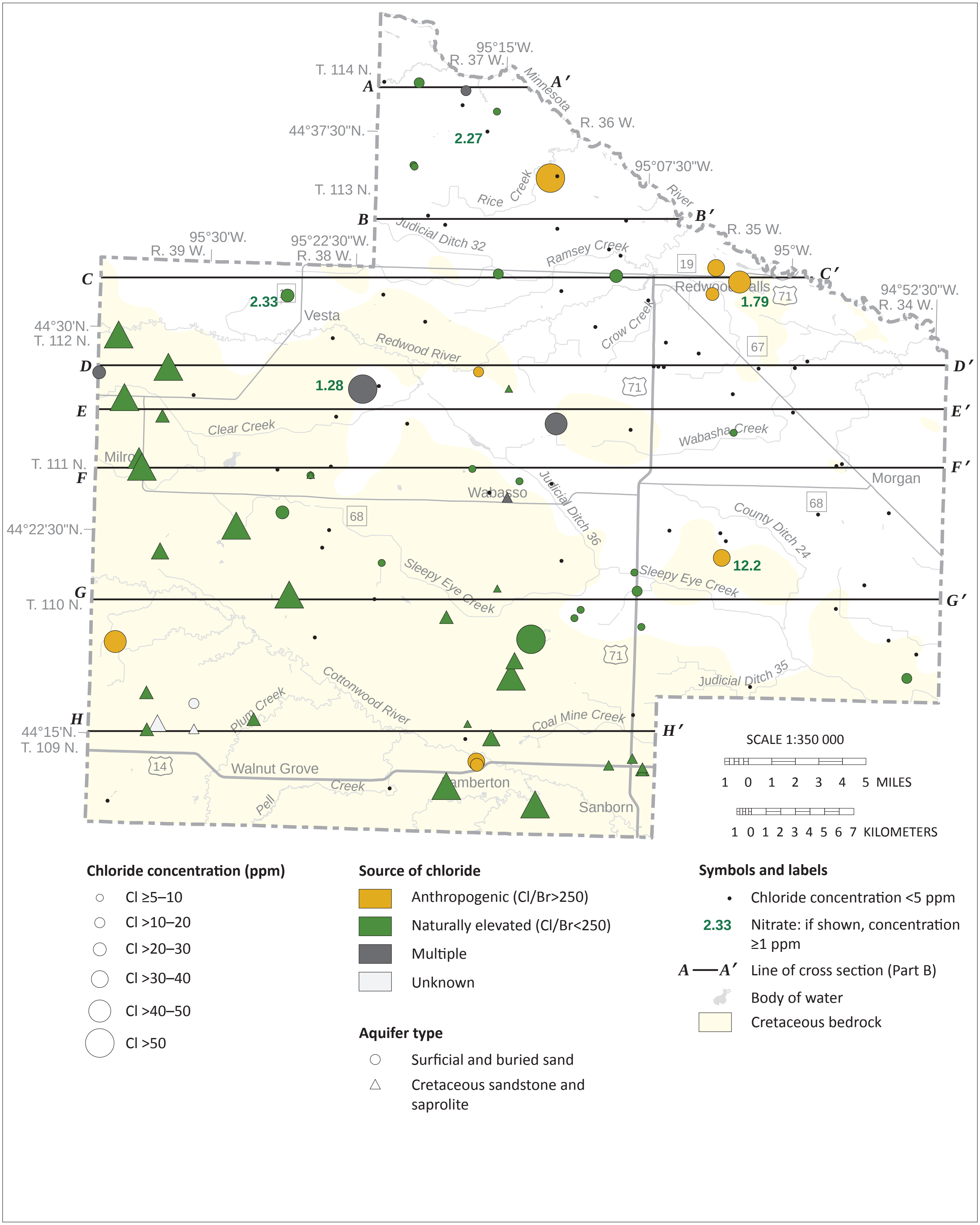


Figure 14. Elevated chloride and nitrate concentrations from groundwater samples

Natural chloride was common in the Cretaceous sandstone aquifers. Anthropogenic chloride is generally not a significant contaminant in the county. Only 5 groundwater samples had elevated concentrations of nitrate and only 1 of these was above the MCL.

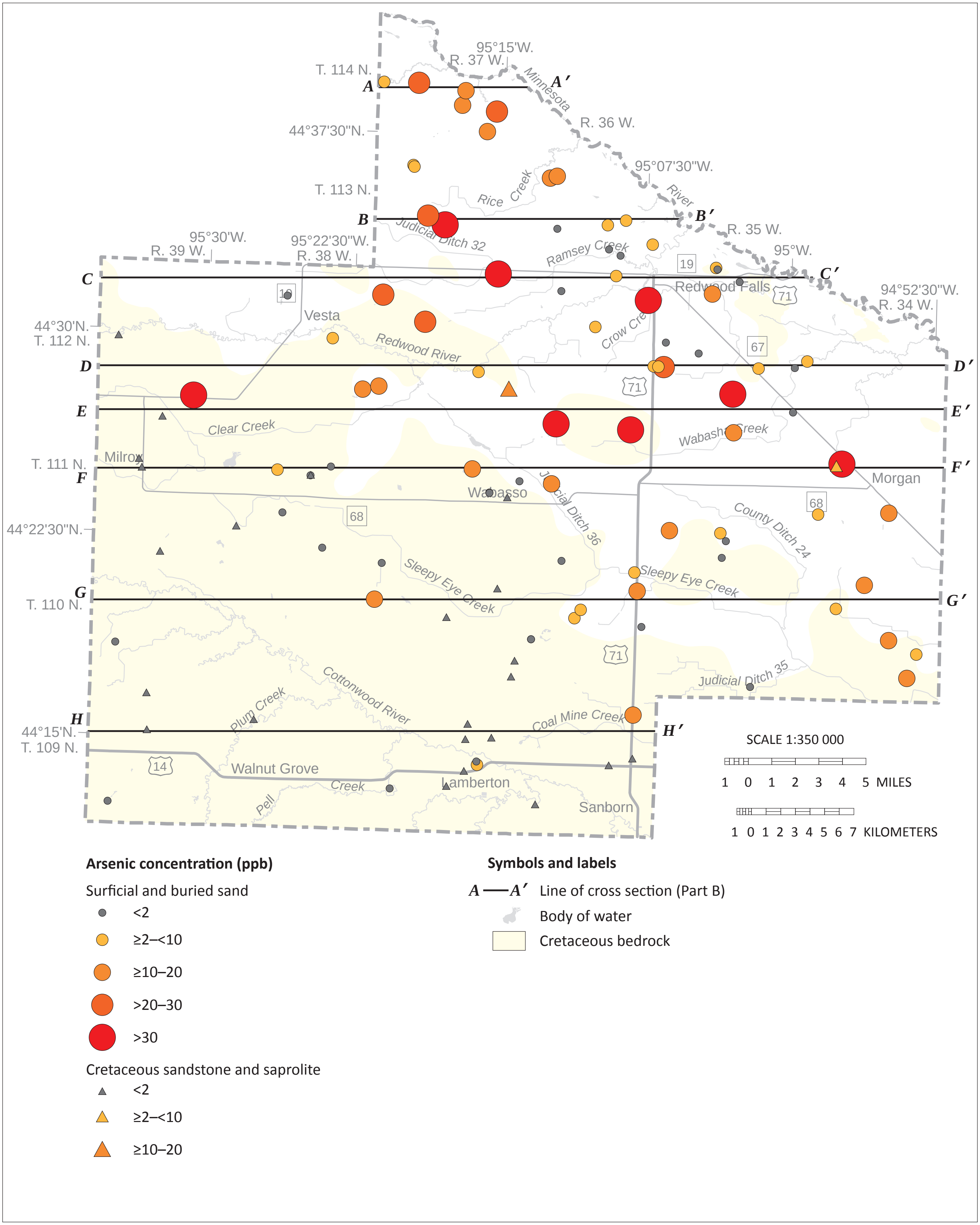
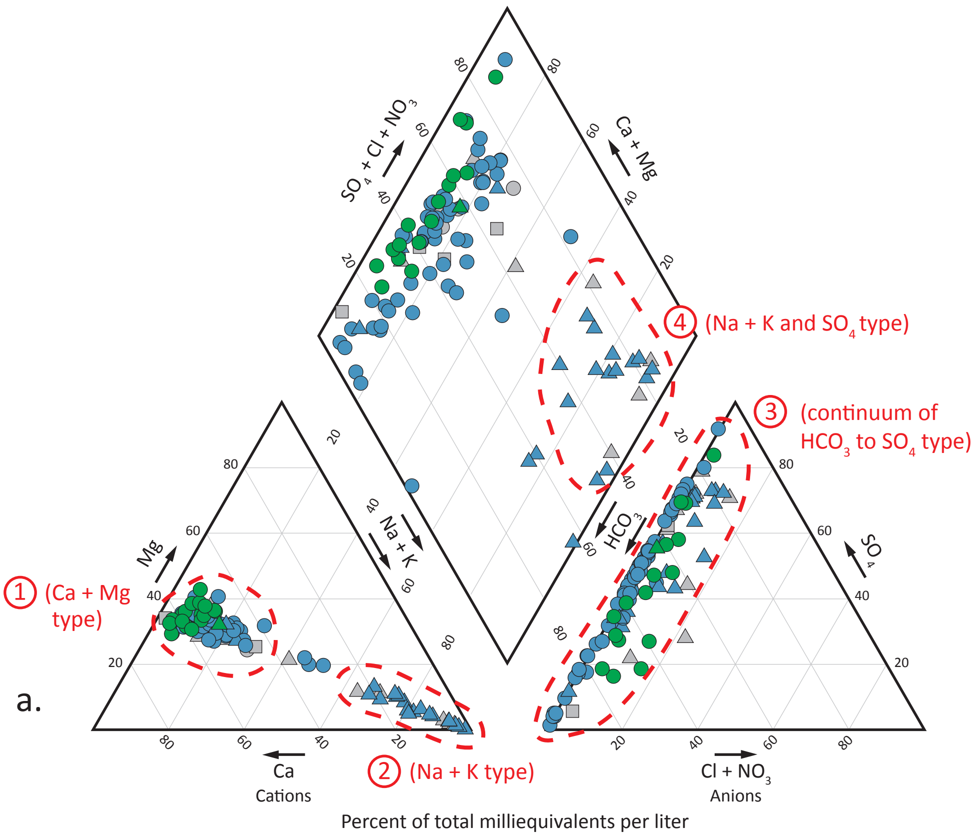


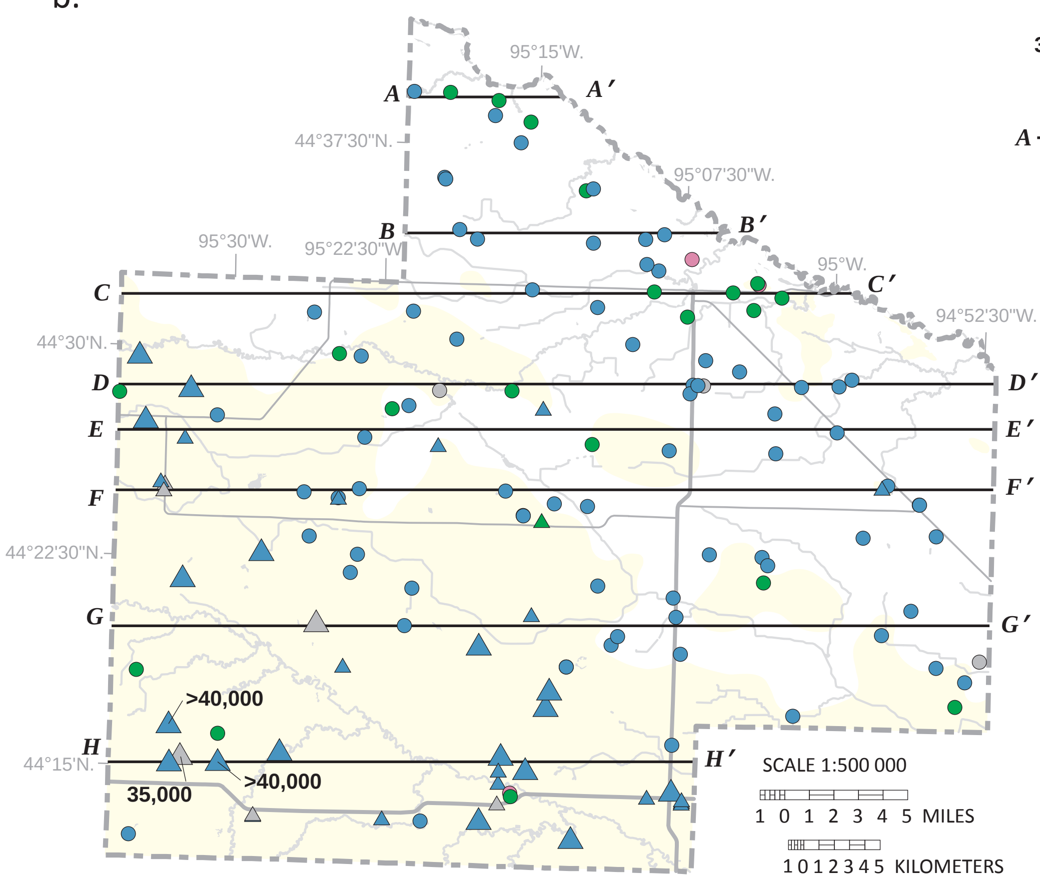
Figure 15. Arsenic

Elevated concentrations of naturally occurring arsenic are common in the county. Of the 112 samples analyzed for arsenic, 80 samples (71 percent) exceeded the method detection limits. The number of those samples that exceeded the MCL of 10 ppb was 34 (30 percent).

a.



b.



Chemistry

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

Aquifer symbol

○ Surficial and buried sand
△ Cretaceous sandstone and saprolite; larger symbols on map indicate Na + K type water
□ Precambrian

Tritium age

Symbol color indicates tritium age of water sample.

Recent
Mixed
Vintage
Not sampled for tritium

Symbols and labels

35,000 Carbon-14 (^{14}C): estimated groundwater residence time in years shown on select wells.
A——*A′* Line of cross section (Part B)
Body of water
Cretaceous bedrock

Figure 16. Piper diagram of groundwater samples from the DNR and MDH

a) Calcium+magnesium **(1)** and sodium+potassium **(2)** are common cation water types from the buried sand, and Cretaceous sandstone and saprolite aquifers, respectively. The anion triangle shows that the buried sand aquifers contain a continuum of bicarbonate to sulfate water types **(3)**. Most of the Cretaceous sandstone and saprolite groundwater samples cluster in the sodium+potassium and sulfate portion of the middle graph **(4)**.

b) Samples with mixed tritium-age water are found throughout the county in all of the general aquifer types. The sodium+potassium type water (larger triangles), which is also typically vintage tritium age, is mostly limited to the southwestern half of the county in the Cretaceous sandstone and saprolite aquifers.

Pollution sensitivity

Pollution sensitivity maps were generated on a county scale to assist citizens and local government in protecting and managing groundwater resources. Pollution sensitivity is defined as the potential for groundwater to be contaminated because of the properties of the hydrogeologic material. Migration of contaminants dissolved in water flowing through unsaturated and saturated sediment is a complex process that is affected by biological degradation, oxidizing or reducing conditions, and other factors. The methods used to interpret pollution sensitivity included the following general assumptions:

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

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

Two models were used to estimate the pollution sensitivity, based on the different properties of the aquifer materials. The following assumptions were applied.

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

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

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

Near-surface materials

Methods

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

The transmission rate varies depending on the texture. Coarse-grained materials generally have faster transmission rates than fine-grained materials. The two primary inputs used to estimate transmission rate are the hydrologic soil group and the surficial geologic matrix texture. Attributes of both are used to estimate the time of travel (Table 1) (Natural Resources Conservation Service, 2016; Part A, Plate 3). Further details, including a discussion of special conditions (bedrock at or near the surface and others), are available in *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

The time of travel through 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 17).
- Areas with a longer travel time (weeks to a year) are rated very low or low.
- Areas of more than a year are rated ultra low. These areas are not present in this county.

Results

Redwood County is dominated by very low and low sensitivity for this shallow 10-foot target depth evaluation (Figure 18). Moderate sensitivity exists in areas where glacial outwash is at the surface near the larger rivers (Minnesota, Redwood, and Cottonwood) and associated tributaries, and smaller streams including Sleepy Eye Creek.

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

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

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

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

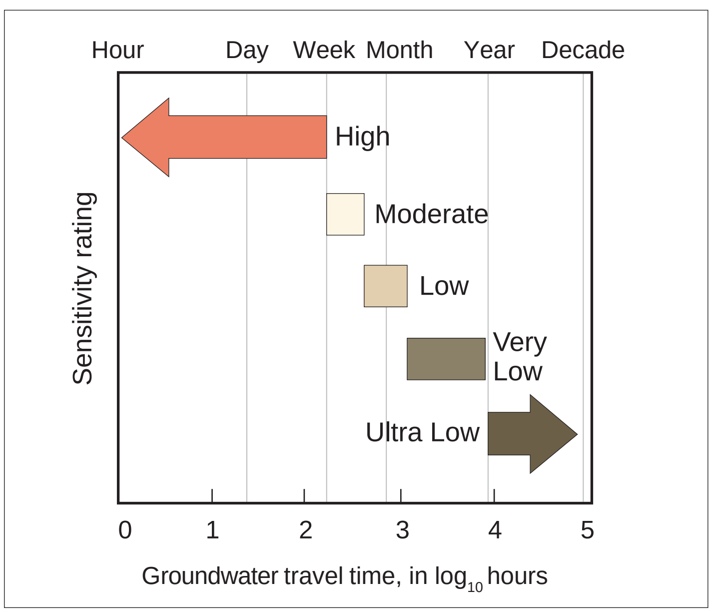


Figure 17. Pollution sensitivity rating for near-surface materials

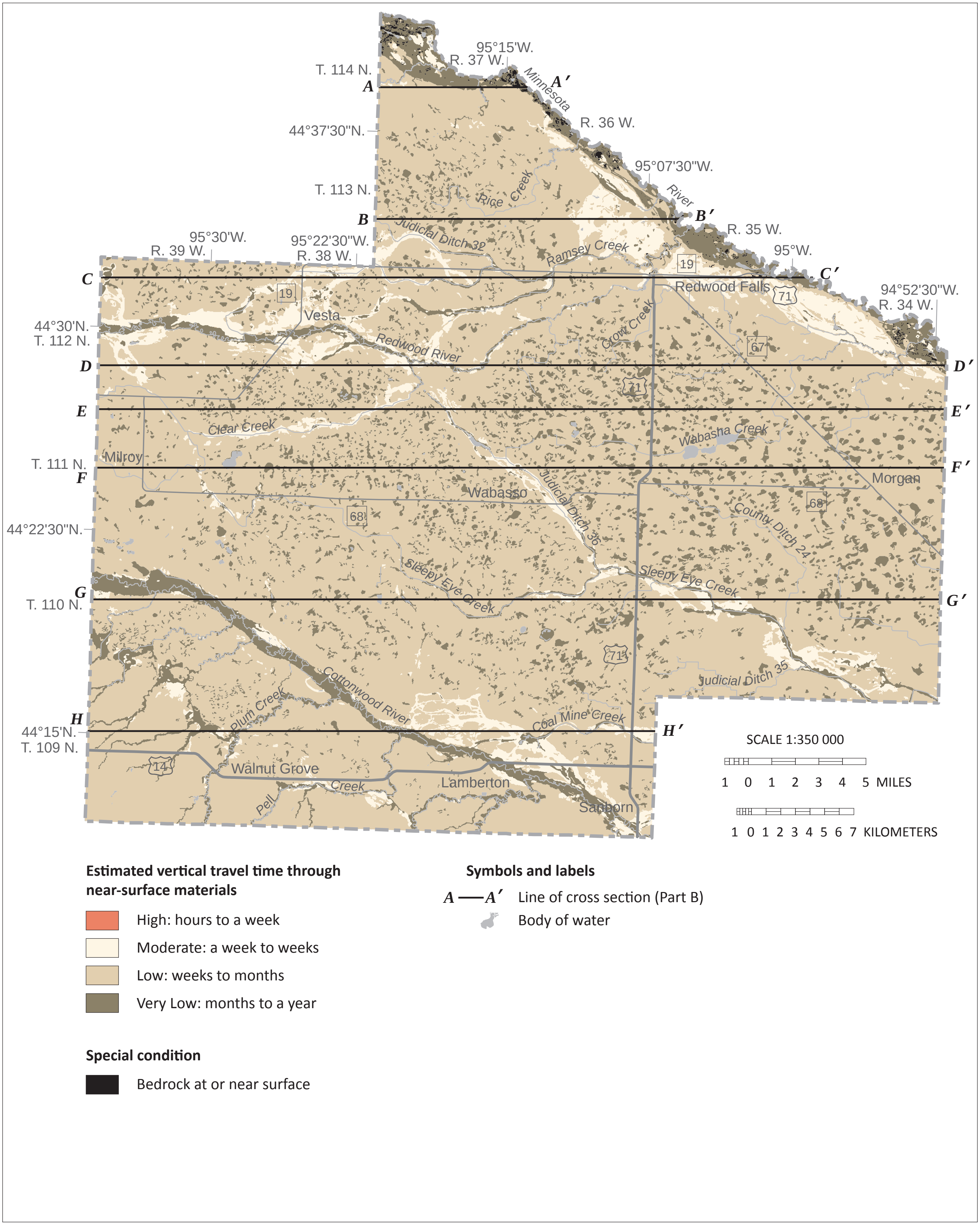


Figure 18. Pollution sensitivity of near-surface materials

Redwood County is dominated by very low to low sensitivity for this shallow 10-foot target depth evaluation. Moderate sensitivity exists in areas where glacial outwash is at the surface.

Buried sand aquifers and bedrock surface

Methods

The sensitivity ratings for the buried sand aquifers and the bedrock surface are based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with ratings of high or very high have relatively short travel times of less than a few years. Areas rated very low or low have estimated travel times of decades or longer (Figure 19).

The DNR developed a pollution sensitivity model that represents how precipitation infiltrates the land surface and recharges portions of deeper aquifers. The 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 20).

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

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

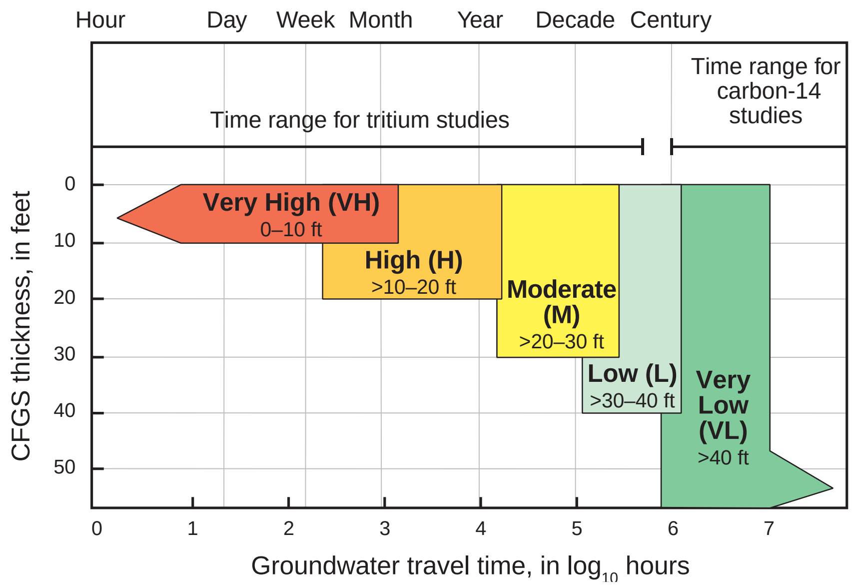


Figure 19. Geologic sensitivity rating for the buried sand aquifers and the bedrock surface

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

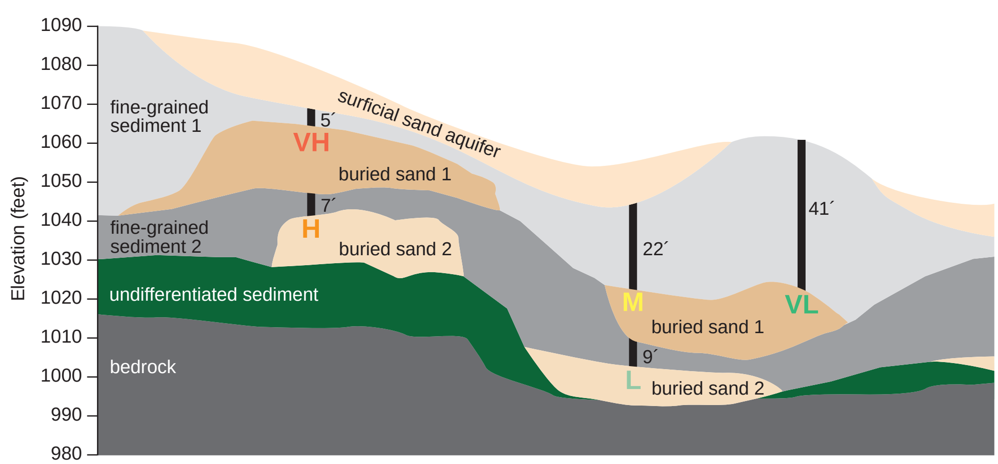


Figure 20. Cross section showing examples of pollution sensitivity ratings

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

Groundwater conditions

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

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

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

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

Ⓛ Groundwater flows laterally.

Ⓤ Groundwater flowpath is unknown.

Ⓓ Groundwater discharges to a surface-water body.

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

Limitations of the model are represented by conditions L (lateral) and U (unknown). Lateral flow of groundwater often results in recent or mixed tritium-age water in aquifers with very low to low sensitivity (condition L). The model can't always predict the origin of recent or mixed tritium-age water in deep, isolated, or protected settings (condition U).

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

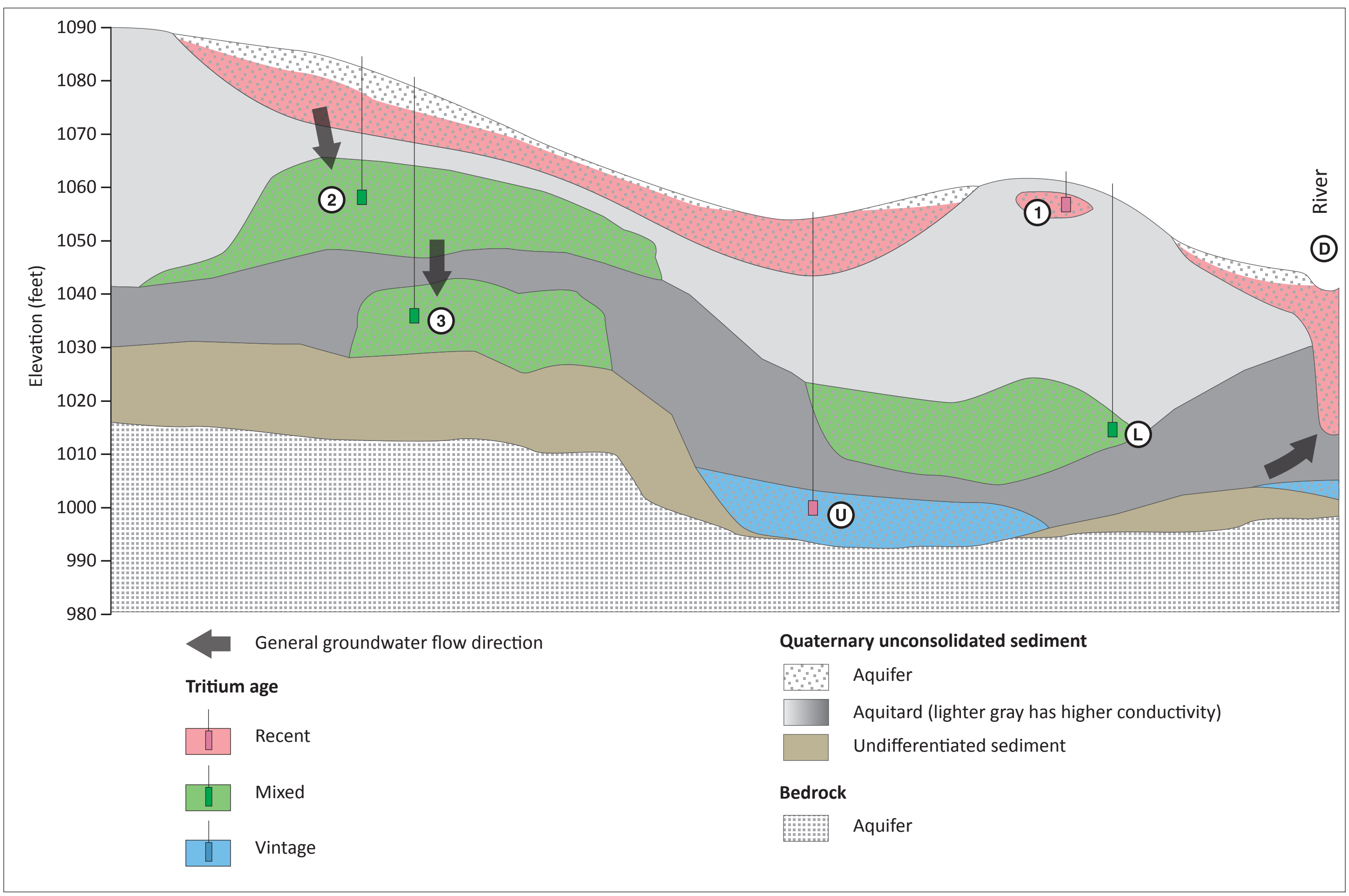


Figure 21. Hypothetical cross section illustrating groundwater conditions

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

Results

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

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

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

The tritium dataset was a combination of sampling efforts by the DNR and the MDH for several projects since 1988. Descriptions of groundwater chemistry and pollution sensitivity were qualitatively compared to the results of the pollution sensitivity modeling. Tritium detections in groundwater samples from aquifers in areas mapped as very low sensitivity should rarely occur, assuming that flow of recent water to the aquifer is vertical and not altered by nearby pumping (Figures 20 and 21).

sv, sn, and sd aquifers (Figure 22)

These units were mapped as limited extent buried sand aquifers at scattered locations. Depths range from approximately 0–50 (sv), 17–50 (sn) and 0–80 (sd) feet. The combined water use of these aquifers is approximately 1 percent of the wells in the county. The pollution sensitivity ranged from very low to very high. Most of the very low to low ratings were for the sd aquifer in the east where portions of this aquifer are the deepest.

From the sd aquifer in the east, 3 samples were analyzed for tritium, resulting in 1 mixed and 2 vintage. The mixed sample located south of County Ditch 24 is in a very low pollution sensitivity part of the sd aquifer but contained elevated concentrations of anthropogenic chloride (38.3 ppm) and nitrate (12.2 ppm). The origin of these anthropogenic indicators is unknown but may be related to well casing problems or unknown geologic conditions. The corresponding pollution sensitivity for the other two sample areas were very low to low, which fits the sensitivity model.

si and sm aquifers (Figure 23)

The sm aquifer was mapped in the northeast and one area of the si aquifer is in the south near Lamberton. Depths range from approximately 0–50 (si) to 0–80 (sm) feet. The combined water use of these aquifers is approximately 2 percent of the wells in the county. The pollution sensitivity includes the entire range of ratings from very low to very high. The higher sensitivity ratings in the aquifers are located along the river valleys where they are shallower.

Both samples collected from the sm aquifer were analyzed for tritium age and resulted in 1 mixed and 1 vintage. The vintage sample had a carbon-14 residence time of 750 years. The corresponding pollution sensitivity for those sampled areas is very low, which fits the sensitivity model. Both samples were analyzed for nitrate and chloride and indicated no elevated anthropogenic concentrations.

s1 and s2 aquifers (Figure 24)

The s1 and s2 aquifers were mostly mapped in the center of the county. Depths for both of these aquifers range from near surface to approximately 120 feet; use is approximately 8 percent of the wells in the county. The pollution sensitivity includes the entire range of ratings from very low to very high. The higher sensitivity ratings for both aquifers are mostly found in the Minnesota and Redwood river valleys where these aquifers are shallower. There are also some moderate sensitivity areas in the west where the s1 aquifer is located at shallower depths.

Of the 14 samples analyzed for tritium age, 4 were mixed and 10 were vintage. One vintage tritium-age sample in the west had a carbon-14 residence time of 450 years. Of the 14 samples analyzed for nitrate, none had elevated concentrations. Of the 14 samples analyzed for chloride, 3 were elevated and 2 of those had an anthropogenic source.

The mixed and vintage tritium-age samples were collected in very low to low sensitivity areas. Most of these results match the vertical recharge model. Near Wabasso, 1 of the mixed tritium-age samples had a carbon-14 residence time of less than 50 years. Near Redwood Falls, 2 others from a very low sensitivity areas were classified as unknown for recharge conditions.

s3 and s4 aquifers (Figure 25)

The s3 and s4 aquifers are distributed across the northern part of the county. For both aquifers, depths range from the near-surface depths to approximately 130 feet; use is 16 percent of the wells in the county. The pollution sensitivity includes the entire range of ratings from very low to very high. The higher sensitivity ratings for both aquifers are mostly in the Minnesota and Redwood river valleys where these aquifers are shallower.

Of the 31 samples collected from these aquifers, 29 were analyzed for tritium age with the following results: 1 recent, 8 mixed, and 20 vintage. Of the 27 samples analyzed for nitrate, 3 were elevated. Of the 24 samples analyzed for chloride, 9 were elevated and 3 of those were anthropogenic.

Recent and mixed tritium-age samples were found at locations mapped with very low to low sensitivities. These tritium detections are likely from groundwater flowing vertically (conditions 1 and 2), laterally, (condition L) or unknown (condition U). The vintage tritium-age samples were located in very low sensitivity areas, which is consistent with the pollution sensitivity model. One of the vintage samples located north of Judicial Ditch 32 had a carbon-14 residence time of 2,000 years.

s5, ws, wr, and vs aquifers (Figure 26)

The s5 aquifer was mapped at locations scattered within the central part of the county, the ws aquifer at scattered locations throughout the county, the wr aquifer at locations in the west, and the vs aquifer only within a very limited area in the southwest. Depths range from approximately 30–100 feet (s5), near surface to 160 feet (ws), 150–240 feet (wr), and near surface to 150 feet (vs). The combined water use of these aquifers is approximately 2 percent of the wells in the county, mostly in the northern portion. The pollution sensitivity of these aquifers is mostly very low to low with some areas of moderate to very high in the west and southern portions of the county where aquifers are shallower in the river valleys.

Of the 21 samples collected from these aquifers, 20 were analyzed for tritium age with the following results: 2 recent, 3 mixed, and 15 vintage. Three of the vintage samples from the northern and eastern parts of the county had carbon-14 residence times ranging from 3,000–4,500 years. Of the 20 samples analyzed for nitrate, one sample located southeast of Vesta was elevated (1.28 ppm). Of the 19 samples analyzed for chloride, 8 were elevated and 2 of those were anthropogenic.

All samples were collected at locations in very low to low sensitivity areas. The mixed and recent tritium-age samples likely represent lateral groundwater flow from upgradient higher sensitivity areas.

su and sb (undifferentiated buried sand) aquifers (Figure 27)

These undifferentiated aquifers were mapped as sand bodies of various sizes across the county. The diagonal trend of the buried sand aquifer that parallels the Minnesota River valley may be more continuous than shown and probably extends to the northwest into the southeastern part of Lac qui Parle County based on regional mapping (Patterson, 1999; Bradt, 2000). This part of the su aquifer occupies a bedrock valley shown on the Bedrock Topography and Depth to Bedrock maps of Part A, Plate 5. Depths range from near surface to approximately 260 feet for both aquifers. These aquifers are used by approximately 12 percent of the wells in the county. The pollution sensitivity is mostly very low with some higher sensitivity ratings in the northern part of the county in the Minnesota River valley, the western part in the Redwood River valley, and the southern part near the Cottonwood River valley.

Of the 24 samples collected from these aquifers, all were tested for tritium age; all but one were vintage and were located in very low sensitivity areas. The 1 mixed sample was located in an area of low sensitivity and also was analyzed for carbon-14 with a residence time of less than 50 years. Of the 23 samples analyzed for nitrate, none were elevated. Of the 24 samples analyzed for chloride, 11 were elevated and 1 of those was anthropogenic.

Bedrock surface (Figure 28)

The type of bedrock at the bedrock surface is variable across the county with Precambrian granitic and gneissic rocks dominant in the northeast and Cretaceous shale dominant in the southwest. The Cretaceous sandstone aquifers are typically not at the bedrock surface, but some groundwater samples were collected from aquifers just below the bedrock surface and are considered in the discussion below. Depths to the bedrock surface range from typically less than 100 feet in the southwest to depths of greater than 100 feet up to 300 feet in the northeast.

This surface mostly has a very low pollution sensitivity with the exception of areas near the Minnesota, Redwood, and Cottonwood rivers and other areas in the western part of the county where the bedrock surface is shallow. A limited number of bedrock samples are shown on Figure 28 for comparison with the bedrock surface pollution sensitivity. Groundwater samples collected from wells with open hole portions that are much deeper than the bedrock surface are likely not representative of bedrock surface pollution sensitivity. Therefore, the only data shown for this comparison are data from wells with open hole sections no deeper than 40 feet.

Of the 10 wells that met this criteria, 9 were completed in Cretaceous sandstone aquifers and one was completed in the saprolite. Of the 9 samples that were analyzed for tritium, 1 was mixed and 8 were vintage. One of the vintage tritium-age samples, located southwest of Redwood Falls, had an approximate carbon-14 residence time of less than 50 years. Of the 7 samples that were analyzed for nitrate, none were elevated. Of the 9 samples that were analyzed for chloride, 7 were elevated but none of those samples were anthropogenic.

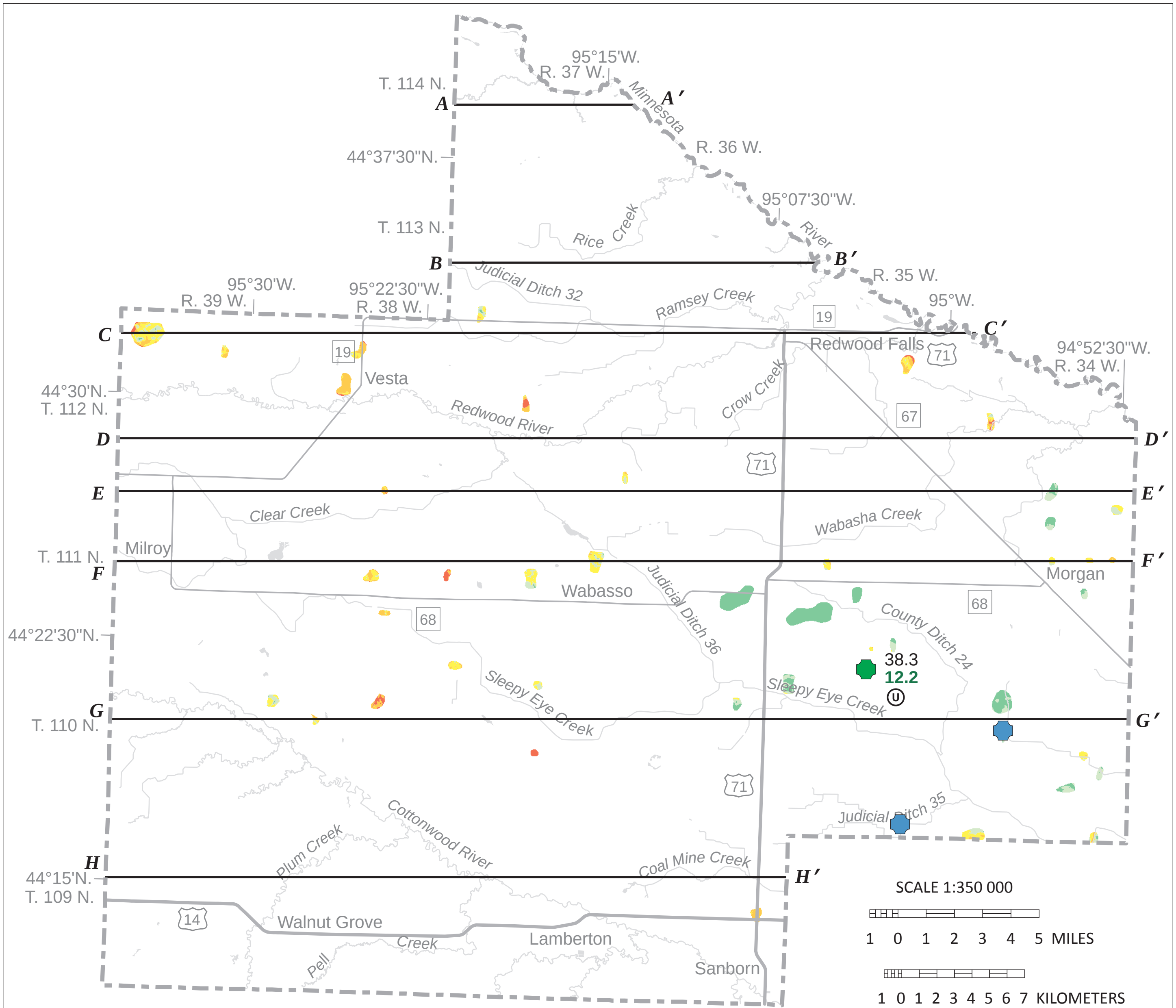
The 1 mixed tritium-age sample was located in a very low pollution sensitivity area east of Wabasso near the center of the county. The source of the tritium in that sample is unknown. All 8 vintage tritium-age samples were in very low pollution sensitivity areas. Most of these results are consistent with the pollution sensitivity model.

Deeper bedrock groundwater chemistry (Figure 29)

The pollution sensitivity model used to create maps of buried sand aquifers and the top of bedrock does not apply to portions of bedrock aquifers that are not at the bedrock surface. However, chemical evidence suggests that large portions of the Cretaceous sandstone aquifers appear unaffected by recent (approximately last 65 years) recharge and anthropogenic contamination. The combination of overlying loamy glacial till and predominance of shale and mudstone in the upper stratigraphic portion of the Cretaceous apparently provides significant protection for these aquifers.

In general, the groundwater chemistry from samples collected in the deeper aquifers below the bedrock surface indicates relatively isolated and probably very low sensitivity conditions. The samples shown in Figure 29 are from wells with open hole sections deeper than the bedrock surface (deeper than 40 feet). The groundwater sample locations shown on this map are mostly from Cretaceous sandstone aquifers and one saprolite location.

Of the 30 wells that met this criteria, 25 were analyzed for tritium and all were vintage. Four samples located in the southwestern portion of the county had carbon-14 residence times of 35,000 to greater than 40,000 years. Of the 27 samples analyzed for nitrate, none were elevated. Of the 25 samples analyzed for chloride, 23 were elevated but none were anthropogenic.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage

Symbols and labels

38.3 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, ‡ multiple sources, + source unknown)

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

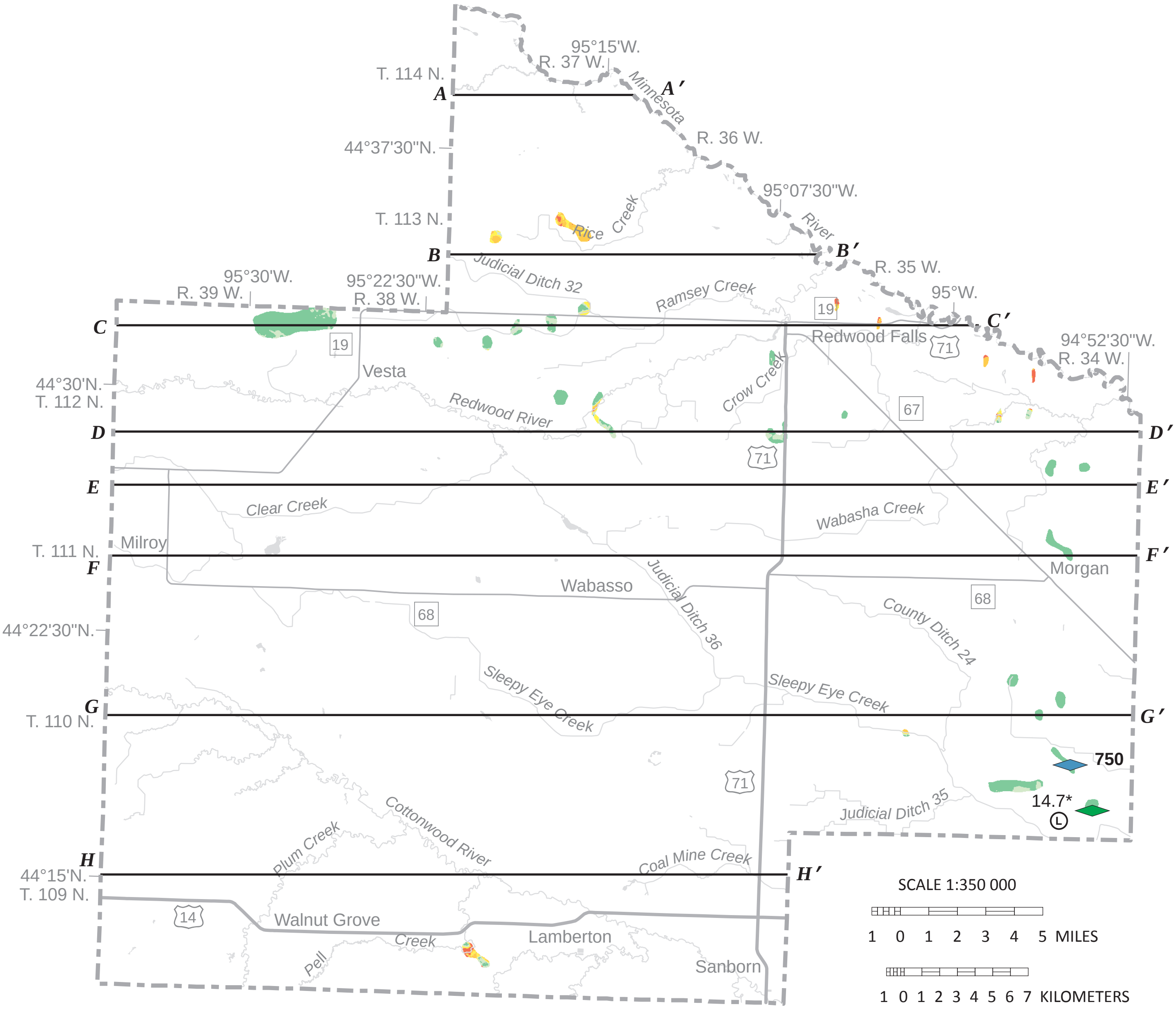
A —— A′ Line of cross section (Part B)

Body of water

Groundwater conditions

Ⓤ Groundwater flow is unknown.

Figure 22. Pollution sensitivity of the sv, sn, and sd aquifers



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage

Symbols and labels

14.7* Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, ‡ multiple sources, + source unknown)

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

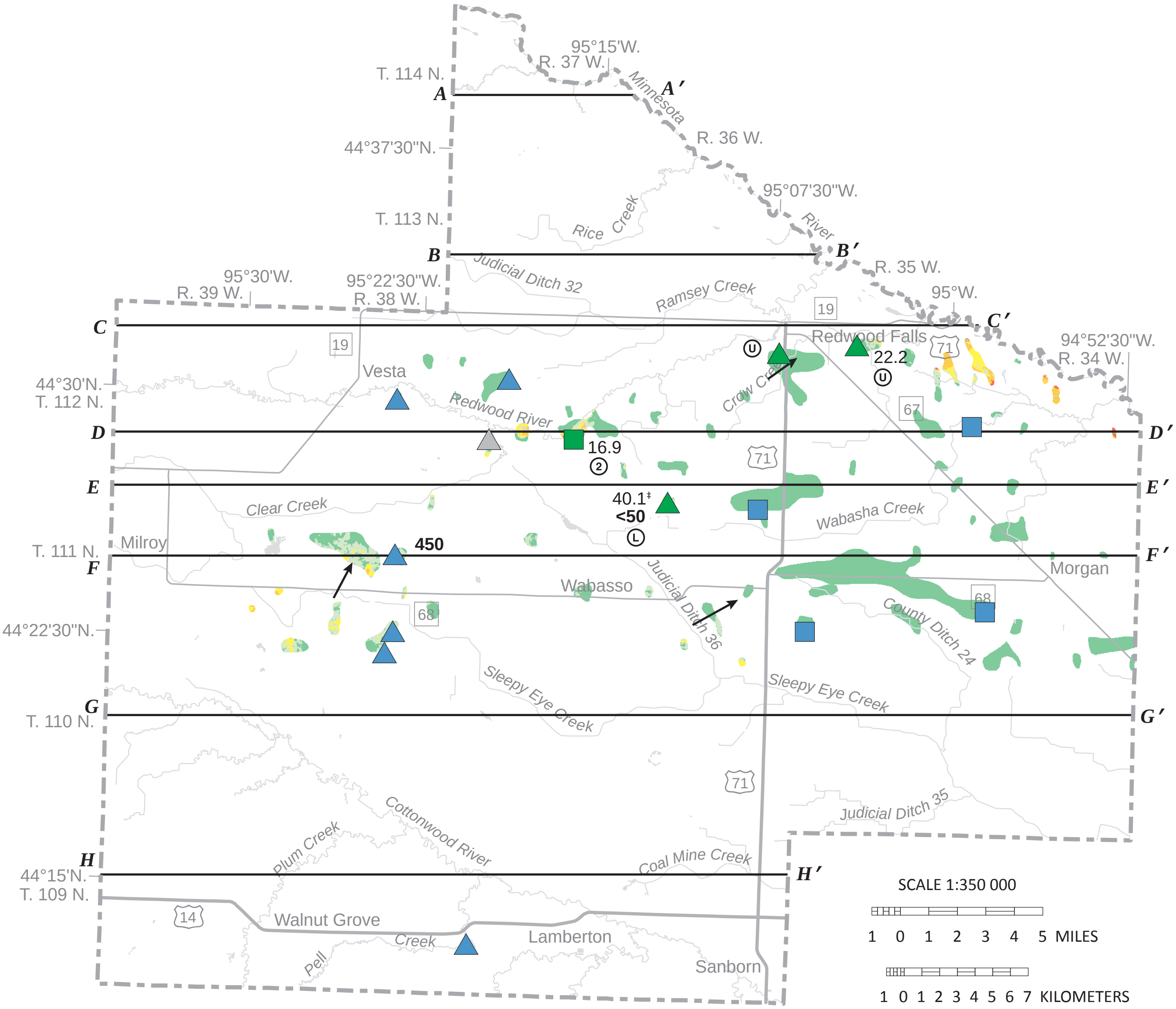
A —— A′ Line of cross section (Part B)

Body of water

Groundwater conditions

(L) Groundwater flows laterally.

Figure 23. Pollution sensitivity of the si and sm aquifers



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage
- Not sampled for tritium.

Sampled well and aquifer symbols

- ▲ s1
- ■ s2

Symbols and labels

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

Groundwater conditions

- ② Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- Ⓛ Groundwater flows laterally.
- Ⓤ Groundwater flow is unknown.

Figure 24. Pollution sensitivity of the s1 and s2 aquifers and groundwater flow directions

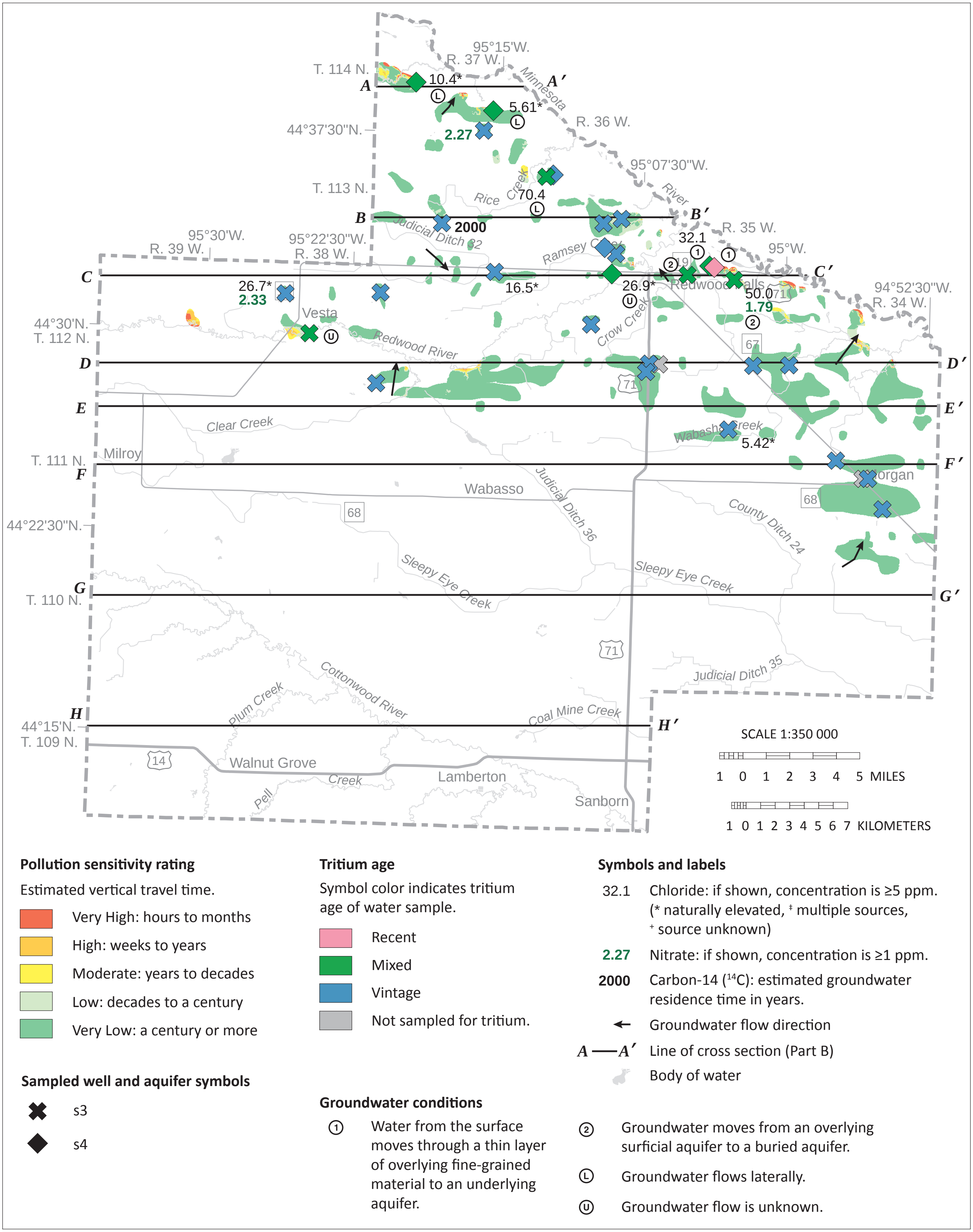


Figure 25. Pollution sensitivity of the s3 and s4 aquifers and groundwater flow directions

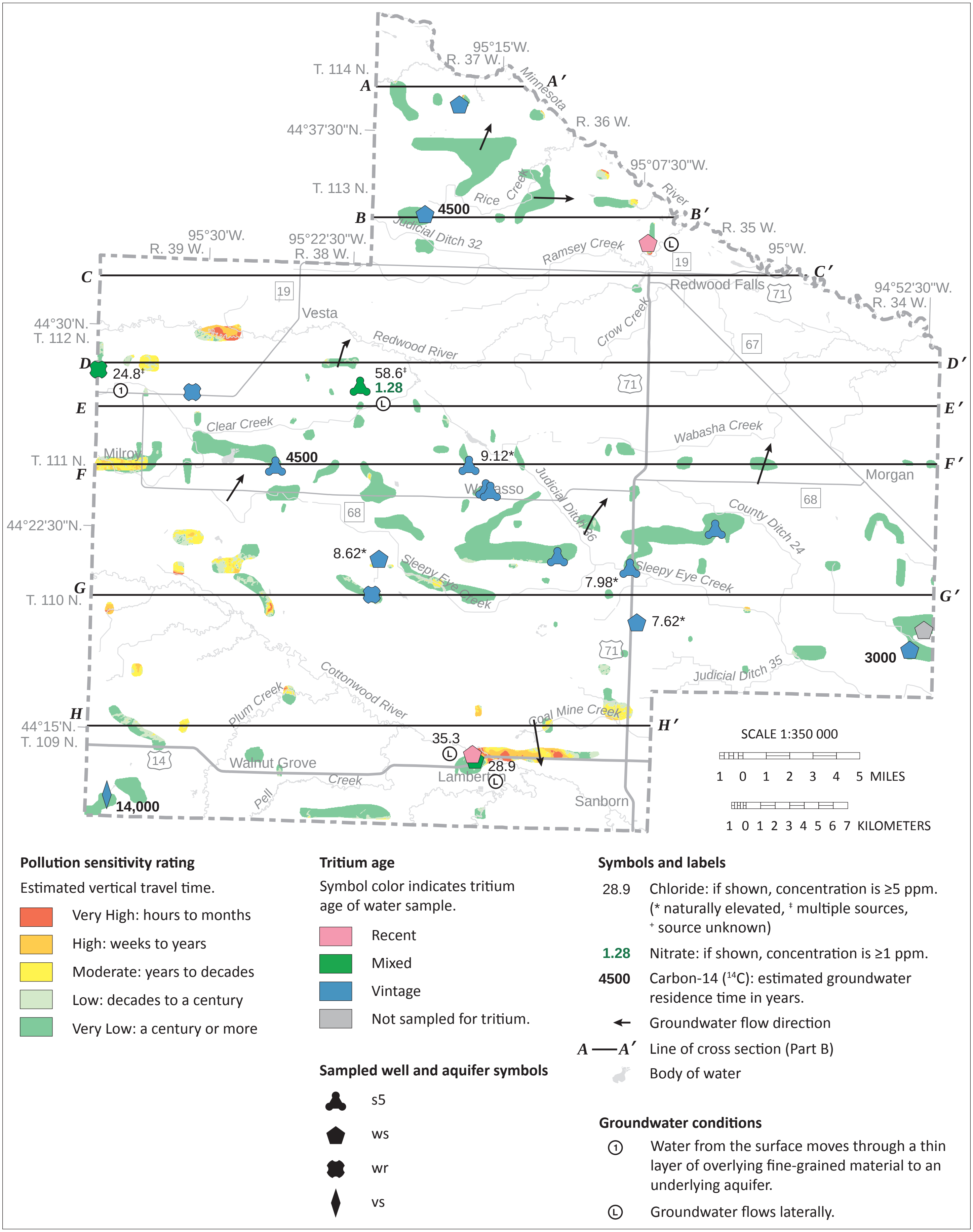


Figure 26. Pollution sensitivity of the s5, ws, wr, and vs aquifers and groundwater flow directions

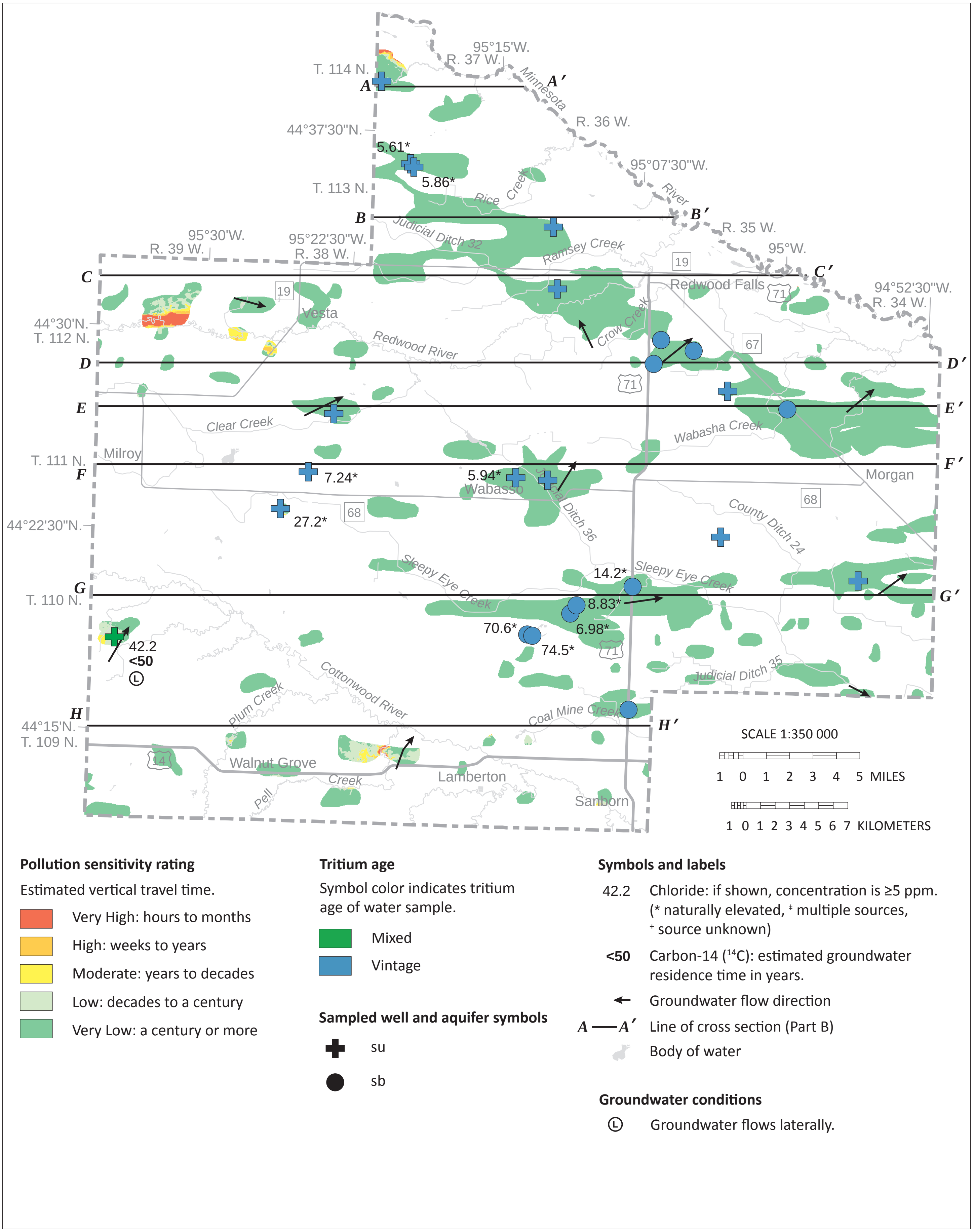
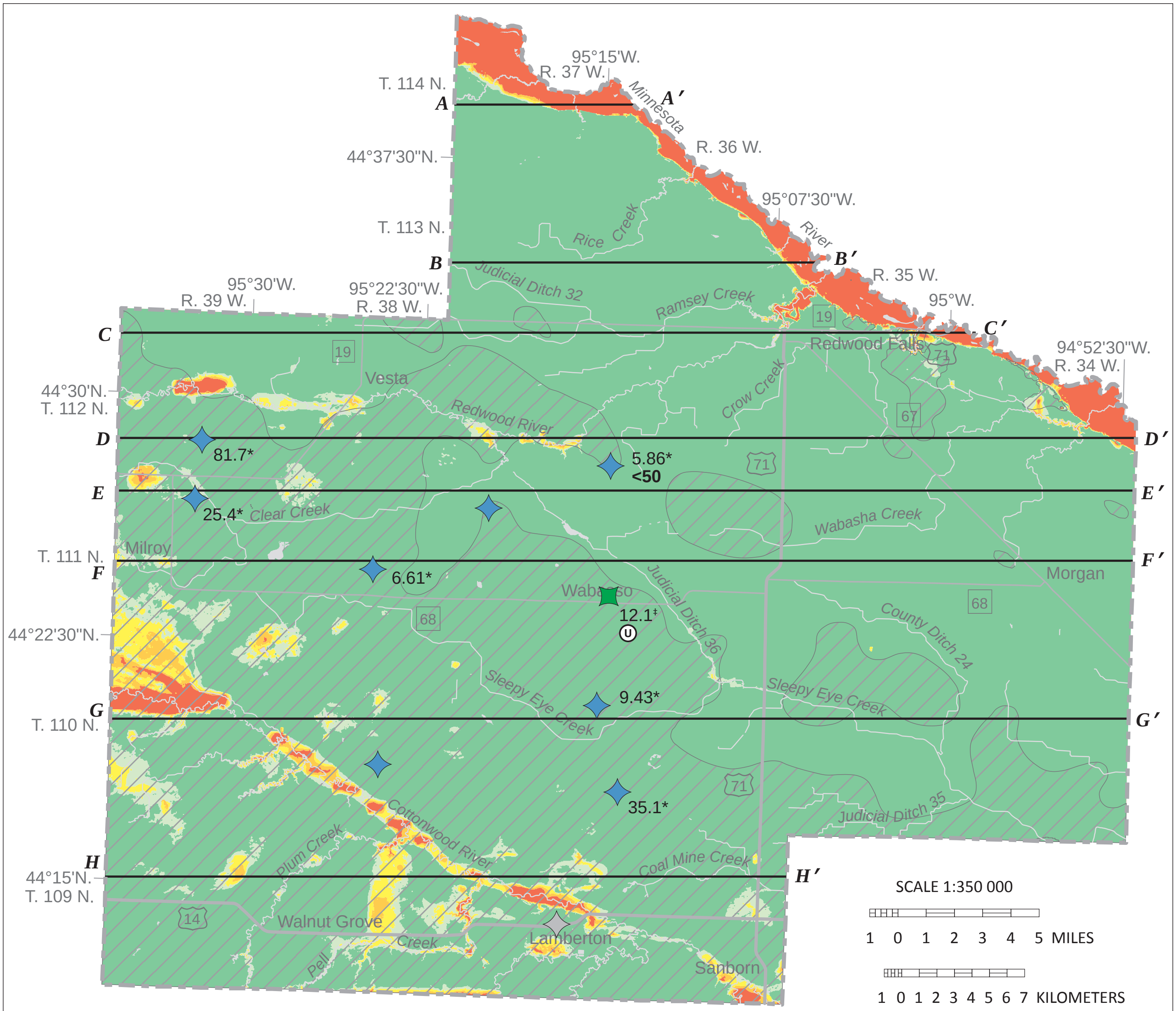


Figure 27. Pollution sensitivity of the su and sb (undifferentiated buried sand) aquifers and groundwater flow directions



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Mixed
- Vintage
- Not sampled for tritium.

Sampled well and aquifer symbols

- Cretaceous undifferentiated (Ku)
- Saprolite (weathered bedrock)

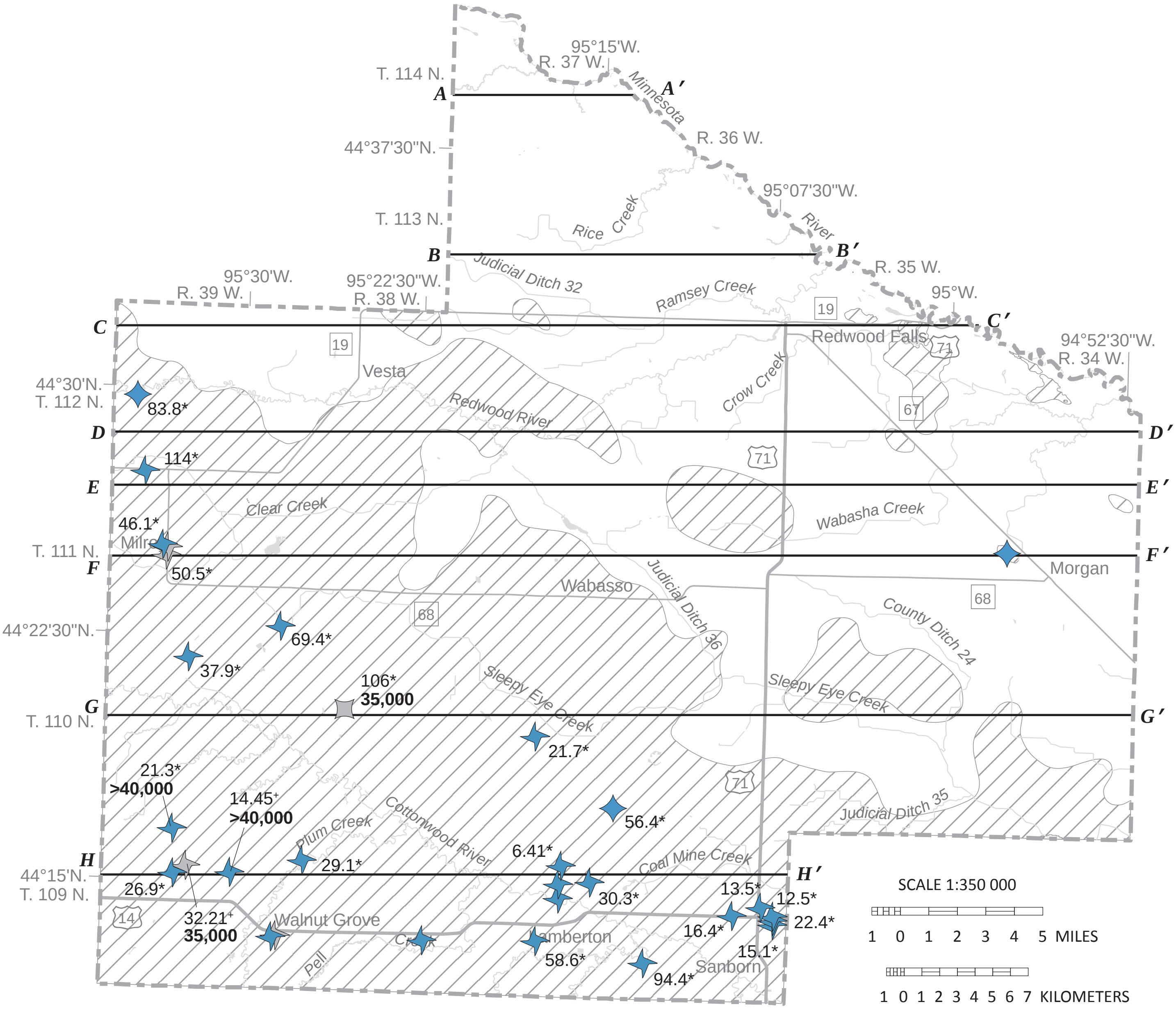
Symbols and labels

- 35.1* Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, ‡ multiple sources, + source unknown)
- <50 Carbon-14 (^{14}C): estimated groundwater residence time in years.
- A —— A′ Line of cross section (Part B)
- Body of water
- Cretaceous bedrock

Groundwater conditions

- Ⓤ Groundwater flow is unknown.

Figure 28. Pollution sensitivity of the bedrock surface



Tritium age

Symbol color indicates tritium age of water sample.

- Vintage
- Not sampled for tritium.

Sampled well and aquifer symbols

- Cretaceous sandstone
- Cretaceous undifferentiated (Ku)
- Saprolite (weathered bedrock)

Symbols and labels

14.45+	Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated, ‡ multiple sources, + source unknown)
>40,000	Carbon-14 (^{14}C): estimated groundwater residence time in years.
A —— A′	Line of cross section (Part B)
	Body of water
	Cretaceous bedrock

Figure 29. Deeper bedrock groundwater chemistry

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 and intersect areas with high-volume municipal pumping.

Eight cross sections were selected from a set of 57 regularly-spaced (1 kilometer) west-to-east cross sections created by the MGS. The cross sections were constructed in GIS using a combination of well data from CWI and the following sections of Part A: Bedrock Geology (Plate 2), Surficial Geology (Plate 3), and Quaternary Stratigraphy (Plate 4). The well information for each cross section was projected onto the trace of the cross section from distances no greater than one-half kilometer.

Relative hydraulic conductivity

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

Glacial sediment layers that act as aquitards (till units) are shown in shades of gray on Plates 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.

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 (Plates 7 and 8).

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

Groundwater recharge and discharge

Downward and lateral flow directions are most common across all of these cross sections, except for the area near the Minnesota (cross sections A–A′ and B–B′), Redwood (cross section C–C′), and Cottonwood (cross section G–G′) rivers. In those areas, groundwater flow is likely upward indicating discharge to these major rivers. In many areas recharge to the deeper aquifers can take a very long time. The residence time can be hundreds or thousands of years where focused recharge does not occur through interconnected buried sand aquifers. The carbon-14 relationships shown on the hydrogeologic cross sections are a useful tool for visualizing this very slow type of recharge through aquitards. Carbon-14 residence time values range from less than 50 to greater than 40,000 years.

Some of the carbon-14 sampling sites were selected as nearby pairs of wells that pump water from a shallow and a deeper aquifer to test the idea that there should be a locally distinct difference in residence time. In a pair of wells in the north, south of Belview (left side B–B′), the shallower s3 aquifer had a residence time of 2,000 years compared to the nearby and deeper ws aquifer well with a residence time of 4,500 years. Another well pair that illustrates very slow groundwater recharge through glacial till aquitards is shown on the left side of cross section F–F′. The well completed in the shallower aquifer (s1) and the deeper aquifer (s5) are located northeast and northwest of Lucan, respectively. The shallow–deep aquifer comparison in this area was 450 years versus 4,500 years.

Other very old residence time results include 4 groundwater samples in the southwestern part of the county. One saprolite sample northeast of Walnut Grove has a residence time of 35,000 years and is shown on the left portion of G–G′, east of Cottonwood River. Three Cretaceous sandstone aquifer samples with residence times of 35,000 to greater than 40,000 years are northwest of Walnut Grove. One of these samples is shown on the left side of cross section H–H′, west of Plum Creek.

Examples of focused recharge shown on the cross sections include:

- Cross section A–A′: one sample on the west side of the cross section where groundwater appears to be recharging the s4 aquifer through the base of an overlying unnamed ravine. This mixed tritium-age sample had an elevated natural chloride value of 10.4 ppm.

- Cross section C–C′: two samples are on the right side of the cross section in eastern Redwood Falls and east of the city limits. Both of these mixed tritium-age samples from the s3 aquifer appear to have been recharged from the overlying surficial aquifer through a relatively thin overlying section of glacial till. The eastern sample of the pair had an elevated anthropogenic chloride concentration (50 ppm) and an elevated nitrate concentration (1.79 ppm).

The groundwater discharge to rivers shown on the cross section is interpreted. Direct evidence of groundwater discharge to rivers in the county is largely beyond the scope of this project. Evidence of groundwater discharge can include hydraulic head or chemical data from multiple wells near rivers showing reversed (upward) gradients. None of these types of data were available for this project. Examples of interpreted groundwater discharge to the Minnesota River is shown on the right side of cross sections A–A′ through D–D′ from fractured Precambrian bedrock. Groundwater flow to the Redwood River is shown at multiple locations on cross sections C–C′ (right side) and D–D′ (center). River discharge is also shown on cross sections G–G′ (left side) and H–H′ (center) to the Cottonwood River.

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 10 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.

All of the specific capacity data listed are for surficial sand (water table) and buried sand aquifers. The surficial sand aquifers have the highest mean values (59 gpm/ft) compared to the buried sand aquifers (24 gpm/ft). Both types of aquifers have a similar, relatively high range of values.

Transmissivity is an aquifer's capacity to transmit water. It provides a more accurate representation of the aquifer properties than specific capacity because it is calculated from longer-term and larger-scale aquifer tests. It is determined by multiplying the thickness of the aquifer by the hydraulic conductivity of the aquifer material (the rate groundwater flows through a unit cross section). The buried sand aquifer transmissivity values had the highest mean value of approximately 14,500 ft^2/day. However, the data lack adequate representation of surficial sand and Cretaceous sandstone aquifers since there were only one and two test results, respectively for those types of aquifers.

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 sand (water table)	12–24	59	10	189	69	12	3,900	-	-	1
Confined buried sand	10–16	24	4	230	86	12–16	14,500	7,000	25,000	8
Cretaceous sandstone	-	-	-	-	-	8	280	220	350	2

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

Groundwater use

A water-use appropriation permit is required from the DNR for groundwater users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year. This provides the DNR with the ability to assess which aquifers are being used and for what purpose. Permits require annual water-use reporting. This information is recorded using Minnesota Permitting and Reporting System (DNR, 2018), which helps the DNR track the volume, source aquifer, and type of water use.

Permitted groundwater use (Table 3) is presented by general aquifer type (Figure 30) and by water use type (Figure 31). The highest volume use is from the buried sand aquifers (74 percent), followed by surficial sand (13 percent), and Cretaceous sandstone (10 percent). The most common water use is for municipal/public water supply (69 percent) followed by livestock watering (13 percent) and petroleum-chemical processing (9 percent). By numbers of wells in the county (approximately 1,500), 86 percent are domestic, and 5 percent are public supply. All the remaining categories, such as commercial, industrial, or irrigation are less than 5 percent by numbers of wells.

Table 3. Reported 2017 water use from DNR groundwater permit holders

Aquifer	Number of wells	Agricultural/food processing	Golf course irrigation	Livestock watering	Municipal/public water supply	Petroleum-chemical processing/ethanol	Total (mgy)	Total (percent of 2017 water use)*
Quaternary								
Surficial sand (water table)	3	-	20	-	-	44	64	13
Buried sand	35	13	12	42	305	3	375	74
Cretaceous sandstone	17	-	-	8	40	-	48	10
Unknown	3	-	-	16	2	-	18	3
Total (mgy)	58	13	32	66	347	47	505	
Total (percent)*		3	6	13	69	9		

Data from MPARS; mgy, million gallons per year; dash mark (-), no use in that category
*Percentage may not equal 100 due to rounding.

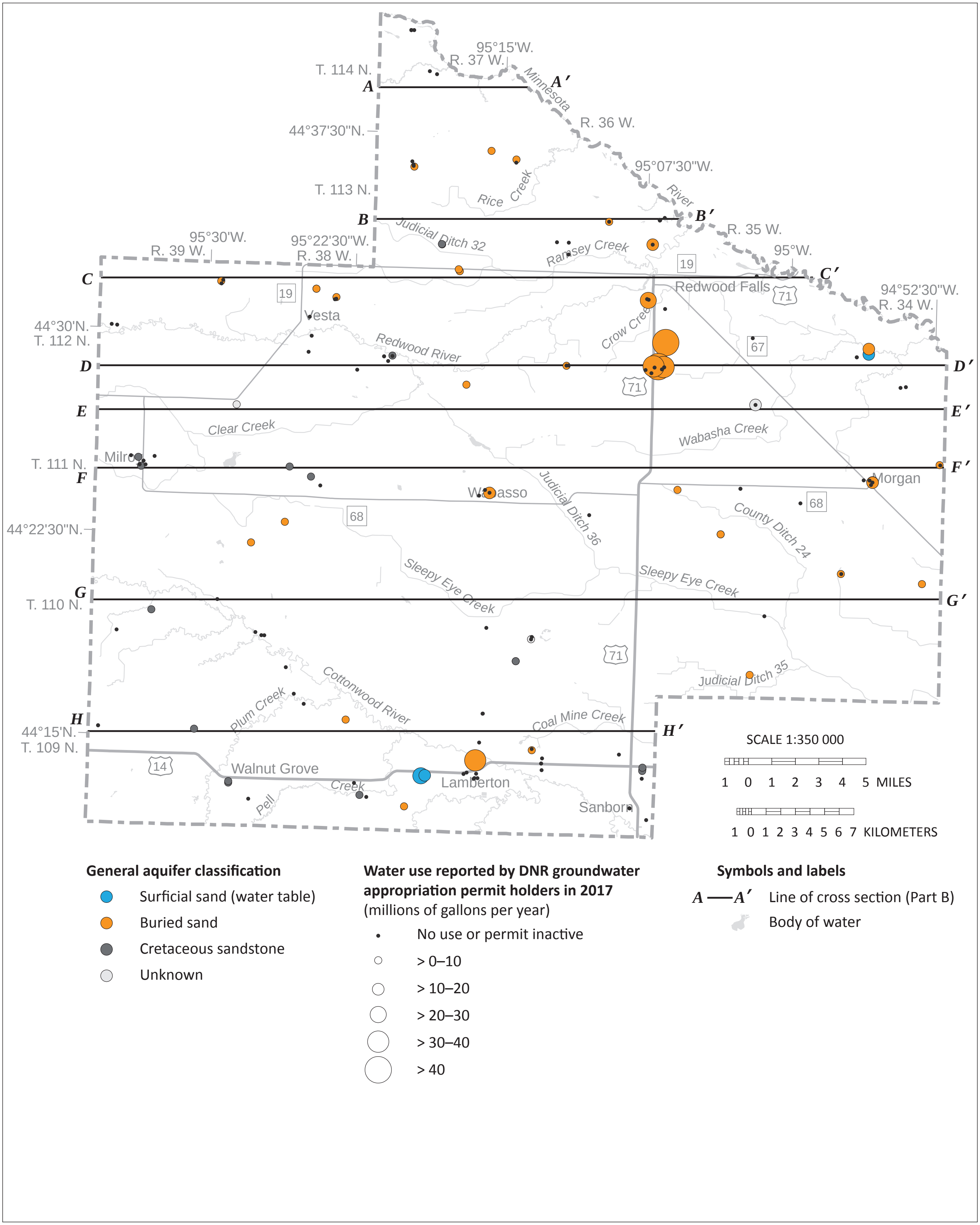


Figure 30. Groundwater use shown by general aquifer classification of DNR appropriation permit holders.

Buried sand aquifers are the most used type of aquifers for high capacity use. The highest use areas include the Redwood Falls and Lamberton areas.

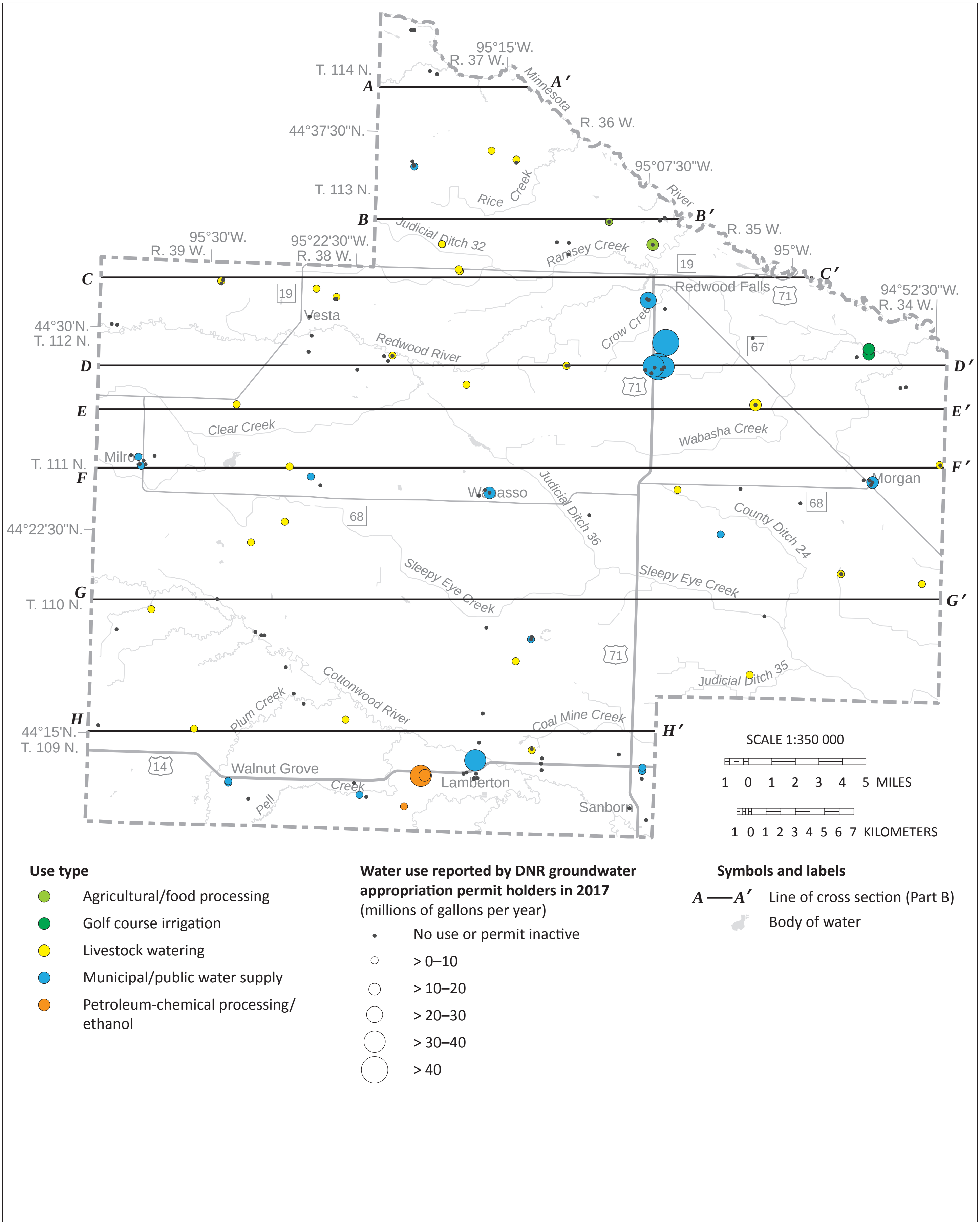


Figure 31. Groundwater use shown by use type of DNR appropriation permit holders.

Municipal/public water supply is the most common type of groundwater use in the Redwood Falls area. Municipal/public water supply and petroleum-chemical processing/ethanol are most common in the Lamberton 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 rapid or significant movement of water.

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

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

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

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

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

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

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

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

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

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

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

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

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

hydraulic—relating to water movement.

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

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

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

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

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

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

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

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

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

Regolith—a layer of loose, heterogeneous superficial deposits covering solid rock.

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

saprolite—a chemically weathered rock.

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

stable isotope—chemical isotopes that are not radioactive.

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

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

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

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

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

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

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

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

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

Appendix A

Groundwater field sample collection protocol

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

Samples were analyzed by DNR staff; the Minnesota Department of Agriculture (MDA); the Minnesota Department of Health (MDH); the University of Minnesota, Department of Earth Sciences Laboratory (U of M); and/or the University of Waterloo Environmental Isotope Laboratory (Waterloo). The well owners received a copy of the results including some background reference information regarding their meaning.

For additional information, contact the County 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	no	no	yes	yes	yes	yes	no	yes
Preservative	no	no	5 ml 10% H_2SO_4 (yellow cap)	no	2.5 ml 20% HNO_3 (red cap)	no	no	NH_4OH to pH 8.5
Refrigeration	no	no	yes	yes	yes	yes	yes, if not analyzed onsite	no
Shelf life	long	long	2–3 weeks	2–3 weeks	2–3 weeks	2–3 weeks	24–48 hours	years
Field duplicate	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	1 for every 20	none
Field blank	none	none	1 for every 20***	1 for every 20***	1 for every 20***	1 for every 20***	none	none
Storage duplicate	yes	yes	no	no	no	no	no	no

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

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

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

Appendix B

Tritium values from precipitation and surface water

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

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: MNgage precipitation station enriched tritium results

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

Tritium age of historic groundwater samples

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

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

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

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

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

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