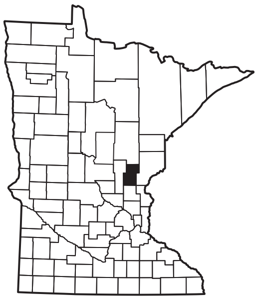
Groundwater Atlas of Kanabec County, Minnesota



County Atlas Series C-38, Part B

Report

To accompany these atlas components:

Plate 6, Water Chemistry

Plate 7, Hydrogeologic Cross Sections

DEPARTMENT OF NATURAL RESOURCES

St. Paul 2020

mndnr.gov/groundwatermapping

The County Atlas Series

The Minnesota County Atlas Series has been produced since 1982. Recent atlases are produced in two parts: Part A: Geology, and Part B: Groundwater (this atlas). Note that prior to 2019 both were titled the "*Geologic* Atlas of X County." The Part B title was changed to "*Groundwater* Atlas of X County" to distinguish the content.

Part A - Geologic Atlas

The precursor to this atlas is Part A, Geologic Atlas of Kanabec County, Minnesota (Boerboom, 2016), published by the Minnesota Geological Survey (MGS). It contains Plate 1, Data-Base Map; Plate 2, Bedrock Geology; Plate 3, Surficial Geology; Plate 4, Quaternary Stratigraphy; Plate 5, Bedrock Topography, Depth to Bedrock, and Sand Distribution Model.

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

Part B - Groundwater Atlas

This atlas was published by the Minnesota Department of Natural Resources, which expanded on the geologic information from Part A. Completed atlases, chemistry data, and more information are available through the Minnesota Department of Natural Resources, Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

Citation for this atlas:
Berg, J.A., 2020, Groundwater Atlas of Kanabec County, Minnesota: Minnesota Department of Natural Resources, County Atlas Series C-38, Part B, report, 2 pls., GIS files.

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

Base maps were modified from MGS, Geologic Atlas of Kanabec County, Minnesota, 2016. Universal Transverse Mercator projection, Zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion factors

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

1 part per million = 1 milligram per liter

1 part per billion = 1 microgram per liter

1 milligram per liter = 1000 micrograms per liter

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

Report contents

Report figures

Report tables

Plates (accompanying folded inserts)

Acknowledgments

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Groundwater Atlas of Kanabec County, Minnesota

by James A. Berg

Executive summary

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

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

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

Kanabec County is located in east-central Minnesota (Figure 1) with land use that is a mix of agricultural, rural, and small towns. The population in 2018 was approximately 16,000 (U.S. Census Bureau, 2019). The county lies mostly within the Snake River watershed and smaller portions of the Rum and Kettle river watersheds.

Kanabec 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 66 degrees Fahrenheit June through August, and 12 degrees Fahrenheit December through February (NOAA, 2019). Average annual precipitation is approximately 28 inches, placing it in the middle of the statewide range of 20 to 36 inches.

Geology and physical hydrogeology (pages 4–17) 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).

Portions of the county are underlain by sand and gravel; other areas are underlain by finer-grained glacial till and lake deposits. The surficial sand has a complex distribution that was controlled by the advance and retreat of the last major ice sheets in the area from the northeast. The surficial sand aquifer is a minor source of groundwater use in the county, but it contributes to surface-water systems. The most commonly used source is the buried sand and gravel aquifers. These were deposited from previous glacial advances and retreats along with a series of intervening fine-grained layers of till and lake sediment.

Beneath the glacial sediments are bedrock sources of groundwater, which include the Hinckley and Fond du Lac aquifers. These provide reliable and widespread sources of groundwater in the eastern portions of the county. Both aquifers are thick (hundreds to thousands of feet) mostly coarse-grained units (Hinckley–sandstone composed of about 96 percent quartz, Fond du Lac–quartzose to mostly feldspar with interbeds of siltstone and shale).

The oldest bedrock is metamorphosed sedimentary and volcanic rock, and various types of granitic igneous rock. These types of bedrock have interlocking grains and crystals that leave few spaces for water (porosity) and few connections for water to flow (permeability). Although they are generally not considered aquifers, low-volume wells can be constructed if the well borehole encounters a fault or fracture that can convey small amounts of water.

Water table (pages 4–7) groundwater flow directions are regionally toward the Snake River and locally toward many of the smaller water bodies. Water-table depths are shallow (0–20 feet) across most of the county. The water table may be deeper along the Snake and Knife river bluff areas, and beneath large drumlins throughout the county but especially in the north.

Buried sand and gravel, and bedrock aquifers (pages 8–17) show potential groundwater flow patterns that are similar to groundwater flow in the water table: predominantly toward the Snake River.

Water chemistry (pages 18–25, 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** in groundwater is relatively widespread in the county. Anthropogenic occurrences (human caused) were found mostly in buried sand and gravel aquifers in the western and southern portions of the county and in the bedrock aquifers in the east and north.
- **Nitrate** was not commonly found. However, elevated occurrences were found in all parts of the county in the surficial, upper buried sand and gravel, and shallow bedrock aquifers.
- **Arsenic** is a naturally occurring, geologic-sourced contaminant in Minnesota, but high concentrations are not common in the county. Those at or above the recommended levels were located in the central part of the county. The Minnesota Department of Health recommends treatment if any arsenic is present.
- **Manganese** is a naturally occurring, geologic-sourced contaminant in Minnesota. Elevated values were found in most of the mapped aquifers in the county.
- **Residence time** in aquifers reflects the wide range of groundwater conditions. A high proportion of tritium detection reflects the relatively permeable nature of glacial sediment and bedrock in the county. Carbon-14 analysis detected water ranging from 550 to 7,500 years.

The pollution sensitivity (pages 26–42) of an aquifer is estimated based on the time it takes water to flow from the land surface through various types and thicknesses of soils and geologic materials. Pollutants are assumed to travel with water at the same rate. The sensitivity is modeled with different methods for the 1) near-surface materials and 2) buried sand and gravel aquifers and the bedrock surface. The model results are evaluated by comparing the pollution sensitivity ratings to chemical constituents such as tritium and carbon-14 data for residence time, and to inorganic chemicals for contamination.

- **Near-surface materials** (pages 26–28) map shows pollution sensitivity is highly variable. A complex distribution of low, moderate, and high sensitivity dominates the central part of the county. Very low sensitivity exists in the southern part of the county where finer-grained lake clay is at the surface. Very high sensitivity is mapped in the northeastern area where it is prone to karst.
- **Buried sand and gravel aquifers** (pages 29–41) exhibit a wide range of pollution sensitivity from mostly very high for the shallowest aquifer (csr) to mostly very low for the deeper aquifers (bsg to the bedrock surface).
- **Bedrock surface** (pages 29–33 and 42) has mostly a very low pollution sensitivity with the exception of scattered areas of moderate to very high sensitivity throughout the county. Larger areas of higher sensitivity are shown in the northern portion where bedrock is relatively shallow.

Hydrogeologic cross sections (pages 43–44, Plate 7) illustrate groundwater flow, residence time, distribution of chemical indicators. Cross sections help define areas of interest such as locations of important groundwater recharge, discharge, and sensitivity to anthropogenic pollution. Groundwater flow in the county is initially downward, then laterally toward surface-water bodies. In many areas recharge to the deeper aquifers can take hundreds or thousands of years, as long as there is no focused recharge through interconnected buried sand and gravel aquifers.

Aquifer characteristics and groundwater use (pages 45–47) 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 and plan for new well installations. The highest volume of groundwater use is from the buried sand aquifers (93 percent). The most common water use by volume is for water supply (75 percent). There are approximately 3,300 nonregulated wells (not requiring an appropriation permit) in the county, primarily for homes. By numbers of wells, 87 percent are domestic (homes) and 2 percent are public supply (cities).

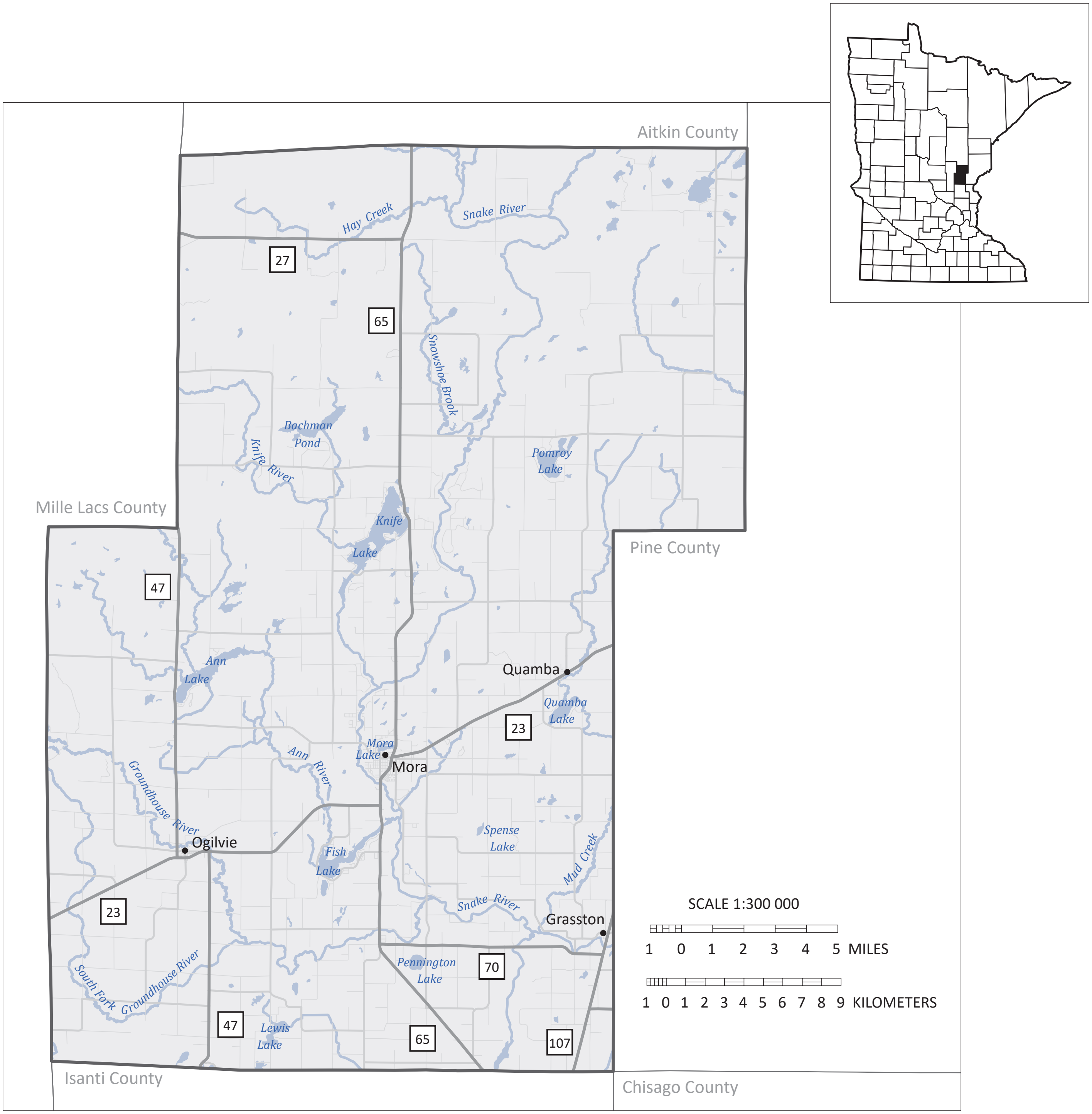


Figure 1. Kanabec County, Minnesota

Geology and physical hydrogeology (Figures 2–13)

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 sediments (Figure 2). The fine-grained sediments include a mixture of sand, silt, clay, and gravel referred to as diamicton or till. Coarser-grained sediments include a mixture of sand and gravel from glacial outwash (deposited in moving water). The complex distribution of surficial sand and gravel is one of the most important geologic features controlling groundwater recharge and the pollution sensitivity of underlying aquifers by anthropogenic contaminants.

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

The last major ice advance in Kanabec County was from the northeast. This Superior ice lobe (Automba phase) deposited most of the fine-grained till at the surface (Figure 2). Much of the surficial sand was deposited from glacial meltwater as sub-glacial esker deposits and proglacial and meltwater fans (Part A, Plate 3, Figures 3 and 4). Some of these glacial stream routes are currently occupied by rivers including portions of the Snake, Groundhouse, Little Ann, and Knife; and lakes including the Knife, Ann, Quamba, and Fish.

Smaller areas of fine-grained glacial lake sediments were deposited in the southern portion of the county as the youngest glacial deposits at the surface. Thinner sandy deposits, including the map unit Qa, were deposited in the postglacial era (Holocene) by smaller and narrower streams. These generally finer-grained sediments are typically on or adjacent to most of the glacial outwash sediment. Drumlins are distinctive topographic features in Kanabec and adjoining counties. These features are hills that are elongated in the direction of glacial ice movement. Drumlins that formed beneath the glacial ice are typically composed of compacted till and can be 50 feet higher than the surrounding landscape.

Water table

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

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

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

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

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

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

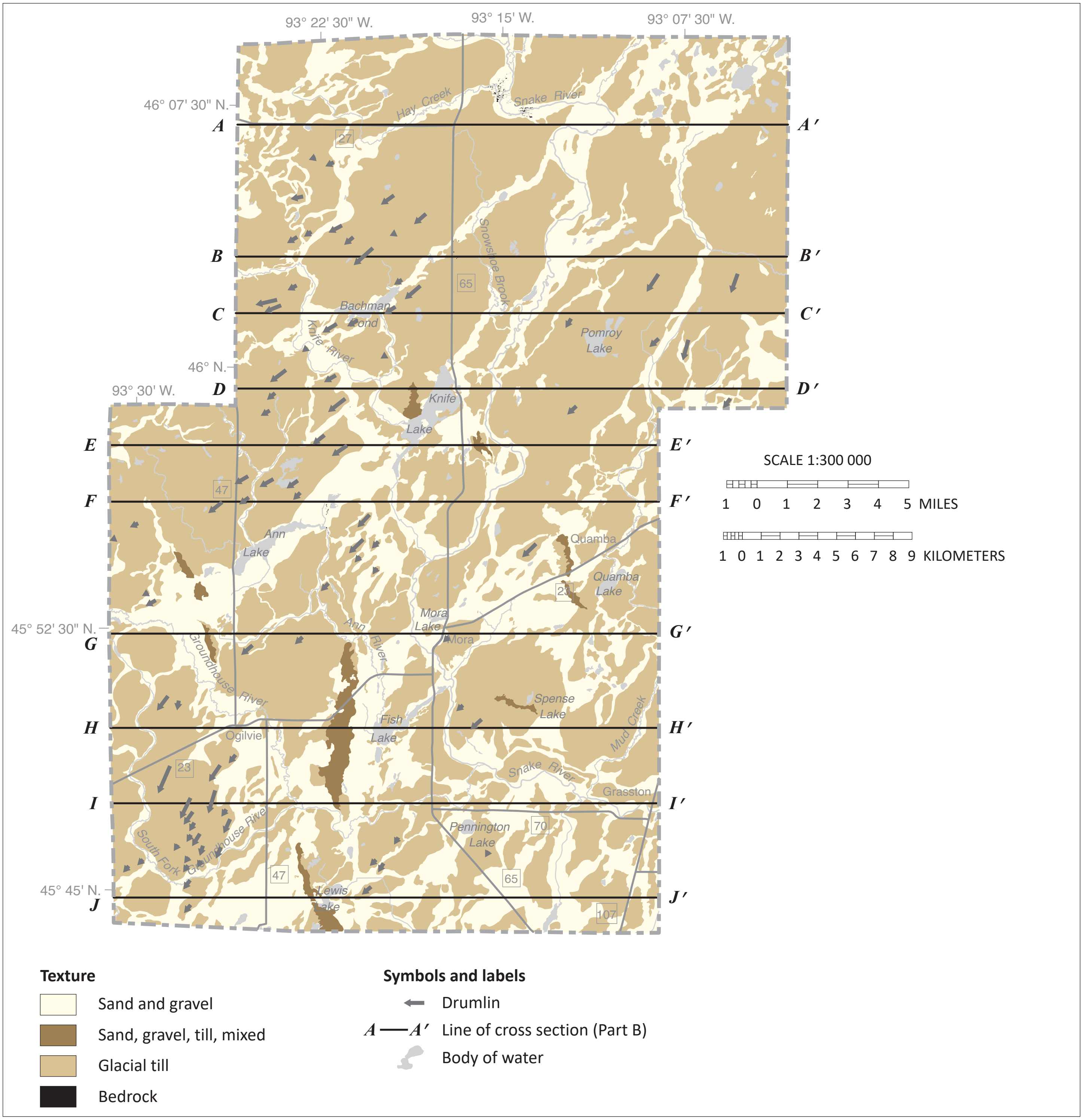


Figure 2. Generalized surficial geologic units

The distribution of surficial sand in Kanabec County was controlled mostly by one late stage glacial event: the advance and retreat of the last major ice sheet from the northeast. The distribution of surficial sand is one of the most important geologic features controlling groundwater recharge and the pollution sensitivity of underlying aquifers (modified from Part A GIS data). Drumlins (glacially formed hills) are shown for comparison with the depth to water table map (Figure 4).

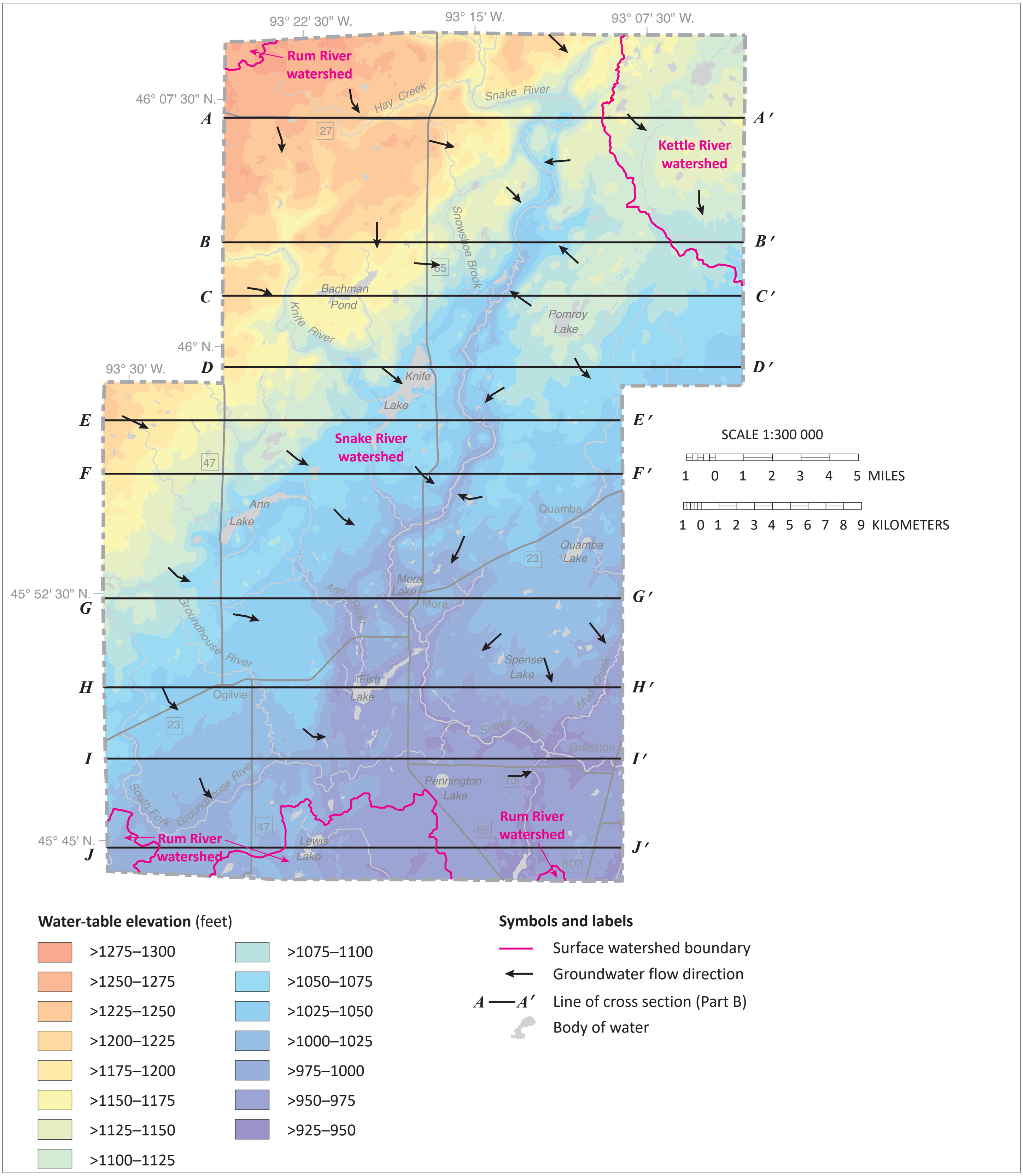


Figure 3. Water-table elevation and groundwater flow directions

Water-table elevations cover a wide range of values with the lowest in the southern portion of the Snake River and associated tributaries. Groundwater flows regionally toward the Snake River and locally toward many smaller water bodies. The highest elevations, with steeper gradients, are northwest of the Snake River along a zone that extends from the west-central to the north-central parts of the county. Only 4 percent of wells in the county are completed in the surficial sand aquifer. Appropriation permit use of this aquifer was less than 1 percent in 2018.

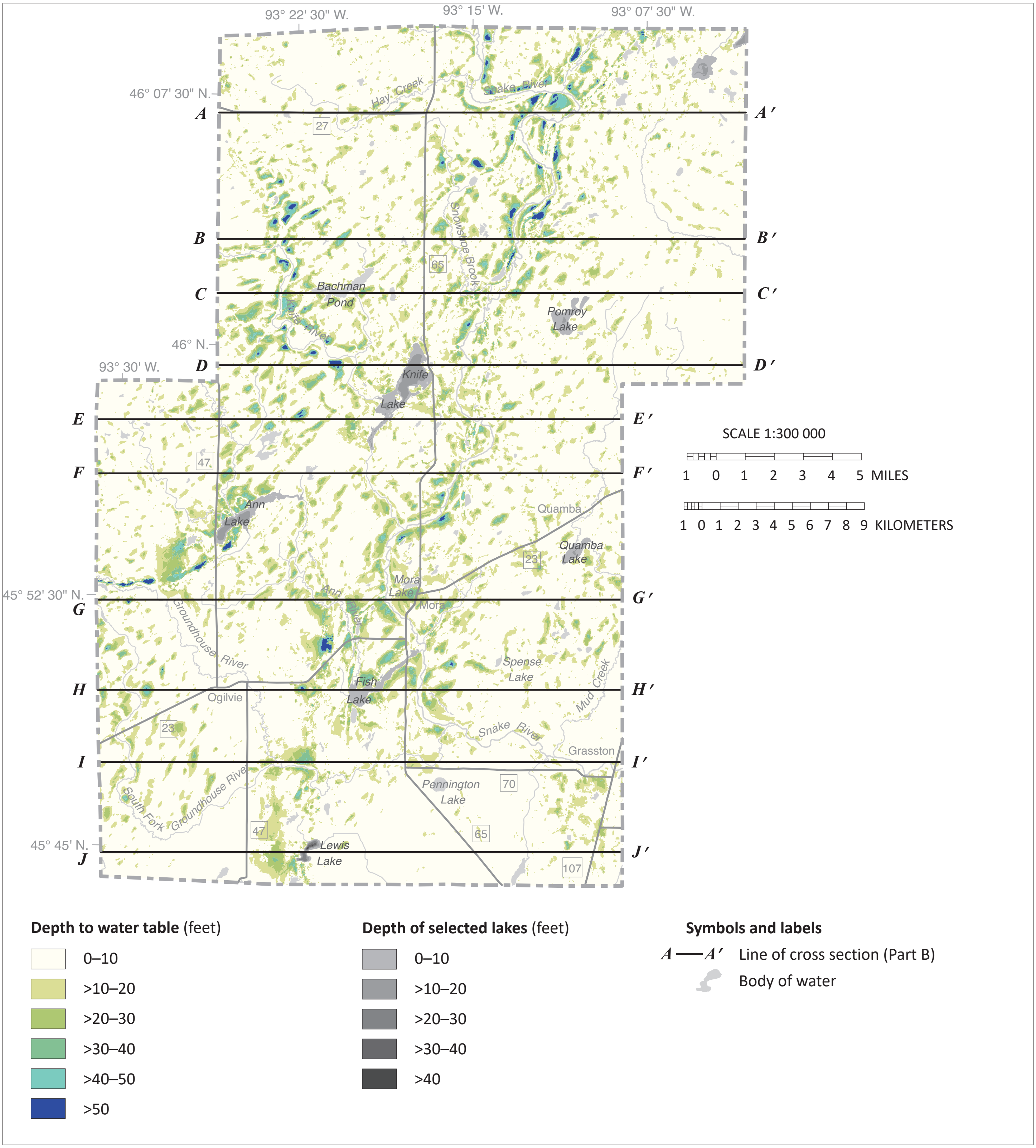


Figure 4. Depth to water table

Water-table depths are shallow (0–20 feet) across most of the county. The water table may be deeper along the Snake and Knife river bluff and beneath large drumlins throughout the county, especially in the north.

Buried aquifers

Sand and gravel

Beneath the surficial geologic deposits are alternating layers of older sand, gravel, and fine-grained deposits from previous glacial advances. Multiple sequences of sand and gravel were deposited by meltwater from the ice lobes through successive advances and retreats. Confining layers (aquitards) that enclose the sand and gravel bodies were formed by unsorted sediment deposited directly by the ice (till), and bedded sediments of clay, silt, and fine-grained sand deposited in ponds and lakes (Part A, Plate 5, Sand Distribution Model–Introduction). These till units tend to be laterally extensive, whereas the buried sand and gravel layers are more limited in extent. Approximately 56 percent of the wells in the county are completed in buried sand and gravel aquifers. Reported water use from this type of aquifer in 2018 was 93 percent of water use in the county.

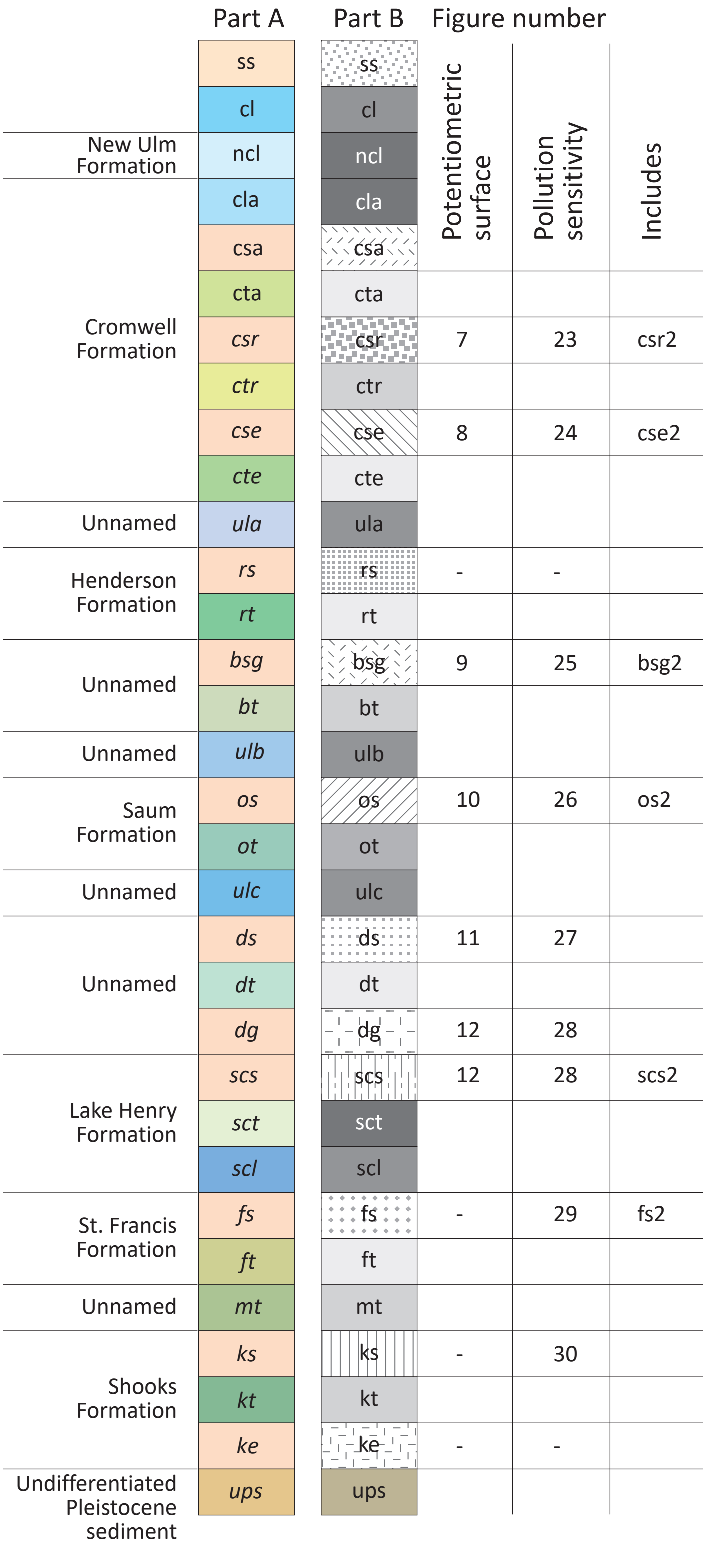
The naming convention for the buried sand and gravel aquifers in this atlas was based on the underlying till unit described in the associated Part A atlas. Detailed descriptions regarding the origin, thickness, and distribution of these glacial deposits are described on Part A, Plate 3 (Glacial History), Plate 4 (Figures 9 and 10), and Plate 5 (Sand Distribution Model).

The stratigraphic column in Figure 5 correlates the glacial geologic units from Part A with the hydrogeologic units of Part B. Part A descriptions are generally classified as 1) *sand and gravel* or 2) *till* or *lake clay*. These are converted into the hydrogeologic descriptions of 1) *aquifer* or 2) *aquitard*.

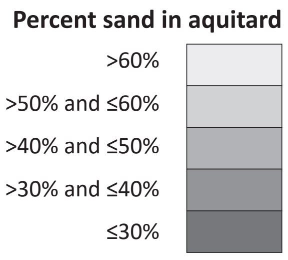
The Part B units are shown as follows:

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

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



	Part A	Part B	Figure number		
			Potentiometric surface	Pollution sensitivity	Includes
	ss	ss			
	cl	cl			
New Ulm Formation	ncl	ncl			
Cromwell Formation	cla	cla			
	csa	csa			
	cta	cta			
	csr	csr	7	23	csr2
	ctr	ctr			
	cse	cse	8	24	cse2
	cte	cte			
Unnamed	*ula*	ula			
Henderson Formation	*rs*	rs	-	-	
	rt	rt			
Unnamed	*bsg*	bsg	9	25	bsg2
	bt	bt			
Unnamed	*ulb*	ulb			
Saum Formation	*os*	os	10	26	os2
	ot	ot			
Unnamed	*ulc*	ulc			
Unnamed	*ds*	ds	11	27	
	dt	dt			
	dg	dg	12	28	
Lake Henry Formation	*scs*	scs	12	28	scs2
	sct	sct			
	scl	scl			
St. Francis Formation	*fs*	fs	-	29	fs2
	ft	ft			
Unnamed	*mt*	mt			
Shooks Formation	*ks*	ks	-	30	
	kt	kt			
	ke	ke	-	-	
Undifferentiated Pleistocene sediment	*ups*	ups			



Percent sand in aquitard

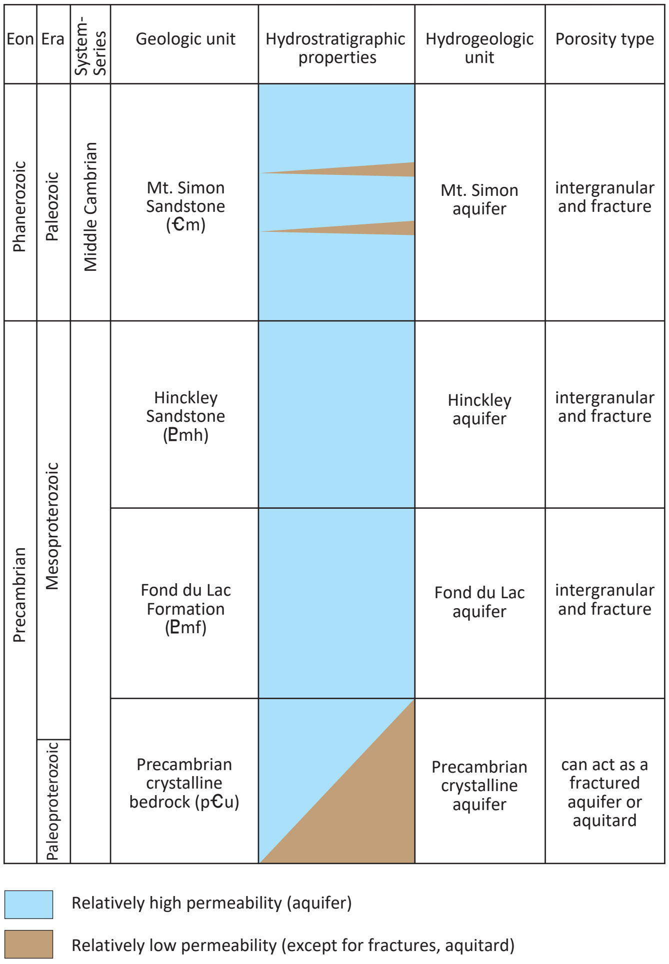
>60%	
>50% and ≤60%	
>40% and ≤50%	
>30% and ≤40%	
≤30%	

Figure 5. Hydrostratigraphy of Quaternary unconsolidated sediment

The maps in this report mostly represent single mapped sand units as shown in the Part A atlas (Plate 4, Figure 10; and Plate 5, Figures 3 through 8). Part A also mapped sand units of limited extent within some major till units. These are named the same name as the major unit, (e.g., cse), with a trailing number added (cse2). In all of the maps in this report, the minor units (last column) are shown along with the same major unit information. For all of the figures that contain major and minor sand units, both units are considered part of the same aquifer.

Bedrock

Although buried sand aquifers represent a widespread and generally available source of groundwater, bedrock sources (Figure 6) also provide reliable and widespread sources of groundwater in the eastern portion of the county, mostly from the Hinckley and Fond du Lac aquifers.



Eon	Era	System-Series	Geologic unit	Hydrostratigraphic properties	Hydrogeologic unit	Porosity type
Phanerozoic	Paleozoic	Middle Cambrian	Mt. Simon Sandstone (€m)	🟦🟫	Mt. Simon aquifer	intergranular and fracture
Precambrian	Mesoproterozoic		Hinckley Sandstone (Ꝑmh)	🟦	Hinckley aquifer	intergranular and fracture
			Fond du Lac Formation (Ꝑmf)	🟦	Fond du Lac aquifer	intergranular and fracture
	Paleoproterozoic		Precambrian crystalline bedrock (p€u)	🟦🟫	Precambrian crystalline aquifer	can act as a fractured aquifer or aquitard

🟦 Relatively high permeability (aquifer)

🟫 Relatively low permeability (except for fractures, aquitard)

Figure 6. Bedrock stratigraphy and hydrostratigraphy

The **Mt. Simon aquifer** is limited and relatively thin in areas of the southern part of the county (Part A, Plate 2). Only 5 located wells in the southeastern part of the county use this aquifer.

The **Hinckley aquifer** is very thick (hundreds of feet along its eastern edge) and is composed of a fine- to medium-grained sandstone of about 96 percent quartz (Part A, Plate 2). Portions in the northeastern part of the county have less than 50 feet of overlying glacial sediment, which makes it prone to the development of karst features (such as sinkholes and solution-enhanced fractures) as in the adjoining Pine County (Boerboom, 2001; Shade, 2002; Berg, 2004). Approximately 19 percent of the located wells in the county are completed in this aquifer.

The **Fond du Lac aquifer** underlies the Hinckley aquifer and has a similar geometry: a vast wedge that is thick in the southeast and thins to the northwest. However, the Fond du Lac is much thicker (more than a kilometer) along its eastern boundary. This formation is described as a medium- to coarse-grained arkosic sandstone (contains substantial feldspar as well as quartz) (Part A, Plate 2). Based on limited specific capacity data from Pine County (Berg 2004, Plate 8, Table 1), this aquifer probably has a lower hydraulic conductivity due to its higher clay content and beds of siltstone and shale. Approximately 9 percent of the located wells in the county are completed in this aquifer.

Undifferentiated Precambrian bedrock is the oldest bedrock of Kanabec County, consisting primarily of faulted and folded metamorphosed sedimentary and volcanic rocks, and various types of granitic igneous rock. The interlocking grains and crystals in these types of rock leave very few spaces for water (porosity) and very few connections for water to flow (permeability). Therefore, all the nonsedimentary Precambrian bedrock has been grouped as one unit for the purposes of this report.

These types of bedrock can act as limited aquifers where overlying sand or sandstone aquifers are not available. Low-volume wells can be constructed if the well borehole encounters a fault or fracture that can convey small amounts of water or when wells are constructed as cisterns (excessively deep). Less than 3 percent of the located wells in the county are completed in this type of fractured bedrock. Most of these are in the western part of county where the overlying glacial sediment is commonly thin, sand aquifers are limited, and sedimentary bedrock is absent or thin (Part A, Plate 2).

Groundwater flow

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

The potentiometric surface of an aquifer represents the potential energy available to move groundwater. Groundwater moves from higher to lower potentiometric elevations, flowing 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. Important recharge areas could be indicated by high elevation areas on the potentiometric surface, when combined with other information. River valleys are typical examples of low elevation discharge areas.

Potentiometric surface maps were created using static water-level data from the CWI, measurements made by the DNR staff, and river elevation points (3000-meter spacing) along the major rivers. River elevation points are included where groundwater discharge is likely. The CWI records represent various climatic and seasonal conditions from the 1950s to 2017. This data variability creates some uncertainty in potentiometric surface elevations (MGS and MDH, 2017).

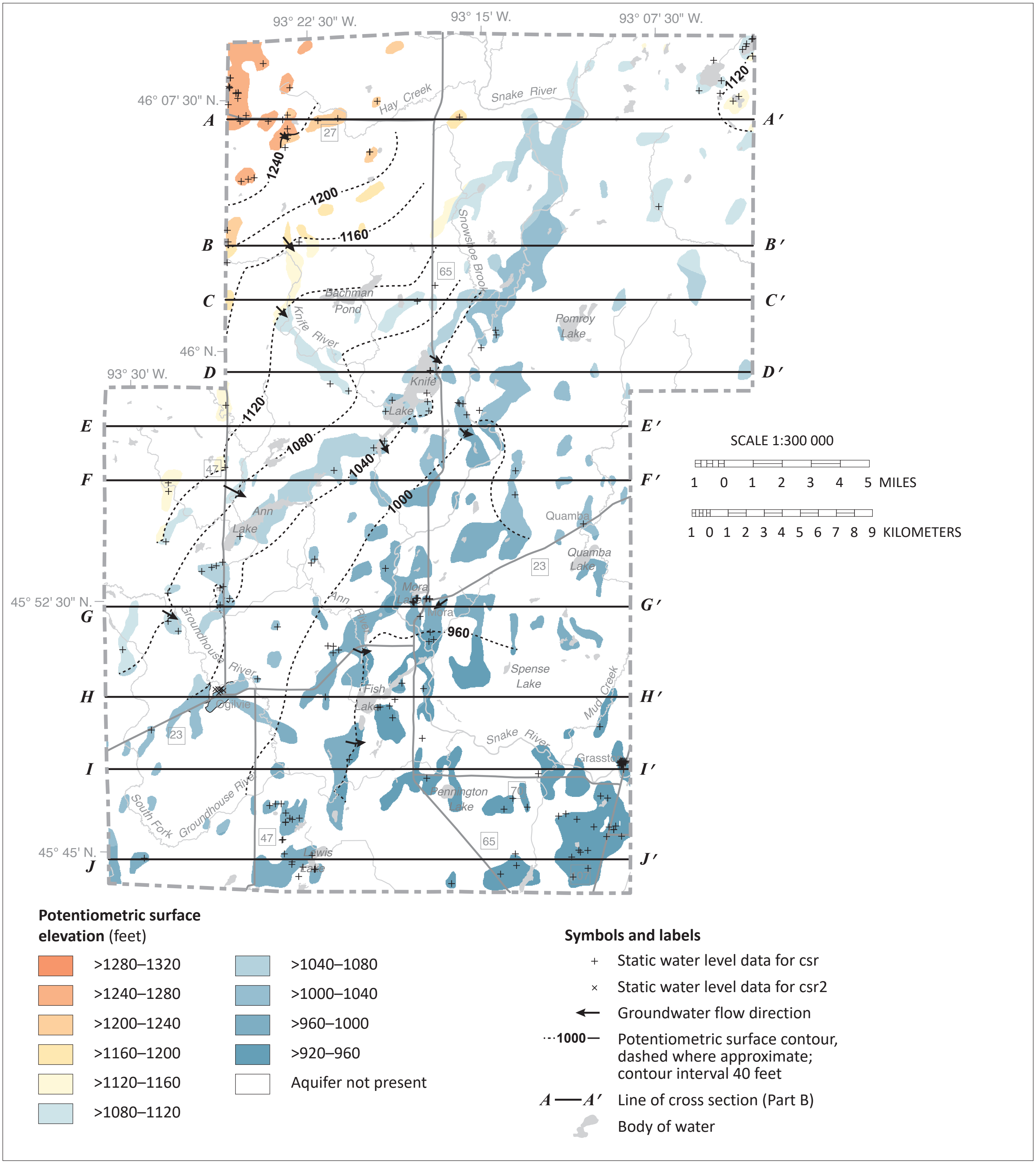


Figure 7. Potentiometric surface of the csr aquifer

The csr is relatively widespread within the county and has southwest to northeast orientation, which might be expected from ice lobes that advanced and retreated from the county from a northeastern source. The dominant groundwater flow direction is toward the Snake River and more local flow is toward the Knife River. Groundwater flow to or from other perennial streams in the area is inconclusive based on interpolated water-elevation data. The csr2 (outlined) was defined only in the southwest.

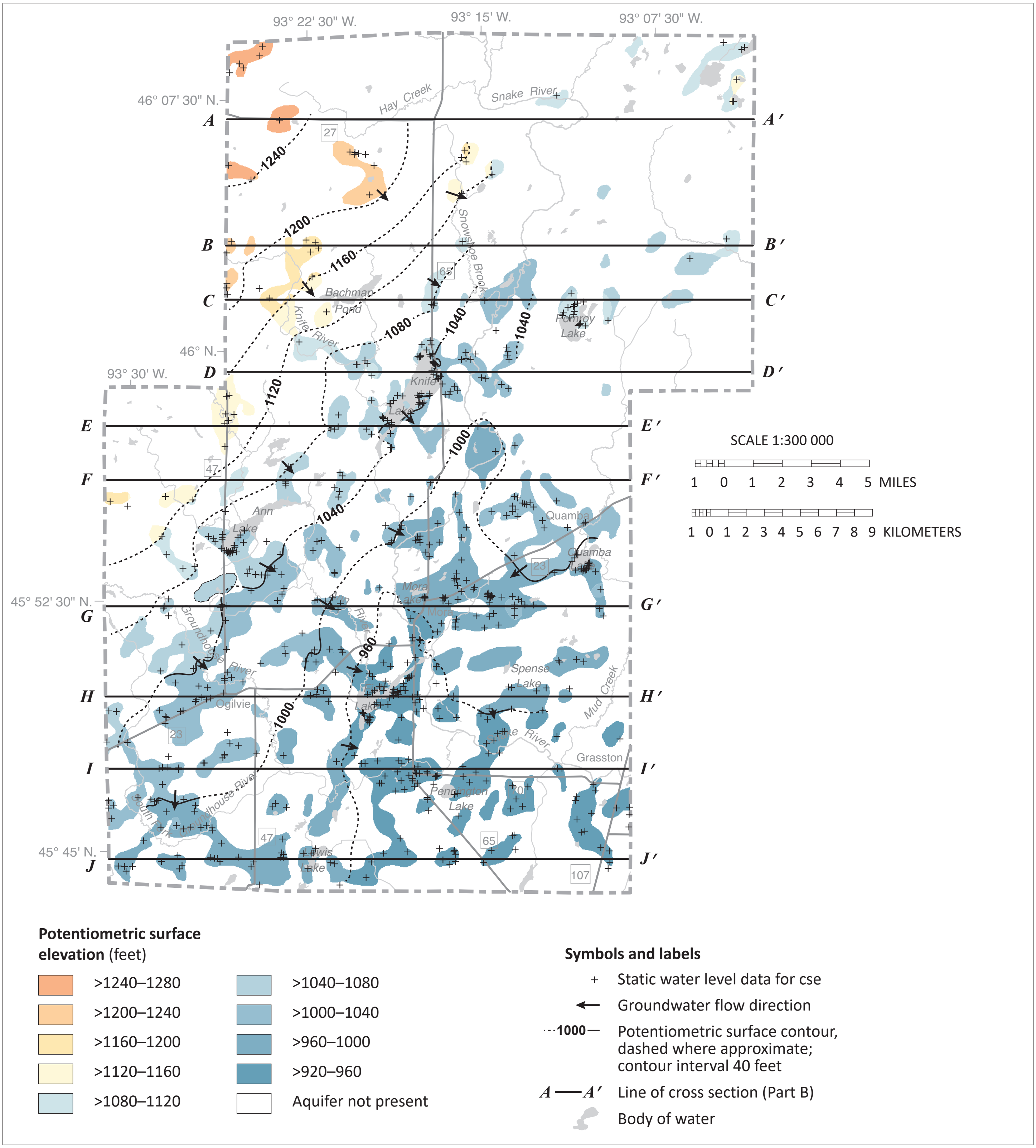


Figure 8. Potentiometric surface of the cse aquifer

The cse is relatively widespread within the county. The dominant groundwater flow direction is toward the Snake River and more local flow is toward the Knife River. The cse2 (outlined) was defined only in the southwest.

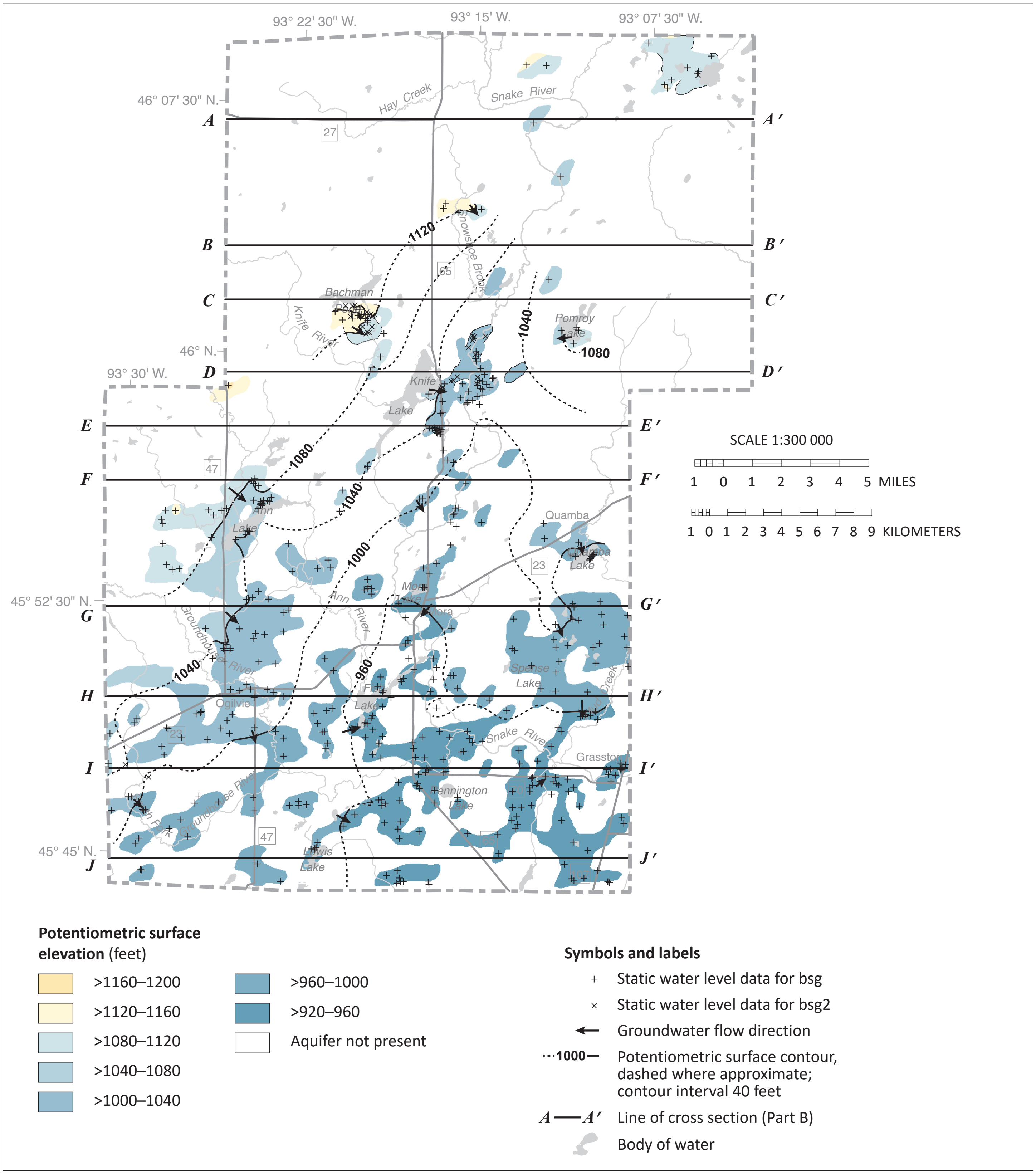


Figure 9. Potentiometric surface of the bsg aquifer

The bsg is extensive in the southern portion of the county but sparse in the north. The dominant groundwater flow pattern is to the Snake River. The map also suggests groundwater flow to Mud Creek in the southeastern part of the county. The bsg2 (outlined) was defined only in the north.

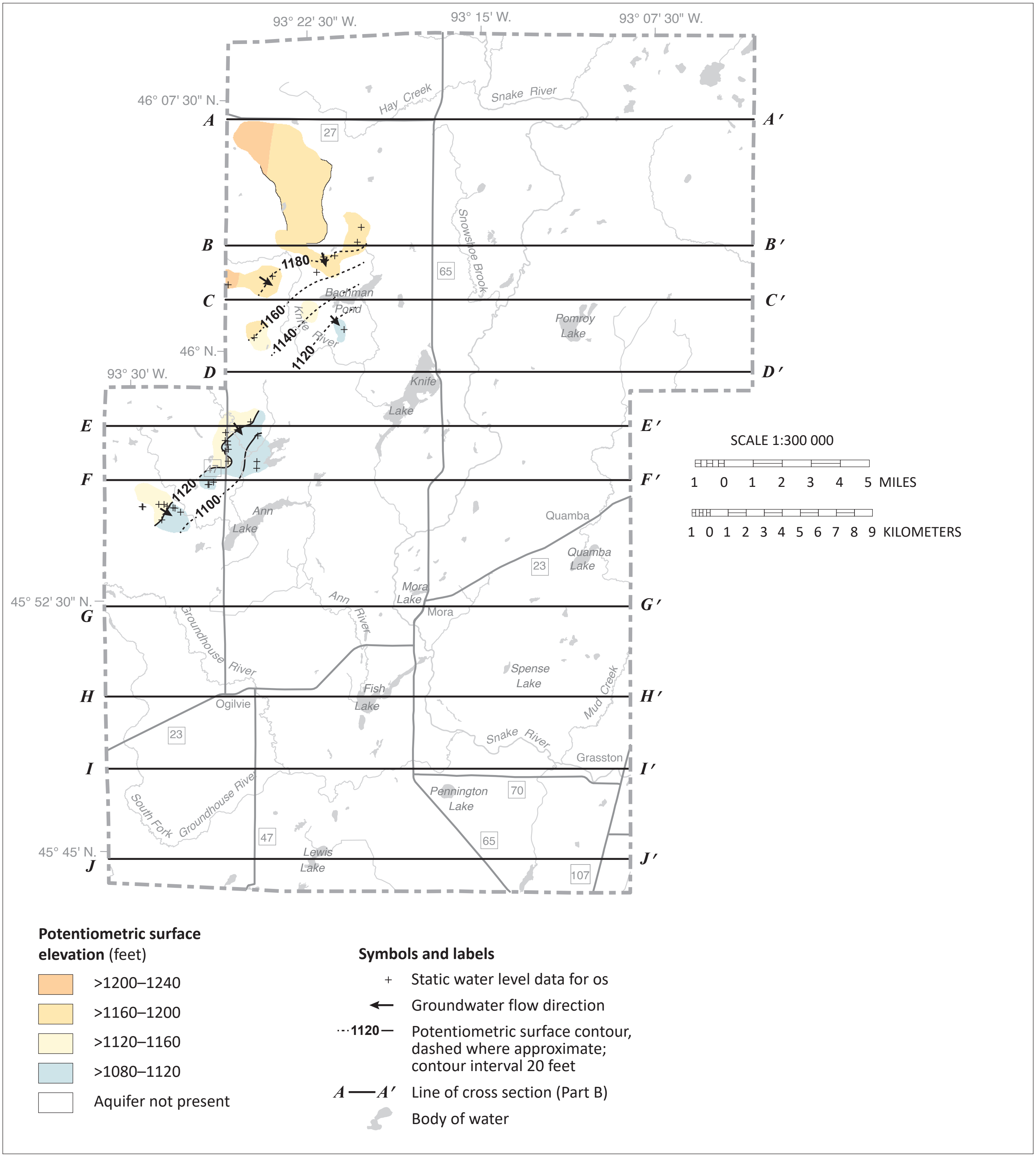


Figure 10. Potentiometric surface of the os aquifer

The os is mapped as a limited extent unit mostly shown in the western part of the county. The dominant groundwater flow pattern is to the Snake River. The os2 (outlined) was defined only in the north.

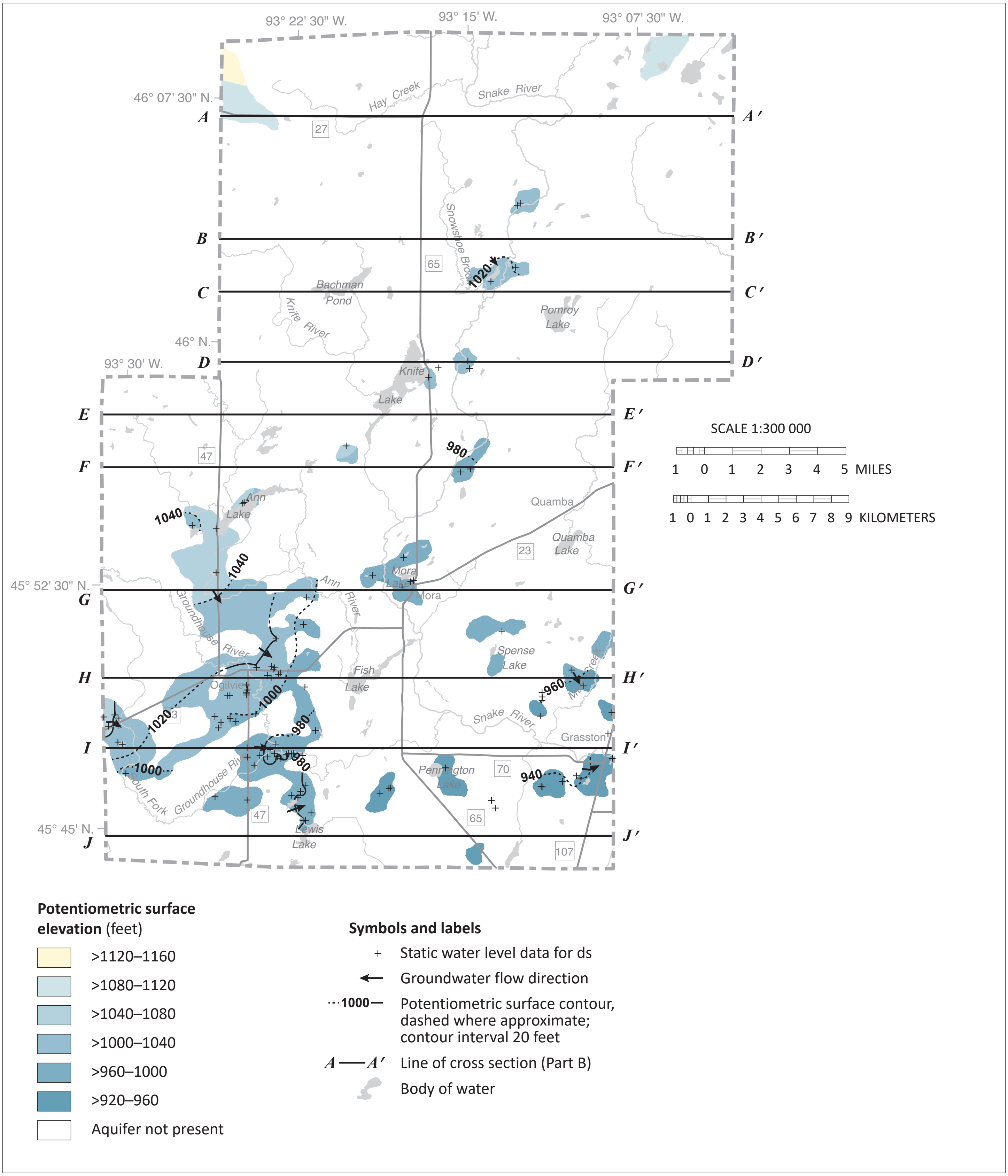
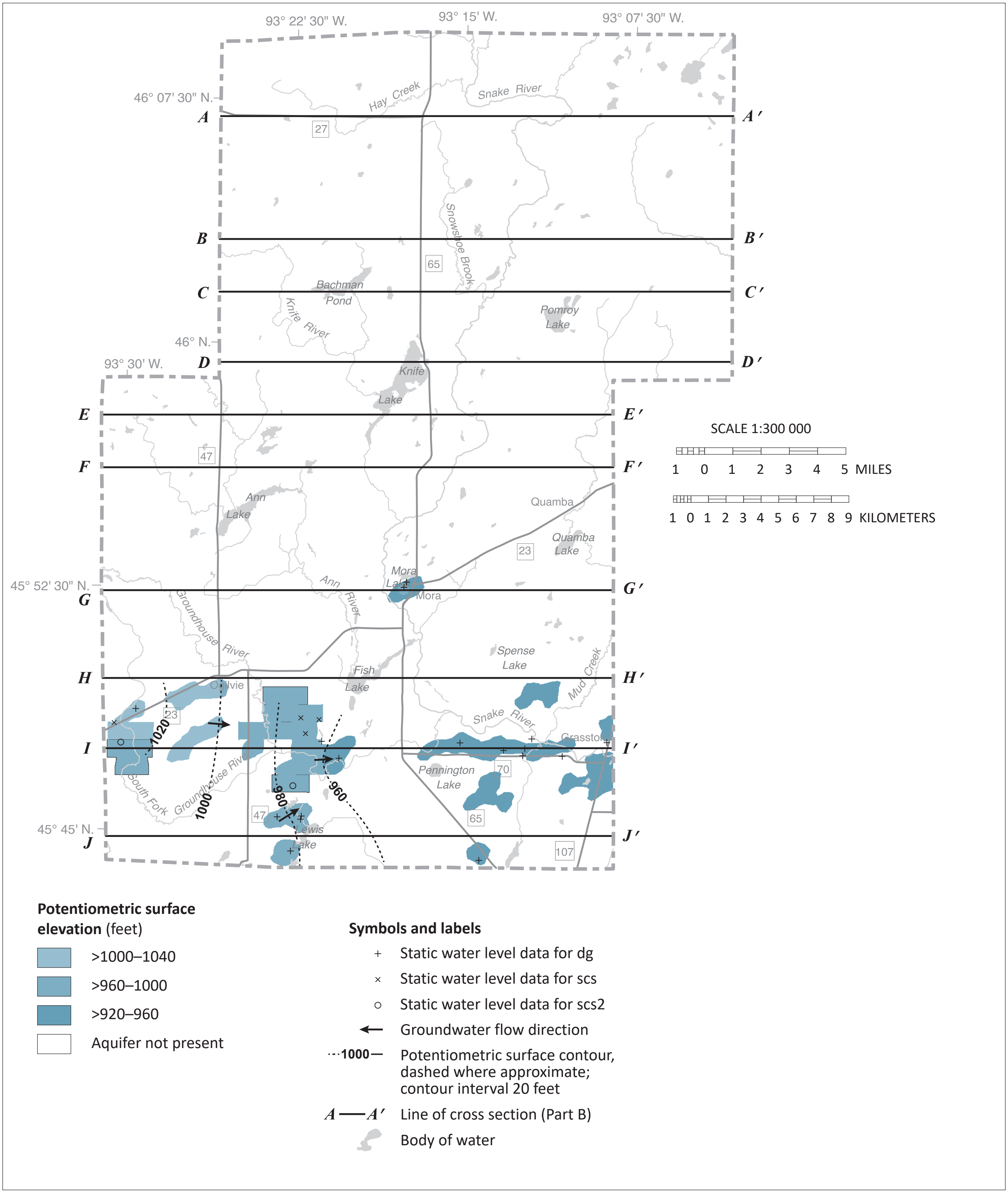


Figure 11. Potentiometric surface of the ds aquifer

The ds is mapped as a limited extent unit mostly shown in the southern part of the county. The dominant groundwater flow pattern is to the Snake River.



Potentiometric surface elevation (feet)

- ▨ >1000–1040
- ▨ >960–1000
- ▨ >920–960
- ☐ Aquifer not present

Symbols and labels

- + Static water level data for dg
- × Static water level data for scs
- ○ Static water level data for scs2
- ← Groundwater flow direction
- ···1000— Potentiometric surface contour, dashed where approximate; contour interval 20 feet
- *A*——*A′* Line of cross section (Part B)
- Body of water

Figure 12. Potentiometric surface of the dg and scs aquifers

The dg and scs are mapped as limited extent units in the southern parts of the county. The dominant groundwater flow pattern is to the Snake River. The scs2 is outlined.

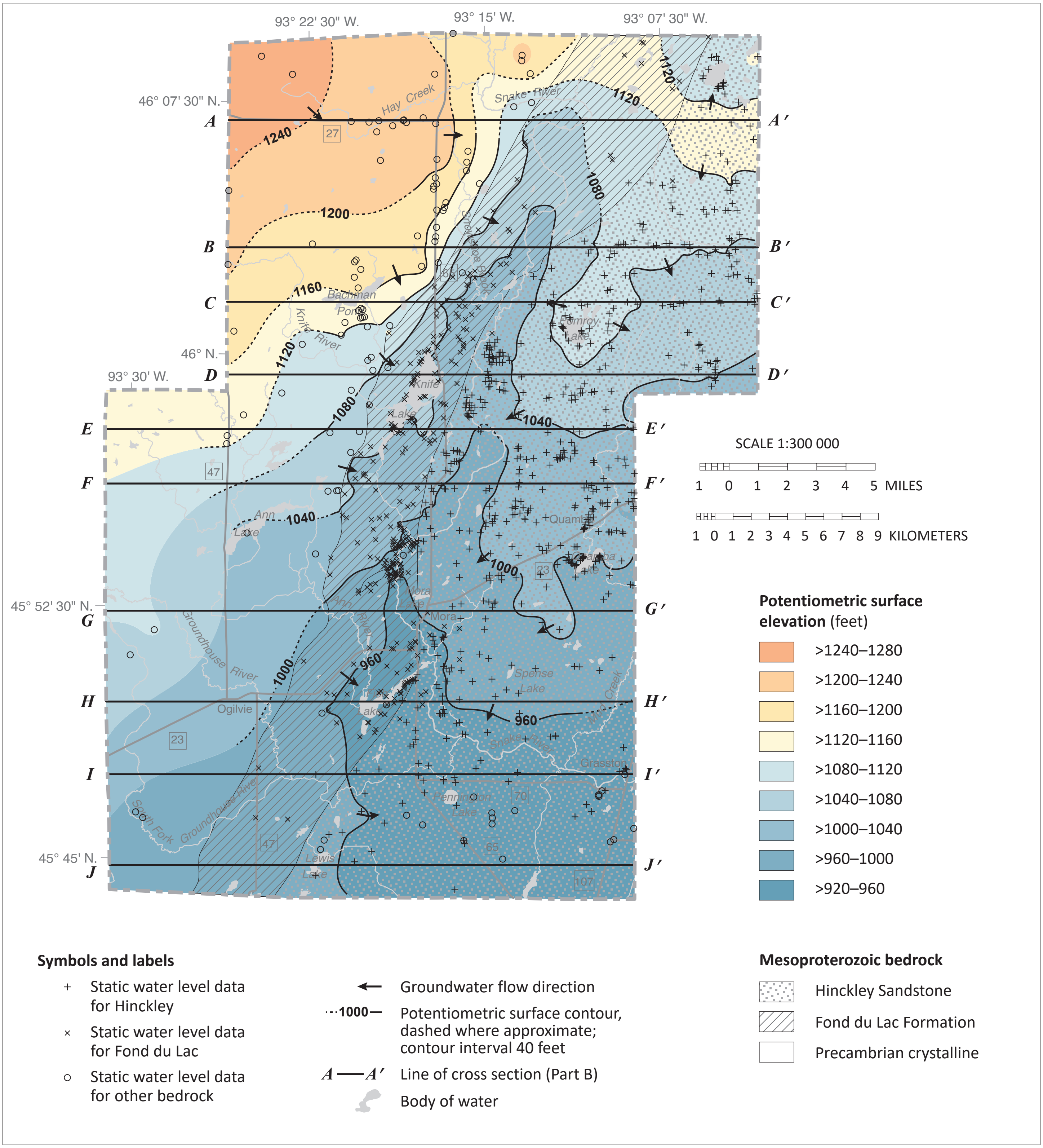


Figure 13. Potentiometric surface of the bedrock aquifers

Water-elevation data from the bedrock aquifers (Mt. Simon, Hinckley, and Fond du Lac), and undifferentiated Precambrian bedrock were mapped together creating a comprehensive picture of groundwater flow for most of the county, with the exception of the southwestern portion where bedrock aquifer data are rare. Similar to all the overlying aquifers, the dominant groundwater flow direction is toward the Snake River. Local groundwater flow may include the Knife River in the western part of the county, and Mud Creek in the southeastern part of the county. A steeper gradient is shown in the northern part of the county near the undifferentiated Precambrian bedrock and Fond du Lac Formation contact due to the low hydraulic conductivity of the undifferentiated Precambrian bedrock and proximity of the Snake River.

Water chemistry (Figures 14–17, Plate 6)

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

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

Water sampling

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

An ideal well-sampling network for the county atlas is distributed evenly across the county, includes populated areas, and targets surface water and groundwater interaction around lakes and larger rivers. The final network sampled for the atlases depends on citizen willingness to participate. Approximately 1000 well owners were contacted for permission to sample; approximately 90 were selected according to county atlas protocol.

Water chemistry data for Kanabec County included wells sampled for this atlas by the DNR along with historical water samples that were incorporated into the interpretations of this report. The total of 102 groundwater samples from wells included: 90 DNR samples collected during the fall of 2017, and 12 Minnesota Department of Health (MDH) samples collected from 1991 to 2017. Additionally, 4 surface-water samples (3 MDH and 1 DNR) were included with dates from 2000 to 2017.

Groundwater recharge sources

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

- 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. This water has been subjected to fractionation where light isotopes evaporated into the atmosphere, leaving water enriched in heavier isotopes.

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

Definition of delta (δ)

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

Results

County results were compared to the global meteoric water line, 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 14). 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.

Evaporative signatures were found in 11 groundwater samples collected in the south-central and southeastern parts of the county and can be traced back to their probable surface-water source (Figures 14 and 15). Eight of these samples were from buried sand aquifers (csr, cse, bsg, ds, and dg) and 3 were from bedrock aquifers (Hinckley and Fond du Lac). The northern 2 samples (csr and cse) located east of Knife Lake were partially sourced from that lake. The 5 samples in the Mora area (bsg, ds, dg, and Fond du Lac) were partially sourced from Lake Mora and smaller lakes and ponds in the area (Figure 15 inset). Samples collected south of the city of Mora (csr and Hinckley) are both downgradient of, and partially sourced from, Fish and Spence lakes. The southern evaporative signature sample (cse) is downgradient of, and partially sourced from, Pennington Lake.

This analysis shows that these surface-water sources (Knife, Mora, Fish, Spence, and Pennington lakes) have strong groundwater connections. These surface-water features, and possibly others in the area, could potentially be affected by high-volume pumping from one or more wells in the area due to these strong connections.

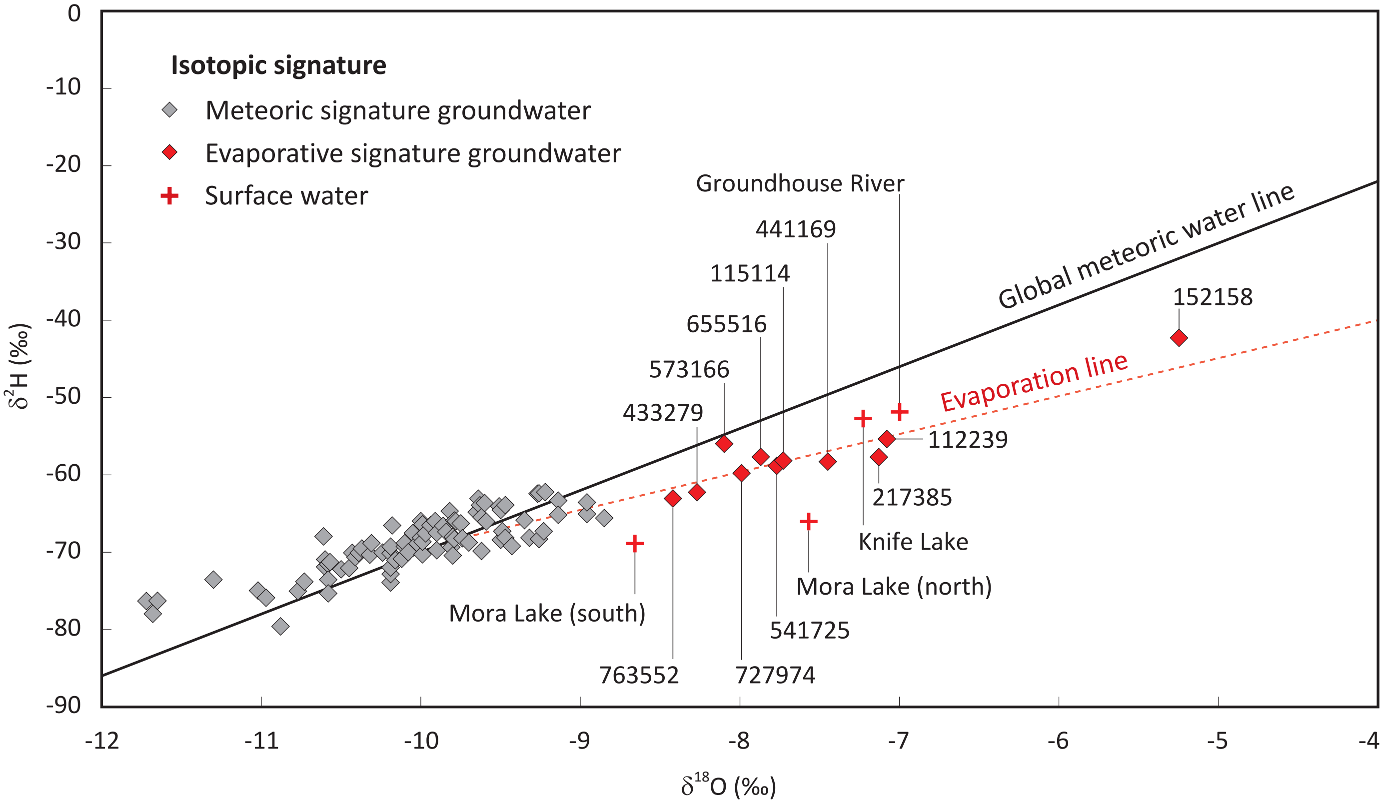


Figure 14. Stable isotope values from water samples

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 was partially from surface-water sources. The local evaporation water line is described by the following equation: $\delta^2H = 4.9\ \delta^{18}O - 20.4$.

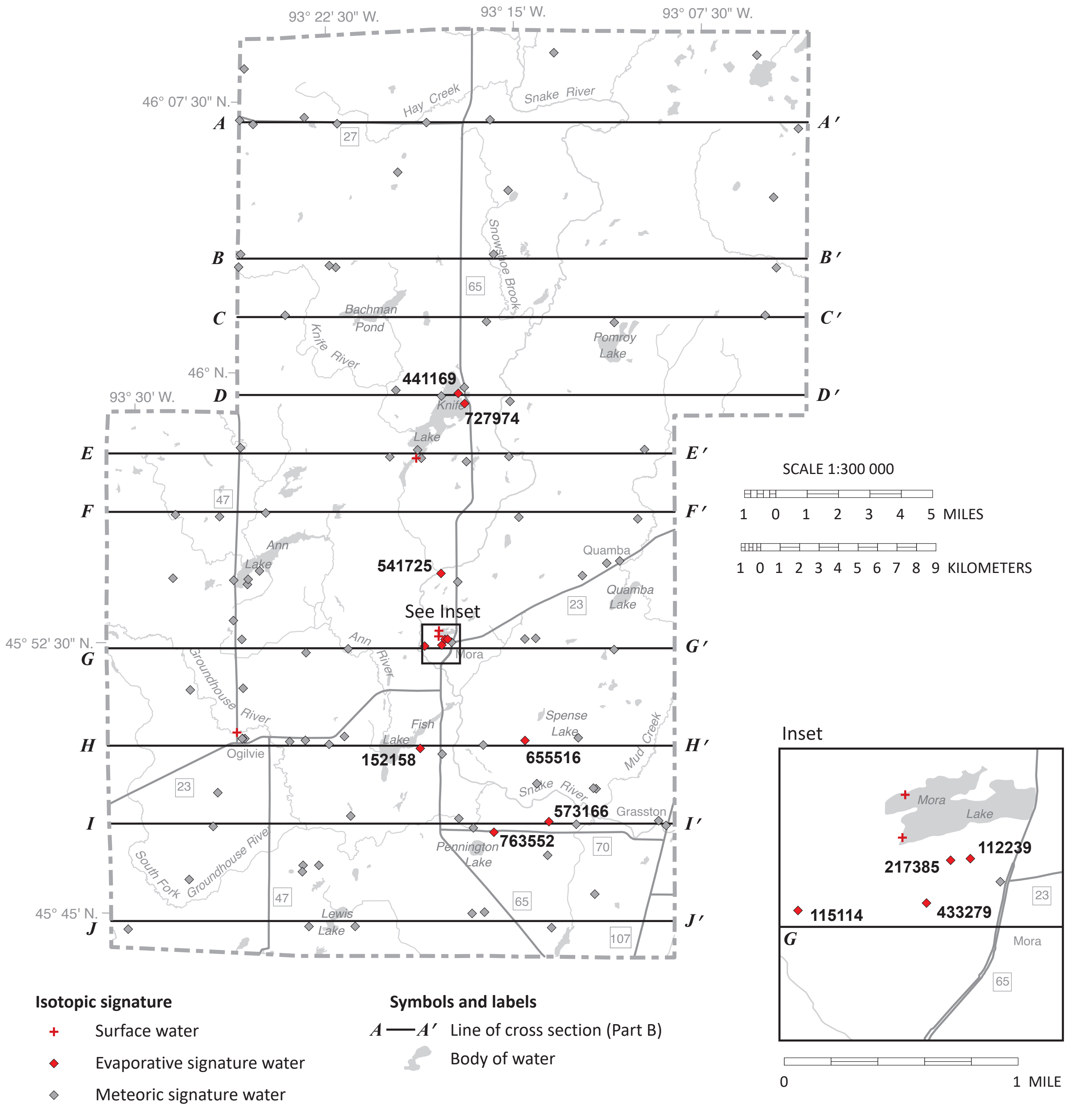


Figure 15. Stable isotope characteristics of groundwater samples

Eleven groundwater samples collected in the south-central and southeastern part of the county exhibited evaporative signatures that can be traced back to their probable surface-water source. The number labels next to the evaporative signature samples are the MDH unique well numbers.

Groundwater residence-time indicators

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

Tritium

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

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

Historical data (sample dates from 1991 to 2017) are used in the residence-time interpretations of this report and are classified according to Table B-2 in Appendix B.

Carbon-14

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

A total of 10 carbon-14 samples were collected for this study. Carbon-14 residence times ranged from 550 years to 7,500 years. These data are described in more detail in the hydrogeologic cross section portion of this report.

Inorganic chemistry of groundwater

Water begins dissolving minerals in the soil, sediment, and bedrock as soon as precipitation infiltrates the soil layer and becomes groundwater. Its chemistry changes as water moves along the flow paths.

Groundwater contamination can come from human (anthropogenic) pollution or from naturally occurring geologic contamination dissolved from the resident material. Elevated levels can indicate short groundwater residence time, high sensitivity, or a potential health problem for drinking water. Anthropogenic sources can be identified by comparing concentrations to naturally occurring background levels.

Water quality evaluations describe contaminants that are potentially harmful (either naturally occurring 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 the indicated levels in the chemical descriptions.

Anthropogenic: caused by human activity.

Naturally occurring: waters contain natural dissolved minerals from the rock and soil. Most are harmless, but certain levels in drinking water can be harmful to your health.

Chemical descriptions

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

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

Organic chemicals are not studied as they are out of the scope of this project, but can be found in reports from other state agencies (e.g., pesticides and their breakdown products, solvents, degreasers, and more).

- **Calcium, magnesium, and sodium cations and bicarbonate anions** are dissolved out of the glacial sediment and bedrock by groundwater. The constituents are derived from limestone and dolomite bedrock sources (Hem, 1985) and are common in glacial sediment groundwater aquifers. Sodium is often present in deep aquifers or at mineral interfaces. As groundwater moves through aquifer systems, calcium and magnesium ions in solution are exchanged for sodium ions (Hounslow, 1995).
- **Sulfate (SMCL 250 ppm)** is largely naturally occurring. High concentrations in groundwater can negatively affect taste and may act as a laxative.
- **Chloride (SMCL 250 ppm, elevated ≥5 ppm; anthropogenic: chloride to bromide ratio ≥250)** can occur naturally from deep sources such as residual brine, or it may come from anthropogenic sources such as road salt, water softener salt, and fertilizer (Davis and others, 1998; Panno and others, 2006).
- **Nitrate-nitrogen (nitrate) (MCL and HRL 10 ppm, elevated ≥1 ppm)** can occur naturally at low concentrations but elevated concentrations are typically from fertilizer and animal or human waste. Nitrate concentrations lessen with time (denitrification) when there is little oxygen in the groundwater. In Minnesota, groundwater with long residence time typically has little available oxygen and little to no nitrate (MDH, 1998; Wilson, 2012).
- **Arsenic (MCL 10 ppb; MCLG 0)** is a naturally occurring element that has been linked to negative health effects, including cancer. It is considered elevated if arsenic is indicated at any level, and 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 analyzed for arsenic (Minnesota Administrative Rules 4725.5650, 2008).

The factors affecting 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, 2017; 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).

Results

Chloride (Figure 16, Plate 6)

Anthropogenic chloride in groundwater is relatively widespread in the county. Of the 98 well samples analyzed for chloride, 45 were anthropogenic but none equaled or exceeded the SMCL. These anthropogenic occurrences were found mostly in buried sand aquifers in the western and southern portions of the county and in the bedrock aquifers in the east and north.

Groundwater samples with chloride to bromide ratios below 250 that also have mixed tritium age are shown as unknown rather than anthropogenic or natural.

Nitrate (Figure 16, Plate 6)

Of the 100 well samples analyzed for nitrate, 13 had elevated concentrations indicative of an anthropogenic source, and 4 were above the MCL with concentrations ranging from 10.5 to 19.2 ppm. The elevated occurrences of nitrate are located in all parts of the county in the surficial, upper buried sand, and shallow bedrock aquifers.

Arsenic (Plate 6)

Concentrations of naturally occurring arsenic above the MCL are not common in the county. Of the 98 samples analyzed for arsenic, only 4 exceeded the MCL; however, 93 exceeded the method detection limits. Those at or above the MCL were located in the central part of the county.

Manganese (Plate 6)

Of the 96 samples analyzed for manganese, 54 were greater than or equal to the HBV. These elevated values ranged from 120 to 1,940 ppb and were found in most of the mapped aquifers.

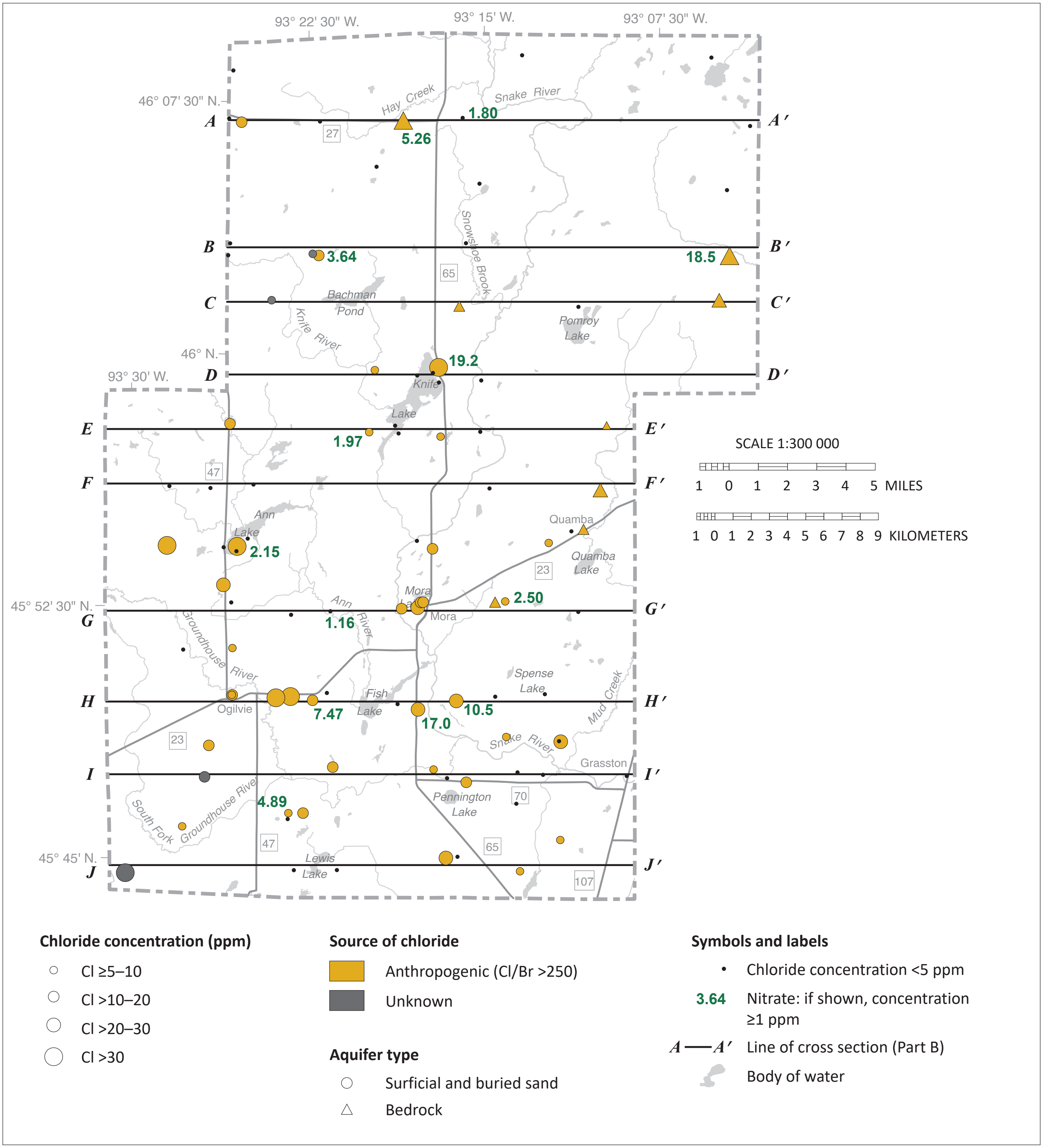


Figure 16. Chloride and elevated nitrate concentrations from groundwater samples

Anthropogenic chloride in groundwater is relatively widespread in the county. Of the 100 well samples analyzed for nitrate, 13 had elevated concentrations indicative of an anthropogenic source, and 4 were above the MCL.

Piper diagram: major cations and anions

The Piper diagram (Figure 17) depicts the relative abundance of common dissolved chemicals in water samples. A more complete hydrogeologic interpretation is created by combining groundwater chemistry data and physical hydrogeologic information, such as groundwater levels and groundwater flow paths. The Piper diagram can reveal information about the following:

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

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

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

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

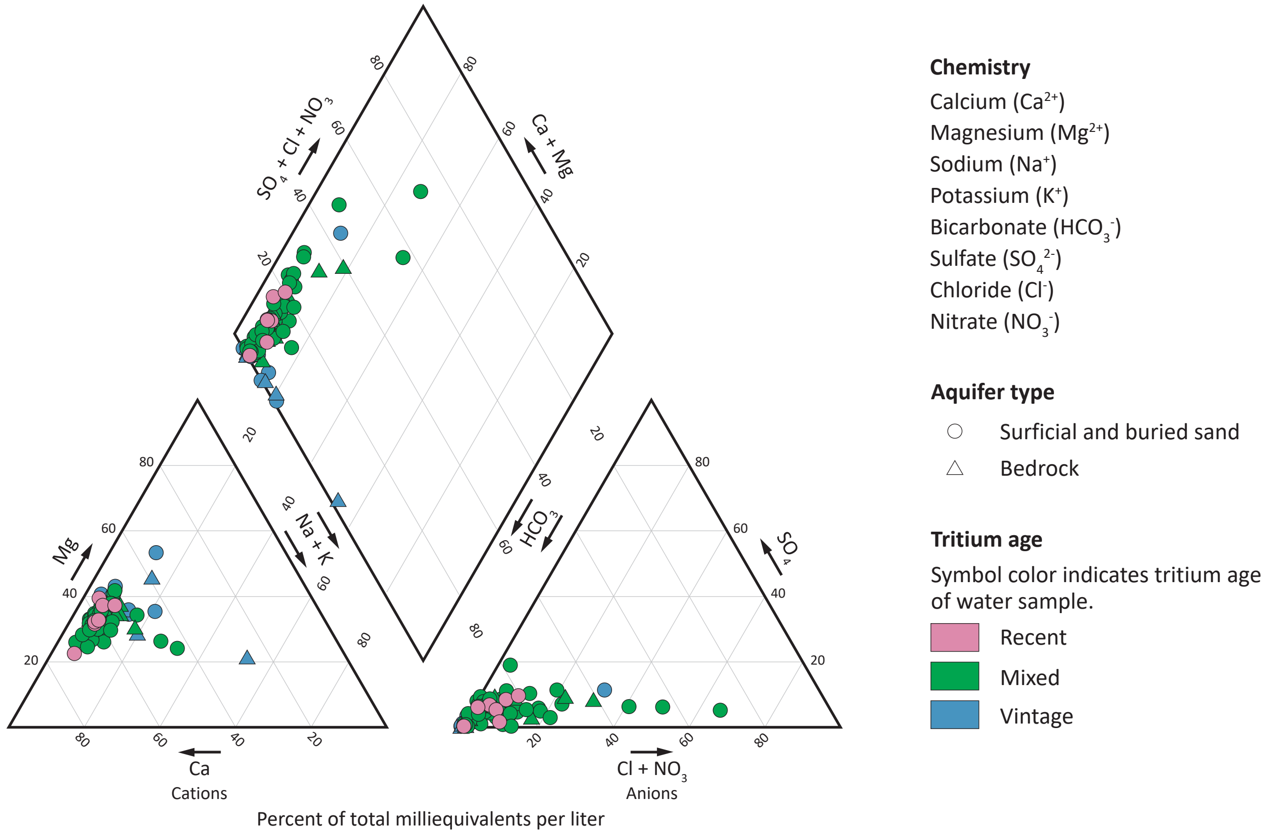


Figure 17. Piper diagram of groundwater samples and tritium age

The cation triangle (lower left) shows that groundwater with a mixture of calcium and magnesium is common in the county with calcium as the dominant ion. This cation type of water was from the buried sand and bedrock aquifers. The anion triangle (lower right) shows several samples from buried sand and bedrock aquifers that trend toward the $Cl+NO_3$ corner of the triangle due to infiltration and recharge from anthropogenic sources as discussed in the previous sections. The sample points in the figure are color coded according to tritium age to help show chemical relationships.

Pollution sensitivity (Figures 18–31)

Pollution sensitivity is defined as the potential for groundwater to be contaminated from the land surface because of the properties of the geologic material. Dissolved contaminants migrate with water through sediment and are typically affected by complex processes such as biological degradation, and oxidizing or reducing conditions. The methods used to interpret pollution sensitivity included the following general assumptions:

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

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

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

The following assumptions were applied in the two models.

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

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

Near-surface materials

Methods

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

The transmission rate varies depending on the texture. Coarse-grained materials generally have faster transmission rates than fine-grained materials. The two primary inputs used to estimate transmission rate are the hydrologic soil group and the surficial geologic matrix texture. Attributes of both are used to estimate the time of travel (Table 1) (Natural Resources Conservation Service, 2019; Part A, Plate 3).

The time of travel through near-surface sediment varies from hours to approximately a year (Figure 18).

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

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

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

Hydrologic Soil Group (0–3 feet)		Surficial Geologic Texture (3–10 feet)		
Group*	**Transmission rate (in/hr)**	**Classification**	**Transmission rate (in/hr)**	**Surficial geology map unit (Part A, Plate 3)**
A, A/D	1	gravel, sandy gravel, silty gravel	1	coe, csa, ts
		sand, silty sand	0.71	al
B, B/D	0.50	silt, loamy sand	0.50	csg, cl
		sandy loam, peat	0.28	cta
C, C/D	0.075	silt loam, loam	0.075	not mapped in county
		sandy clay loam	0.035	not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	cla, ncl
–	–	glacial lake sediment of Lake Agassiz	0.000011	Not present in the county

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

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

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

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

Group C: water transmission is somewhat restricted.

Group D: water movement is restricted or very restricted.

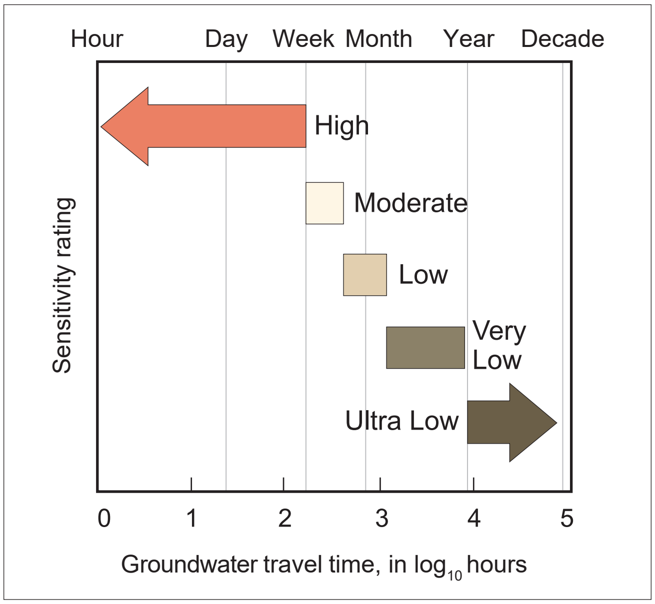


Figure 18. Pollution sensitivity rating of near-surface materials–travel time and ratings

Results

Pollution sensitivity conditions are highly variable within the county (Figure 19). A complex distribution of low, moderate, and high pollution sensitivity dominates the central portion. The high sensitivity areas mostly match the areas of sand and gravel shown on Figure 2. Very low sensitivity exists in the southern part of the county where fine-grained lake sediment is at the surface.

Possible karst conditions exist in the northeast due to relatively shallow Hinckley Sandstone. Karst is defined as terrain with distinctive landforms and hydrology created primarily from the dissolution of soluble rocks (DNR, 2016c). Features such as sinkholes, caves, and springs are common in this type of terrain. Karst allows a direct, very rapid exchange between surface water and groundwater and significantly increases groundwater contamination risk from surface pollutants. For mapping purposes possible karst areas are defined as karst-prone bedrock (carbonate, St. Peter and Hinckley sandstones) within 50 feet of the land surface.

Although most karst in Minnesota occurs in carbonate rock (limestone and dolomite), the Hinckley sandstone has been recognized as karst. Sandstone karst has been documented in adjacent Pine County in the general area of Askov (Boerboom, 2001; Part A, Plate 6; Shade, 2002). No documented evidence of karst features currently exists in northeastern Kanabec County.

Surveyed karst features and locations in the state can be downloaded as a GIS layer from *Karst Feature Inventory Points* through the Geospatial Commons (University of Minnesota School of Earth Sciences, 2018). Springs in the state can be found in the *Minnesota Spring Inventory*, as an online interactive map or GIS layer (DNR, 2019a).

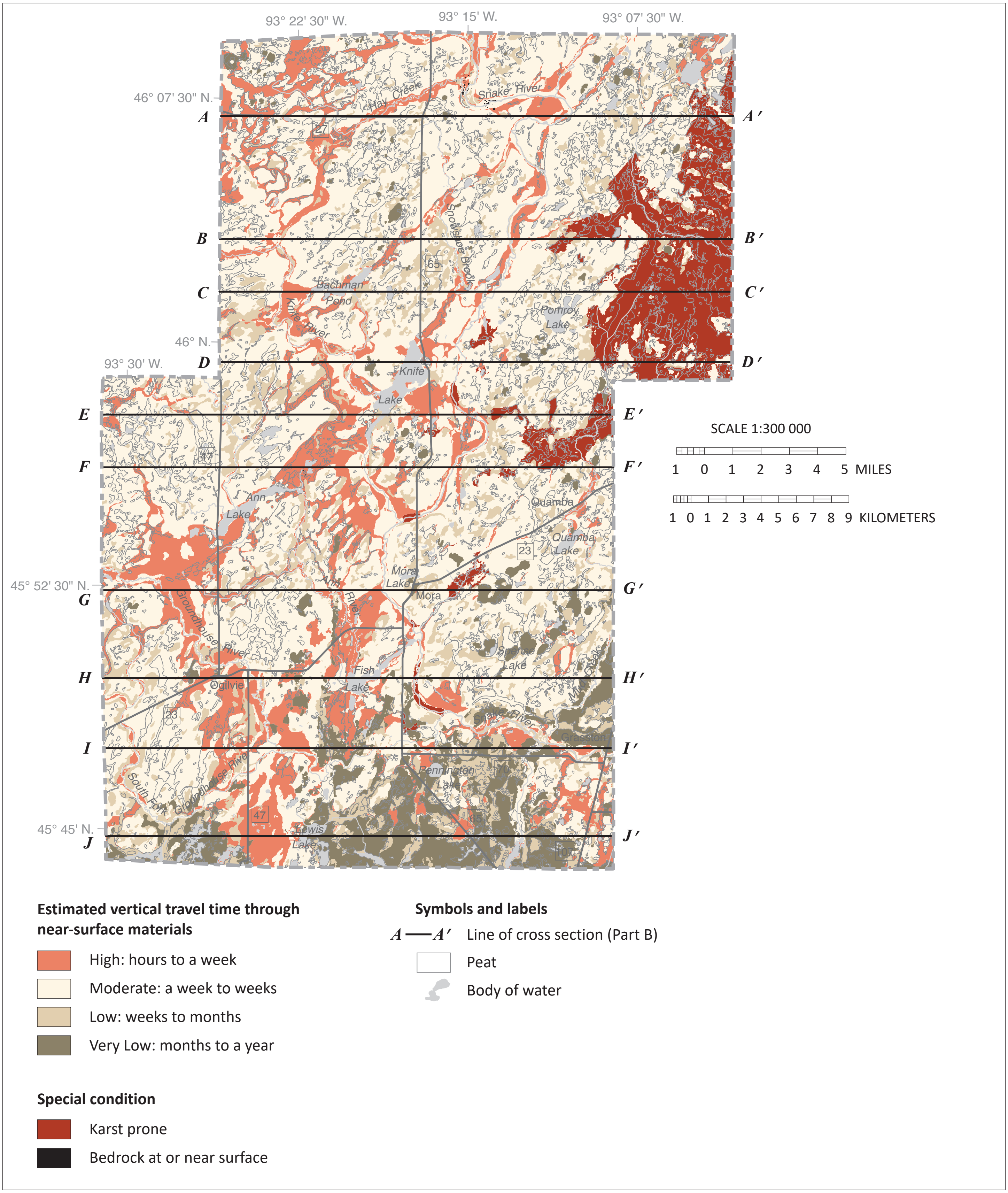


Figure 19. Pollution sensitivity of near-surface materials

Pollution sensitivity conditions are highly variable within the county. A complex distribution of low, moderate, and high pollution sensitivity dominates the central part of the county. Possible karst conditions exist in the northeast due to relatively shallow Hinckley Sandstone. Very low sensitivity exists in the southern part of the county where finer-grained till is at the surface.

Buried sand aquifers and bedrock surface

Methods

The sensitivity rating for the buried sand aquifers and the bedrock surface is based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with ratings of high or very high have relatively short travel times of less than a few years. Areas rated low or very low have estimated travel times of decades or longer (Figure 20).

The DNR developed a pollution sensitivity model that represents how precipitation infiltrates the land surface and recharges portions of deeper aquifers. The central concept is that focused (relatively rapid) recharge occurs where aquifers overlap and are connected by complex pathways. The model assumes that the thickness of fine-grained sediment overlying an aquifer is inversely proportional to the sensitivity of an aquifer. The thicker the fine-grained sediment, the longer it takes for water to move through it (Figure 21).

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

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

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

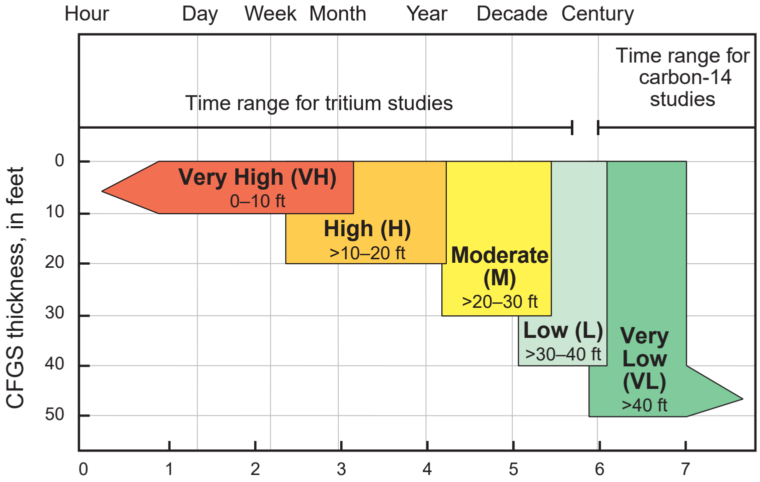


Figure 20. Pollution sensitivity rating for the buried sand aquifers and the bedrock surface

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

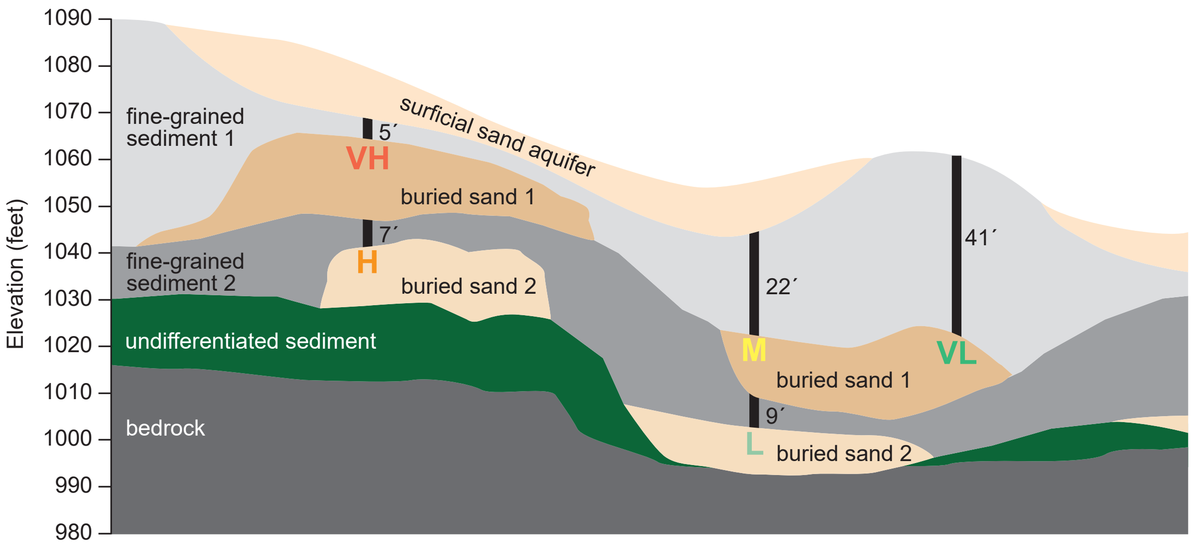


Figure 21. Cross section showing examples of pollution sensitivity ratings

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.

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

Ⓤ Groundwater flowpath is unknown.

Ⓓ Groundwater discharges to a surface-water body.

In general, conditions 1, 2, 3, and the associated tritium-age water (recent and mixed) match the type of vertical groundwater flow and focused recharge that is assumed in the pollution sensitivity model. These conditions provide some validation of the model in areas of moderate to very high sensitivity (Figure 22).

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

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

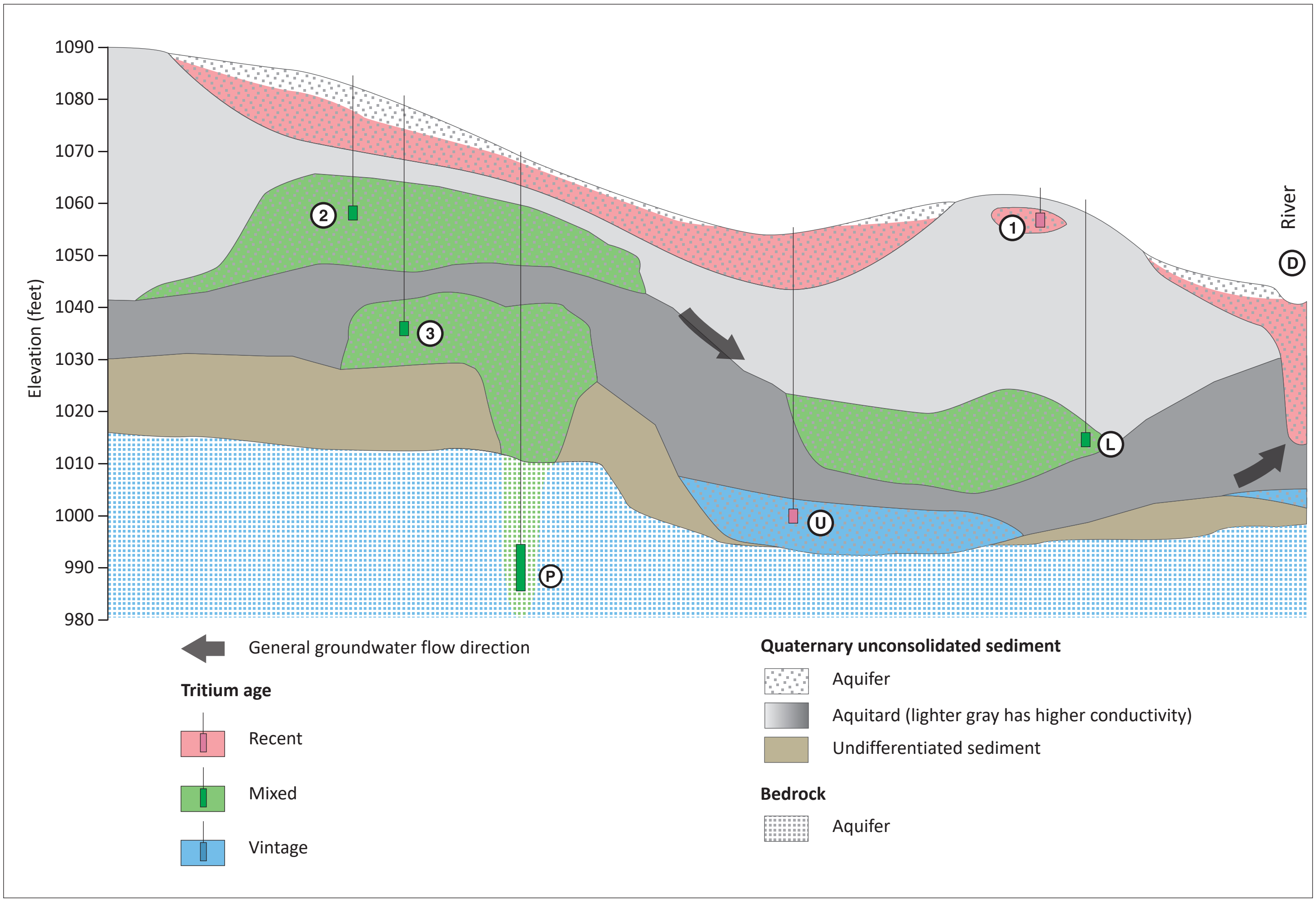


Figure 22. Hypothetical cross section illustrating groundwater conditions

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 (Figure 5) and includes the depth, thickness, spatial distribution, and pollution sensitivity. The model results include groundwater flow direction derived from potentiometric surfaces to aid in understanding the groundwater conditions and the distribution of particular chemical constituents.

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

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

The tritium dataset was a combination of sampling efforts by the DNR and the MDH (MDH for several projects since 1991). Descriptions of groundwater chemistry and pollution sensitivity were qualitatively compared to the results of the pollution sensitivity modeling. Tritium detections in groundwater samples from aquifers in areas mapped as very low sensitivity should rarely occur, assuming that flow of recent water to the aquifer is vertical and not altered by nearby pumping or well integrity issues (Figure 22).

csr aquifer (Figure 23)

The csr aquifer is found throughout the county. Depths range from the near surface to 50 feet. It is used by approximately 7 percent of the wells in the county. The pollution sensitivity is mostly high to very high with several small areas scattered around the county that ranged from moderate to very low.

Of the 12 samples collected, all were analyzed for tritium, resulting in 11 mixed and 1 vintage tritium age. Of the mixed samples, 3 also contained anthropogenic chloride (8.24 to 139 ppm) and 1 contained elevated nitrate (1.8 ppm).

Of the mixed tritium-age samples, 8 were near low to high sensitivity portions of the aquifer throughout the county; 3 were at very low sensitivity parts of the aquifer but were downgradient from higher sensitivity areas that could have sourced more recent recharge. These were located in the northwest, west, and southeastern parts of the county.

The vintage sample near the northwestern corner of the county was in a low sensitivity part of the aquifer. These results are consistent with the pollution sensitivity model.

cse aquifer (Figure 24)

The cse aquifer is found throughout the county. Depths range from approximately 20–80 feet. It is used by approximately 20 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.

Of the 30 samples collected from this aquifer, all were analyzed for tritium resulting in 2 recent, 24 mixed and 4 vintage tritium age. All of the recent and mixed samples were analyzed for nitrate: 9 were elevated above background levels, and 3 exceeded the MCL. All of the recent and mixed samples were analyzed for chloride: 16 had elevated concentrations that were anthropogenic, and 3 had a chloride source that was considered unknown.

Seven of the recent and mixed tritium-age samples were from scattered locations in the southern part of the county in areas of low to high pollution sensitivity.

Sixteen of the mixed tritium-age samples from throughout the county were located in low to very low sensitivity parts of the aquifer. However, these samples were downgradient from higher pollution sensitivity areas that could have sourced more recent recharge. The relatively high sand content of most of the aquitards in this county may also be responsible for these mixed tritium-age samples in these areas.

The 4 vintage tritium-age samples were located in areas of low to very low pollution sensitivity. Two of the vintage samples were also analyzed for carbon-14 residence time and had values of 550 and 3,500 years. These results are consistent with the pollution sensitivity model.

bsg aquifer (Figure 25)

The bsg aquifer is mostly found in the central and southern parts of the county. Depths range from approximately 40–130 feet. It is used by approximately 13 percent of the wells in the county. The pollution sensitivity is mostly very low but includes the entire range of ratings from very low to very high.

Of the 20 samples collected, 18 were analyzed for tritium, resulting in 5 recent, 11 mixed, and 2 vintage. All the samples were analyzed for nitrate; none had elevated concentrations. Of the 19 samples analyzed for chloride, 11 were elevated and all appeared to be from anthropogenic sources.

Three of the mixed tritium-age samples were located in areas of low to high pollution sensitivity. The 2 vintage samples had carbon-14 residence times of 1,100 and 1,300 years and were from areas of low to very low pollution sensitivity. These results are consistent with the pollution sensitivity model.

Nine of the recent and mixed tritium-age samples from throughout the county were at low to very low sensitivity parts of the aquifer. However, these samples were downgradient from higher pollution sensitivity areas that could have been the source of more recent recharge. The relatively high sand content of most of the aquitards in this county may also be responsible for mixed tritium-age samples in these areas.

os aquifer (Figure 26)

The os aquifer is found in the northwest part of the county. Depths range from approximately 80–190 feet. It is used by approximately 1 percent of the wells in the county. The pollution sensitivity is very low. The 1 sample collected was analyzed for tritium with a vintage tritium-age result and did not contain elevated nitrate or chloride. These results are consistent with the pollution sensitivity model.

ds aquifer (Figure 27)

The ds aquifer is found mostly in the southern parts of the county. Depths range from approximately 70–200 feet. It is used by approximately 3 percent of the wells in the county. The pollution sensitivity is mostly very low to low with some small areas of moderate to high.

Of the 5 samples collected from this aquifer, all were analyzed for tritium with the following results: 1 recent, 3 mixed, and 1 vintage. All samples were analyzed for nitrate, and none were elevated. Of the 4 samples analyzed for chloride, 2 were elevated (16.4 to 39 ppm) and from an anthropogenic source.

The recent and mixed tritium-age samples were collected at locations in very low pollution sensitivity areas with no apparent upgradient higher pollution sensitivity areas. Therefore, the source of tritium in these samples is considered unknown (condition U). The vintage sample was located in a very low sensitivity area, which is consistent with the pollution sensitivity model.

dg and scs aquifers (Figure 28)

These aquifers are found in the southern part of the county. Depths range from approximately 90–180 feet. It is used by approximately 1 percent of the wells in the county. The pollution sensitivity is mostly very low.

Of the 5 samples collected from this aquifer, all were analyzed for tritium with the following results: 1 recent and 4 mixed. All samples were analyzed for nitrate, and none were elevated. Of the 5 samples analyzed for chloride, 4 were elevated (10.8 to 26.5 ppm) and from an anthropogenic source.

The recent and mixed tritium-age samples were collected at locations in very low pollution sensitivity areas with no apparent upgradient higher pollution sensitivity areas. Therefore, the source of tritium in these samples is considered unknown (condition U).

The 2 samples in the city of Mora (mixed tritium age) contained water with an evaporative signature, indicating that some of the groundwater from the dg aquifer in that area is sourced from Lake Mora.

fs and ks aquifers (Figures 29 and 30)

These aquifers are found in the western part of the county. Depths range from approximately 160–230 feet (fs) and 190–280 feet (ks). The pollution sensitivity is mostly very low.

Not enough wells were completed in either of these aquifers to allow mapping of groundwater flow directions and no samples were collected from either aquifer for laboratory analysis.

Bedrock surface (Figure 31)

The type of bedrock at the bedrock surface is variable across the county. The Hinckley Sandstone, Fond du Lac Formation, and small areas of the Mt. Simon Sandstone occupy the eastern portion of the county, whereas Precambrian igneous and metamorphic bedrock occupy the western portion.

Depths to the bedrock surface are typically less than 80 feet in the northern and eastern portions and western edge. Most of the deeper bedrock areas coincide with a buried bedrock valley along the northern portion of the Snake River and a buried bedrock valley in the western part of the county. Depths to bedrock in the buried bedrock valleys are commonly 200 to 350 feet (Part A, Plate 5).

The Mt. Simon, Hinckley, and Fond du Lac aquifers are used by approximately 27 percent of the wells in the county; granitic and metamorphic bedrock are approximately 3 percent. This surface mostly has a very low pollution sensitivity with the exception of large areas in the northeast and north-central portion, with scattered higher pollution sensitivity areas throughout the remainder of the county where the bedrock surface is shallow.

Of the 25 samples from the bedrock aquifers, 24 were analyzed for tritium, resulting in 17 mixed and 7 vintage tritium age. Two vintage samples were from the granitic bedrock in the northern part of the county with carbon-14 residence times of 1,600 and 5,500 years. Two 2 vintage samples from the Hinckley and Fond du Lac aquifers in the southern part of the county had carbon-14 residence times of 1,300 and 1,800 years. Of the 23 samples analyzed for nitrate, only 2 were elevated. Of the 23 samples analyzed for chloride, 8 were elevated and anthropogenic.

Of the 17 mixed tritium-age samples, 7 were in low to high pollution sensitivity areas throughout the county. All 7 vintage samples were in very low pollution sensitivity areas. All of these results are consistent with the pollution sensitivity model. Of the 9 mixed samples that were located in very low pollution sensitivity areas, all were downgradient from higher pollution sensitivity areas (condition L) that could have been the source of more recent recharge. The relatively high sand content of most of the aquitards in this county may also be responsible for mixed tritium-age samples in these areas.

Other evidence of lateral flow is shown by 2 evaporative signature samples in the Mora area. The sample southeast of Mora, in addition to having an evaporative signature, was vintage tritium age, and had a carbon-14 residence time of 1,800 years. These geochemical characteristics suggest surface to groundwater connections that have a very long history. The third evaporative signature sample shown south of the Snake River has an uncertain evaporative origin.

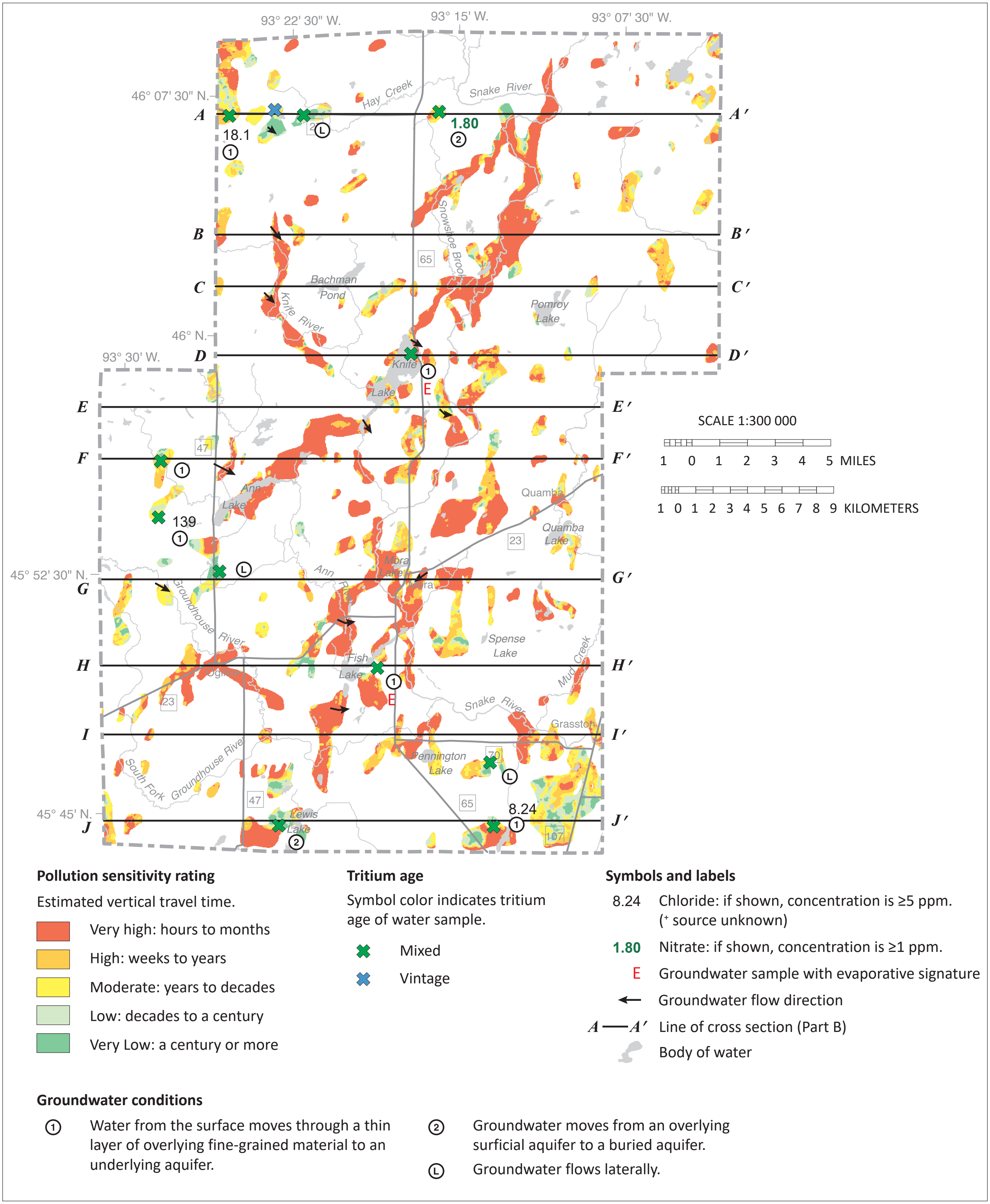


Figure 23. Pollution sensitivity of the csr aquifer and groundwater flow directions

Depths of the csr aquifer ranged from approximately near surface to 50 feet. It is used by approximately 7 percent of wells in the county. The pollution sensitivity is mostly high to very high with several small areas scattered around the county that ranged from moderate to very low.

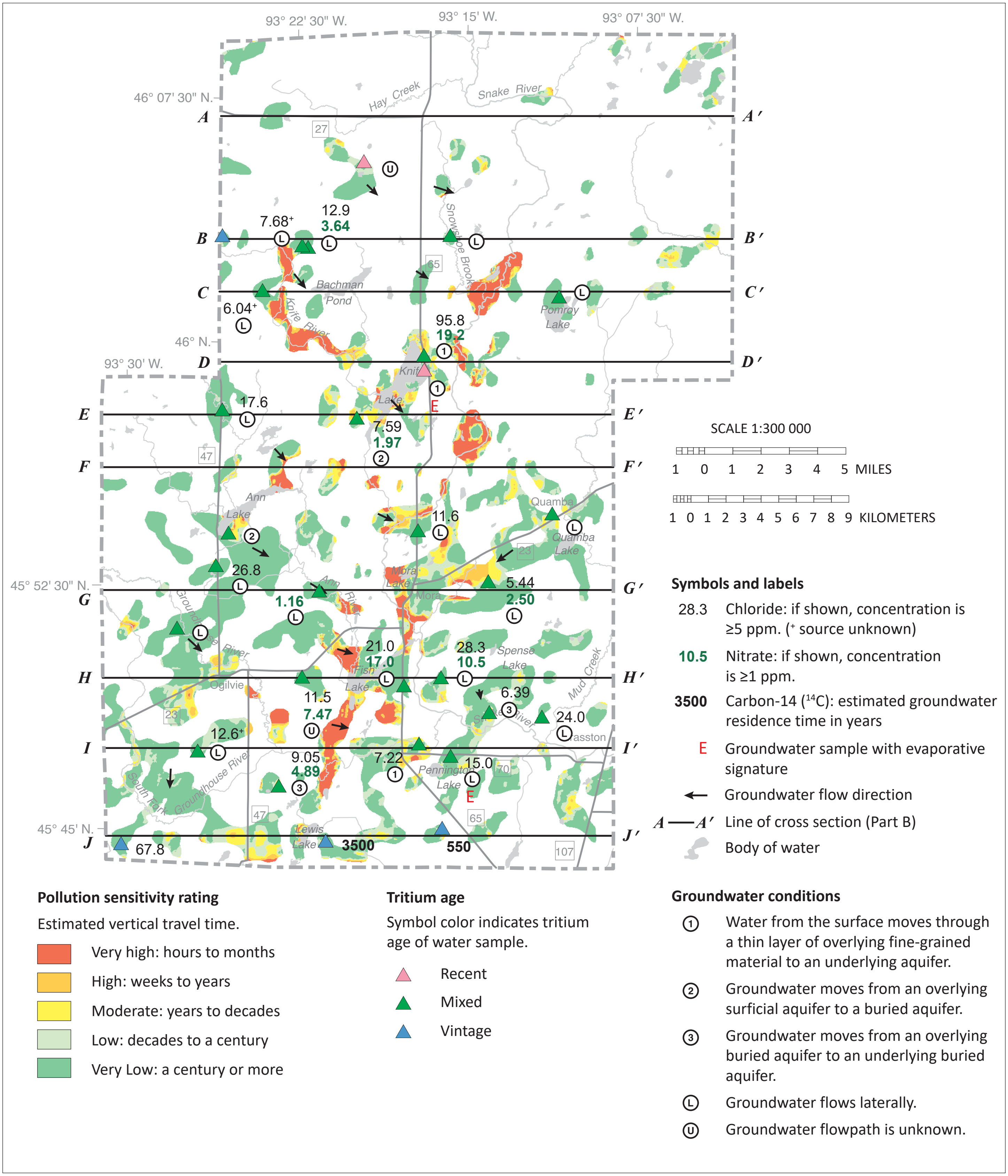
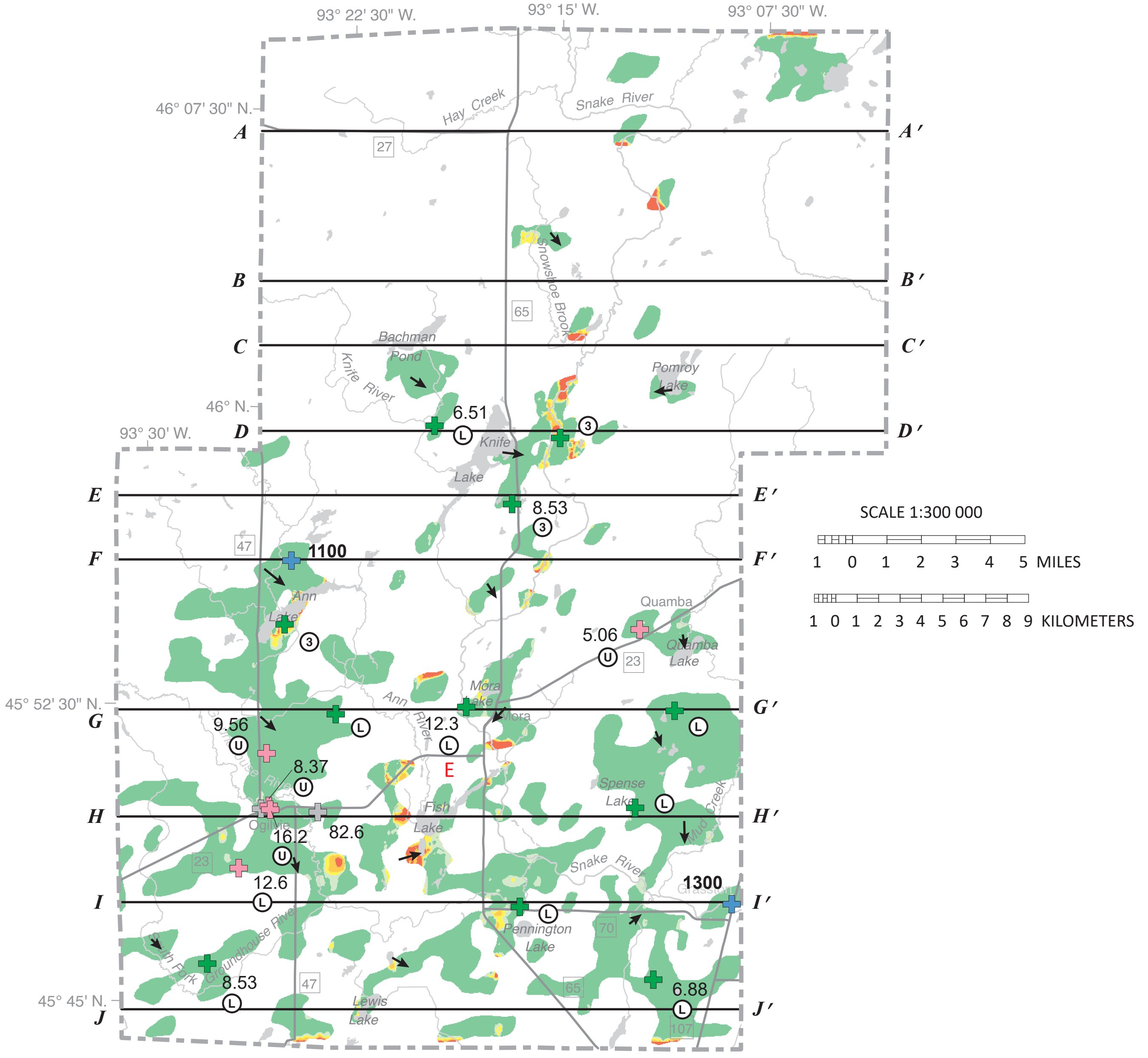


Figure 24. Pollution sensitivity of the cse aquifer and groundwater flow directions

Depths of the cse aquifer range from approximately 20–80 feet. It is used by approximately 20 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.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- ✚ Recent
- ✚ Mixed
- ✚ Vintage
- ✚ Not sampled for tritium

Symbols and labels

12.6	Chloride: if shown, concentration is ≥5 ppm. (* source unknown)
1300	Carbon-14 (^{14}C): estimated groundwater residence time in years
E	Groundwater sample with evaporative signature
←	Groundwater flow direction
A—*A′*	Line of cross section (Part B)
▨	Body of water

Groundwater conditions

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

Ⓛ Groundwater flows laterally.

Ⓤ Groundwater flowpath is unknown.

Figure 25. Pollution sensitivity of the bsg aquifer and groundwater flow directions

Depths of the bsg aquifer range from approximately 40–130 feet. It is used by approximately 13 percent of the wells in the county. The pollution sensitivity of this aquifer is mostly very low but includes the entire range of ratings from very low to very high.

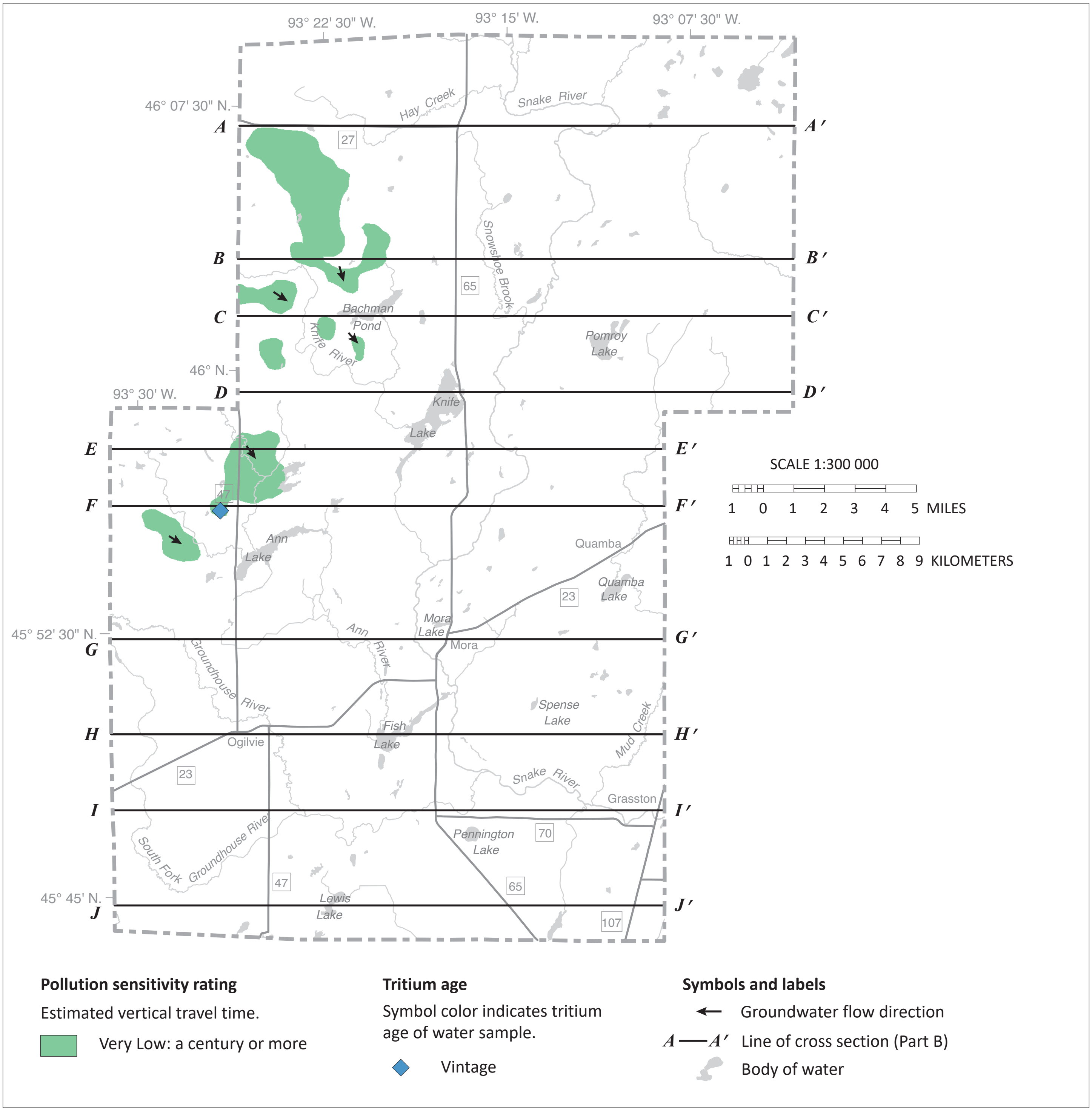


Figure 26. Pollution sensitivity of the os aquifer and groundwater flow directions

Depths of the os aquifer range from approximately 80–190 feet. It is used by approximately 1 percent of the wells in the county. The pollution sensitivity of this aquifer is very low.

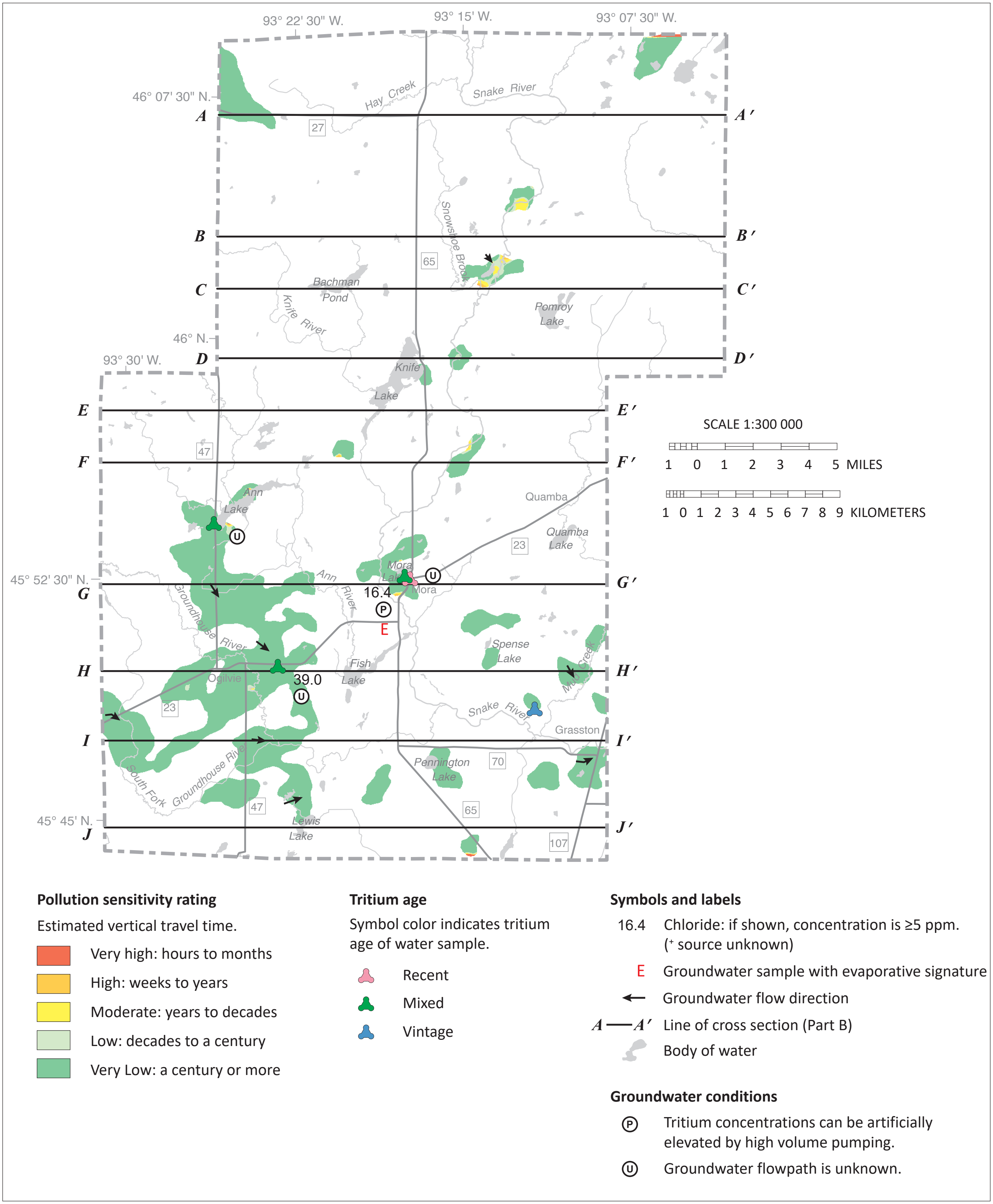


Figure 27. Pollution sensitivity of the ds aquifer and groundwater flow directions

Depths of the ds aquifer range from approximately 70–200 feet. It is used by approximately 3 percent of the wells in the county. The pollution sensitivity of this aquifer is mostly very low to low with some small areas of moderate to high.

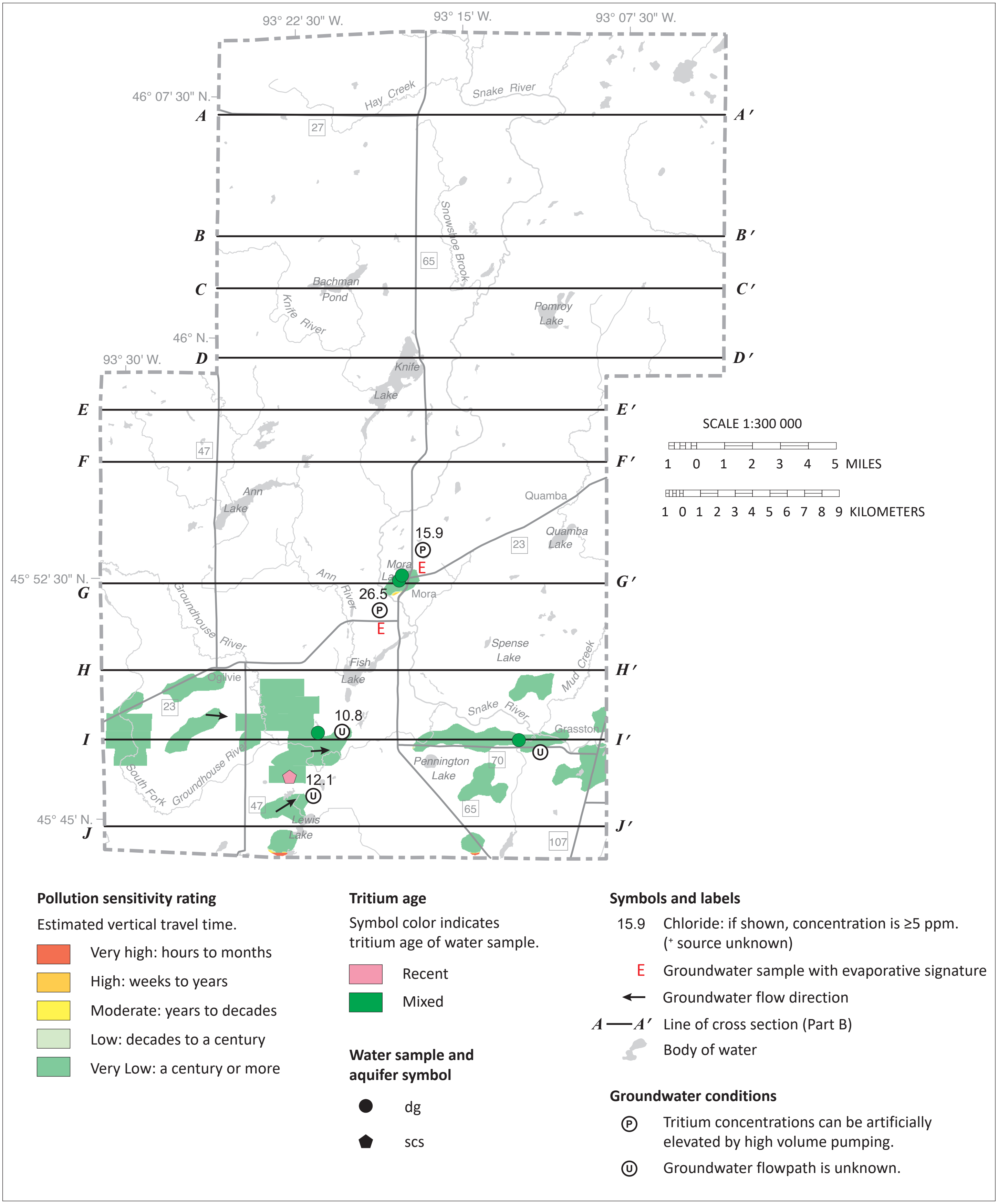


Figure 28. Pollution sensitivity of the dg and scs aquifers and groundwater flow directions

Depths of the dg and scs aquifers range from approximately 90–180 feet. It is used by approximately 1 percent of the wells in the county. The pollution sensitivity of these aquifers is mostly very low.

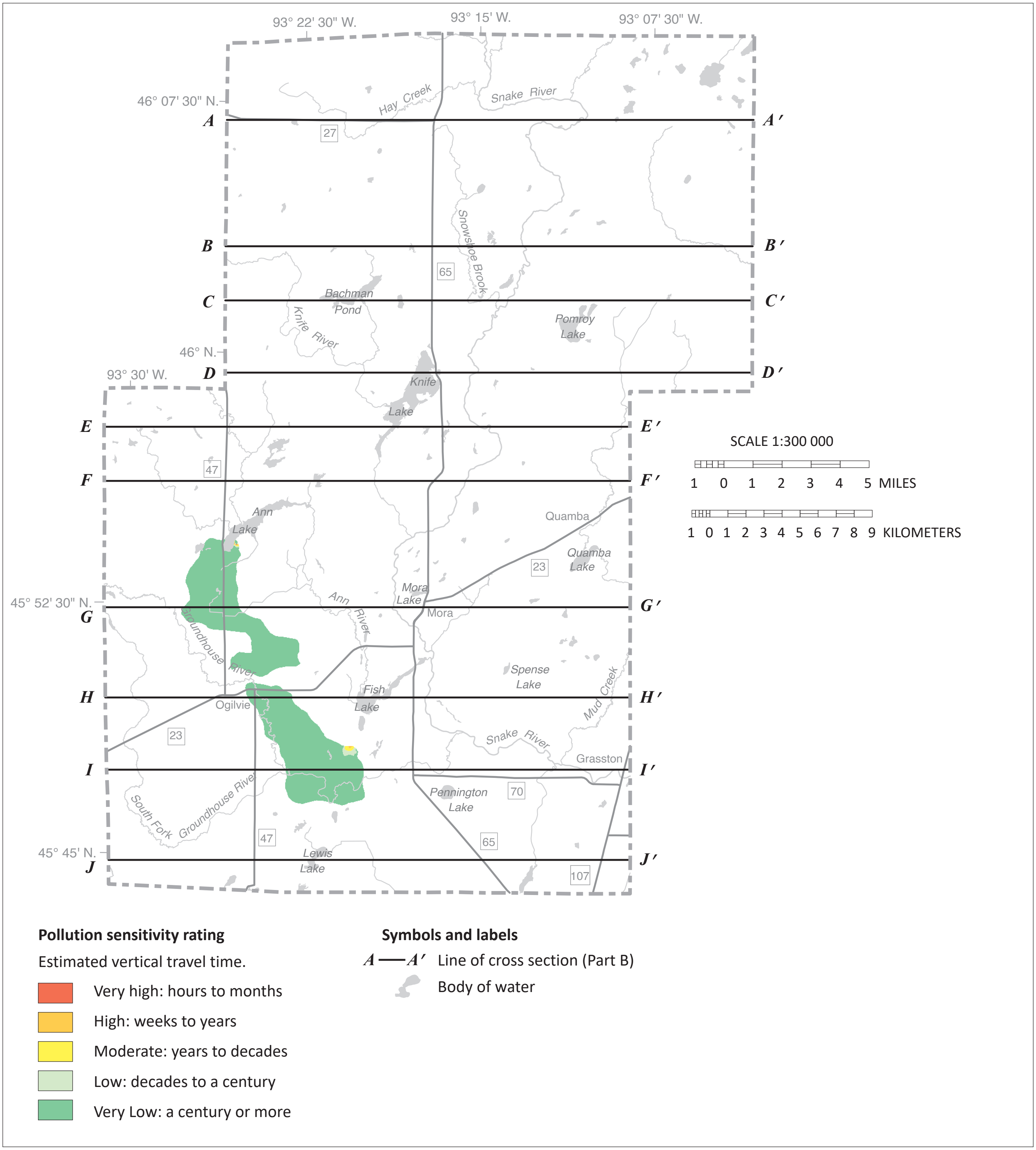


Figure 29. Pollution sensitivity of the fs aquifer

Depths of the fs aquifer range from approximately 160–230 feet. The pollution sensitivity is mostly very low. Not enough water level information was available for estimating groundwater flow directions.

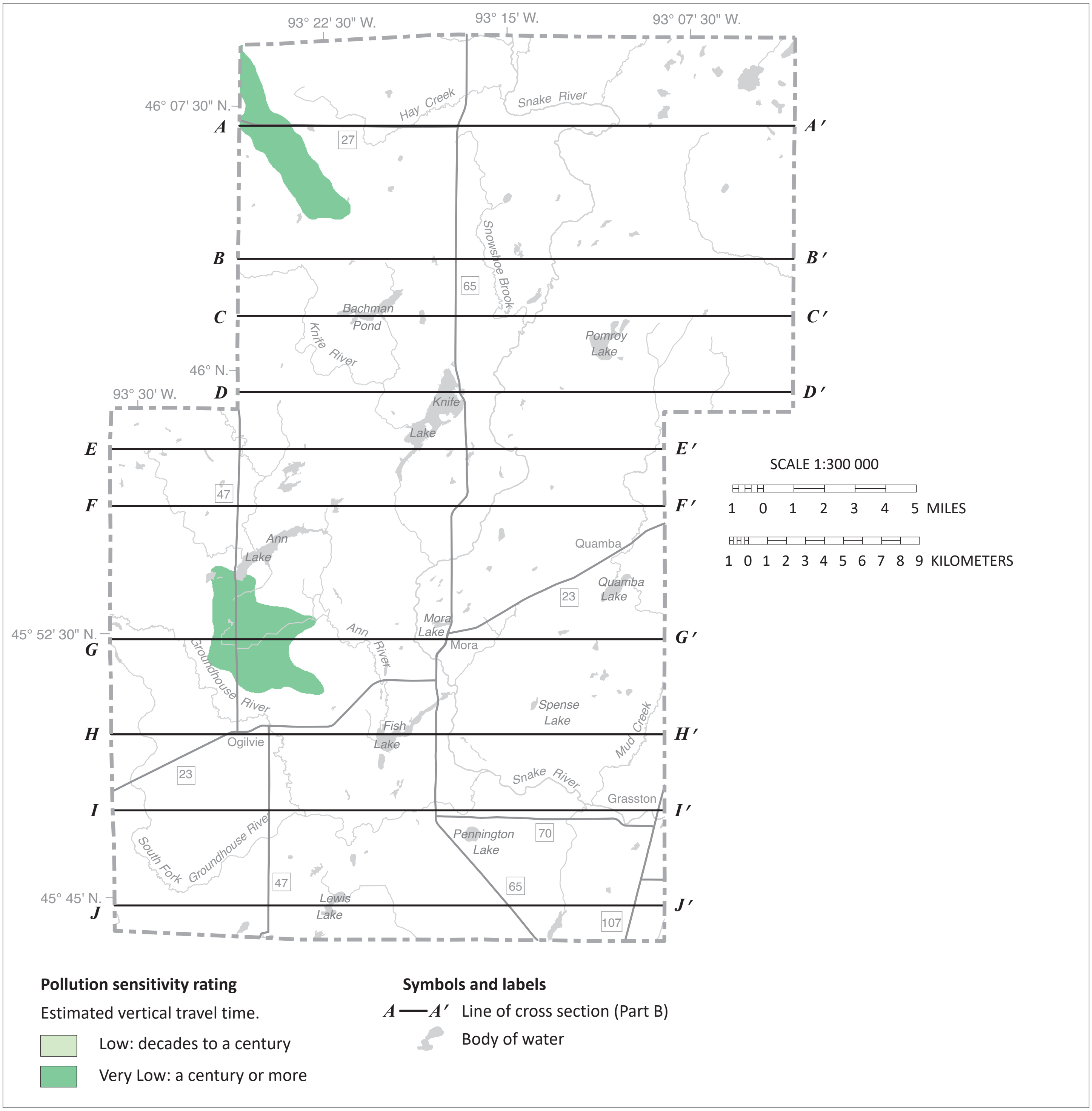


Figure 30. Pollution sensitivity of the ks aquifer

Depths of the ks aquifer range from approximately 190–280 feet. The pollution sensitivity of this aquifer is mostly very low. No water level information was available for estimating groundwater flow directions.

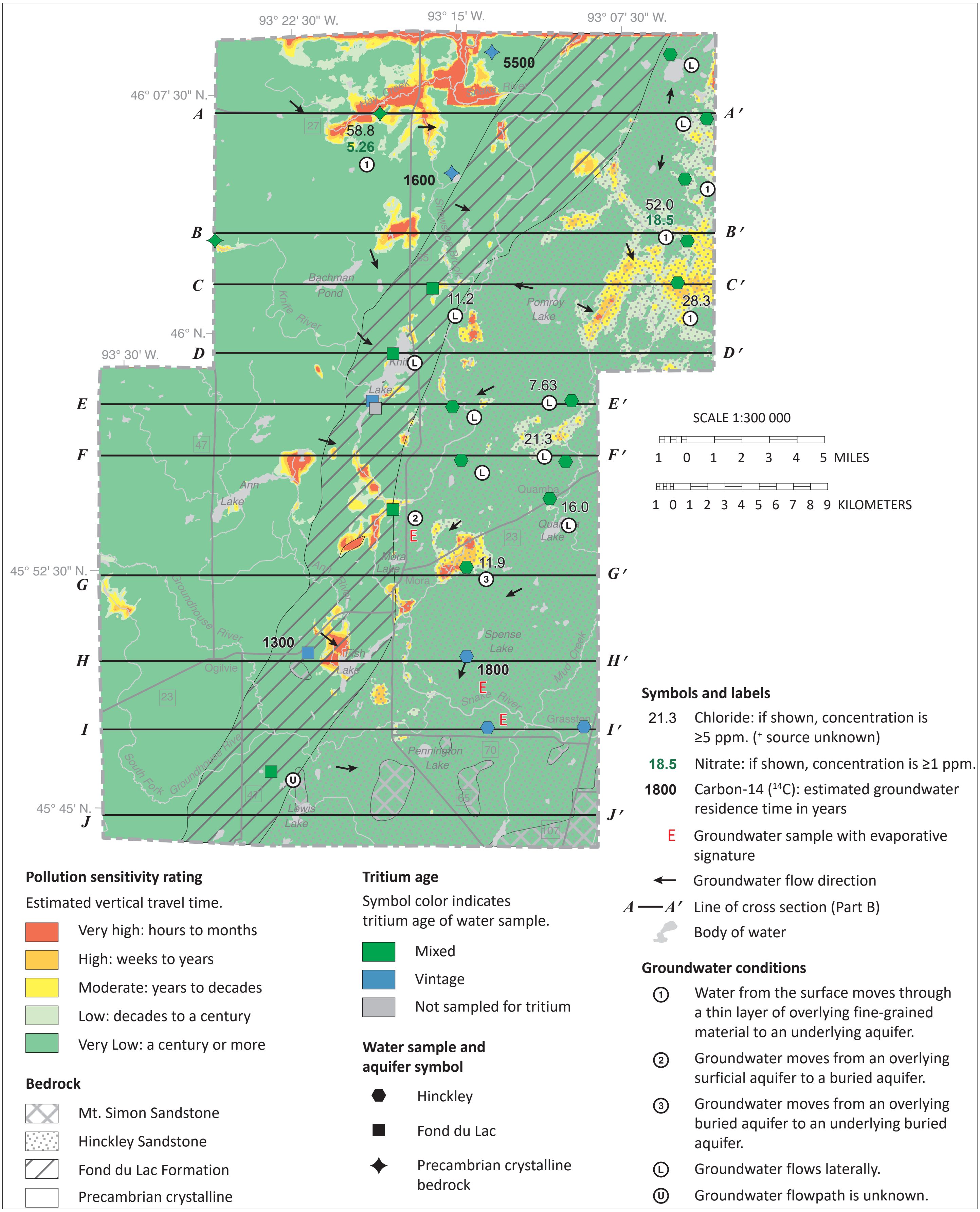


Figure 31. Pollution sensitivity of the bedrock surface and groundwater flow directions

The type of bedrock at the bedrock surface is variable across the county. This surface has mostly very low pollution sensitivity with the exception of large areas in the northeast and north-central portions, with scattered higher pollution sensitivity areas throughout the remainder of the county where the bedrock surface is shallow.

Hydrogeologic cross sections (Plate 7)

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

The 10 cross sections were selected from a set of 44 regularly-spaced (1 kilometer) west-to-east cross sections created by the MGS. Each was constructed in GIS using a combination of well data from CWI and sections of Part A: Bedrock Geology (Plate 2), Surficial Geology (Plate 3), and Quaternary Stratigraphy (Plate 4). Well information 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. Percent sand is based on the average matrix texture of each glacial aquitard. 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 the plate. Lighter shades indicate aquitards with higher relative hydraulic conductivity.

Groundwater flow direction

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

The equipotential contours and flow arrows show that the groundwater flow is initially downward, then laterally toward surface-water discharge areas such as major rivers or lakes. 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. Flow is upward in some areas indicating discharge to surface water bodies. In many areas recharge to deeper aquifers can take hundreds to thousands of years, provided rapid focused recharge does not occur through interconnected aquifers.

Slow recharge

The carbon-14 relationships shown on the cross sections help visualize very slow recharge through aquitards. Residence time values in Kanabec County range from 550 to 7,500 years. Results on the cross sections include two of the oldest samples on the left end of A–A′ (3,000 years) and the middle of J–J′ (3,500 years). Even though the A–A′ sample is significantly deeper than the J–J′ sample (164 feet versus 68 feet) these samples have similar older residence times due to a lack of focused recharge.

Younger residence time samples (1,100 to 1,800 years) are shown on F–F′ left side (beneath the Little Ann River), H–H′ center (west of Fish Lake), H–H′ right side (west of Snake River), and I–I′ right side (east of Snake River). All of these samples are from depths typical of many wells in the county, and are overlain by a similar stack of loamy to sandy aquitards, which are also typical across most of the county.

The youngest carbon-14 residence time in the county of 550 years is shown on the right side of J–J′, west of Highway 65. Unlike the older samples, the relatively younger age of this sample is probably due to some focused recharge from the overlying thick surficial sand to the buried cse aquifer.

Rapid focused recharge

Thin overlying aquitards (condition ①). Focused recharge occurs through the thin overlying aquitards that are common throughout the county. This condition is shown on A–A′ left side (2 samples), B–B′ right side, C–C′ right side, D–D′ left side (3 samples east of Knife Lake), F–F′ left side (near Camp Creek), H–H′ center (east of Fish Lake), I–I′ right side, (Groundhouse River area), and J–J′ right side (2 samples). Of these 12 samples, 7 had elevated concentrations of chloride and 3 had elevated concentrations of nitrate.

Interconnected aquifers (condition ② and ③). Focused recharge is also common through interconnected aquifers. Examples are shown on A–A′ center (east of MN65), D–D′ center (beneath the Snake River), E–E′ center (west of Knife Lake), E–E′ right side (west of MN65), G–G′ right side (east of Spring Brook), and J–J′ left side (west of Lewis Lake). Of these 6 samples, 4 had elevated concentrations of chloride and 2 had elevated concentrations of nitrate.

Lateral flow (condition Ⓛ). Recent and mixed tritium-age samples that had no obvious downward recharge pathways were possibly recharged at some upgradient location. These types of water migrated laterally and downgradient due to normal groundwater flow gradients. This common condition is found on all the cross sections with the exception of J–J′.

Unknown source (condition Ⓤ). Detections of recent and mixed tritium-age water where the source is unknown are shown on G–G′ right side (east of the Snake River), H–H′ left side (4 samples), and I–I′ left of center (east of the Groundhouse River), I–I right side (west of Rice Creek). Possible reasons for this unknown condition include the following:

- Corroded or ungrouted well casings leak surface water or surficial groundwater to otherwise buried aquifers.
- Unmapped buried sand aquifers have hydraulic connections to the surface.
- Sandy loam aquitards allow seepage of recent or mixed tritium-age groundwater faster than the pollution sensitivity model would predict.

Recharge from open-water bodies. Evaporative signature water is shown on D–D′ left side (downgradient side of Knife Lake), G–G′ left side (4 samples east of Snake River in the city of Mora), H–H′ right side (2 samples east and west of Snake River), and I–I′ right side (2 samples east of Groundhouse River). The source of the evaporative water on the D–D′ example is obvious from the cross section (Knife Lake). The other sources from the other cross sections are not obvious since the lakes are out of the plane of the cross sections. These are probably Mora Lake (G–G′), Fish Lake and Lake Spence (H–H′), and Pennington Lake (I–I′) (Figure 15).

High-volume pumping (condition Ⓟ). Of the 4 evaporative signatures on G–G′ from the Mora area, 3 are from municipal wells clustered close to Lake Mora. High-volume pumping probably creates a higher gradient that draws mixed tritium-age water with evaporative signatures to greater depths than might otherwise be expected.

Discharge

Discharge to surface-water bodies (condition Ⓓ). Discharge to the Snake River (A–A′ through H–H′), Knife River (C–C′ and D–D′) and Fish Lake (H–H′) is mostly based on converging groundwater flow directions based on static water level data from CWI. Possible groundwater discharge to Bachman Pond (C–C′) is more speculative based on the shape of contours for the csr aquifer (Figure 7).

Aquifer characteristics and groundwater use (Figure 32)

Aquifer specific capacity and transmissivity

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

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

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

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

The buried sand aquifers have the highest mean value (37 gpm/ft) compared to the bedrock aquifers: Hinckley, Fond du Lac, and combined Hinckley and Fond du Lac (11, 31, and 12 gpm/ft, respectively). These sets of data may not be representative due to the low number of tests (Table 2).

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

Similar to the specific capacity dataset the amount of available transmissivity data was limited. Data were only available for 3 tests from buried sand aquifers. These data show a high range of values (2,300 to 32,600 ft^2/day) and a relatively high mean value (15,200 ft^2/day).

Table 2. Specific capacity and transmissivity of selected wells

Aquifer	Specific capacity (gpm/ft)					Transmissivity (ft^2/day)				
	Casing diam. (in.)	Mean	Min	Max	No. of tests	Casing diam. (in.)	Mean	Min	Max	No. of tests
Unconsolidated										
Buried sand (QBAA)	12–16	37	6	61	3	10–16	15,200	2,300	32,600	3
Bedrock										
Hinckley	11	11	–	–	1	–	–	–	–	–
Fond du Lac	12	31	–	–	1	–	–	–	–	–
Hinckley and Fond du Lac	8	12	–	–	1	–	–	–	–	–

Specific capacity data adapted from the CWI

Transmissivity data are from aquifer test data compiled by the DNR

QBAA: Quaternary buried artesian aquifer

Dash means no data

Groundwater use

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

Permitted groundwater use (Table 3) is presented by water use category (Figure 32). The highest volume use is from the buried sand aquifers (93 percent). The most common water use is for water supply (75 percent). There are approximately 3,300 located wells in the county. By total numbers of wells, 87 percent are domestic and 2 percent are public supply.

Table 3. Reported 2018 water use from DNR groundwater permit holders in millions of gallons per year (mgy)

Aquifer	Number of wells	Industrial processing	Noncrop irrigation	Special categories	Water supply	Total (mgy)	Total (percent)
Quaternary							
Surficial sand (water table)	–	<1	–	–	–	<1	<1
Buried sand	13	25	–	3	115	143	94
Bedrock							
Hinckley sandstone	1	–	7	–	–	7	5
Unknown	2	–	–	2	–	2	1
Total (mgy)	–	25	7	5	115	152	
Total (percent)	–	16	5	3	76		

Data from MPARS; mgy, million gallons per year

Dash marks (–) indicate no use in those categories

Percentage may not equal 100 due to rounding.

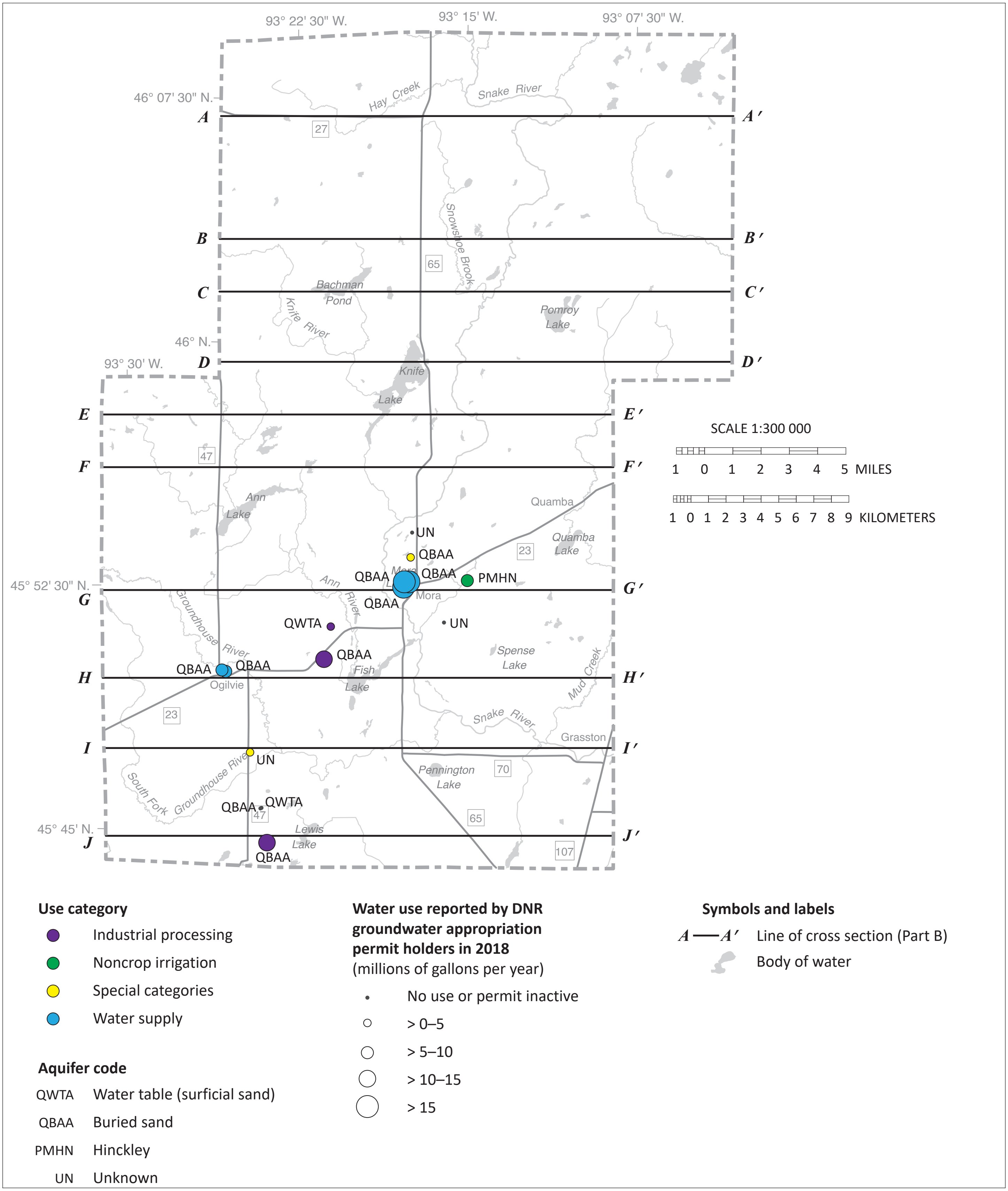


Figure 32. Groundwater use shown by use category and general aquifer classification

Buried sand is the most used aquifer type for high-volume use by DNR appropriation permit holders.

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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 is perpendicular to these lines in the direction of decreasing pressure.

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

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

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

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

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

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

hydraulic—relating to water movement.

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

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

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

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

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

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

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

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

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

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

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

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

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

stable isotope—chemical isotopes that are not radioactive.

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

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

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

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

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

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

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

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

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

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

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

Appendix A

Groundwater field sample collection protocol

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

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

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

Appendix Table A. Groundwater field sample collection and handling details

Parameter	**Tritium (^{3}H)**	**^{18}O and Deuterium (^{2}H)**	**Nitrate/Nitrite & Total Phosphorus**	**Br, F, Cl, SO_4**	**Metals**	**Alkalinity**	**^{14}C**
Lab	Waterloo	Waterloo	MDA	MDA	MDA	DNR	UMN
Sample container	500 ml HDPE	60 ml HDPE	250 ml plastic	250 ml plastic	250 ml plastic	500 ml plastic	30 or 55 gallon plastic-lined drum
Head space	yes	yes	yes	yes	yes	no	yes
Rinse	no	no	yes*	yes*	yes*	yes**	no
Filter	no	no	yes	yes	yes	no	yes
Preservation	none	none	Sulfuric acid (H_2SO_4) to pH <2, Cool to ≤6°C	Cool to ≤6°C	Nitric acid (HNO_3) to pH <2 ***	Cool to ≤6°C, if not analyzed onsite	NH_4OH to pH 10 to precipitate carbonate
Holding time	long	long	28 days	28 days	6 months	24–48 hours	long
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	none
Field blank	none	none	1 for every 20****	1 for every 20****	1 for every 20****	none	none
Storage duplicate	yes	yes	no	no	no	no	no

*Rinse the bottle three times with filtered sample water prior to collection. Rinse 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.

***Metals sample bottle is stored at 0-6°C for convenience. Refrigeration is not required.

****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. 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 2019.

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)	Sample type
05/21/2012–06/20/2012	8.7	Precipitation composite
09/30/2012–10/30/2012	6.7	Precipitation composite
05/09/2014–06/09/2014	7.0	Precipitation composite
10/01/2014–10/31/2014	6.7	Precipitation composite
05/01/2015–05/31/2015	5.3	Precipitation composite
08/17/2016–09/16/2016	8.3	Precipitation composite
04/01/2017–04/30/2017	8.1	Precipitation composite
09/06/2017–10/06/2017	6.5	Precipitation composite
10/03/2018–11/01/2018	3.7	Precipitation composite
04/11/2019	13.4	Snow
04/04/2019–05/04/2019 (excluding 04/11/2019)	12.1	Precipitation composite
09/09/2019–10/03/2019	5.0	Precipitation composite

Tritium age of historic groundwater samples

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

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

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

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

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

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