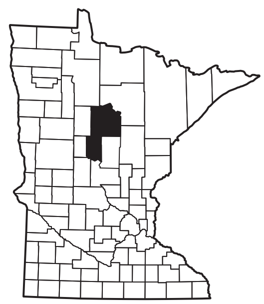
Groundwater Atlas of Cass County, Minnesota

Report



County Atlas Series C-43
Part B - Hydrogeology

To accompany these atlas components:

Plate 7, Water Chemistry

Plate 8, Hydrogeologic Cross Sections

DEPARTMENT OF NATURAL RESOURCES

St. Paul 2023

mndnr.gov/groundwatermapping

The County Atlas Series

The Minnesota County Geologic 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 B - Groundwater Atlas

This atlas was published by the Minnesota Department of Natural Resources, who expanded on the geologic information from Part A. More atlases and information are available online at the Minnesota Department of Natural Resources, Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

Citation for this atlas:

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Acknowledgments

Authors/GIS James A. Berg and Rachel E. Lindgren; Cartographer Holly Johnson; Editor Ruth MacDonald.

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Contributors from the staff of the Groundwater Atlas Program include: Randy Bradt, John Barry, Paul Putzier, Todd Petersen, Wes Rutelonis, Vanessa Baratta, and Dan Cronquist.

Part A - Geologic Atlas

The precursor to this atlas is Part A, Geologic Atlas of Cass County, Minnesota (Lusardi and others, 2018), published by the Minnesota Geological Survey. It contains Plate 1, Data-Base Map (Pettus, M.C. and Chandler, V.W.); Plate 2, Bedrock Geology (Radakovich, A.L. and Chandler, V.W.); Plate 3, Surficial Geology (Lusardi, B.A. and Nguyen, M.K.); Plate 4, Quaternary Stratigraphy (Lusardi, B.A., Nguyen, M.K., and Staley, A.E.); Plate 5, Sand Distribution Model (Lusardi, B.A., Nguyen, M.K., Staley, A.E., and Hamilton, J.D.); and Plate 6, Bedrock Topography and Depth to Bedrock (Radakovich, A.L. and Chandler, V.W.).

Information is available online at the Minnesota Geological Survey's County Geologic Atlas page (cse.umn.edu/mgs/county-geologic-atlas).

Report Contents

Report Figures

Report Tables

Plates (accompanying folded inserts)

Technical reference

Maps were compiled and generated in a geographic information system. Digital data products are available from the Minnesota DNR Groundwater Atlas Program.

Maps were prepared from Minnesota 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 in the offices of the Minnesota Geological Survey and the Minnesota 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 the Minnesota Geological Survey, *Geologic Atlas of Cass County, Minnesota, 2018.* 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 $foot^2$ per day = 7.48 gallons per day per foot

Groundwater Atlas of Cass County, Minnesota

by James A. Berg and Rachel E. Lindgren

Executive summary

This report and the accompanying plates are Part B of the Cass 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) (Lusardi and others, 2018).

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 atlas **report** details the methods, results, and interpretations for groundwater in Cass County. **Plate 7** illustrates the water chemistry; **Plate 8** uses hydrogeologic cross sections to show general groundwater flow directions and residence time within the aquifers. The following gives an outline of the detailed sections that follow the executive summary.

Physical setting and climate (page 4) describes the location of the county, summarizes the average temperature and precipitation, and lays the framework for how these influence groundwater recharge.

Geology and physical hydrogeology (pages 4–21) describes the aquifers and aquitards and identifies hydrostratigraphic characteristics and corresponding geologic units from Part A.

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 aquifers are an important source of groundwater in the county and contribute to surface-water systems. They have a complex distribution that was deposited from the advance and retreat of the last major ice sheets from the northeast and northwest.
- The buried sand and gravel aquifers are the most commonly used source. These were deposited from previous glacial advances and retreats along with a series of intervening fine-grained layers of till and lake sediment.
- Bedrock wells are rare in the county. Beneath the glacial sediment the much older bedrock is made of 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).

Groundwater-elevation maps give a broad look at the direction of groundwater flow in unconfined conditions (water-table elevation) and confined conditions (potentiometric-surface elevation).

- *Water-table elevations* cover a wide range of values. The highest values and gradients are in the south and scattered in the central portion; lowest values are near the Leech Lake River and Leech Lake in the north and the Pine and Crow Wing rivers in the south. The high relief and complex post-glacial topography has created a complex pattern of groundwater flow in the water table and buried aquifers. *Water-table depths* tend to be shallow (0–20 feet) in the north but are highly variable over short distances in most other portions.
- *Regional groundwater flow direction* is predominantly from the topographic highs in the west (Hackensack area) and south (crest of the St. Croix moraine), flowing radially outward toward major surface-water features (north to Leech and Woman lakes; south to Pine River, Crow Wing River, and Gull Lake).

Water chemistry (pages 22–29, Plate 7) provides information about the water source, generalized 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. These can indicate high sensitivity from the land surface or problems with naturally occurring geologic contaminants.

- *Chloride and nitrate* were found in buried sand and gravel aquifers but were not very high or widespread because of the relatively low density of urbanization.
- *Arsenic* is a naturally occurring, geologic-sourced contaminant in Minnesota groundwater, but high concentrations were not common. The Minnesota Department of Health recommends treatment if any arsenic is present.

- *Manganese* is a naturally occurring, geologic-sourced contaminant in Minnesota groundwater. The majority of samples analyzed for manganese were elevated and were found in most of the mapped buried sand and gravel aquifers.
- *Residence time* in aquifers reflects the wide range of groundwater conditions. Tritium was detected in a high proportion of groundwater samples, reflecting the relatively permeable nature of the glacial sediment. Carbon-14 analysis detected water ranging from 600 to 4,500 years.

Pollution sensitivity (pages 30–52) 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 select chemistry from mapped aquifers.

- Pollution sensitivity of *near-surface materials* ranges from low to high, with a significant portion in the moderate to high categories. The low sensitivity areas are associated with mixed moraine sediment and finer-grained (sandy loam and loamy) till deposits. The high sensitivity areas that dominate the central and southern parts are mostly glacial outwash from the last ice lobe that retreated from the area.
- Pollution sensitivity of the *buried sand and gravel aquifers and bedrock surface* exhibits a wide range from mostly very high for the shallowest aquifers (bds1, hsi1, and iss1) to a complex distribution in the intermediate depth aquifers (hsi2, iss2, hsa1, and iss3) to mostly very low for the deeper buried sand and gravel aquifers and bedrock surface.

Hydrogeologic cross sections (pages 53–54, Plate 8) illustrate groundwater flow, residence time, and distribution of chemical indicators. Cross sections help define areas of interest such as locations of important groundwater recharge, discharge, and sensitivity to pollution.

Groundwater flow is initially downward, then laterally toward surface-water bodies. In many areas recharge to the deeper aquifers can take hundreds or thousands of years if there is no focused recharge through interconnected buried sand and gravel aquifers.

Aquifer characteristics and groundwater use (pages 55–58) summarizes specific capacity tests, aquifer tests, water use records, and groundwater level monitoring data for each aquifer. These data can be used to characterize aquifer recharge in the county and plan for new well installations.

The highest volume of permitted groundwater use is from the surficial sand and gravel aquifers. The most common water use is for crop irrigation. By total numbers of wells, most are for domestic use and a much smaller proportion is for water supply and crop irrigation.

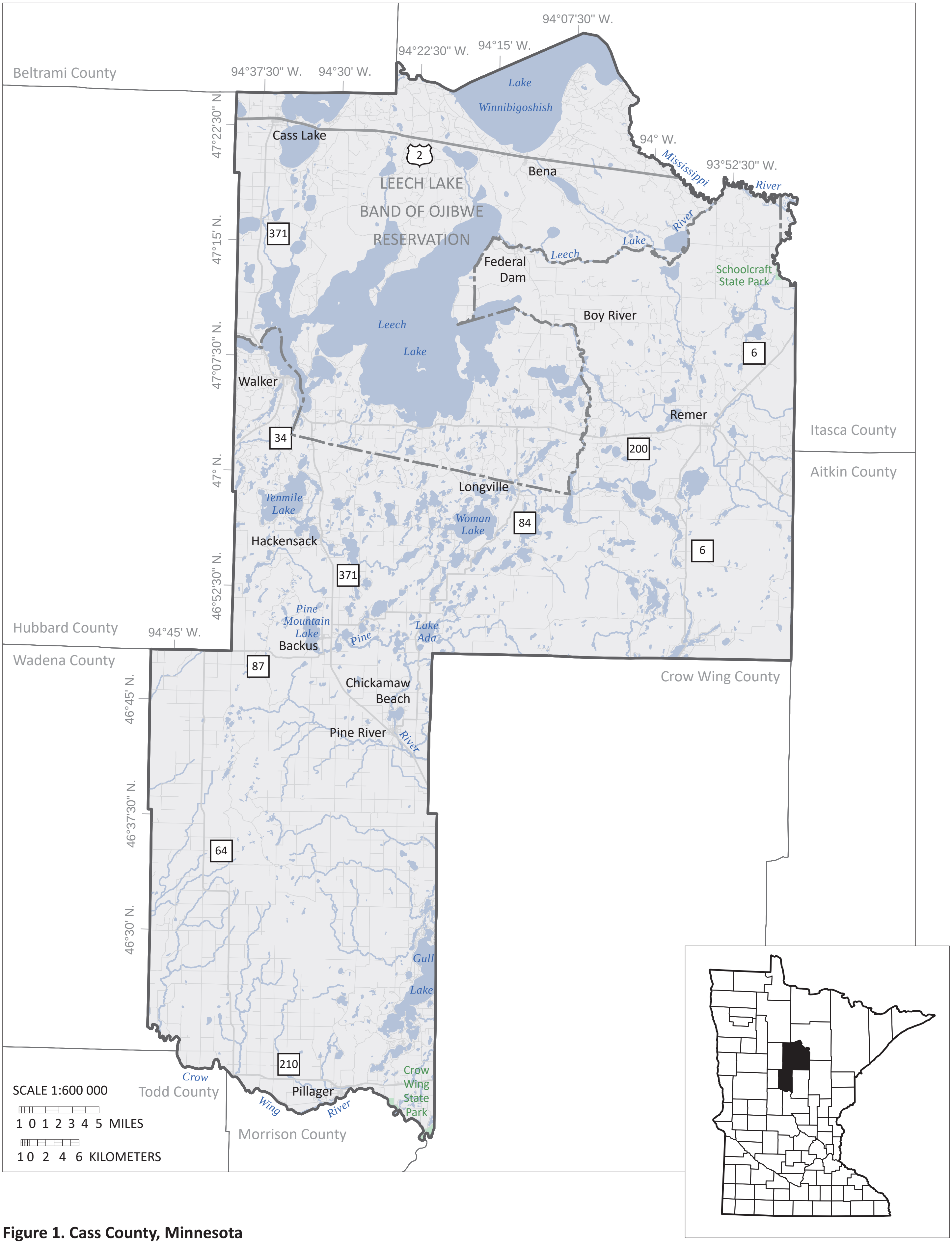


Figure 1. Cass County, Minnesota

Physical setting and climate

Cass County is in north-central Minnesota (Figure 1) with land use that is a mix of agricultural, rural, forest, and small towns. The population in 2019 was approximately 30,000 (U.S. Census Bureau, 2021). The county lies within the watersheds of the Leech Lake River, Pine River, Crow Wing River, and portions of the Mississippi River.

The 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. The average temperature (30-year) was approximately 66 degrees Fahrenheit June through August, and 12 degrees Fahrenheit December through February (NOAA, 2021). Average annual precipitation (30-year) is approximately 27 inches, placing it in the middle of the statewide range of 20 to 36 inches.

Climate variations in temperature and precipitation affect groundwater resources over time. From 1895 through the summer of 2021, the average annual temperature in Cass County increased by 3.5 degrees Fahrenheit. The temperature increases have been fastest during winter, at night, and especially in the past five decades. Since 1970 daily minimum temperatures have risen approximately 40 percent faster than daily maximum temperatures, and average winter temperatures have risen approximately three times faster than average summer temperatures.

Annual precipitation in Cass County has increased by 1.8 inches since 1895, and intense rainfall events that have produced daily totals in excess of 1, 2, and 3 inches were more common between 1990 and 2021 than in any other period on record.

Projections summarized in the 2014, 2017, and 2018 National Climate Assessments indicate that Cass County will warm by an additional 2 to 4 degrees Fahrenheit by 2050, while annual precipitation will increase by an additional 1 to 2 inches (Pryor and others, 2014; Vose and others, 2017; Easterling and others, 2017; Jay and others, 2018). Shorter-term variations leading to episodes of cooler conditions and drought can be expected even as trends toward warmer and wetter conditions continue.

Geology and physical hydrogeology

Surficial aquifers

The origin of the topography and surficial deposits of the county can be traced back to advances and retreats of glacial ice (Part A, Plate 3) that deposited fine-grained and coarse-grained sediment (Figure 2). The fine-grained sediment includes a mixture of clay, silt, and sand and gravel (diamicton or till).

The coarser-grained sediment includes 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.

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

Glacial meltwater flowed into Cass County from several ice margins, depositing sediment from multiple source regions, or *provenances*. Much of the historical origin relies on drainage patterns, topographic interpretations, and composition.

The most recent glacial event in this area was the Wisconsinan glacial episode from about 110,000 to 11,700 years ago, ending at the start of the Holocene Epoch. The surficial geology was largely created by a full advance from the northeast across the county, and a partial retreat of two adjacent ice lobes (Wadena and Rainy lobes of the Alexandria phase). Linear hills (drumlins) were formed trending southwest in the southern part of the county.

The northern-most lobe (Wadena) deposited the till of the Hewitt Formation; the southernmost lobe (Superior) deposited the till of the Independence Formation. Both of these formations are relatively coarse (sandy loam to loamy sand textures) which makes them leaky aquitards.

After their partial retreat both of these lobes readvanced becoming the Itasca and Brainerd lobes of the Itasca phase. These formed the Itasca and St. Croix moraines at the margin of the ice lobes where the advance stalled (stagnation moraine) and deposited a complex assemblage of fine-grained and coarse sediment in topographically raised and arcuate landforms.

Meltwater from the Itasca and Brainerd lobes flowed south and west, depositing most of the surficial sand outwash in the county and burying some of the

Alexandria-phase drumlins in the west. Fine- to medium-grained sand on and between drumlins may have been controlled by buried ice blocks between the drumlins, allowing deposition of outwash over both the high and low areas. Post-glacial eolian processes (wind erosion and deposition) further modified the surface expression of the drumlins.

In the final glacial phase, a Koochiching lobe from the northwest advanced across northern Cass County and deposited a finer-grained till formation (Blackduck Formation, loamy till). The till is relatively thin (less than 25 feet) over glacial sediment of the Hewitt and Independence formations. Meltwater from the Koochiching lobe also deposited a glacial lake sand unit north of the Itasca moraine in the northern portion of the county.

Ice lobes west of the county (Des Moines and Red River lobes) produced meltwater that deposited sand and gravel into what is now the Crow Wing River, appearing as wide terraces at the southern border.

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. This aquifer provides water to approximately 20 percent of the wells in the county.

The water table is generally a subdued expression of the surface topography. Shallow water-table flow is typically consistent with surface-flow direction and watershed boundaries. Flow is generally from local highs to river tributaries, lakes, and wetlands.

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

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

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

Groundwater flow is generally from local high-elevation areas through the underlying aquifers to streams, lakes, and wetlands.

Water-table elevations cover a wide range of values. The highest values and highest gradients are found along the St. Croix moraine in the southwest and scattered locations in the central portion. The lowest values are near the Leech Lake River and Leech Lake in the north and the Pine and Crow Wing rivers in the south.

The central Itasca moraine area has complex topography and groundwater flow directions. This pattern is evident not only in the water table, but throughout the entire sequence of aquifers. Groundwater-flow divides generally coincide with the larger watershed boundaries of the Mississippi, Leech Lake, Pine, and Crow Wing rivers.

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).

Water-table depths in the north tend to be shallow (0–20 feet), but most other portions have high variability over short distances. In the south, the influence of the drumlin topography is apparent where the water table may be deeper beneath the crests of these features. The Itasca moraine area south of Leech Lake is highly variable.

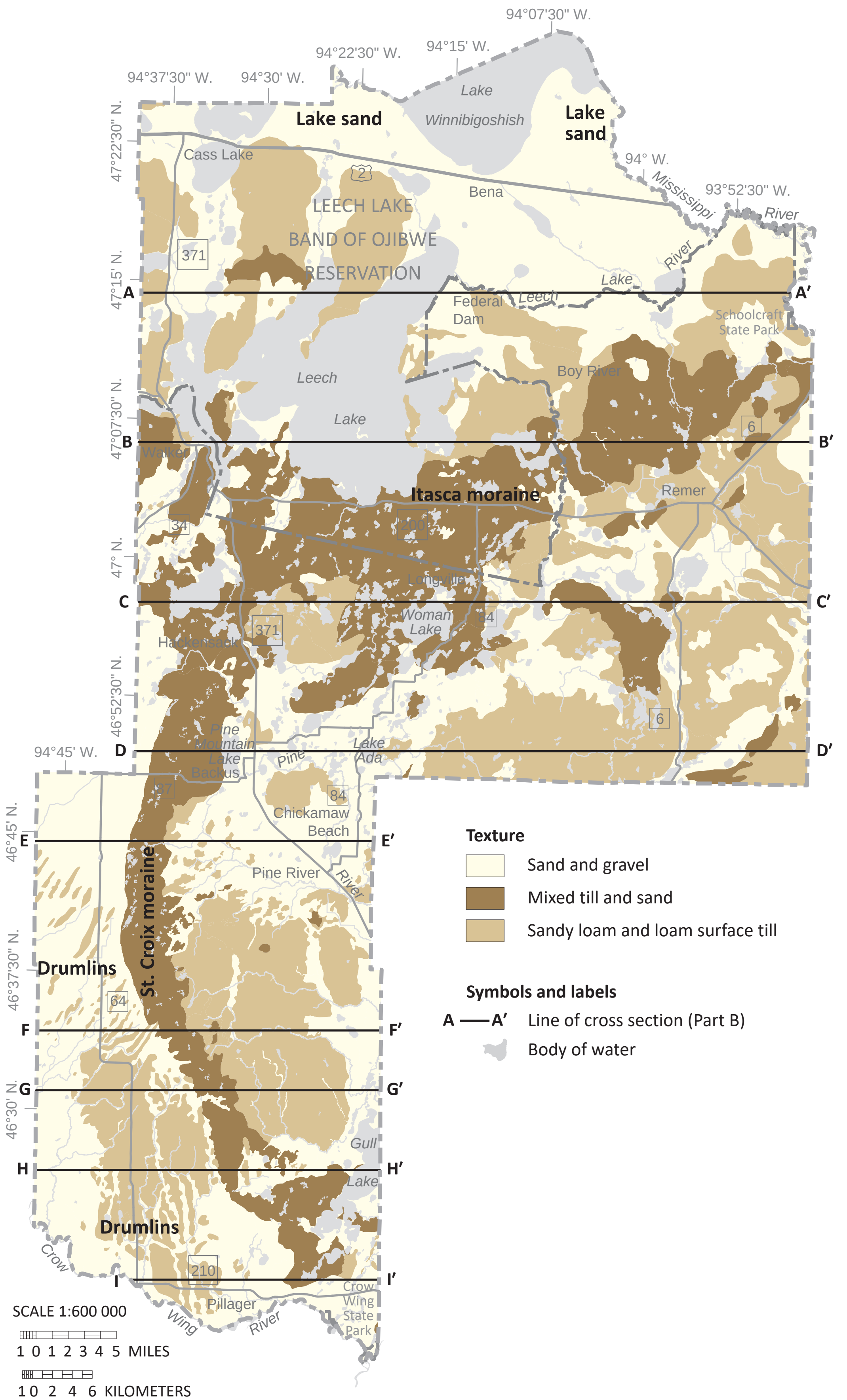


Figure 2. Generalized surficial geologic units

The distribution of surficial sand, mixed-texture moraine material, and till was controlled by late stage glacial events: the advance and retreat and partial advance and retreat of major ice sheets from the northeast and a partial advance and retreat of an ice lobe from the northwest.

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).

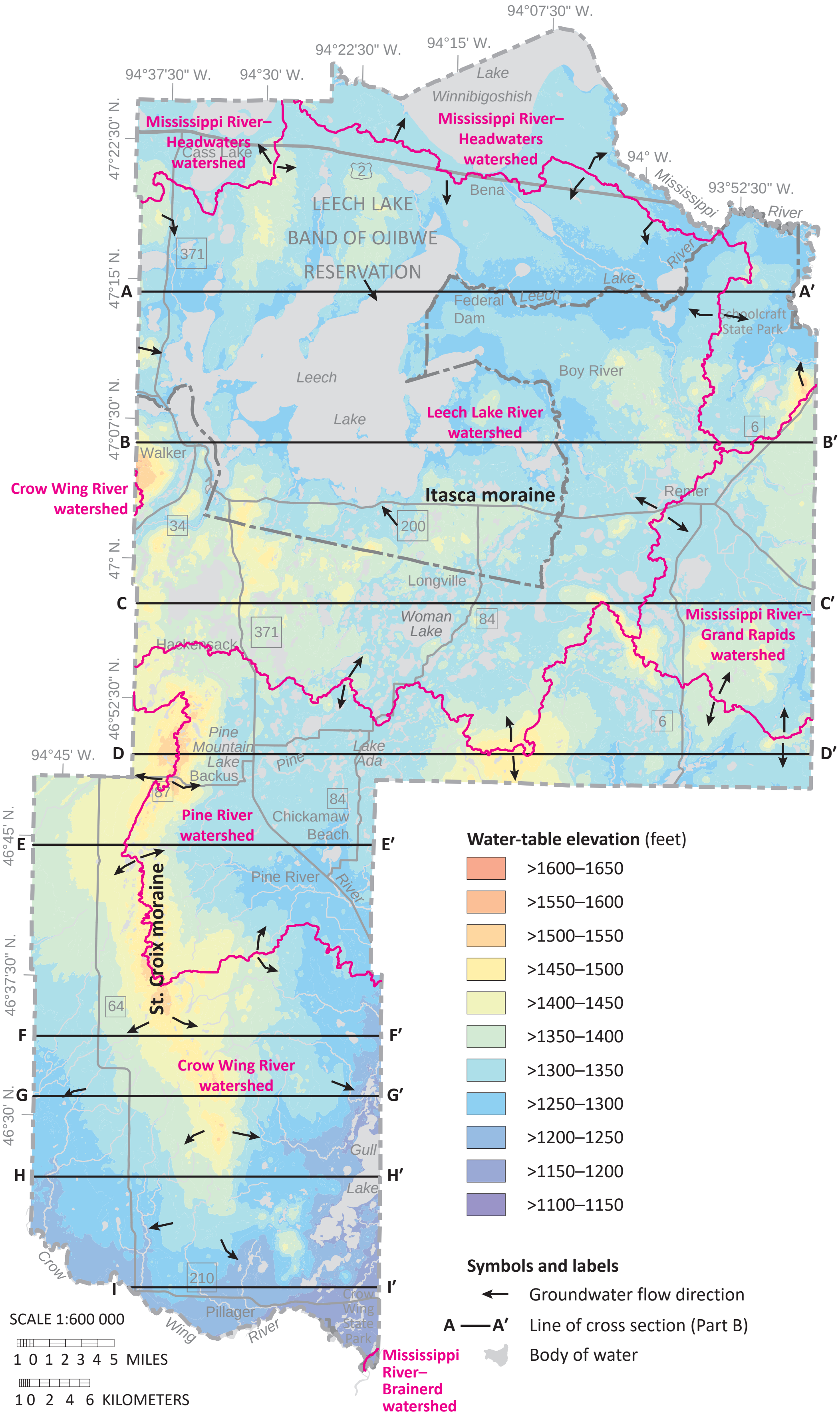


Figure 3. Water-table elevation and groundwater flow directions

Water-table elevations cover a wide range of values.

The highest values and gradients are found along the St. Croix moraine in the southwest and scattered locations in the central portion.

The lowest values are near the Leech Lake River and Leech Lake in the north and the Pine and Crow Wing rivers in the south.

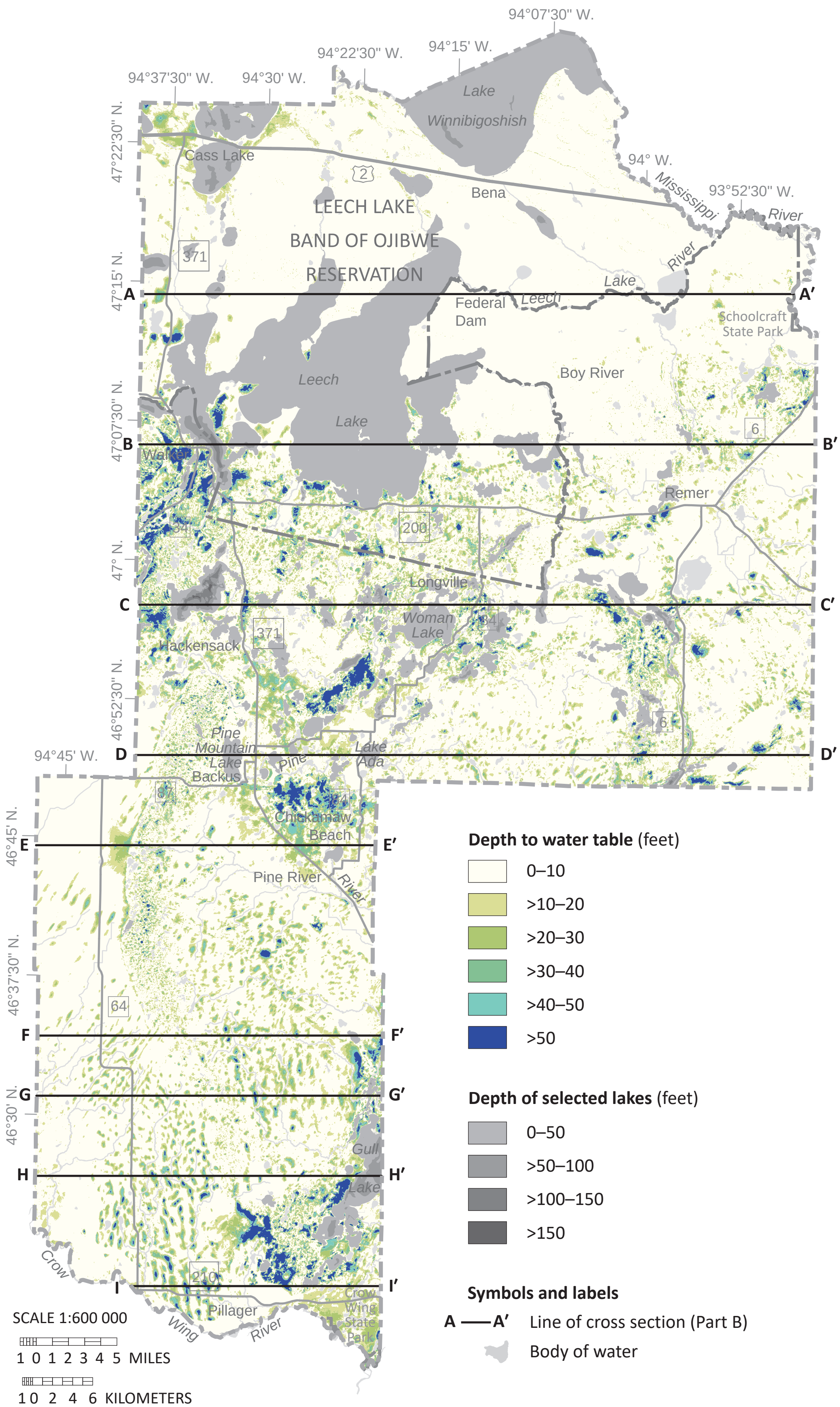


Figure 4. Depth to water table

Water-table depths tend to be shallow (0–20 feet) in the north but are highly variable over short distances in most other areas.

Buried aquifers

Sand and gravel

Beneath the surficial geologic deposits are alternating layers of older sand, gravel, and fine-grained deposits from previous glacial advances. Multiple sequences of sand and gravel were deposited by meltwater from ice lobes during 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 sediment 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.

The buried sand and gravel layers are more limited than surficial sand but still common. Approximately 80 percent of wells in the county are completed in buried sand and gravel aquifers.

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 found in Part A, Plate 3 (Glacial History), Plate 4 (Figures 1 and 3), 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, and can generally be described as follows.

- **Sand and gravel** units are described as **aquifers**.
- **Till or lake clay** units are usually described as **aquitards**.

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 are referred to as ***buried sand*** aquifers.

The sand units have been combined into groups on the maps for potentiometric surface and pollution sensitivity based on stratigraphic similarity (Figure 5).

Figures 6–10

The underlying 5 groups (hsi2/iss2, hsa1/iss3, hsa2/iss4, hsa3/iss5, and hsa4/iss6) are mapped as pairs of units each deposited by separate but contiguous and contemporaneous ice lobes (Part A, Plate 5, Figures 5–9). In effect, these units are stratigraphically very similar and may function as the same aquifer.

Figure 11

The brs1, brs2, and brs3 units are all subdivisions of the same formation (Browerville), are partially overlapping, and therefore may have hydraulic connections.

Figure 12

The mls1/sfs1 grouping occurs mostly as partially overlapping units in the southern part of the county which may also have hydraulic connections. The overlying scs unit is included with this group because its extent was too limited to be shown alone on maps of this scale.

Figures 13–14

The two underlying unit groups (mls2/sfs2 and mls3/sfs3) were created mostly because of stratigraphic associations and acknowledgment in the Part A descriptions that all of these units may be transitional to overlying units (Part A, Plate 5, Figures 12–15).

Figure 15

The ebs1/ebs2 group was created based on an association detailed in Part A (Plate 5, Figure 16). The underlying sks unit was included in this group because of stratigraphic association and limited extent.

Other

None of the remaining underlying units (es1, es2, usw, mn, uns1, and uns2) are shown with mapped potentiometric surfaces because of limited extent, lack of sufficient data, and map scale. They are, however, shown on the pollution sensitivity section of the report.

Bedrock

Few wells are completed in bedrock because surficial and buried sand aquifers are widespread and available. Where these are not present, well owners must rely on groundwater from bedrock. There are only four bedrock wells in the county out of the approximately 12,000 wells listed in CWI.

Figure 5. Quaternary hydrostratigraphy

The sand units have been combined into groups on the maps for potentiometric surface and pollution sensitivity.

Formation/epoch	Member/ phase	Sediment type	Part A	Part B	Remarks	Potentiometric surface figure	Pollution sensitivity figure
Holocene		lake	sc	sc	unconfined	Figure 3	Figure 24
		alluvium	pgs	pgs			
Terrace		sand and gravel	tel / teu	te			
Undifferentiated Pleistocene		sand and gravel	ou	ou			
Blackduck		outwash	bds	bds			
		till	bdt1	bdt1			
		lacustrine	bdl2	bdl2*			
		till	bdt2	bdt2*			
Hewitt	Itasca	till	hti0	hti0	mostly unconfined		
		outwash	hsi1	hsi1			
		till	hti1	hti1			
Independence	S Long Lake	till	ist0	ist0	mostly unconfined		
		lacustrine	isl1	isl1*			
		outwash	iss1	iss1			
		till	ist1	ist1			
		lacustrine	isl2	isl2*			
Hewitt	Itasca	outwash	hsi2	hsi2	mostly confined	Figure 6	Figure 25
		till	hti2	hti2			
Independence	S Long Lake	outwash	iss2	iss2			
		till	ist2	ist2			
Hewitt	Alexandria	outwash	hsa1	hsa1	mostly confined	Figure 7	Figure 26
		till	hta1	hta1			
Independence	S Long Lake	outwash	iss3	iss3			
		till	ist3	ist3			
Hewitt	Alexandria	outwash	hsa2	hsa2	mostly confined	Figure 8	Figure 27
		till	hta2	hta2			
Independence	S Long Lake	outwash	iss4	iss4			
		till	ist4	ist4			
Hewitt	Alexandria	outwash	hsa3	hsa3	confined	Figure 9	Figure 28
		till	hta3	hta3			
Independence	S Long Lake	outwash	iss5	iss5			
		till	ist5	ist5			
		outwash	iss6	iss6	confined	Figure 10	Figure 29
		till	ist6	ist6			
Hewitt	Alexandria	outwash	hsa4	hsa4			
Browerville		outwash	brs1	brs1	confined	Figure 11	Figure 30
		till	brt1	brt1			
		outwash	brs2	brs2			
		till	brt2	brt2			
		outwash	brs3	brs3			
		till	brt3	brt3			
Unnamed Superior			uts	uts*		-	-
Lake Henry	Sauk Centre	outwash	scs	scs	confined	Figure 12	Figure 31
		till	sct	sct			
	Meyer Lake	outwash	mls1	mls1			
		till	mlt1	mlt1			
St. Francis	lower	outwash	sfs1	sfs1			
		till	sft1	sft1			
Lake Henry	Meyer Lake	outwash	mls2	mls2	confined	Figure 13	Figure 32
		till	mlt2	mlt2			
St. Francis	lower	outwash	sfs2	sfs2			
		till	sft2	sft2			
Lake Henry	Meyer Lake	outwash	mls3	mls3	confined	Figure 14	Figure 33
		till	mlt3	mlt3			
St. Francis	lower	outwash	sfs3	sfs3			
		till	sft3	sft3			
Eagle Bend		outwash	ebs1	ebs1	confined	Figure 15	Figure 34
		till	ebt1	ebt1			
		outwash	ebs2	ebs2			
		till	ebt2	ebt2			
		lacustrine	ebl3	ebl3*			
Shooks		outwash	sks	sks			
		till	skt	skt			
Elmdale		outwash	es1	es1	confined	-	Figure 35
		till	et1	et1			
		outwash	es2	es2			
		till	et2	et2			
Unnamed Winnepeg		outwash	usw	usw			
		till	utw	utw			
Mulligan		lacustrine	ml	ml*			
		outwash	ms	ms			
		till	mt	mt			
older			uns1	uns1			
			ups1	ups1			
			uns2	uns2			
			ups2	ups2			

Percent sand in aquitard

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

* indicates unit is not shown on cross sections.
Dash (-) indicates limited or no data.

Groundwater flow

Potentiometric-surface maps show the direction of groundwater flow. In confined aquifers hydrostatic pressure is greater than atmospheric pressure which results in water levels in wells penetrating the aquifer to rise above the top of the aquifer. These water levels are converted to elevations above sea level and contoured to create a map of the potentiometric surface for each aquifer, similar to how land-surface elevations are contoured for topographic maps.

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

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

Potentiometric-surface maps were created using static water-level data from the CWI, measurements made by DNR staff, and river elevation points along the major rivers and streams where groundwater discharge is likely. The CWI records represent various climatic and seasonal conditions from 1966 to 2018. This data variability creates some uncertainty in potentiometric-surface elevations.

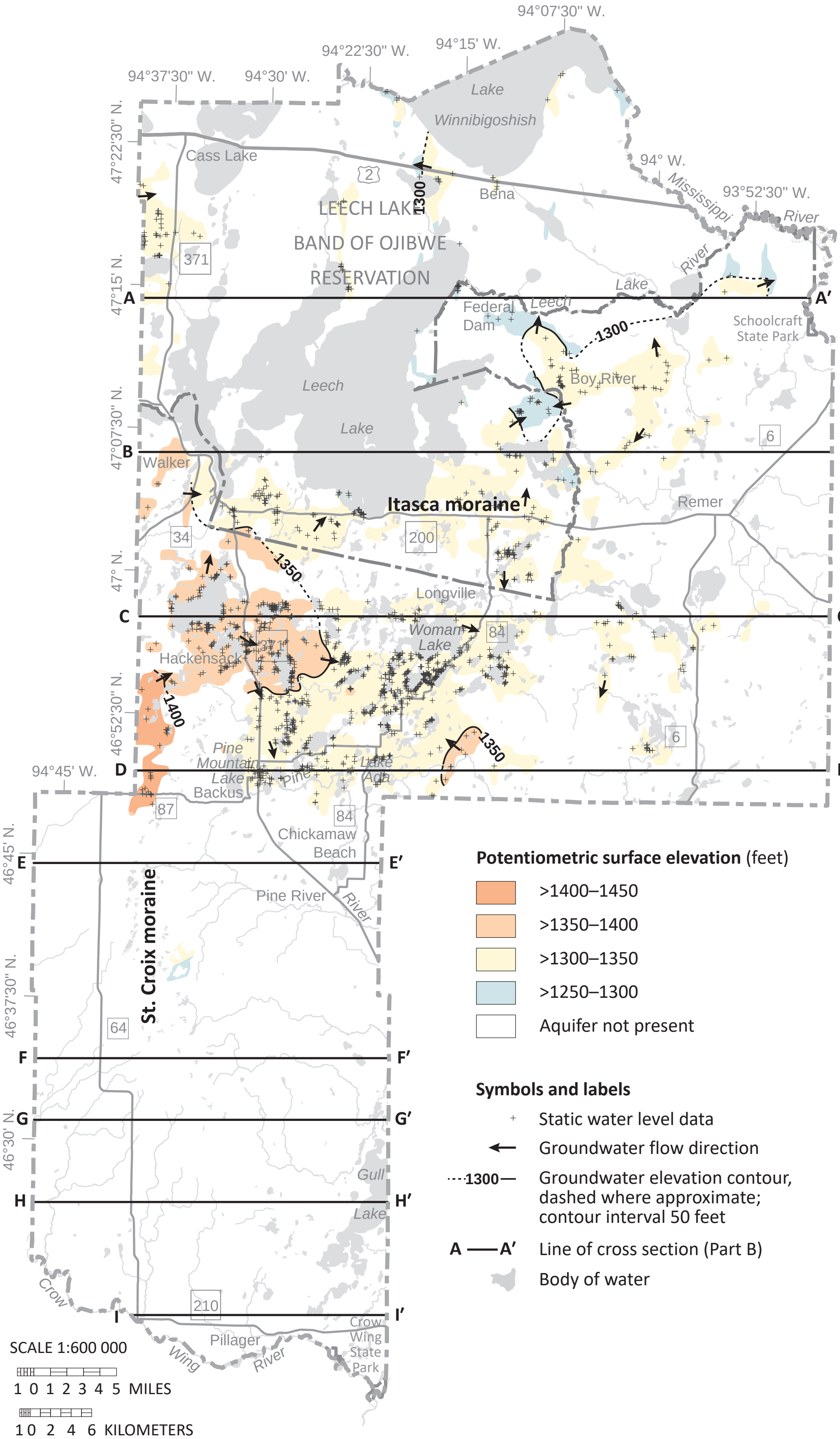


Figure 6. Potentiometric surface of the hsi2 and iss2 aquifers

From the elevated topographic area west and southwest of Hackensack, groundwater flows in a radial pattern to the northeast toward Leech Lake and southeast toward the Pine River.

East of this topographically high area is the lower portion of the Itasca moraine.

Groundwater flow in this area is complex and with variable local flow directions over short distances. East of Leech Lake flow is typically northwest toward the Leech Lake River.

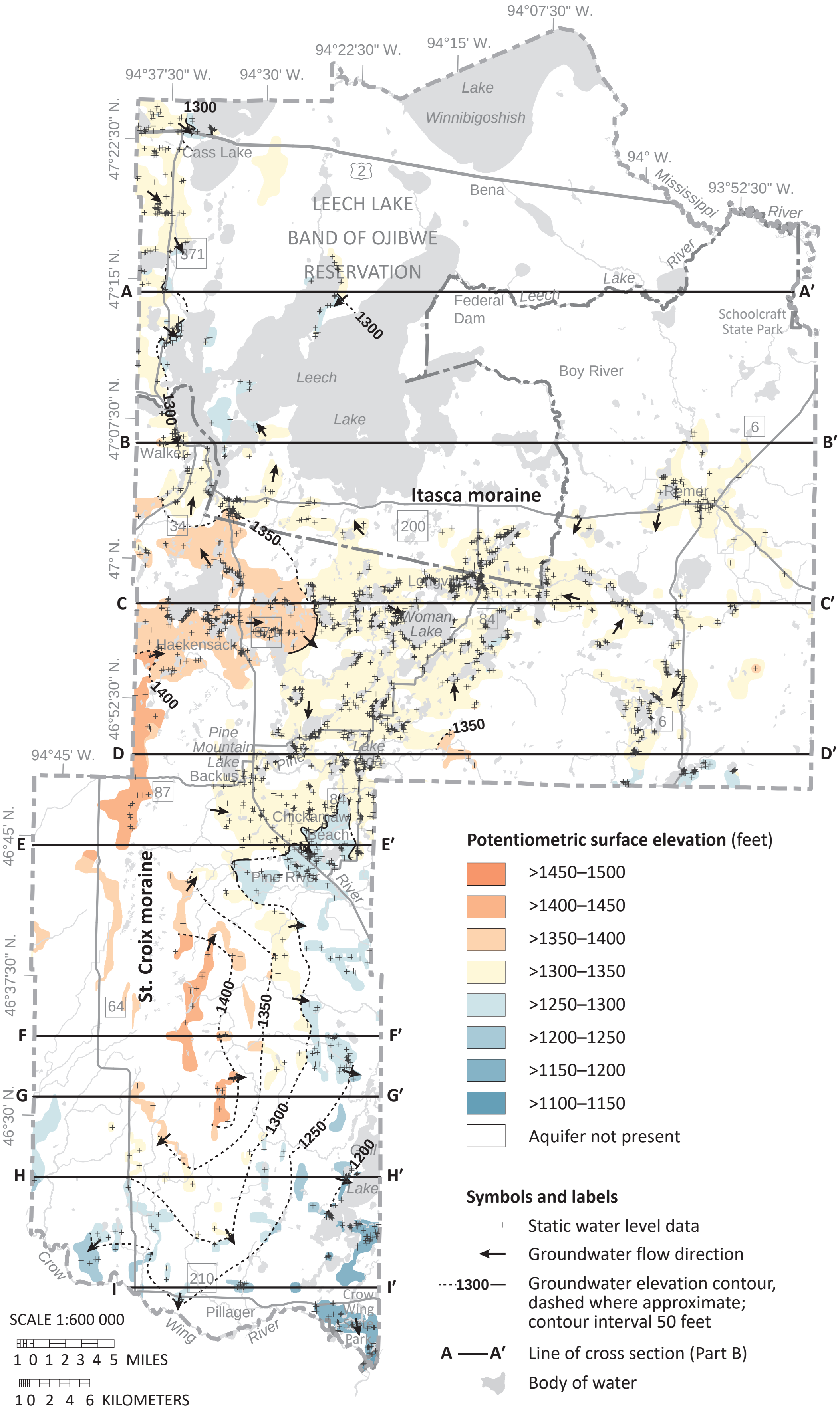


Figure 7. Potentiometric surface of the hsa1 and iss3 aquifers

The dominant flow directions are from the topographic highs of the two moraines radially toward major surface-water features.

In the north, flow is from the western portion of the Itasca moraine (Hackensack area) radially toward Leech and Woman lakes.

In the south, flow is from the crest of the St. Croix moraine radially toward Pine River, Crow Wing River, and Gull Lake.

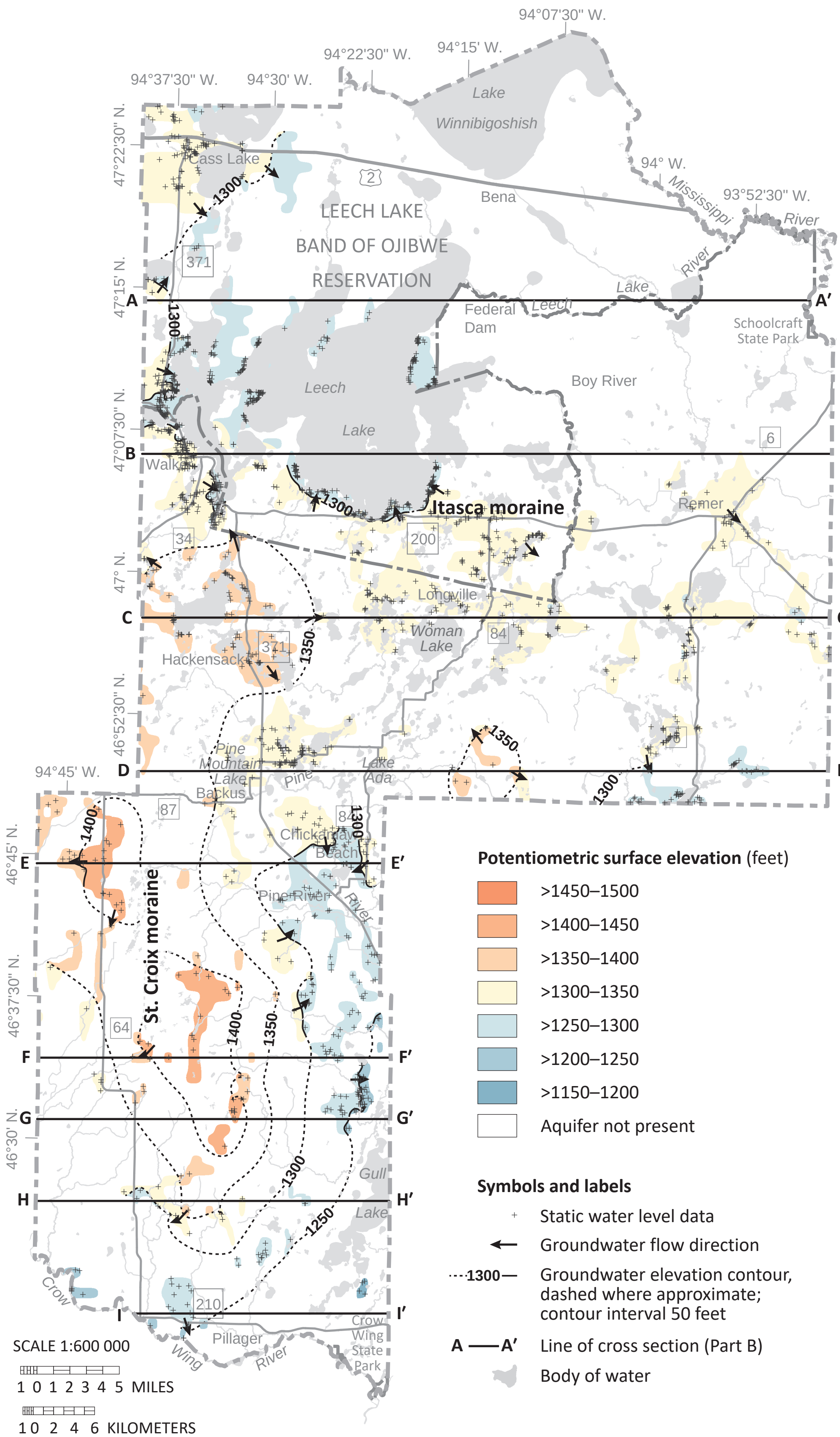


Figure 8. Potentiometric surface of the hsa2 and iss4 aquifers

The dominant flow directions are from the topographic highs of the two moraines radially toward major surface-water features.

In the north, flow is from the western portion of the Itasca moraine (Hackensack area) radially toward Leech and Woman lakes.

In the south, flow is from the crest of the St. Croix moraine radially toward Pine River, Crow Wing River, and Gull Lake.

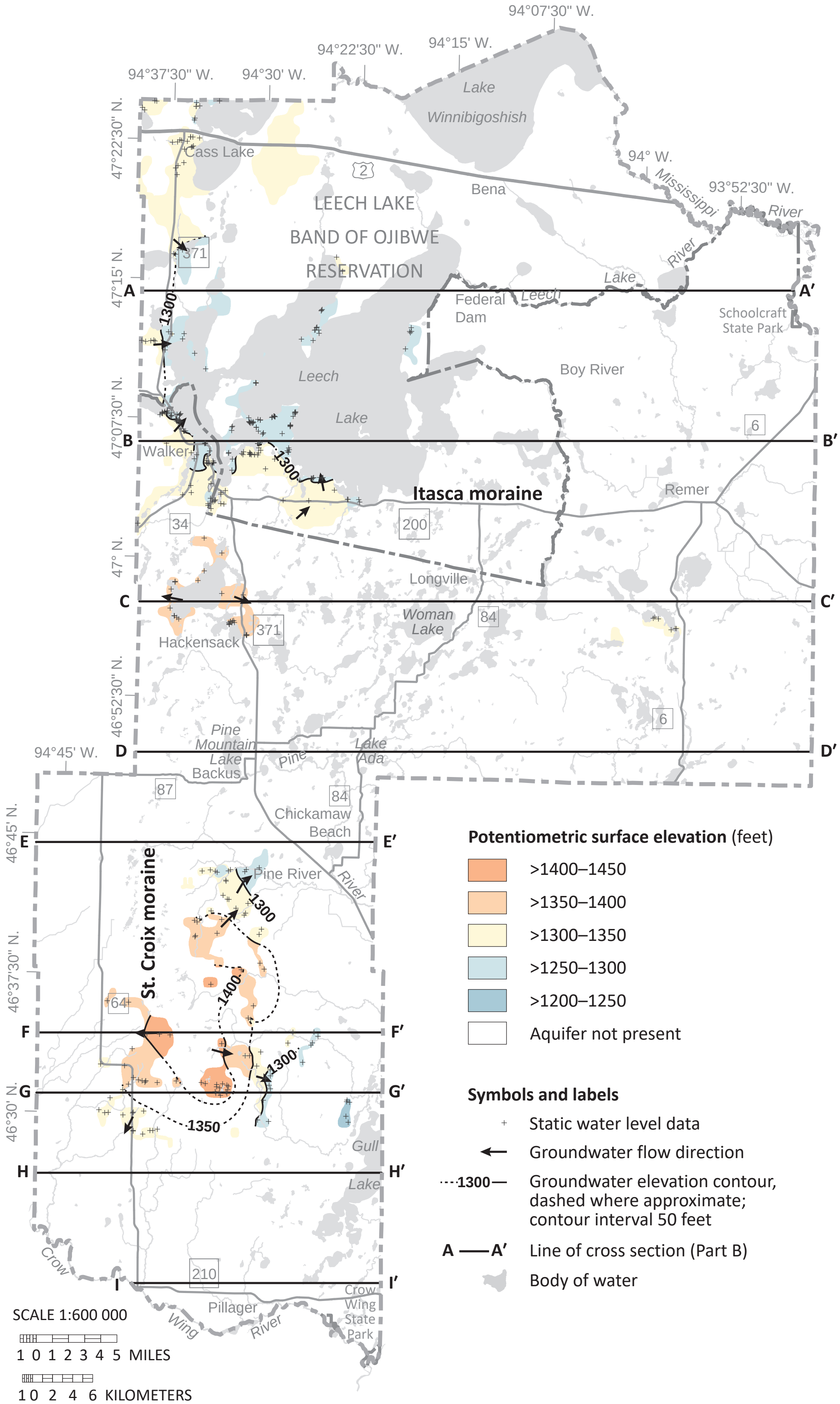


Figure 9. Potentiometric surface of the hsa3 and iss5 aquifers

Although the mapped extents of these aquifers are limited, groundwater flow in the north is dominantly toward Leech Lake.

In the south, flow is radial from the crest of the St. Croix moraine toward the Pine and Crow Wing rivers.

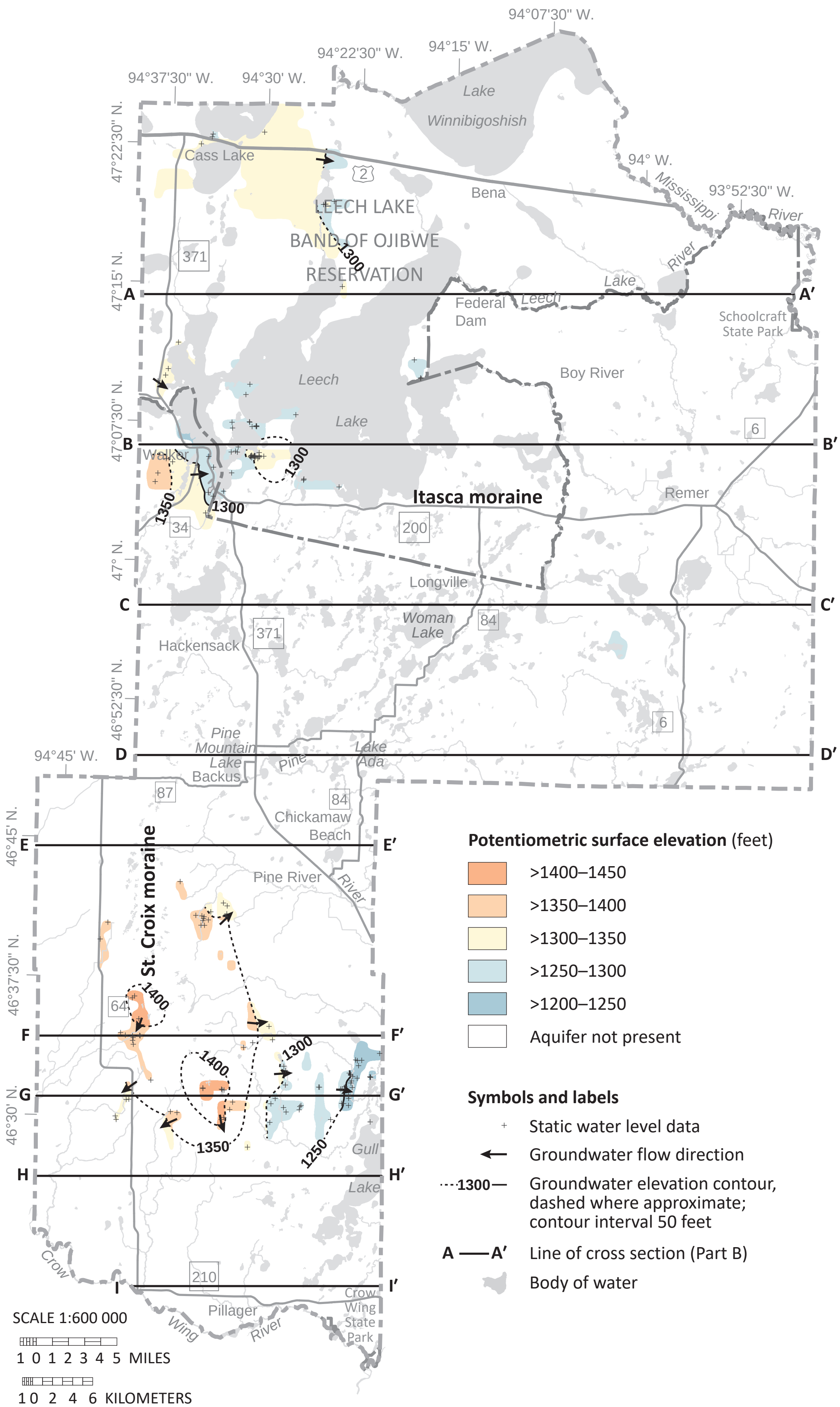


Figure 10. Potentiometric surface of the hsa4 and iss6 aquifers

The mapped extents of these aquifers are limited. A small mapped area in the north, west of Leech Lake flows toward Leech Lake.

In the south, groundwater flows radially from the crest of the St. Croix moraine toward the Pine and Crow Wing rivers.

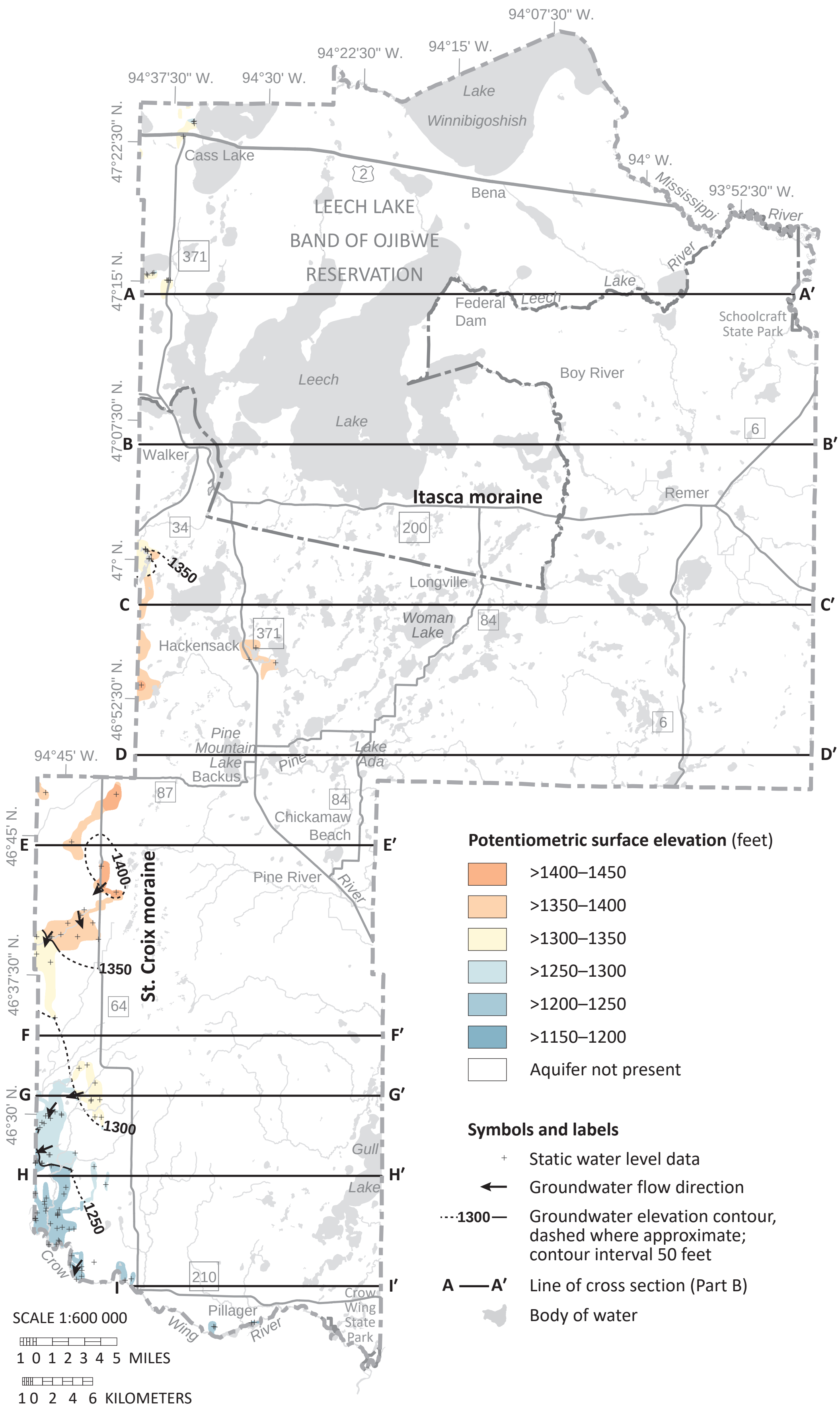


Figure 11. Potentiometric surface of the brs1, brs2, and brs3 aquifers

The mapped extents for these aquifers are mostly limited to the southwest. The dominant flow is southwest from the St. Croix moraine to the Crow Wing River.

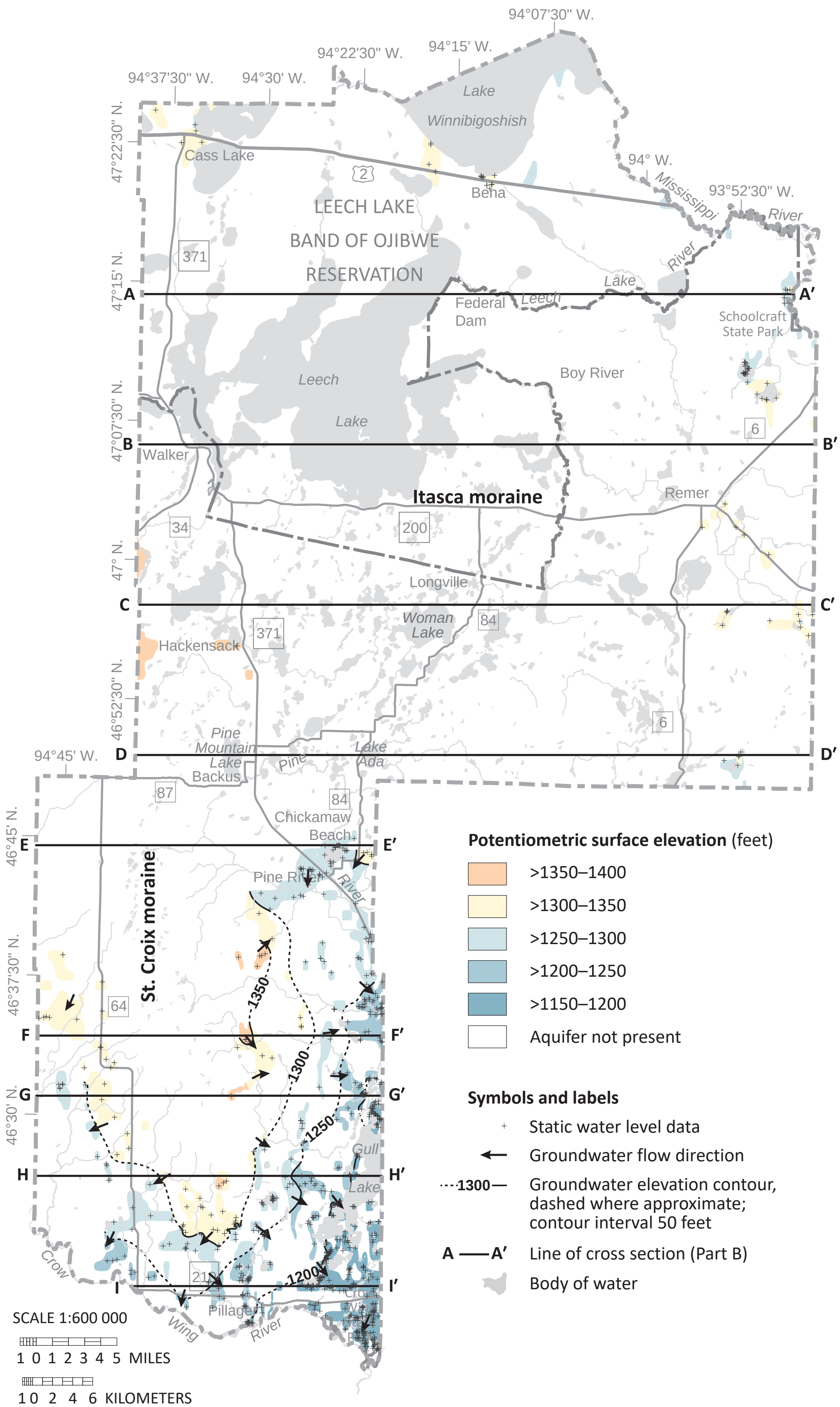


Figure 12. Potentiometric surface of the scs, mls1, and sfs1 aquifers

Most of the mapped portions of these aquifers are in the south.

Flow is radial from the St. Croix moraine: southwest and south toward the Crow Wing River and east toward the Pine River and Gull Lake.

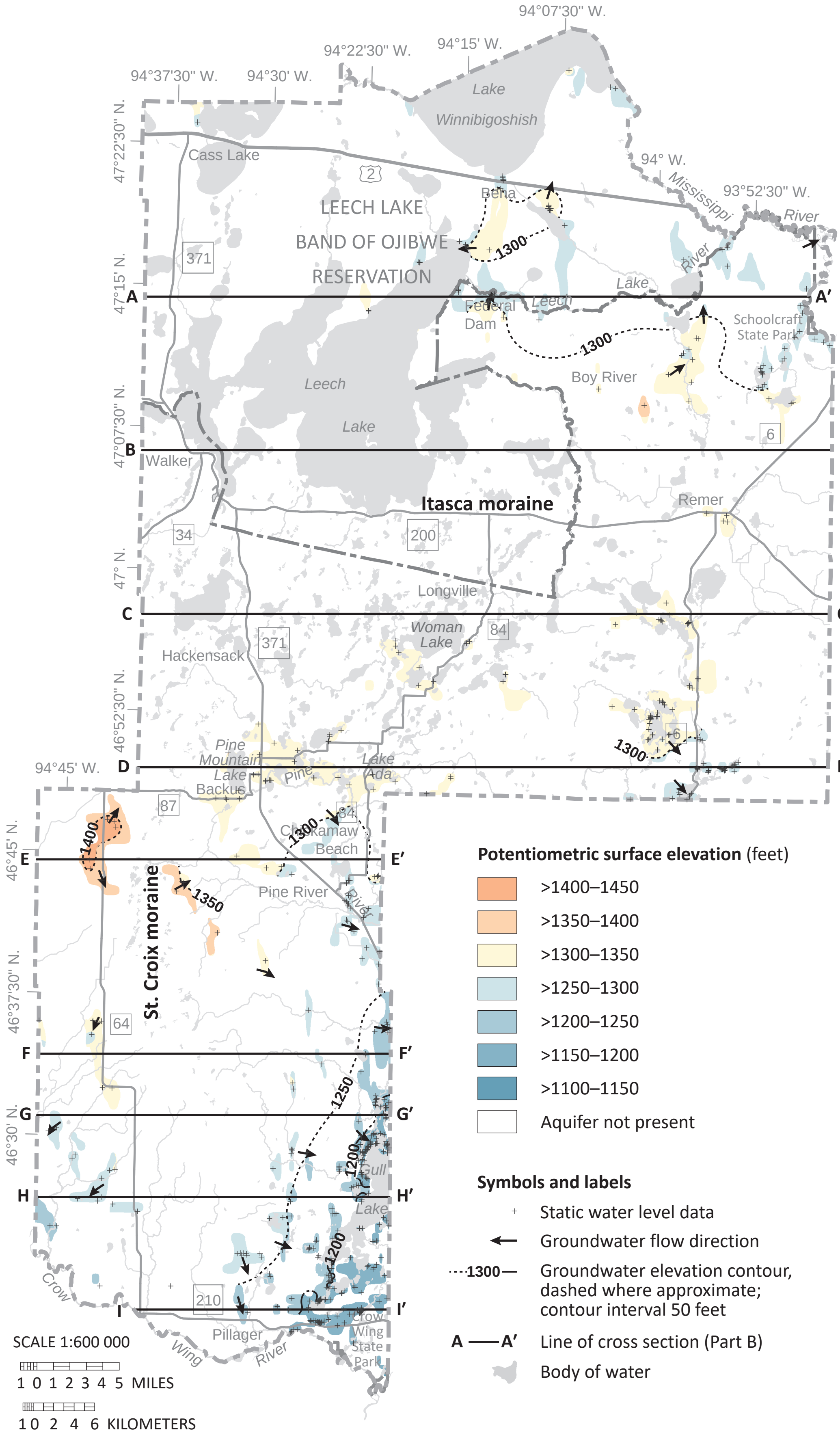


Figure 13. Potentiometric surface of the mls2 and sfs2 aquifers

Flow in the south is radial from the St. Croix moraine similar to the previously described unit.

Other mapped portions in the northeast show groundwater flow toward the Leech Lake River.

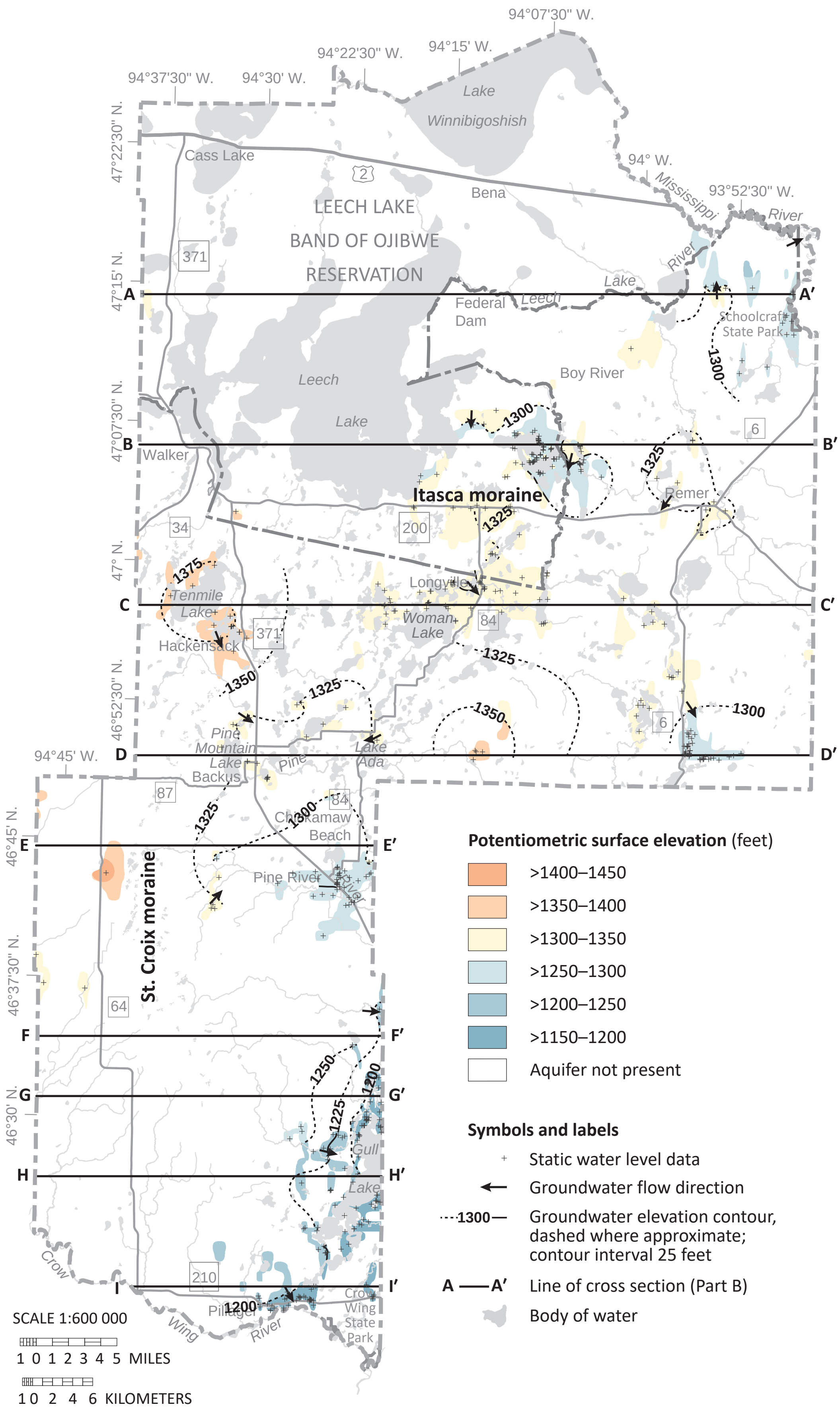


Figure 14. Potentiometric surface of the mls3 and sfs3 aquifers

Much of the mapped portions of these aquifers is in the central portion of the county where groundwater flow directions tend to be complex.

Tenmile Lake in the west near Hackensack appears to be near the apex of flow which radiates easterly and south toward the Pine River.

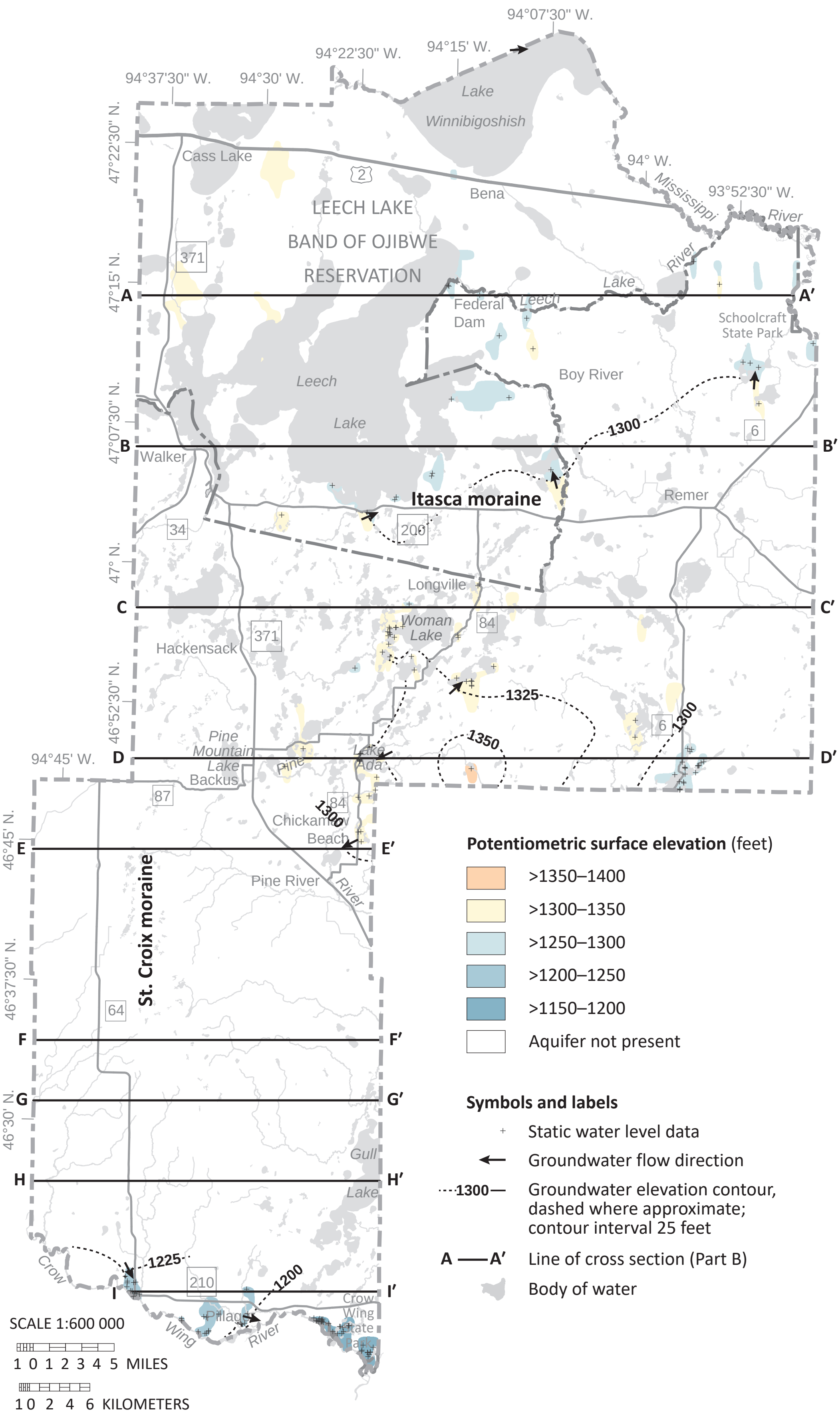


Figure 15. Potentiometric surface of the ebs1, ebs2, and sks aquifers

For these aquifers of limited extent, only broad trends can be made in a county-scale evaluation.

Flow in the north and central portions appears to be toward Leech Lake and the Leech Lake River.

Water chemistry (Plate 7)

The types of dissolved elements and compounds in groundwater provide information about the recharge areas, groundwater flow paths, and approximately when the water entered the ground (residence time). All groundwater originated as precipitation or surface water that infiltrated 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 moved into the subsurface since the 1950s. Carbon-14 is used to determine groundwater residence times of a century to millennia.
- The distribution of select chemicals can indicate areas where groundwater consumption is a potential concern to human health.

Water sampling

Samples were collected from wells in aquifers most frequently used for domestic water supply. Wells were also selected to get an even distribution across the county, include populated areas, and target surface-water and groundwater interaction around lakes and larger rivers. Samples were collected according to the protocols outlined in Appendix A.

The final network sampled depends on citizen willingness to participate. Approximately 1000 well owners were contacted for permission to sample; 90 were selected according to county atlas protocol.

Sampling for Cass County also included 10 surface-water samples from lakes to provide some context for stable isotope and tritium chemistry. The dataset also includes 50 groundwater samples and 4 surface-water samples collected by the Minnesota Department of Health (MDH) from 1993 to 2018.

Groundwater recharge

Stable isotopes of oxygen and hydrogen are used to distinguish between groundwater that was recharged by direct infiltration of precipitation at the land surface, from groundwater recharged through lakes or open-water wetlands, or a mixture of the two. 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 unique isotopic signatures for groundwater with different recharge pathways (Kendall and Doctor, 2003).

- **Meteoric isotopic signature:** groundwater recharged from unaltered precipitation. The water infiltrated directly into the ground, leaving the isotopic ratio unchanged.
- **Evaporative isotopic signature:** groundwater recharged through surface water, such as lakes or open-water wetlands. This water has been fractionated by evaporation: the lake water retains the heavier isotopes and the lighter isotopes move into the atmosphere.

To identify the source 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: $\delta\ (^0/_{00}) = (R_x / R_s - 1) * 1000$. R represents the ratio of the heavy to light isotope, $^{18}O/^{16}O$ or $^{2}H/^{1}H$. R_x represents the ratio of the sample. R_s represents the ratio in VSMOW. Delta values are reported in units of parts per thousand ($^0/_{00}$ or permil) relative to VSMOW.

County results were compared to the global meteoric water line, which was developed from precipitation data from around the world (Craig, 1961).

Results

Most of the groundwater samples plot along the **global meteoric water line** in the left portion of the stable isotope graph (Figure 16). 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.

There are 24 groundwater samples that plot along the **evaporation line**. These samples represent groundwater in aquifers that receive a portion of their recharge from surface water. Each sample's position along the evaporation line depends on the isotopic composition of the surface-water-recharge source and the proportion of surface-water recharge.

The evaporation line on Figure 16 was established by drawing a trendline using stable isotope values collected from 10 lakes sampled synoptically for this study. Four additional lake samples collected by MDH are shown but were not used to develop this trendline.

The degree of evaporation, and thus fractionation, is primarily related to the residence time of water in the lake. With longer time lake water is subject to greater evaporation which leads to greater fractionation of the stable isotopes. Lake water residence time is largely determined by the ratio of the area of the watershed to the area of the lake. Generally, the smaller the ratio the longer the residence time, and therefore greater fractionation of the stable isotopes.

Lakes including **Leech, Ada, Tenmile, and Loon** have small watershed-to-lake-area ratios with longer residence times and more fractionation. Other lakes including **Vermillion, Winnibigoshish, Pine Mountain, Cass, and Gull** have larger ratios with shorter residence time, so they are subject to less evaporation and thus have lesser degrees of fractionation.

Exceptions to this general rule include **Birch, Woman, and Norway** lakes. These lakes have greater fractionation than their watershed-to-lake-area ratios would indicate when compared to other basins with similar ratios. The excess fractionation results from already fractionated water from lakes in the upstream watershed contributing to inflow.

Another exception is a sample collected from **Lake May** by MDH. This lake has a similar watershed-to-lake-area ratio as Cass and Vermillion lakes, yet it plots on the global meteoric water line and does not show any evaporative fractionation.

Lake May is one in a series of small lakes that feed into Leech Lake. These lakes lie in a small valley bordered by uplands that rise over 150 feet to the southeast and approximately 300 feet to the northwest. It is possible that these lakes are fed by springs located along the base of these upland features. The uplands have few lakes, therefore groundwater would likely have a meteoric isotopic signature. The absence of fractionation supports that either water does not reside long in Lake May or that groundwater provides a significant contribution of inflow, or a combination of the two.

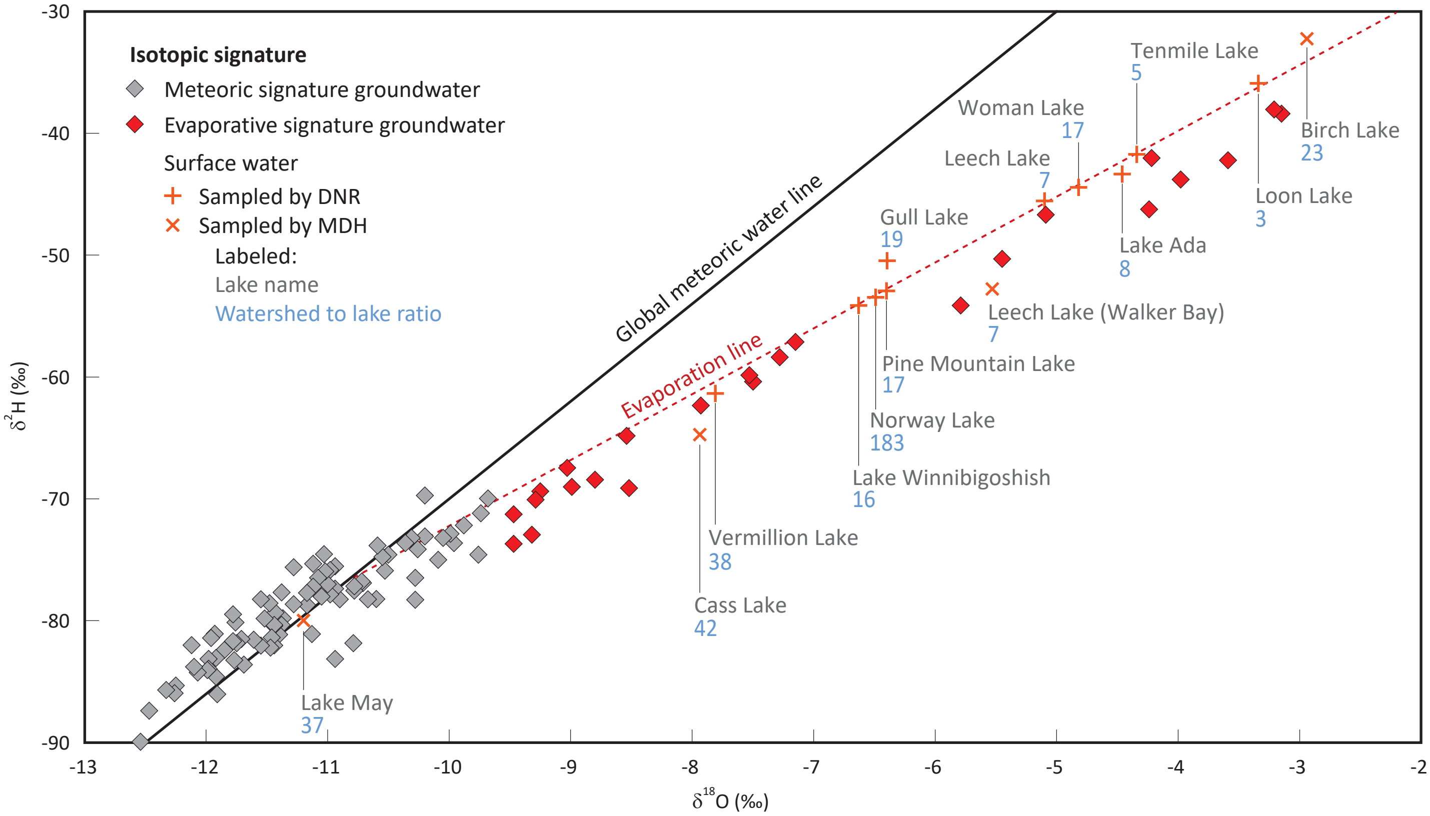


Figure 16. Graph of stable isotope values from water samples

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

The **evaporation line** represents the isotopic composition of surface water that has been fractionated by evaporation. Groundwater that plots along the evaporation line received some portion of its recharge from surface water. The local evaporation line is described by the equation: $\delta^2H = 5.4\ \delta^{18}O - 18.2$, calculated using samples collected for this study from 10 lakes in Cass County that were sampled synoptically. Four historic lake samples collected by MDH are also shown.

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 has a half-life of 12.32 years (Lucas and Unterweger, 2000) and is used to estimate groundwater residence time from the 1950s to today.

The highest tritium concentrations in precipitation occurred between 1953 and 1983 (Michel and others, 2018). Groundwater residence time was estimated by using the location and tritium concentration of the sample and the history of tritium deposition from precipitation at that general location. A complete description of the tritium-age method is described in the procedures document *Tritium age classification: revised method for Minnesota* (DNR and MDH, 2020).

- **Cold War era**: water entered the ground during the peak period of atmospheric tritium concentration from nuclear weapons testing, late 1950s and 1960s (greater than 15 tritium units [TU]).
- **Modern**: water entered the ground since about 1953.
- **Mixed**: water is a mixture of modern and premodern.
- **Mostly premodern**: water likely entered the ground before 1953. Samples categorized as mostly premodern are presumed to consist predominantly of premodern groundwater, with the possibility of a small amount of modern water. Tritium is not detected and the premodern threshold is below the detection limit. Because of analytical limitations it is not possible to determine whether the actual tritium value is above or below the premodern cutoff.
- **Premodern**: water entered the ground before 1953.

The method to calculate tritium age was changed because there is no longer enough tritium in the atmosphere to use the Alexander and Alexander (1989) method.

Atlases through C-39 used *recent*, *mixed*, and *vintage* tritium age from the above Alexander and Alexander method.

Atlases from C-40 on use *modern*, *mixed*, and *premodern* tritium age from the GW-05 revised method (DNR and MDH, 2020).

The following is true for the purposes of all atlases.

Pre-1953 groundwater recharge is implied by both **vintage** and **premodern** tritium age.

Post-1953 groundwater recharge is implied by both **recent** and **modern** tritium age.

Carbon-14

Selected mostly premodern 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 less than 100 to greater than 40,000 years.

Carbon-14 sample collection, analysis, and modeling is described in Alexander and Alexander, 2018. When precipitation infiltrates the unsaturated zone it adsorbs carbon dioxide, including carbon-14, from biogenic soil gases forming carbonic acid. This mildly acidic water dissolves calcite and dolomite present in the soil or bedrock.

Approximately half of the dissolved carbon in the groundwater comes from atmospheric carbon in the soil zone during infiltration and half comes from very old bedrock sources where carbon-14 has decayed completely. Plant communities present at the time of infiltration determine soil $\delta^{13}C$ ratios that are used within the model to estimate the groundwater residence time.

A total of 10 carbon-14 samples were collected for this study. Carbon-14 residence times ranged from 600 to 4,500 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. The 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 can 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.

Risk Assessment Advice (RAA): technical guidance concerning exposures and risks to human health. RAA values contain more uncertainty than HRLs.

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 (geologically sourced): waters contain natural dissolved minerals from the rock and soil. Most are harmless, but certain levels in drinking water can be harmful to health.

The following chemicals are naturally occurring. 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 were not sampled as they are out of the scope of this project.

Chemical descriptions and results

Chloride (Figure 17)

SMCL 250 ppm, elevated ≥5 ppm, anthropogenic: chloride/bromide ratio >250

Chloride can occur naturally from deep sources such as residual brine, or it can come from an anthropogenic source such as road salt, water softener salt, or fertilizer (Davis and others, 1998; Panno and others, 2006).

Results

Of the 121 well samples analyzed for chloride, 37 were elevated and anthropogenic; none equaled or exceeded the SMCL.

Anthropogenic chloride in buried sand aquifers was found in all parts of the county. However, because of the relatively low density of urbanization in the county most of the chloride detections were not very high or widespread. Most of the higher concentrations (>30 ppm) were found in or near the city limits of Cass Lake, Pine River, and Walker.

Nitrate-nitrogen (nitrate) (Figure 17)

MCL and HRL 10 ppm, elevated ≥1ppm

Nitrate can occur naturally at low concentrations but elevated concentrations can indicate impacts 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).

Results

Of the 127 well samples analyzed for nitrate, 15 had elevated concentrations indicative of an anthropogenic source, and 1 was above the MCL with a concentration of 12.9 ppm.

The elevated occurrences of nitrate were in all parts of the county in the surficial and buried sand aquifers.

Arsenic

MCL 10 ppb; MCLG 0

Arsenic is a naturally occurring element that has been linked to negative health effects, including cancer. If arsenic is present 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 per Minnesota Administrative Rule 4725.5650 (Minnesota Legislature, 2008).

The factors affecting arsenic concentrations in groundwater are not completely understood. There is a strong correlation between arsenic in groundwater and glacial sediment derived from rocks northwest of Minnesota (Erickson and Barnes, 2005a). Nicholas and others (2017) found that changes in redox conditions are largely responsible for releasing solid phase arsenic into groundwater via one of three mechanisms: desorption, reductive dissolution, or oxidative dissolution, and that the aquitard-aquifer interface is very geochemically active. Erickson and others (2019) found that both reductive and oxidative arsenic mobilization mechanisms are active in Minnesota drinking water aquifers.

Research also indicates that arsenic concentrations are higher in wells that have short-screened sections near the boundary of an aquifer and aquitard (Erickson and Barnes, 2005b; Erickson and others, 2018).

Results

Of the 115 samples analyzed for arsenic, 10 exceeded the MCL and 98 exceeded the method detection limits.

Concentrations above the MCL were not common but were found in the northeastern and southern portions of the county (Plate 7).

Manganese

HBV 100 ppb; SMCL 50 ppb

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

Results

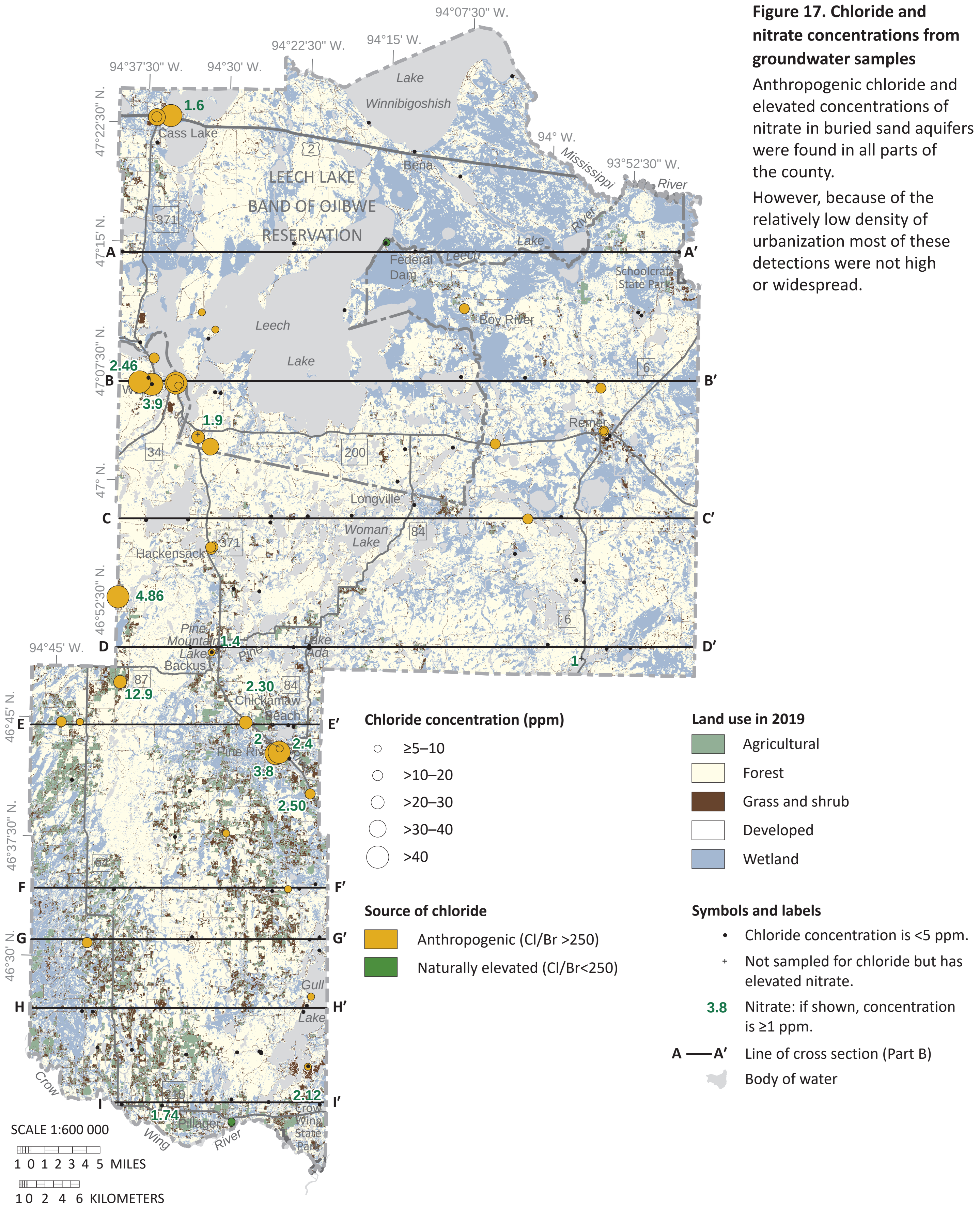
For Cass County, 110 samples were analyzed for manganese; 78 of them were greater than or equal to the HBV. These elevated values ranged from 101 to 1,330 ppb and were found in most of the mapped buried and bedrock aquifers in all parts of the county (Plate 7).

Statewide, manganese concentrations were greater than the HBV 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).

Figure 17. Chloride and nitrate concentrations from groundwater samples

Anthropogenic chloride and elevated concentrations of nitrate in buried sand aquifers were found in all parts of the county.

However, because of the relatively low density of urbanization most of these detections were not high or widespread.



Major cations and anions and the Piper diagram

Calcium, magnesium, and sodium cations and bicarbonate anions are dissolved out of glacial sediment and bedrock by groundwater. The constituents are derived from limestone and dolomite bedrock and are also common in glacial sediment groundwater aquifers (Hem, 1985). Bicarbonate is also derived from carbon dioxide present in the atmosphere and in soil above the water table.

Sodium is often present in deep aquifers or at mineral interfaces. As groundwater moves through aquifer systems, calcium and magnesium ions are exchanged for sodium ions (Hounslow, 1995). Potassium is naturally released from the weathering of silicate minerals (Hem, 1985). In agricultural areas, fertilization provides an additional source of potassium.

Water is considered hard or soft by the concentrations of calcium and magnesium, with hard water containing higher levels. Though not required, most residents typically soften their water to improve the taste and smell and to limit the build-up of minerals (scale) on plumbing fixtures, the insides of pipes, and hot water heaters.

The Piper diagram (Figure 18) graphically represents each water sample for the most common ionic constituents in natural waters: calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and nitrate.

The Piper diagram can reveal information about the following.

- The source of dissolved chemicals as water travels through the aquifers and aquitards
- Water chemistry changes along the groundwater flow path because of ion exchange, precipitation, solution, and mixing of different water types
- Distribution of water types

The Piper diagram has three components: a cation triangle, an anion triangle, and a central diamond. Each sample collected by the DNR is represented by one data point on each. The sample points on each triangle (ternary diagram) reflect the relative percentages of the major cations (lower left triangle) and anions (lower right triangle). These are projected onto the diamond grid. The sample points in the figure are color coded according to tritium age to show chemical relationships.

Chemistry

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

Tritium age

Symbol color indicates tritium age of water sample.

- Cold War era
- Modern
- Mixed
- Mostly premodern

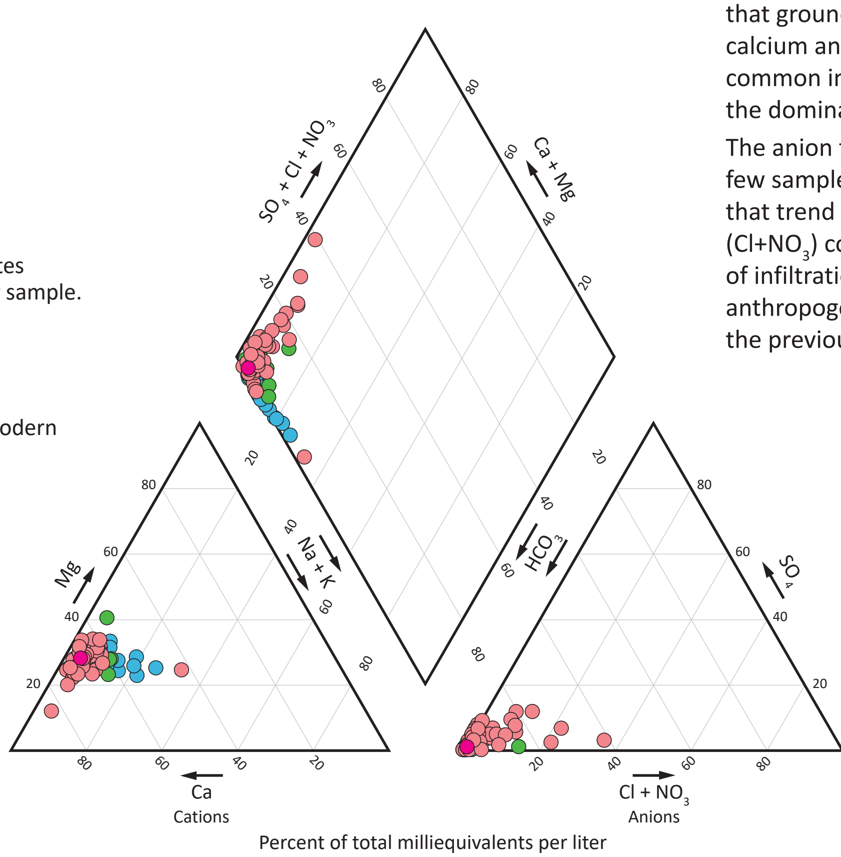


Figure 18. Piper diagram of groundwater samples and tritium age

The cation triangle (lower left) shows that groundwater with a mixture of calcium and magnesium (Ca and Mg) is common in the county with calcium as the dominant ion.

The anion triangle (lower right) shows a few samples from buried sand aquifers that trend toward the chloride + nitrate ($Cl+NO_3$) corner of the triangle because of infiltration and recharge from anthropogenic sources as discussed in the previous sections.

Pollution sensitivity

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 travels 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 can 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 models is the relative rate of water 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 the pollution sensitivity ratings to tritium and carbon-14 for residence time and to other chemistry for anthropogenic sources.

Areas of high sensitivity can be areas of high recharge. In addition to soil properties, land cover 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, 2020; Part A, Plate 3).

The time of travel through near-surface sediment varies from hours to approximately a year (Figure 19).

- 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.

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

Results

Pollution sensitivity conditions range from high to low within the county with a significant portion of the county in the moderate to high categories (Figure 20).

The **high** sensitivity areas that dominate the central and southern parts are mostly glacial outwash from the ice lobe that formed the St. Croix moraine (Brainerd lobe) and other undetermined sources. The high sensitivity areas are largely associated with areas of sand and gravel shown on Figure 2.

The large **moderate** sensitivity area in the north is because of loamy sand deposits from a glacial lake that is also part of the Blackduck Formation.

The **low** sensitivity areas in the southern portion are because of the mixed sediment of the St. Croix moraine and the sandy loam and loamy sand till deposits of the Hewitt Formation. Low sensitivity areas in the north are mostly associated with the mixed sediment of the Itasca moraine but also the loamy till deposits of the Blackduck Formation in the northwest.

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	al, bdo, hio, hioc, iso, isoc, ou, ouc, tel, teu
		sand, silty sand	0.71	isl
B, B/D	0.50	silt, loamy sand	0.50	bdl
		sandy loam, peat	0.28	hig, hta, hti, htiw, isg, ist, istw
C, C/D	0.075	silt loam, loam	0.075	bdg, bdt, hl
		sandy clay loam	0.035	Not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Not mapped in county
--	--	glacial lake sediment of Lake Agassiz	0.000011	Not present in county

Note that peat is used as an overlay on the map because of 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.

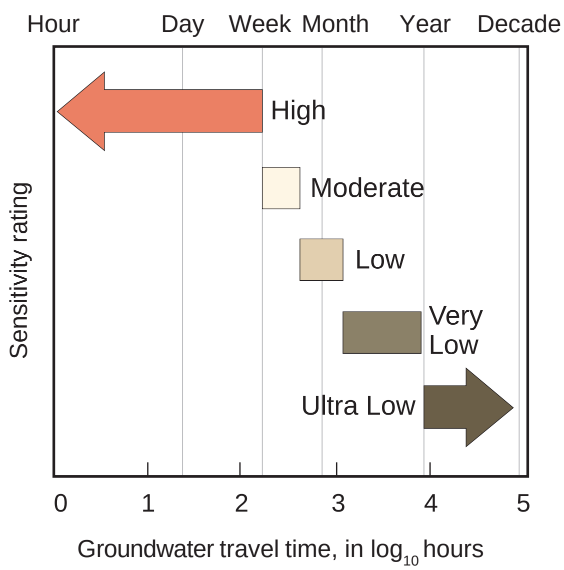


Figure 19. Pollution sensitivity rating of near-surface materials: travel time and ratings

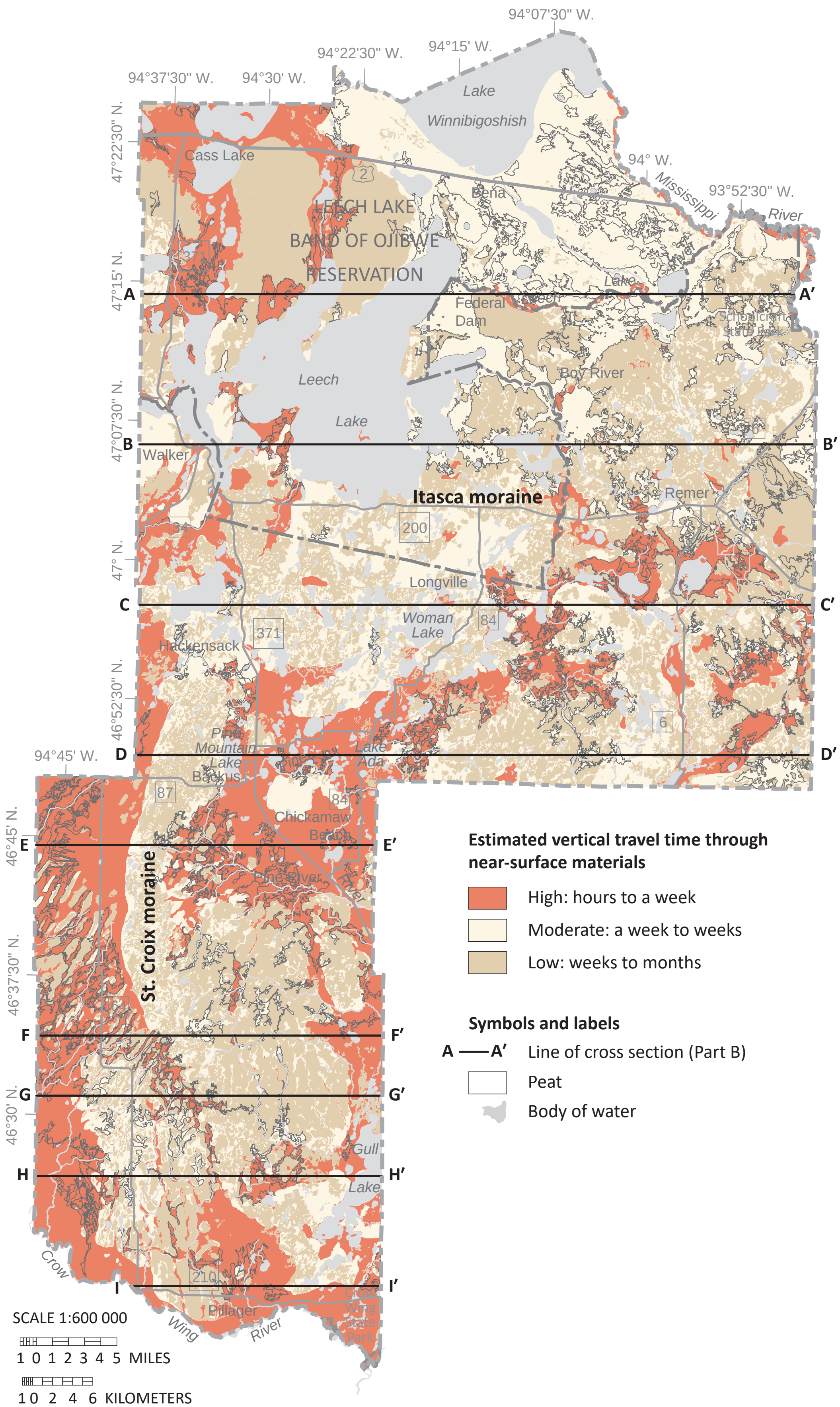


Figure 20. Pollution sensitivity of near-surface materials

A significant portion of the county is in the high to moderate categories. The high sensitivity areas that dominate the central and southern parts are mostly related to glacial outwash from the ice lobe that formed the St. Croix moraine.

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 21).

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 22).

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. For more details, see *Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment thickness* (DNR, 2016c).

The model results were combined with groundwater flow directions (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.

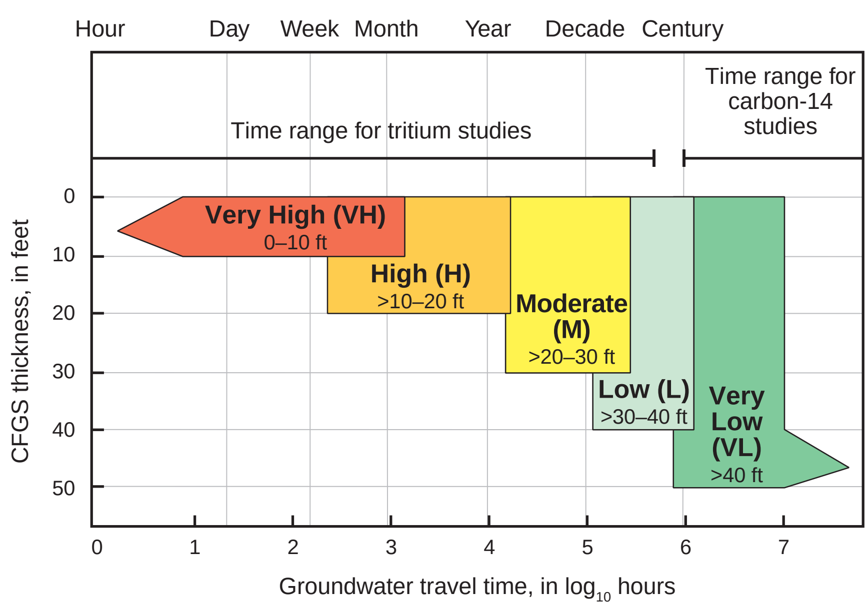


Figure 21. Pollution sensitivity rating for the buried sand aquifers and the bedrock surface

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

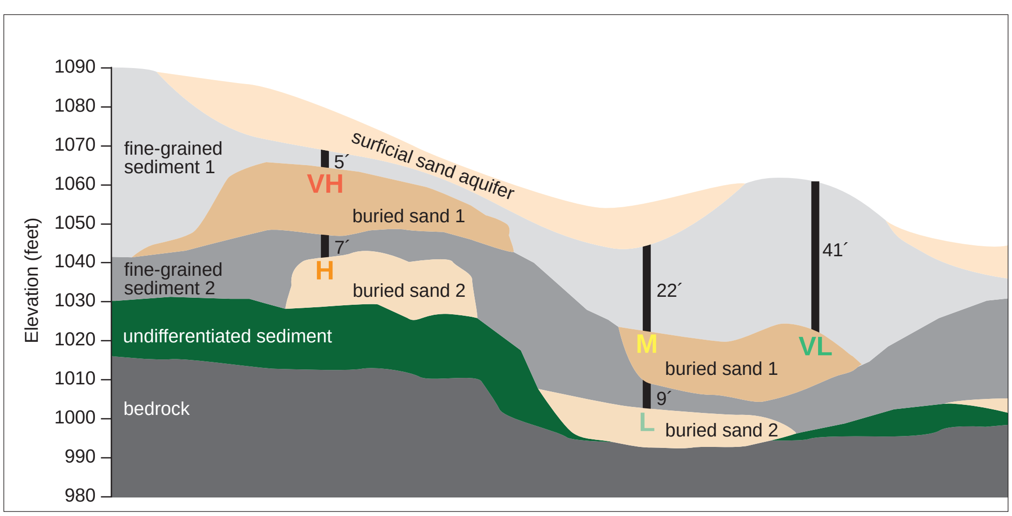


Figure 22. Cross section examples of pollution sensitivity ratings

Sensitivity ratings are based on the cumulative thickness of overlying fine-grained sediment.

Each vertical black line is labeled with the thickness of fine-grained sediment.

The letter at the base of the line indicates the sensitivity rating.

Groundwater conditions

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

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

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

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

(L) Groundwater flows laterally.

(P) Tritium concentrations are likely artificially elevated by high-volume pumping.

(U) Groundwater flowpath is unknown.

(D) Groundwater discharges to a surface-water body.

In general, conditions 1, 2, 3, and the associated modern or mixed tritium-age water 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 very high to moderate sensitivity. (Figure 23)

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

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

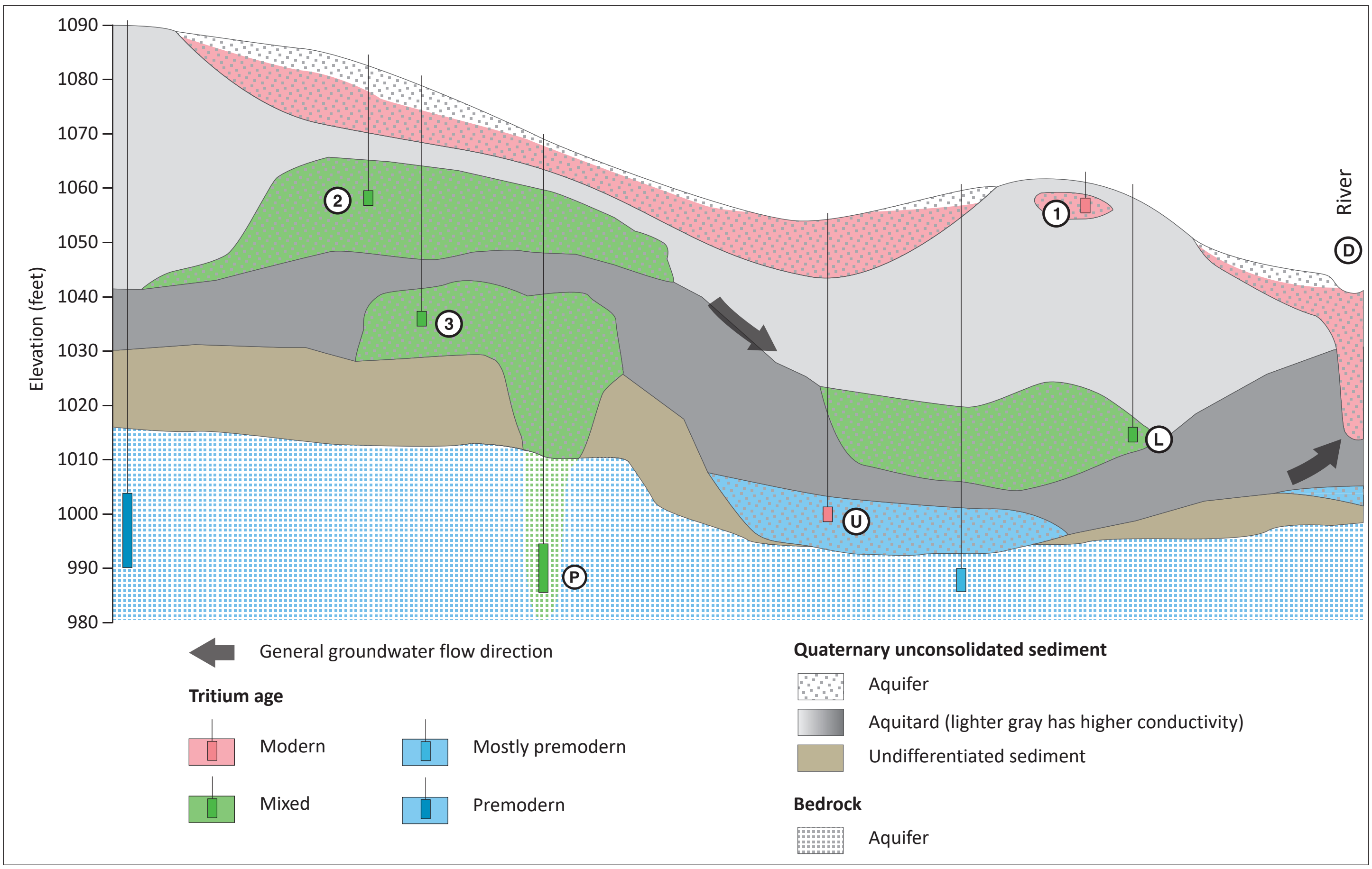


Figure 23. Hypothetical cross section illustrating groundwater conditions

This cross section shows interpretations of why tritium might be present in groundwater samples under 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 (chloride and nitrate).

Higher sensitivity is associated with the following:

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

Lower sensitivity is associated with mostly premodern tritium age and no anthropogenic chloride or nitrate.

The tritium dataset was a combination of sampling efforts by the DNR and the MDH for several projects since 1993. 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 modern tritium-age water to the aquifer is vertical and not altered by nearby pumping or well integrity issues.

In the following summaries, most of these chemistry results are consistent with the results of the pollution sensitivity model.

bds, hsi1, and iss1 aquifers (Figure 24)

- *Extent*: These units are surficial or mostly surficial and present over most of the county.
- *Depth*: 0–50 feet. The greatest depths occur in the northeastern area of the county, where the iss1 aquifer is partially covered by fine-grained units.
- *Thickness*: 0–70 feet.
- *Use*: Approximately 5 percent of county wells with known construction information are completed in the hsi1 and iss1 aquifers.
- *Pollution sensitivity*: Values are mostly very high, because of surface exposures over most of the county.
- *Residence time*: Samples were collected from 8 wells from the iss1 aquifer; 4 were analyzed for tritium with the following results: 3 modern and 1 mixed.

  The mixed sample was in the southeastern part of the county along the eastern shore of Upper Gull Lake where upward gradients appear to be mixing mostly premodern and modern groundwater in this discharge area (Plate 8, east side of cross section G–G′).
- *Anthropogenic chemistry*: Of the 7 samples analyzed for chloride, 5 were elevated and anthropogenic. Of the 8 samples analyzed for nitrate, 3 were elevated.

hsi2 and iss2 aquifers (Figure 25)

- *Extent:* These units are mostly present in the northern portion of the county.
- *Depth*: 0–100 feet. Depths are highly variable across the extent of these aquifers resulting in highly variable patterns of pollution sensitivity.
- *Thickness*: 0–50 feet.
- *Use*: Approximately 13 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* Values range from very high to very low with a complex distribution of values.
- *Residence time*: Samples were collected from 14 wells; 12 were analyzed for tritium with the following results: 1 Cold War era, 5 modern, 3 mixed, and 3 mostly premodern.

  Most of the modern or mixed samples were in areas with very high to moderate sensitivity. However, two samples east of Leech Lake were in very low sensitivity areas but downgradient from areas of higher sensitivity.

  All of the mostly premodern samples were in areas of low to very low sensitivity. One sample northwest of Remer had a carbon-14 residence time value of 2,000 years.
- *Anthropogenic chemistry*: Of the 10 samples analyzed for chloride, 4 were elevated but 1 was from natural sources. Of the 12 samples analyzed for nitrate, 2 were elevated.

  Most of these elevated samples were in areas of very high to moderate sensitivity. The natural chloride sample east of Leech Lake near the Leech Lake River may be because an upward gradient discharged older groundwater from crystalline bedrock to the Leech Lake River.

hsa1 and iss3 aquifers (Figure 26)

- *Extent*: most of the county with the exception of the northeast.
- *Depth*: 0–140 feet. Depths are highly variable across the extent of these aquifers resulting in highly variable patterns of pollution sensitivity.
- *Thickness:* 0–50 feet.
- *Use:* Approximately 21 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* Values range from very high to very low with a complex distribution.
- *Residence time:* Samples were collected from 29 wells; 25 were analyzed for tritium with the following results: 21 modern, 3 mixed, and 1 mostly premodern.

  Most of the modern or mixed samples were in areas with very high to low sensitivity. Six samples in the central and southern portions of the county were in very low sensitivity areas but downgradient from areas of higher sensitivity.

  The mostly premodern sample was in an area of low sensitivity in the central part of the county west of Pine Mountain Lake, with a carbon-14 residence time value of 2,000 years.
- *Anthropogenic chemistry:* Of the 26 samples analyzed for chloride, 13 were elevated and anthropogenic. Of the 26 samples analyzed for nitrate, 5 were elevated. Most of these elevated samples were in areas of very high to moderate sensitivity.

hsa2 and iss4 aquifers (Figure 27)

- *Extent:* most of the county with the exception of the northeast.
- *Depth:* 0–170 feet. Depths are highly variable across the extent of these aquifers resulting in a highly variable pattern of sensitivity.
- *Thickness:* 0–50 feet.
- *Use:* Approximately 14 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* Values range from very high to very low with a complex distribution. The most common value is very low with the exception of areas in the central part of the county near the Pine River where very high to moderate values are most common.
- *Residence time:* Samples were collected from 25 wells; 21 were analyzed for tritium with the following results: 15 modern, 2 mixed, and 4 mostly premodern.

  Most of the modern or mixed samples were in areas with very high to low sensitivity. Five samples throughout the county were in very low sensitivity areas: 4 received lateral (L) recharge from upgradient areas of higher sensitivity and 1 on the west end of I–I′ had an unknown (U) source of recharge.

  The 4 mostly premodern samples were in areas of high to very low sensitivity. The 1 in the high sensitivity area is near the Pine River at Chickamaw Beach where there is an upward gradient of older groundwater with a carbon-14 residence time value of 600 years discharging to the Pine River. The evaporative signature at the same location suggests some mixing of downward flowing groundwater from nearby Norway Lake in Chickamaw Beach.
- *Anthropogenic chemistry*: Of the 22 samples analyzed for chloride, 7 were elevated and anthropogenic. Of the 23 samples analyzed for nitrate, 3 were elevated. Most of these elevated samples were in areas of very high to moderate sensitivity.

hsa3 and iss5 aquifers (Figure 28)

- *Extent:* northwest and southern parts of the county.
- *Depth:* 0–200 feet.
- *Thickness:* 0–40 feet.
- *Use:* Approximately 3 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* The most common value is very low. Smaller areas of very high to low sensitivity are scattered throughout the county.
- *Residence time:* Samples were collected from 12 wells; 10 were analyzed for tritium with the following results: 4 modern, 4 mixed, and 2 mostly premodern.

  Of the modern or mixed samples, 2 were in areas with moderate to low sensitivity near Hackensack. The other 6 were throughout the county in very low sensitivity areas: 4 were likely downgradient from areas of higher sensitivity and were affected by lateral (L) groundwater movement; the other 2 were unknown (U).

  The 2 mostly premodern samples were in areas of very low sensitivity. The 1 in the southeast had a carbon-14 residence time value of 2,500 years.
- *Anthropogenic chemistry*: Of the 11 samples analyzed for chloride, 6 were elevated. Of the 10 samples analyzed for nitrate, none were elevated.

hsa4 and iss6 aquifers (Figure 29)

- *Extent*: mostly in the northwest and southern parts of the county.
- *Depth*: 0–300 feet.
- *Thickness:* 0–50 feet.
- *Use:* Approximately 1 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* The most common value is very low. Higher sensitivities are limited to a few aquifers in the far southeast.
- *Residence time:* Samples were collected from 2 wells. Both were analyzed for tritium, were mostly premodern, and were in areas of very low sensitivity. One of these samples in the south had a carbon-14 residence time of 950 years.
- *Anthropogenic chemistry*: Of the 2 samples analyzed for chloride, none were elevated. Of the 2 samples analyzed for nitrate, none were elevated.

brs1, brs2, and brs3 aquifers (Figure 30)

- *Extent:* mostly along the western border.
- *Depth:* 0–230 feet.
- *Thickness*: 0–50 feet.
- *Use:* Less than 1 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* Values range from very high to very low. The southwestern sand bodies are commonly very high to low, whereas the remainder of the extent is mostly very low.
- *Residence time:* Samples were collected from 3 wells. All were analyzed for tritium with the following results: 2 modern and 1 mixed.

  All 3 samples were in areas with very low sensitivity and the groundwater flow pathway at these locations is unknown (U).
- *Anthropogenic chemistry*: Of the 3 samples analyzed for chloride, 2 were elevated and were in areas of very low sensitivity. The origin is considered unknown (U).

  None of the 3 samples analyzed for nitrate were elevated.

scs, mls1, and sfs1 aquifers (Figure 31)

- *Extent*: mostly present in the southern part of the county.
- *Depth*: 0–250 feet.
- *Thickness:* 0–55 feet.
- *Use*: Approximately 6 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity*: Values range from very high to very low with complex patterns scattered throughout the county.
- *Residence time*: Samples were collected from 11 wells; 10 were analyzed for tritium with the following results: 6 modern, 3 mixed, and 1 mostly premodern.

  Of the modern or mixed samples, 5 were in areas with very high to low sensitivity; 1 was in the southwest in a very low sensitivity area, but it is likely downgradient from areas of higher sensitivity and is affected by lateral (L) groundwater movement. The other 2 samples have groundwater flow pathways that were unknown (U).

  The 1 mostly premodern sample southwest of Lake Winnibigoshish was in a very low sensitivity area.
- *Anthropogenic chemistry*: Of the 10 samples analyzed for chloride, 1 was elevated and was in an area of very low sensitivity; its origin is unknown (U).

  Of the 11 samples analyzed for nitrate, 1 was elevated, and was in an area of very high sensitivity.

mls2 and sfs2 aquifers (Figure 32)

- *Extent:* mostly present in the southern, northeastern, and east-central parts of the county.
- *Depth:* 0–200 feet.
- *Thickness:* 0–30 feet.
- *Use:* Approximately 5 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity*: Values range from very low to very high with complex patterns scattered throughout the county.
- *Residence time*: Samples were collected from 12 wells; 11 were analyzed for tritium with the following results: 2 modern, 3 mixed, and 6 mostly premodern.

  Of the modern or mixed samples, 2 were in areas with moderate sensitivity. Three of the modern or mixed samples in the southeast were in very low sensitivity areas and the groundwater flow pathways at these locations is unknown (U).

The 6 mostly premodern samples are in very low sensitivity areas; 3 samples in the northeast were evaluated for carbon-14 residence time with values ranging from 1,000 to 4,500 years.

- *Anthropogenic chemistry*: Of the 12 samples analyzed for chloride, none were elevated. Of the 12 samples analyzed for nitrate, none were elevated.

mls3 and sfs3 aquifers (Figure 33)

- *Extent:* mostly present in the southern, northeastern, and east-central parts of the county.
- *Depth:* 0–240 feet.
- *Thickness:* 0–30 feet.
- *Use:* Approximately 4 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* Very low sensitivity is the most common value with local areas of higher sensitivity.
- *Residence time:* Samples were collected from 15 wells. All were analyzed for tritium with the following results: 4 modern, 4 mixed, and 7 mostly premodern.

  Of the modern and mixed samples, 1 in Longville was in an area with moderate sensitivity; 2 were in the southeast in very low sensitivity areas, but were likely downgradient from areas of higher sensitivity and were affected by lateral (L) groundwater movement; 4 were in the eastern portions of the county in very low sensitivity areas. The groundwater flow pathways of these locations is unknown (U).

  The 6 mostly premodern samples are in very low sensitivity areas; 1 sample in the northwest had a carbon-14 residence time of 2,500 years.
- *Anthropogenic chemistry:* Of the 10 samples analyzed for chloride, 2 were elevated but from natural sources. Both were near the southeastern corner of the county in Pillager, along the Crow Wing River. The natural chloride in these samples is likely from an upward gradient discharging older groundwater from crystalline bedrock to the Crow Wing River (east side of cross section I–I′).

  None of the 11 samples analyzed for nitrate were elevated.

ebs1, ebs2, and sks aquifers (Figure 34)

- *Extent:* The ebs2 and sks aquifers are mostly mapped in the north; ebs1 is only mapped in the south along the Crow Wing River.
- *Depth:* 0–230 feet.
- *Thickness:* 0–25 feet.
- *Use:* Approximately 1 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* Very low sensitivity is the most common value with local areas of higher sensitivity along the Crow Wing River.
- *Residence time:* Samples were collected from 3 wells. All were analyzed for tritium with the following results: 2 modern and 1 mixed.

  Of these, 2 samples in Motley and west of Lake Ada were in very low sensitivity areas but were likely downgradient from areas of higher sensitivity and are affected by lateral (L) groundwater movement. The sample near Lake Ada had an evaporative signature indicating that some of the water in this sample is from lake water that also contained detectable tritium.

  The other sample in the central portion of the county near Woman Lake is in a very low sensitivity area. The groundwater flow pathway at that location is unknown (U).
- *Anthropogenic chemistry:* Of the 3 samples analyzed for chloride and nitrate, none were elevated.

es1, es2, usw, ms, uns1, and uns2 aquifers (Figure 35)

- *Extent:* The es1, uns1, and uns2 aquifers are mapped in all parts of the county; es2 and ms are only mapped in the north; and usw is only mapped in the south.
- *Depth:* 25–400 feet.
- *Thickness:* 0–30 feet.
- *Use:* Approximately 2 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* Very low sensitivity is the most common value.
- *Residence time:* Samples were collected from 2 wells. Both were analyzed for tritium with the following results: 1 modern and 1 mostly premodern.

The modern sample in the southeastern portion of the county near Upper Gull Lake is in a very low sensitivity area. The groundwater flow pathway at that location is unknown (U).

The mostly premodern sample near Leech Lake is in a very low sensitivity area.

- *Anthropogenic chemistry:* Of the 2 samples analyzed for chloride and nitrate, none were elevated.

Bedrock surface (Figure 36)

- *Extent:* all parts of the county.
- *Depth:* 0–850 feet.
- *Use:* Less than 1 percent of county wells with known construction information are completed in these aquifers.
- *Pollution sensitivity:* Very low sensitivity is the most common value. Some areas of higher sensitivity are mapped in the south.
- *Residence time:* No samples were collected.
- *Anthropogenic chemistry:* No samples were collected.

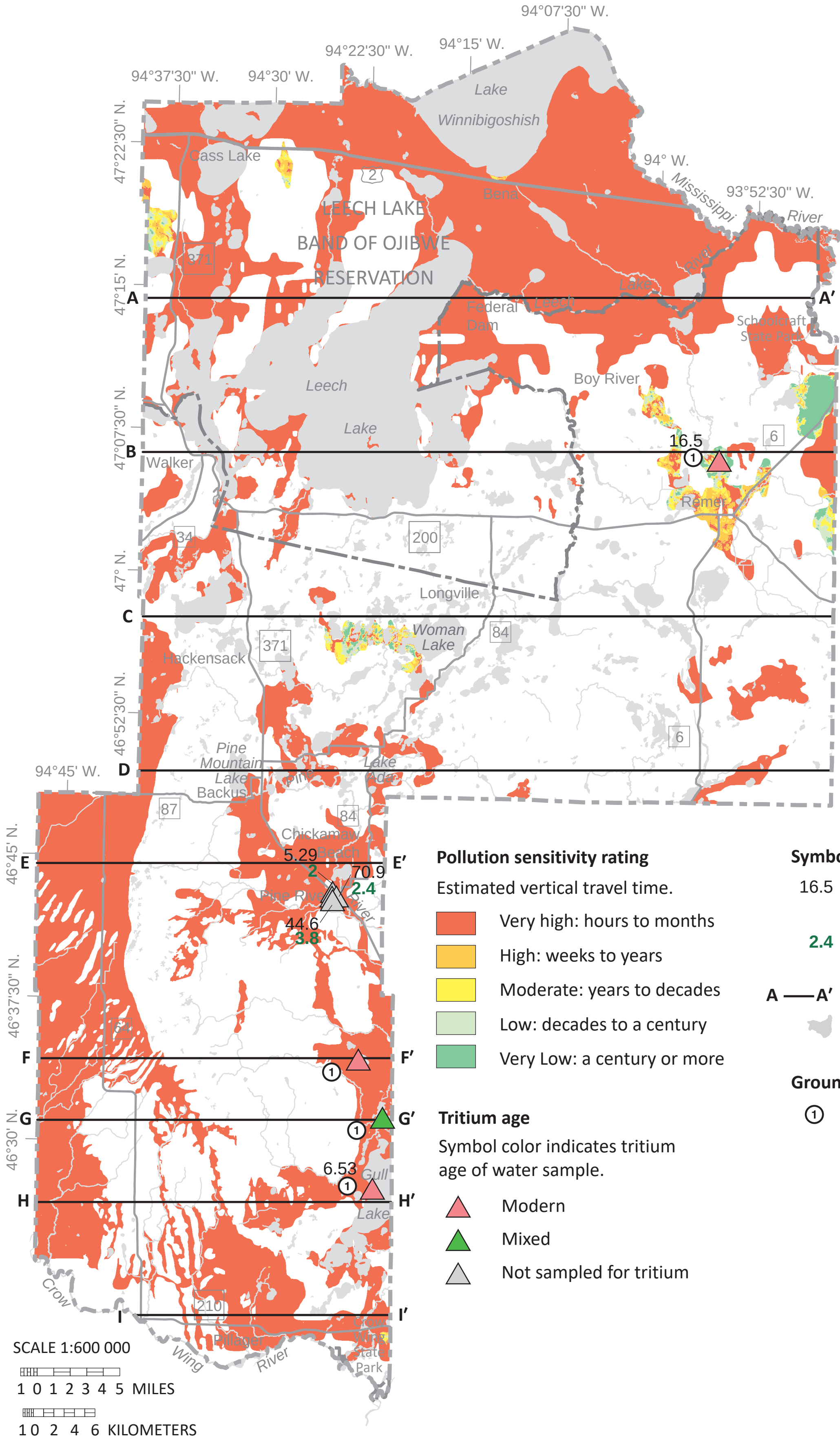


Figure 24. Pollution sensitivity of the bds, hsi1, and iss1 aquifers and groundwater flow directions

Sensitivity is mostly very high, because of surface exposures over most of the county.

Approximately 5 percent of county wells with known construction information are completed in the hsi1 and iss1 aquifers.

Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Modern
- Mixed
- Not sampled for tritium

Symbols and labels

- 16.5 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
- 2.4 Nitrate: if shown, concentration is ≥1 ppm.
- A —— A' Line of cross section (Part B)
- Body of water

Groundwater conditions

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

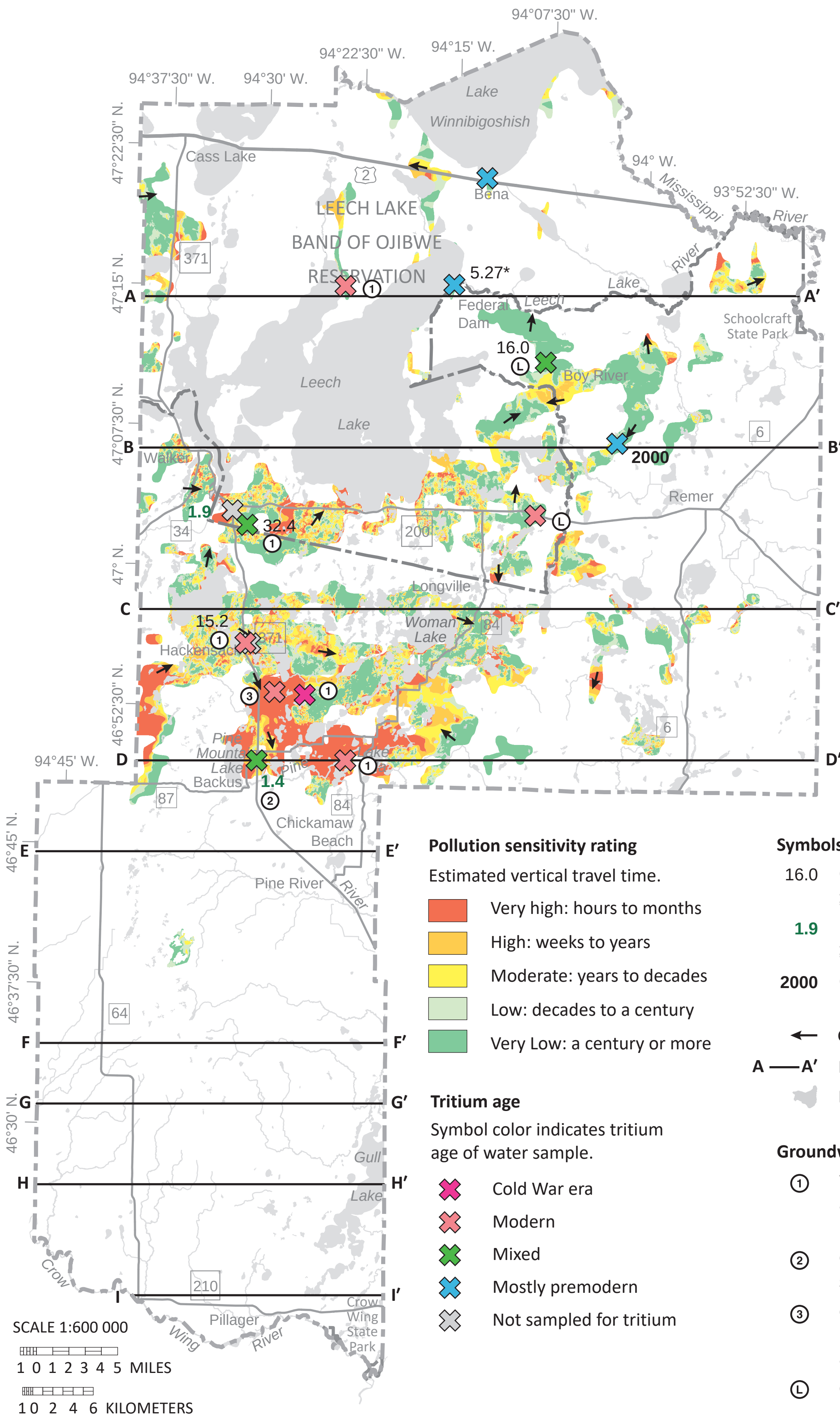


Figure 25. Pollution sensitivity of the hsi2 and iss2 aquifers and groundwater flow directions

Sensitivity is very low to very high with a complex distribution of values.

Approximately 13 percent of county wells with known construction information are completed in these aquifers.

Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Cold War era
- Modern
- Mixed
- Mostly premodern
- Not sampled for tritium

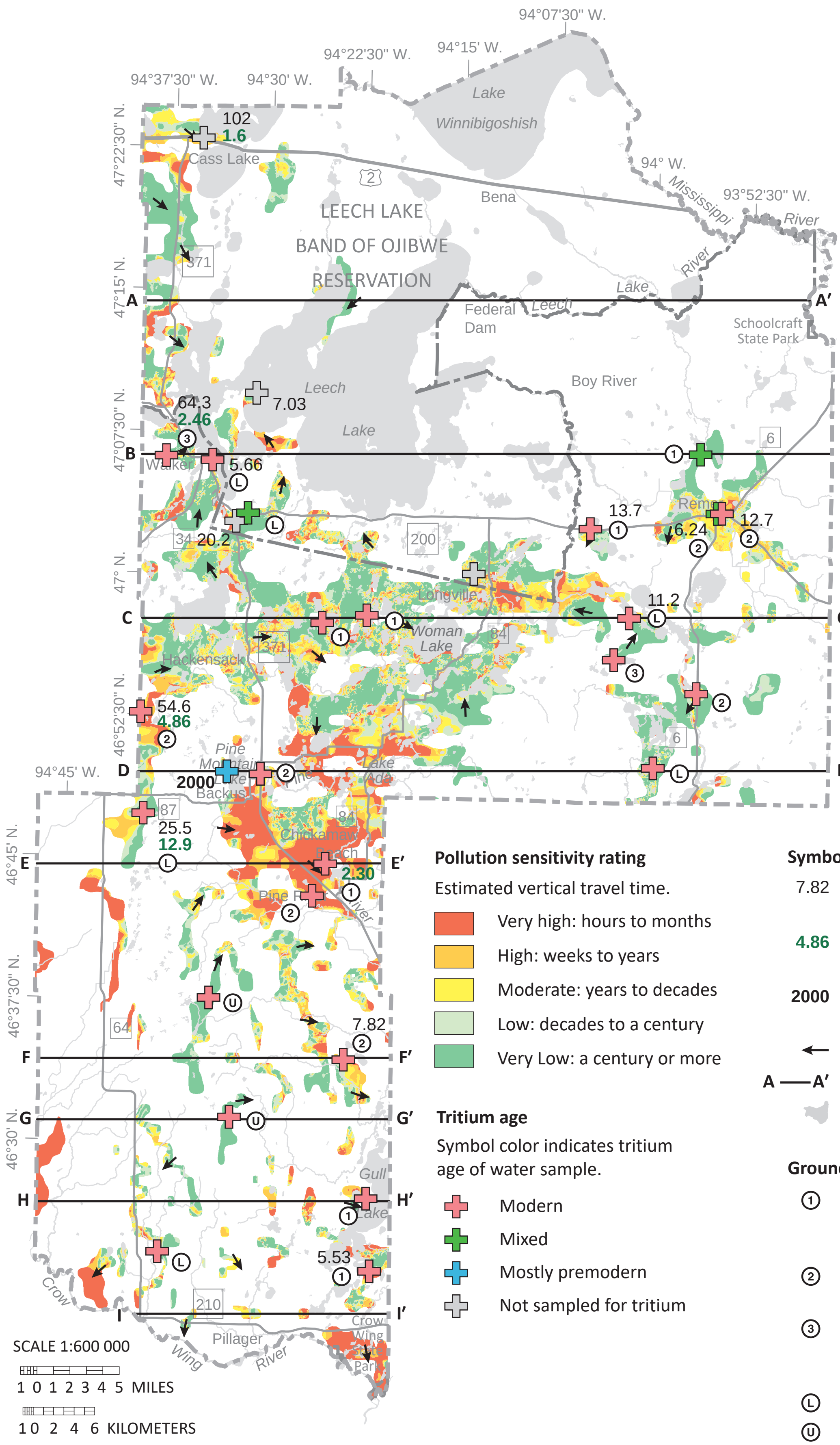
Symbols and labels

- 16.0 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
- 1.9 Nitrate: if shown, concentration is ≥1 ppm.
- 2000 Carbon-14 (^{14}C): estimated groundwater residence time in years
- ← Groundwater flow direction
- A —— A' Line of cross section (Part B)
- Body of water

Groundwater conditions

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

L. Groundwater flows laterally.



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.

- Modern
- Mixed
- Mostly premodern
- Not sampled for tritium

Symbols and labels

7.82	Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
4.86	Nitrate: if shown, concentration is ≥1 ppm.
2000	Carbon-14 (^{14}C): estimated groundwater residence time in years
←	Groundwater flow direction
A —— A'	Line of cross section (Part B)
	Body of water

Groundwater conditions

- (1) Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
- (2) Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- (3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- (L) Groundwater flows laterally.
- (U) Groundwater flowpath is unknown.

Figure 26. Pollution sensitivity of the hsa1 and iss3 aquifers and groundwater flow directions

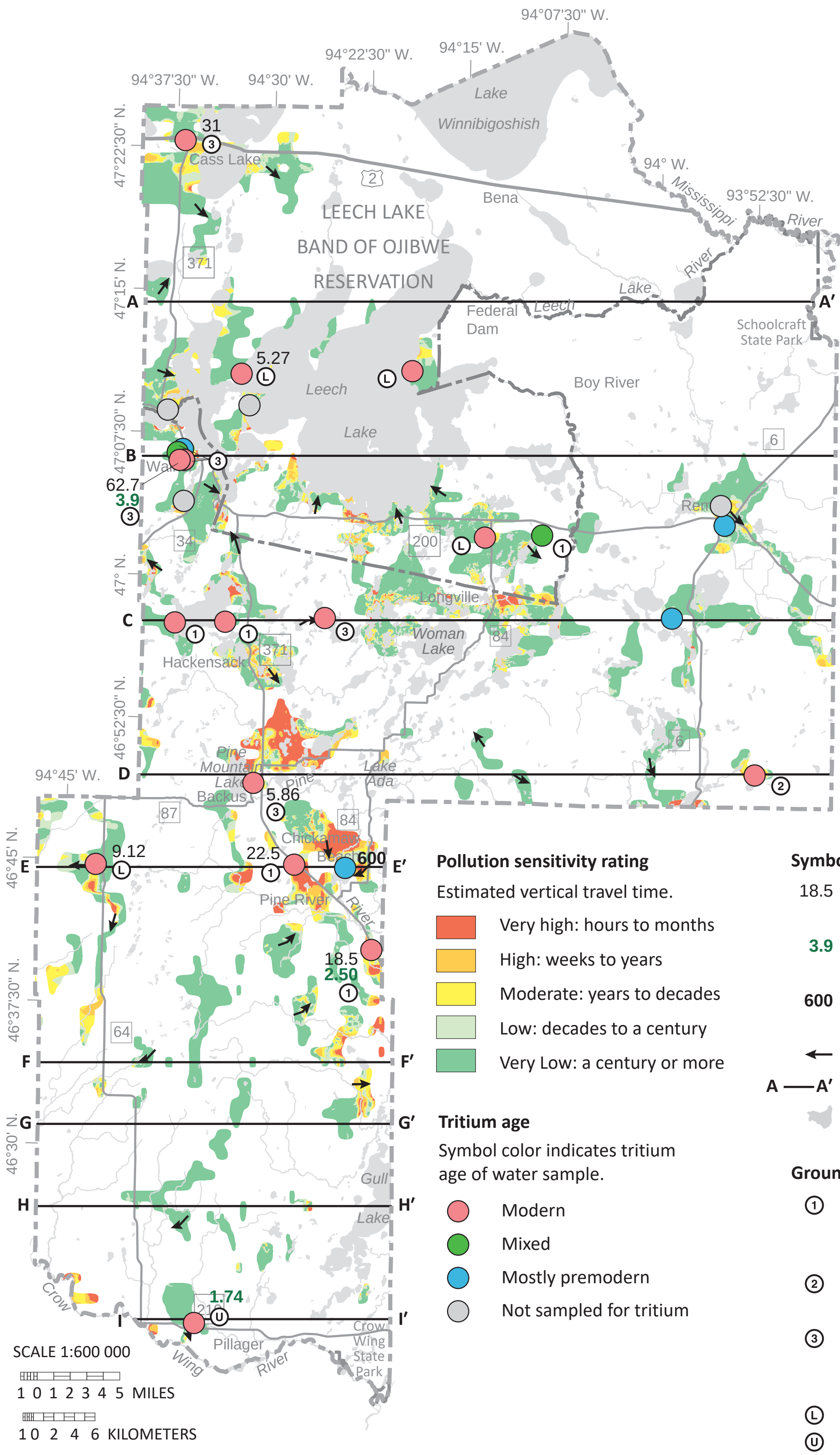
Sensitivity is very low to very high with a complex distribution of values.

Approximately 21 percent of county wells with known construction information are completed in these aquifers.

Figure 27. Pollution sensitivity of the hsa2 and iss4 aquifers and groundwater flow directions

Sensitivity is very low to very high with a complex distribution of values. The most common value is very low with the exception of areas near the Pine River in the central part of the county where moderate to very high values are most common.

Approximately 14 percent of county wells with known construction information are completed in these aquifers.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Modern
- Mixed
- Mostly premodern
- Not sampled for tritium

Symbols and labels

- 18.5 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
- 3.9 Nitrate: if shown, concentration is ≥1 ppm.
- 600 Carbon-14 (^{14}C): estimated groundwater residence time in years
- ← Groundwater flow direction
- A —A′ Line of cross section (Part B)
- Body of water

Groundwater conditions

- ① Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
- ② Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- ③ Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- Ⓛ Groundwater flows laterally.
- Ⓤ Groundwater flowpath is unknown.

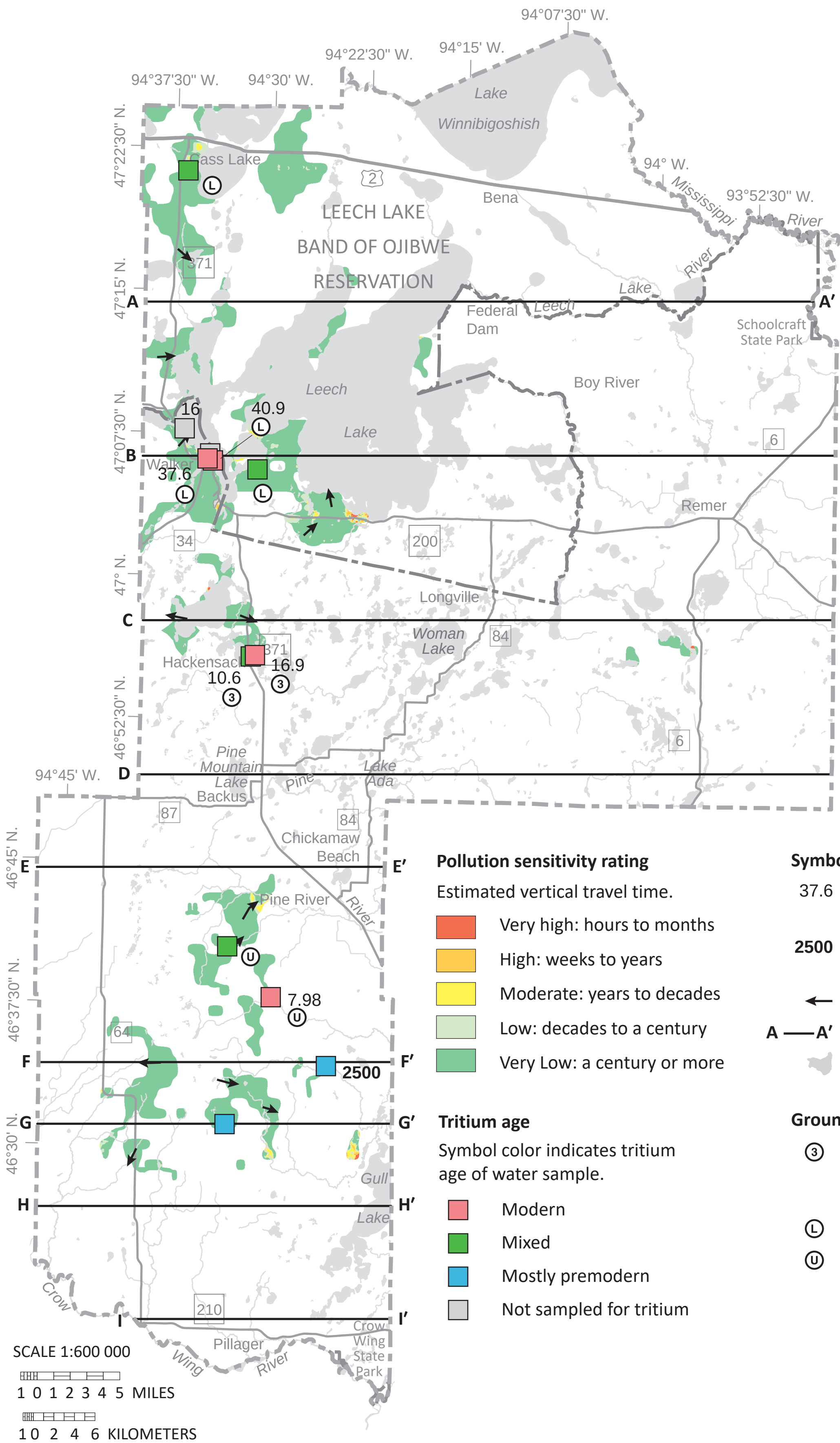


Figure 28. Pollution sensitivity of the hsa3 and iss5 aquifers and groundwater flow directions

The most common value is very low. Smaller areas of very high to low sensitivity with complex patterns are scattered throughout the county.

Approximately 3 percent of county wells with known construction information are completed in these aquifers.

Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Modern
- Mixed
- Mostly premodern
- Not sampled for tritium

Symbols and labels

- 37.6 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
- **2500** Carbon-14 (^{14}C): estimated groundwater residence time in years
- ← Groundwater flow direction
- A —— A' Line of cross section (Part B)
- Body of water

Groundwater conditions

- ③ Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- Ⓛ Groundwater flows laterally.
- Ⓤ Groundwater flowpath is unknown.

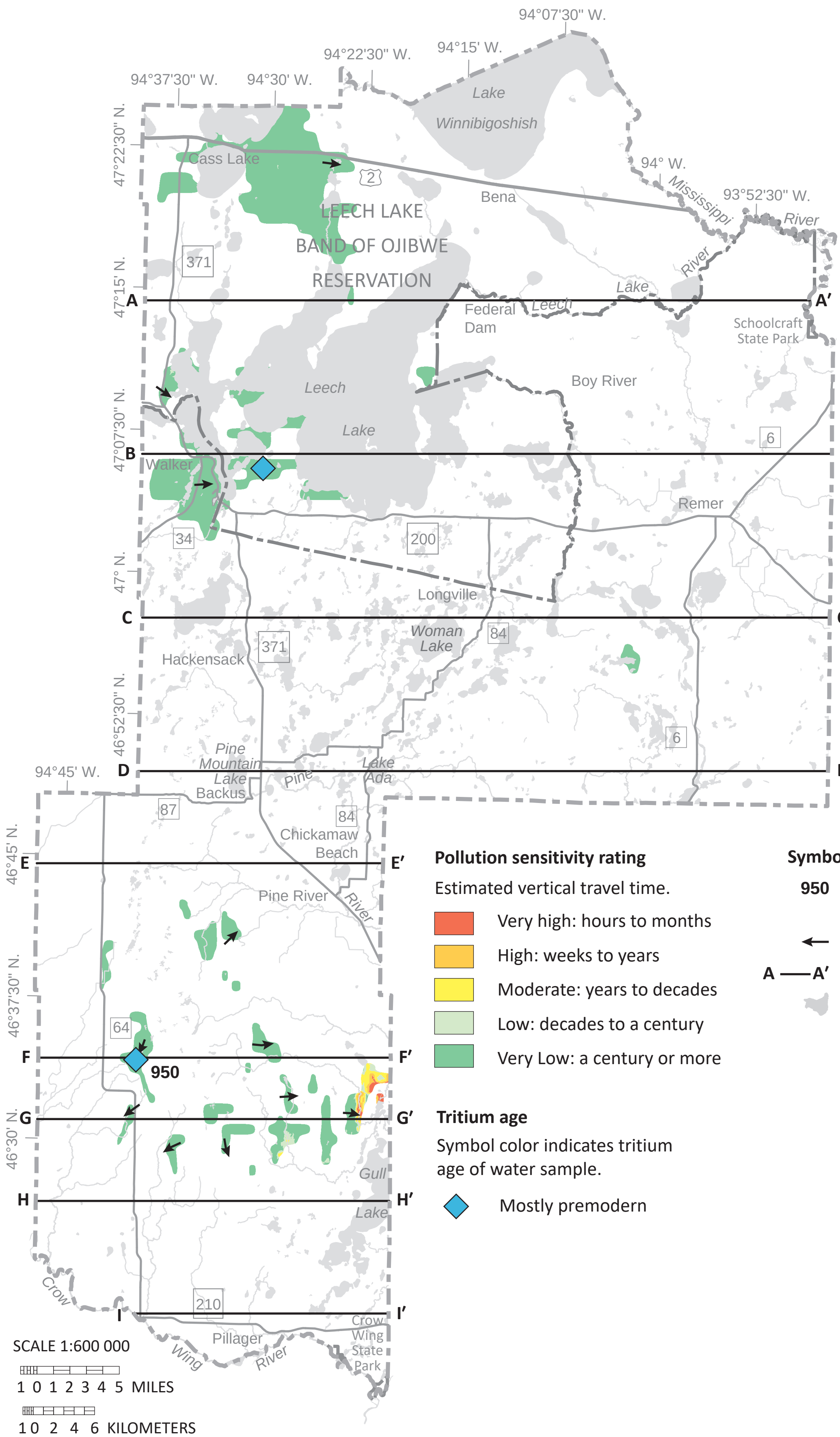


Figure 29. Pollution sensitivity of the iss6 and hsa4 aquifers and groundwater flow directions

The most common value is very low. Higher sensitivities are limited to a few aquifers in the far southeast.

Approximately 1 percent of county wells with known construction information are completed in these aquifers.

Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Mostly premodern

Symbols and labels

- **950** Carbon-14 (^{14}C): estimated groundwater residence time in years
- Groundwater flow direction
- A —— A′ Line of cross section (Part B)
- Body of water

Figure 30. Pollution sensitivity of the brs1, brs2, and brs3 aquifers and groundwater flow directions

Values range from very low to very high. The southwestern sand bodies are commonly low to very high, whereas the remainder of the extent is mostly very low sensitivity.

Less than 1 percent of county wells with known construction information are completed in these aquifers.

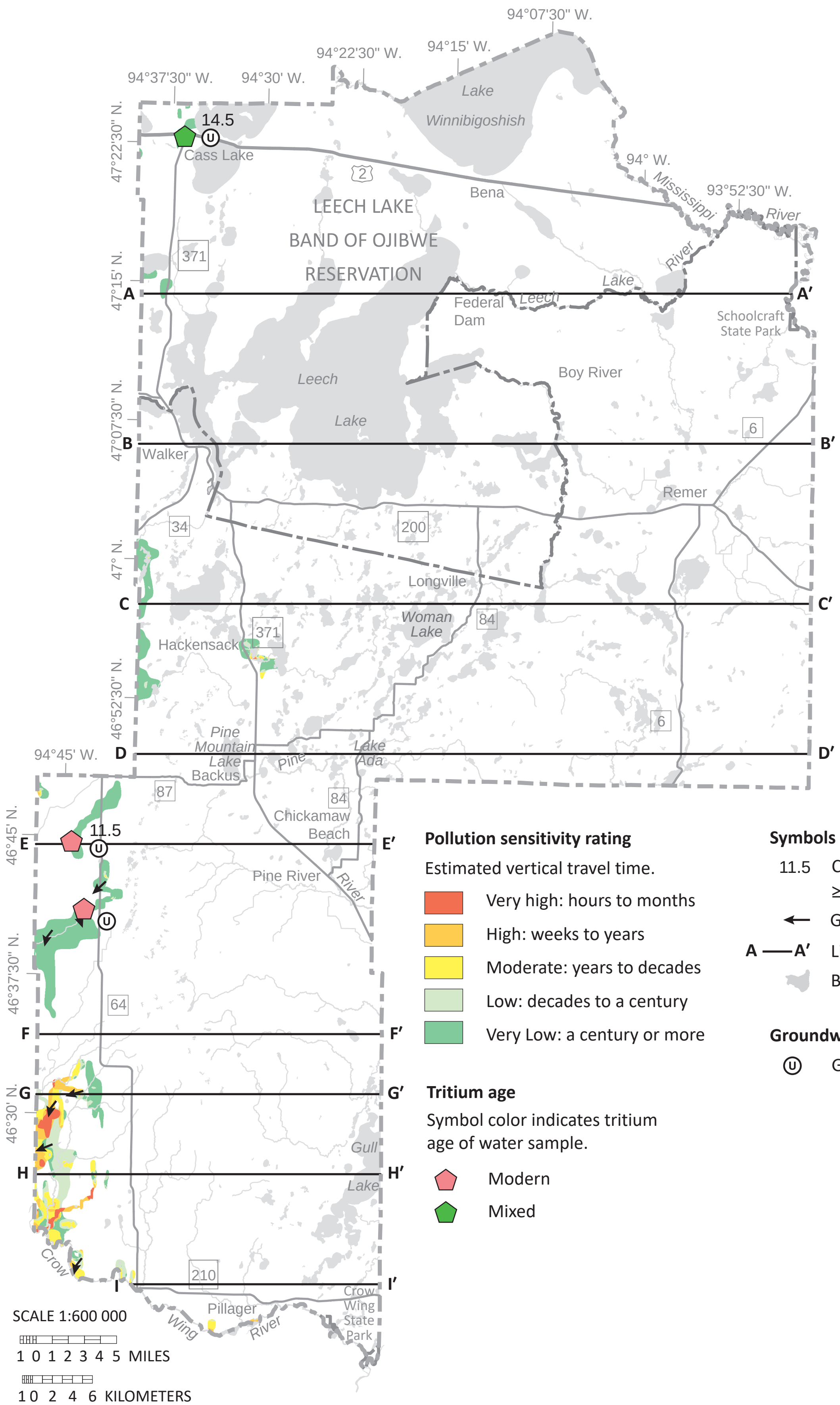
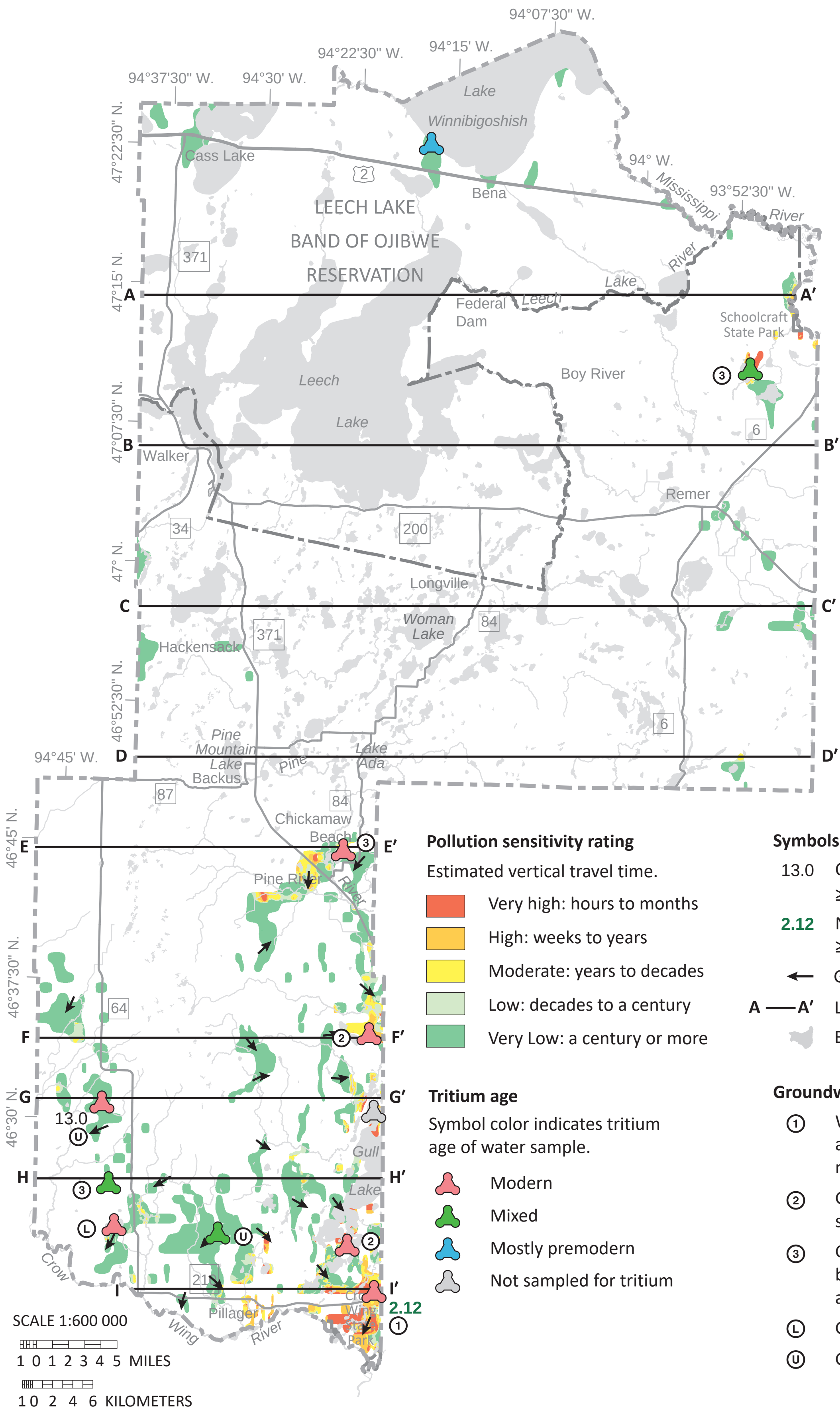


Figure 31. Pollution sensitivity of the scs, mls1, and sfs1 aquifers and groundwater flow directions

Values range from very low to very high sensitivity with complex patterns scattered throughout the county.

Approximately 6 percent of county wells with known construction information are completed in these aquifers.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Modern
- Mixed
- Mostly premodern
- Not sampled for tritium

Symbols and labels

- 13.0 Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
- 2.12 Nitrate: if shown, concentration is ≥1 ppm.
- Groundwater flow direction
- A —A' Line of cross section (Part B)
- Body of water

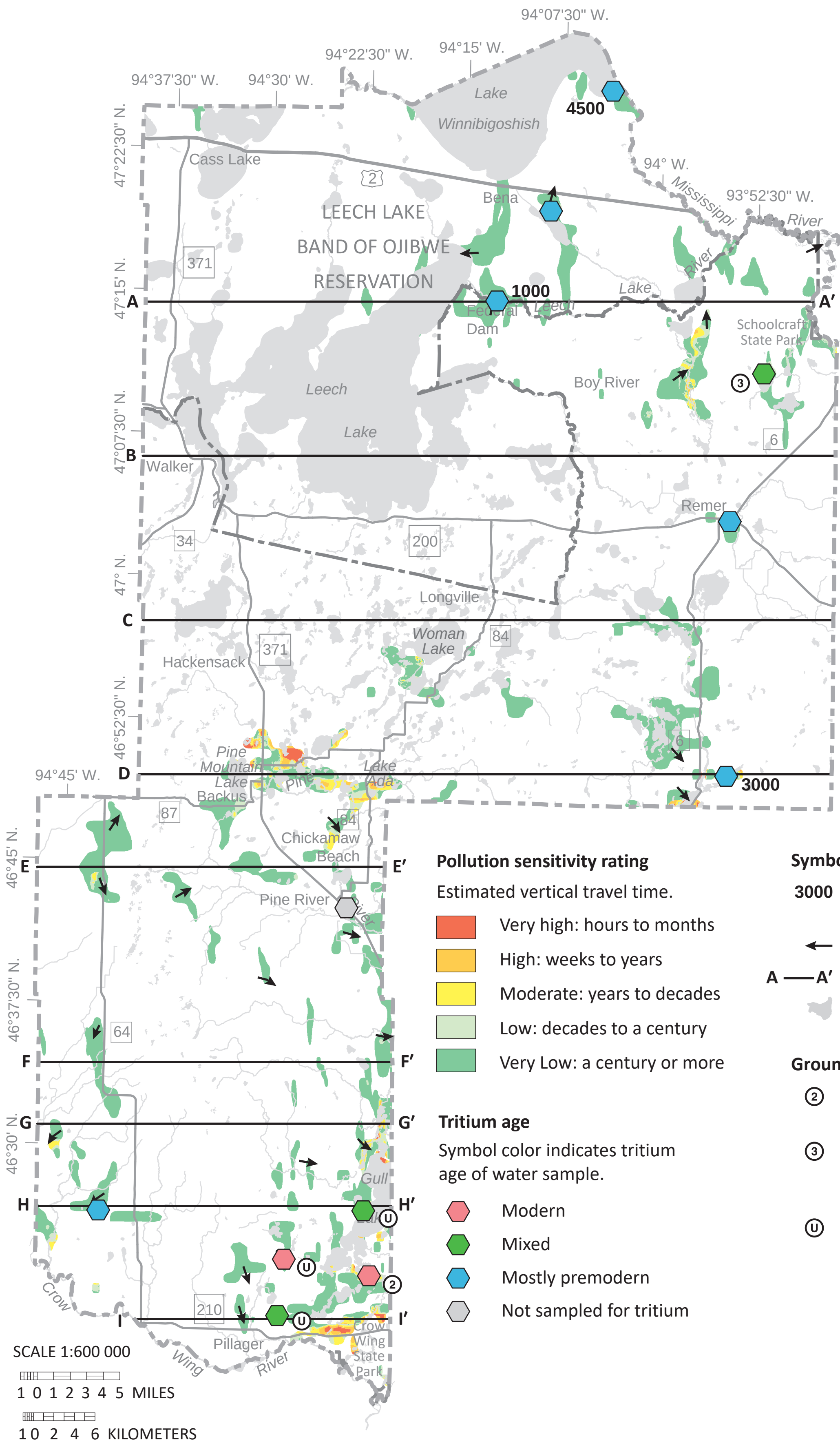
Groundwater conditions

- (1) Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
- (2) Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- (3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- (L) Groundwater flows laterally.
- (U) Groundwater flowpath is unknown.

Figure 32. Pollution sensitivity of the mls2 and sfs2 aquifers and groundwater flow directions

Values range from very low to very high sensitivity with complex patterns scattered throughout the county.

Approximately 5 percent of county wells with known construction information are completed in these aquifers.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Modern
- Mixed
- Mostly premodern
- Not sampled for tritium

Symbols and labels

3000 Carbon-14 (^{14}C): estimated groundwater residence time in years

← Groundwater flow direction

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

Body of water

Groundwater conditions

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

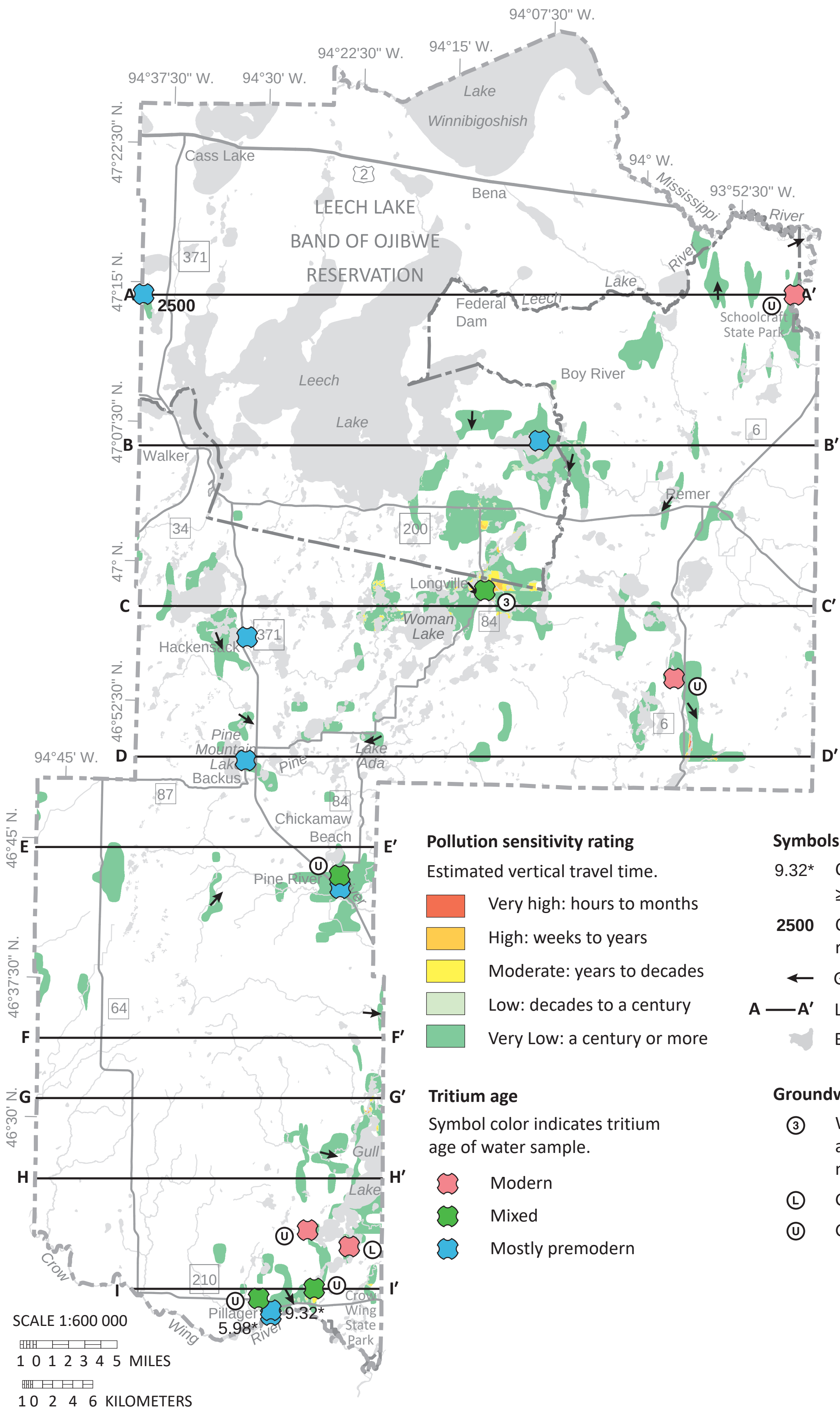
(3) Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.

(U) Groundwater flowpath is unknown.

Figure 33. Pollution sensitivity of the mls3 and sfs3 aquifers and groundwater flow directions

Very low sensitivity is the most common value with local areas of higher sensitivity.

Approximately 4 percent of county wells with known construction information are completed in these aquifers.



Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Modern
- Mixed
- Mostly premodern

Symbols and labels

- 9.32* Chloride: if shown, concentration is ≥5 ppm. (* naturally elevated)
- **2500** Carbon-14 (^{14}C): estimated groundwater residence time in years
- ← Groundwater flow direction
- A —— A′ Line of cross section (Part B)
- Body of water

Groundwater conditions

- ③ Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
- Ⓛ Groundwater flows laterally.
- Ⓤ Groundwater flowpath is unknown.

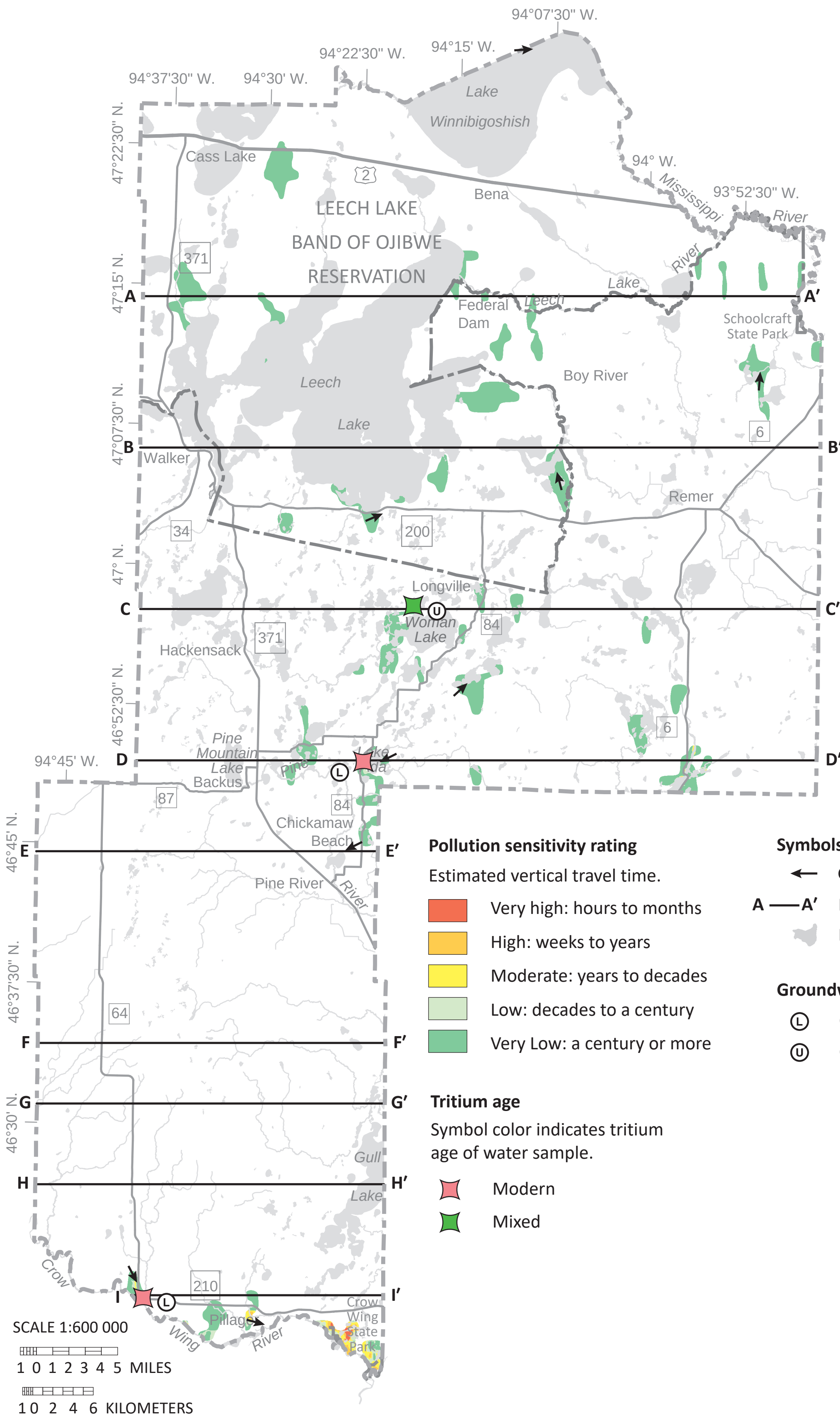


Figure 34. Pollution sensitivity of the ebs1, ebs2, and sks aquifers and groundwater flow directions

Very low sensitivity is the most common value with local areas of higher sensitivity along the Crow Wing River.

Approximately 1 percent of county wells with known construction information are completed in these aquifers.

Pollution sensitivity rating

Estimated vertical travel time.

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

Tritium age

Symbol color indicates tritium age of water sample.

- Modern
- Mixed

Symbols and labels

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

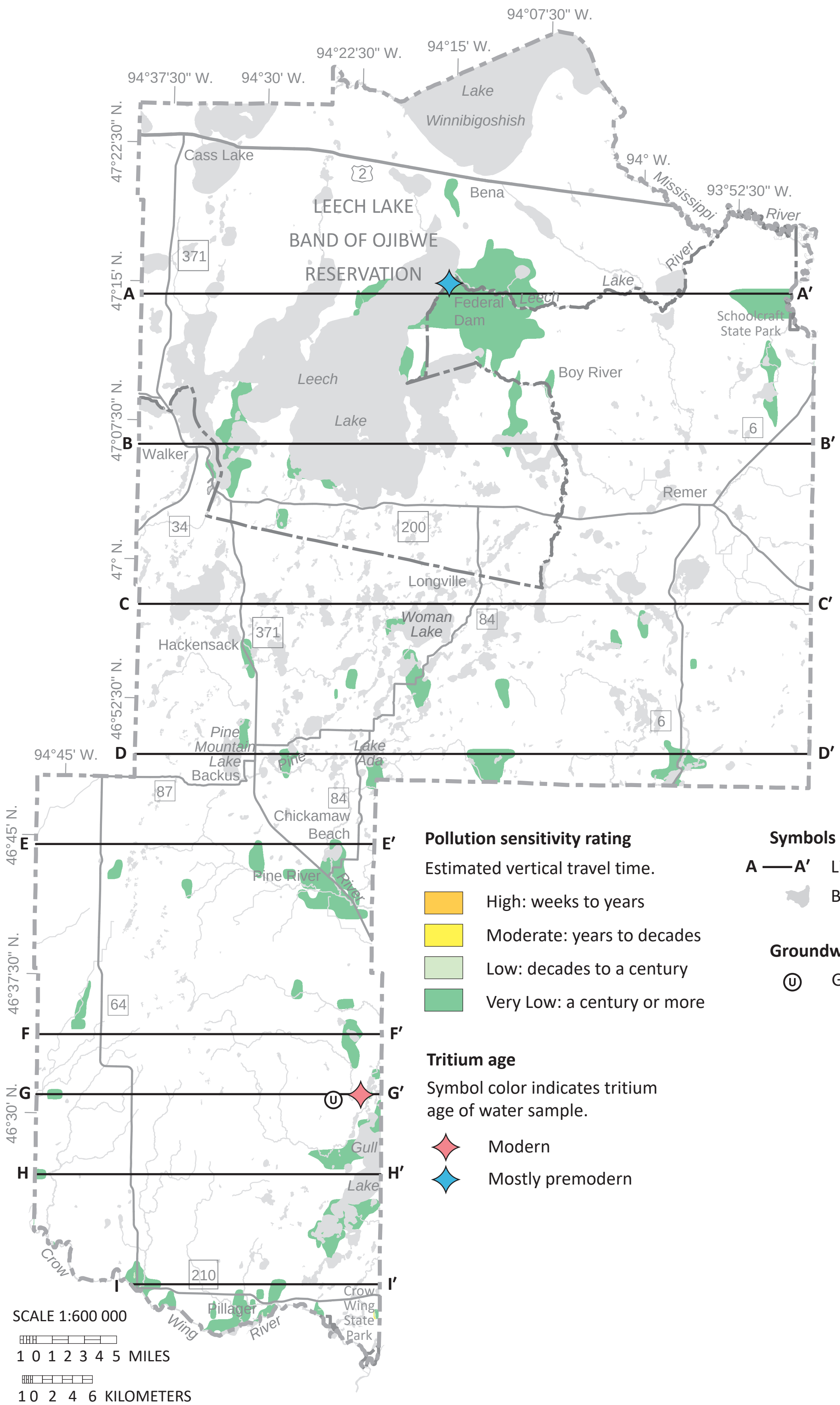
Groundwater conditions

- (L) Groundwater flows laterally.
- (U) Groundwater flowpath is unknown.

Figure 35. Pollution sensitivity of the es1, es2, usw, ms, uns1, and uns2 aquifers

Very low sensitivity is the most common value.

Approximately 2 percent of county wells with known construction information are completed in these aquifers.



Pollution sensitivity rating

Estimated vertical travel time.

- 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.

- Modern
- Mostly premodern

Symbols and labels

- A —— A' Line of cross section (Part B)
- Body of water

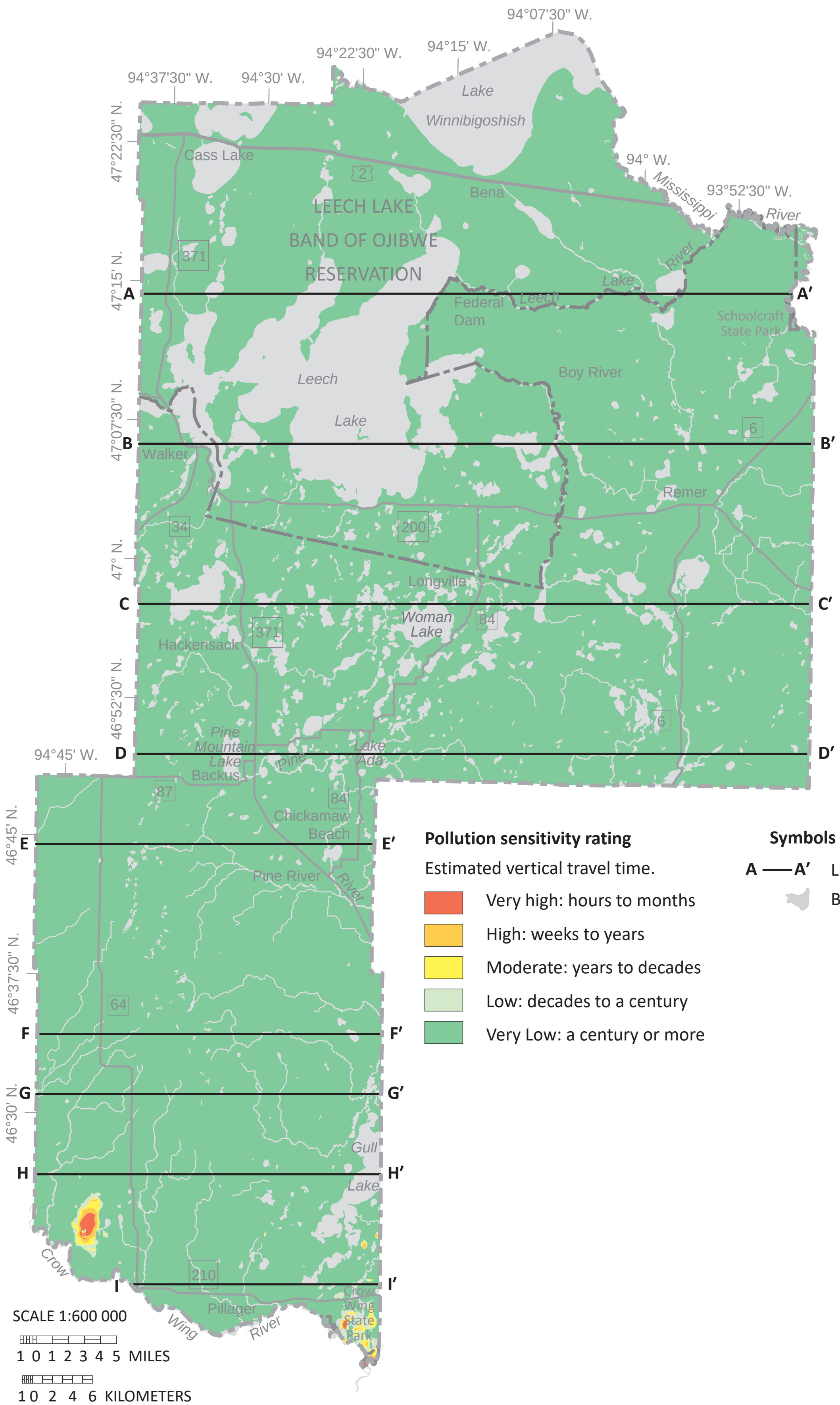
Groundwater conditions

- Ⓤ Groundwater flowpath is unknown.

Figure 36. Pollution sensitivity of the bedrock surface

Very low sensitivity is the most common value. Some areas of higher sensitivity are mapped in the south.

Less than 1 percent of county wells with known construction information are completed in these aquifers.



Pollution sensitivity rating

Estimated vertical travel time.

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

Symbols and labels

- A —— A′ Line of cross section (Part B)
- Body of water

Hydrogeologic cross sections (Plate 8)

The hydrogeologic cross sections shown on Plate 8 illustrate the horizontal and vertical extent of aquifers and aquitards, the relative hydraulic conductivity of aquitards, general groundwater flow direction, areas of groundwater recharge and discharge, and groundwater residence time. These were chosen to incorporate existing data collected by the MDH and to provide representative examples of county hydrogeology.

The nine cross sections were selected from a set of 135 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 (Part A, Plate 4, Table 2). 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. Lighter shades indicate 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 (Plate 8). 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 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 flow directions are indicated on the cross sections as follows. The northern portion of the county is more difficult to define because of a general lack of data and low topographic relief, particularly on A–A′ and B–B′.

- A–A′ and B–B′ west side, where groundwater flows east from a topographic high toward the greater Leech Lake area.
- A–A′ east side, where groundwater flow diverges from a minor topographic high east toward the Mississippi River and west toward the Leech Lake River.
- C–C′ has many more wells and associated water elevation data. This and the higher topographic relief near the Itasca moraine allow better definition of flow directions. This cross section passes through the higher western portion of the Itasca moraine and shows distinct flow through lakes and shallow buried aquifers (hsa1, hsa2, and hsi2) to the lower and flatter areas to the east (Baby and Woman lakes, and the Rice Lake area), with a strong component of downward flow.
- D–D′ shows two topographically elevated areas in the west and central portions that locally divide groundwater flow. These two recharge areas create convergent groundwater flow to Pine Mountain Lake in the west and Lake Ada in the east. East of the central topographic high, groundwater flow converges on Lake Roosevelt and Crooked Lake.
- E–E′, F–F′, G–G′, and H–H′ show the dominant influence of the topographically elevated St. Croix moraine as a groundwater divide.
- E–E′ east side, groundwater flow converges on the Pine River, a discharge area.
- F–F′, G–G′, and H–H′ east side, flow appears to be upward indicating discharge to Loon Lake (F–F′), Upper Gull Lake and Roy Lake (G–G′), and Gull Lake (H–H′).
- I–I′ west side, there is also a groundwater divide.
- Other groundwater flow is dominantly to the southeast toward the Crow Wing River which is out of the plane of the cross section. Some possible discharge to the Gull River is shown on the east side.

Groundwater recharge and discharge

Downward and lateral flow is common across all of the cross sections. Flow is upward in some areas indicating discharge to surface-water bodies. Recharge to deeper aquifers can take hundreds to thousands of years as evidenced by residence times determined using carbon-14 analysis, provided that 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 Cass County range from 600 to 4,500 years.

Results include samples on A–A′ west of MN 371 (2,500 years) and near Federal Dam (1,000 years), and a relatively shallow sample on B–B′ east of Boy River (2,000 years). All of these samples have similar residence times because of a lack of focused recharge.

Samples on D–D′ west of Pine Mountain Lake (2,000 years) and east side near Crooked Lake (3,000 years) are also relatively shallow but are probably older than expected because of upwelling groundwater discharging to the nearby lakes.

The youngest carbon-14 value is on E–E′ east of the Pine River (600 years). This area is probably also upwelling with discharge to the Pine River, but also mixing with locally or upgradient lake-water recharge, as suggested by the evaporative signature.

On F–F′, samples are shown near CR T215 (950 years) and CR T183 (2,500 years). The carbon-14 sample on the east side appears to receive focused recharge through interconnected buried sand layers. The results of the pollution sensitivity model support this observation: moderate to very high for the iss5 aquifer in this area (Figure 28). However, the carbon-14 age of 2,500 years is much older than expected from focused recharge, suggesting there may be significant upward flow of older groundwater at this location.

Rapid focused recharge

Thin overlying aquitards (condition ①).

Focused recharge occurs through the thin overlying aquitards that are common throughout the county: B–B′ east side (1 sample), C–C′ west side in the Tenmile Lake to Baby Lake area (4 samples), D–D′ east of Lake Hattie, E–E′ east side near MN 371 and the Pine River (2 samples), F–F′ east side near Loon Lake, G–G′ east side near Upper Gull Lake, H–H′ east side near Gull Lake, and I–I′ east side east of Gull River. Of these 12 samples, 1 had an elevated concentration of chloride and 2 had elevated concentrations of nitrate.

Interconnected aquifers (conditions ② and ③).

Focused recharge is also common through interconnected aquifers: B–B′ west side (4 samples), C–C′ west near Webb Lake, D–D′ west near Backus (2 samples) and east near Crooked Lake, E–E′ east of Pine River, F–F′ east near Loon Lake (2 samples), and H–H′ west near CR T214. Of these 12 samples, 3 had elevated concentrations of chloride and 3 had elevated concentrations of nitrate.

Lateral flow (condition Ⓛ).

Modern and mixed tritium-age samples that had no obvious downward recharge pathways were possibly recharged at some upgradient location. Groundwater is assumed to have migrated laterally and downgradient because of normal groundwater flow gradients. This common condition is found on B–B′ east near Leech Lake (2 samples), C–C′ center near Upper Trelipe Lake, D–D′ center near Lake Ada and CR 155, E–E′ east near MN 64, and I–I′ near Motley.

Unknown source (condition Ⓤ).

Modern or mixed tritium-age water was detected in areas where the pollution sensitivity model predicts very low to low sensitivity. Examples are shown on A–A′ east near the Mississippi River; C–C′ center near Woman Lake; D–D′ west near Lake Ada; E–E′ west of CR 111; G–G′ west near CR 106, center near Deer Lake, and east near Upper Gull Lake; H–H′ east near Gull Lake; and I–I′ west of Seven Mile Creek, center near CR H1, and east of Sylvan Lake.

Possible reasons for the 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 shallower aquifers or the surface.
- Sandy loam aquitards allow seepage of recent or mixed tritium-age groundwater faster than the pollution sensitivity model predicts.

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

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

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

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

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

The surficial sand aquifers have the highest mean value (29 gpm/ft) and a very wide range of values compared to the buried sand aquifers.

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 mean transmissivity value was higher in the surficial sand (12,000 ft^2/day). Only 4 tests were available from the surficial sand aquifers and may not represent the full range values, however transmissivity values calculated from aquifer tests are generally more representative of aquifer properties than those calculated for specific capacity. The buried sand aquifer data show a high range of values (215 to 10,600 ft^2/day).

Table 2. Specific capacity and transmissivity of selected wells

Unconsolidated aquifer	Specific capacity (gpm/ft)					Transmissivity (ft^2/day)				
	Casing diam. (in.)	Mean	Min	Max	No. of tests	Casing diam. (in.)	Mean	Min	Max	No. of tests
Surficial sand (water table–QWTA)	8–24	29	1	114	33	6–16	12,000	5,660	18,000	4
Confined buried sand (QBAA)	8–12	17	1	68	29	4–12	3,800	215	10,600	12

Specific capacity data adapted from the CWI.

Transmissivity data are from aquifer test data compiled by the DNR.

QWTA: Quaternary water-table aquifer, QBAA: Quaternary buried artesian aquifer.

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, 2021).

Permitted groundwater use (Table 3) is presented by aquifer type (Figure 37) and water use category (Figure 38). The highest volume use is from the surficial sand aquifers (53 percent). The most common water use is for agricultural irrigation (57 percent). There are approximately 12,000 located wells in the county. By total numbers of wells, 94 percent are domestic, 5 percent are water supply, and 1 percent is irrigation.

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

Aquifers	Number of wells	Agricultural irrigation	Industrial processing	Noncrop irrigation	Special categories (aquaculture and pollution containment)	Water-level maintanence	Water supply	Total (mgy)	Total (percent)
Surficial sand (water table)	93	515	70	50	149	<1	57	841	53
Buried sand	94	403	16	95	232	na	127	758	47
Total (mgy)	na	918	86	145	381	<1	694	1,599	na
Total (percent)	na	57	5	9	24	<1	4	na	na

Data from MPARS; mgy, million gallons per year.

Percentage might not equal 100 due to rounding.

na = not applicable

Figure 37. Groundwater use shown by general aquifer classification

The highest volume use is from the surficial sand aquifers (53 percent).

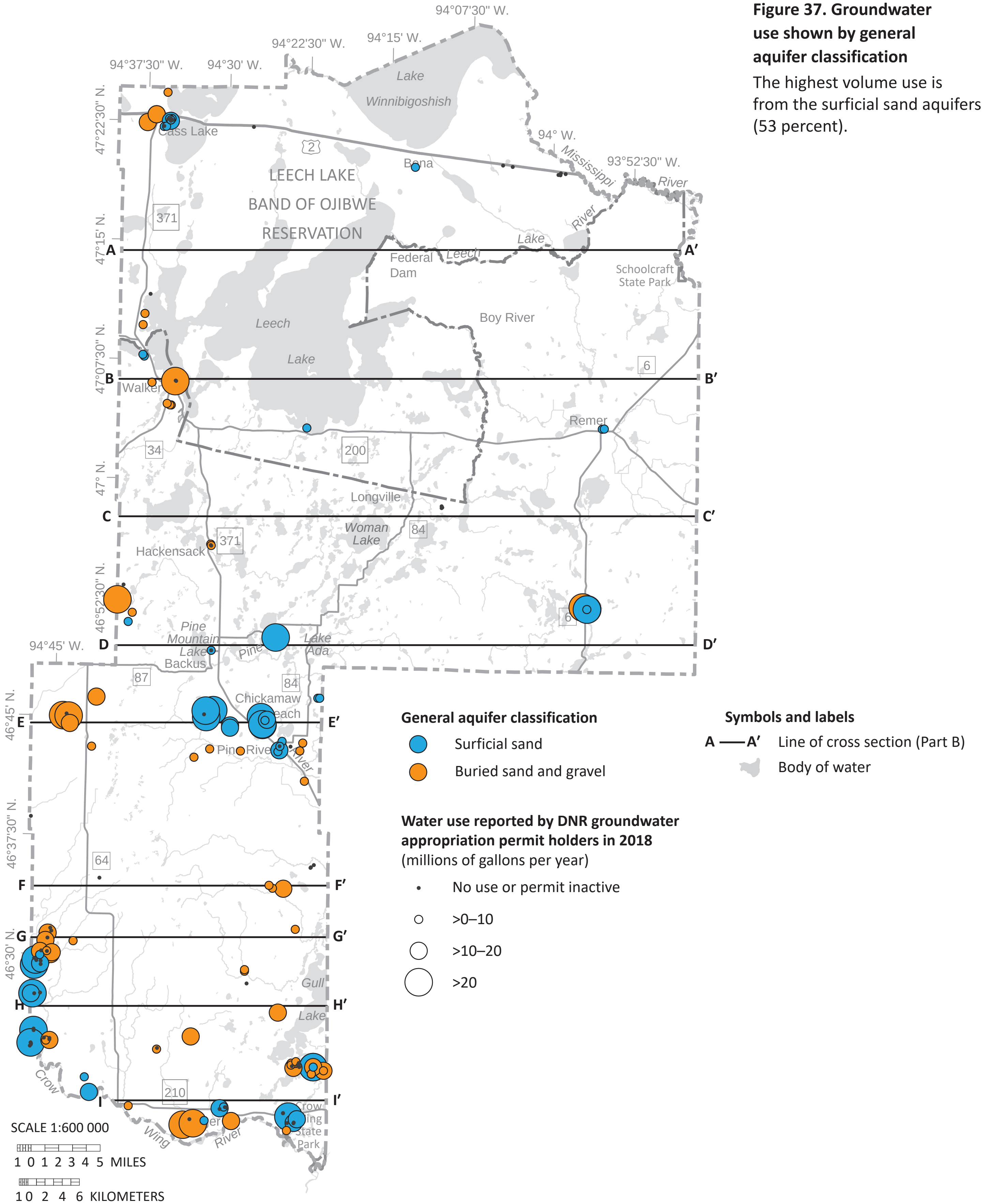
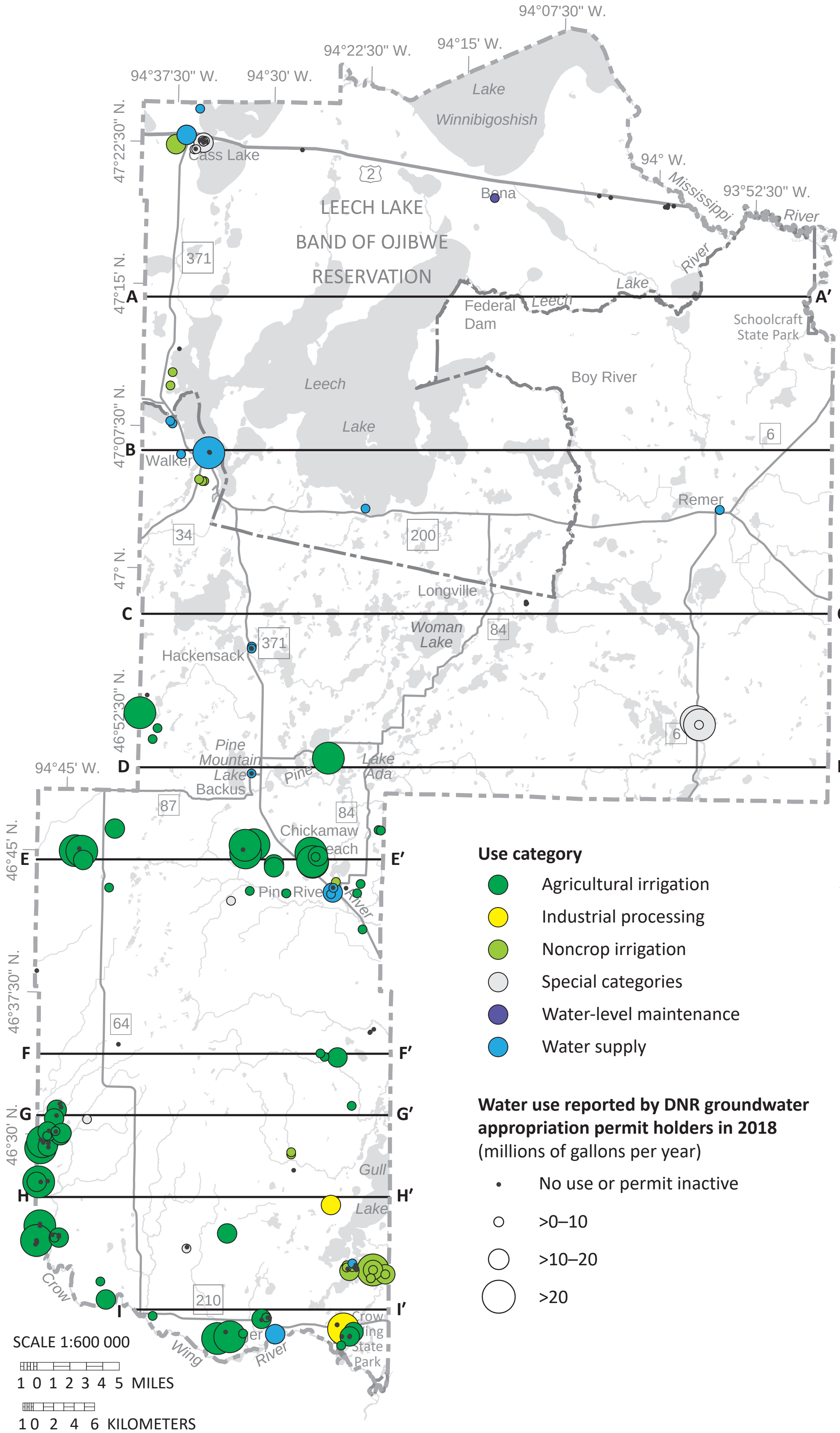


Figure 38. Groundwater use shown by use category

The most common water use is for agricultural irrigation (57 percent).



Use category

- Agricultural irrigation
- Industrial processing
- Noncrop irrigation
- Special categories
- Water-level maintenance
- Water supply

Symbols and labels

- A —— A′ Line of cross section (Part B)
- Body of water

Water use reported by DNR groundwater appropriation permit holders in 2018
(millions of gallons per year)

- No use or permit inactive
- >0–10
- >10–20
- >20

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Glossary

adsorbed—individual molecules, atoms, or ions gathering on surfaces.

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

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 100 to greater than 40,000 years before present.

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

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

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

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

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

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

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

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

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

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

hydraulic—relating to water movement.

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

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

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.

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

provenance—place of origin.

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.

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.

synoptic—The collection of samples from several locations during a short period of time.

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

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

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

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

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

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

watershed—the area of land 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 for laboratories analysis.

Samples were analyzed by DNR staff, the Minnesota Department of Agriculture (MDA), or the University of Waterloo Environmental Isotope Laboratory (Waterloo). The University of Minnesota (UMN) assisted in collection and data analysis of carbon-14 samples.

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

Appendix Table A. Groundwater field sample collection and handling details

Parameter	Tritium (^3H)	^{18}O and Deuterium (^2H)	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 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	1 for every 20 samples	none
Field blank	none	none	1 for every 20 samples****	1 for every 20 samples****	1 for every 20 samples****	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.

***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 for determining atmospheric values. Samples came from two main sources:

Precipitation (daily or composite) were collected at two DNR gages in Minnesota: the DNR MNgage precipitation monitoring station MWDM5 in Maplewood (Twin Cities metropolitan area) and the DNR CoCoRaHS precipitation monitoring station MN-SL-137 in Hibbing. Precipitation was collected daily and most samples were composited for approximately 30 days.

A lake-water sample was collected near the shore where the water depth is approximately 1 meter.

For additional tritium information, contact the DNR Groundwater Atlas Program page (mndnr.gov/groundwatermapping). For additional weather station information, contact the administering program.

- MNgage (https://climateapps.dnr.state.mn.us/HIDENsityEdit/HIDENweb.htm)
- CoCoRaHS (https://www.cocorahs.org)

Appendix Table B. Enriched tritium results

Sample Location	Sample date range	Tritium (TU)	Sample type
MNgage precipitation station (MWDM5)	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
	4/11/2019	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
	09/01/2020–09/30/2020	7.7	Precipitation composite
CoCoRaHS precipitation station (MN-SL-137)	09/01/2020–10/01/2020	8.1	Precipitation composite
Woman Lake	9/13/2018	6.5	Lake: littoral zone

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. Tritium ages for all samples (current and historic) are calculated based on sample date using the method described in *Tritium age classification: revised method for Minnesota* (DNR and MDH, 2020).

The Cold War era classification is a special case and implies that groundwater sampled for this atlas infiltrated into the ground in the late 1950s and 1960s. The Cold War era classification is only assigned to samples collected contemporaneously with this atlas (in 2018).

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