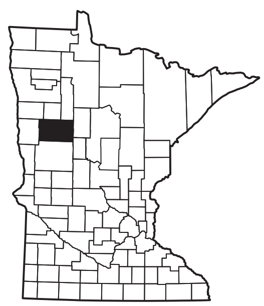
Groundwater Atlas of Becker County, Minnesota

County Atlas Series C-42, Part B - Hydrogeology



Report

To accompany these atlas components:

Plate 7, Water Chemistry
Plate 8, Hydrogeologic Cross Sections
Plate 9, 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 products and information are available online at Minnesota Department of Natural Resources, Groundwater Atlas Program page (mndnr.gov/groundwatermapping).

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Acknowledgments

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Contributors from staff at the Minnesota Department of Natural Resources include Vanessa Baratta, John Barry, Wes Rutelonis, Jim Berg, Todd Petersen, Rachel Lindgren, and Paul Putzier.

Special thanks to all the well owners who graciously offered to let us collect water samples from their wells. Without their voluntary participation this program would not be able to achieve its goals.

Part A - Geologic Atlas

The precursor to this atlas is *Geologic Atlas of Becker County, Minnesota, C-42, Part A* (Bauer and others, 2016), published by the Minnesota Geological Survey. It contains Plate 1, Data-Base Map (Bauer and Chandler); Plate 2, Bedrock Geology (Jirsa and Chandler); Plate 3, Surficial Geology (Marshall and Gowan); Plate 4, Quaternary Stratigraphy (Gowan and Marshall); Plate 5, Supplemental Quaternary Stratigraphy and Sand Distribution Model (Gowan, Marshall, and Hamilton); Plate 6, Bedrock Topography and Depth to Bedrock (Radakovich and Chandler).

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

Report Contents

Report Figures

Aquifer characteristics and groundwater use

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 Department of Natural Resources Groundwater Atlas Program at mndnr.gov/groundwatermapping.

Maps were prepared from Minnesota Department of Natural Resources 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 Minnesota Department of Natural Resources does not warrant the accuracy, completeness, or any implied uses of these data. Users may wish to verify critical information; sources include both the references here and information on file in the offices of the Minnesota Geological Survey and the Minnesota Department of Natural Resources. 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 Becker County, Minnesota*, 2016. Universal Transverse Mercator projection, Zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion factors

1 inch per hour = 7.056 x 10^{-6} meter per second
1 part per million = 1 milligram per liter
1 part per billion = 1 microgram per liter
1 $foot^2$ per day = 7.48 gallons per day per foot

Groundwater Atlas of Becker County, Minnesota

by Randy J. Bradt

Executive summary

This report and the accompanying plates describe the groundwater characteristics of the county and were produced by the Minnesota Department of Natural Resources (DNR). They build on the geology described in Part A, previously published by the Minnesota Geological Survey (MGS) (Bauer and others, 2016).

The atlas illustrates the hydrogeologic setting using maps, plates, figures, tables, and text. Principal products include groundwater flow maps, illustrations summarizing the results for select water chemistry constituents, aquifer pollution sensitivity maps, and geologic cross sections. Key elements and findings are summarized below.

Physical setting and climate (page 3) 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 4–18) describes the aquifers and aquitards and identifies their hydrostratigraphic characteristics and corresponding geologic units from Part A. Groundwater-elevation maps give a broad look at the direction of groundwater flow in unconfined conditions (water-table elevation) and confined conditions (potentiometric-surface elevation).

- Throughout the county the water table is mostly within 10 feet of the land surface. Groundwater flow is generally consistent with surface topography with flow beginning at higher elevations and discharging at lower elevations where streams, lakes, and wetlands are often found.
- Most well owners in the county find sufficient water supplies from the thick Quaternary sediment deposited by multiple glacial events. Buried sand aquifers provide water for the majority of domestic wells, but the thick and laterally extensive surficial sands also yield a significant amount of water. Additional water supply may be present in deeper thick glacial deposits, but currently no wells have penetrated the full thickness.

Water chemistry (pages 19–30, Plate 7) provides information about the following.

Groundwater recharge pathways: recharge from direct infiltration of precipitation can be distinguished from recharge via surface-water.

- Most groundwater in the county is recharged by direct infiltration of precipitation. Several groundwater samples contained evidence of contributions from lake water, most of which were in proximity to lakes. One case near Big Cormorant Lake showed a plume of lake water descending beneath a shallow aquifer and intersecting a deeper aquifer.

Groundwater residence time: the time elapsed since water infiltrated the land surface to when it was sampled. This is estimated using tritium and carbon-14 analysis.

- Water that recharged since 1953 was often found in aquifers less than 100 feet below the land surface. However, it can be absent in wells as shallow as 25 feet and present in wells much deeper than 100 feet, reflecting complex groundwater flow systems.
- Groundwater that recharged prior to 1953 was found to have residence times ranging from less than 100–25,000 years.

Inorganic chemistry:

Human (anthropogenic) sources are useful indicators for identifying where groundwater is being impacted by land use activities.

- Chloride concentrations suggesting anthropogenic sources were found mostly in surficial and shallow buried sand aquifers in or near Detroit Lakes, with a few additional sites to the east and northeast. Naturally-occurring chloride was found in a few shallow buried sand aquifers, but most was found in deeper buried sand aquifers in the western third of the county.

- Nitrate concentrations suggesting anthropogenic sources were found in the surficial and shallow buried sand aquifers in only a few of the wells sampled. However, a separate study targeting nitrates found it more prevalent in the Pineland sands.

There are a variety of naturally occurring chemicals in water. Some can affect the aesthetics, while others may pose a health concern.

- Arsenic was detected in most of the samples with approximately 30 percent exceeding the drinking water standard. The highest concentrations were mostly in the western third of the county.
- Manganese was detected in most of the samples with over 60 percent exceeding the drinking water standard. No discernible spatial patterns or correlations with specific aquifers were found.

Pollution sensitivity (pages 31–48) is defined as the time required for a contaminant to travel vertically from the land surface to the water table, the buried aquifer, or the bedrock surface. Two models are used to estimate the pollution sensitivity. Pollution sensitivity of the **near-surface materials** estimates travel time to the water table. Pollution sensitivity of **buried aquifers and the bedrock surface** estimates travel time to a buried aquifer or the bedrock surface.

- Pollution sensitivity of *near-surface materials* ranges from very low to high. The bulk of very low sensitivity is in the far western portion of the county, where fine-grained sediment is at the surface. Low and moderate sensitivity occurs to the east where areas of sediment have proportionally higher sand content. High sensitivity occurs in the eastern two-thirds of the county, near Detroit Lakes, and in far southwestern Becker County where sand and gravel deposits from glacial outwash cover large areas.
- Pollution sensitivity of *buried sand and gravel aquifers* varies from very low to very high according to how much aquitard material is stacked vertically above the aquifer. Aquifers closest to the land surface have high pollution sensitivities over much of their extent. In contrast, the deep buried aquifers generally are not very sensitive to pollution. However, there are some areas with high topographic relief and sandier aquitards where relatively young water (post-1953) has penetrated to greater depths than what is expected based on the pollution sensitivity rating. The northwestern portion of the county generally has the lowest sensitivity where topographic relief is low and groundwater flow ranges from weakly downward to vertically upward.

Hydrogeologic cross sections (pages 49–50, plates 8 and 9) illustrates the horizontal and vertical extent of aquifers and aquitards, the relative hydraulic conductivity of aquitards, general groundwater flow direction, and groundwater residence time.

- Groundwater generally flows downward and laterally toward perennial streams and lakes.
- The penetration depth of younger water varies. Thick surficial sands in the east, along the Otter Tail River, and in the southwest allow post-1953 water to penetrate to greater depths more easily. Other areas where water may penetrate to greater depths include higher sand content surficial and near-surface tills in the center and east, areas of high topographic relief, and where surficial and buried sands vertically overlap.
- In the western third of the county vertical recharge to the buried sands is more restricted by the lower sand content surficial and near-surface tills.
- In the northwest part of the county the penetration depth of young groundwater is limited by weak downward gradients and upward groundwater flow.

Aquifer characteristics and groundwater use (pages 51–60) summarizes specific capacity tests, aquifer tests, water use records, and groundwater level monitoring data.

- Over 75 percent of the wells in the county are for domestic use and do not require a DNR water appropriations permit. Permits are required for wells that extract more than 10,000 gallons per day or over 1 million gallons per year.
- Approximately 50 percent of the permitted groundwater use by volume was from surficial sand aquifers and the rest from buried sand aquifers.
- In 2018 the largest permitted groundwater use by volume was for irrigation (70 percent). The second largest was for municipal water supply (17 percent) with most of the water coming from buried sand aquifers. The annual reported water use from municipal wells varies little from one year to the next, whereas volumes for irrigation vary significantly depending on soil moisture conditions during each year's growing season.

Physical setting and climate

Minnesota is a headwaters state where water is replenished solely by precipitation. Water flow and levels fluctuate with wet and dry years. Levels fluctuate rapidly in rivers and water-table aquifers following precipitation. Water takes longer to travel to deeply buried aquifer systems so the changes are often delayed. Surface water leaves the state by a network of rivers that flow north to the Red River basin, east to the Great Lakes basin, southwest to the Missouri River basin, or southeast to the Mississippi River basin. Groundwater provides baseflow to streams and major river systems.

Becker County (Figure 1) is in northwestern Minnesota and had a population of 35,183 on April 1, 2020 (U.S. Census Bureau, 2020). The county has numerous lakes and wetlands covering over 10 percent of its 1,445 square mile surface. A regional watershed divide bisects the county. Slightly more than a quarter of the eastern portion drains south and east toward the Mississippi River. The remaining western portion drains south, west, and north, and ultimately discharges to the north-flowing Red River.

The climate is characterized as cool and subhumid with a large temperature difference between summer and winter. Average temperatures are approximately 66°F June through August, and 11°F December through February (NOAA, 2019). Average annual precipitation is approximately 26 inches, placing it in the lower half of the statewide range of 20–36 inches.

From 1895 through 2021, average annual temperatures increased by 2.8°F. The increases were fastest during winter, at night, and especially in the past five decades. Since 1970, daily minimum temperatures have risen 47 percent faster than daily maximum temperatures, and average winter temperatures have risen more than four times faster than average summer temperatures. Annual precipitation has increased by 2.8 inches since 1895, and intense rainfall events producing daily totals in excess of 1, 2, and 3 inches were more common between 1990 and 2021 than in any other period on record (DNR, 2022).

Climate projections summarized in the 2014, 2017, and 2018 National Climate Assessments indicate that Becker County will warm by an additional 2–4°F by 2050, while annual precipitation will increase by an additional 1–3 inches. Short-term variations can be expected leading to episodes of cooler conditions and drought even as trends toward warmer and wetter conditions continue (Pryor and others, 2014; Vose and others, 2017; Easterling and others, 2017; Jay and others, 2018).

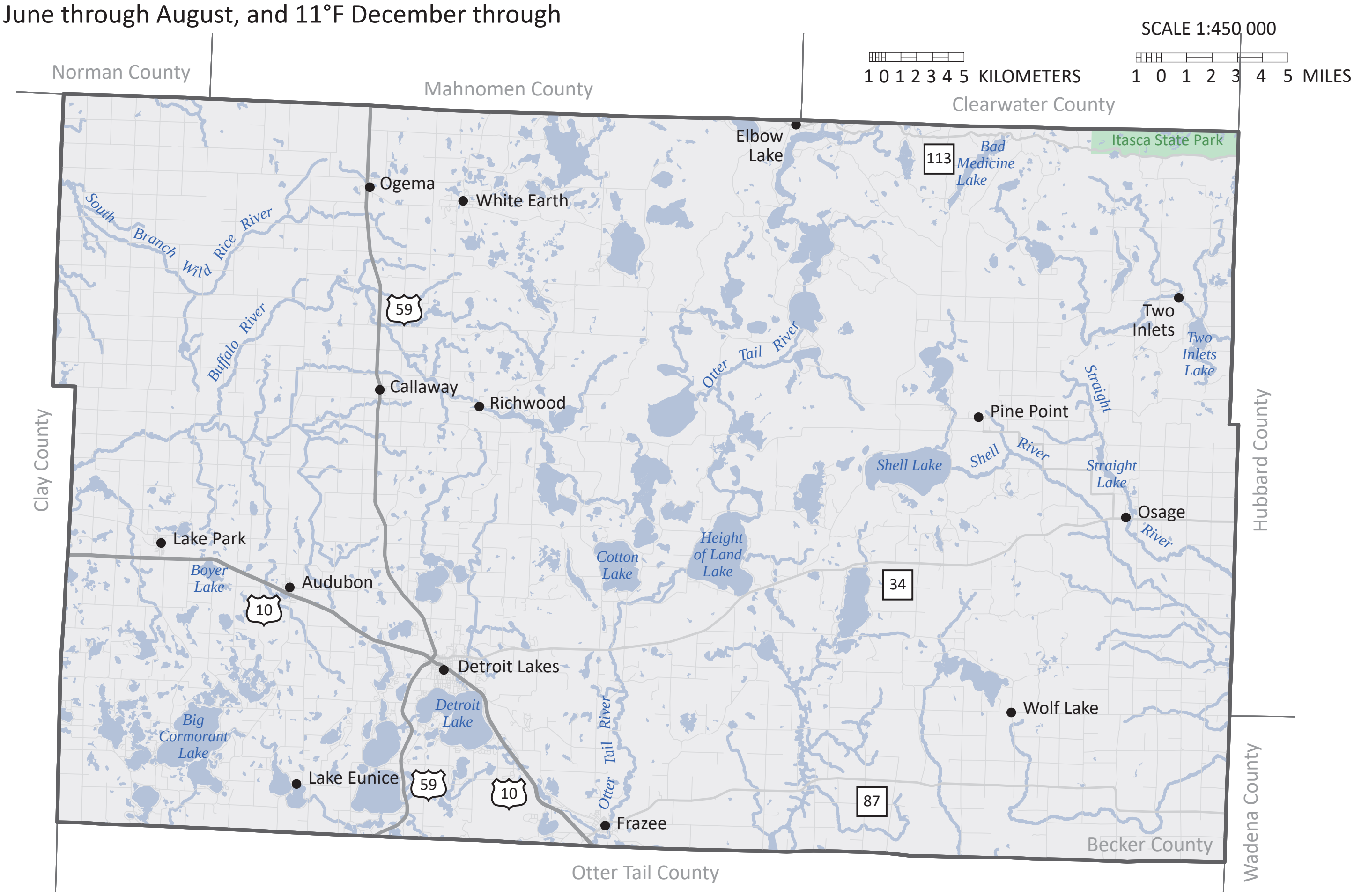


Figure 1. Becker County, Minnesota

Hydrogeology and groundwater flow

Hydrogeology

Quaternary hydrostratigraphy

A stratigraphic column is used to describe the vertical sequence of geologic units found in the county with the oldest units on the bottom and the youngest on top. This report depicts the geologic units in the Quaternary unconsolidated sediment: the most recent geologic period, encompassing the last 2.6 million years. In Minnesota, sediment deposited during this timeframe includes glacial and postglacial deposits. These units are depicted in the hydrostratigraphic column (Figure 2) as either aquitards or aquifers based on their ability to transmit water.

Aquifers readily transmit water and are generally coarse-grained outwash sand and gravel deposits where the saturated thickness yields sufficient water for the intended use.

Aquitards do not readily transmit water and generally fall into one of two textural categories.

- Sediment mixture of sand, silt, clay, and gravel referred to as till (also diamicton).
- Fine-grained silt and clay deposited in both ice-walled lakes and depressions.

Relative rates of groundwater recharge can be inferred from surficial geology textural information. Surficial geology in Figure 3 was reclassified into the 3 textural categories described above. The coarse-grained outwash deposits readily transmit water and are likely where groundwater recharge is greatest.

Surficial sand aquifers

Some of the thickest and most widespread outwash sands were deposited in eastern Becker County (Figure 4) as glacial meltwater flowed south from the Wadena lobe depositing sand and gravel of the Park Rapids outwash plain (Part A, Plate 3, Figure 2C). At the same time additional meltwater from the Brainerd lobe in the northeast flowed from the St. Croix moraine southwest to deposit sand and gravel of the Oshawa outwash plain. Together these deposits largely define the Pineland Sands, an area where crop farming is often dependent on irrigation, which cover portions of Becker, Hubbard, Wadena, and Cass counties (Figure 5).

Later ice advances of the Red River lobe also deposited outwash sand and gravel including the north-south trending Battle Creek outwash plain in central Becker County and another in southwest Becker County referred to as the Detroit Lakes outwash plain (Part A, Plate 3, Figure 2D–2F). Approximately 21 percent of the wells in the county are completed in the surficial sand aquifer.

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

Buried sand aquifers

Beneath the surficial geologic deposits are alternating layers of sand, gravel, and fine-grained material from earlier glacial advances. The naming convention for the buried sand and gravel aquifers in this atlas is based on the underlying till unit as described in the associated Part A atlas (Figure 2).

Aquitards (confining layers) enclose the sand and gravel bodies. These include 1) unsorted sediment deposited directly by the ice (till), and 2) bedded sediment of clay, silt, and fine-grained sand deposited in ponds and lakes. The till units tend to be laterally extensive.

The glacial sediment in Becker County varies in thickness from 190 to almost 1,200 feet. The thickest sediment is coincident with a deep bedrock valley in the center and northeast. Geology relies heavily on information from drillers logs. Areas with thick glacial deposits have very little information available about aquifers at depth because drillers often find water at shallower depths.

Over 75 percent of the wells rely on buried sand and gravel aquifers for their water supply. The buried sand aquifers are represented in the report maps for potentiometric surfaces.

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

Bedrock aquifers

Bedrock in Becker County consists of Precambrian-age metamorphic and intrusive crystalline rocks locally overlain by much younger Cretaceous-age sandstone and mudstone. Very little is known about their water supply potential since no wells are completed in bedrock. Wells are generally not completed in bedrock as there is sufficient water supplied by the surficial and buried sand aquifers, and because bedrock is often hundreds to over 1,000 feet deep.

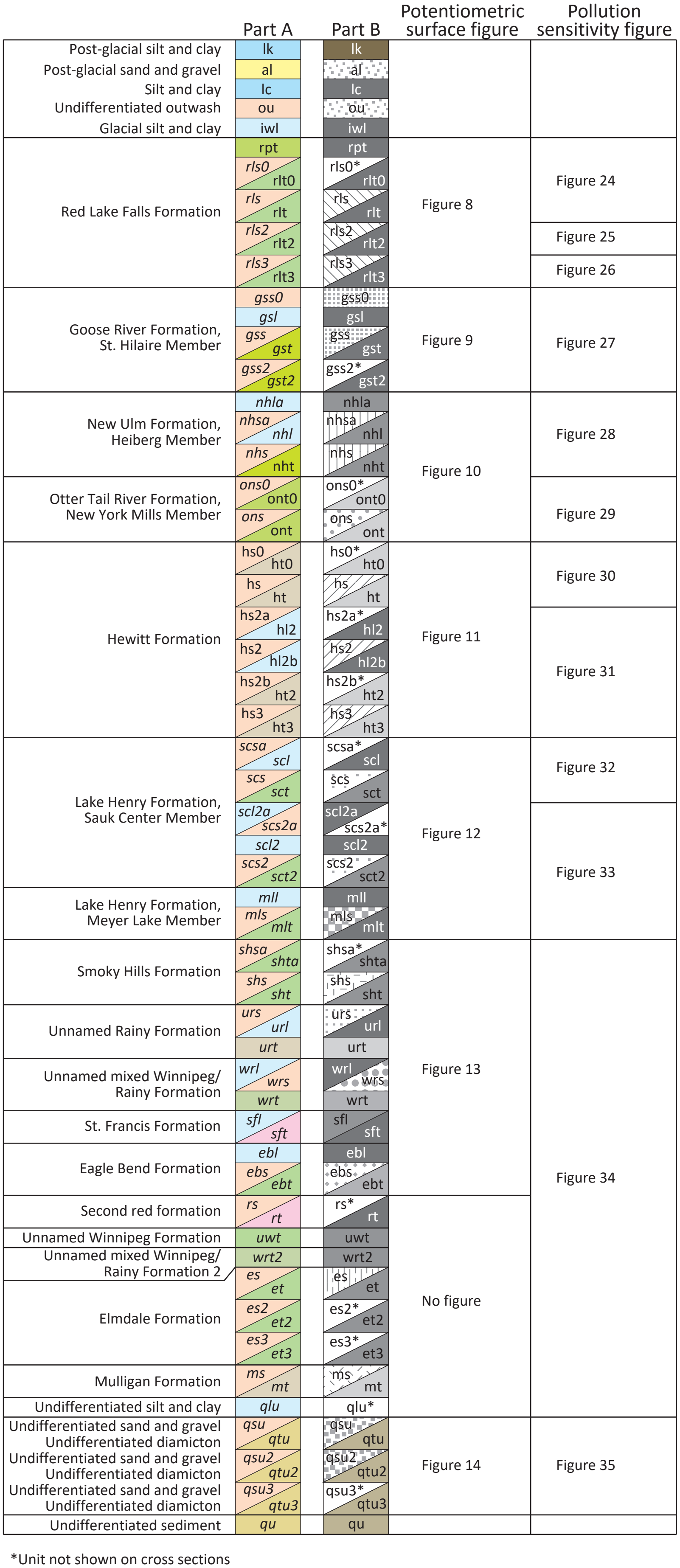


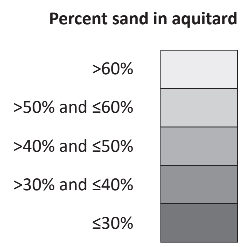
Figure 2. Hydrostratigraphy of Quaternary unconsolidated sediment

This hydrostratigraphic column correlates the unconsolidated geologic units from Part A with the hydrogeologic units of Part B as follows:

- ***Sand and gravel*** units from Part A are described as ***aquifers*** in Part B, shown with ***patterns***.
- ***Till or lake clay*** units from Part A are usually described as ***aquitards*** in Part B, shown as ***shades of gray***.

  The shades represent 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***.



The right columns show the grouping of mapped buried sands used for producing the potentiometric surface maps and pollution sensitivity maps.

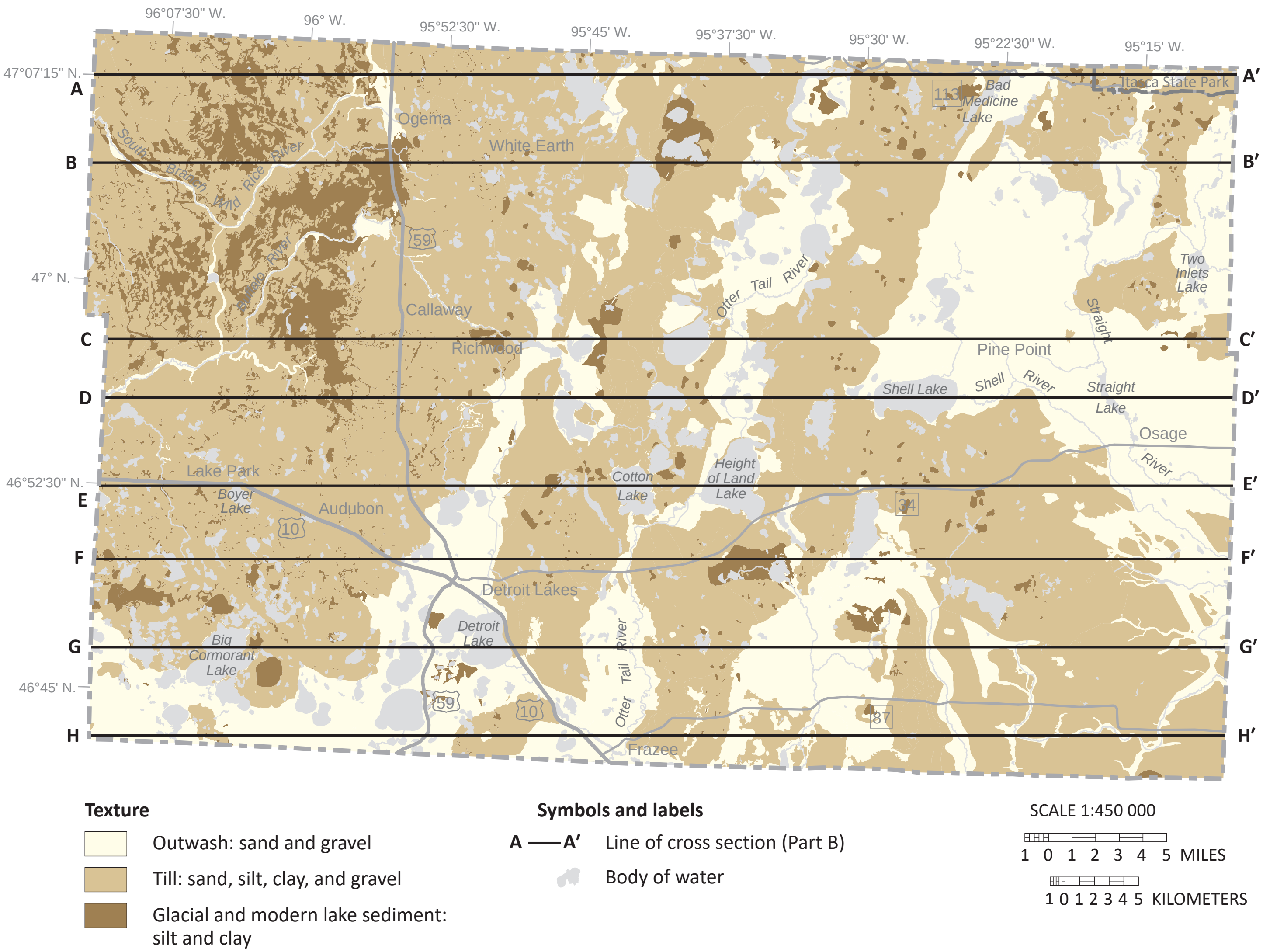


Figure 3. Surficial geologic units - generalized textural classification

Surficial geologic units are grouped by texture into three classifications: Outwash (sand and gravel) till (a mixture of sand, silt, clay, and gravel), and glacial and modern lake sediment (silt and clay). The outwash has the highest permeability and is where groundwater recharge is greatest.

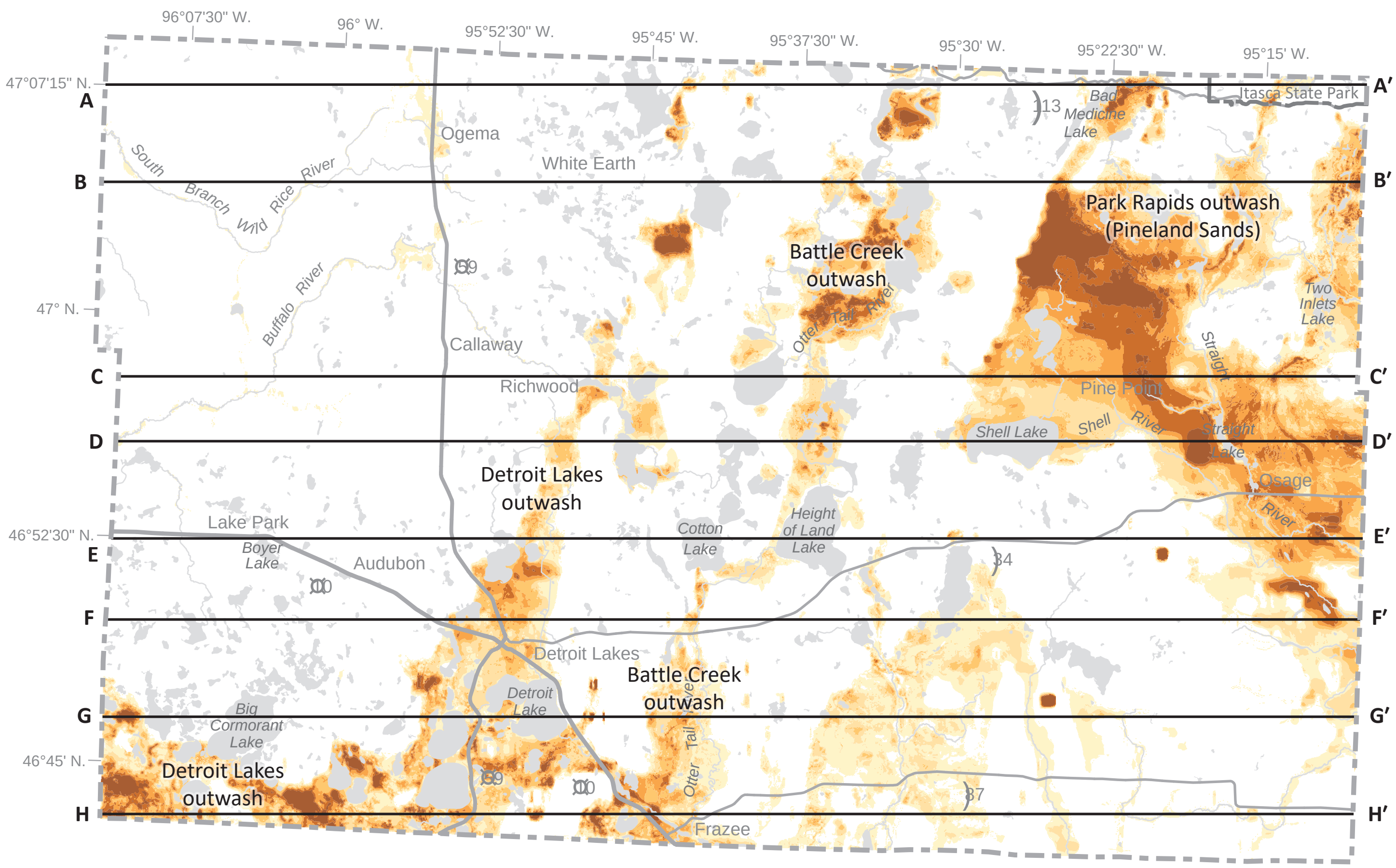


Figure 4. Surficial sand

There are three surficial outwash deposits: Detroit Lakes, Battle Creek, and Park Rapids. The thickest and most extensive sands are the Park Rapids Outwash in eastern Becker County. This is part of a larger area known as the Pineland Sands, an area where crop farming is often dependent on irrigation.

Estimated surficial sand and gravel thickness (feet)

- 0
- >0–20
- >20–40
- >40–60
- >60–80
- >80–100
- >100

SCALE 1:450 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 KILOMETERS

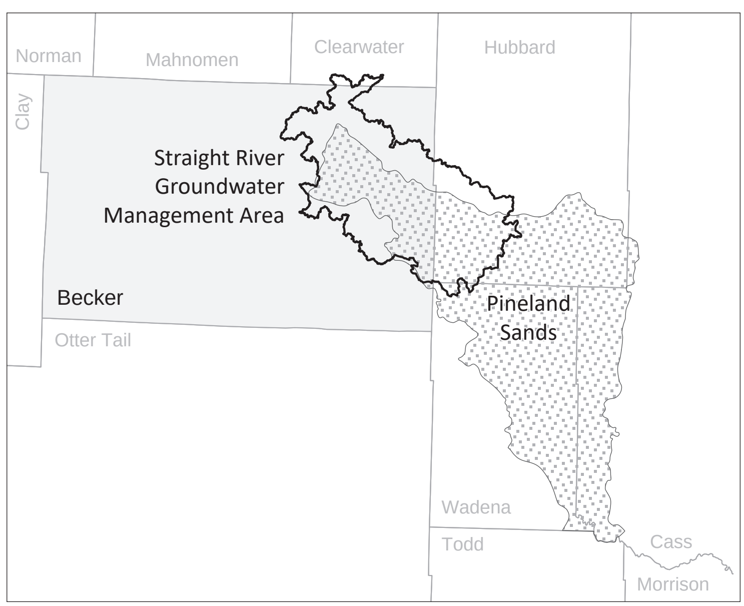
Symbols and labels

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

Body of water

Figure 5. Pineland Sands

The Pineland Sands cover portions of Becker, Hubbard, Wadena, and Cass counties along the Straight River. As part of a statewide analysis of groundwater resources, the DNR identified the Straight River as an area of specific concern where groundwater resources are at risk of overuse and degraded quality. In 2017, the DNR established the *Straight River Groundwater Management Area* and approved an action plan to ensure sustainable groundwater use (DNR, 2017).



Groundwater flow

There are two types of maps illustrating groundwater flow in this report.

1. The **water-table map** illustrates the *shallowest* groundwater flow where groundwater is *unconfined* and at equilibrium with atmospheric pressure. Groundwater flows from higher to lower elevations.
2. **Potentiometric surface maps** describe groundwater flow for *buried* aquifers where groundwater is *confined* and hydrostatic pressure exceeds atmospheric pressure. Groundwater flows from higher to lower pressure.

Water table (Figures 6–7)

The water table is the surface between the unsaturated and saturated zones where water pressure equals atmospheric pressure. Water-table elevations are contoured similar to land-surface elevations on a topographic map. The water table occurs in both aquifer and aquitard sediment across the entire county. Although it is shown in the figure as a static surface, it fluctuates over time. Surficial sand aquifers are present where there is sufficient saturated thickness and yield to install a well and pump water.

The **water-table elevation** is generally a subdued expression of the surface topography with flow directions typically consistent with surface-water flow and watershed boundaries. Locally, flow direction is generally from topographic highs to river tributaries, lakes, and wetlands.

The maps provide guidance for many applications, but site-specific information is needed at local scales. The water table is a dynamic system that varies in response to changes in recharge and discharge. Some of these changes include seasonal weather conditions, land-use practices, vegetation composition and distribution, and large groundwater withdrawals.

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

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

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

Depth to water table 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).

Potentiometric surface (Figures 8–14)

Potentiometric surface maps show the general horizontal direction of groundwater flow in buried sand aquifers. In these confined aquifers hydrostatic pressure is greater than atmospheric pressure, causing the water level in a well to rise above the top of an aquifer. The elevations of these water levels are contoured similar to land-surface elevations on a topographic map.

The potentiometric surface of an aquifer represents the potential energy to move groundwater. As groundwater moves from higher to lower potentiometric elevations it flows perpendicular to the contours, depicted with arrows on the maps.

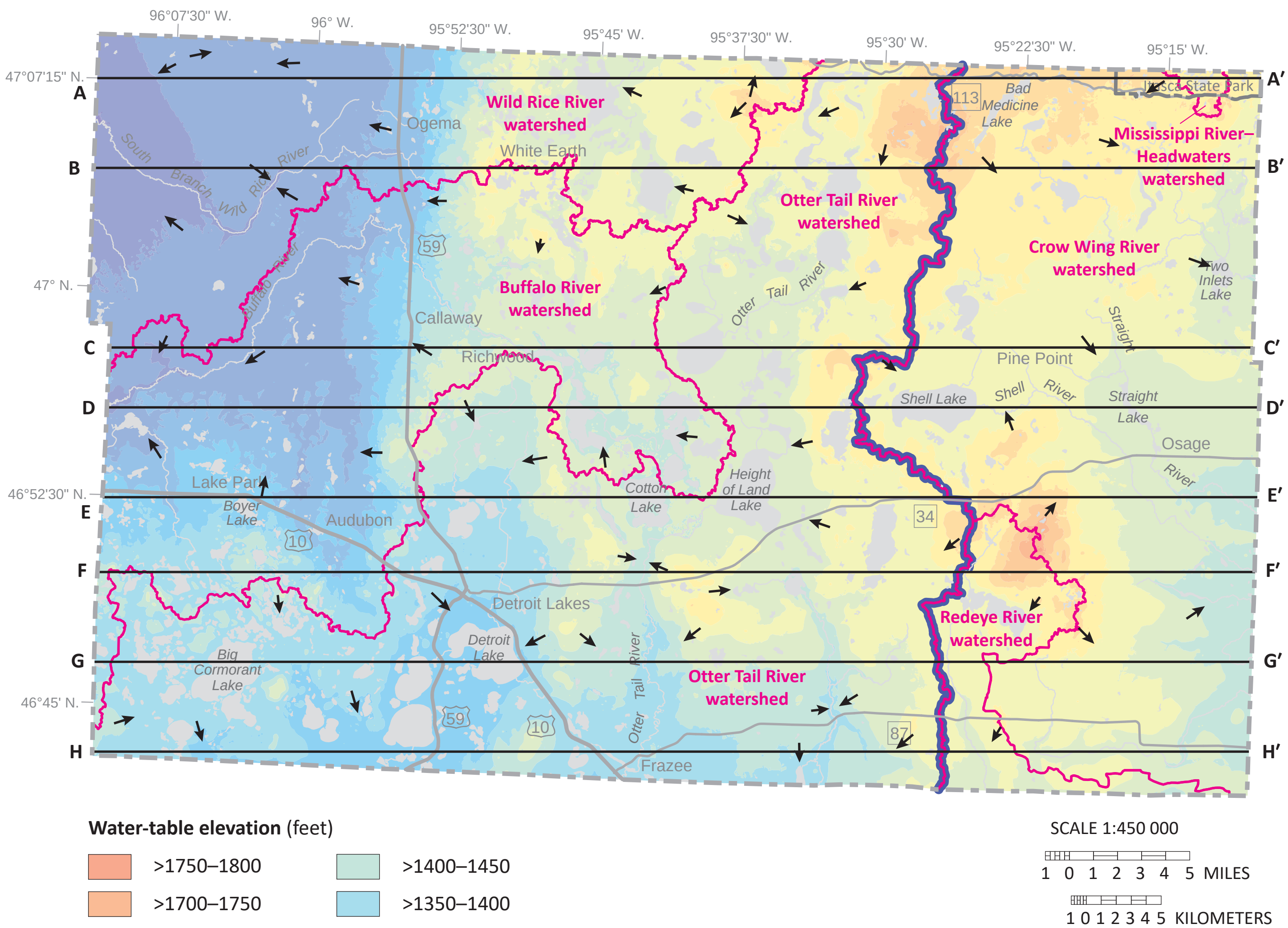
Potentiometric surface maps were created using static water-level data from the County Well Index (CWI), measurements made by DNR staff, and LiDAR derived surface elevation points along the major rivers and streams where a stream is likely in hydraulic connection with the aquifer being contoured. The CWI records represent water levels collected under various climatic and seasonal conditions from 1950s to 2018 (MGS and MDH, 2018). This data variability creates some uncertainty in potentiometric surface elevations.

1. Water-level data from adjacent aquifers were combined into composite groups to limit the number of potentiometric surface maps while still presenting an appropriate level of detail (Figure 2).

The water levels in wells associated with the buried sand aquifers have a median depth of 30 feet below the land surface. Almost 80 percent of the water levels are within 60 feet of the land surface. Contouring these water levels produced potentiometric surfaces that generally correspond to surface topography.

In the far eastern portion of the county groundwater flow is generally toward the east and southeast. Groundwater flow in south-central and parts of the southwest is to the south and west. Groundwater flow for the northwest portion of the county is to the west and northwest.

Flowing wells are also depicted on each of the potentiometric surface maps. Wells flow where the aquifer confining pressure is sufficient to bring water to a point above the land surface. These wells often occur near groundwater discharge regions such as rivers or lakes or along the base of topographic uplands.



Water-table elevation (feet)

>1750–1800	>1400–1450
>1700–1750	>1350–1400
>1650–1700	>1300–1350
>1600–1650	>1250–1300
>1550–1600	>1200–1250
>1500–1550	>1150–1200
>1450–1500	>1100–1150

Symbols and labels

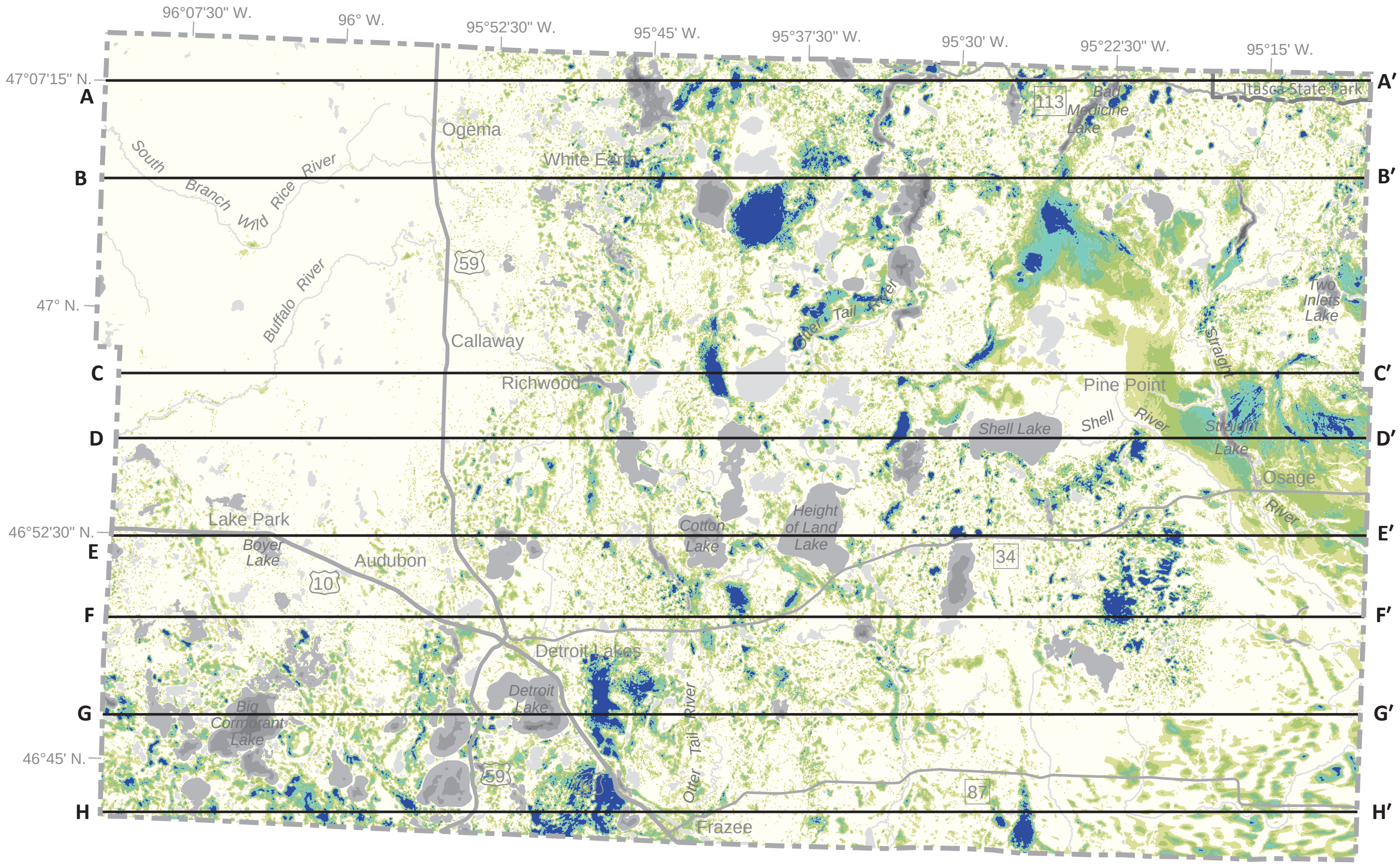
- Surface watershed boundary
- Laurentian watershed divide
- Groundwater flow direction
- A —— A' Line of cross section (Part B)
- Body of water

Figure 6. Water-table elevation and groundwater flow directions

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

The Laurentian watershed divide traverses Becker County from south to north with the eastern quarter draining three major watersheds generally east and southeast toward the Mississippi River (the Mississippi River Headwaters, Crow Wing River, and Redeye River watersheds).

The western three-quarters drains northwest and west via the Wild Rice River and Buffalo River watersheds and south via the Otter Tail River watershed. All these watersheds eventually discharge to the Red River.



Depth to water table (feet)

- 0–10
- >10–20
- >20–30
- >30–40
- >40–50
- >50

Symbols and labels

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

Body of water

SCALE 1:450 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 KILOMETERS

Depth of selected lakes (feet)

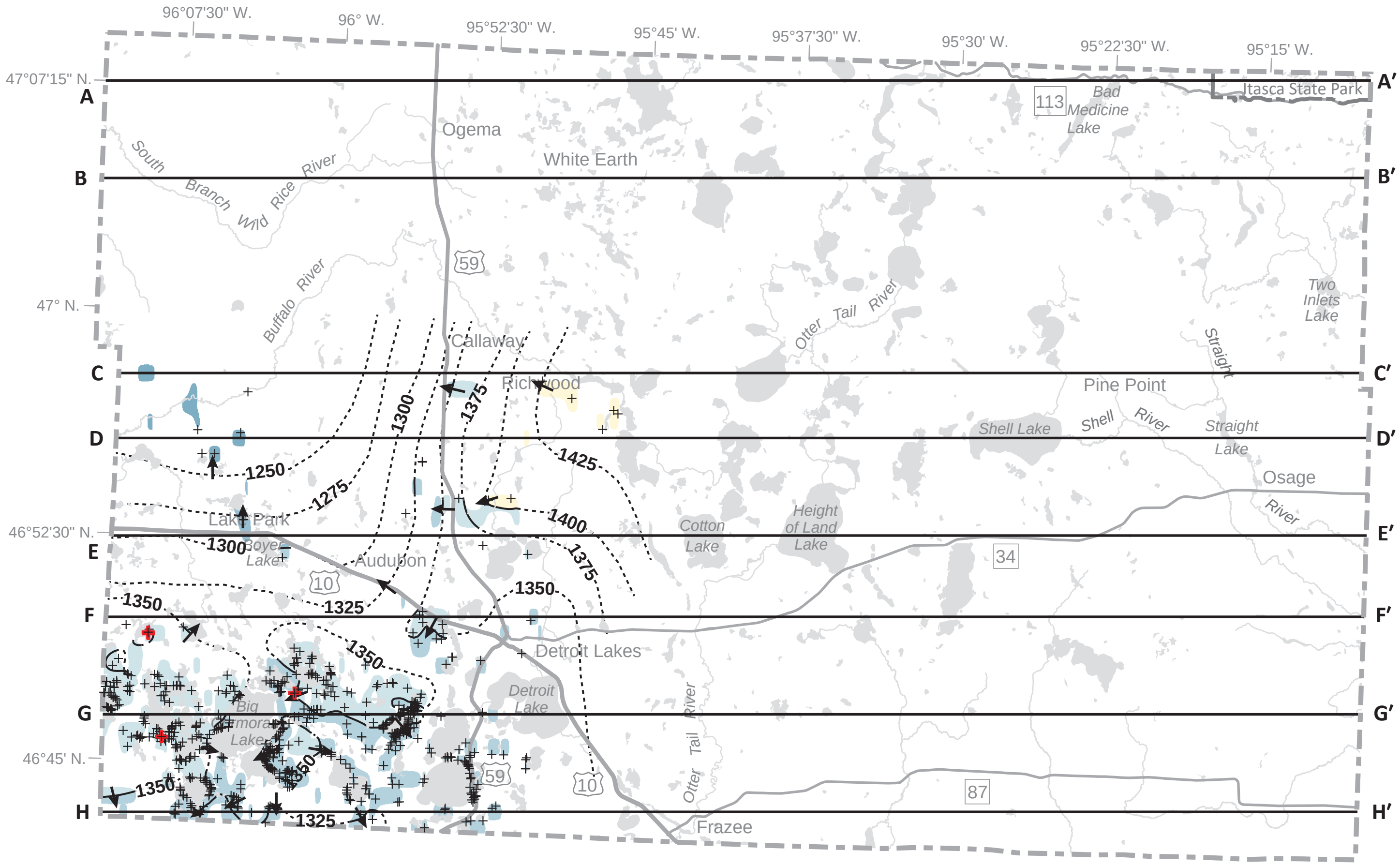
- 0–25
- >25–50
- >50–75
- >75–100
- >100

Figure 7. Depth to water table

The water table is commonly less than 10 feet below the land surface in most of the county. This is especially apparent in the west-central and northwest portions where the water table is in fine-grained sediment and there is limited topographic relief.

Greater depths are found where glacial sediment forms localized areas of higher elevation, along steep slopes, and where surficial sand deposits are at higher elevations and adjacent to low areas on the landscape (Part A, Plate 3, Surficial Geology).

The depth to water table may be overestimated where these features are composed of fine-grained sediment and no corresponding water-level data are available for that feature. This results from contouring data from adjacent lower elevations across localized areas of higher elevation. Site-specific data would be needed to establish a more accurate depth to water table.



Potentiometric surface elevation (feet)

>1400–1450	>1250–1300
>1350–1400	>1200–1250
>1300–1350	Aquifer not present

SCALE 1:450 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 KILOMETERS

Symbols and labels

- + Static water level data–nonflowing well
- + Static water level data–flowing well
- ← Groundwater flow direction
- ···1300— Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- A —— A′ Line of cross section (Part B)
- Body of water

Figure 8. Potentiometric surface of the rls0, rls, rls2, and rls3 aquifers

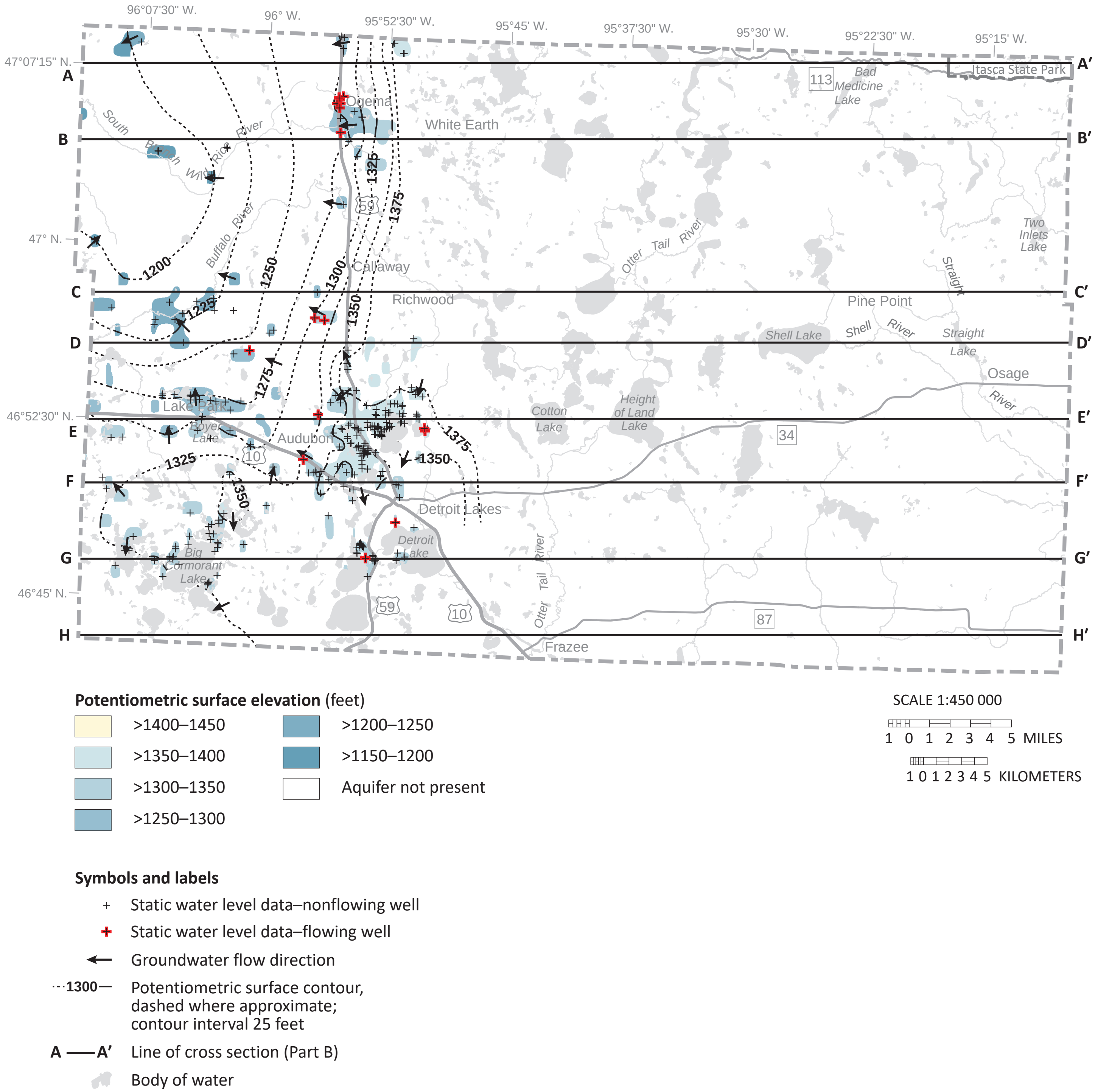
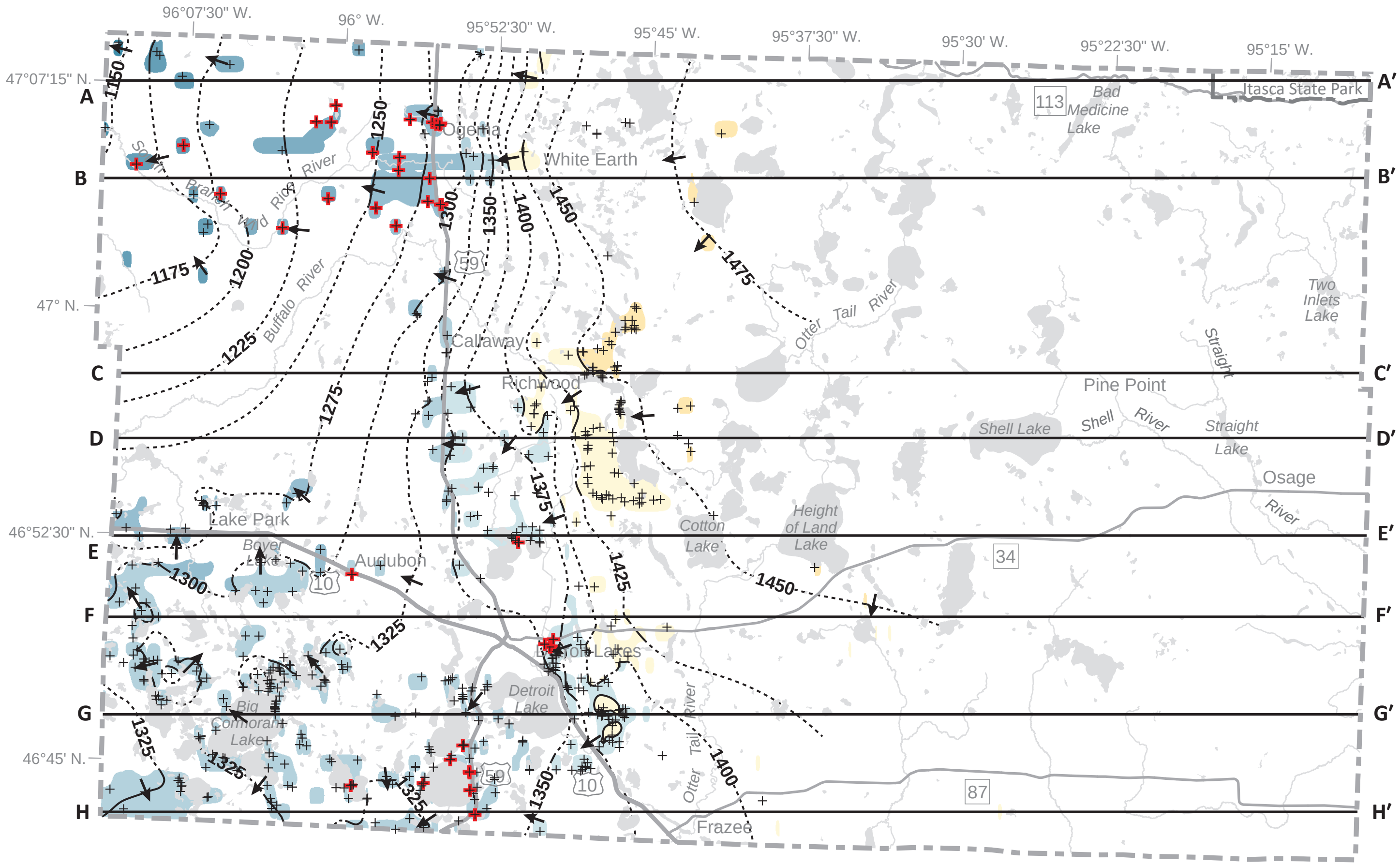


Figure 9. Potentiometric surface of the gss0, gss, and gss2 aquifers



Potentiometric surface elevation (feet)

- >1450–1500
- >1400–1450
- >1350–1400
- >1300–1350
- >1250–1300
- >1200–1250
- >1150–1200
- >1100–1150
- Aquifer not present

SCALE 1:450 000

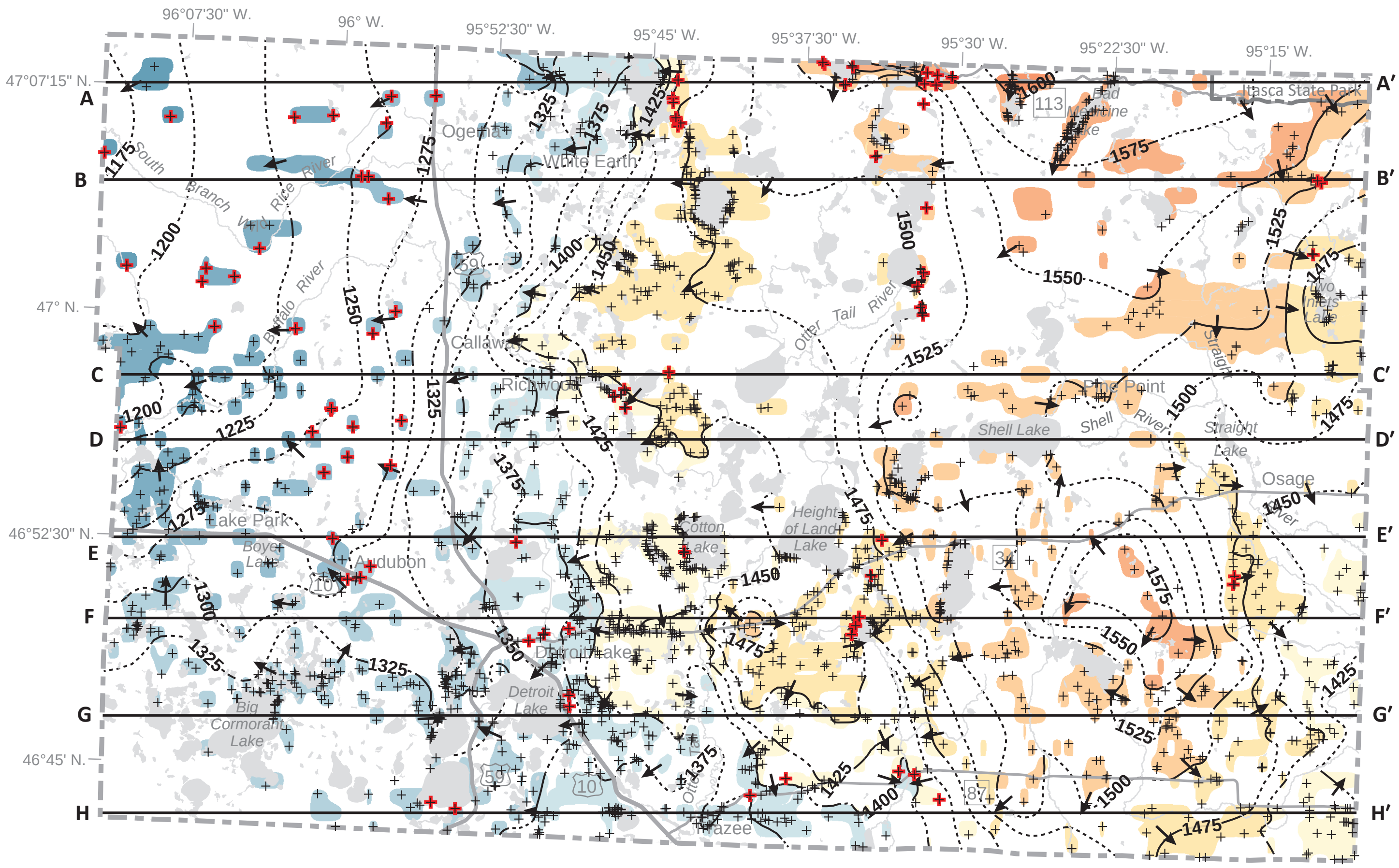
1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 KILOMETERS

Symbols and labels

- + Static water level data–nonflowing well
- + Static water level data–flowing well
- ← Groundwater flow direction
- ···1300— Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- A —— A′ Line of cross section (Part B)
- Body of water

Figure 10. Potentiometric surface of the nhsa, nhs, ons0, and ons aquifers



Potentiometric surface elevation (feet)

- >1600–1650
- >1550–1600
- >1500–1550
- >1450–1500
- >1400–1450
- >1350–1400
- >1300–1350
- >1250–1300
- >1200–1250
- >1150–1200
- Aquifer not present

SCALE 1:450 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 KILOMETERS

Symbols and labels

- + Static water level data–nonflowing well
- + Static water level data–flowing well
- ← Groundwater flow direction
- ···1300— Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- A —— A′ Line of cross section (Part B)
- Body of water

Figure 11. Potentiometric surface of the hs0, hs, hs2a, hs2, hs2b, and hs3 aquifers

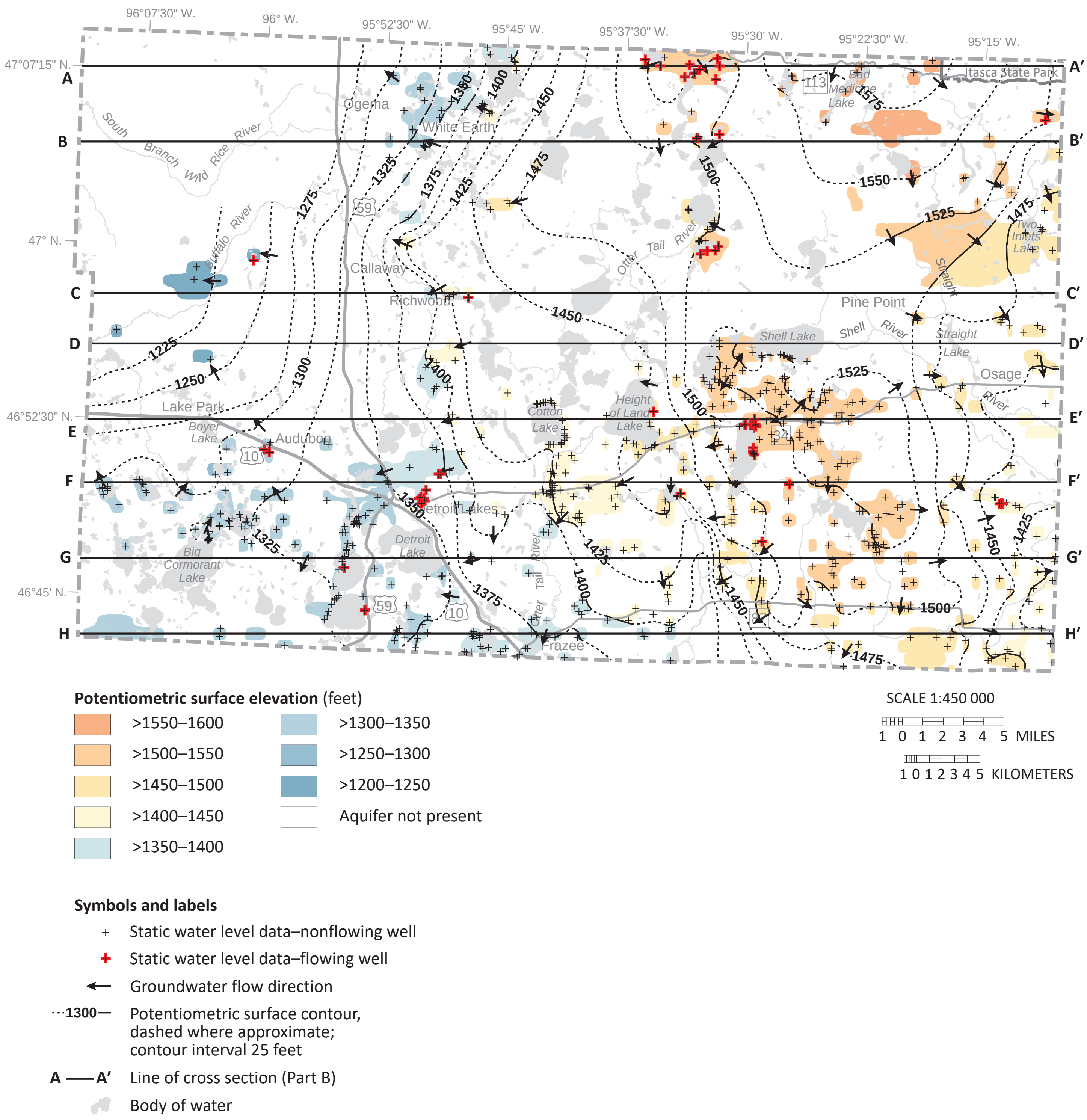
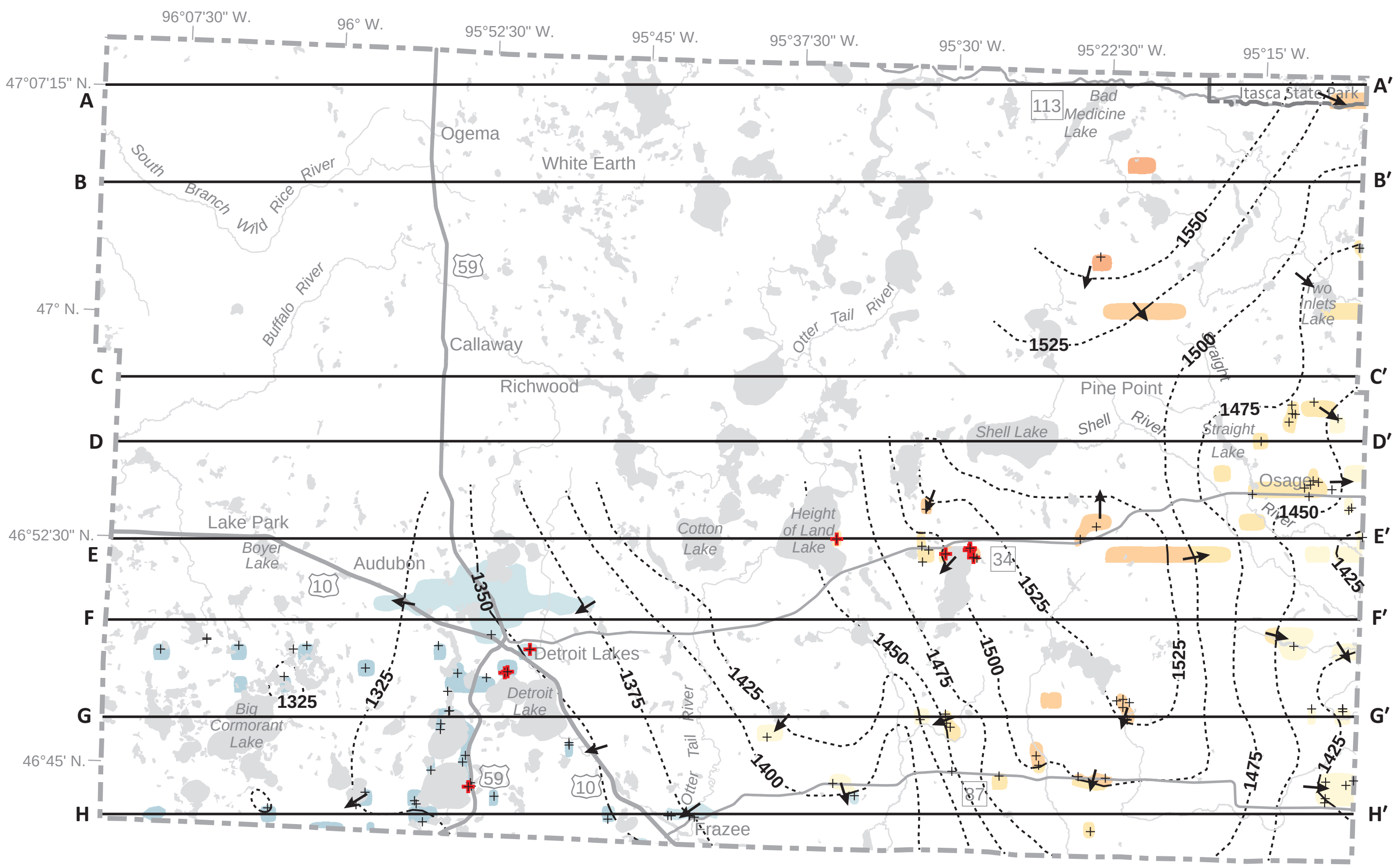


Figure 12. Potentiometric surface of the scsa, scs, scs2a, and scs2 aquifers



Potentiometric surface elevation (feet)

- >1550–1600
- >1500–1550
- >1450–1500
- >1400–1450
- >1350–1400
- >1300–1350
- Aquifer not present

SCALE 1:450 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 KILOMETERS

Symbols and labels

- Static water level data–nonflowing well
- Static water level data–flowing well
- Groundwater flow direction
- ···1400— Potentiometric surface contour, dashed where approximate; contour interval 25 feet
- A —— A′ Line of cross section (Part B)
- Body of water

Figure 13. Potentiometric surface of the shsa, shs, urs, wrs, and ebs aquifers

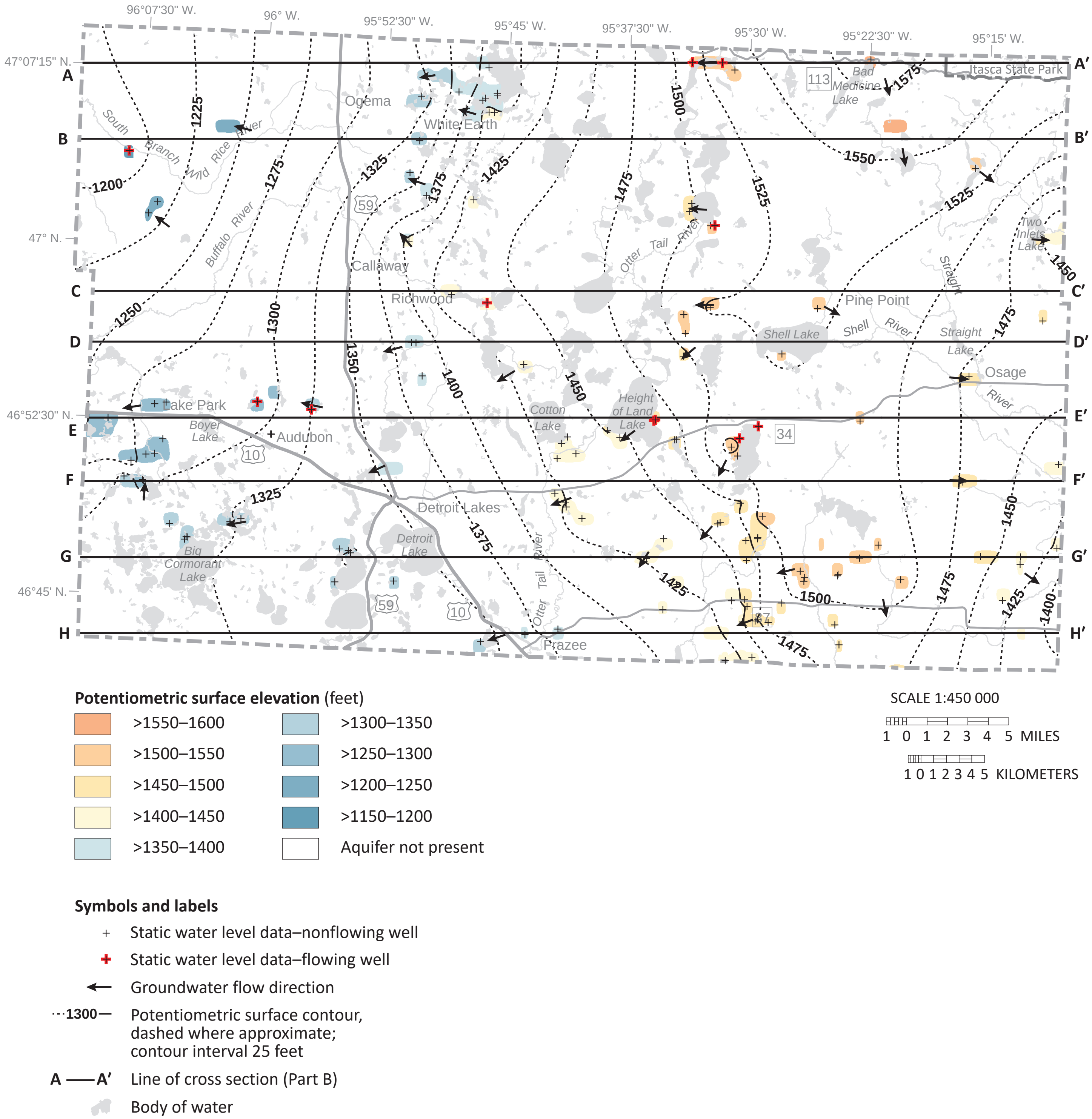


Figure 14. Potentiometric surface of the qsu, qsu2, and qsu3 aquifers

Water chemistry (Plate 7)

Chemical constituents in groundwater can provide information about the source of groundwater recharge, the chemical evolution along groundwater flow paths, and approximately when the precipitation entered the ground (residence time).

All groundwater originated as precipitation or surface water that infiltrated through soil layers into pores and crevices of aquifers and aquitards.

Water chemistry is used to provide information about the following:

- Groundwater recharge pathways: direct infiltration of precipitation can be distinguished from recharge through surface water using stable isotopes.
- Residence time: time elapsed from when water entered the ground to when it was pumped from a well or discharged at a spring.
- Chemical constituents of concern: those that may pose a potential health risk.
- Anthropogenic indicators: chemicals that have been introduced by human activities.

Water sampling

Samples were collected from wells in aquifers used for domestic water supply. Wells were selected to get an even distribution across the county, include populated areas, and target surface-water and groundwater interaction around lakes and larger rivers. Groundwater samples were collected according to the protocols outlined in Appendix A. The final network sampled depended on citizen willingness to participate. Approximately 1,000 well owners were contacted for permission to sample.

The DNR collected water samples and standard field parameters from 90 wells and 11 lakes. The results were combined with historical chemistry data including 77 well samples from the Minnesota Department of Health (MDH), 15 well samples and 1 lake sample from the DNR Otter Tail Regional Hydrogeologic Assessment, and 2 well samples from the U.S. Geological Survey.

Groundwater recharge pathways

Stable isotopes of oxygen and hydrogen are used to distinguish groundwater recharged by direct infiltration of precipitation at the land surface from groundwater recharged through lakes or open-water wetlands. Surface water that is open to the atmosphere can evaporate, which will change the isotopic composition through the process of *fractionation*.

Fractionation occurs because oxygen and hydrogen each have isotopes of different masses (^{18}O and ^{16}O, and ^{2}H and ^{1}H). This causes each isotope to evaporate at different rates, leaving the water with different ratios of heavy to light isotopes, resulting in unique isotopic signatures for groundwater with different recharge pathways (Kendall and Doctor, 2003).

- **Meteoric isotopic signature**: groundwater recharged from unevaporated 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 was subjected to fractionation by evaporation resulting in lake water with a heavier isotopic ratio.

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 is Vienna Standard Mean Ocean Water (VSMOW).

Definition of delta (δ)

The stable isotope composition of oxygen and hydrogen are reported as δ values: $\boldsymbol{\delta\ (^0/_{00}) = (R_x / R_s - 1)*1000}$.

- R represents the ratio of the heavy to light isotope, e.g., $^{18}O/^{16}O$ or $^{2}H/^{1}H$.
- R_x represents the ratio of the sample.
- R_s represents the ratio in the standard.

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

Results

Figure 15 compares county results to the **global meteoric water line**, which was developed from precipitation data from around the world (Craig, 1961). Groundwater samples plot primarily along the global meteoric water line, indicating that most of the groundwater is recharged by precipitation directly infiltrating into the subsurface.

A portion of the precipitation ends up in surface-water bodies where evaporation fractionates the stable isotopes of hydrogen and oxygen along an **evaporation line** below and to the right of the global meteoric water line. The evaporation line was established by sampling 12 lakes for stable isotopes and plotting their results to establish a range of lake isotopic ratios for comparison against groundwater samples.

For practicality in the following discussion, only oxygen stable isotope values are used for reference. The lake $\delta^{18}O$ isotopic values ranged from -8.0 to -3.6, reflecting the differences in the degree of evaporation of each lake. The degree of evaporation is primarily related to the residence time of water in the lake, which is largely determined by the ratio of the area of the watershed to the area of the lake. Generally, the greater the ratio, the shorter the residence time.

Two Inlets Lake has the largest watershed to lake area ratio, a relatively short residence time with less evaporation, and the lightest isotopic value (-8.0).

Big Cormorant, Wolf, and Boyer Lakes have the smallest ratios, relatively long residence times with greater evaporation, and the heaviest isotopic values (-4.15 to -3.6).

Bad Medicine Lake has a similar value (-3.9) even though it has a much larger ratio. The greater residence time is likely because the lake is a closed basin with no definable surface outlet for drainage.

Groundwater samples plot along the evaporation line where lake water is providing some portion of their recharge. Each sample's position is based on the initial $\delta^{18}O$ value of the lake source and the proportion of lake water and precipitation that recharged the aquifer.

Several groundwater samples plot along the evaporation line, but only 11 with a $\delta^{18}O$ value greater than -9 were identified as having an evaporative isotopic signature. There are additional groundwater samples with $\delta^{18}O$ values less than -9 that receive some portion of lake recharge. However, as samples plot closer to the global meteoric water line it becomes increasingly difficult to distinguish those that receive a portion of their recharge from a lake source from those that do not. This is because we often do not have isotopic data for lakes recharging many of the groundwater samples, and we don't always know which lake or lakes provide recharge to that aquifer.

Figure 16 represents an example of groundwater recharge from Big Cormorant Lake. The figure was taken from cross section G–G′ (Plate 9) and modified to show stable isotope data for Big Cormorant Lake and three adjacent wells. The flow path that this lake water takes as it travels vertically downward and slightly to the west can be inferred from the equipotential lines and the stable isotope data.

The sample on the east side of the lake is from a deep well (172 feet) in the nhs aquifer. It has a $\delta^{18}O$ value of -8.51 which indicates a greater proportion of the recharge water is from precipitation with a smaller portion from the lake. On the west side of the lake a sample from a shallow well (64 feet) in the rls2 aquifer has a $\delta^{18}O$ value of -12.04 which indicates directly infiltrating precipitation. A sample from the deeper well (177 feet) in the gss aquifer has a $\delta^{18}O$ value of -4.77, close to that of the water currently in the lake (-3.72). Therefore, the lake recharge plume is descending beneath the shallow rls2 aquifer and intersecting the deeper gss aquifer.

Figure 18 illustrates additional evidence of lake recharge to the gss aquifer as supported by the sample's cation chemistry (expressed in milliequivalents). On the piper cation triangle the gss aquifer (no. 1) plots toward the top of the diagram near samples from Cotton Lake (star) and three downgradient shallow wells on the lake's western shore (no. 2). These are the only samples where magnesium exceeds calcium. Most of the groundwater samples plot toward the lower left portion of the triangle where calcium is the dominant cation.

Ideally a comparison of water chemistry would be made between a sample from the gss aquifer and Big Cormorant Lake. Since neither calcium nor magnesium data were collected from this lake, other evidence will be presented to show that magnesium is likely the dominant cation in Big Cormorant Lake because this is commonly the case for other lakes in the area.

Magnesium was the dominant cation in five of seven lakes, including Cotton Lake, that were sampled for the Otter Tail Regional Hydrogeologic Assessment (Eckman and Berg, 2002). Therefore, groundwater samples with magnesium as the dominant cation suggest a lake source of recharge.

The observed dominance of magnesium is either the result of calcium depletion, increased magnesium uptake, or both. A comparison of magnesium-dominant lake and groundwater samples to nearby calcium dominant groundwater samples (in equivalents per liter) found similar magnesium concentrations, but depleted calcium concentrations.

Lakes with magnesium as the dominant cation may be losing calcium due to biotic utilization of calcium by freshwater flora and fauna (Wetzel, 2001). Heiskary and Lindon (2010) found that on an equivalent basis magnesium replaces calcium as the dominant cation in lakes in the central hardwood forest ecoregion in Minnesota, where both Cotton and Big Cormorant lakes are found.

Additionally, only two groundwater samples collected for this atlas had magnesium as the dominant cation, and both had evaporative isotopic signatures greatly enriched in the heavier isotopes suggesting a significant contribution of lake recharge.

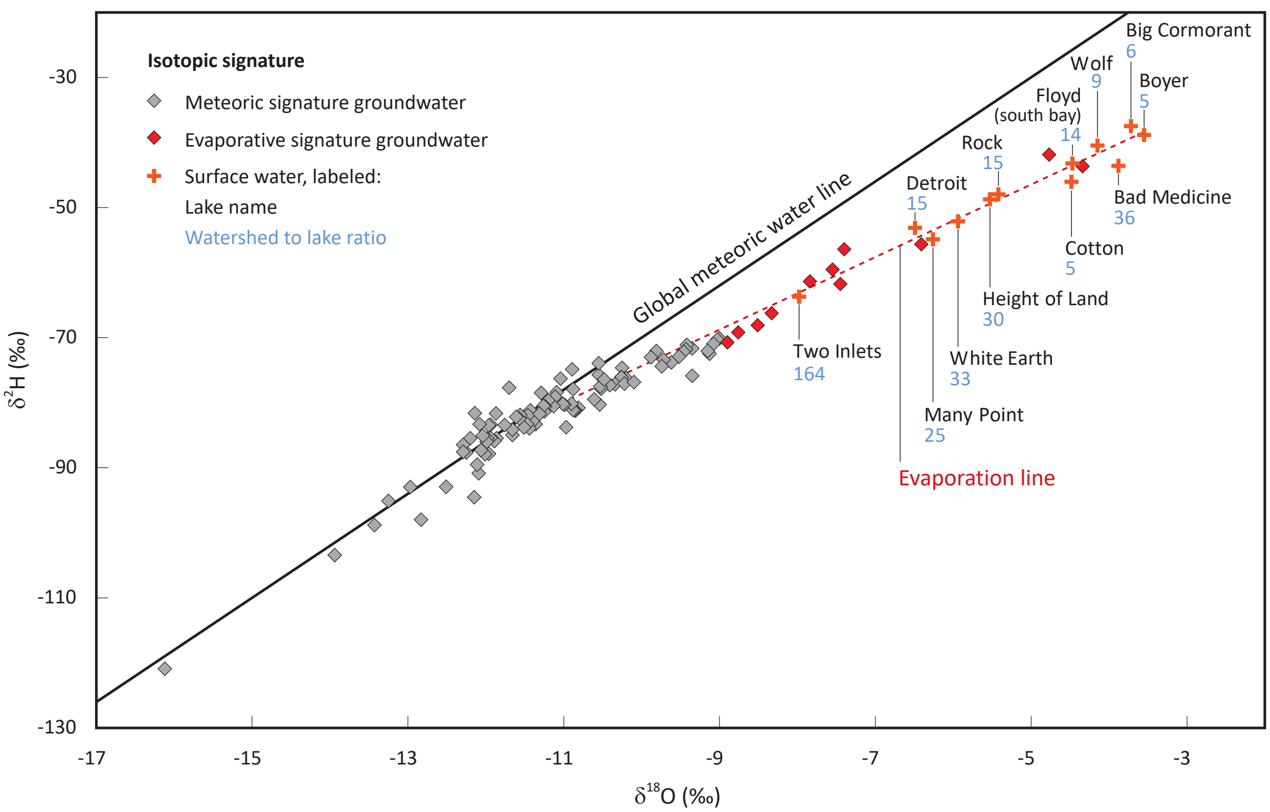


Figure 15. Stable isotope values from water samples

The **meteoric water line** represents the isotopic composition of precipitation. Groundwater that plots on the meteoric water line indicates recharge of directly infiltrated precipitation. The **global meteoric water line** was developed using precipitation samples from around the world and is described by the following equation: $\delta^2H = 8.0\ \delta^{18}O + 10.0$.

The **evaporation line** represents the isotopic composition of surface water that has been fractionated by evaporation. Groundwater that plots on the evaporation line indicates recharge through surface water. The local evaporation line is described by the equation: $\delta^2H = 5.6\ \delta^{18}O - 18.5$, calculated from 12 lakes in Becker County.

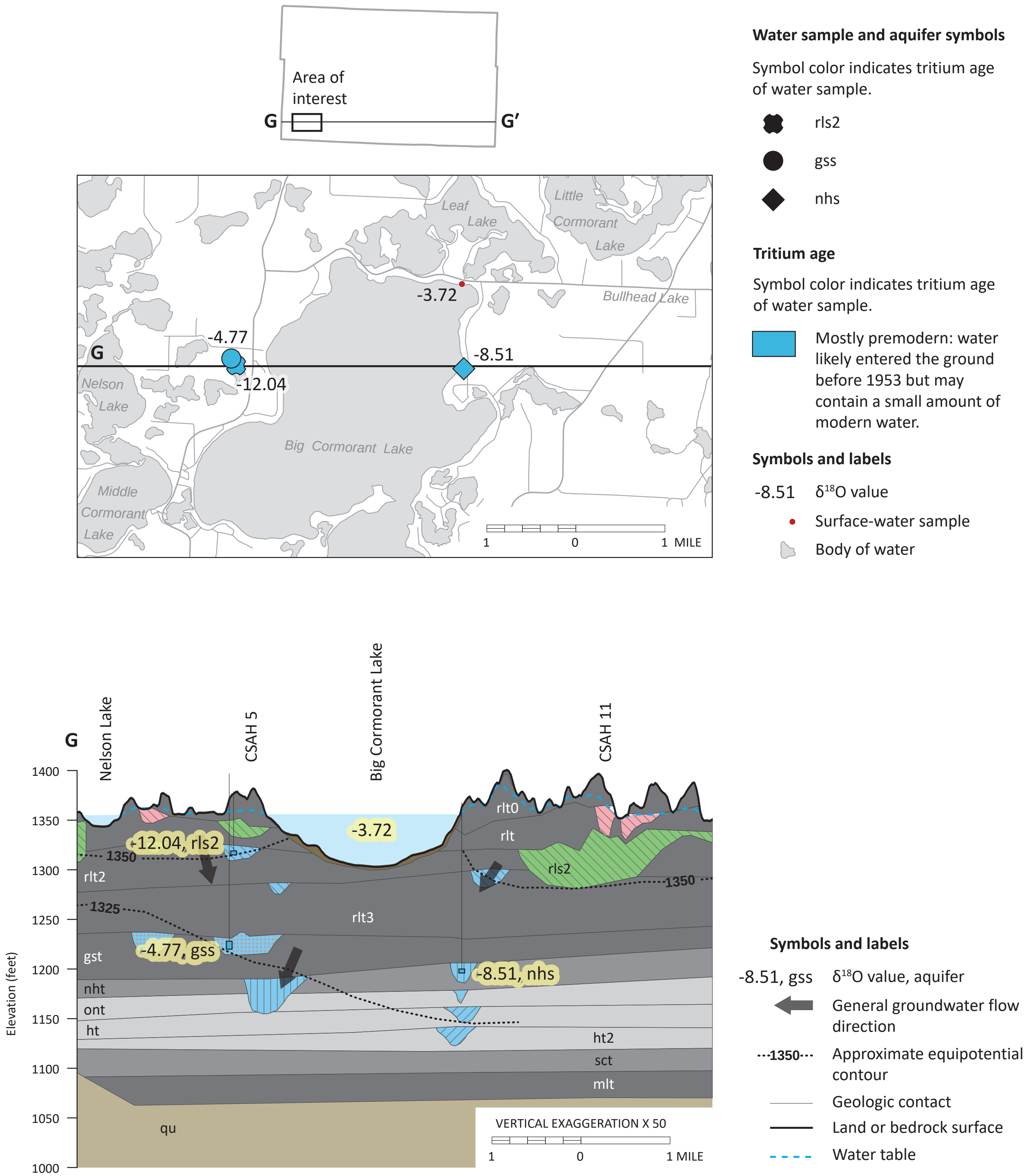


Figure 16. Lake recharge path beneath Big Cormorant Lake

Lake water moves vertically downward to the gss aquifer, passing beneath the overlying shallower rls2 aquifer as it moves in generally westward.

On the east side of the lake, the nhs aquifer had a slight evaporative signature in a deep well (172 feet). On the west side, the rls2 aquifer contained no evaporative signature in a shallow well (64 feet), while the gss aquifer contained a significant evaporative signature in a deeper well (177 feet). Figure modified from Plate 9, cross section G–G′.

Groundwater residence time

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 using analysis of two radioactive isotopes: tritium and carbon-14.

Tritium

Tritium concentration is used to estimate groundwater residence time from before the 1950s to today. Although tritium is a naturally occurring isotope of hydrogen, atmospheric concentrations were 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).

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).

- **Modern**: water entered the ground after 1953.
- **Mixed**: water is a mixture of modern and premodern.
- **Mostly premodern**: water likely entered the ground before 1953 but may contain a small amount of modern water.
- **Premodern**: water entered the ground before 1953.

> For hydrogeologic interpretation, premodern *includes* mostly premodern.
>
> Data shown on figures and plates *uses both* premodern and mostly premodern.

A total of 91 tritium samples were collected for this study: 90 from wells and 1 from Height of Land Lake. An additional 48 tritium samples are included from previous studies. Residence times ranged from premodern to modern tritium age. Results are summarized using three well-depth categories.

- Less than 100 feet deep: of 63 total wells, 46 had modern or mixed tritium-age water.
- 100–200 feet deep: of 45 total wells, 12 had modern or mixed tritium-age water.
- Greater than 200 feet deep: of 27 total wells, only 3 had mixed tritium-age water.

Carbon-14

Select wells with premodern tritium-age results were further sampled for carbon-14 (^{14}C) to estimate longer residence times of less than 100 to greater than 40,000 years. This naturally occurring isotope has a half-life of 5,730 years. Carbon-14 sample collection, analysis, and modeling is described in Alexander and Alexander, 2018.

When precipitation infiltrates the unsaturated zone it absorbs carbon dioxide, including carbon-14, from biospheric soil gases forming carbonic acid. This mildly acidic water dissolves calcite and dolomite present in the soil or bedrock. 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. 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.

The residence times appear to generally relate to two factors: well depth and the length of the groundwater flow path from the recharge area to the aquifer (Figure 17). A total of 10 samples collected for this study were combined with 9 samples from previous studies. The following summarizes the 19 samples in three well-depth categories.

Less than or equal to 100 feet (6 wells)

- 5 samples had residence times of less than 100 to just over 1,000 years old.
- 1 sample was 4,000 years old from a 64-foot well in the surficial sand aquifer. The available information of the physical hydrogeologic conditions cannot explain the long residence time, but the age suggests possible upwelling supplying older water to this portion of the surficial aquifer.

Greater than 100 feet to 200 feet (8 wells)

- 6 samples were less than 4,500 years old from aquifers in areas of high local topographic relief and elevation. The relatively younger ages are likely the result of aquifers intercepting water that is recharged nearby.
- 2 samples from the lowlands in far western and northwestern Becker County were 14,000 and 25,000 years old. This significantly older water was the result of long groundwater flow paths from distant upland recharge areas to the east and south, as shown in the potentiometric surface maps. Additionally, groundwater flow in this part of the county is often older water from depth moving upward toward the land surface, unlike most of the uplands where groundwater is moving vertically downward.

Greater than 200 feet to 414 feet (5 wells)

- 2 samples from the deepest wells (384 and 414 feet) had residence times of 8,000 and 10,000 years respectively.
- 2 samples from municipal wells (232 and 237 feet) had residence times from less than 100 years to 1,100 years, respectively. These are Detroit Lakes public supply wells that are only a few hundred feet apart in the same aquifer. Pumping may have brought in young water from the overlying aquifers to the buried sand aquifer.
- The final sample (245 feet) had a residence time of less than 100 years. This is plausible in portions of the county, however the chemistry suggests a complicated chemical evolution along its flow path, reducing confidence in the modeled groundwater age.

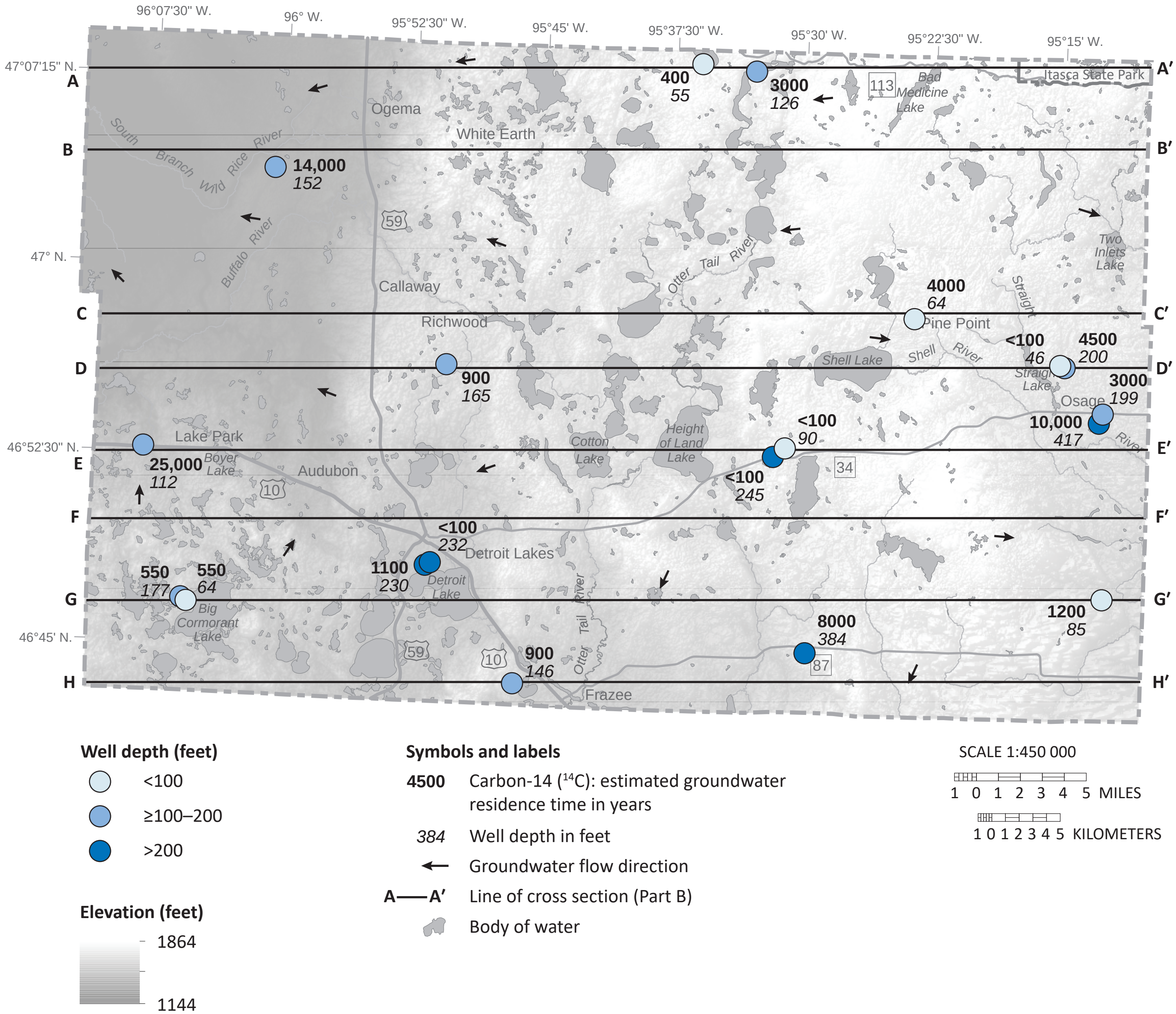


Figure 17. Carbon-14 results plotted on LiDAR surface elevations

In general, the oldest water corresponds to the deepest wells, except in the lowlands in the far west and northwest where very old water is encountered at much shallower depths. Those wells likely intercept groundwater with long flow paths that recharged in upland areas to the east and south.

Inorganic chemistry of groundwater

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

Groundwater may reasonably be expected to contain some contaminants. The Safe Drinking Water Act defines *contaminant* as any physical, chemical, biological, or radiological substance or matter in water (SWDA, et seq., 1974). The presence of contaminants does not necessarily indicate that the water poses a health risk. Some contaminants may be harmful if consumed above certain levels in drinking water, while others may negatively affect the aesthetics of water.

Groundwater contaminants can be anthropogenic or from dissolution of naturally-occurring geologic material. For a select group of dissolved contaminants, this atlas uses the following guidelines.

Drinking Water 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, 2012)

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

Chemical descriptions and results

Inorganic constituents of groundwater are described below and the sample results are compared to drinking water guidelines. Major cations and anions are reported in units of parts per million (ppm). Trace elements, such as arsenic and manganese, are reported in units of parts per billion (ppb).

Calcium, Magnesium, Sodium, Potassium, and Bicarbonate

No drinking water guidelines. Reported in ppm.

Calcium, magnesium, sodium, and potassium cations and bicarbonate anions are dissolved out of sediment and bedrock by groundwater.

The calcium, magnesium, and bicarbonate constituents are derived from limestone and dolomite bedrock sources (Hem, 1985) and are common in groundwater.

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 fertilizers provide an additional source of potassium.

Water with higher concentrations of calcium and magnesium is considered hard. Though not required, many residents soften their water to limit the build-up of minerals (scale) on plumbing fixtures, the insides of pipes, and water heaters.

Sampling results

All of these constituents are common in Minnesota groundwater. There are currently no guidelines for these constituents.

Chloride

SMCL 250 ppm

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). Concentrations above the SMCL can cause a salty taste in drinking water.

Samples at or above 5 ppm chloride are assigned a source.

- Anthropogenic if the chloride/bromide ratio is greater than or equal to 300.
- Natural if the chloride/bromide ratio is less than 300.

Sampling results

Of the 129 well samples analyzed for chloride, 39 were above 5 ppm for making source determinations. However, a source determination was not made for 1 of the samples because the bromide reporting limit was too high. Of the remaining 38 samples, 16 had a natural source and 22 an anthropogenic source.

- The 16 samples with naturally sourced chloride were from wells mostly in the western third of the county. All but 4 are from wells greater than 100 feet deep.
- The 22 samples with anthropogenic chloride were from wells in or near Detroit Lakes with additional sites to the northeast and east. The majority (16) were from wells less than or equal to 100 feet deep.
- None of the samples equaled or exceeded the SMCL for chloride.

Nitrate-nitrogen (nitrate)

MCL and HRL 10 ppm

Nitrate can occur naturally but concentrations greater than 1 ppm can indicate anthropogenic impacts from fertilizer or animal and human waste (MDH, 1998; Wilson, 2012). Nitrate concentrations may 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.

Nitrate concentrations are classified as follows.

- Anthropogenic if greater than 1 ppm.
- Natural if less or equal to 1 ppm.

Sampling results

Of the 130 samples analyzed for nitrate, 6 had concentrations suggesting an anthropogenic source.

- Of the 5 wells in shallow buried sand aquifers (54–70 feet), 4 are within 3 miles of the city of Detroit Lakes and 1 is in the Pineland Sands region.
- The 1 well in a deep buried sand aquifer (245 feet) was approximately 5 miles south of the city of Wolf Lake. The nitrate concentration was barely anthropogenic (1.01 ppm). An anthropogenic source is unlikely since the well was so deep, the water was premodern tritium age, and there was no dissolved oxygen in the water.
- None of the measured concentrations equaled or exceeded the MCL for nitrate.

The limited number of samples with anthropogenic nitrate concentrations were largely due to the objectives of atlas sampling which do not target nitrates in groundwater. However, a study published by the Department of Agriculture (MDA, 2019) targeted nitrates in groundwater. Three townships in the Pineland Sands were selected due to the presence of intensive row crop agriculture and "vulnerable geology." The median depth of sampled wells was 65 feet. The results found that 34 of 183 wells sampled were anthropogenic (defined by MDA as 3 ppm or greater). Nitrates equaling or exceeding the MCL in each of the three townships ranged from 6.6–12.5 percent of the wells sampled.

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, 2019). Current science cannot predict which wells will have high arsenic concentrations, therefore water from all newly constructed drinking-water wells is tested 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).

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).

Sampling results

Of the 152 samples analyzed, arsenic was detected in 141, with 57 exceeding the MCL. Concentrations were as high as 65 ppb. Approximately 75 percent of the exceedances were in the western third of the county in tills sourced from the northwest (Part A, Plate 3, Figure 2). This is consistent with a study on arsenic distribution which concluded that the conditions for mobilizing arsenic are favorable in the fine-grained, comparatively rich organic sediment that was sourced from northwest provenance late Wisconsin-aged drift (Erickson and Barnes, 2005a).

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, 2021). In addition to health effects, concentrations above the SMCL can cause negative secondary effects, such as poor taste, odor, and water discoloration (stained laundry and plumbing fixtures).

Statewide, manganese concentrations were greater than the HBV in drinking-water wells for 57 percent of water-table aquifers and 63 percent of buried sand aquifers sampled (MDH, 2012). 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).

Sampling results

Of the 118 samples analyzed, manganese was detected in 116, with 98 greater than or equal to the SMCL, and 74 of those exceeding both the HBV and the SMCL. Concentrations were as high as 1,980 ppb. No discernible spatial patterns or correlations with specific aquifers were found.

Boron

RAA 500 ppb

Boron is a naturally occurring element that has been linked to negative health effects. The MDH developed risk the RAA for boron in drinking water at 500 ppb to protect formula-fed infants (MDH, 2017).

Sampling results

Of the 90 samples analyzed, boron was detected in all, with 2 greater than the RAA. The highest concentrations were from wells in the western third of the county.

Iron

SMCL 0.3 ppm

Iron is a common naturally-occurring element in Minnesota groundwater. At levels above the SMCL iron may give water a metallic taste; cause yellow, red, or brown stains on dishes, laundry, and plumbing fixtures; and can clog wells, pumps, sprinklers, dishwashers, and other devices.

Sampling results

Of the 119 samples analyzed iron was detected in 113, with 102 equaling or exceeding the SMCL. The largest concentration was 11.9 ppm. No discernible spatial patterns or correlations with specific aquifers were found.

Sulfate

SMCL 250 ppm

Sulfate is largely naturally occurring and is produced from the oxidation of sulfide minerals and the dissolution of gypsum. Minor amounts are introduced from the burning of fossil fuels (Crawford and Lee, 2015). High concentrations in groundwater can negatively affect taste and can act as a laxative.

Sampling results

Of the 122 samples analyzed for sulfate, 3 were greater than the SMCL and were as high as 881 ppm. Only 15 samples had greater than 50 ppm sulfate, all in the western third of the county.

Piper diagram

The Piper diagram (Figure 18) graphically represents the chemistry of each 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
- Water chemistry changes along a groundwater flow path due to cation exchange, dissolution of minerals, and mixing of different water types

The Piper diagram has three components: a cation triangle, an anion triangle, and a central diamond. The cations and anions are shown in the left and right triangles, respectively. The center diamond shows a composite of cations and anions.

The most common water type in Becker County is calcium-magnesium bicarbonate. Concentrations of other ions including sodium, sulfate, chloride, and nitrate are proportionally higher for some samples causing them to plot outside of the prevailing range for cations and anions.

Cation ternary diagram

There appears to be a relationship between percent sodium plus potassium and groundwater residence time. The red line in the cation triangle is where sodium plus potassium are 10 percent of the total milliequivalents per liter of the major cations. Most samples below the threshold to the left of the line have modern, mixed, and premodern tritium age. Most samples above the threshold to the right of the line have premodern tritium age. This relationship suggests that calcium and magnesium cation exchange with sodium takes decades or longer and over longer flow path distances.

One possible explanation is that sodium adsorbed on the clay size fraction of till likely exchanges with dissolved calcium and magnesium ions as the water slowly moves through these sediments. Most samples above the threshold occur in the western third of the county where ice advances were often from northwesterly-sourced provenances: the Riding Mountain and mixed Riding Mountain/Winnipeg. These tills have a higher proportion of clay for sodium to adsorb onto than tills in central and eastern Becker County that originated from more easterly provenances. One exception is a 275-foot well in the southeast which has the greatest degree of cation exchange. This well is screened entirely in till for a length of 120 feet, therefore supporting that the fine-grained material is a likely source of adsorbed sodium.

The milliequivalents of calcium in groundwater samples is proportionally higher than magnesium in all but four groundwater samples (labeled as 1 and 2 in Figure 18). These likely receive a significant portion of their recharge from lake water. One sample is from a deep well west of Big Cormorant Lake (1). Three shallow well samples from the western shores of Cotton Lake plot near a lake-water sample collected from Cotton Lake (2).

Anion ternary diagram

Most of the samples plot in the lower left corner where bicarbonate is the dominant anion. The 13 samples outlined in yellow have either anthropogenic nitrate or anthropogenic chloride, or both. Several samples plot in a trend toward increasing proportions of chloride plus nitrate, and all are mixed tritium age. One exception is a premodern tritium-age sample from a 275-foot well that had 1.01 ppm nitrate. The nitrate is likely from a natural source or is the result of sampling error or a well construction problem.

Also plotted are 7 samples with increasing proportions of sulfate. These occur in the western third of the county where some glacial deposits are composed of sediment that originated from the northwest Riding Mountain provenance, where Cretaceous sediment is known to have sources of sulfur from pyrite and gypsum.

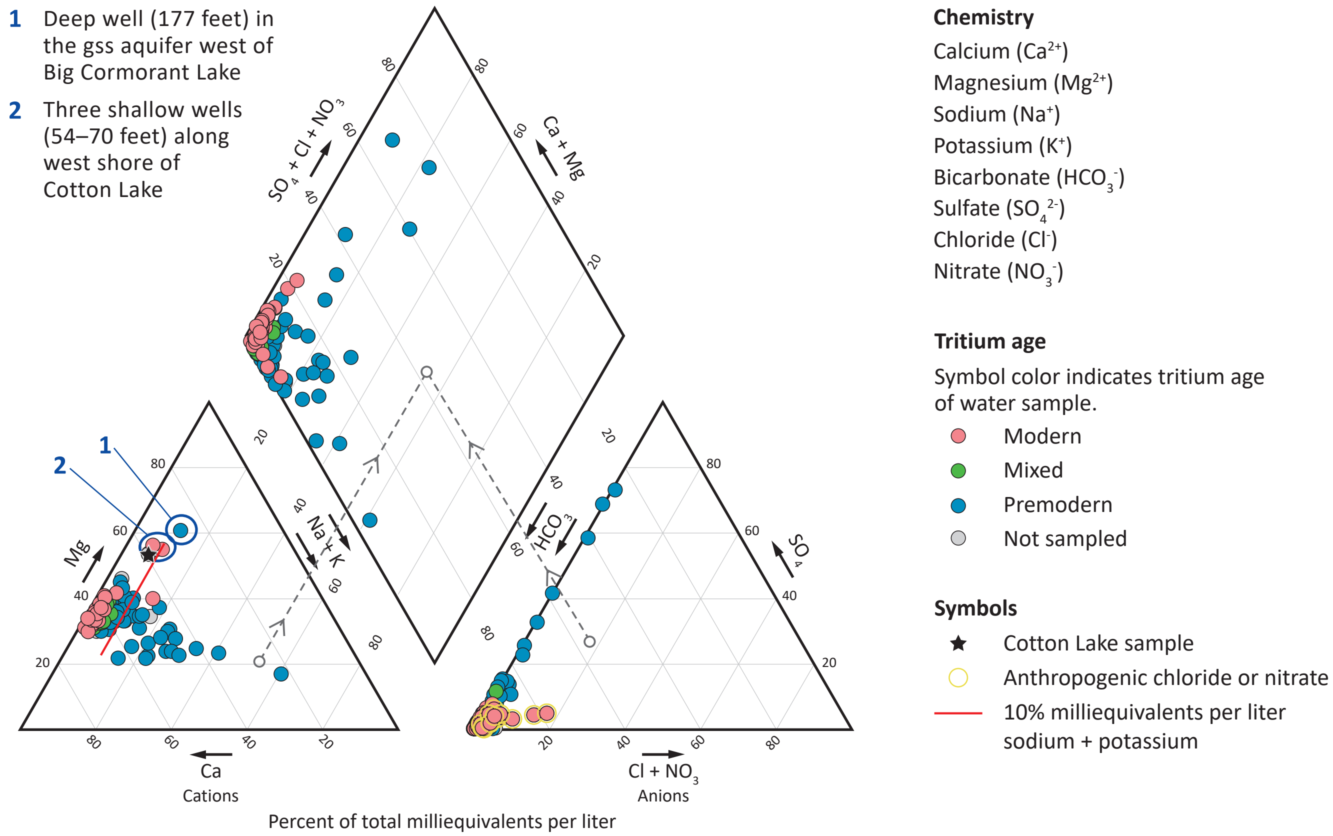


Figure 18. Piper diagram of groundwater samples from the DNR and MPCA

The diagram compares the relative proportions of major cations and anions in groundwater from all the sampled wells.

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

The **cation triangle** shows several samples plotting along a trend toward the sodium plus potassium axis. This trend reflects the exchange of sodium (in sediments) with calcium and magnesium (in water). The largely premodern tritium age supports widely disseminated sodium and long groundwater flow paths.

Lake recharge to groundwater is supported by magnesium as the dominant cation found only in four sampled wells (labeled no. 1 and no. 2) and a sample collected from Cotton Lake, as well as the evaporative stable isotope signatures in the 4 well samples.

On the **anion triangle**, anthropogenically sourced chloride and nitrate (highlighted with a yellow circle) are associated with modern and mixed tritium-age bicarbonate waters with a few samples trending toward the chloride plus nitrate ($Cl+NO_3$) corner of the triangle.

Samples plotting along a trend of increasing proportions of sulfate are primarily premodern tritium age reflecting longer flow paths and longer groundwater residence time. These samples are from the west and northwestern portions of the county where northwest-sourced tills may contain iron sulfides and gypsum sources of sulfate.

Pollution sensitivity

Pollution sensitivity is defined for this report as the time for a contaminant to travel from the land surface to a specific target: water table, buried aquifer, or the bedrock surface. There are two pollution sensitivity models: 1) the near-surface materials model estimates travel time to the water table, and 2) the buried sand aquifers and bedrock surface model estimates travel time to their respective surfaces. Both models estimate travel time, but each uses a different method.

Both methods include the following general assumptions:

- Flow paths are vertical and downward from the land surface through the soil and underlying sediment to the water table, a buried aquifer, or the bedrock surface.
- A contaminant travels at the same rate as water.
- A dissolved contaminant moves with water from the surface and is not chemically or physically altered over time.

Areas of high sensitivity can be areas of high recharge. Land cover also affects potential recharge (Smith and Westenbroek, 2015) but is not included in the models.

Near-surface materials model

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 the land surface. The first 3 feet is assumed to be soil; the next 7 feet is assumed to be surficial geologic material. If there are no soil data, the transmission rate is based on 10 feet of the surficial geologic unit.

The transmission rate varies depending on 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 (Table 1) (Natural Resources Conservation Service, 2020) and the surficial geologic matrix texture (Part A, Plate 3). Attributes of both are used to estimate the time of travel.

Travel time varies from hours to approximately a year; ratings are shown on Figure 19. For further details, see *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

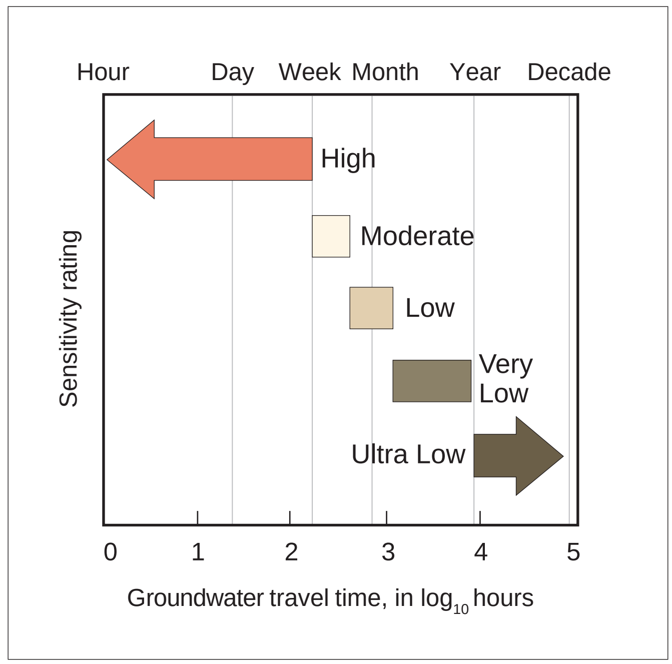


Figure 19. Pollution sensitivity rating of near-surface materials: travel time and ratings

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	Qs
		sand, silty sand	0.71	Qb
B, B/D	0.50	silt, loamy sand	0.50	not mapped in county
		sandy loam, peat	0.28	Qhg, Qoc, Qhs, Qhc
C, C/D	0.075	silt loam, loam	0.075	Qa, Qns, Qos
		sandy clay loam	0.035	not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	Qug, Qil, Ql, Qlg, Qls, Qlw, Qus

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

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

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

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

Group C: water transmission is somewhat restricted.

Group D: water movement is restricted or very restricted.

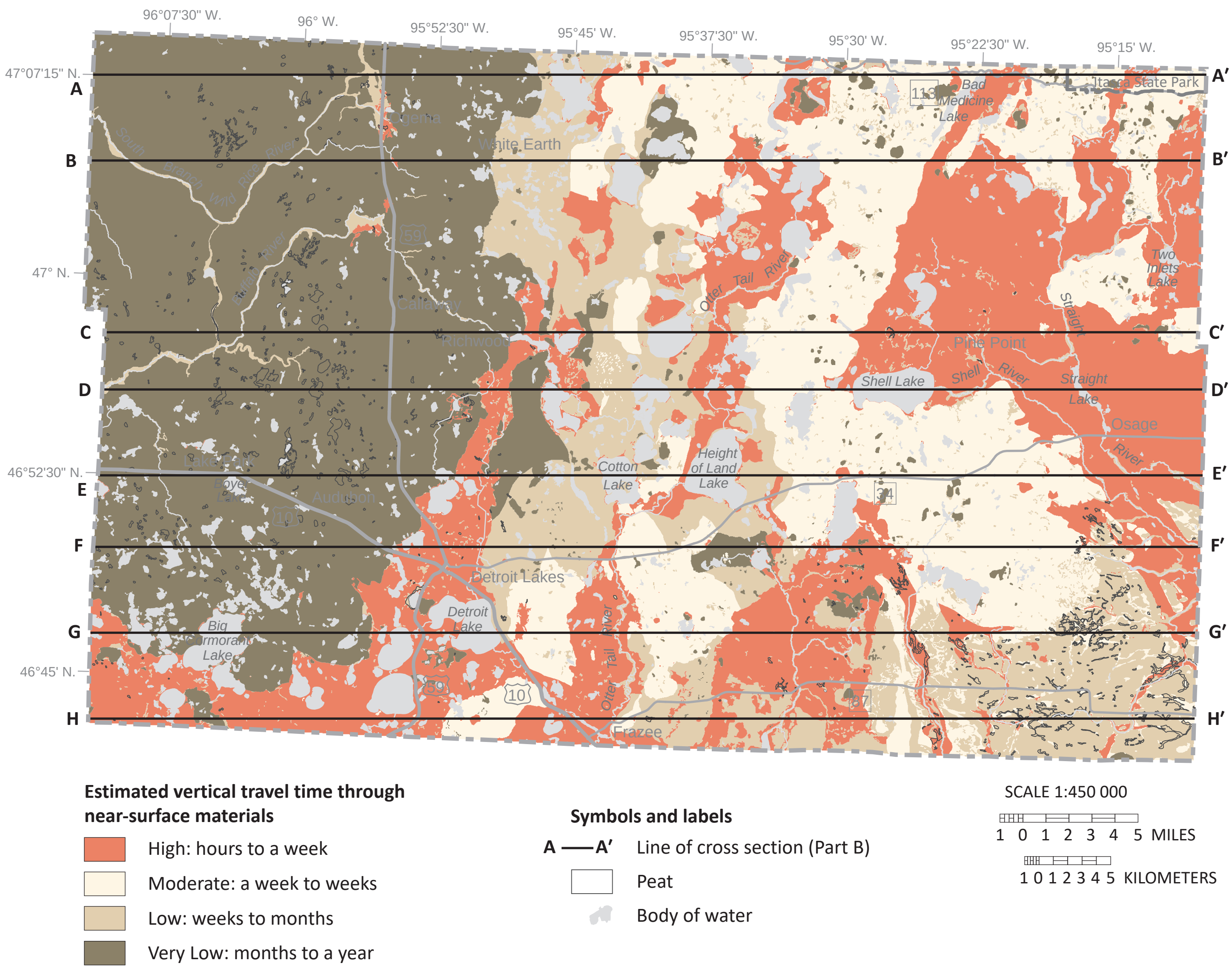


Figure 20. Pollution sensitivity of near-surface materials

Very low sensitivity is associated with the clay loam and silty clay loam deposits of the Red Lake Falls Formation including postglacial lake sediment. These cover nearly the entire western third of the county. Additional lake sediment is scattered throughout the remainder.

Low sensitivity is associated with loam-textured sediment of the Otter Tail River Formation running north-south in the central part of the county, and sandy loam sediment of the Hewitt Formation in the southeast. Scattered deposits also include alluvial stream deposits and other small areas where the soils and geologic textures dictate a lower sensitivity. Together, very low and low sensitivity encompass approximately 50 percent of the county.

Moderate sensitivity is mostly associated with sandy-loam textured sediment of the Otter Tail River and Hewitt formations found primarily in the central and eastern parts of the county.

High sensitivity is associated with glacial outwash sand and gravel covering large portions of the eastern two-thirds of the county, around Detroit Lakes, and in the far southwest. The most laterally extensive and thickest of these deposits are the Pineland Sands in the eastern part of the county where irrigation is used extensively to support agricultural practices.

Buried sand aquifer and bedrock surface model

Method

The pollution sensitivity of buried sand aquifers and the bedrock surface is an estimate of the time it takes for water to travel from the land surface to the buried aquifer or bedrock surface (travel time). This was defined by the Geologic Sensitivity Workgroup (1991).

The model applies to unconsolidated geologic sediment and assumes that all sediment above and between buried sand aquifers and down to the bedrock surface is an aquitard: fine grained with low hydraulic conductivity.

The estimate of travel time is assumed to be proportional to the cumulative fine-grained sediment (CFGS) thickness overlying a buried sand aquifer or the bedrock surface (Figures 21 and 22). The thicker the fine-grained sediment, the longer it takes for water to move through it. The model does not consider differences in sediment texture or permeability of aquitard materials. For more details, see *Procedure for determining buried aquifer and bedrock surface pollution sensitivity based on cumulative fine-grained sediment thickness* (DNR, 2016c).

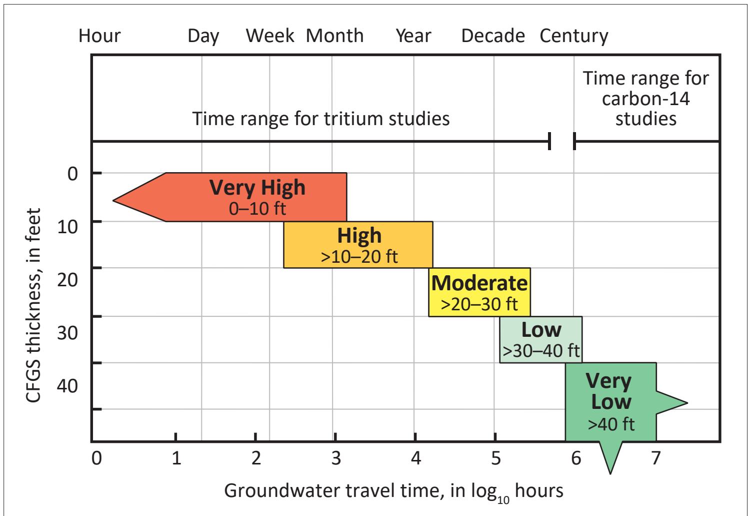


Figure 21. Pollution sensitivity rating for the buried sand aquifers and the bedrock surface

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

This model has five classes of pollution sensitivity based on overlapping time of travel ranges (Very High, High, Moderate, Low, and Very Low).

Areas with ratings of high or very high have relatively short estimated travel times of less than a few years.

Areas rated low or very low have estimated travel times of decades or longer. Travel time varies from hours to thousands of years.

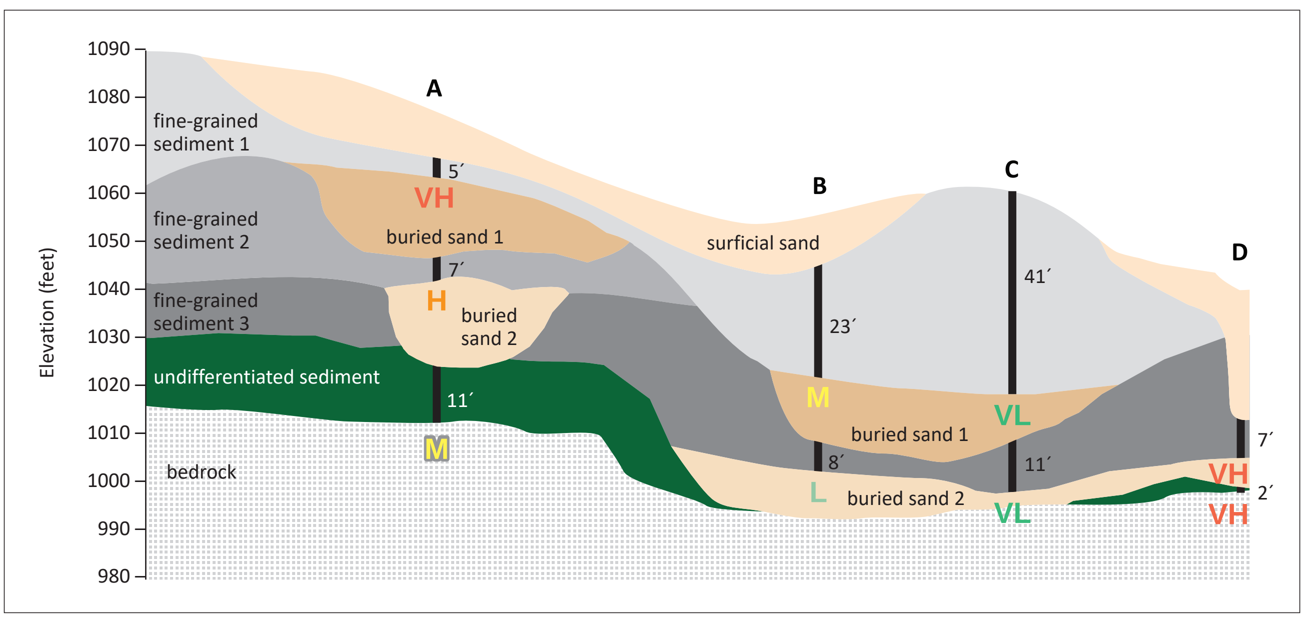


Figure 22. Cross section illustration of the pollution sensitivity model

The pollution sensitivity model assigns sensitivity ratings to buried sands and the bedrock surface based on the cumulative thickness of overlying fine-grained sediment. Sites A–D indicate aquitard thicknesses from the land surface to the bedrock surface. For example, site A pollution sensitivity ratings are as follows:

Site A: 5 feet (buried sand 1: Very High) + 7 feet = 12 feet (buried sand 2: High) + 11 feet = 23 feet (bedrock surface: Moderate)

The pollution sensitivity of buried sands and the bedrock surface varies with overlying cumulative aquitard thickness.

Groundwater conditions

The modeled pollution sensitivity results are compared to groundwater residence times from tritium and carbon-14 samples and to the presence of anthropogenic chemical indicators (nitrate and chloride). In general aquifers with *higher pollution sensitivity* are expected to have *mixed or modern* tritium-age water, and anthropogenically sourced chemicals if a source is present.

Aquifers with *very low pollution sensitivity* ratings are generally expected to have *premodern* tritium-age water. Where this is not the case, the following groundwater conditions provide alternative explanations for how mixed or modern tritium-age water has traveled to an aquifer.

Ⓛ **Lateral flow:** aquifer may have received lateral recharge from upgradient areas of higher pollution sensitivity.

Ⓟ **Pumping**: high-volume pumping may have enhanced recharge rates and changed local groundwater flow directions.

Ⓤ **Unknown**: neither the pollution sensitivity model nor groundwater conditions explained the presence of mixed or modern tritium-age water.

Where aquifers with *higher sensitivity* have *premodern* tritium-age water, the following condition may be present.

Ⓓ **Discharge**: older water upwelled from deep aquifers and discharged to shallow aquifers.

Groundwater flow directions derived from potentiometric surfaces are included to aid in identifying areas where lateral groundwater flow may be introducing water from higher sensitivity areas to downgradient areas of low or very low sensitivity. Equipotential contours are used to aid in identifying areas where upwelling older groundwater interacts with aquifers near the surface.

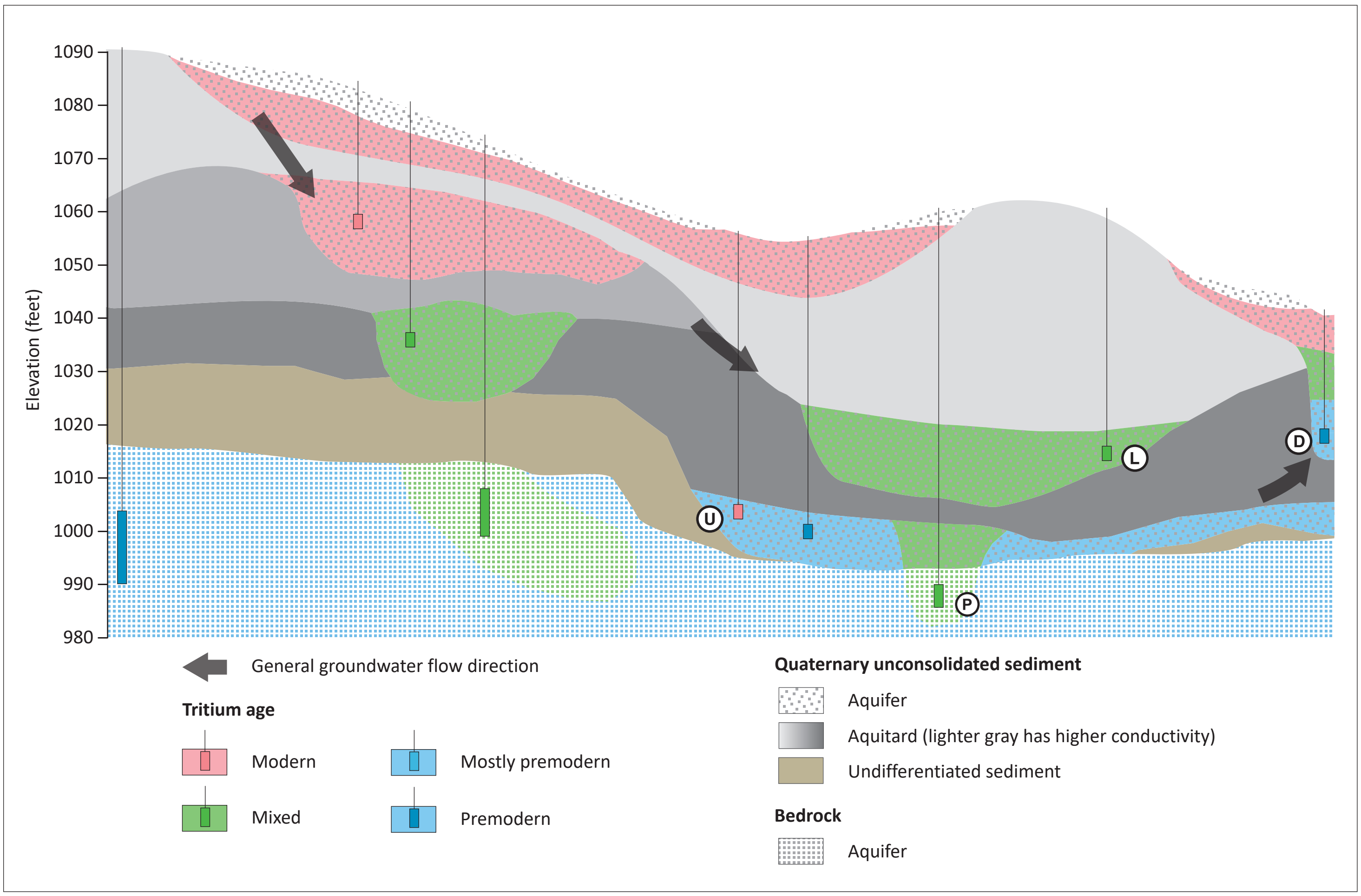


Figure 23. Cross section illustration of groundwater conditions

Buried sand and bedrock aquifers are shaded to indicate modern, mixed, or premodern tritium-age water. Wells sampled for tritium are shown for comparison. Groundwater condition labels are present where the tritium age of a water sample contradicts the pollution sensitivity rating for the aquifer where the sample was taken. This figure was developed from Figure 22.

Results

The following section provides a general characterization of the buried aquifers in stratigraphic order (Figure 2) and includes aquifer depth and spatial distribution, pollution sensitivity, and the approximate percentage of wells completed in each aquifer.

The modeled pollution sensitivity results are compared to groundwater residence times from tritium and carbon-14 samples, and to the presence of anthropogenic chemical indicators (nitrate and chloride).

Buried sand aquifers (Figures 24–35)

See results with figures on the following pages.

Bedrock surface (no figure)

The bedrock surface ranges from 190 feet to over 1,100 feet below the land surface. Bedrock generally consists of crystalline bedrock overlain locally by sandstone and mudstone.

No water supply wells are completed in bedrock because sufficient water is generally available in the overlying Quaternary sediment. Therefore, no pollution sensitivity map was generated for the bedrock surface.

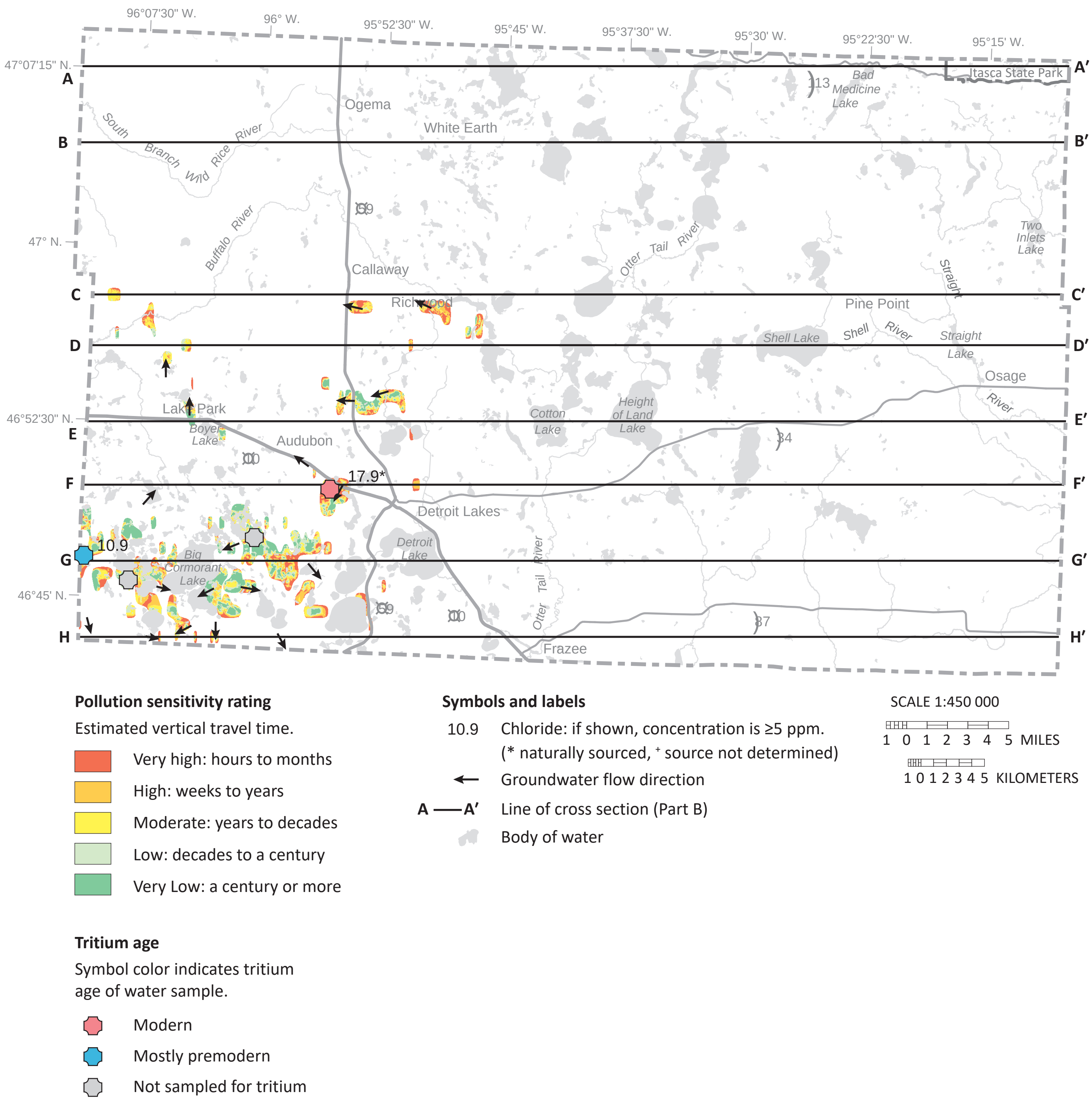


Figure 24. Pollution sensitivity of the rls0 and rls aquifers and groundwater flow directions

These buried sand aquifers are limited to the southwestern portion of the county. Depths range from approximately 0–76 feet, with a mean of 32 feet. They are used by approximately 5 percent of the wells in the county. The pollution sensitivity ranged from very low to very high.

Of the 2 samples analyzed for tritium, 1 was modern and 1 was premodern tritium age. Of the 2 samples analyzed for chloride both were greater than 5 ppm, 1 was from a natural source, and the other was anthropogenic. Of the 2 samples analyzed for nitrate, both were naturally sourced.

The tritium results were generally consistent with the pollution sensitivity ratings. The sample with modern tritium was in an area of higher sensitivity. The premodern sample was collected from a well in an area of low sensitivity.

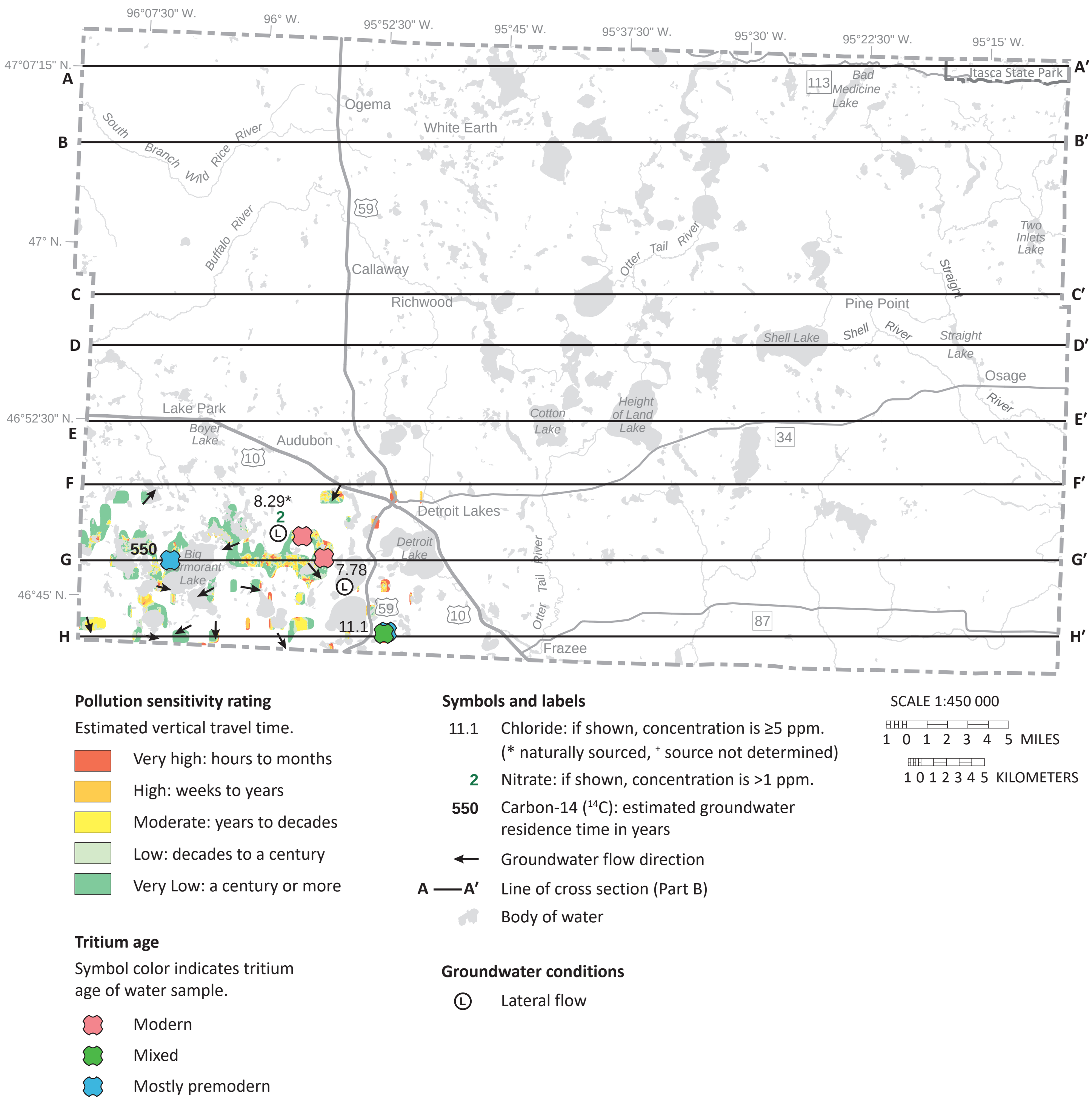


Figure 25. Pollution sensitivity of the rls2 aquifer and groundwater flow directions

This buried aquifer is limited to the southwestern portion of the county, south and west of Detroit Lakes. Depth ranges from approximately 0–123 feet, with a mean of 61 feet. It is used by approximately 5 percent of the wells in the county. The pollution sensitivity ranged from very low to very high.

Of the 5 samples analyzed for tritium, 2 were modern, 1 was mixed, and 2 were premodern tritium age. Of the 5 samples analyzed for chloride, 3 were greater than 5 ppm, and all 3 were from an anthropogenic source. Of the 5 samples analyzed for nitrate, 1 was anthropogenic (2 ppm).

The 2 modern tritium-age samples less than 2 miles west of Detroit Lakes were from aquifers with very low or low sensitivity and were likely laterally recharged from adjacent areas of higher sensitivity. Just over 2.5 miles southwest of Detroit Lakes was a buried sand aquifer with high and very high sensitivity, 1 mixed and 1 premodern tritium-age water sample, and anthropogenic chloride. The absence of tritium in portions of this shallow aquifer was likely from groundwater flowing mostly horizontal with possible upward flow, bringing in older water. The premodern tritium-age sample had a carbon-14 residence time of 550 years.

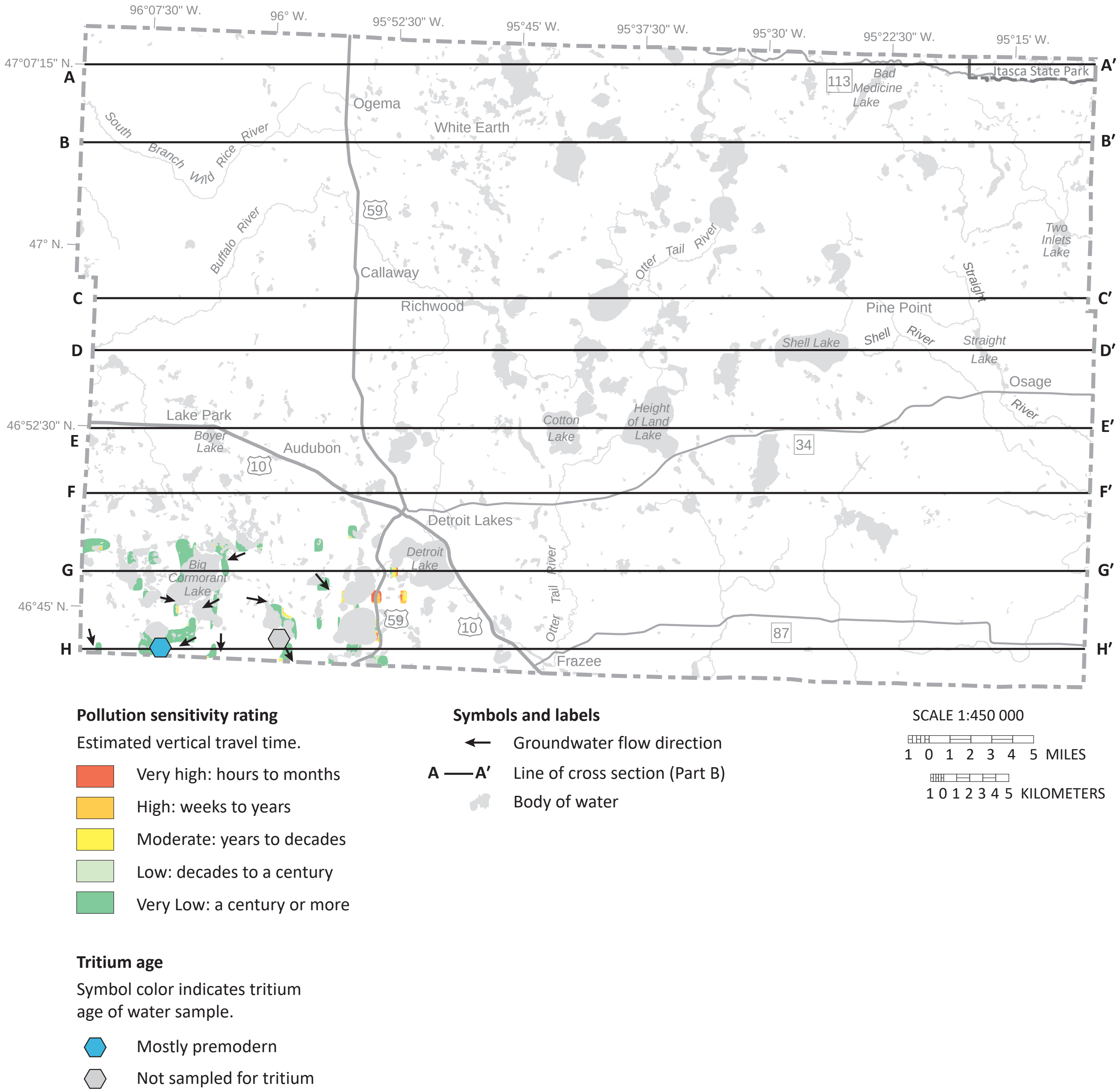


Figure 26. Pollution sensitivity of the rls3 aquifer and groundwater flow directions

This buried aquifer is limited to the southwestern portion of the county, south and west of Detroit Lakes. Depths range from approximately 27–161 feet, with a mean of 94 feet. It is used by approximately 2 percent of the wells in the county. The pollution sensitivity ranged from very low to very high.

The 1 sample analyzed for tritium was premodern tritium age, chloride was less than 5 ppm, and nitrate was below detection. The sample was in an area of very low sensitivity and the premodern tritium age was consistent with the pollution sensitivity.

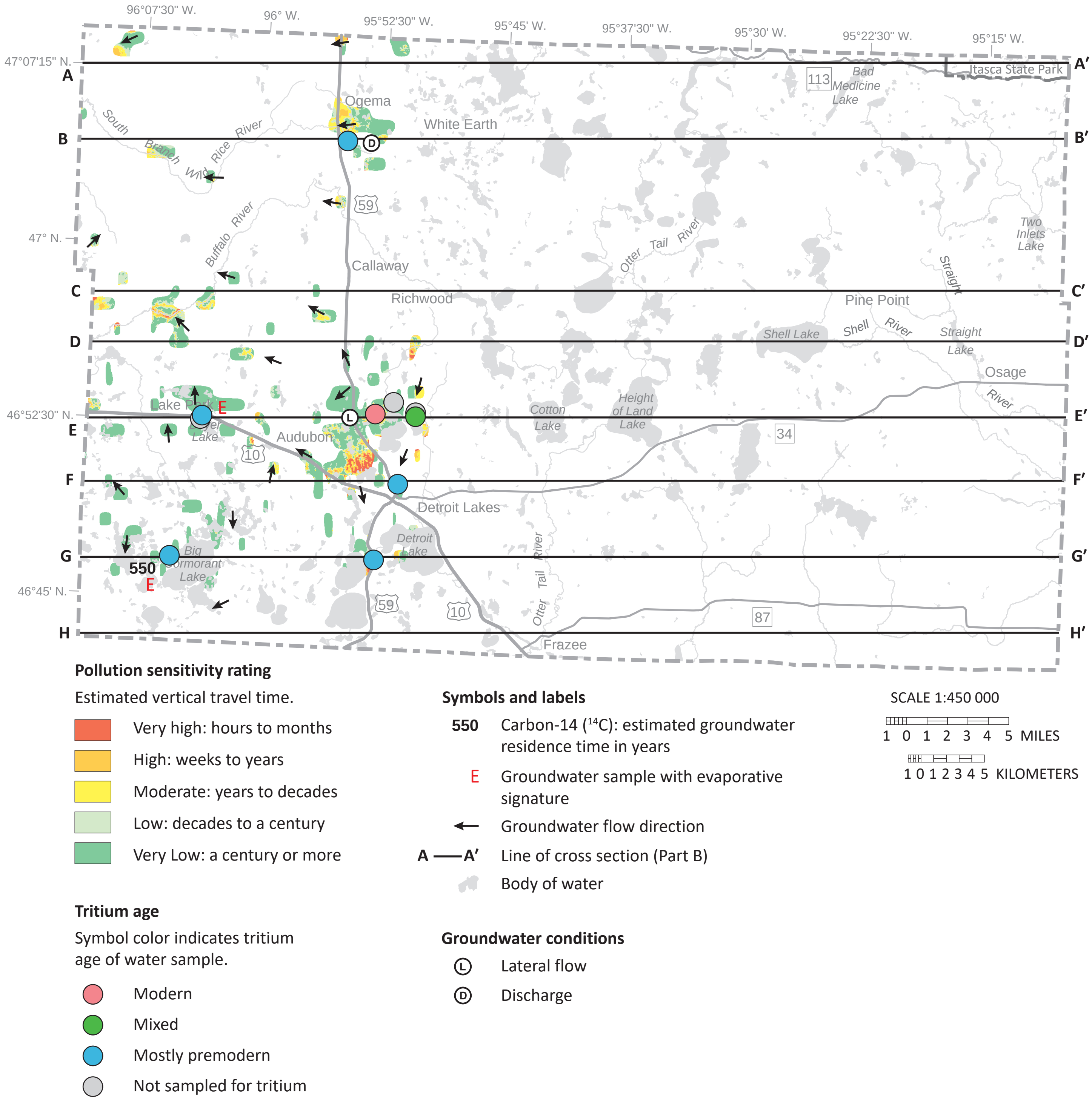


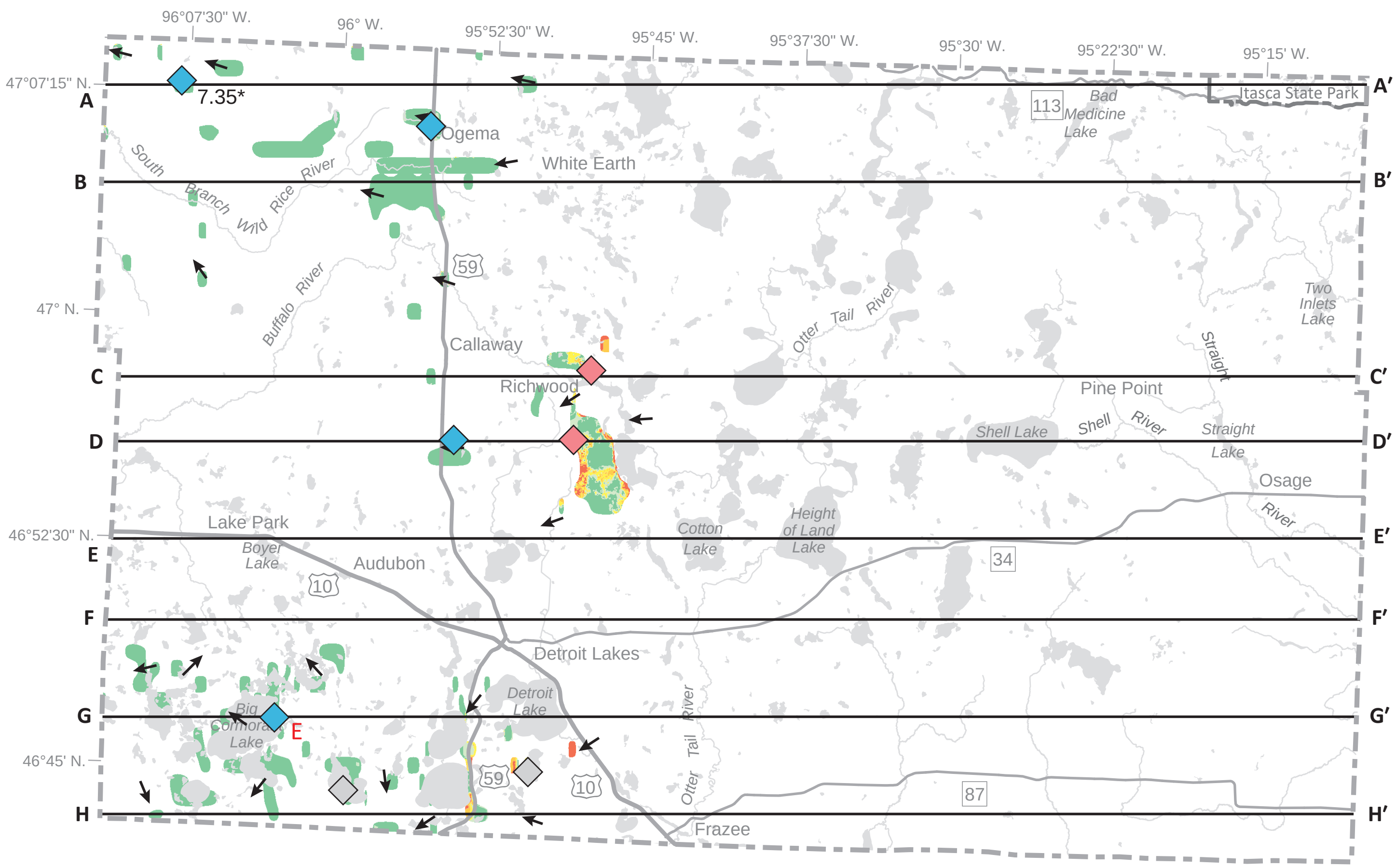
Figure 27. Pollution sensitivity of the gss0, gss, and gss2 aquifers and groundwater flow directions

These buried sand aquifers are limited to the western third of the county. Depths range from approximately 0–95 (gss0), 0–138 (gss), and 29–53 (gss2) feet, with a mean of 65 feet. They are used by approximately 5 percent of the wells in the county. Pollution sensitivity ranged from very low to very high.

Of the 7 samples analyzed for tritium, 1 was modern, 1 was mixed, and 5 were premodern tritium age. Of the 7 samples analyzed for chloride and nitrate, all chloride samples were below 5 ppm, and nitrate was naturally sourced.

The mixed and modern samples were approximately 2 miles north of Detroit Lakes along cross section line E–E′. The mixed sample was in a high sensitivity area. The modern sample was in a very low sensitivity area and likely received lateral recharge from a nearby higher sensitivity area.

Of the 5 premodern samples, 4 were in areas of very low sensitivity from wells over 100 feet deep. The other was from a 25-foot well south of Ogema in an area of high sensitivity. The absence of tritium was likely due to groundwater upwelling at the base of the adjacent upland. One of the premodern samples on the west end of cross section line G–G′ was in an area of very low sensitivity and had a carbon-14 residence time of 550 years.



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
- Mostly premodern
- Not sampled for tritium

Symbols and labels

- 7.35* Chloride: if shown, concentration is ≥5 ppm. (* naturally sourced, + source not determined)
- E Groundwater sample with evaporative signature
- ← Groundwater flow direction
- A —A′ Line of cross section (Part B)
- Body of water

SCALE 1:450 000

1 0 1 2 3 4 5 MILES

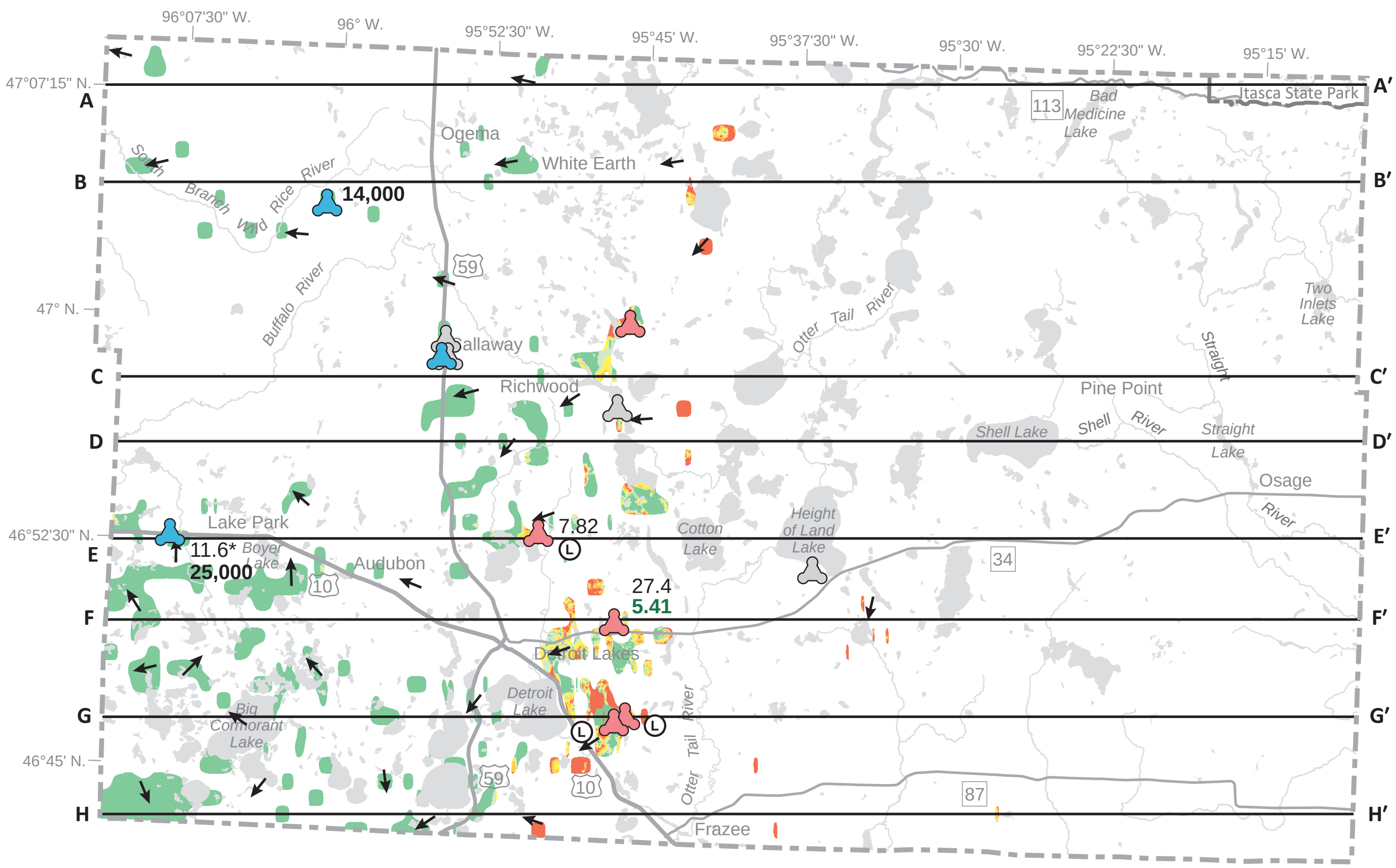
1 0 1 2 3 4 5 KILOMETERS

Figure 28. Pollution sensitivity of the nhsa and nhs aquifers and groundwater flow directions

These buried sand aquifers are limited to the western portion of the county. Depths range from approximately 25–131 (nhsa), and 0–197 (nhs) feet, with a mean of 95 feet. They are used by approximately 3 percent of the wells in the county. Pollution sensitivity includes the entire range of very low to very high, with the higher sensitivities limited to the eastern extent.

Of the 6 samples analyzed for tritium, 2 had modern and 4 had premodern tritium age. Of the 5 samples analyzed for chloride, 1 was above 5 ppm and from a natural source. Of the 5 samples analyzed for nitrate, all were naturally sourced.

The samples that had modern tritium age are approximately 5 miles east and southeast of Callaway; 1 along cross section line C–C′ and the other along cross section line D–D′. Both were in areas of higher sensitivity. The premodern tritium-age samples were in areas of very low sensitivity.



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
- Mostly premodern
- Not sampled for tritium

Symbols and labels

27.4	Chloride: if shown, concentration is ≥5 ppm. (* naturally sourced, + source not determined)
5.41	Nitrate: if shown, concentration is >1 ppm.
25,000	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

Ⓛ Lateral flow

SCALE 1:450 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 KILOMETERS

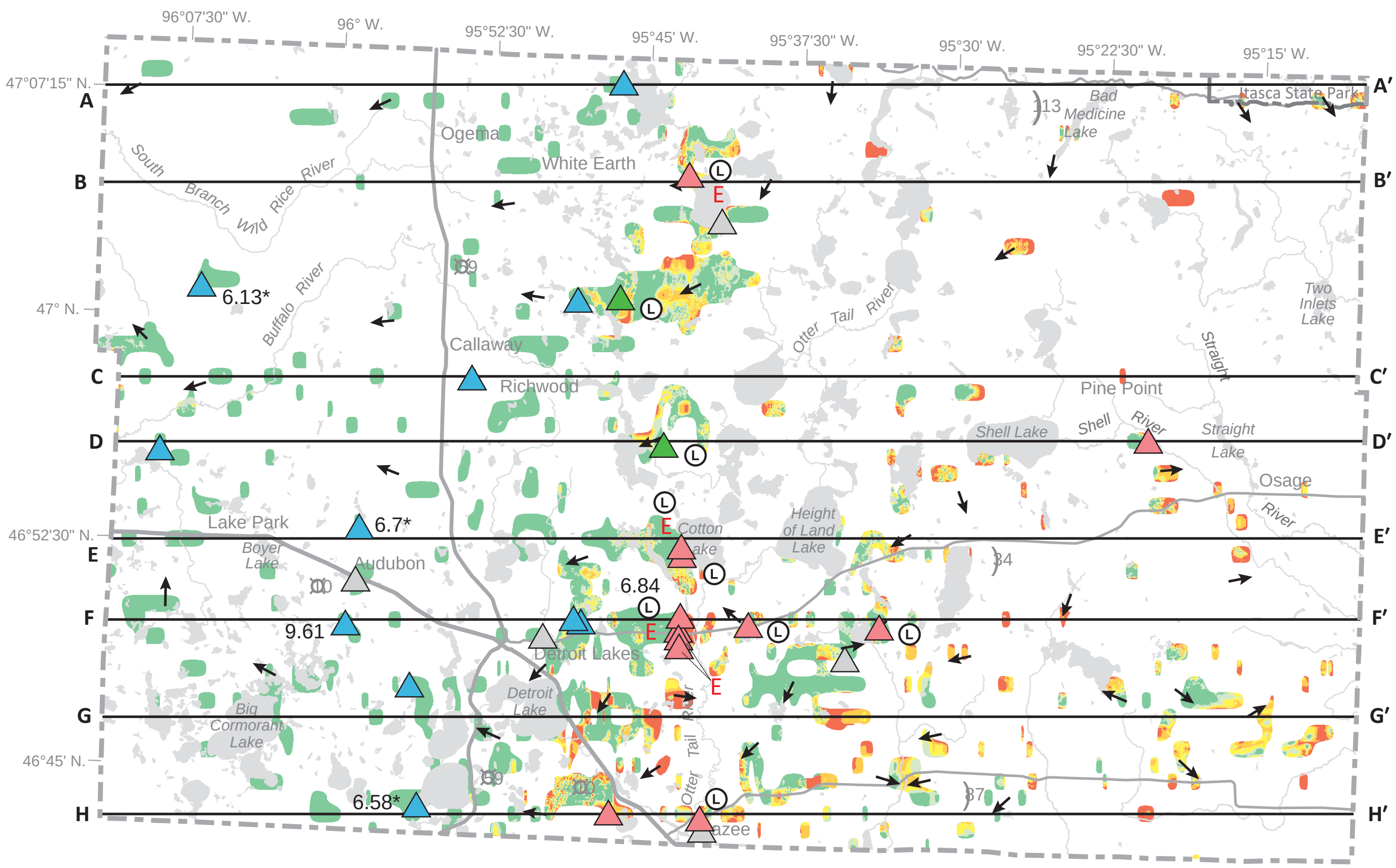
Figure 29. Pollution sensitivity of the ons0 and ons aquifers and groundwater flow directions

These buried sand aquifers are mostly limited to the western portion of the county with a few deposits extending farther to the east. Depths range from approximately 0–29 (ons0), and 0–260 (ons) feet, with a mean of 114 feet. They are used by approximately 6 percent of the wells in the county. Very low sensitivity dominates the western aquifer extent with higher sensitivities farther to the east.

Of the 8 samples analyzed for tritium, 5 were modern and 3 were premodern tritium age. Of the 9 samples analyzed for chloride, 3 were above 5 ppm, 2 were from anthropogenic sources, and 1 was from a natural source. Of the 9 samples analyzed for nitrate, 1 was anthropogenic.

Of the samples with modern tritium age, 2 were from areas of higher sensitivity, 3 were from areas of very low and low sensitivity, and all had a portion of the aquifer mapped as higher sensitivity. Recharge at the very low and low sensitivity locations was likely lateral flow from adjacent higher sensitivity areas.

The 3 premodern samples were all in very low sensitivity areas; 2 had carbon-14 residence times of 14,000 and 25,000 years.



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

- 6.84 Chloride: if shown, concentration is ≥5 ppm. (* naturally sourced, + source not determined)
- E Groundwater sample with evaporative signature
- ← Groundwater flow direction
- A —— A' Line of cross section (Part B)
- Body of water

SCALE 1:450 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 KILOMETERS

Tritium age

Symbol color indicates tritium age of water sample.

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

Groundwater conditions

- (L) Lateral flow

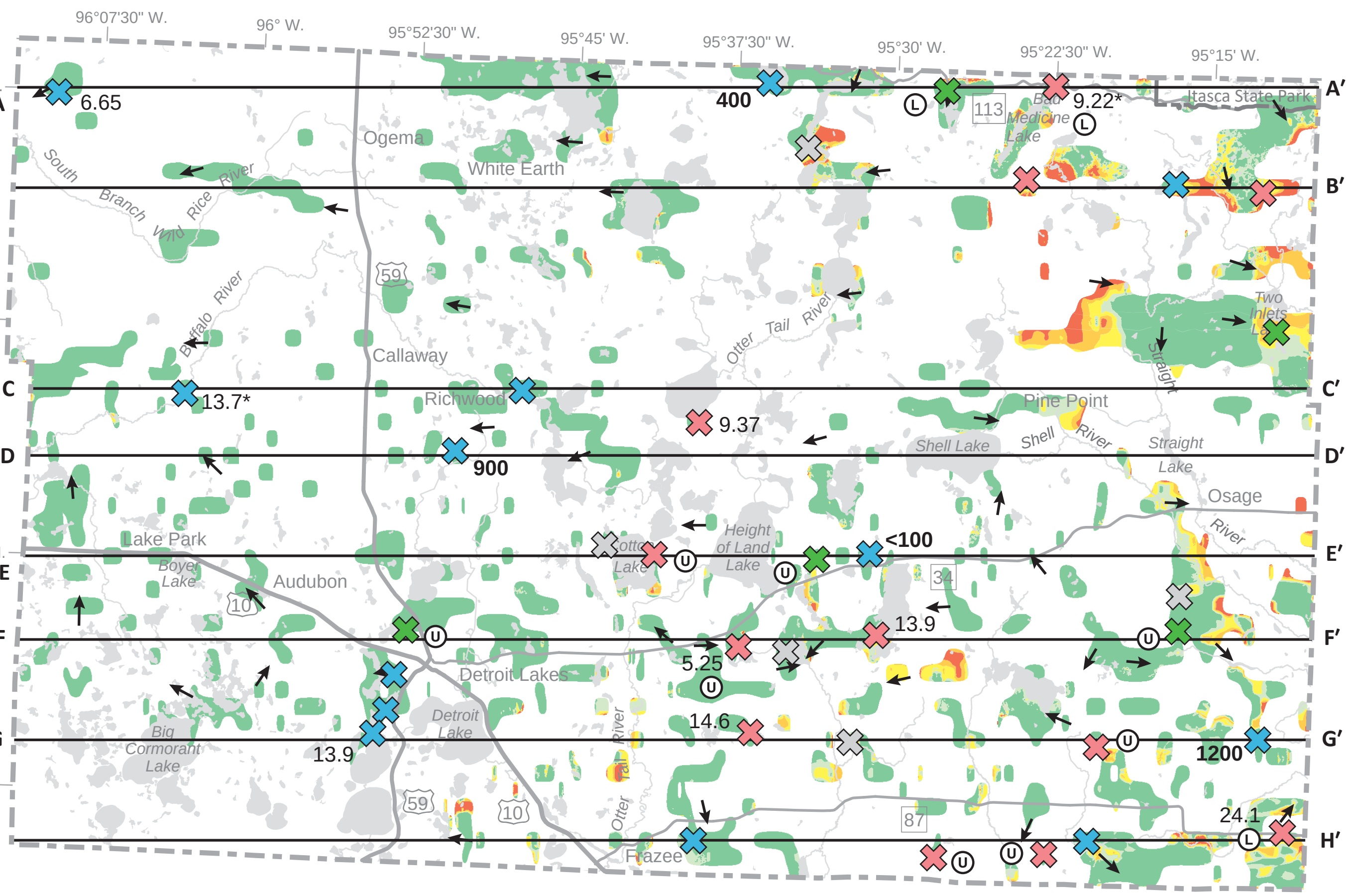
Figure 30. Pollution sensitivity of the hs0 and hs aquifers and groundwater flow directions

These buried sand aquifers are widespread discontinuous deposits throughout the county. Depths range from approximately 0–80 (hs0), and 0–191 (hs) feet, with a mean of 75 feet. They are used by approximately 15 percent of the wells in the county. Very low sensitivity dominates the western portion of the aquifer with higher sensitivities farther east.

Of the 25 samples analyzed for tritium, 12 were modern, 2 were mixed, and 11 were premodern tritium age. Of the 22 samples analyzed for chloride, 5 were above 5 ppm, 2 had anthropogenic sources, and 3 had natural sources. Of the 23 samples analyzed for nitrate, none were anthropogenic.

The samples with detectable tritium and the sample with anthropogenic chloride were in the higher sensitivity aquifers in the eastern half of the county. Their mean well depth was approximately 82 feet.

The premodern samples were limited to the lower sensitivity aquifers in the western portion, and their mean well depth was approximately 130 feet. For wells with detectable tritium in very low sensitivity areas, the likely source of recharge was lateral flow from upgradient higher sensitivity portions of the aquifer.



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

- 14.6 — Chloride: if shown, concentration is ≥5 ppm. (* naturally sourced, ⁺ source not determined)
- **900** — Carbon-14 (^{14}C): estimated groundwater residence time in years
- Groundwater flow direction
- A —— A′ — Line of cross section (Part B)
- Body of water

SCALE 1:450 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 KILOMETERS

Tritium age

Symbol color indicates tritium age of water sample.

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

Groundwater conditions

- Ⓛ Lateral flow
- Ⓤ Unknown

Figure 31. Pollution sensitivity of the hs2a, hs2, hs2b, and hs3 aquifers and groundwater flow directions

These buried sand aquifers are widespread discontinuous deposits throughout the county. Depths range from approximately 12–158 (hs2a), 0–207 (hs2), 102–204 (hs2b), and 86–261 (hs3) feet. The hs2 aquifer represents most of this group. Mean depth is approximately 100 feet. These aquifers are used by approximately 20 percent of the wells in the county. Very low sensitivity dominates the western extent with higher sensitivities farther to the east.

Of the 30 samples analyzed for tritium, 12 were modern, 5 were mixed, and 13 were premodern tritium age. Of the 28 samples analyzed for chloride 9 were above 5 ppm, 7 from anthropogenic sources, and 2 from natural sources. Of the 28 samples analyzed for nitrate, none were anthropogenic.

The samples with mixed and modern tritium-age water were mostly in the east in areas with very low to moderate sensitivities. The pathway for mixed and modern tritium-age water in samples in very low sensitivity areas was either from lateral flow from upgradient areas of higher sensitivity, or the pathway was unknown. The premodern samples were mostly in very low sensitivity areas, which was consistent with the pollution sensitivity model; 4 had carbon-14 residence times ranging from less than 100–1,200 years.

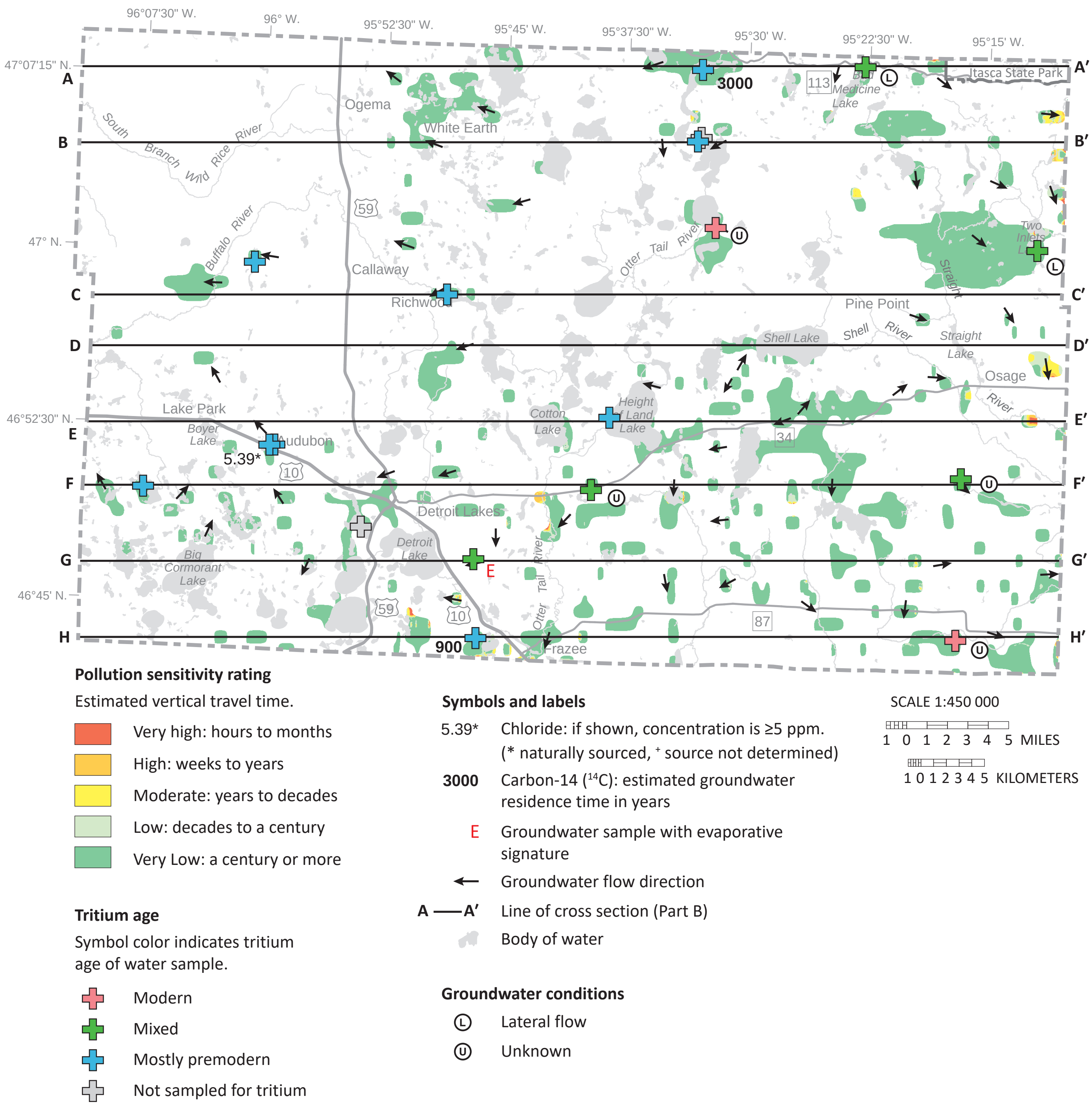


Figure 32. Pollution sensitivity of the scsa and scs aquifers and groundwater flow directions

These buried sand aquifers are widespread discontinuous deposits throughout most of the county. Depths range from approximately 95–156 (hs0), and 23–278 (hs) feet, with a mean of approximately 150 feet. It is used by approximately 10 percent of the wells in the county. Very low sensitivity dominates the western extent of the aquifer with a few scattered higher sensitivities in south-central and eastern portions of the county.

Of the 16 samples analyzed for tritium, 2 were modern, 5 were mixed, and 9 were premodern tritium age. Of the 16 samples analyzed for chloride, 1 was above 5 ppm and from a natural source. Of the 14 samples analyzed for nitrate, none were anthropogenic.

The samples with mixed and modern tritium-age water were from the south-central and eastern portion of the county at locations with very low and low sensitivities. The pathway for mixed and modern tritium-age water was either from lateral flow from upgradient areas of higher sensitivity, or the pathway was unknown. The unknown sources may have been from well construction problems that allowed shallow water to enter the well or enhanced recharge from unmapped sand bodies.

The premodern tritium-age samples were in very low sensitivity areas, which was consistent with the pollution sensitivity model; 2 had carbon-14 residence times of 900 and 3,000 years.

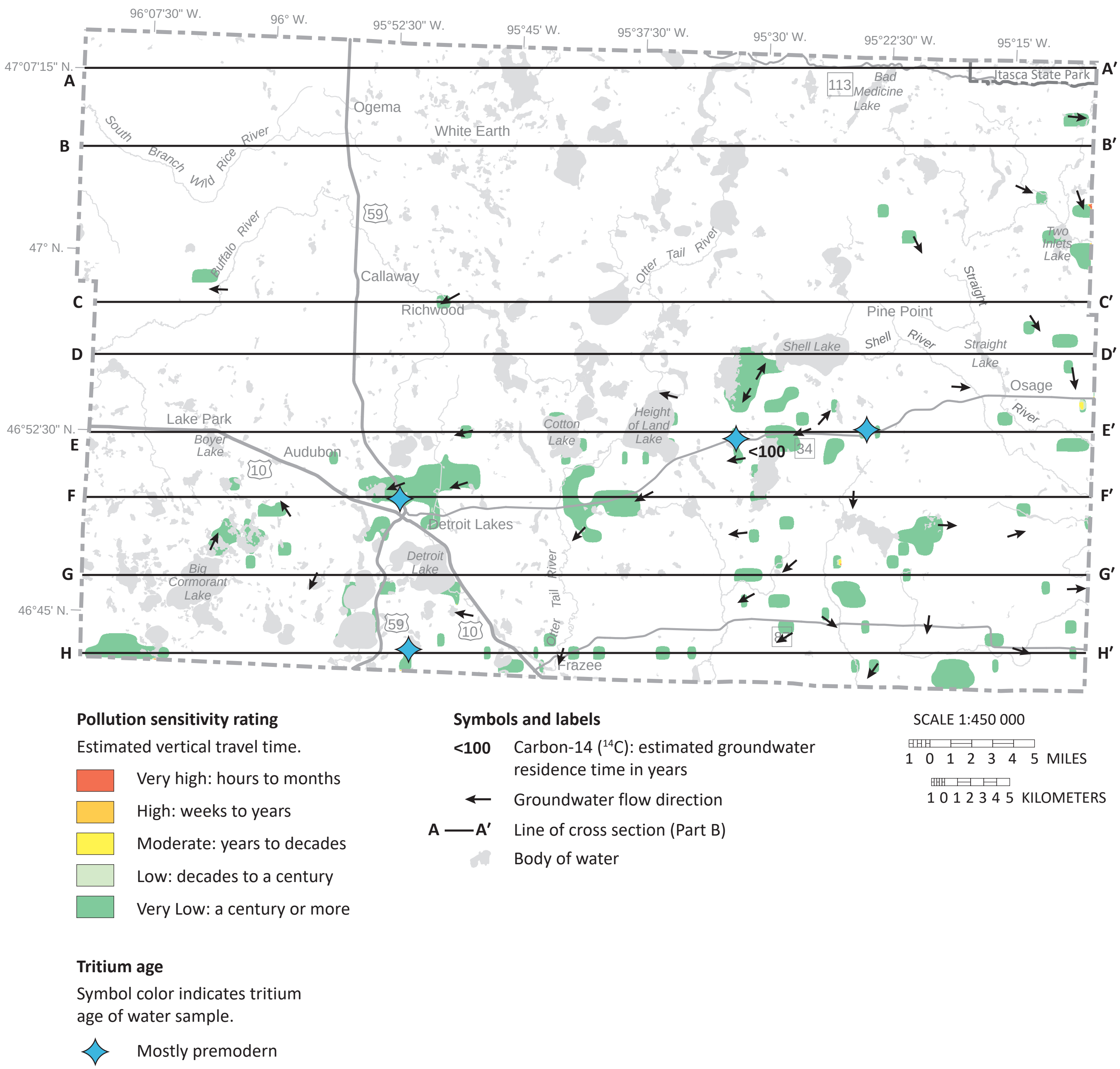


Figure 33. Pollution sensitivity of the scs2a, scs2, and mls aquifers and groundwater flow directions

These buried sand aquifers are discontinuous deposits throughout the south and far eastern portions of the county. Depths range from approximately 178–223 (scs2a), 112–303 (scs), and 59–306 (mls) feet. The scs2 and mls aquifers represent most of the buried sand aquifers in this group. The mean depth is approximately 193 feet. They are used by approximately 4 percent of the wells in the county. Pollution sensitivity is predominantly very low with only isolated higher sensitivities.

Of the 4 samples analyzed for tritium, all were premodern tritium age. Of the 4 samples analyzed for chloride, none were above 5 ppm. Of the 4 samples analyzed for nitrate, none were anthropogenic.

The premodern tritium-age samples were in very low sensitivity areas, which was consistent with the pollution sensitivity model. One from a 245-foot well had a carbon-14 residence time of less than 100 years.

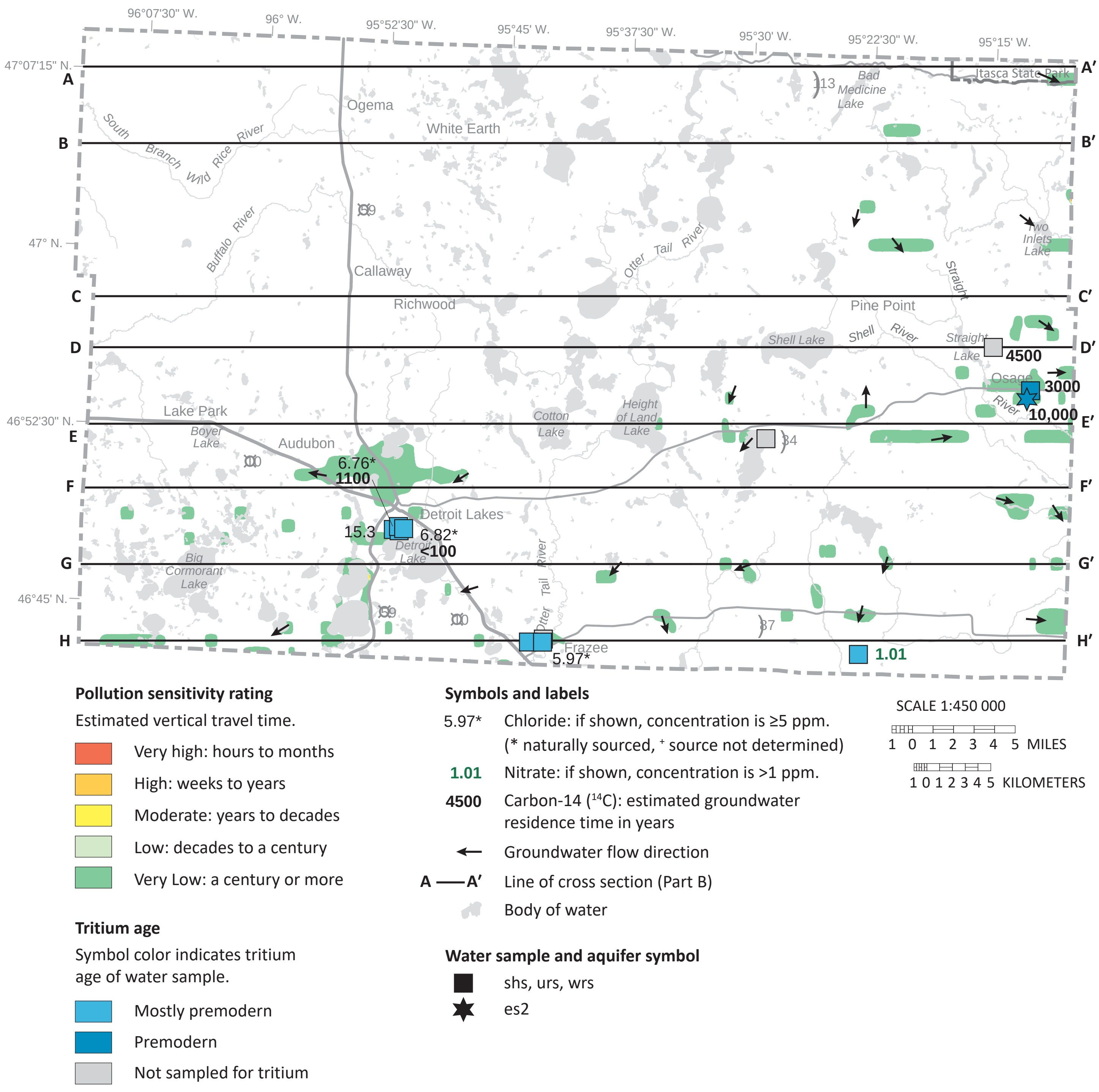


Figure 34. Pollution sensitivity of the shsa, shs, urs, wrs, ebs, rs, es, es2, es3, and ms aquifers and groundwater flow directions

These buried sand aquifers are discontinuous deposits throughout the south and far eastern portions of the county. As a group, depths range from approximately 115–402 feet. The shs, urs, and wrs aquifers represent most of the group. A representative mean depth is approximately 259 feet. They are used by approximately 2 percent of the wells in the county. Pollution sensitivity is predominantly very low.

Of the 9 samples analyzed for tritium, all were premodern tritium age. Of the 8 samples analyzed for chloride, 4 were above 5 ppm, 3 from natural sources, and 1 was anthropogenic. Of the 10 samples analyzed for nitrate, 1 was barely anthropogenic (1.01 ppm). The nitrate is not likely indicating an anthropogenic source because the sample also has premodern tritium-age water.

The premodern tritium-age samples were all in very low sensitivity areas, which was consistent with the pollution sensitivity model. Of the 5 samples analyzed for carbon-14 residence time, 3 in the far east-central end of the county ranged from 3,000–10,000 years. The other 2 were production wells in the city of Detroit Lakes with values of less than 100 and 1,100 years, even though both wells were in the same aquifer and separated by less than 200 feet. A plausible explanation is that groundwater pumping was drawing in overlying modern or mixed tritium-age water into the aquifer to mix with premodern tritium-age water.

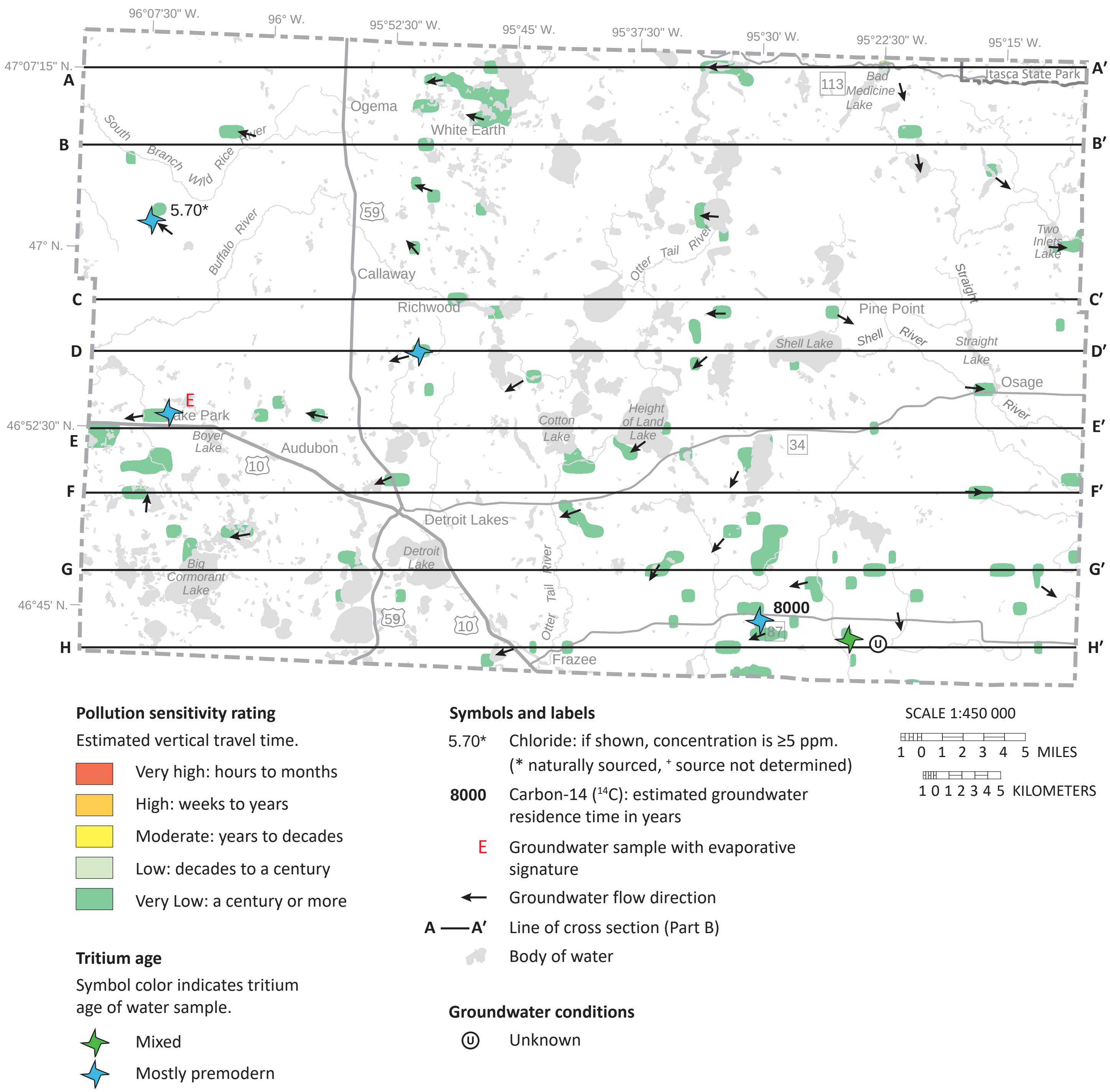


Figure 35. Pollution sensitivity of the qsu, qsu2, and qsu3 aquifers and groundwater flow directions

These buried sand aquifers are widespread discontinuous deposits throughout most of the county. As a group, depths range from approximately 113–417 feet. The qsu aquifer represents most of the group. A representative mean depth is approximately 265 feet. It is used by approximately 2 percent of the wells in the county. Pollution sensitivities are very low.

Of the 5 samples analyzed for tritium, 1 was mixed and 4 were premodern tritium age. Of the 5 samples analyzed for chloride, 1 was above 5 ppm and from a natural source. Of the 5 samples analyzed for nitrate, none were anthropogenic.

The 1 sample with mixed tritium is from a well 315 feet deep in the southeast. The presence of tritium at this depth was inconsistent with other wells in the county and suggested the well condition may be compromised, thus allowing young water to enter the well.

The 4 remaining samples were in areas of very low sensitivity and their premodern tritium-age was consistent with the model results. One sample had a carbon-14 residence time of 8,000 years.

Hydrogeologic cross sections (Plates 8 and 9)

The hydrogeologic cross sections shown on Plates 8 and 9 illustrate the horizontal and vertical extent of aquifers and aquitards, general groundwater flow direction, residence time, and chemistry.

The eight cross sections were selected from a set of 54 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 1/2 kilometer.

Relative hydraulic conductivity of Quaternary aquitards

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 5). 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.

The western third of the county has the lowest sand content (around 30 percent) in the surficial and shallow aquitards. These likely provide better groundwater protection than the much sandier aquitards (greater than 50 percent sand) at depth in the western part of the county that transition to surficial and shallow aquitards in central and eastern Becker County.

Groundwater flow and residence time

The direction of **groundwater flow** is interpreted on the cross sections as *equipotential contours* constructed from measured water levels in wells. The water-level data are contoured to show groundwater flow along the cross section. The contours can be used to identify the groundwater flow direction, recharge zones, and discharge zones.

Estimated **groundwater residence time** is indicated for aquifers on the cross sections by shading with one of three colors. Residence time was assigned based on available chemistry data (tritium age, chloride, and nitrate). Where chemistry data were not available, residence time was assigned by other means including interpreting penetration depths of modern tritium-age water, pollution sensitivity of the aquifer, and relative permeability of aquitards.

Equipotential contours are shown for those areas where there were enough wells to delineate flow directions. Areas with limited or no well control included the Tamarac National Wildlife Refuge and undeveloped forested areas in the north-central part of the county and the Hamden Slough National Wildlife Refuge to the west. Where there is sufficient well control, the equipotential contours and flow arrows show that the groundwater flows initially downward, then laterally toward surface-water discharge areas including lakes, wetlands, and perennial streams.

Large changes in elevation are often associated with the strongest downward vertical gradients. Where these areas are coincident with stacked buried sands there is often a greater depth of penetration of modern and mixed tritium-age groundwater. Examples of these can be seen on Plate 9, cross section G–G′ just west of center, near CSAH 54; and in F–F′ center, between CSAH 29 and MNTH 34. At each location mixed or modern tritium-age water was present at depths exceeding 200 feet. In general, tritium is seldom found greater than 100 feet.

In lowland areas adjacent to topographic uplands, water pressure in deeper confined aquifers is sometimes greater than the water pressure in overlying shallow confined aquifers. Since groundwater flows from higher to lower pressure, groundwater is discharging upward (upwelling) at these locations bringing older water toward the surface. Where pressure in the aquifer is sufficiently high, wells completed in the aquifer will flow at the surface.

On Plate 9, cross section B–B′ just west of center, a sample was collected just east of USTH 59 from a 25-foot well. The adjacent upland rises over 300 feet to the east to locations near CSAH 21. This sample from the shallow aquifer was found to have premodern tritium-age water even though it is in an area of high pollution sensitivity (Figure 27). The absence of tritium is likely due to upwelling of older groundwater. Evidence of upwelling can be seen on the potentiometric surface map in Figure 9 showing multiple flowing wells near the sampled well.

This upwelling also provides groundwater discharge to several calcareous fens in the county including the Spring Creek WMA South fen (Ogema) approximately 1 mile northwest of the city of Ogema. Upwelling may also be providing groundwater discharge to the northern end of Elbow Lake in the north-central part of the county (Plate 8, cross section A–A′, east of center) as indicated by multiple flowing wells at that end of the lake.

Some of the oldest groundwater residence times were found in aquifers in the topographically lowest elevations in far west-central and northwest Becker County. Long groundwater flow paths from upland recharge areas to the east are suggested by the absence of mixed or modern tritium-age water, the relatively old groundwater resident times, and the significant number of flowing wells.

In the western portions of cross section A–A′ south to cross section D–D′ land-surface elevations are 200–300 feet lower than adjacent uplands to the east. A sample from a 152-foot well just south of cross section B–B′ (not shown) had a residence time of 14,000 years.

On Plate 9, E–E′ far west, a second sample from a 112-foot well had a residence time of 25,000 years. Two additional wells in Clay County are not shown but fall between cross sections A–A′ and B–B′ less than a mile west of the Becker border. These had very old residence times of 14,000 years and 20,000 years at depths of 69 and 133 feet, respectively (Berg, 2018).

Groundwater recharge

Precipitation is the source of recharge to the water table in surficial unconsolidated deposits, a portion of which will then provide recharge to deeper aquifers. Much of the infiltrating precipitation does not recharge the water table due to evaporation, plant transpiration, and discharge to surface-water features. Potential recharge at the land surface in Becker County averages 4.6 inches per year and ranges two standard deviations from 1.2–8.0 inches (Smith and Westenbroek, 2015).

Groundwater recharge to buried sand aquifers and bedrock aquifers is generally less than 1 percent of average precipitation, or roughly 0.26 inches per year, and is dependent upon unconsolidated matrix texture and thickness (Delin and Falteisek, 2007).

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

Specific capacity and transmissivity describe how easily water moves through an aquifer. Larger values 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-lift pumping), the pumping-test data were obtained from CWI for wells with the following criteria:

- 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.

Transmissivity is an aquifer's capacity to transmit water. It provides a more accurate representation of 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).

Table 2. Specific capacity and transmissivity of selected wells (Figure 36)

Quaternary 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 unconfined	ss	8–24	55.9	10.3	192	14	12	36,800	--	--	1
Buried sand unconfined	rls	12	113	--	--	1	--	--	--	--	--
Buried sand confined	ons	10–12	10.3	2.4	18.2	2	--	--	--	--	--
	hs	12	24.0	18.4	29.6	2	12	6,610	2,130	11,100	2
	hs2	12	23.0	9.4	31.6	7	12	1,630	--	--	1
	shs	12	45.4	--	--	1	--	--	--	--	--
	urs	10–16	26.5	20.0	35.9	4	12–16	6,500	4,960	8,830	3
	es2	12	4.8	--	--	1	--	--	--	--	--
	qsu/unkn	--	--	--	--	--	5	9,720	--	--	1
	qu	8–10	2.6	0.6	6.6	3	10	121	102	140	2

Specific capacity data adapted from the CWI

Transmissivity data are from aquifer test data compiled by the DNR

Dash (--) means no data

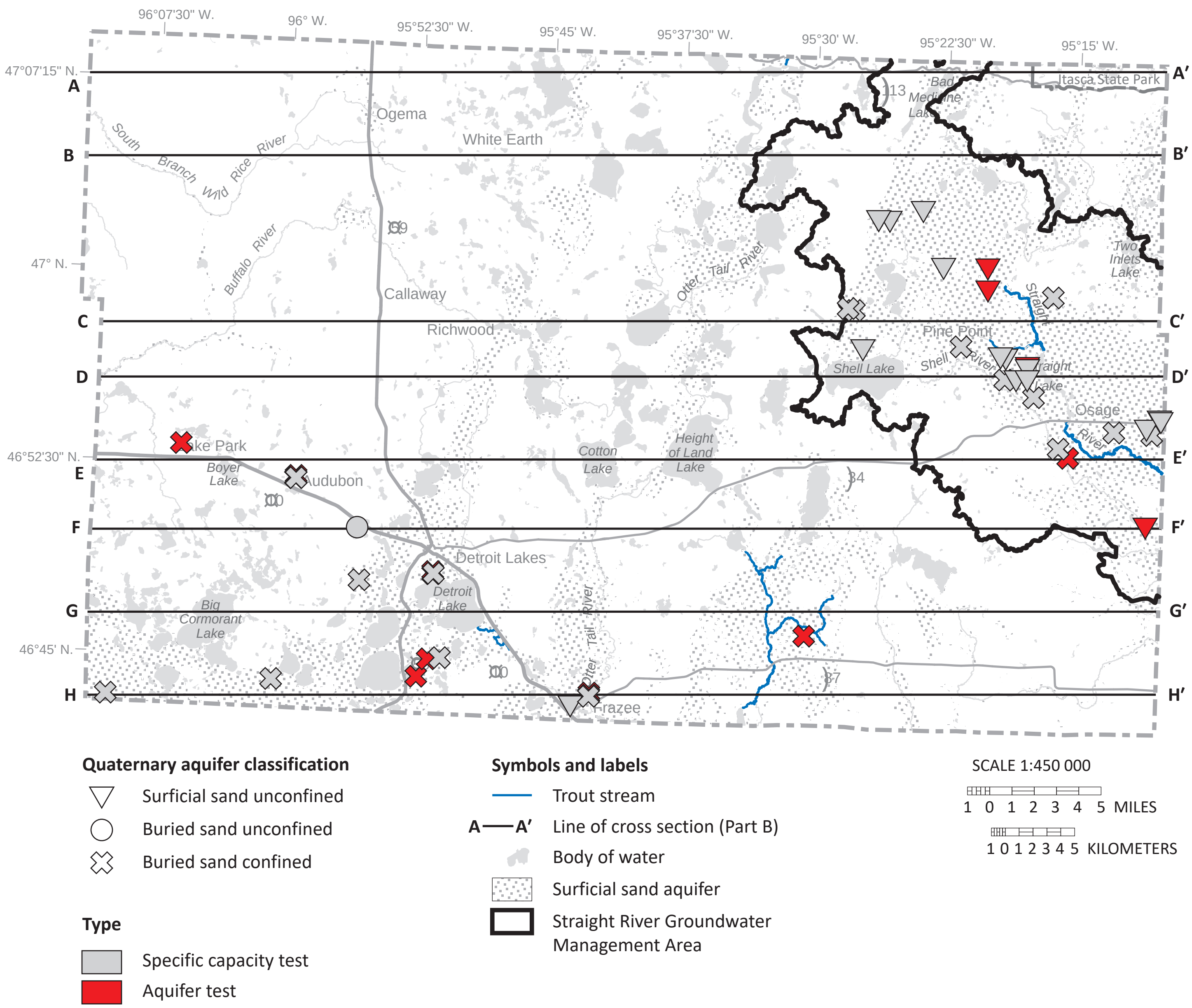


Figure 36. Well locations for specific capacity and aquifer tests

Specific capacity was determined for 35 wells in Becker County. The wells in south-central and southwest are mostly in confined buried sand aquifers over 150 feet, and include public supply, irrigation, industrial, and other uses.

The wells in the east are in the Pineland Sands region. These are all irrigation wells with over 50 percent in the surficial sand aquifer and the rest in buried sands.

The surficial sand aquifers have the highest mean values (56 gpm/ft) compared to the buried sand aquifers (45 gpm/ft and less). The exception is a buried sand unconfined well completed in a 124-foot thick rls aquifer just west of Detroit Lakes with a value of 113 gpm/ft.

Transmissivity was determined for 10 wells (Table 2). The 1 surficial sand aquifer had a higher mean value (36,800 ft^2/ day) than the 9 buried sand aquifers (121–9,720 ft^2/ day).

Groundwater level monitoring

The DNR maintains a statewide groundwater level monitoring program for assessing groundwater resources, determining long-term trends, interpreting impacts of pumping and climate, planning for water conservation, evaluating water conflicts, and managing water resources (DNR, 2019a).

Hydrographs depict groundwater levels over time and are useful for determining trends and provide insight into how aquifers respond to recharge events, pumping stresses, and changing climatic conditions.

Hydrographs from well nests are often the most useful. Well nests consist of closely spaced wells that are constructed in different aquifers. The hydraulic relationship between the different aquifers (vertical gradient) is needed to understand groundwater flow and the impacts of water use and other changes on the groundwater system.

In Becker County, observation wells are constructed in both surficial and buried sand aquifers, with the largest concentration in the Pineland Sands where there are a large number of irrigation wells (Figures 5 and 37). The Straight River flows through this area and is reliant on groundwater discharge to the stream to sustain its resident trout population.

The hydrographs shown in Figures 38–41 were produced from data retrieved from the DNR Cooperative Groundwater Monitoring Program (DNR, 2019a). Periods of drought are represented by light gray shaded regions and are determined based on the Palmer Drought Severity Index. A drought is declared when the index is less than or equal to -3 for a period of 6 or more consecutive months.

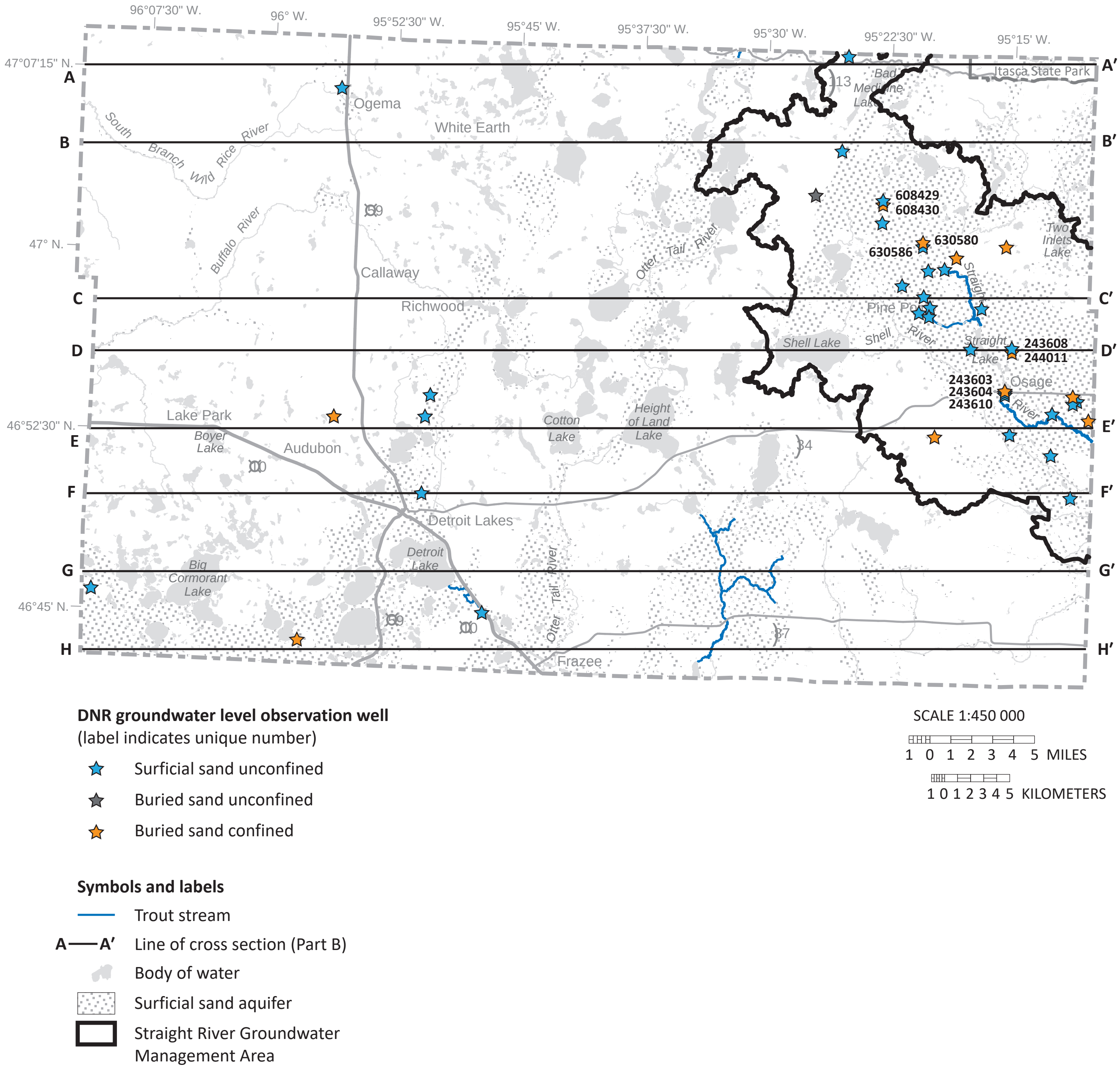


Figure 37. Actively monitored DNR observation wells

The largest concentration of wells is in the Pineland Sands where there are many irrigation wells. The Straight River flows through this area and is reliant on groundwater discharge to the stream to sustain its resident trout population.

The DNR identified a region largely defined by the Straight River and its contributing watersheds as an area of specific concern where groundwater resources are at risk of overuse and degraded quality. The DNR worked with an advisory team representing agriculture, local government, and other agencies to establish the Straight River Groundwater Management Area (SRGWMA). This includes parts of southern Clearwater, northeast Becker, southwest Hubbard, and northwest Wadena counties (Figure 5).

Management plans were developed to guide DNR actions in managing the appropriation and use of groundwater within the SRGWMA (DNR, 2017). The goal is to ensure that groundwater use will be sustainable and will not harm ecosystems, water quality, or the ability of present and future generations to meet their needs.

Unique identifiers are shown for sites used for creating hydrographs in this report.

Figure 38. Groundwater hydrograph of water-level trends of four observation wells in northeast Becker County

Water-level trends rise and fall in response to seasonal and long-term wet and dry periods. At both locations groundwater is moving vertically downward indicated by higher water elevations in the shallow wells compared to their respective deeper wells.

The hydrograph portrays well-water levels in the northeast portion of the county at two locations separated by less than 3 miles. Each has a nest of two closely spaced wells in different aquifers. The shallow wells at both sites are in the surficial sand aquifer (ou), and their respective deeper wells are in buried sand aquifers.

A bar graph representing precipitation is positioned between water levels for the two well nests. Each bar represents the cumulative departure from normal precipitation for the current month and 5 previous months. Wetter periods are generally associated with deviations above zero and drier periods with below zero. The light gray shaded vertical bar identifies a short duration drought in 2012 (classified using the monthly Palmer Drought Severity Index).

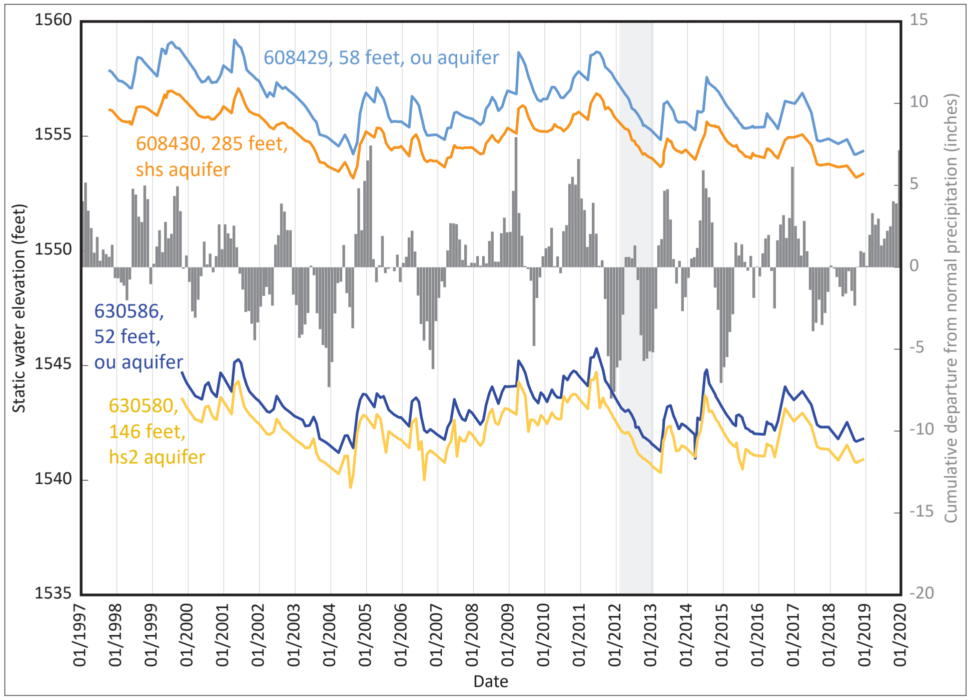


Figure 39. Groundwater hydrograph of water-level trends of two nested observation wells in far eastern Becker County

Water levels were at their lowest in 1991 following a period of drought and rose as much as 4 feet peaking in 2000. Thereafter water levels declined and rose approximately 2 feet in response to changing precipitation conditions, including a short-duration drought in 2012.

The shallow well (46 feet) is in the surficial sand aquifer (ou) and the deeper well (199.6 feet) is in a buried sand aquifer (shs). The collection of water levels commenced during a drought that started in 1988 and ended in 1991.

Water levels are plotted against cumulative departure from normal precipitation. The bar graph along the bottom corresponds to the precipitation values on the right. Each bar represents the cumulative departure from normal precipitation for the current month and 5 previous months. Wetter periods are generally associated with deviations above zero and drier periods with below zero.

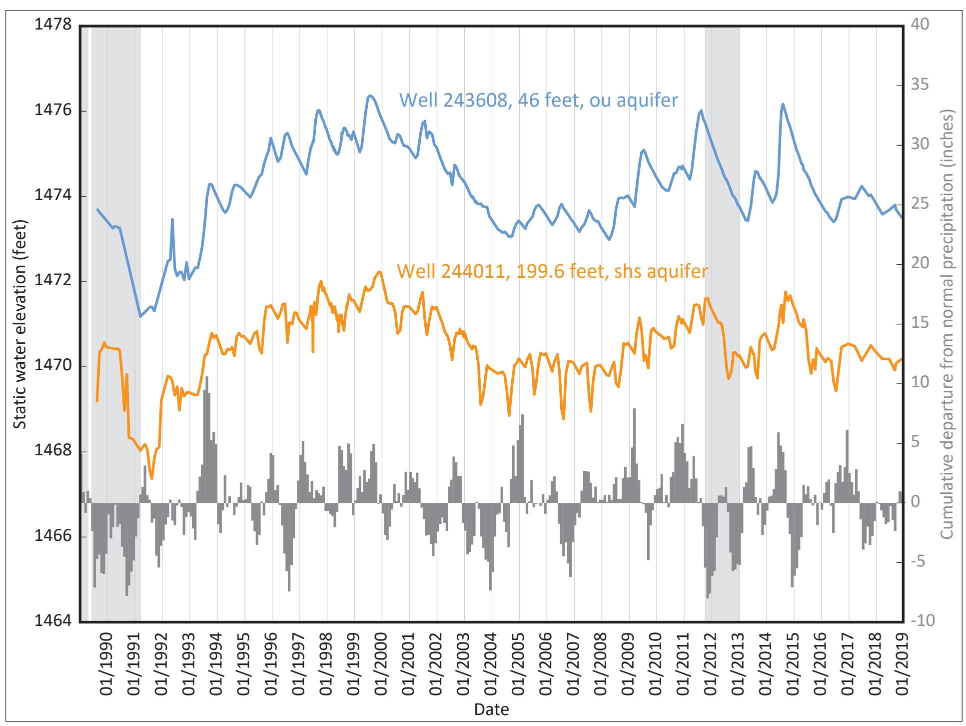


Figure 40. Groundwater hydrograph for two observation well nests in eastern Becker County of responses to large withdrawals

In each well nest, the buried aquifer has drawn down water levels associated with the irrigation season. The two sites are separated by approximately 7 miles. Each site has one well in the shallow surficial sand and one in a deeper buried sand aquifer.

1. ou aquifer 52 feet
   hs2 aquifer 146 feet
2. ou aquifer 46 feet
   shs aquifer 199.6 feet

The sites are at very different elevations, so the static water elevations were normalized to facilitate water-level comparison of the two sites.

The bar graph along the bottom corresponds to the precipitation values on the right. Each bar represents the cumulative departure from normal precipitation for the current month and 5 previous months. Wetter periods are generally associated with deviations above zero and drier periods with below zero.

Water levels in all four wells generally rose and fell in response to short and long-term precipitation trends. At both sites, water levels for the buried sand aquifers also show seasonal drawdowns that correspond to the crop irrigation season.

The hs2 aquifer shows sharp declines followed by rapid recoveries. These individual events represent large-volume irrigation pumps cycling on and off near and in the same aquifer as the observation well. There are eight irrigation wells within 1 mile that pumped a total of 130 million gallons in 2018. Most of the reported water use is from the same aquifer as the deep observation well.

The shs aquifer shows declining water levels during the irrigation season with recovery later in the fall after irrigation has ended. The nearest irrigation well is almost 1.5 miles to the southwest and in a different aquifer. The nearest irrigation wells in the same aquifer are over 2.5 miles to the southeast. These seasonal water-level drawdowns could be in response to the cumulative impact of groundwater withdrawals from multiple distant irrigation wells over the irrigation season.

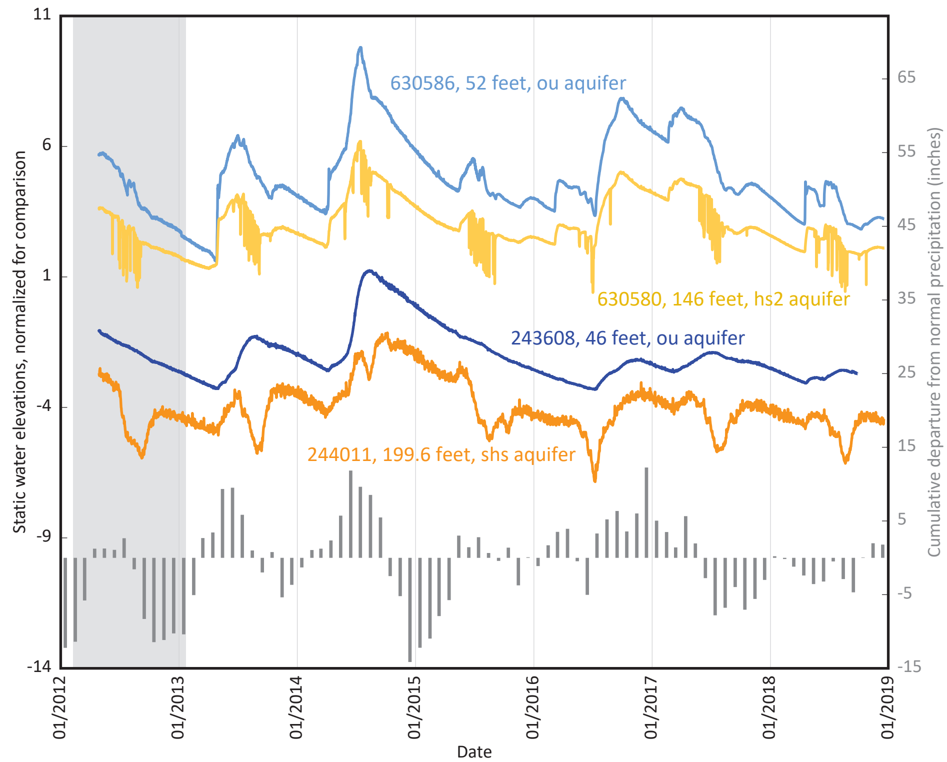


Figure 41. Groundwater hydrographs for a nest of three observation wells downstream of Straight Lake

The water level trends at this site portray the influence of the Straight River Dam and the operation of a fish rearing pond on the local hydrogeology. Just downstream of Straight Lake is a nest of three observation wells. Two wells are in the surficial outwash (ou, one shallow and one deep) and the third is in a deeper buried sand aquifer (shs).

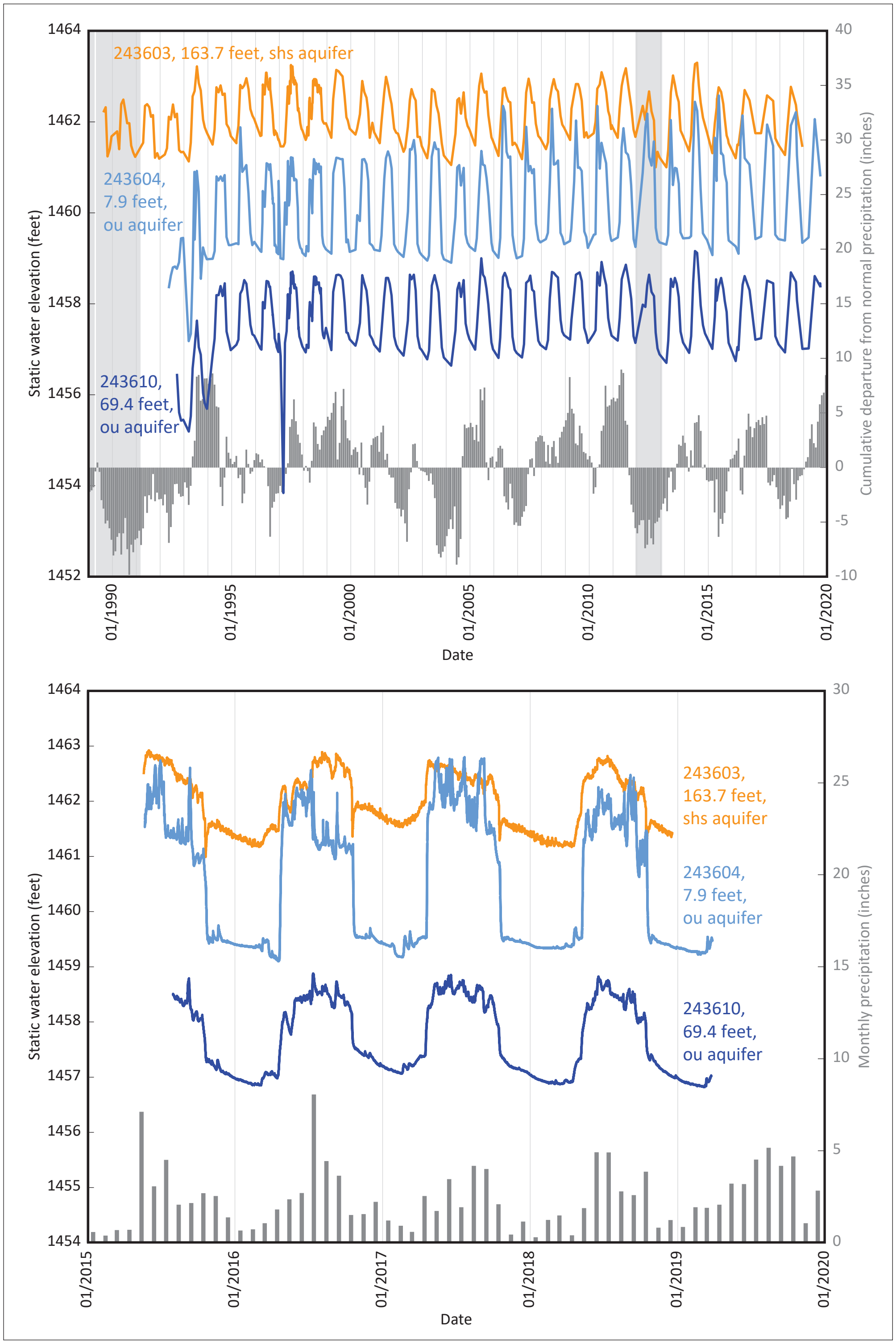
The upper figure compares long term trends to monthly precipitation and provides only general water-level information corresponding to wet periods and dry periods. The strong annual cycles of water-level fluctuation mask seasonal water-level trends.

The well nest is useful for determining vertical groundwater flow direction. Downward flow within the surficial aquifer is indicated by the decline of water-level elevations with increasing well depth. The downward gradient is likely limited to a localized area of artificially elevated water levels associated with the Straight Lake dam.

The deeper buried sand aquifer (shs) has a higher water-level elevation than the two shallower wells, indicating upward flow beneath the surficial sand aquifer. Groundwater is likely upwelling into the surficial sand aquifer and mixing with recharge from the surface.

Two additional well nests farther downstream along the Straight River in Hubbard County show upward gradients indicating that this river is supported by groundwater discharge.

The lower figure is a 5-year portion of the upper hydrograph with higher resolution water-level changes provided by data loggers installed in 2015. The annual cycles show sharp water-level declines in mid to late October followed by sharp rises in April every year. This annual cycle corresponds to the filling and draining of the fish rearing pond immediately adjacent to the well nest. The water-level responses are greatest in the shallowest well (approximately 2 feet) and are subdued with increasing well depth.



Groundwater use

CWI provides information for the 6,374 wells in Becker County. Of the wells with identified aquifers, most were completed in the buried sand aquifers (78 percent), followed by surficial sand (ss) aquifers (21 percent), and Quaternary sand unknown aquifers (1 percent).

The majority of the wells were for domestic use (79 percent), followed by municipal supply (7 percent), irrigation (3 percent), and other (11 percent).

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 the Minnesota Permitting and Reporting System (MPARS), which helps the DNR track the volume, source aquifer, and type of water use.

Water use for DNR permit holders in 2018 is shown in Figure 42 by water use types and in Figure 43 by general aquifer classification (DNR, 2019b). Table 3 uses data collected for 215 permitted wells. Three water-use types collectively made up 92 percent of the permitted water used in 2018.

1. Agricultural crop irrigation was the largest water use type with approximately 67 percent of the total usage. Use was concentrated within the boundaries of the Straight River Groundwater Management Area in eastern Becker County where coarse-textured soils do not readily retain moisture. The amount of water needed each year varied significantly. Water usage in 2017 was approximately 45 percent greater than 2018. The demand for irrigation water is concentrated into 3 or 4 months associated with the growing season. Slightly more than 50 percent of the permitted irrigation wells were completed in the surficial sand aquifer and the rest were completed in buried sand aquifers.
2. Municipal/public water supply was the second largest water use type (17 percent) with water coming entirely from buried sand aquifers, chiefly the urs aquifer used by the cities of Detroit Lakes and Frazee. Demand for municipal water is more consistent throughout the year than irrigation and does not change significantly from year to year.
3. Sand and gravel washing was the third largest (8 percent) from buried sand aquifers.

Table 3. Reported 2018 water use from DNR groundwater permit holders

		Use types (mgy)								
Quaternary aquifer	**No. of wells**	**Agricultural crop irrigation**	**Municipal/ public water supply**	**Sand and gravel washing**	**Pollution containment**	**Golf course irrigation**	**Snow/ice making**	**Other**	**Total (mgy)**	**Total (percent)**
Surficial sand unconfined	108	1,571	--	85	51	1	--	0	1,707	47
Buried sand confined	100	829	606	206	103	79	--	0	1,823	50
Buried sand unconfined	3	3	28	--	--	15	--	0	47	1
Undifferentiated sediment, unknown confinement	4	32	--	--	--	0	30	0	62	2
Total (mgy)	--	2,435	634	290	154	96	30	16	3,656	N/A
Total (percent)	--	67	17	8	4	3	1	0	--	100
Highest annual use by permit 2014–2018		3,529	657	343	154	104	30	28	--	--

Data from MPARS; mgy, million gallons per year

Dash marks (--) indicate no use in those categories; N/A indicates not applicable

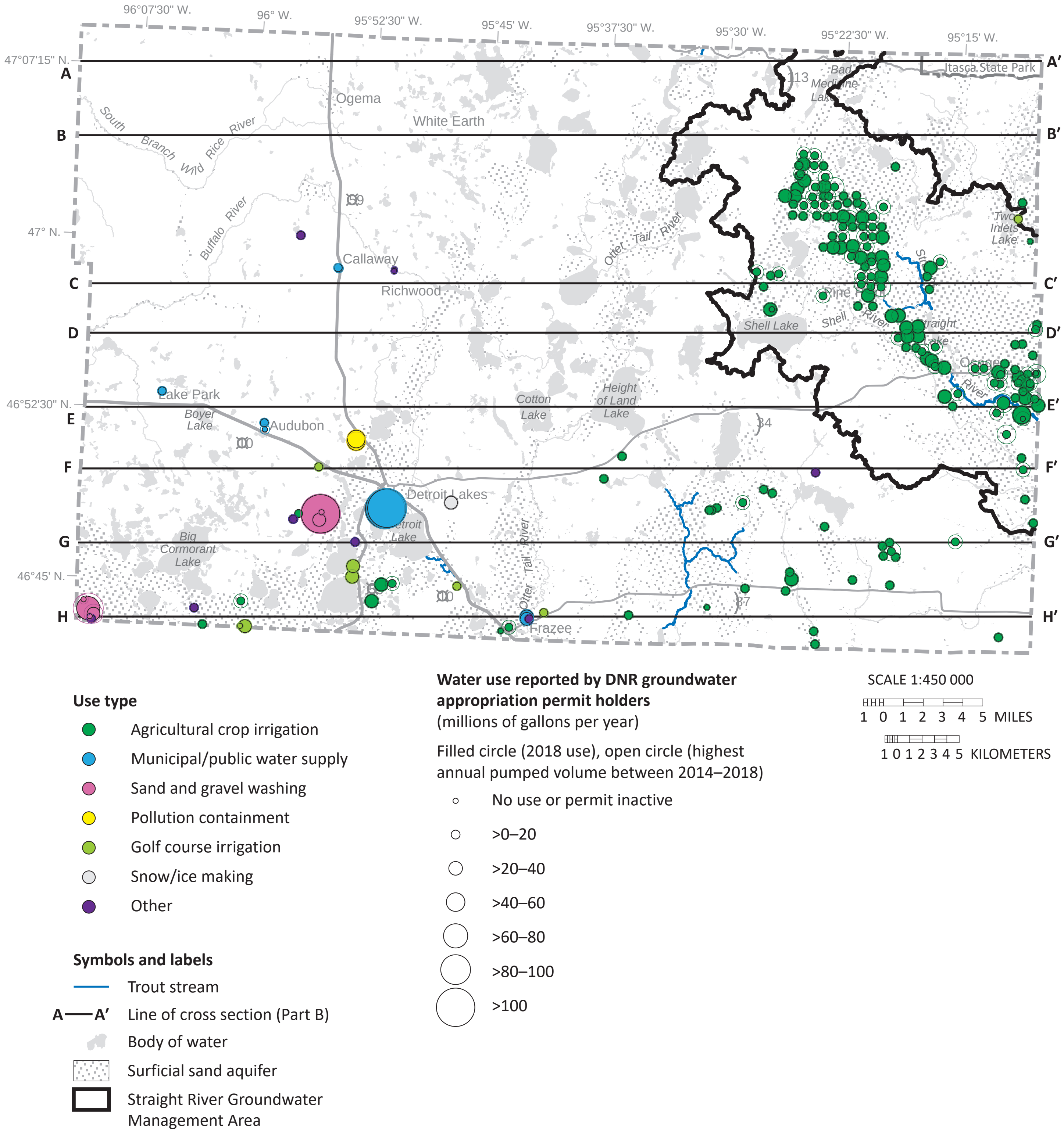


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Figure 42. Distribution of groundwater permits by volume and use category

Agricultural crop irrigation was the largest permitted groundwater use type by volume with the majority of wells in the Pineland Sands area. Municipal/public groundwater use was second with most of the water coming from the urs buried sand aquifer to supply water for the city of Detroit Lakes.

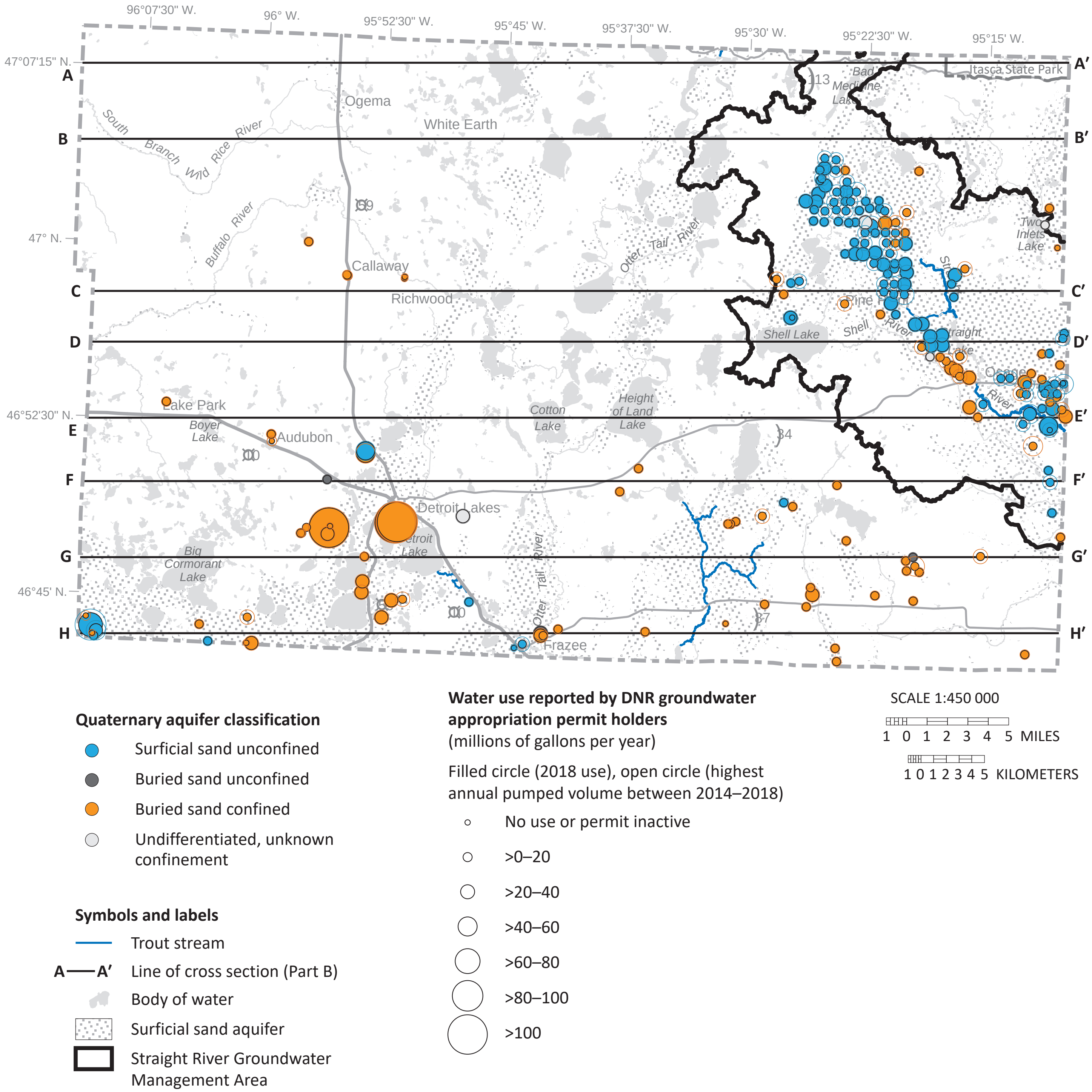

Figure 43. Distribution of groundwater permits by general aquifer classification

Nearly equal portions of groundwater use in 2018 were from surficial sand and buried sand aquifers. The most significant water use in surficial deposits was from the Pineland Sands area.

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Glossary

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

air-lift pumping—water is pumped from a well by releasing compressed air into a discharge pipe (air line) lowered into the well. It is commonly used only for well development, not water production.

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

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

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

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

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

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

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

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

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

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

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

denitrification—is a microbially facilitated process where nitrate (NO_3^-) is ultimately reduced to nitrogen gas (N_2). Typically, denitrification occurs in anoxic environments, where the concentration of dissolved oxygen is depleted.

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

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

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

formation—a fundamental unit of lithostratigraphy. A formation consists of a 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.

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

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

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

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

provenance—the place of origin of a glacier.

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

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

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

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

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

stable isotope—chemical isotopes that are not radioactive.

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

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

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.

unconsolidated—sediment that is loosely arranged, where the particles are not cemented together.

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.

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

Appendix A

Groundwater field sample collection protocol

Groundwater samples were collected from an outside faucet or hydrant. The wells were purged prior to sampling to remove stagnant water from the well bore and plumbing system. Samples were collected after 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 laboratory analysis.

Samples were analyzed by DNR staff, the Minnesota Department of Agriculture (MDA), the Minnesota Department of Health (MDH), 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	Carbon-14 (^{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-inch tube and purge 1 liter 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 Minnesota 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 (mndnr.gov/groundwatermapping)

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

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	12.1	Precipitation composite
	(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
Lake-water sample (Height of Land Lake)	6/20/2018	6.1	Limnetic Zone

Tritium-age methodology

The method to calculate tritium age was revised in 2020 due to decreasing tritium in the atmosphere. This changed the nomenclature for subsequent atlases.

Atlases C-1 through C-39 use the method from *Residence times of Minnesota groundwaters* (Alexander and Alexander, 1989) with the terms recent, mixed, and vintage tritium age.

Atlases from C-40 on use the method from *Tritium age classification–revised method for Minnesota, GW-05* (DNR and MDH, 2020) with the terms modern, mixed, and premodern tritium age.

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.

DEPARTMENT OF NATURAL RESOURCES

500 Lafayette Road
St. Paul, MN 55155-4040
888-646-6367 or 651-296-6157
mndnr.gov

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