

Geologic Atlas of Clay County, Minnesota

County Atlas Series C-29

Part B, Hydrogeology



Report

To accompany these atlas components:

[Plate 6, Water Chemistry](#)

[Plate 7, Hydrogeologic Cross Sections, A–A' through E–E'](#)

[Plate 8, Hydrogeologic Cross Sections, F–F' through I–I'](#)



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County Geologic Atlas Program

The Minnesota County Geologic Atlas series has been produced since 1982. Recent atlases are produced in two parts. For Clay County:

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

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

Explanations of the history and purpose of the program, atlas applications, map sales, and descriptions of the Part A and Part B components are available online:

Part A, Geology, MGS [page](http://www.mngs.umn.edu/county_atlas/countyatlas.htm) (http://www.mngs.umn.edu/county_atlas/countyatlas.htm)

Part B, Hydrogeology, DNR [page](http://mndnr.gov/groundwatermapping) (mndnr.gov/groundwatermapping)

Technical Reference

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

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

Base maps were modified from MGS, Clay County Geologic Atlas, Part A, 2014. Universal Transverse Mercator projection, Zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Conversion Factors

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

1 part per million = 1 milligram per liter

1 part per billion = 1 microgram per liter

1 milligram per liter = 1000 micrograms per liter

1 gallon per day per foot = 0.1337 foot² per day

1 foot² per day = 7.48 gallons per day per foot

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Geologic Atlas of Clay County, Minnesota, Part B

By James A. Berg

Introduction

This report and the accompanying plates are Part B of the Clay County Geologic Atlas. Part B describes the hydrogeology and is produced by the Minnesota Department of Natural Resources (DNR). It builds on the geology described in Part A, which was previously published by the Minnesota Geological Survey (MGS).

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

The **report** details the methods, results, and interpretations for the county. **Plate 6** illustrates the water chemistry. **Plates 7 and 8** use hydrogeologic cross sections to show groundwater flow directions and residence time within aquifers. The following describes the sections incorporated into this atlas.

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

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

Pollution sensitivity is modeled for the following:

- 1) The sensitivity of *near-surface materials* is an estimate of the time it takes for water to infiltrate the land surface to a depth of 10 feet. This model is based on hydrologic soil groups and surficial geologic matrix textures.
- 2) The sensitivity of *buried sand and gravel aquifers and the bedrock surface* is based on the cumulative thickness of fine-grained sediment (aquitard material) overlying an aquifer or the bedrock surface. The model results are evaluated by comparing the pollution sensitivity ratings to chemical constituents such as tritium and carbon-14 data for residence time, and to inorganic chemicals for contamination.

Hydrogeologic cross sections illustrate groundwater flow, residence time, and distribution of chemicals. Cross sections help define areas of interest, such as locations of important groundwater recharge, discharge, and sensitivity to pollution.

Aquifer characteristics and groundwater use summarizes specific capacity tests, aquifer tests, and water use records for each aquifer, where available. These data help hydrogeologists plan for new well installations to meet requirements for a given use. Selected DNR groundwater level monitoring, pumping, and precipitation data is also summarized to provide an example of monitoring efforts that are underway in the county.

A Geologic Atlas User's Guide is available from the MGS for additional information on the history and purposes of the program, various atlas applications, and descriptions of the Part A components (Setterholm, 2014).

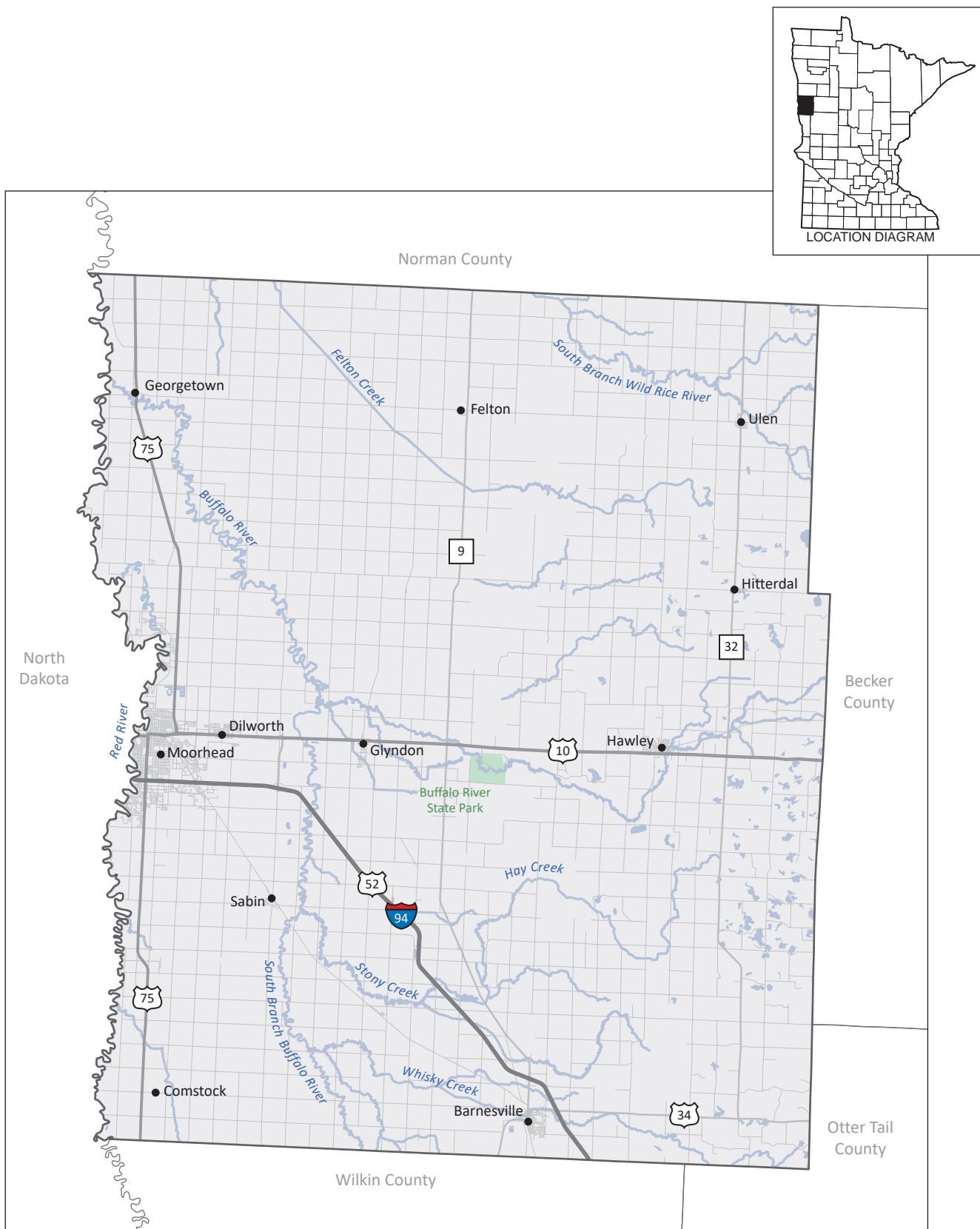


Figure 1. Clay County landmarks

Geology and physical hydrogeology

Clay County is in northwestern Minnesota (Figure 1) and is mostly agricultural and rural with small towns. The population in 2016 was approximately 63,000 (U.S. Census Bureau, 2017). Moorhead (western border) has the largest area of developed land and is the largest user of water. The county lies within the watersheds of the Red River (Upper and Marsh River portions), Wild Rice River, Buffalo River and Otter Tail River (Figure 2). The Red River forms the western border and is the largest river in the region. The western half of the county is part of a glacial lake plain and has little topographic relief and few lakes or wetlands.

The eastern part has higher land elevations, a hummocky topography, and numerous lakes and wetlands.

Clay County is in the northern continental United States and is characterized as a cool subhumid climate with a large temperature difference between summer and winter. Summers are relatively cool with an average temperature of approximately 68 degrees Fahrenheit and a winter average temperature of 9 degrees Fahrenheit (NOAA, 2017). Average annual precipitation is approximately 24 inches, placing it in the lower portion of the statewide range of 20 to 36 inches.

Surficial aquifers

The regional topography and distribution of surficial deposits of Clay County were created as multiple glacial ice lobes advanced into and retreated from the area (Part A, Plate 3) during the last ice age. Multiple advances of the Wadena lobe from the northeast created thicker sediment layers regionally, resulting in higher elevations and hummocky topography in the eastern portion of the county. This dominates the west-central part of the state and is commonly referred to as the Alexandria moraine (Wright, 1972). Each advance deposited layers of sand, gravel, and till, also known as diamicton (a finer-grained glacial deposit of unsorted sand, silt, and clay). These deposits formed the Hewitt Formation.

After the final retreat of the Wadena lobe the source of glacial movement shifted. Several advances of the Des Moines lobe came from the north and northwest and deposited sand and gravel and thick till deposits of the New Ulm, Goose River, and Red Lake Falls formations. These formations overlapped the Alexandria moraine to the east.

In the final phase of the ice age in this region, a great mass of ice in Canada melted and formed a large glacial lake that extended into Minnesota (Lake Agassiz). Sediment from this lake settled into a layer of clay up to 140 feet thick in the western portion of the county, burying and isolating most of the sand and gravel aquifers by a thick layer of impermeable clay.

Water table

The water table is the surface between the unsaturated and saturated zones where the water pressure equals the atmospheric pressure. The water table occurs in both aquifer and aquitard sediment across the entire county. The water table in the figures is shown as a static surface but actually changes over time. Surficial sand and gravel aquifers are present below the water table where there is

sufficient saturated thickness and yield to install a well and economically pump groundwater.

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

Water-table elevation (Figure 2) was estimated from several sources of data:

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

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

Depth to water table (Figure 3) was derived by subtracting the water-table elevation from the land-surface elevation. More details on how both maps were constructed can be found in *Methods for estimating water-table elevation and depth to water table* (DNR, 2016a).

Water-table elevations in Clay County cover a wide range of values ranging from high elevations in the east on the Alexandria moraine to lower values in the western half (Red River Valley). The main groundwater flow directions are westerly toward the Red River. Local water-table flow is

toward tributaries of the Red River such as the Wild Rice and Buffalo rivers, and Whisky and Stony creeks. Water-table depths are shallow (0–10 feet) in the flatter western part of the county and some parts of the eastern portion. Most

of the deeper water-table areas are beneath the hills of the Alexandria moraine area where depths 10 to greater than 30 feet may be common, especially in the southeastern part of the county.

Buried sand and gravel aquifers

Beneath the surficial geologic deposits are alternating layers of older sand and gravel and fine-grained deposits from previous glacial advances. The naming convention for the buried sand and gravel aquifers in this atlas was based on the underlying till unit described in the associated Part A atlas.

The stratigraphic column in Figure 4 summarizes the geologic units and hydrogeologic properties of the glacial sequence and correlates the corresponding Part A and B unit names and map labels. In this atlas, the *buried sand and gravel aquifers* will be referred to as ***buried sand aquifers***.

Some of the buried sand units have been combined into groups on the maps for potentiometric surface and pollution sensitivity. Many aquitards (till and lake clay units) defined in Part A have limited extents and lateral continuity. Where these exist, the sand layers around them are considered part of the same aquifer for the purposes of this county-scale project.

However, using hydrogeologic associations alone risks including isolated sand bodies that are not hydraulically connected, so some groups were broken up based on lithostratigraphic associations. The most significant aquitards used to create these groups include the Lake Agassiz deposits (sl and bl), and till units gdt, nht, ht1, and ht2. The least extensive aquitards include the lake sediment units (with the exception of the Lake Agassiz deposits) and till units ont, nvt, brt, gvt, x1t, x2t, x3t, qtu1, and qtu2.

Potentiometric surfaces

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

The potentiometric surface of an aquifer represents the potential energy that is available to move groundwater. As groundwater moves from higher to lower potentiometric elevations it flows perpendicular to the potentiometric elevation contours. Flow directions are shown on Figures 5 through 13.

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

Potentiometric surface maps were created from static water level data from the County Well Index (CWI), measurements made by DNR staff, and river elevation points along the major rivers and streams. The CWI records represent various climatic and seasonal conditions from 1956 through 2015. This data variability creates some uncertainty in potentiometric surface elevations.

River and stream elevation points were included in parts of some of the potentiometric surface estimations. Elevation data were included because these features are typically groundwater discharge locations for the relatively shallow buried sand aquifers. Estimations that included river elevation data are the rlf aquifer; and the eastern portions of the gr aquifer group, nh aquifer group, and ot/nv aquifer group (Figures 5–8, respectively).

All the potentiometric surface maps in Figures 5 through 13 show a general pattern of west and northwest flow toward the Red River. Some exceptions are found on Figure 5 (rlf aquifer group). Local flow patterns in the Buffalo aquifer are complex because of long-term pumping effects. Converging groundwater flow patterns due to pumping are also apparent in the Moorhead area in the nh aquifer, ot/nv and dg/br aquifer group, and the h1 and h2 aquifers (Figures 7–11, respectively).

Aquifer discharge to rivers also creates convergent flow toward the river. This type of local groundwater flow is apparent in the gr aquifer group, nh aquifer, and ot/nv aquifer group maps (Figures 6–8, respectively) in the northeastern part of the county along the South Branch Wild Rice River. Convergent groundwater flow created by groundwater discharge is also apparent along the Buffalo River in the east-central part of the county in the gr and ot/nv aquifer groups, the h1 and h2 aquifers, and the h3/h4 aquifer group (Figures 6, 8–12, respectively).

Bedrock aquifers

Our direct knowledge of bedrock geologic units and aquifers in Clay County is based on several scattered drill holes (Part A, Plate 2) because most water-well users are able to find adequate aquifers in the shallower overlying buried sand aquifers. The bedrock or bedrock related groundwater sources are used to a very limited extent in the county and include fractured Precambrian crystalline (metamorphic and volcanic) bedrock, the upper weathered portions (saprolite) of this crystalline bedrock, and the overlying Cretaceous sandstone.

The entire county is underlain by the Precambrian bedrock but its use as a water source is very rare and limited to one reported location for domestic use north of Dilworth. The extent of the saprolite above the bedrock is also poorly understood because of the relative lack of deep boreholes in the county. The saprolite layer consists of clay that was originally the feldspar crystals of the Precambrian bedrock, and can also include intact clasts of the original bedrock. The relict rock clasts and fracturing within the saprolite may create enough porosity and permeability to allow limited groundwater flow and storage within the layer. Only eight reported domestic wells in the western portions of the county use this layer as an aquifer.

Cretaceous shale and sandstone is limited to five small (less than a section) locations in the western part of the county, but may be more extensive in the county based on mapping in adjoining North Dakota (Part A, Plate 2). Four wells, three domestic and one public supply, produce water from the Cretaceous sandstone in the western part of the county.

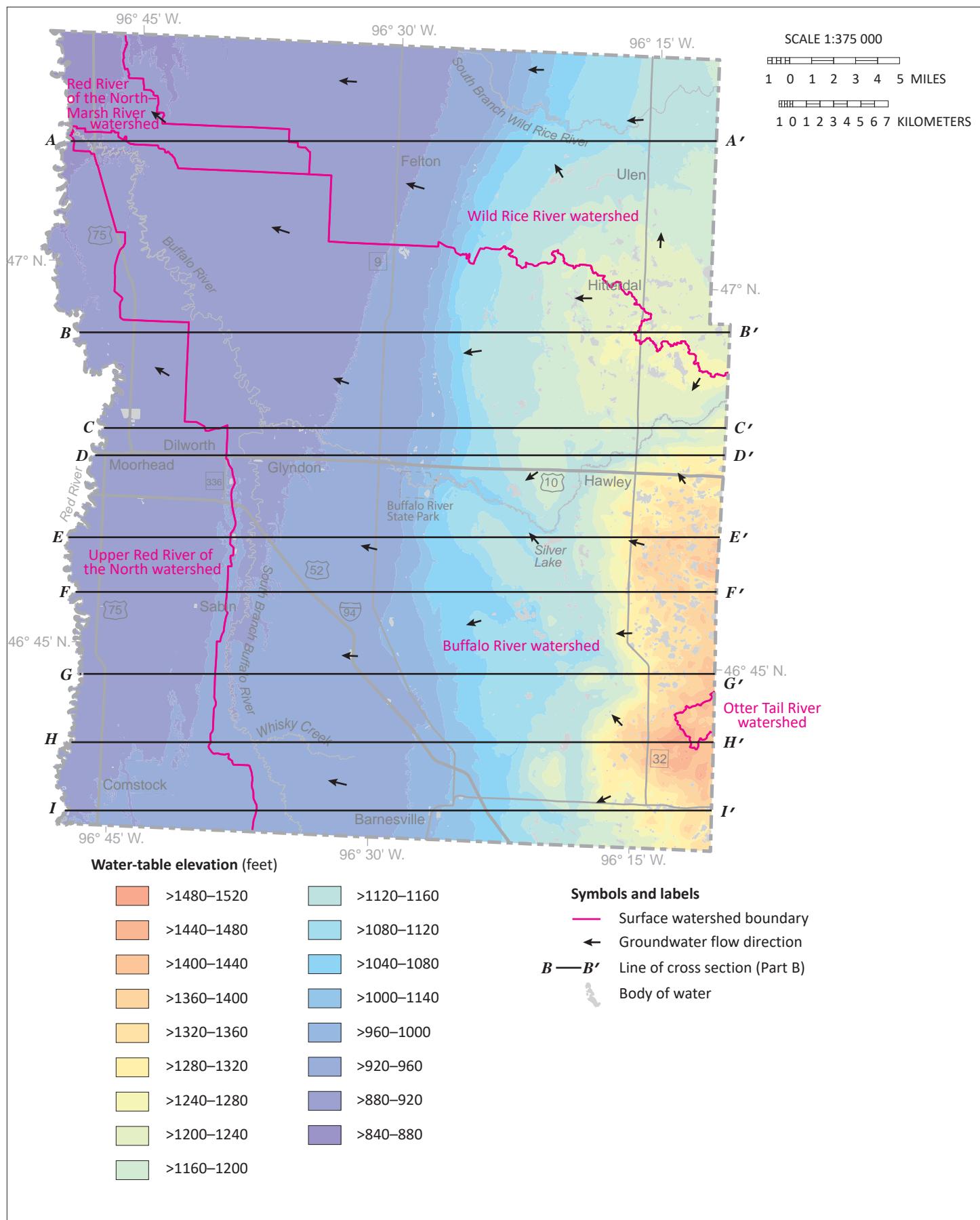


Figure 2. Water-table elevation and groundwater flow directions

The main groundwater flow directions are westerly toward the Red River. Local water-table flow directions are toward tributaries of the Red River, such as the Wild Rice and Buffalo rivers, and Whisky and Stony creeks.

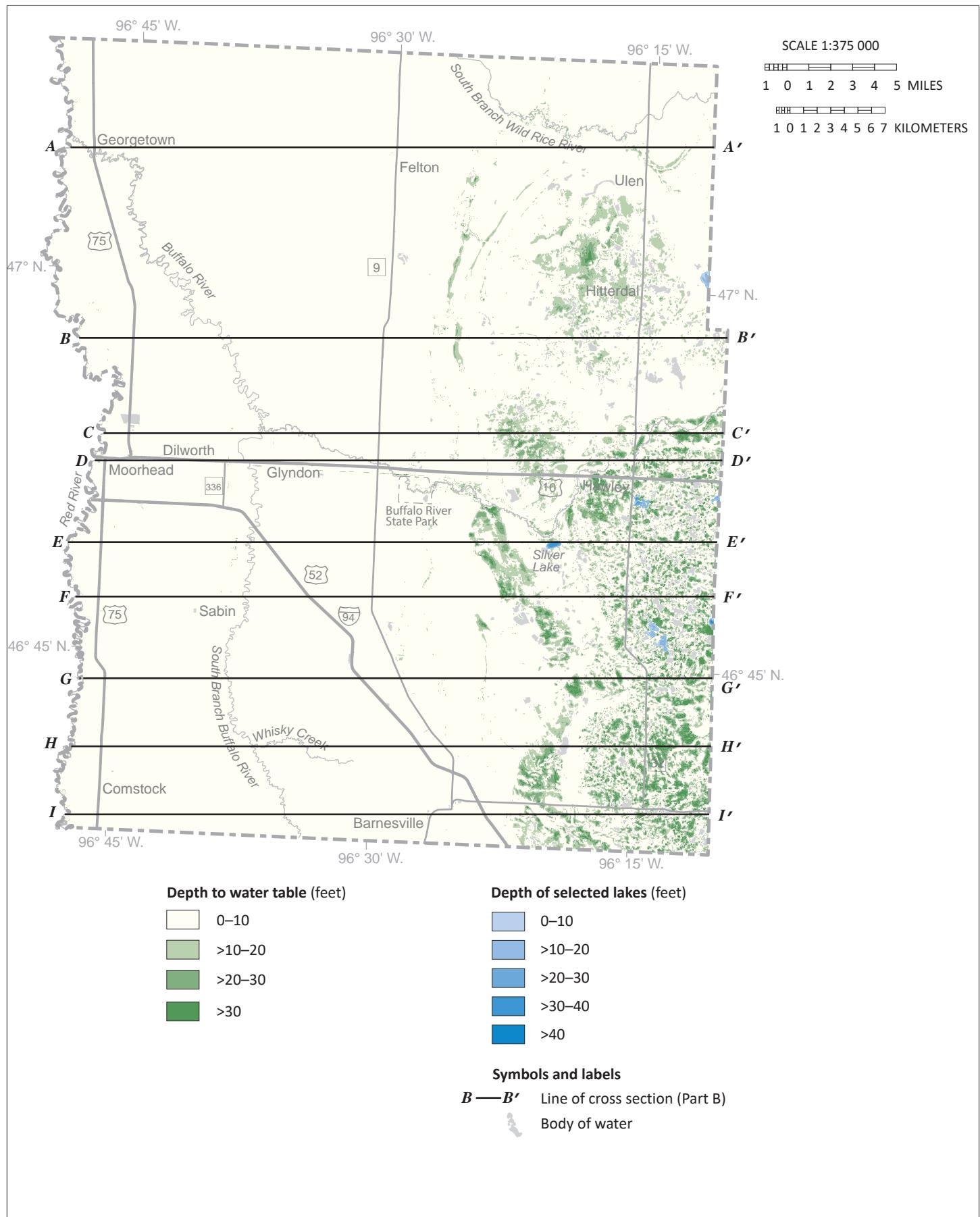


Figure 3. Depth to water table

Water-table depths are shallow (0–10 feet) in the flatter western part of the county and some of the eastern portion. Most of the deeper water-table areas are beneath the hills of the Alexandria moraine where depths of 10 to greater than 30 feet may be common, especially in the southeastern part of the county.

Geologic units	Part A	Aquifer group	Part B	Figures
Surficial sand and gravel	ha, wls, wlg	ss		
Sherack Formation	sl			
Poplar River Formation	prf	prf		No figure
Brenna Formation	bl			
	ro, roc			
Red Lake Falls Formation	rpt			
	rlt	rlf		
	rgs (Buffalo aquifer)			5, 25
	grb, gro			
Goose River Formation	gss, gsg			
	gst	gr		
	gds, gdg			
	gdt			
	nhl			
New Ulm Formation (1)	nhs, nhg	nh		
	nht			
	olu			
Otter Tail River Formation	osu, ogu			8, 29
	otu			
	ons	ot/nv		8, 29
	ont			
New Ulm Formation (2)	nvs, nvg			8, 29
	nvt			
	dgs, dgg			
Gardar Formation	dgt	dg/br		9, 30
	brl			
Buffalo River Formation	brs			9, 30
	brt			
	hl1			
Hewitt Formation (1)	hs1, hg1	h1		
	ht1			
	hl2			
Hewitt Formation (2)	hs2, hg2	h2		11, 32
	ht2			
	hl3			
Hewitt Formation (3)	hs3, hg3			12, 33
	ht3			
	hl4			
Hewitt Formation (4)	hs4, hg4	h3/h4		12, 33
	ht4			
	bvs, bvg			34
Browerville Formation	bvt			
	gvt			
Gervais Formation	x1l			
	x1s	bv/x		34
	x1t			
Unnamed formation	x2s			34
	x2t			
	x3s			34
	x3t			
	qsu1			13, 35
Undifferentiated sediment	qtu1	qu		
	qsu2			
	qtu2			
	qu			13, 35

Figure 4. Hydrostratigraphy of Quaternary unconsolidated sediment

Correlation of Part A and B unit names and map labels.

Part A

Sediment texture description is shown on the left side for reference and unit identification only. Generally, Part A geologic descriptions are classified as either sand and gravel (tan), or till and lake clay (greens and blues).

Part B

The generalized geologic descriptions are converted into the hydrogeologic descriptions of aquifer or aquitard, respectively.

Aquifers are shown with *patterns*.

Aquitards are shown with shades of gray. The shades correspond to the percent sand content indicating relative hydraulic conductivity. Lighter shades indicate higher conductivity.

Units of *undifferentiated* sediment are shown in *brown*.

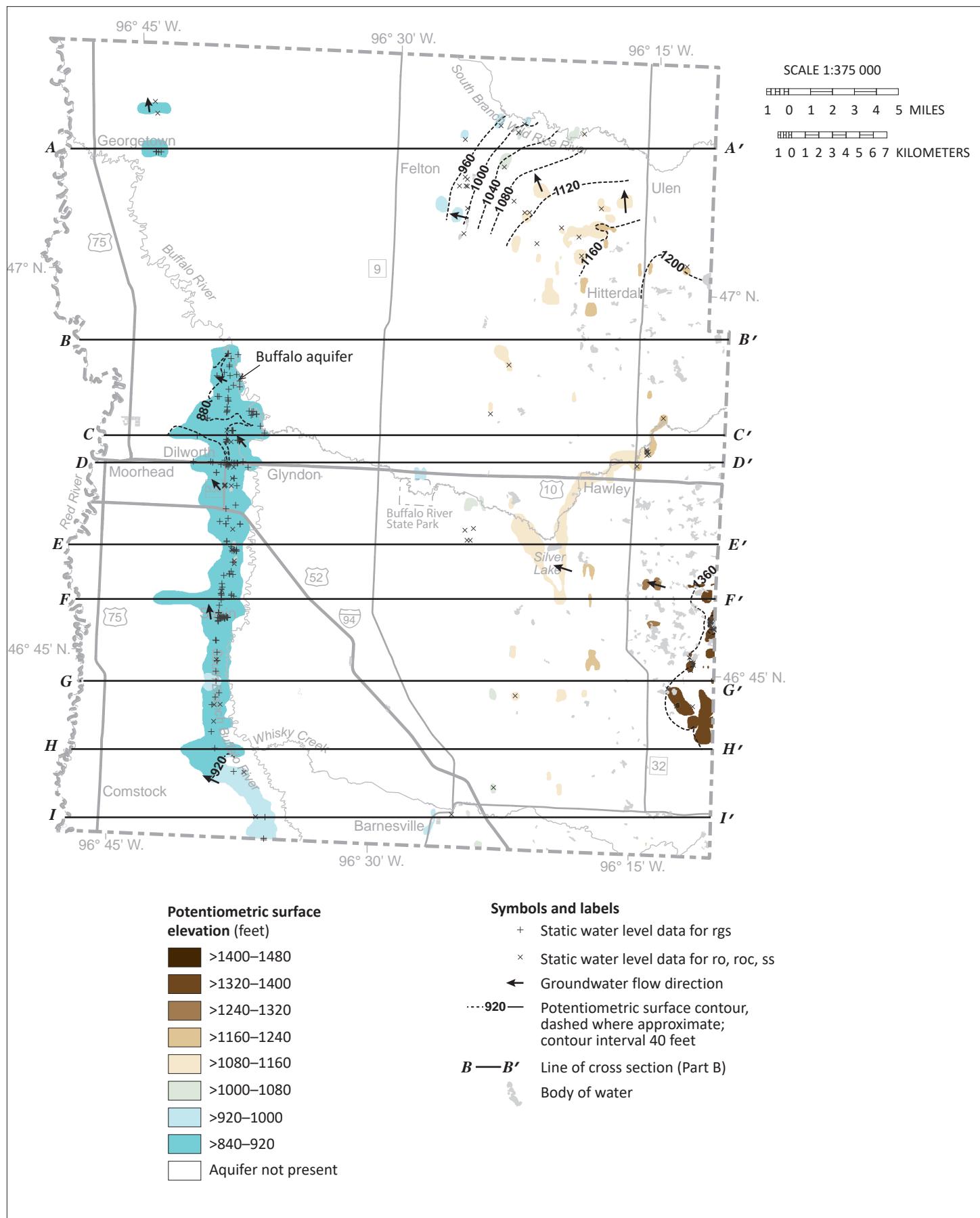


Figure 5. Potentiometric surface of the rif aquifer group

The general groundwater flow pattern is west and northwest toward the Red River. The ro and roc units are shown in the eastern part of the county. The rgs unit (Buffalo aquifer) is in the western portion, shown east of Moorhead to the southern county border.

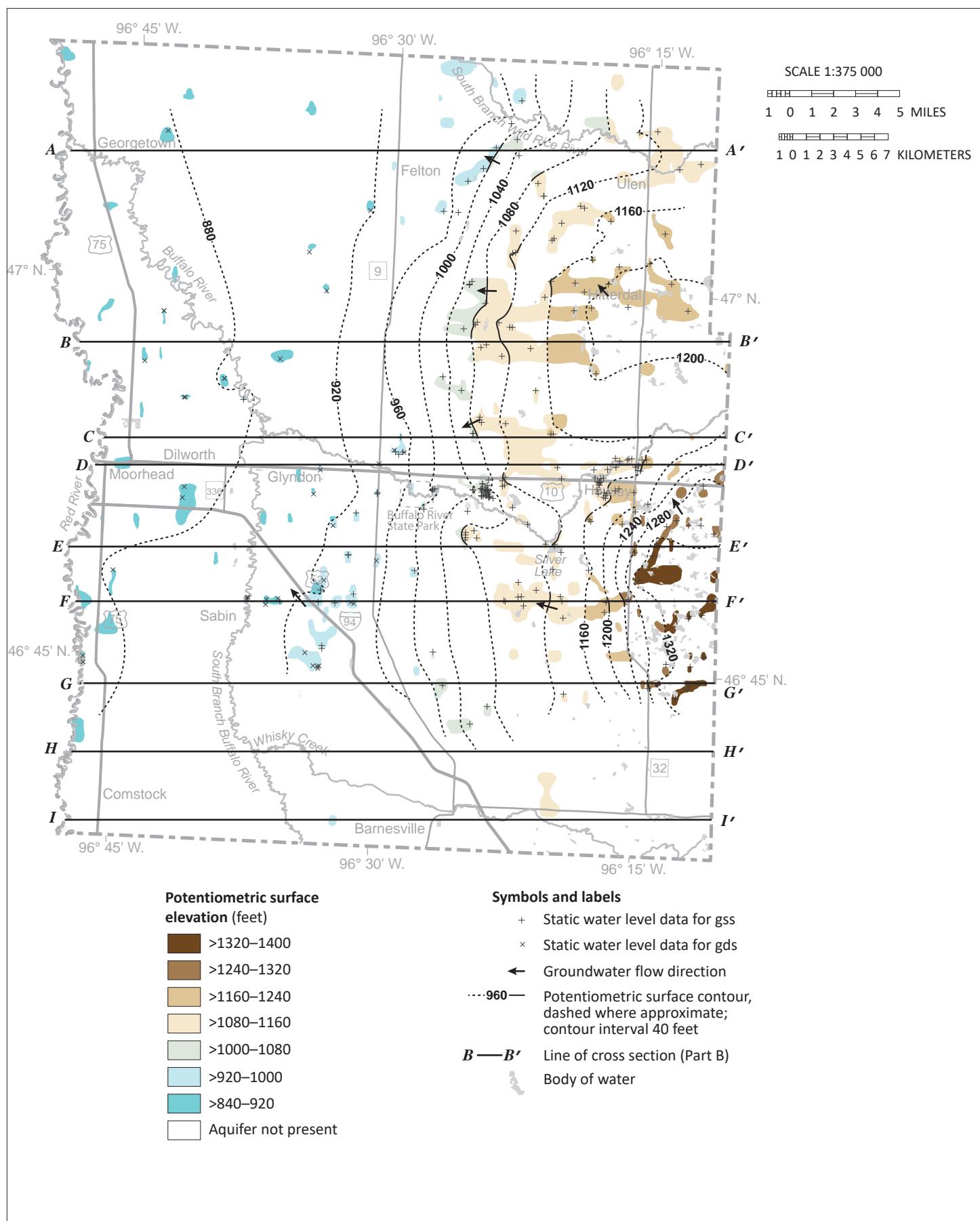


Figure 6. Potentiometric surface of the gr aquifer group

The general groundwater flow pattern is west and northwest toward the Red River. Aquifer discharge to rivers also creates convergent flow toward rivers. This type of local groundwater flow is apparent in the northeastern part of the county along the South Branch Wild Rice River and the Buffalo River in the east-central part of the county.

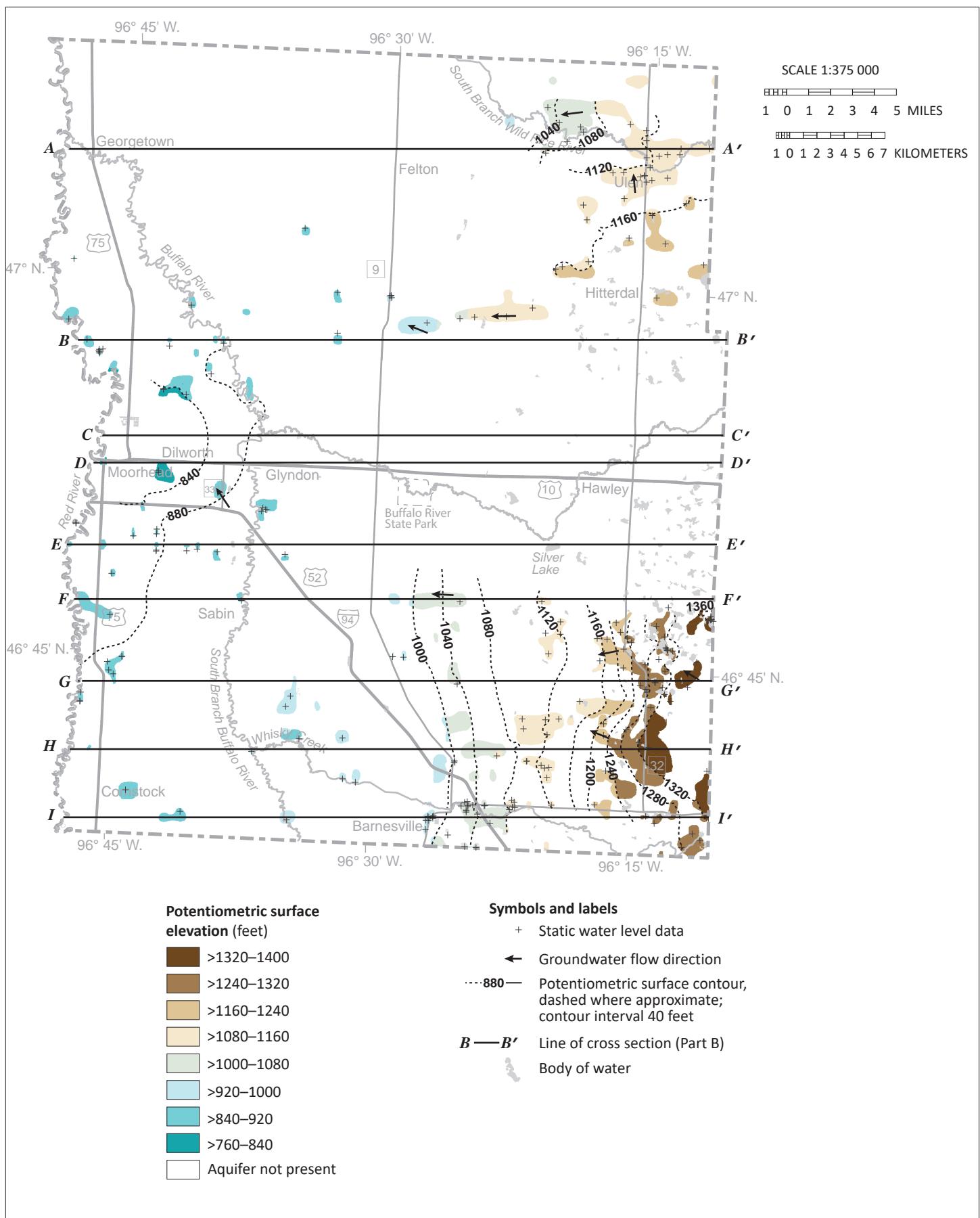


Figure 7. Potentiometric surface of the nh aquifer

The general groundwater flow pattern is west and northwest toward the Red River. Converging groundwater flow in the Moorhead area is from groundwater pumping. Aquifer discharge to rivers also creates convergent flow toward rivers. This type of local groundwater flow is apparent in the northeastern part of the county along the South Branch Wild Rice River.

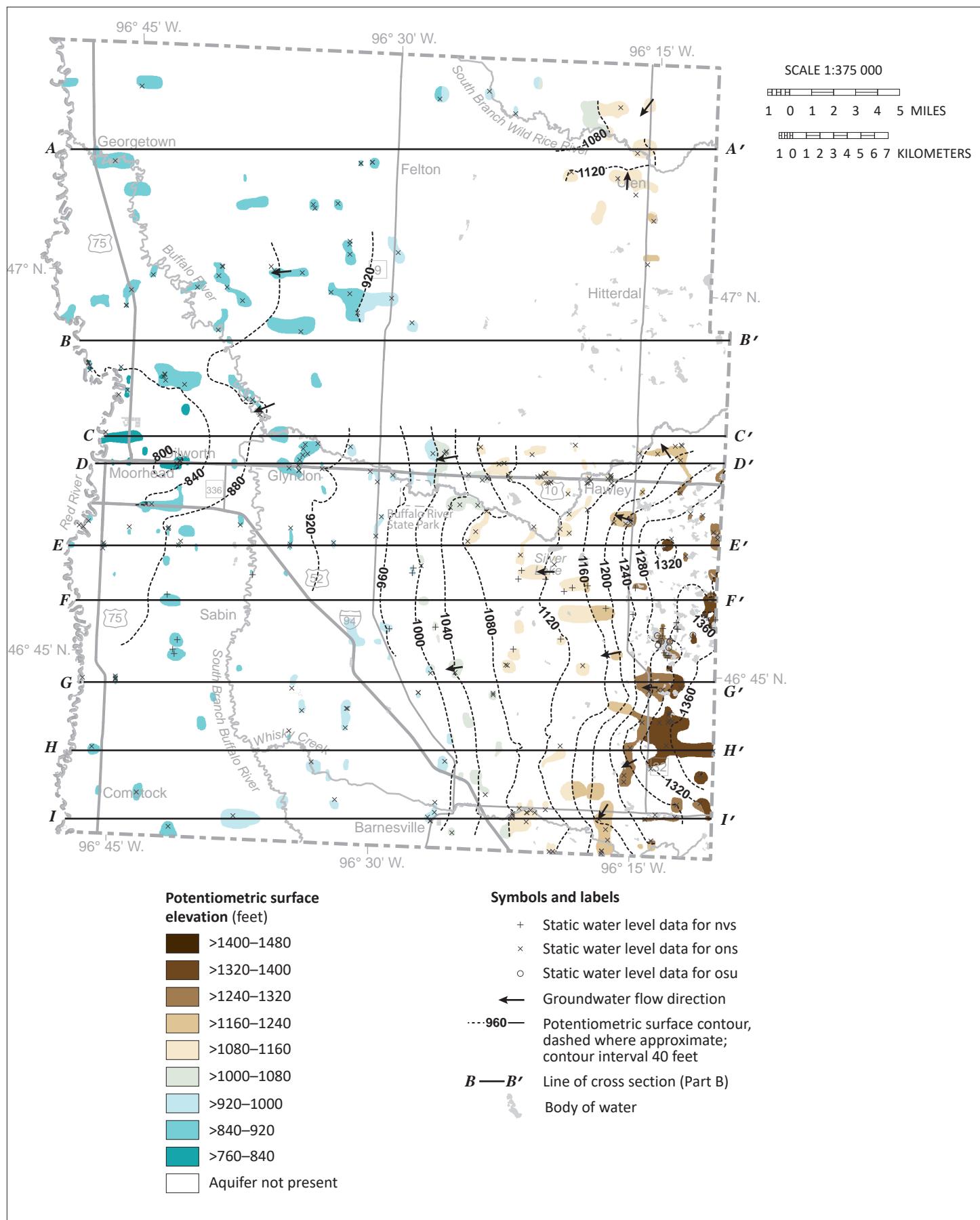


Figure 8. Potentiometric surface of the ot/nv aquifer group

The general groundwater flow pattern is west and northwest toward the Red River. Converging groundwater flow in the Moorhead area is due to groundwater pumping. Aquifer discharge to rivers also creates convergent flow toward rivers. This type of local groundwater flow is apparent in the northeastern part of the county along the South Branch Wild Rice River and in the east-central part of the county in the Buffalo River.

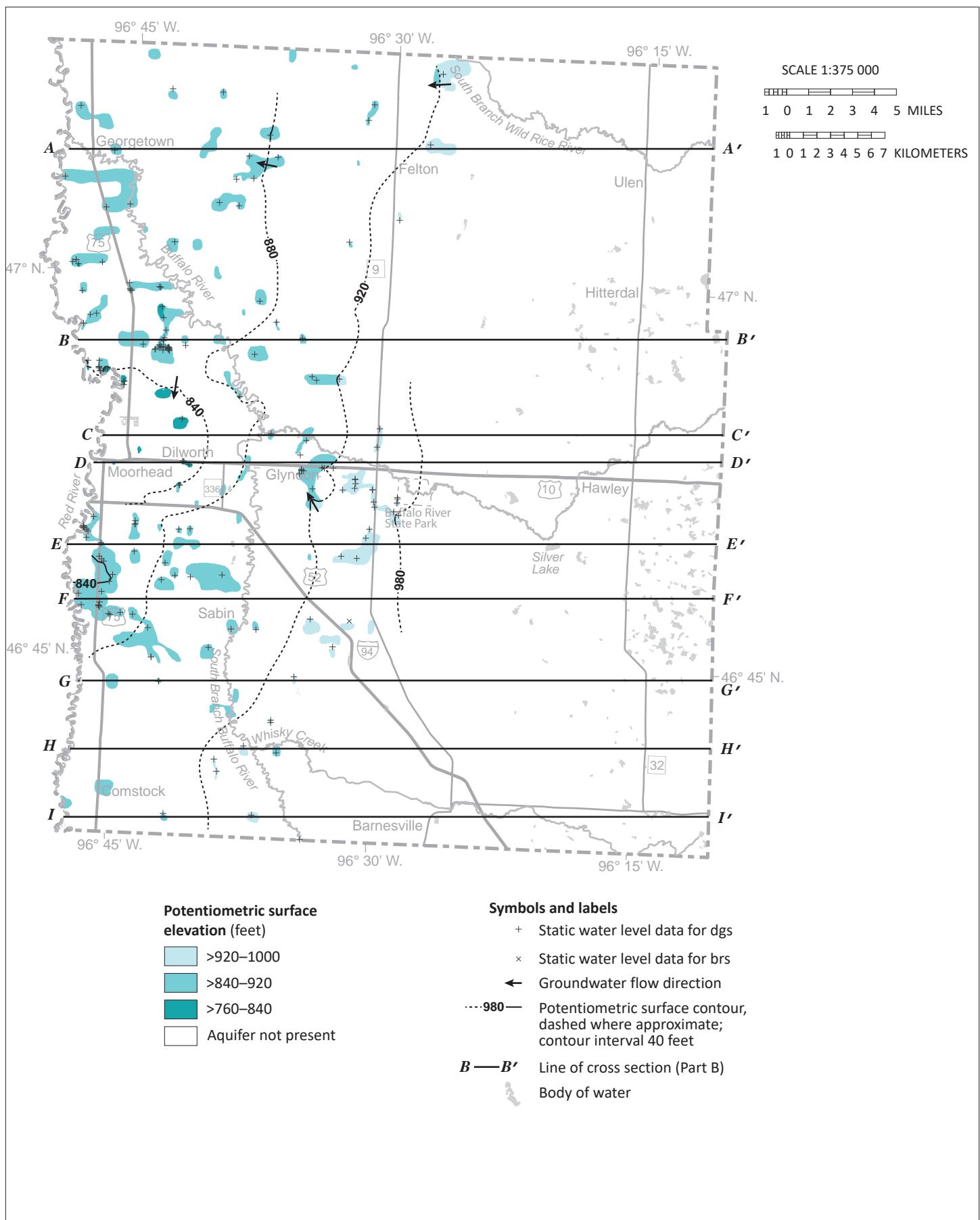


Figure 9. Potentiometric surface of the dg/br aquifer group

The general groundwater flow pattern is west and northwest toward the Red River. Converging groundwater flow in the Moorhead area is from groundwater pumping.

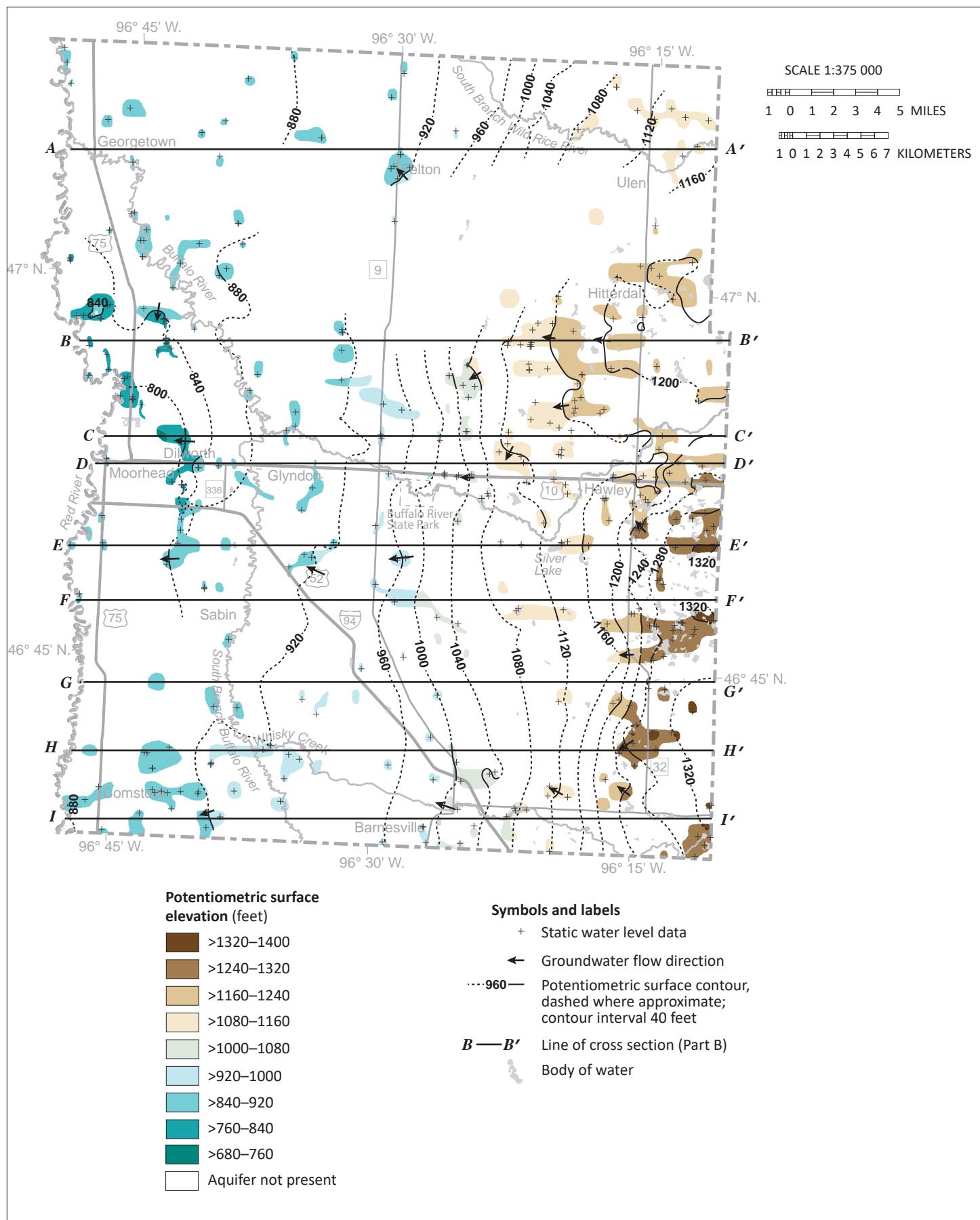
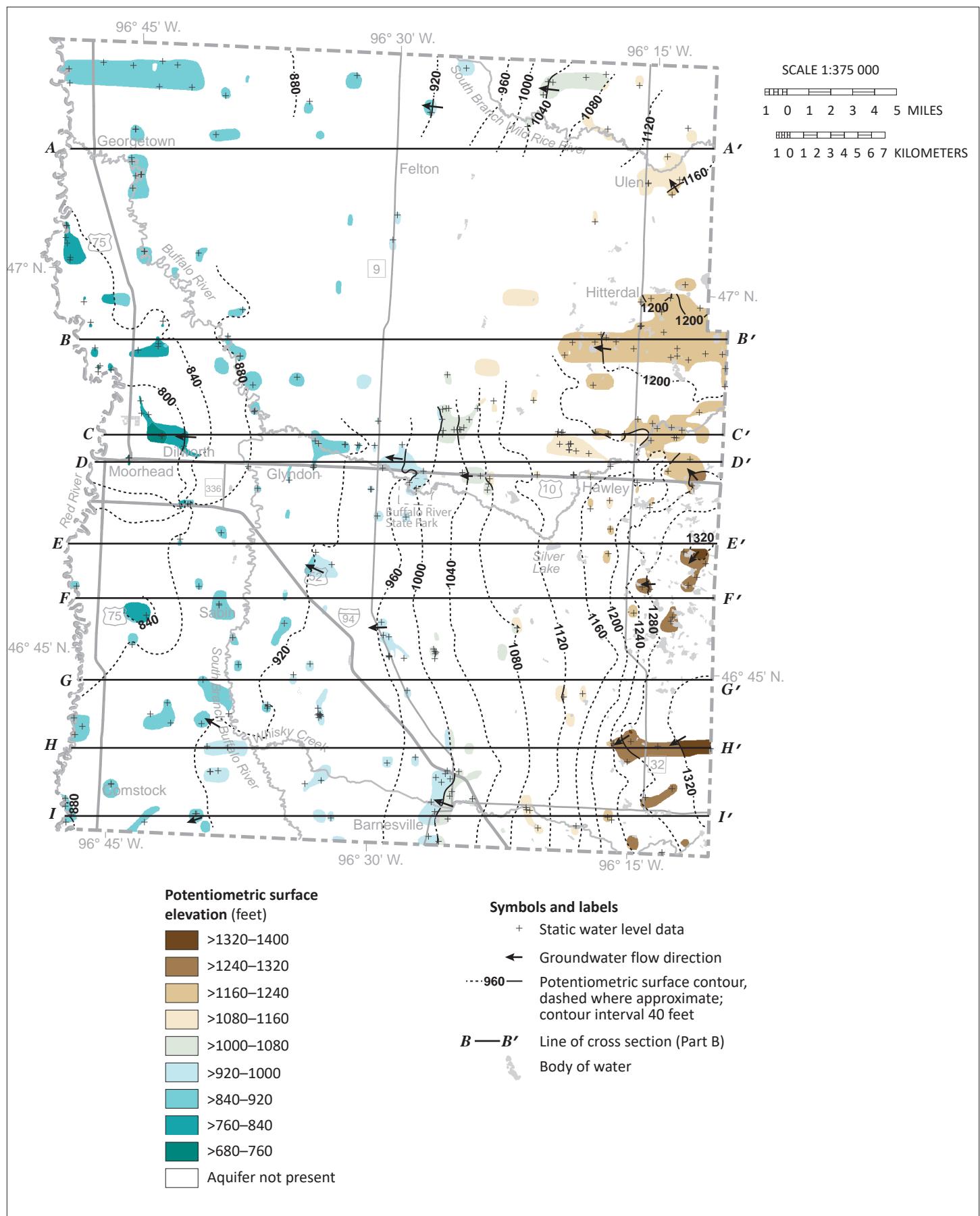


Figure 10. Potentiometric surface of the h1 aquifer

The general groundwater flow pattern is west and northwest toward the Red River.



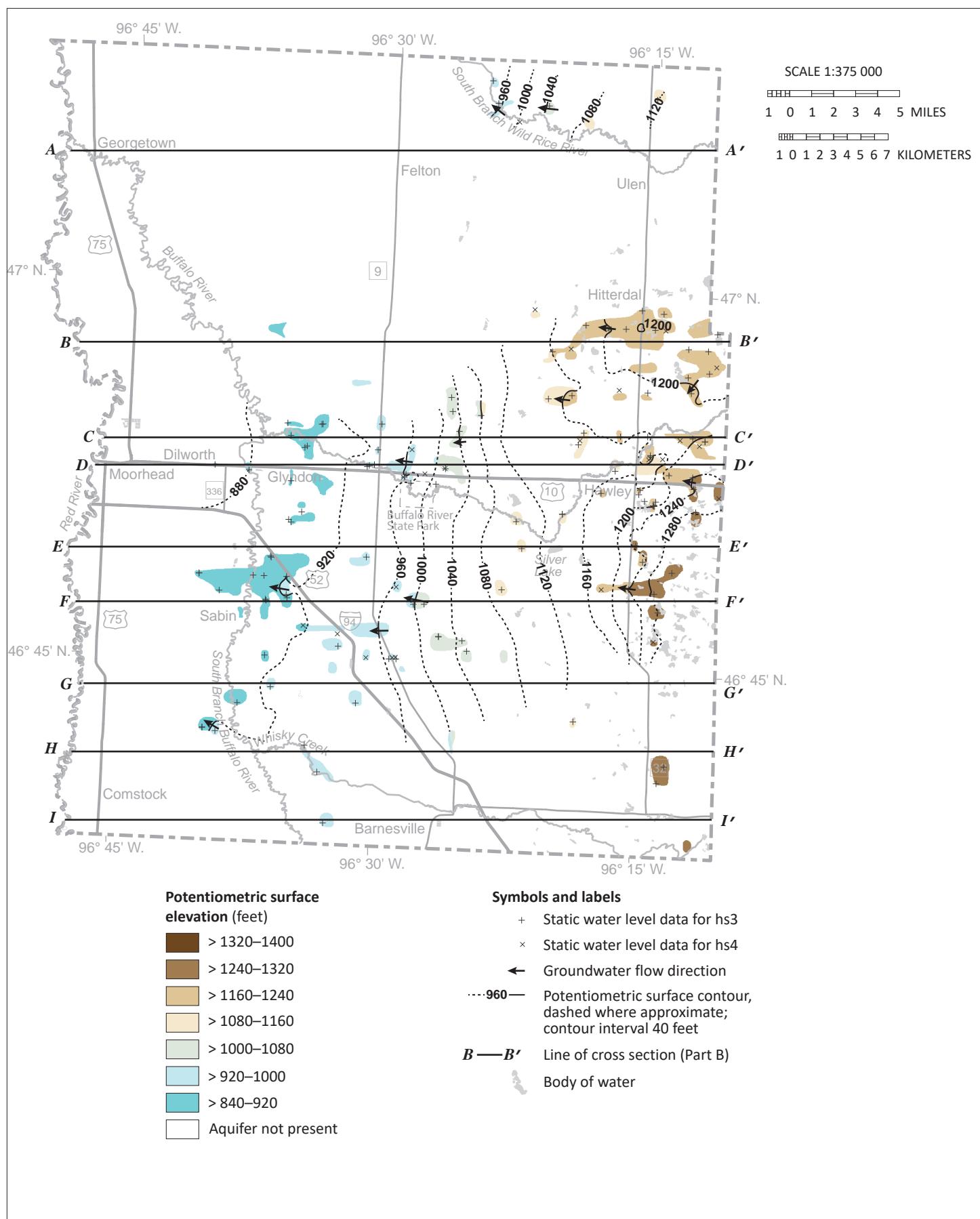


Figure 12. Potentiometric surface of the h3/h4 aquifer group

The general groundwater flow pattern is northwest toward the Red River.

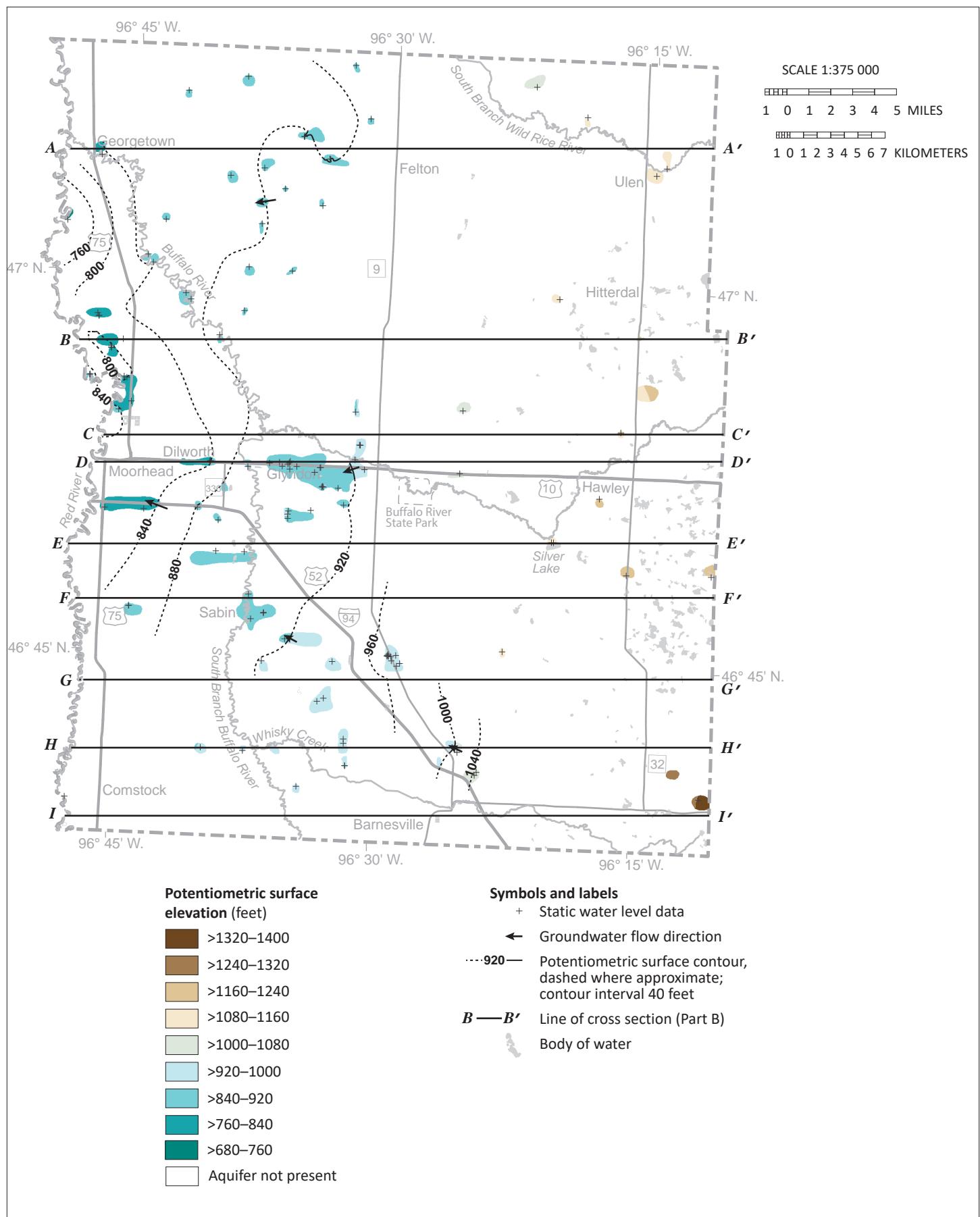


Figure 13. Potentiometric surface of the qu aquifer group

The general groundwater flow pattern is west and northwest toward the Red River.

Water chemistry (Plate 6)

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

- Groundwater recharged from surface water can be identified from the effect of evaporation on the isotopes of hydrogen and oxygen. Stable isotope data are used in this report as indicators of the water source and to infer the climate and atmospheric temperature at the time the water fell as precipitation. Cold climatic conditions of precipitation from the last ice age can be inferred from these data. When evaluated in this manner, the stable isotope data are ancient atmospheric temperature indicators.
- Groundwater residence time is estimated from tritium and carbon-14 isotopes. Tritium is used to identify water that has moved into the subsurface since the 1950s. Carbon-14 is used to determine groundwater residence times of centuries to millennia.
- The distribution of select chemical elements can indicate areas where groundwater consumption is a potential concern to human health.

Groundwater recharge sources and paleoclimates

Chemical changes occur as water moves from precipitation to groundwater. These chemical characteristics can help determine whether groundwater was recharged directly from precipitation, lake water, or a mixture of the two. Stable isotopes of oxygen and hydrogen were used for determining groundwater and surface-water interactions (Kendall and Doctor, 2003) and to infer the relative ancient atmospheric temperature of the precipitation that is now in aquifers (Persons and others, 2007; Remenda and others, 1994).

Oxygen and hydrogen each have two main stable isotopes: ^{18}O and ^{16}O , and ^2H and ^1H . The different mass of the isotopes causes each to evaporate at different rates, which results in fractionation, leaving behind different ratios of heavy to light isotopes. This results in isotopic signatures that are unique to groundwater with different sources of recharge and atmospheric temperatures during precipitation.

Water sampling

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

An ideal well-sampling network for the atlas is evenly distributed across the county, includes populated areas, and targets surface water and groundwater interaction around lakes and larger rivers. The network depends on citizen willingness to participate. Approximately 1000 well owners were contacted and approximately 30 percent gave permission for sampling. Of the well owners who responded (approximately 300), 89 locations were chosen for sampling.

The sampling from Clay County for this project included 89 well samples and 1 lake sample, 36 well samples from a previous DNR project (Trojan, 1997), 7 well samples from the Minnesota Pollution Control Agency (MPCA), and 35 well and 3 surface-water samples from the Minnesota Department of Health.

- Groundwater recharged from *surface water* such as lakes or wetlands has an *evaporative* isotopic signature favoring *heavier* isotopes. It was subjected to fractionation where the lighter isotopes preferentially evaporated into the atmosphere.
- Groundwater recharged directly from *precipitation* has a *meteoric* isotopic signature. The water infiltrated directly into the ground, leaving the isotopic ratio *unchanged*.
- Groundwater recharged from *glacial precipitation* favors a *lighter* isotopic signature. The colder temperatures of the Pleistocene era increased the fractionation, which occurred in two processes. First, the lighter ^{16}O isotope evaporated from the ocean more easily, creating clouds with slightly more ^{16}O than seawater.

Second, the heavier ^{18}O isotopes were preferentially removed by precipitation as the clouds traveled. The clouds that finally reached the interior of the continent had a lower $^{18}\text{O}/^{16}\text{O}$ ratio, creating snow with a relatively light isotopic signature (Figure 14 illustration at top).

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

Definition of delta (δ)

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

Recharge results

In the Figure 14 chart (bottom), county results are compared to the global meteoric water line, which was developed from precipitation data from around the world (Craig, 1961).

Surface water (evaporative)

The stable isotope samples that were altered by fractionation during evaporation plot on the far right of the graph along a trend that has a lower slope than the global meteoric water line. These include four surface-water samples for reference and two groundwater samples from the southeastern part of the county. The sample near the eastern end of cross section F-F' has numerous surface-water source possibilities from lakes and wetlands in adjoining Becker County. The sample east of Barnesville is probably sourced from a small lake just west of Tansem Lake.

The absence of evaporative signatures from wells near other lakes or lake areas does not necessarily indicate that evaporative signature water is rare in Clay County groundwater, but may be more of an artifact of the sampling strategy. Samples from wells at ideal locations and depths are not always available because of permission limitations. Samples were limited to wells volunteered by homeowners.

Precipitation (meteoric)

The majority of the Clay County samples plot along the meteoric water line which indicates that these samples are from precipitation (rain and snow melt) that infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface-water bodies.

This group of direct infiltration samples can be further divided into samples that were from snow and ice melt from the last ice age (glacial), samples from precipitation that fell after the last ice age (post-glacial), and mixtures of those two endpoints (glacial and post-glacial).

The lighter isotopic sample values plot on the lower left and occur mostly in the western portion of the county (Figure 15) beneath the Lake Agassiz clay (f and Brenna formations). Remenda and others (1994) indicated a threshold for glacial ice water at approximately $\delta^{18}\text{O} = -19$. This light isotopic signature indicates the precipitation was from a much colder ice-age climate that existed across Minnesota and North America.

After the glaciers receded, post-glacial recharge of heavier isotopic water mixed with and replaced these lighter isotopic waters in all but the most isolated aquifers, such as those beneath the impermeable Lake Agassiz clay. Carbon-14 residence times are shown on Figure 15 for reference. Three of the glacial meltwater samples have residence times ranging from 30,000 to 40,000 years, which matches part of the Wisconsinan Episode (Part A, Plate 4, Figure 2). Similar relicts of Pleistocene precipitation from aquifers beneath the Lake Agassiz clay also exist across the state border in North Dakota (Ripley, 2000) and Manitoba (Remenda and others, 1994). Mixed glacial groundwater may have also been found in relatively isolated aquifers in adjoining Wilkin County (Berg, 2012).

The approximate extent of the Lake Agassiz clay is delineated in Figure 15 by the thickness (color gradation) and the beach ridges that were created at the shorelines (zone of irregular lines). This 2- to 6-mile wide zone of beach ridges gradually increases in land elevation from west to east. The ridge farthest west and lowest in elevation marks the approximate eastern edge of the lake clay and will be used as a hydrogeologically significant reference line for many figures in this report.

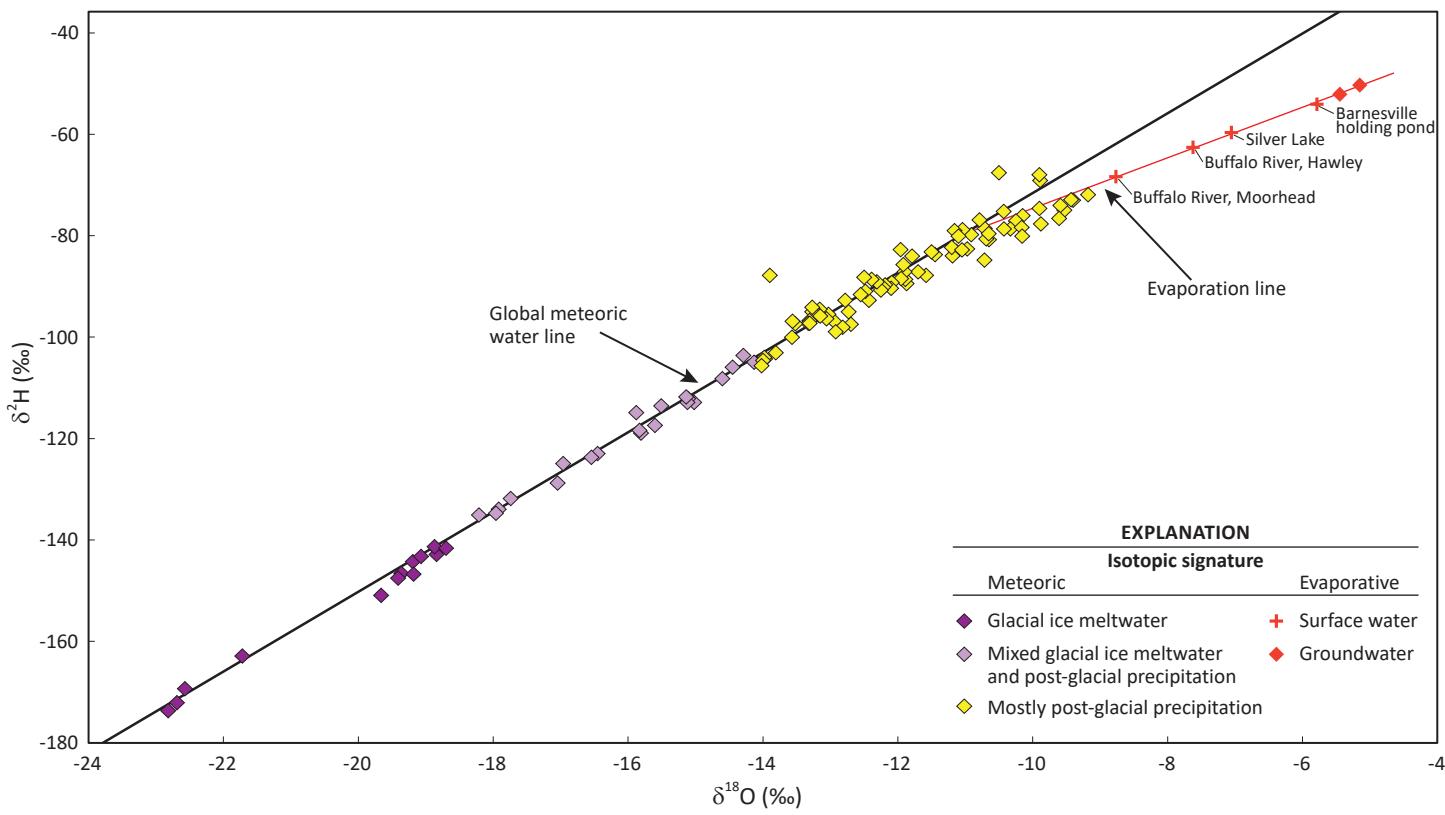
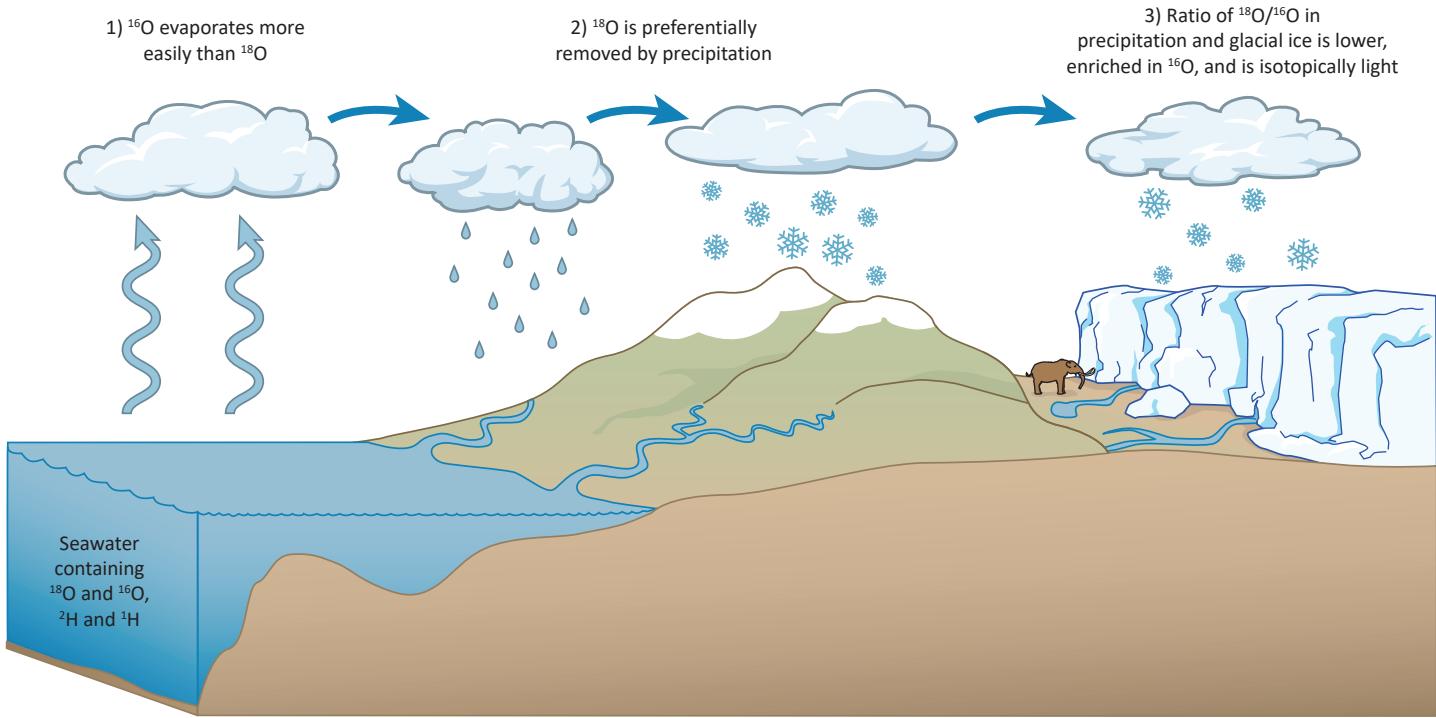


Figure 14. Stable isotopes

Top illustration: changing isotopic signatures of water vapor and precipitation. Groundwater recharged during glacial periods favors a lighter isotopic signature. The colder temperatures of the Pleistocene era increased the fractionation, which occurred in two processes. First, the lighter ^{16}O isotope evaporated from the ocean more easily, creating clouds with slightly more ^{16}O than seawater. Second, the heavier ^{18}O isotopes were preferentially removed by precipitation as the clouds traveled. The clouds that finally reached the interior of the continent had a lower $^{18}\text{O}/^{16}\text{O}$ ratio, creating snow with a relatively light isotopic signature.

Bottom graph: stable isotope values from water samples are compared to the global meteoric water line. Groundwater from direct infiltration of precipitation generally plots along the meteoric water line. Groundwater from melted glacial ice water is indicated for samples shown on the lower left of the graph. Groundwater recharged from surface-water sources plots along an evaporation line at a shallower slope. The transition between the mixed glacial ice meltwater and post-glacial precipitation category to the mostly post-glacial precipitation category is uncertain but may be a range of ^{18}O values spanning $\delta^{18}\text{O} = -14$. Figure 15 shows locations for these types of recharge.

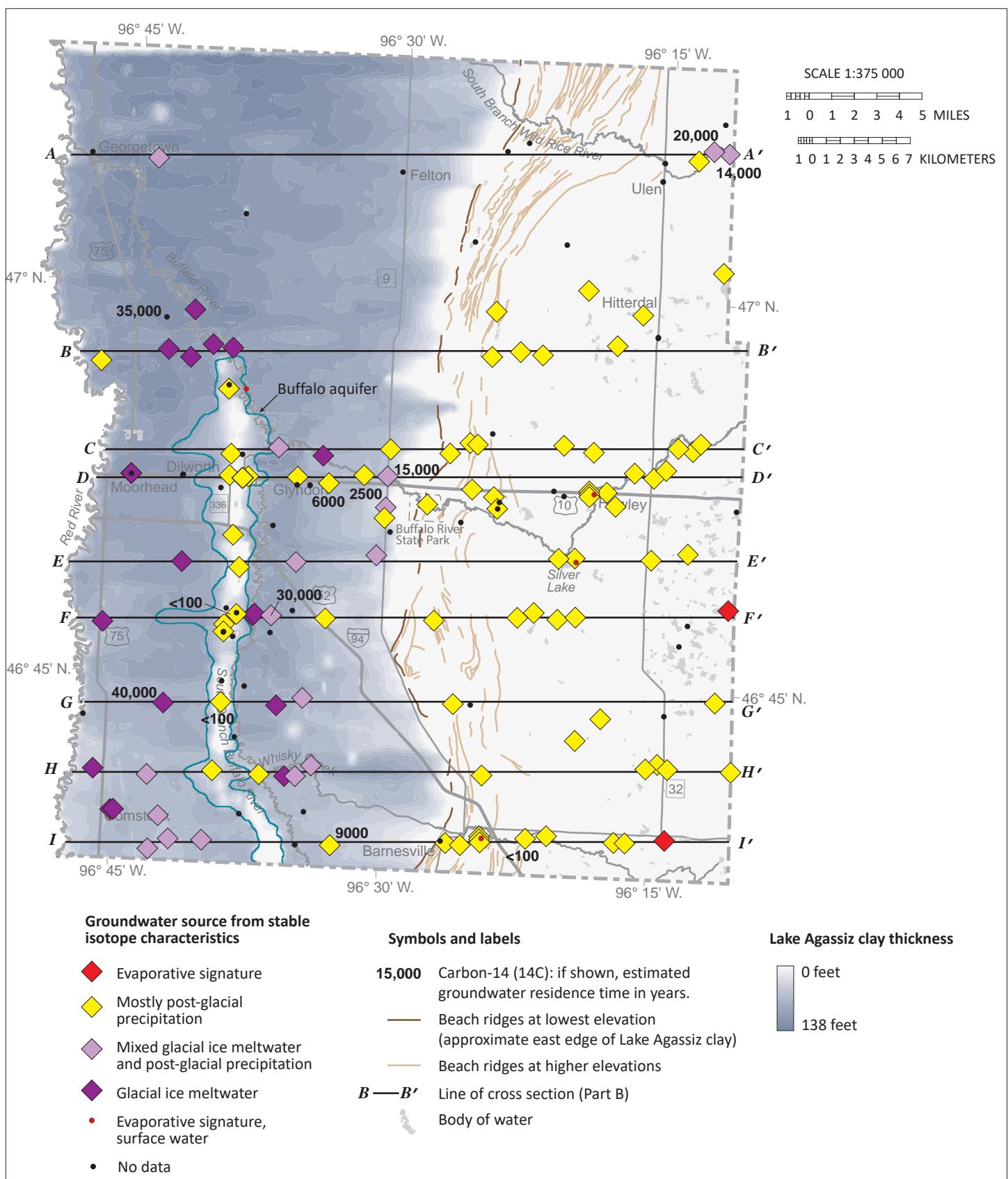


Figure 15. Groundwater stable isotope characteristics, carbon-14 residence time, and extent of Lake Agassiz clay

The lighter isotopic sample values occur mostly in the western portion of the county beneath the Lake Agassiz clay (glacial ice meltwater and mixed glacial ice meltwater). The lightest isotope groundwater (most negative values) indicate precipitation in a colder climate that existed across Minnesota. Groundwater recharged from *post-glacial precipitation* that infiltrated directly into the ground is mostly associated with the eastern part of the county and the extent of the Buffalo aquifer. Groundwater recharged from *surface water* such as lakes or wetlands has an *evaporative* isotopic signature and is found at scattered locations in the eastern part of the county.

Groundwater residence time indicators

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

Tritium

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

- **Cold War era:** water entered the ground from the peak period of atmospheric tritium concentration from nuclear

bomb testing, 1958–1959 and 1961–1972 (greater than 15 TU).

- **Recent:** water entered the ground since about 1953 (8 to 15 TU).
- **Mixed:** water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- **Vintage:** water entered the ground before 1953 (less than or equal to 1 TU).

Historical data were used in the residence time interpretations of this report (sample dates from 1991 to 1996). More than 20 years later the groundwater in the aquifers that yielded these samples has moved and recharged. Therefore the tritium samples from historical data that were originally classified as *Cold War era* have been recategorized as *recent* (Appendix B).

Carbon-14

The carbon-14 (^{14}C) isotope is used to estimate the residence time for selected vintage and mixed tritium-age samples. This naturally occurring isotope has a half-life of 5,730 years, and is used to estimate groundwater residence time ranging from 100 to over 40,000 years (Alexander and Alexander, 1989). Carbon-14 samples of less than 100 years are represented as <100 on maps and cross sections.

Inorganic chemistry of groundwater

Water begins dissolving minerals in the soil, sediment, and bedrock as soon as precipitation infiltrates the soil layer and becomes groundwater. Water chemistry is used to characterize changes in inorganic chemistry as water moves deeper.

Water quality describes contaminants that are potentially harmful (natural or anthropogenic) and aesthetics (hardness, taste, odor, color). The following guidelines are used in this atlas.

U.S. Environmental Protection Agency (EPA 2017 July, EPA 2017 March):

- **Maximum Contaminant Level (MCL):** legally enforceable federal standards that apply to public water systems, to limit the levels of contaminants in drinking water.
- **Maximum Contaminant Level Goal (MCLG):** nonenforceable health goals set on possible health risks from exposure over the course of a lifetime.
- **Secondary Maximum Contaminant Level (SMCL):** nonenforceable guidelines for contaminants that may cause cosmetic or aesthetic effects in drinking water.

Minnesota Department of Health (MDH, 2012a):

- **Health Risk Limit (HRL):** the concentration of a groundwater contaminant, or a mixture of contaminants, that can be consumed with little or no risk to health and which has been promulgated under rule.
- **Health Based Value (HBV):** derived using the same algorithm as HRLs; however, they have not yet been promulgated as rules.

Results of water sample analysis are presented for inorganic chemistry, including the major cations and major anions, reported in units of parts per million (ppm). Trace elements such as arsenic and manganese are typically reported in units of parts per billion (ppb). The following chemicals are naturally occurring. Some are harmful at elevated levels, others can be elevated by anthropogenic activities.

- **Calcium, magnesium, and sodium cations; bicarbonate anions** are dissolved out of the glacial sediment and bedrock by groundwater. The calcium, magnesium, and bicarbonate constituents are derived from limestone and dolomite bedrock sources (Hem, 1985) and are common in groundwater in glacial sediment aquifers. Sodium is

often present in deep aquifers or at mineral interfaces. As groundwater moves through aquifer systems, calcium and magnesium ions are exchanged for sodium ions (Hounslow, 1995).

- **Sulfate** is largely naturally occurring, and is an important constituent of groundwater in parts of the county. High concentrations in groundwater can negatively affect the taste and may act as a laxative (SMCL 250 ppm).
- **Chloride** can occur naturally from deep sources such as residual brine, or it may come from road salts, water softener salts, and fertilizers (SMCL 250 ppm). Chloride is elevated if concentrations are greater than or equal to 5 ppm. It is anthropogenic if chloride/bromide ratios are greater than 250.
- **Nitrate-nitrogen (nitrate)** can occur naturally at low concentrations but elevated concentrations (greater than or equal to 1 ppm) are typically from fertilizer and animal or human waste (MDH, 1998; Wilson, 2012). Both the MCL and HRL for nitrate is 10 ppm. Nitrate concentrations lessen with time (denitrification) when there is little oxygen in the groundwater. In Minnesota, groundwater with long residence time typically has little available oxygen and little to no nitrate.
- **Arsenic** is a naturally occurring element that has been linked to negative health effects, including cancer. The EPA MCL is 10 ppb, the MCLG is zero. The MDH advises domestic well owners to treat drinking water if arsenic values equal or exceed method reporting limits (MDH, 2018a). Current science cannot predict which wells will have high arsenic concentrations, therefore newly constructed wells are tested for arsenic if they are used for drinking water (Minnesota Administrative Rules 4725.5650, 2008).
- **Manganese** is a naturally occurring element that is beneficial to humans at low levels, but high levels may harm the nervous system (MDH, 2018c). In addition to health effects, elevated manganese concentrations (greater than 50 ppb) can cause negative secondary effects such as poor taste, odor, and water discoloration (stained laundry and plumbing fixtures). The current HBV for manganese is 100 ppb.

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

Results

Chloride

This anion is an anthropogenic contaminant in the Buffalo aquifer area and at scattered locations in the eastern

part of the county (Figure 16). Of the 105 samples with elevated chloride, 22 (21 percent) also had elevated chloride/bromide ratios. Most of these were in the upper (shallowest) aquifer groups (rlf, gr, and nh). Otherwise, most of the elevated chloride in groundwater samples is from natural sources.

In Clay County, chloride/bromide ratios less than 250 indicate that the chloride is likely from a deep natural source, based on comparisons with other chemical data and published references (Davis and others, 1998; Panno and others, 2006). Natural sources in the western part of the county could be from chloride that was retained from the inclusion of connate brine deposited with the marine sediments (Hem, 1985). Flow through the underlying materials (glacial sediments and Cretaceous and Precambrian bedrock) is very slow and flushing of the natural chloride is limited, similar to the relict glacial ice meltwater retained in aquifers beneath the Lake Agassiz clay. Conversely, the lack of anthropogenic chloride in buried aquifers in the western portion of the county is because of the protective effect of the Lake Agassiz clay.

Nitrate

Of the 159 samples tested for nitrate, 7 (4 percent) were elevated. Most were present in the eastern portion of the county in the relatively shallow gr and h1 aquifer groups (well depths 45 to 78 feet) but also in deeper wells in the nh and h2 aquifers (117 to 264 feet, respectively) in the southeastern part of the county (Figure 16, cross section H–H').

Arsenic

Of the 133 samples tested for arsenic in Clay County, 117 (88 percent) had values above the reporting limits (Figure 17) indicating a natural water quality problem for the majority of well owners in the county. Detectable arsenic values were found in all sampled aquifers or aquifer groups with the exception of the bv/x group. However, only two samples from the bv/x group were analyzed for arsenic. A similar high proportion of elevated arsenic values in Clay County groundwater (74 percent greater than 2 ppb) have been found in samples collected from 2008 to 2016 in new private wells (MDH, 2018b).

The factors affecting elevated arsenic concentrations in groundwater are not completely understood. There is a strong correlation with glacial sediments derived from rocks northwest of Minnesota, from the Riding Mountain provenance (Erickson and Barnes, 2005a). High arsenic concentrations are believed to be caused by naturally-occurring arsenic-bearing minerals that are associated with small shale particles in these tills. Some of this arsenic

was previously released and then adsorbed to surfaces of mineral crystals and other small particles during earlier oxidizing conditions. This surface-adsorbed arsenic (the most chemically available form) is released to groundwater under reducing conditions (Erickson and Barnes 2005b; Nicholas and others, 2011; Thomas, 2007). Research also indicates that arsenic concentrations are increased in wells that have short-screened sections near the boundary of an aquitard and aquifer (Erickson and Barnes, 2005a).

Manganese

Of the 150 samples tested for manganese in Clay County, 89 (59 percent) equaled or exceeded the 100 ppb HRL indicating a natural water quality problem for the majority of well owners in the county (Plate 6). Elevated manganese is widespread, does not appear to follow any spatial pattern, and was present in every aquifer group.

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

Piper diagram: major cations and anions

The Piper diagram graphically represents groundwater types based on the relative amounts of major chemical constituents. Unique geology and hydrogeology of the county groundwater may require special consideration or treatment because of relative concentrations of dissolved ions. This Piper classification and associated map can help in understanding the distribution and possible causes of more mineralized types of water. In addition, corroborating information for pollution sensitivity conditions is provided by the spatial distribution of groundwater types characteristic of hydraulically isolated or open recharge conditions.

The most basic classification is based on electrical charge: cations have a positive charge and anions have a negative charge. These are further divided into the three major cations: calcium, magnesium, or sodium+potassium; and the three major anions: bicarbonate, sulfate and chloride+nitrate. The relative proportions of these dissolved ions differ depending on the water's original interaction with the atmosphere, any subsequent interactions with anthropogenic sources, and the aquifer.

Concentrations in groundwater are shown in milliequivalents in Figure 18a. Anions are shown in the lower left triangle (ternary diagram); cations are in the lower right. The lines from the two ternary diagrams are projected onto the central diamond-shaped field and the intersections are plotted to show the overall chemical characteristics of the groundwater. This part of the diagram often provides a clearer visual representation of distinctive water types. Tritium age is shown on all the points as colors to indicate residence time.

Water types were interpreted from clusters of sample concentrations with a similar range of values. The naming convention used the two principal end members in the cation and anion groups (Back, 1966; Wilson, 2012). The first accounted for 50 percent or more of the total and the second for at least 10 percent. One of the more obvious associations shown on the cation triangle is the cluster of recent and mixed tritium with the calcium-magnesium type water. The calcium and magnesium minerals in the soil and shallow glacial sediments are easily dissolved by precipitation as it infiltrates from the surface on the way to the underlying aquifer. With time and groundwater flow, this water evolves to a more sodium-rich type through ion exchange with clay minerals. The higher calcium-magnesium content is a normal and expected consequence of the shorter residence time. This type of water is mostly found in the eastern part of the county where the Lake Agassiz clay is absent, and also in the Buffalo aquifer where there are extensive surficial exposures or relatively thin overlying layers of fine-grained protective material.

A distinct sodium type of water is delineated in the lower right corner of the cation triangle (sodium + calcium, 50 to less than 90 percent), shown as triangle symbols. This type occurs entirely in the western portion of the county (Figure 18b). The aquifer groups containing groundwater with this cation type include units in the lower part of the stratigraphic sequence that are also mostly overlain by the Lake Agassiz clay (dg, h1, h2, h3, h4, and qu). These relatively deep and isolated conditions suggest a type of water that may be from deep bedrock sources and have been relatively unaltered by recharge for a very long time.

In the anion triangle, most samples plot along a narrow band ranging from bicarbonate (bicarbonate, 90 to 100 percent; sulfate less than 10 percent), and bicarbonate-sulfate (bicarbonate 50 to less than 90 percent; sulfate greater than 10 percent). Most samples contained sulfate concentrations less than 250 ppm but some in the western part of the county exceeded 250 ppm (shown as square symbols).

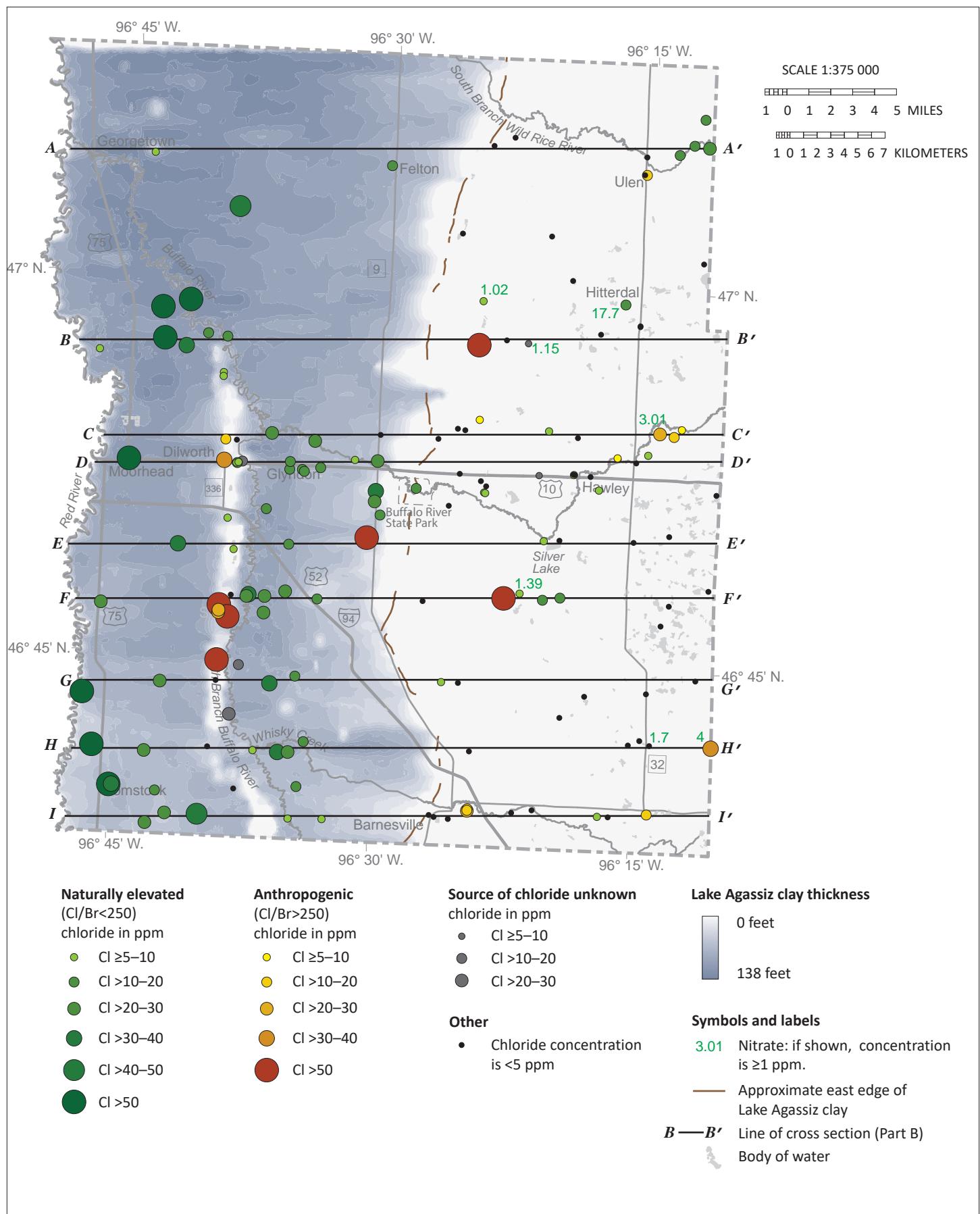


Figure 16. Chloride and elevated nitrate concentrations

Natural chloride is common in the western part of the county with the exception of the Buffalo aquifer area. The samples with elevated nitrate were found in the eastern part of the county.

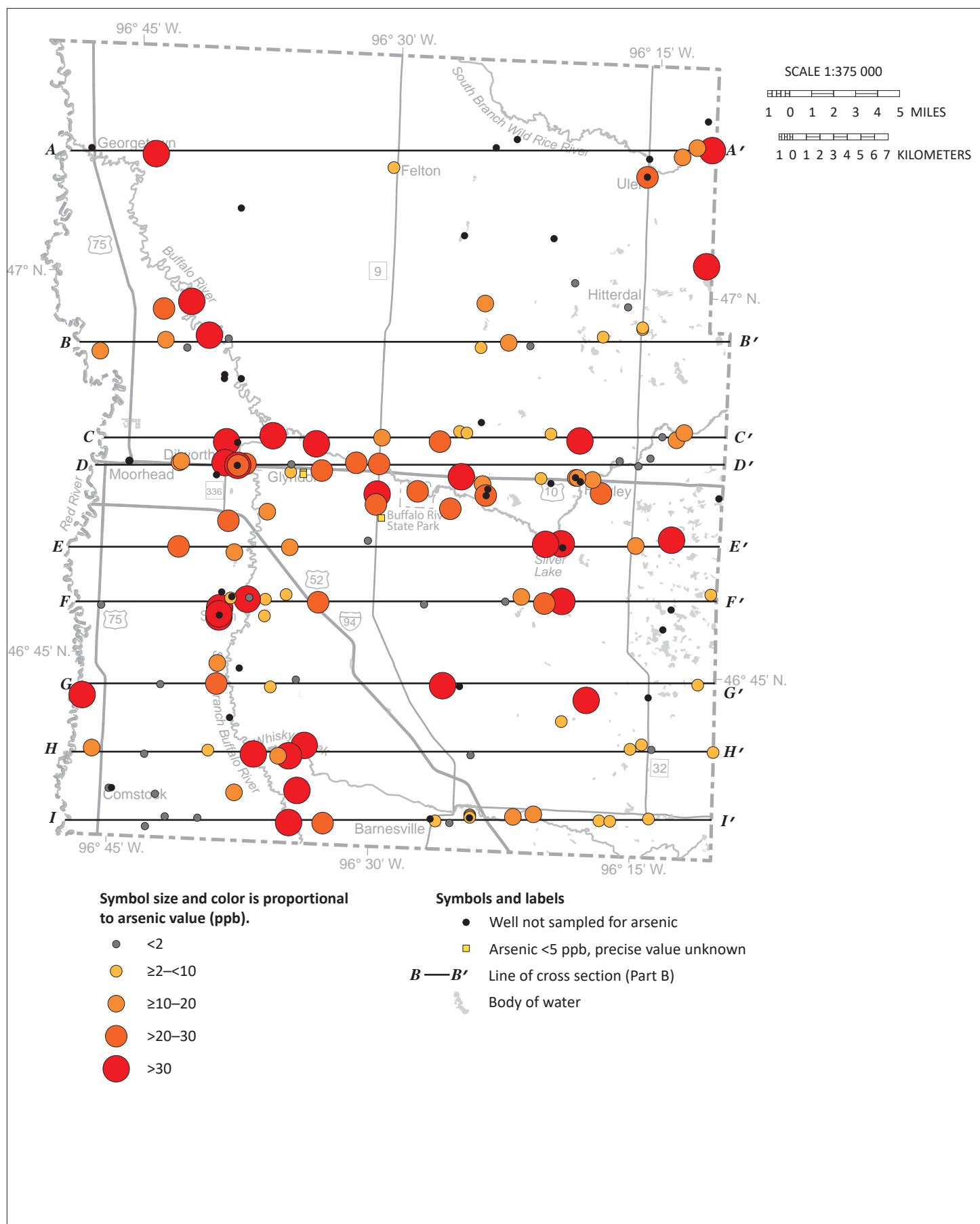
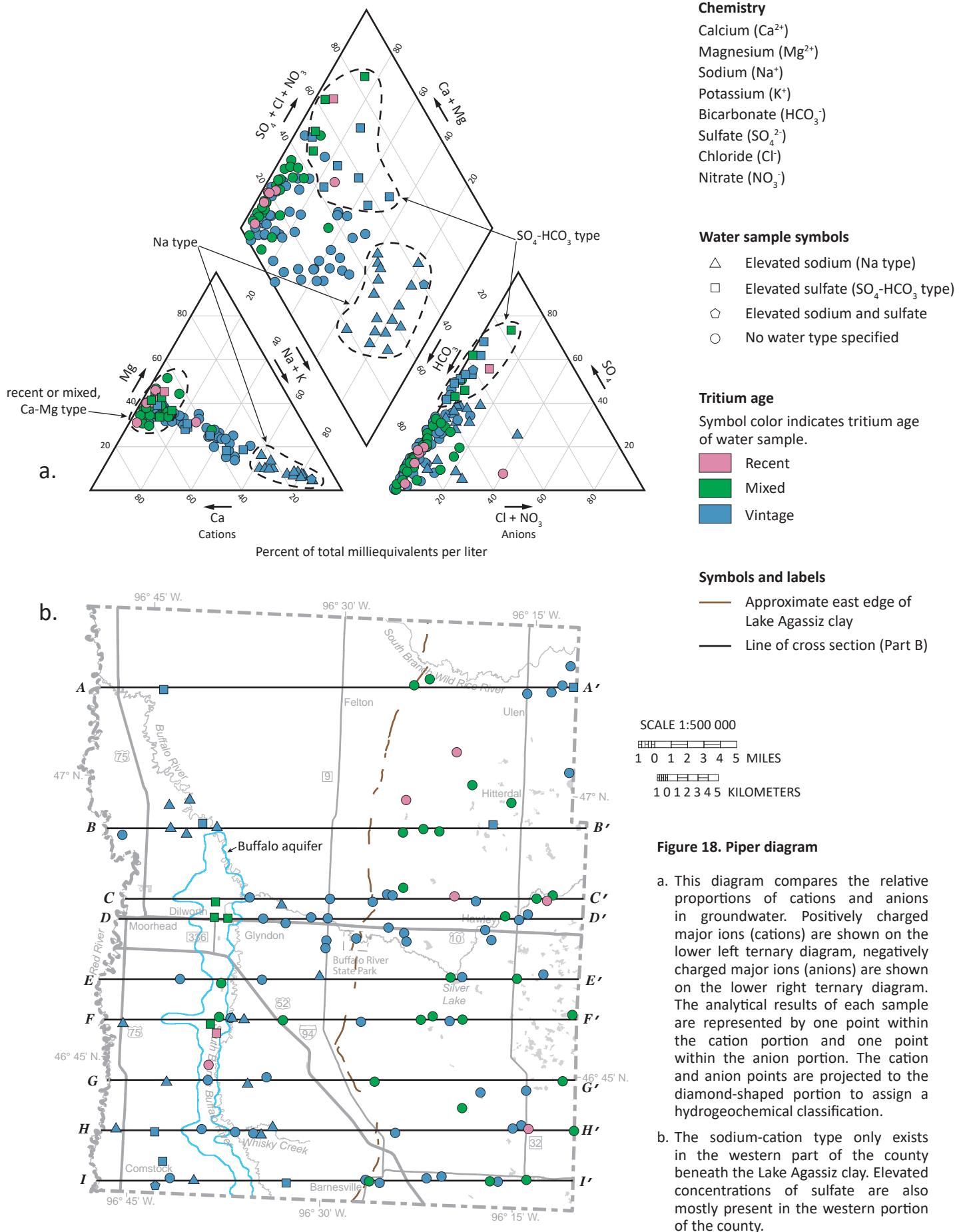


Figure 17. Arsenic values from buried sand aquifers

Of the 133 samples tested for arsenic, 117 (88 percent) had values that equaled or exceeded the method detection limit indicating a naturally occurring water quality problem for the majority of well owners in the county.



Pollution sensitivity

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

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

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

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

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

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

The central concept for both types of pollution sensitivity maps is the relative rate of groundwater movement. This is described as *infiltration* in the unsaturated zone, and *recharge* in the saturated zone. The maps can be used as a tool for planning aquifer recharge projects using high-quality water. Areas with high infiltration rates (as shown on the near-surface pollution sensitivity map) or likely areas with focused recharge (as shown on the buried pollution sensitivity maps) may indicate candidates for further investigation of factors such as depth to water table, pipeline infrastructure, and water source locations. Statewide quantitative recharge maps are available from the U.S. Geological Survey (Smith and Westenbroek, 2015; Delin and others, 2007).

Near-surface materials

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

The transmission rate will vary depending on the texture. Coarse-grained materials have faster transmission rates than fine-grained materials. The two primary inputs used to estimate transmission rate are the hydrologic soil group and the surficial geologic matrix texture. Attributes of both are used to estimate the time of travel (Table 1) (USDA-NRCS, 2011; Part A, Plate 4). Further details are available in *Methods to estimate near-surface pollution sensitivity* (DNR, 2016b).

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

- Areas with a relatively short travel time (hours to a week) are rated high sensitivity (Figure 19).
- Areas with a longer travel time (weeks to a year) are rated low or very low.
- Areas of more than a year are rated ultra-low.

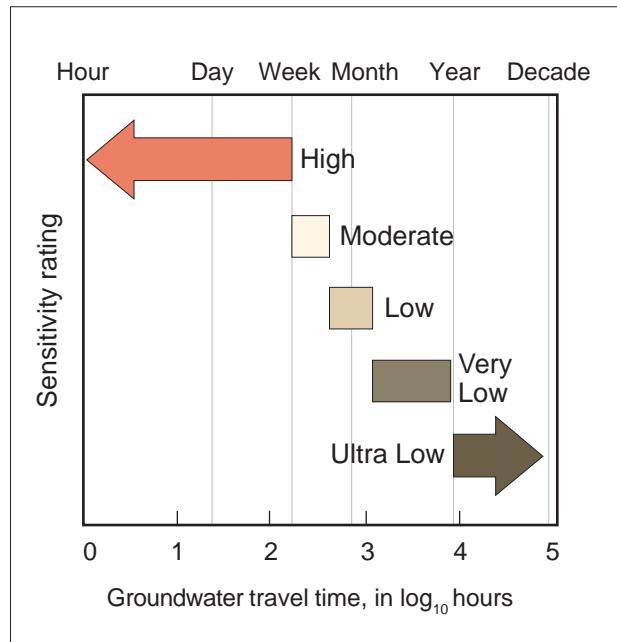


Figure 19. Geologic sensitivity rating for near-surface materials

Table 1. Transmission rates used to assess the pollution sensitivity rating of 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	ha, grb, grc, gro, ro, roc, wlg
		sand, silty sand	0.71	Not mapped in county
B, B/D	0.50	silt, loamy sand	0.50	wls
		sandy loam	0.28	ruw
C, C/D	0.075	silt loam, loam	0.075	rgs, rl, rlw, ru, gsw
		sandy clay loam	0.035	Not mapped in county
D	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015	gst, sld**, slw**
--	--	glacial lake sediments of Lake Agassiz	0.000011	sld, slw

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 (USDA-NRCS, 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.

**These units were assigned a lower rate (0.000011 inches/hour) according to transmission rates of Remenda and others (1994).

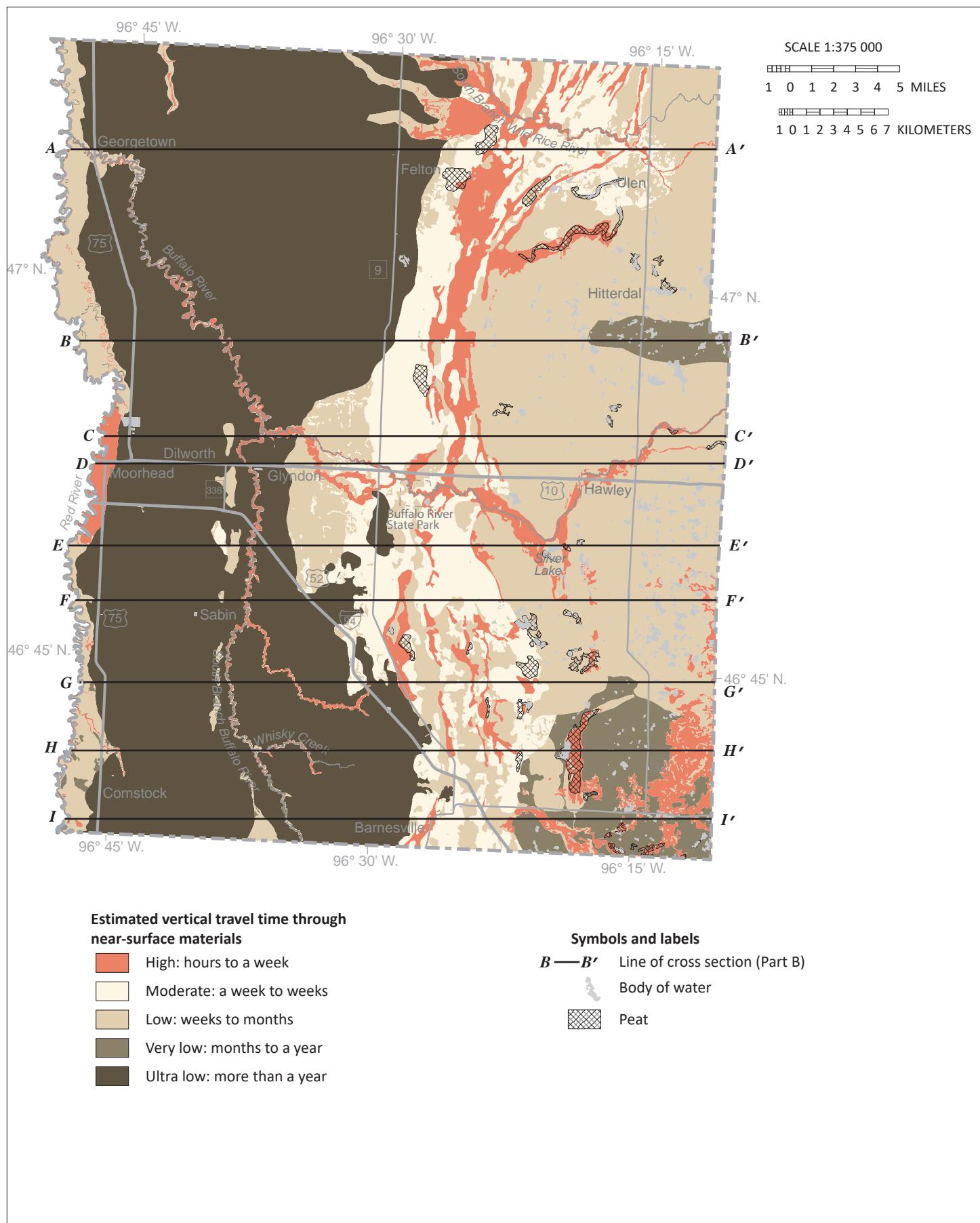


Figure 20. Pollution sensitivity of near-surface materials

The pollution sensitivity model used to create this map assumes a 10-foot deep water table and vertical travel of possible pollutants through unsaturated near-surface materials.

Buried sand aquifers and bedrock surface

The sensitivity rating for the buried sand aquifers and the bedrock surface are based on estimated vertical travel times defined by the Geologic Sensitivity Workgroup (1991). Travel time varies from hours to thousands of years. Areas with ratings of high or very high have relatively short travel times of less than a few years. Areas rated low or very low have estimated travel times of decades or longer (Figure 21).

The DNR developed a pollution sensitivity model that represents how precipitation infiltrates the land surface and recharges portions of deeper aquifers. The central concept is that focused (relatively rapid) recharge occurs where aquifers overlap and are connected by complex pathways. The model assumes that the thickness of fine-grained sediment overlying an aquifer is inversely proportional to the sensitivity of an aquifer. The thicker the fine-grained sediment, the longer it takes for water to move through it (Figure 22).

GIS software was used to calculate cumulative thickness of the sediment layers in the county. Thicknesses of 10 feet or less were rated very high sensitivity, thicknesses greater than 40 feet were rated very low, and intermediate thicknesses were rated intermediate.

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

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

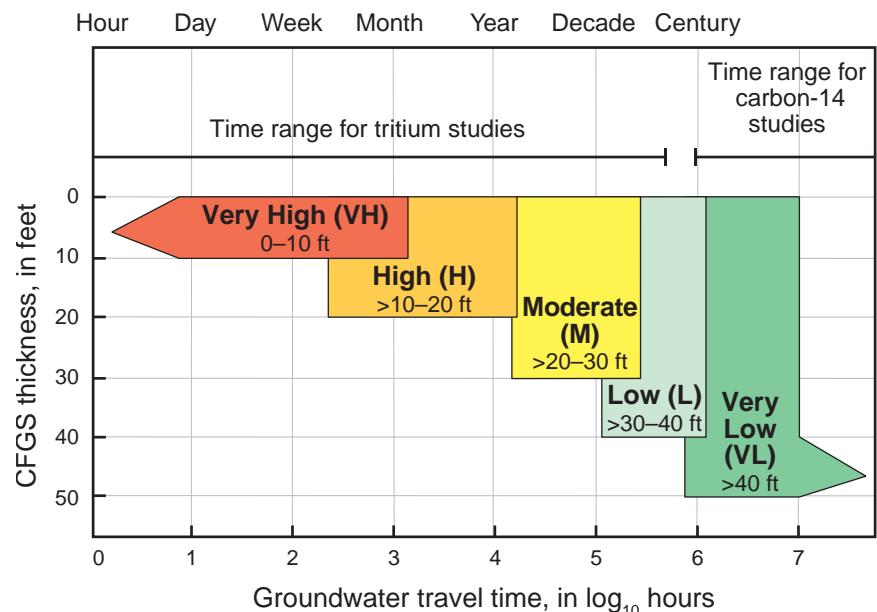


Figure 21. Geologic sensitivity rating for the buried sand aquifers and the bedrock surface
Sensitivity is defined by estimated vertical travel time. The numbers following each rating represent the *cumulative fine-grained sediment thickness* overlying an aquifer.

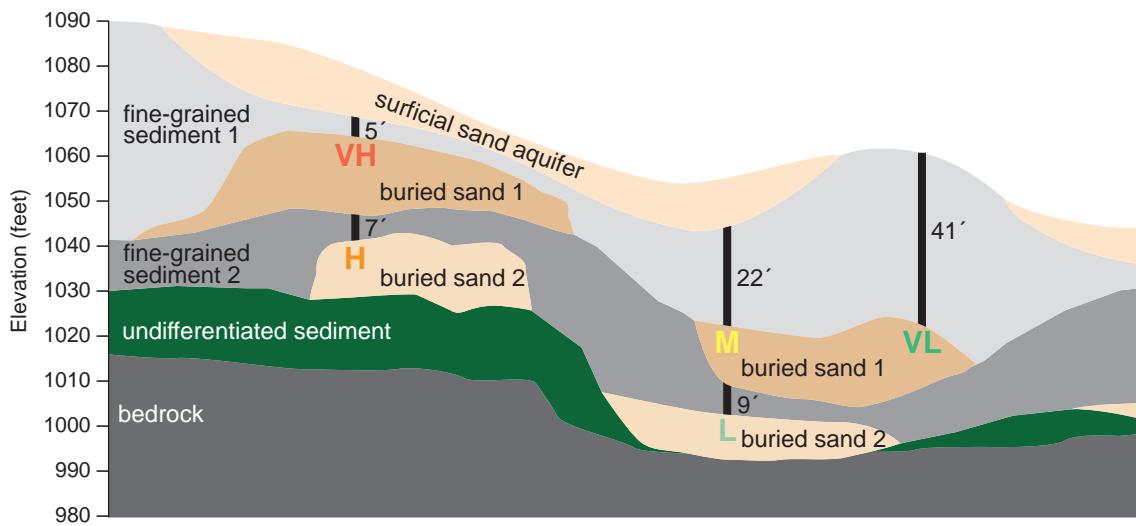


Figure 22. Cross section showing examples of pollution sensitivity ratings
Sensitivity ratings are based on the cumulative thickness of overlying fine-grained sediment. Each vertical black line is labeled with the thickness of fine-grained sediment. The letter at the base of the line indicates the sensitivity rating.

Groundwater conditions

Groundwater recharge, presumed flow paths, and discharge can be evaluated using the combination of tritium-age water samples, equipotential contours, water chemistry, and relative hydraulic conductivity. The following conditions provide a way of linking pollution sensitivity with residence time and anthropogenic indicators (tritium, anthropogenic chloride, and nitrate) (Figure 23).

- ① Water from the surface moves through a thin layer of overlying fine-grained material to an underlying aquifer.
- ② Groundwater moves from an overlying surficial aquifer to a buried aquifer.
- ③ Groundwater moves from an overlying buried aquifer to an underlying buried aquifer.
- ④ Groundwater flows laterally.
- ⑤ Groundwater flowpath is unknown.
- ⑥ Groundwater discharges to a surface-water body.

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

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

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

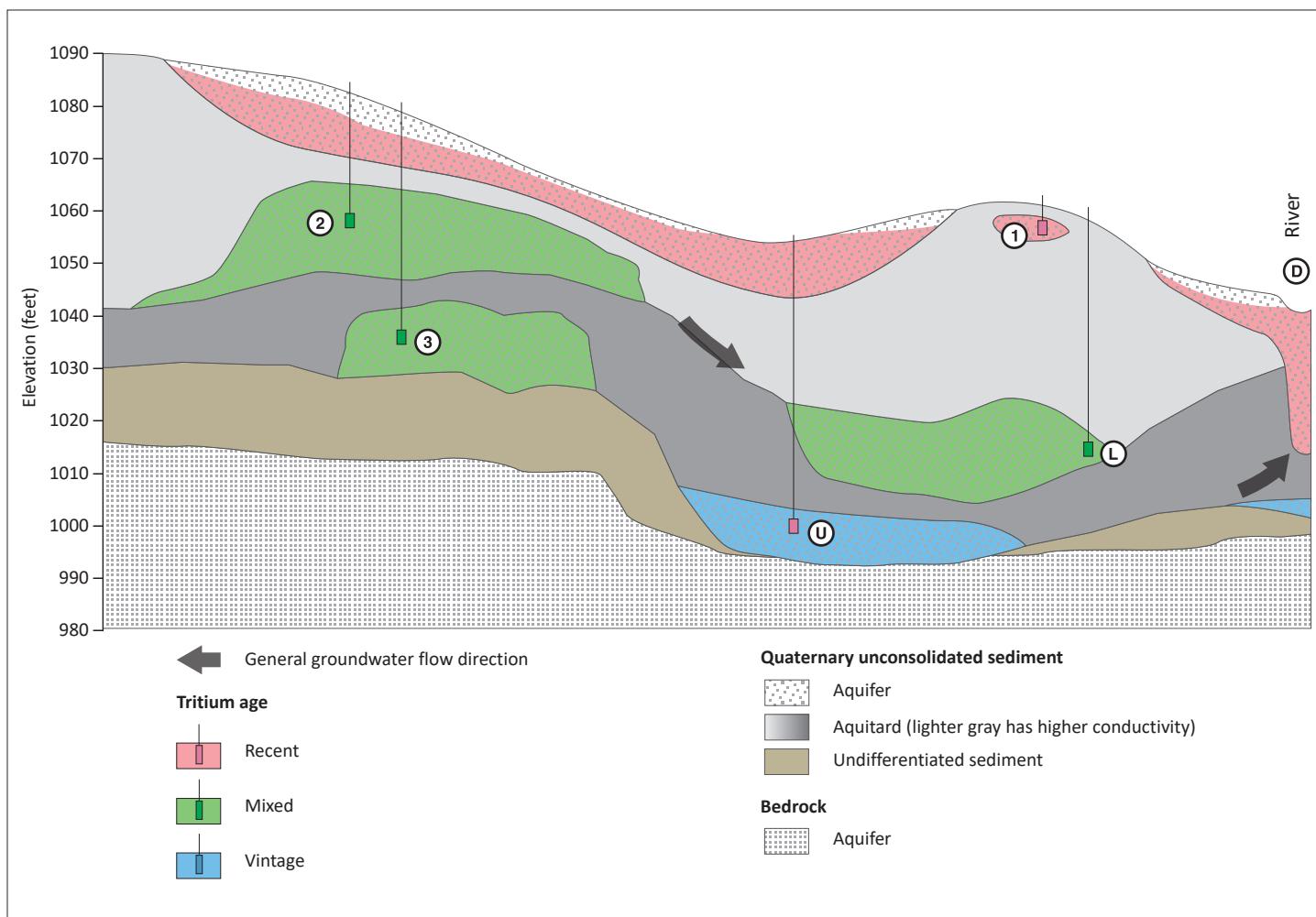


Figure 23. Hypothetical cross section illustrating groundwater conditions

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

Results

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

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

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

The tritium dataset is a conglomeration of sampling efforts by the DNR and the Minnesota Department of Health (MDH) for several projects since 1989. None of these sampling plans were randomized in a way that would allow a statistical comparison to the results of the pollution sensitivity modeling. Therefore, the descriptions of groundwater chemistry and pollution sensitivity are mostly qualitative. Tritium detections in groundwater samples from aquifers in areas mapped as very low sensitivity should rarely occur assuming that flow of recent water to the aquifer is vertical (Figure 21).

prf aquifer (Figure 24)

This aquifer is relatively shallow (less than 10 to 40 feet), is positioned between the two formations of the Lake Agassiz clay, and has a limited extent in the western portion of the county. Its use as an aquifer is relatively rare. Water-level data were insufficient for determining groundwater flow but it is probably westerly.

Sensitivity: The aquifer exhibits mostly high to very high sensitivity with a few areas of very low to moderate sensitivity north of Moorhead.

Chemistry: One tritium sample from this aquifer was collected from a well in a low sensitivity area north of Moorhead. This sample had a vintage tritium age which is consistent with the sensitivity rating at that location. Chloride values at that location and another location west of Felton had naturally elevated values (7.8 and 49 ppm, respectively).

rlf aquifer group (Figures 25 and 26)

This aquifer group consists of the ro, roc, and rgs units and is also relatively shallow. Large areas of the ro and roc

units are surficial but locally buried by layers of peat up to 16 feet thick. The rgs unit (Buffalo aquifer, Figure 26) is also present at the surface and as a buried unit, depending on its location in the county, with the buried portions overlain by the sl and bl clay units up to 100 feet thick.

Sensitivity: The shallow buried portions of the units in the eastern part of the county locally have sensitivities in the moderate to very high range. The Buffalo aquifer in the western part of the county has the entire range of sensitivity and is moderately to very highly sensitive along almost its entire extent in the county.

Chemistry: Most samples from rlf aquifers collected for chemical analysis were from the Buffalo aquifer area with the exception of 1 location east of Georgetown. Of the 19 samples tested for tritium, 14 had mixed and 2 had recent tritium age. The mixed and recent tritium-age samples matched well the moderate to very high sensitivity areas. Two samples from wells southeast of Moorhead were analyzed for carbon-14 residence time. These samples had a residence times of less than 100 years, consistent with the very high sensitivity of those locations. Of the 15 samples with elevated chloride, 7 had elevated concentrations of anthropogenic chloride, including an area east of Moorhead and locations near Sabin. Of the 18 samples tested for nitrate, none had an elevated concentration.

gr aquifer group (Figure 27)

The gr aquifer group mostly consists of units grb, gro, gss, gds, and gdg. These units are dominantly in the eastern portion of the county with several isolated and scattered sand and gravel bodies in the west part of the county. The gro and grc units in the southeastern portion of the county are mostly surficial but a portion is overlain by a large area of peat and is therefore included in this group of buried aquifers.

Sensitivity: Moderate to very high pollution sensitivity areas are common in the east-central and southeast portions of this aquifer group. Very low and low sensitivity is common in the western and northern portions of the county.

Chemistry: Of the 25 samples tested for tritium, 14 had mixed and 3 had recent tritium age. Most of these were collected at locations of moderate to very high pollution sensitivity. Six of the mixed and recent tritium-age samples in very low to moderate sensitivity areas may be attributed to lateral flow from upgradient higher sensitivity areas. One sample east of Glyndon in the gds unit had a carbon-14 residence time of 15,000 years. This is consistent with the very low sensitivity of this area. Of the 18 samples with elevated chloride concentrations, 4 were anthropogenic, located in the east central portion of the county. All 27 samples were tested for nitrate, with elevated concentrations (1.02 to 17.7 ppm) found in 3

samples from the eastern portion of the county, 2 north and west of Hitterdal, and 1 southwest of Hawley.

nh aquifer group (Figure 28)

The nh aquifer group consists of map units nhs and nhg. These units mostly exist in the northeastern, southeastern, and southwestern portions of the county.

Sensitivity: Moderate to very high pollution sensitivity areas are common in the southeastern portions of the county and fewer areas in the northeast. Very low and low sensitivity are also common in these areas; the western part of the county has all very low sensitivity for this group. This group represents a transitional layer from the groups that are stratigraphically higher and more sensitive to those stratigraphically lower and less sensitive.

Chemistry: Of the 16 samples tested for tritium, 6 had mixed and 1 had recent tritium age. All of these mixed and recent tritium-age samples were collected at locations of moderate to high pollution sensitivity. One sample in the nhs unit northeast of Ulen had a carbon-14 residence time of 14,000 years. This is consistent with the very low sensitivity of this area. Of the 11 samples with elevated chloride concentrations, the 5 samples with anthropogenic signatures were mostly from the southeast portion of the county and 1 was from the northeastern part of the county in Ulen. Of the 22 samples tested for nitrate only 1 sample had an elevated concentration (1.7 ppm) located in a moderate to high sensitivity area east of Barnesville.

ot/nv aquifer group (Figure 29)

The ot/nv aquifer group mostly consists of units osu, ogu, and ons. These units are somewhat evenly distributed across the county with the exception of an area south and west of Hitterdal.

Sensitivity: Moderate to very high pollution sensitivity areas are mostly found in the southeastern portion of the county. The very low sensitivity rating characterizes most of the remainder of the county.

Chemistry: Of the 11 samples tested for tritium, 2 had mixed and 1 had recent tritium age. The 2 mixed tritium-age samples were collected at locations of moderate pollution sensitivity. The 1 recent tritium-age sample, west of Hawley, was in a very low sensitivity area and may be caused by lateral migration of recently recharged groundwater from an upgradient location. One sample evaluated for carbon-14 residence time in the osu unit, east of Barnesville, had residence time of less than 100 years. This sample was collected near a low to moderate sensitivity area. Of the 6 samples with elevated chloride concentrations none were anthropogenic. Of the 12 samples tested for nitrate, none had an elevated concentration.

dg/br aquifer group (Figure 30)

The dg/br aquifer group mostly consists of units dgs, dgg, and brs. These units mostly exist in the western portion of the county.

Sensitivity: Mostly very low pollution sensitivity exists with the exception of a relatively small area of moderate to very high sensitivity south of Sabin near the Buffalo River.

Chemistry: All 12 samples were tested for tritium and had vintage tritium age. Two samples were analyzed for carbon-14 residence time. Samples collected north and south of Moorhead had residence times of 35,000 and 40,000 years, respectively. These samples and all of the vintage tritium-age samples were from areas with very low pollution sensitivities. All 12 samples had elevated chloride concentrations and 1 southeast of Glyndon was anthropogenic (198 ppm). All 12 samples were tested for nitrate and none had an elevated concentration.

h1 aquifer (Figure 31)

The h1 aquifer mostly consists of units hs1 and hg1. These units exist throughout the county.

Sensitivity: Mostly very low pollution sensitivity exists with the exception of moderate to high sensitivity areas in the east-central part of the county in the Hawley/Hitterdal area.

Chemistry: Of the 16 samples tested for tritium, 3 samples in the northeastern portion of the county had mixed tritium age. Two of these 3 samples were in very low sensitivity areas but downgradient from higher sensitivity areas. Therefore, a lateral recharge condition is shown on Figure 31 at the two locations. One sample (133-foot depth) northeast of Ulen had a residence time of 20,000 years.

All of the samples with elevated anthropogenic chloride and nitrate were located in the Hawley/Hitterdal area. Of the 12 samples with elevated chloride concentrations, 1 northeast of Hawley and 1 northeast of Glyndon were anthropogenic (23.9 and 5 ppm, respectively). Of the 17 samples tested for nitrate, 2 had an elevated concentration (1.15 and 3.01 ppm). Both samples were between Hitterdal and Hawley.

h2 aquifer (Figure 32)

The h2 aquifer mostly consists of units hs2, hg2, and ht2. These units exist throughout the county.

Sensitivity: Mostly very low pollution sensitivity exists with the exception of small areas of moderate to high sensitivity in the east-central part of the county in the Hawley/Hitterdal area.

Chemistry: Of the 22 samples tested for tritium, 4 had mixed or recent tritium ages in the eastern and southwestern portion of the county. Three of these samples were in

very low sensitivity areas. One mixed sample northeast of Hawley near the Buffalo River appears to be the result of lateral flow. The cause for the mixed or recent tritium conditions in the other 3 samples is unknown. Of the 13 samples with elevated chloride concentrations, 2 were anthropogenic, located northeast of Hawley (11.3 ppm) and northeast of Barnesville (33 ppm). All 23 samples were tested for nitrate; 1 in the southeast corner of the county had an elevated concentration (4 ppm).

h3/h4 aquifer group (Figure 33)

The h3/h4 aquifer group mostly consists of units hs3, hg3, hs4, and hg4. These units exist mostly in the central and southern portions of the county.

Sensitivity: This aquifer group exhibits nearly all very low pollution sensitivity.

Chemistry: Of the 10 samples tested for tritium, 9 had a vintage tritium age. The 1 mixed tritium-age sample was located southeast of Hawley; the cause is unknown. Two samples in the southwestern portion of the county were analyzed for carbon-14 residence time: 1 sample south of Glyndon had a residence time of 30,000 years and 1 sample west of Barnesville had a residence time of 9,000 years. Of the 7 samples with elevated chloride concentrations, none were anthropogenic. All 12 samples were tested for nitrate and none had an elevated concentration.

bv/x aquifer group (Figure 34)

The bv/x aquifer group mostly consists of units x1s, x2s, and x3s. These units exist mostly in the western portion of the county.

Sensitivity: This aquifer group exhibits all very low pollution sensitivity.

Chemistry: Of the 2 samples tested for tritium, both had a vintage tritium age.

None of the samples tested for chloride and nitrate had an elevated concentration.

qu aquifer group (Figure 35)

The qu aquifer group mostly consists of units qsu1 and qsu2. These units exist throughout the county.

Sensitivity: This aquifer group exhibits very low pollution sensitivity.

Chemistry: Of the 6 samples tested for tritium, all had a vintage tritium age. Two samples were analyzed for carbon-14 residence times east of Glyndon in the qsu1 (2,500 years) and qsu2 (6,000 years). Of the 8 samples with elevated chloride concentrations, none were anthropogenic. All 9 samples were tested for nitrate and none had an elevated concentration.

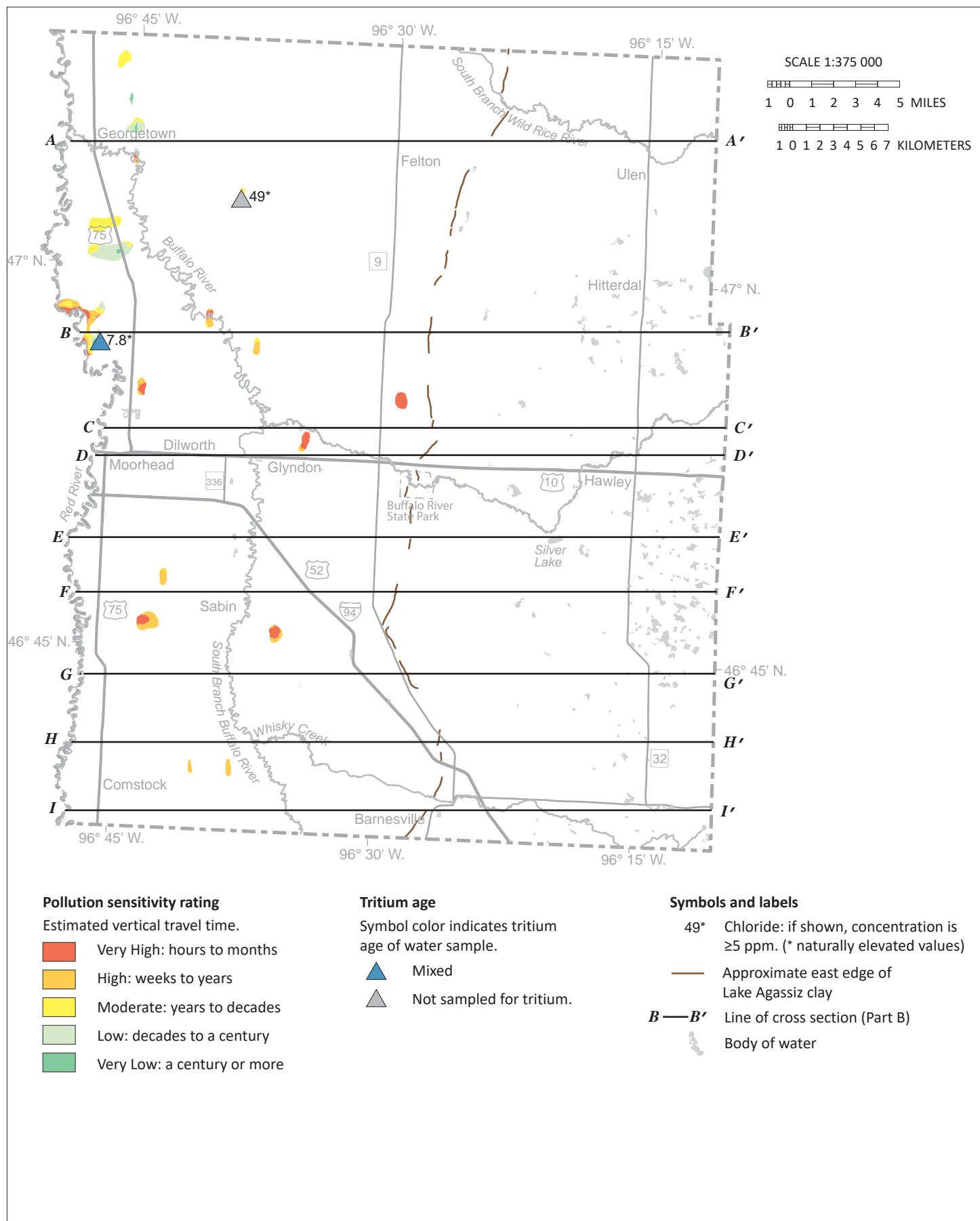


Figure 24. Pollution sensitivity of the prf aquifer

The shallow prf aquifer is mostly sensitive to very sensitive with very low to moderate sensitivity areas north of Moorhead.

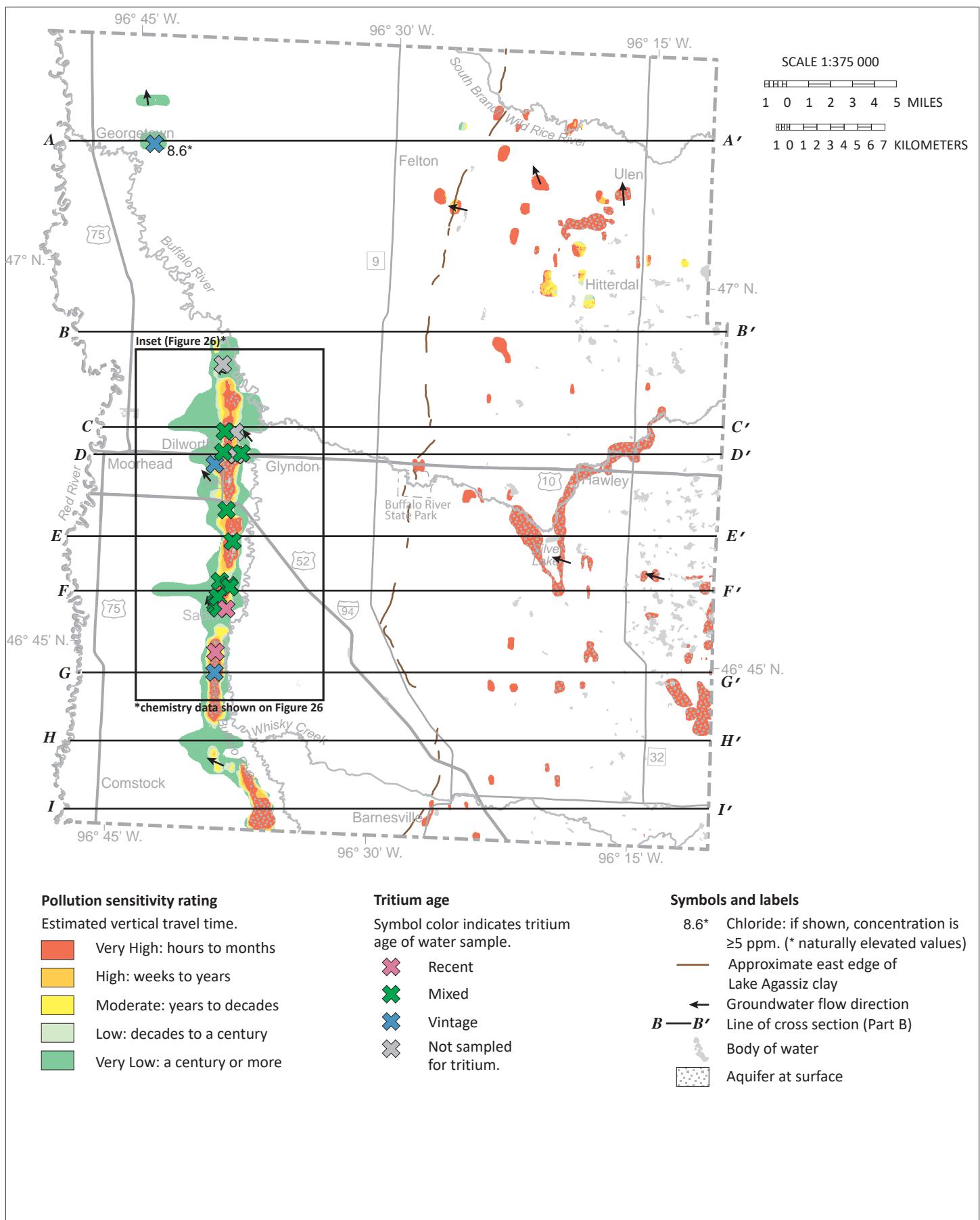


Figure 25. Pollution sensitivity of the rif aquifer group

The depth to the top of this aquifer group ranges from less than 10 feet to approximately 120 feet. The relatively shallow and surficial rif aquifer group is moderate to very highly sensitive in the eastern part of the county. The Buffalo aquifer (rgs unit) in the western part of the county has sensitivity ranging from very low to very high. See details of inset in Figure 26.

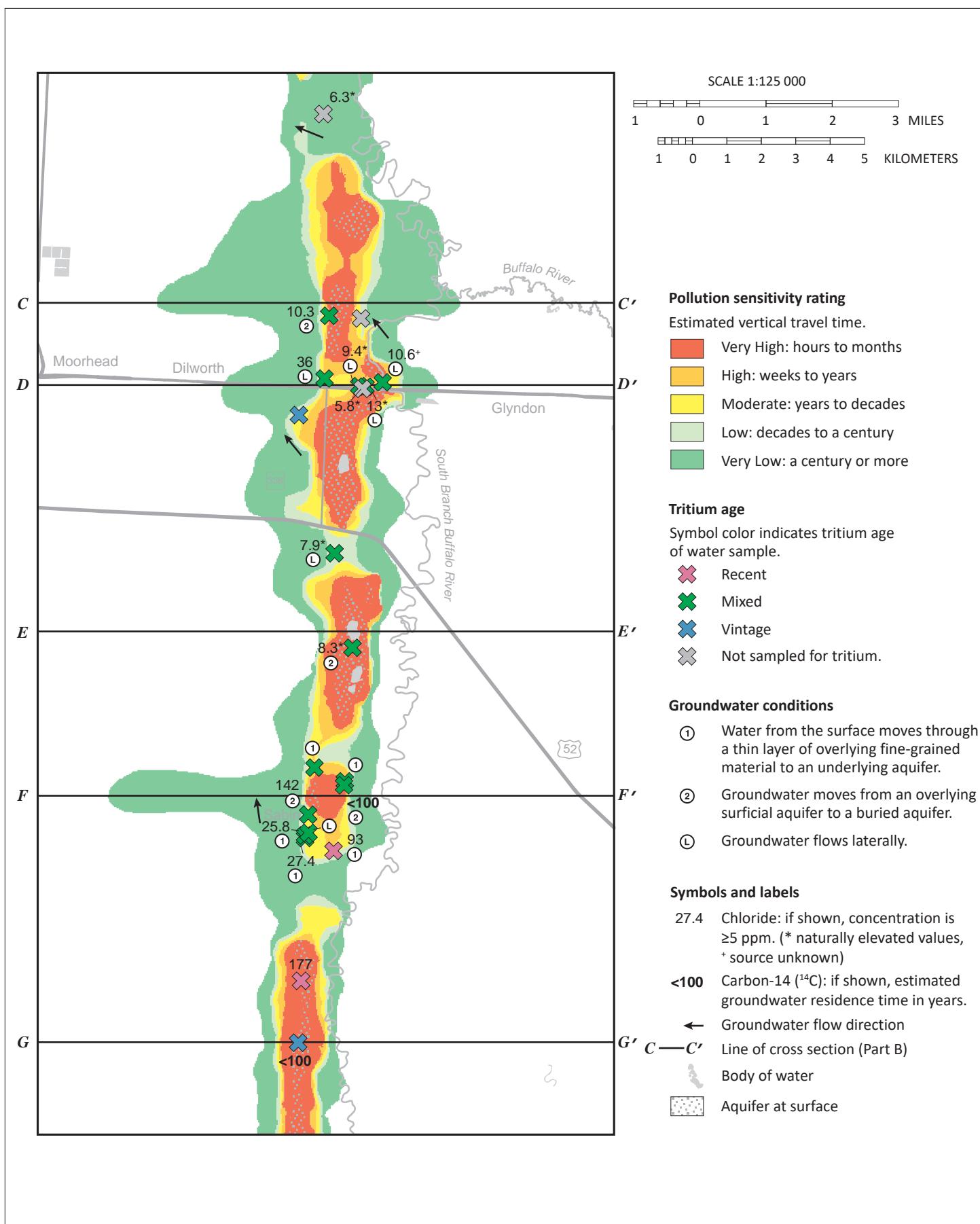


Figure 26. Pollution sensitivity of the Buffalo aquifer (inset from Figure 25)

The central axis portion of the Buffalo aquifer exhibits moderate to very high sensitivity due to thin or absent overlying fine-grained layers (clay and silt).

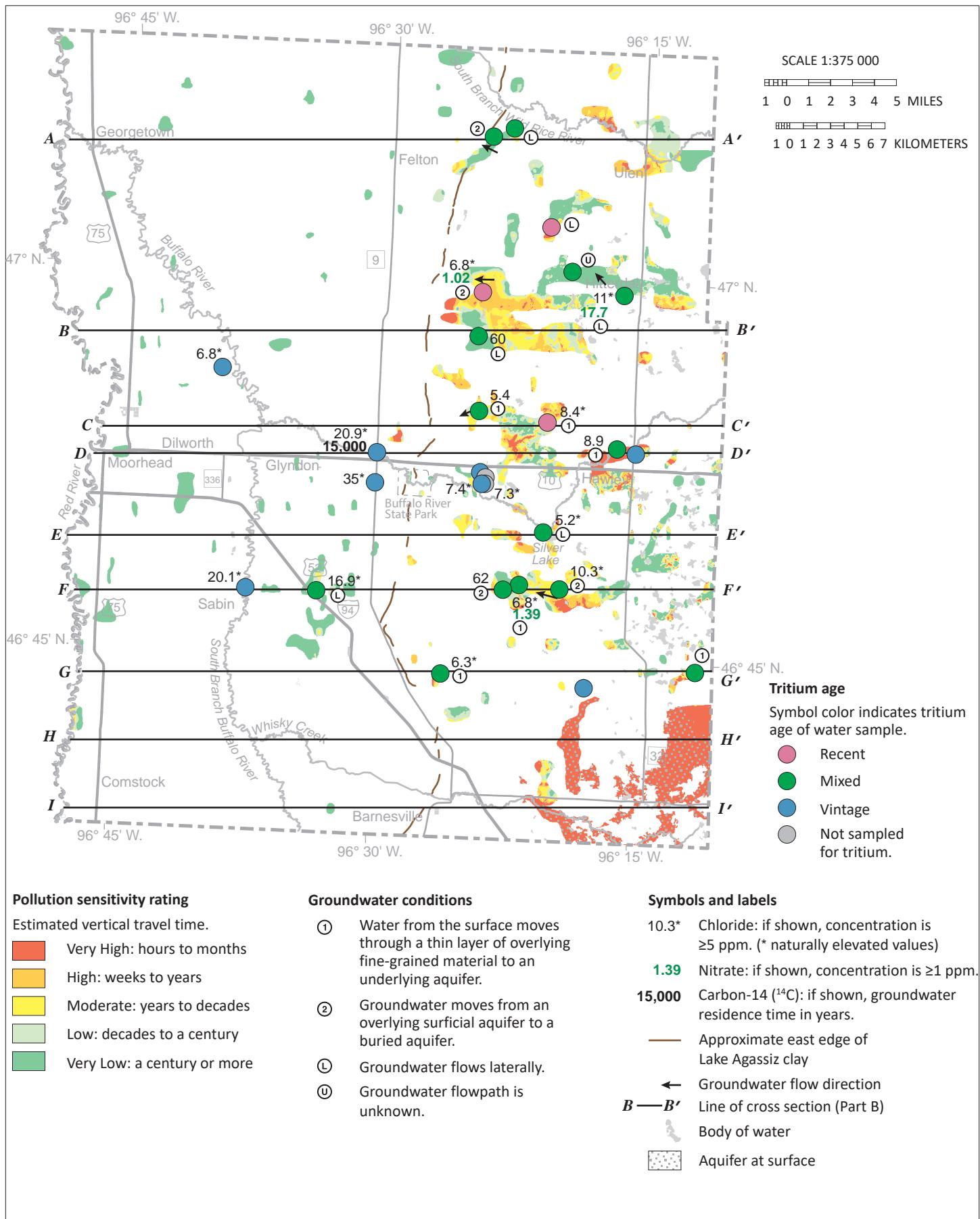


Figure 27. Pollution sensitivity of the gr aquifer group and groundwater flow directions

Moderate to very high pollution sensitivity areas are common in the east-central and southeast portions of this aquifer group. Very low to low sensitivity is common in the western and northern portions of the county. The depth to the top of this aquifer group ranges from less than 10 feet to approximately 130 feet.

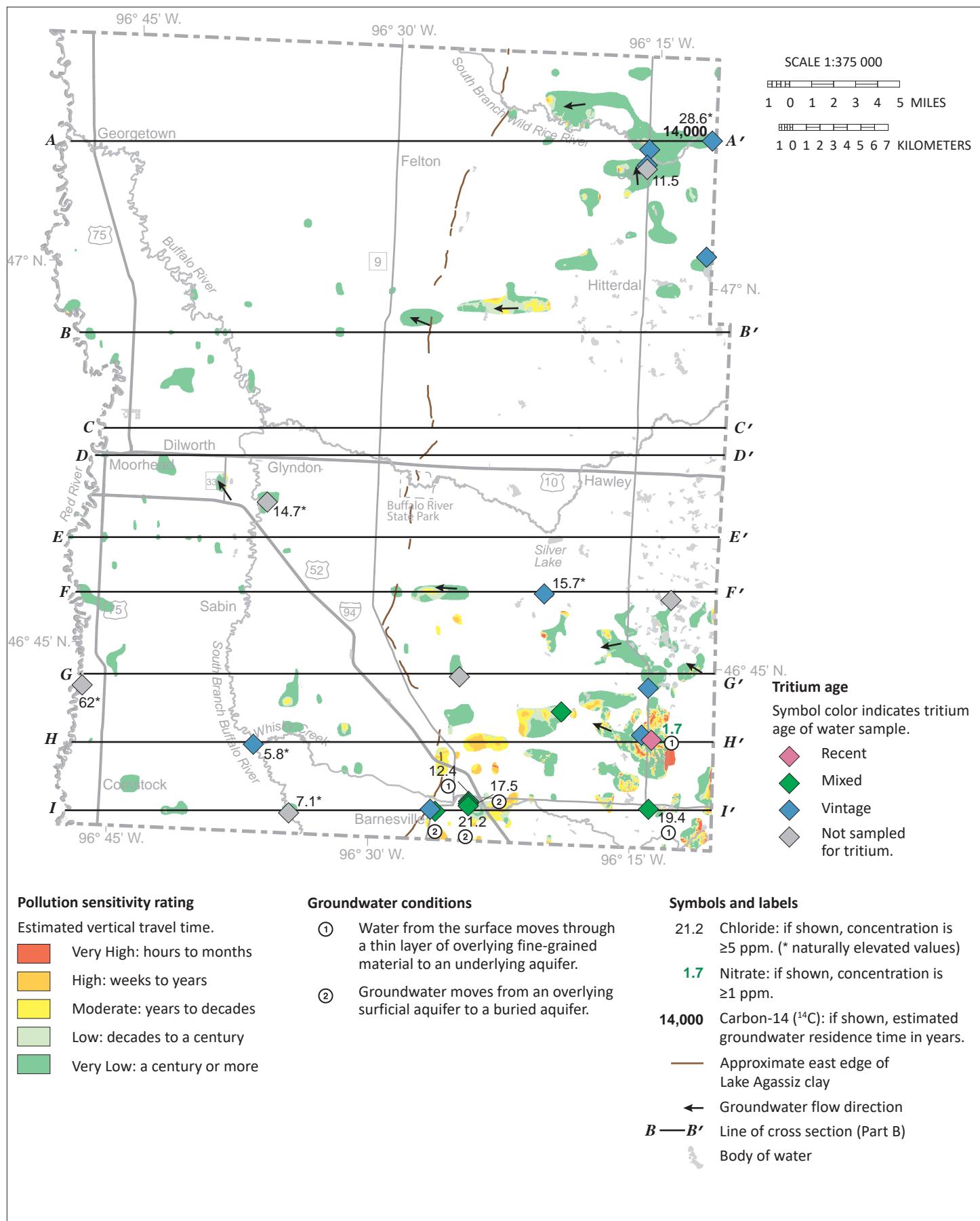


Figure 28. Pollution sensitivity of the nh aquifer group and groundwater flow directions

This group has a wide range of pollution sensitivity and represents a transitional layer from the groups higher in the stratigraphic column that are more sensitive to the groups that are lower and less sensitive. The depth to the top of this aquifer group ranges from less than 10 feet to approximately 190 feet.

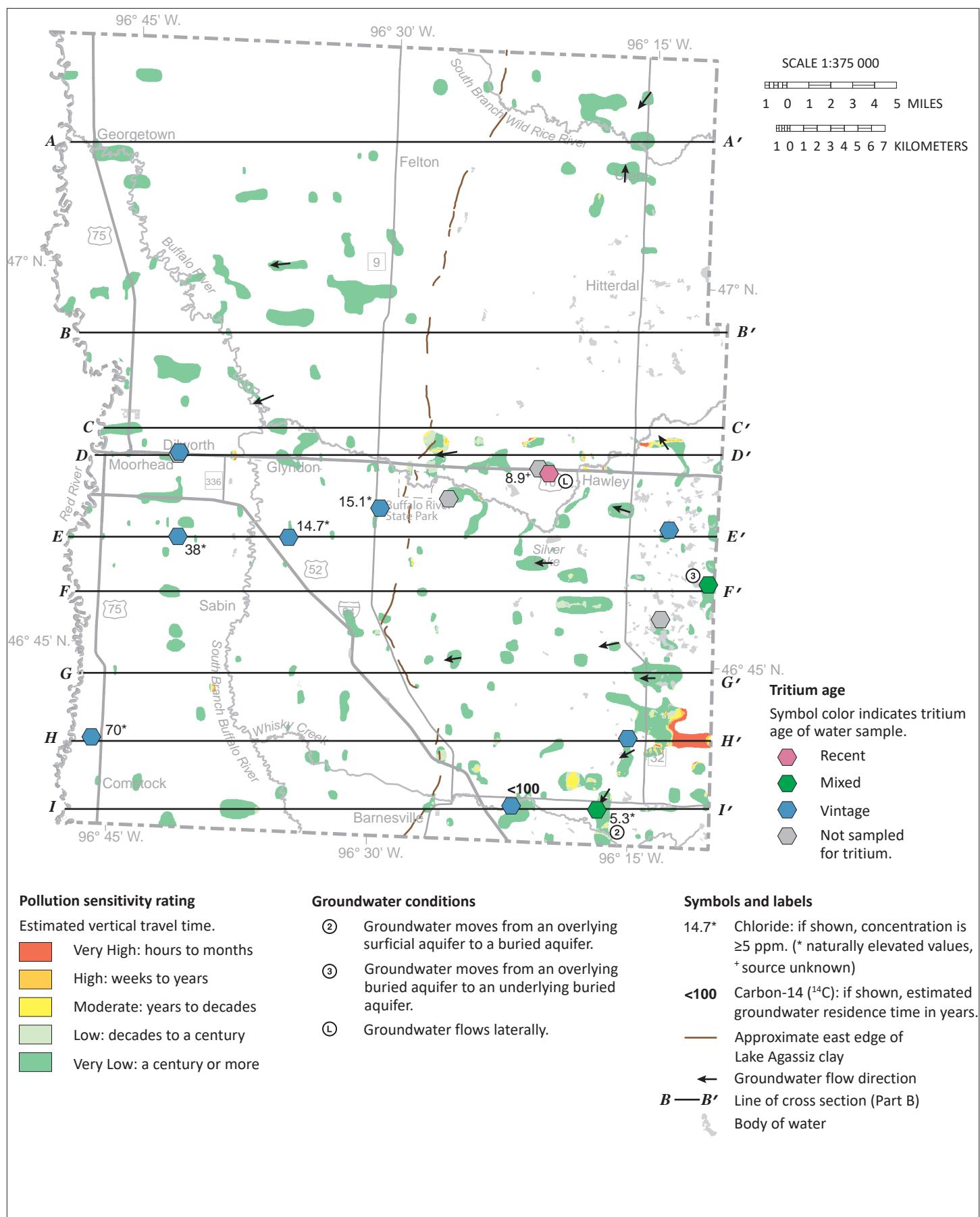


Figure 29. Pollution sensitivity of the ot/nv aquifer group and groundwater flow directions

Moderate to very high pollution sensitivity areas are mostly found in the southeastern portion of the county. The very low sensitivity rating characterizes most of the remainder of the county. The depth to the top of this aquifer group ranges from less than 10 feet to approximately 160 feet.

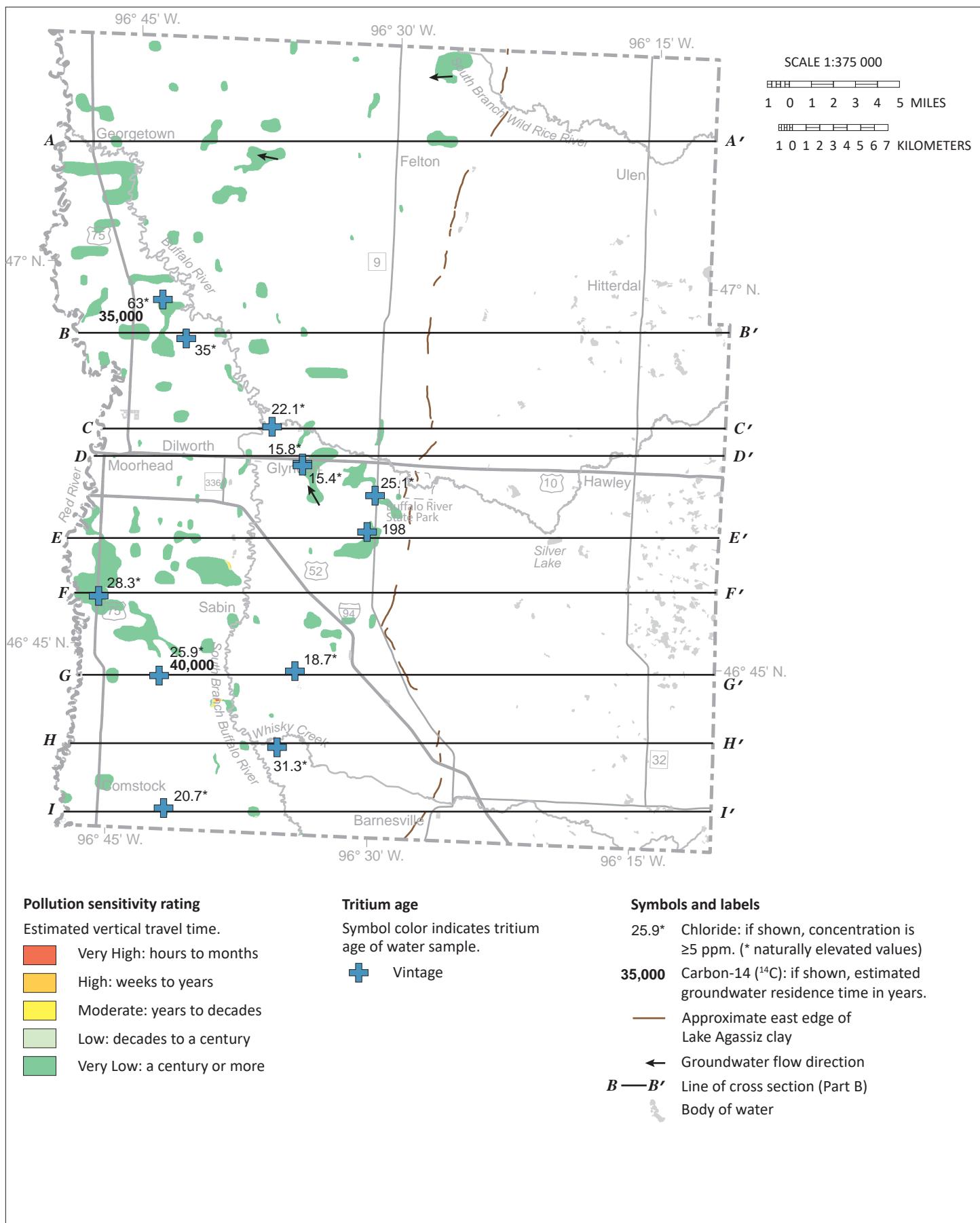


Figure 30. Pollution sensitivity of the dg/br aquifer group and groundwater flow directions

This aquifer group exhibits mostly very low pollution sensitivity with the exception of a relatively small area of moderate to very high sensitivity south of Sabin near the Buffalo River. The depth to the top of this aquifer group ranges from approximately 80 to 180 feet.

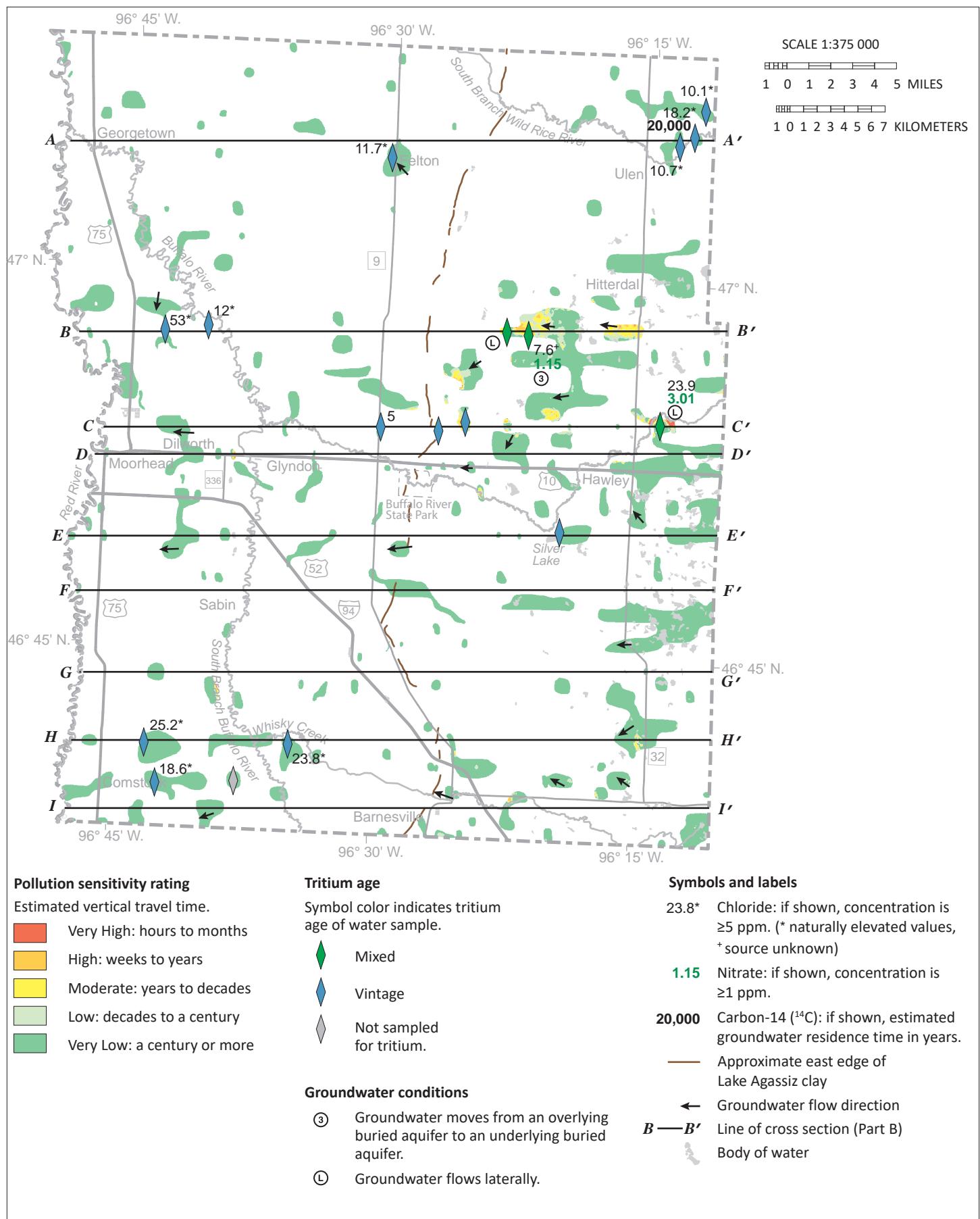


Figure 31. Pollution sensitivity of the h1 aquifer and groundwater flow directions

This aquifer group exhibits mostly very low pollution sensitivity. The depth to the top of this aquifer group ranges from approximately 20 to 290 feet.

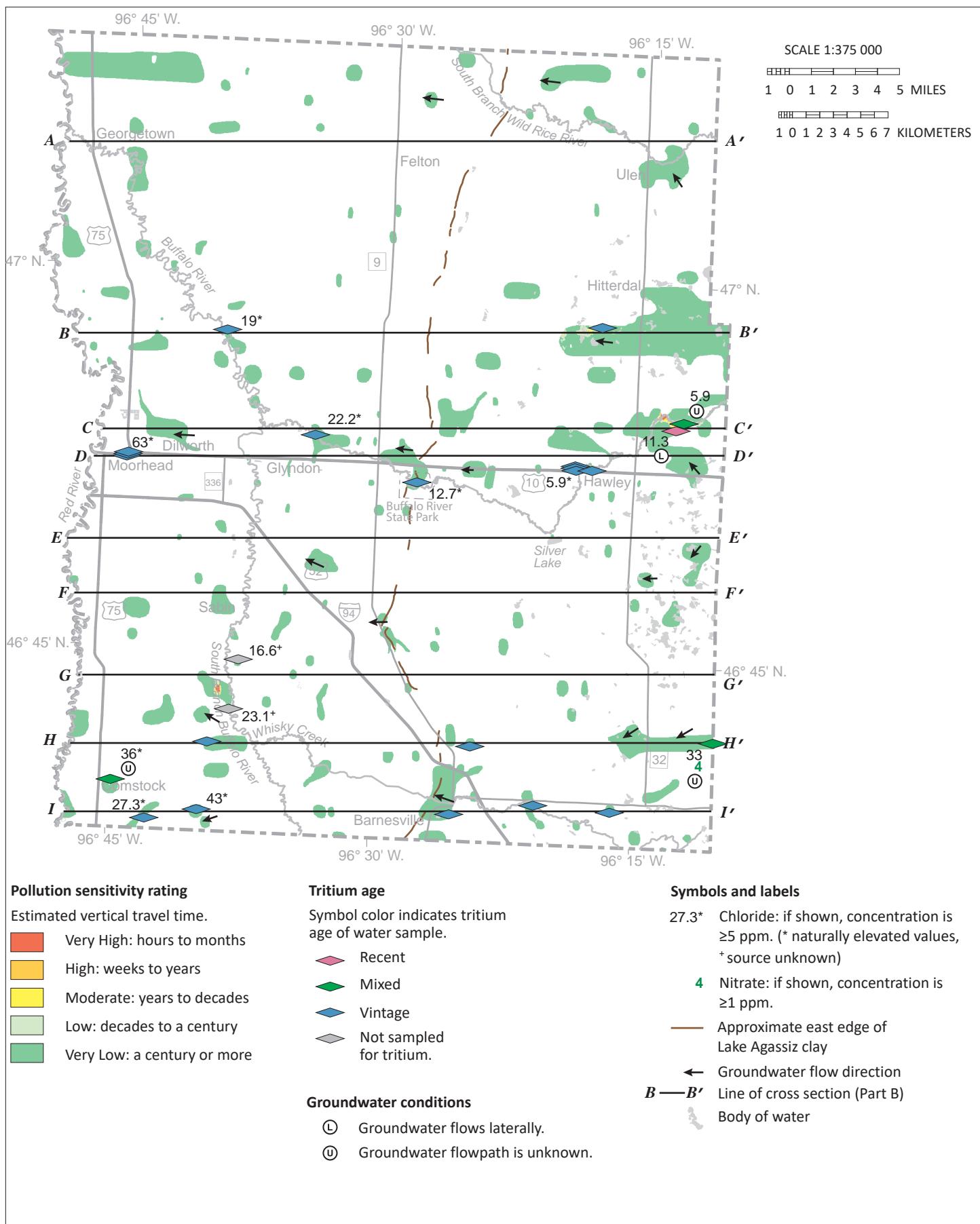


Figure 32. Pollution sensitivity of the H2 aquifer and groundwater flow directions

This aquifer group exhibits mostly very low pollution sensitivity. The depth to the top of this aquifer group ranges from approximately 20 to 330 feet.

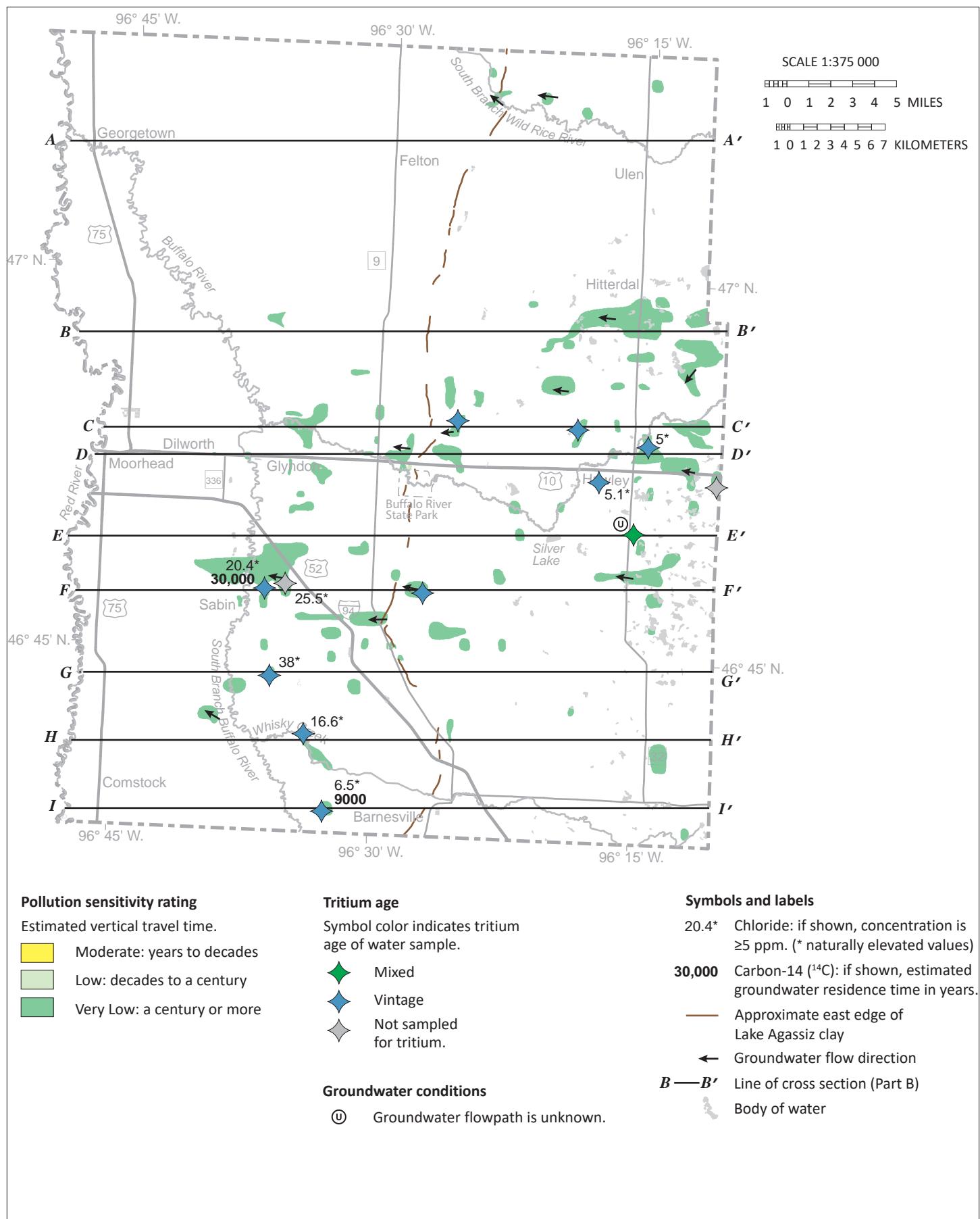


Figure 33. Pollution sensitivity of the h3/h4 aquifer group and groundwater flow directions

This aquifer group exhibits very low pollution sensitivity. The depth to the top of this aquifer group ranges from approximately 30 to 480 feet.

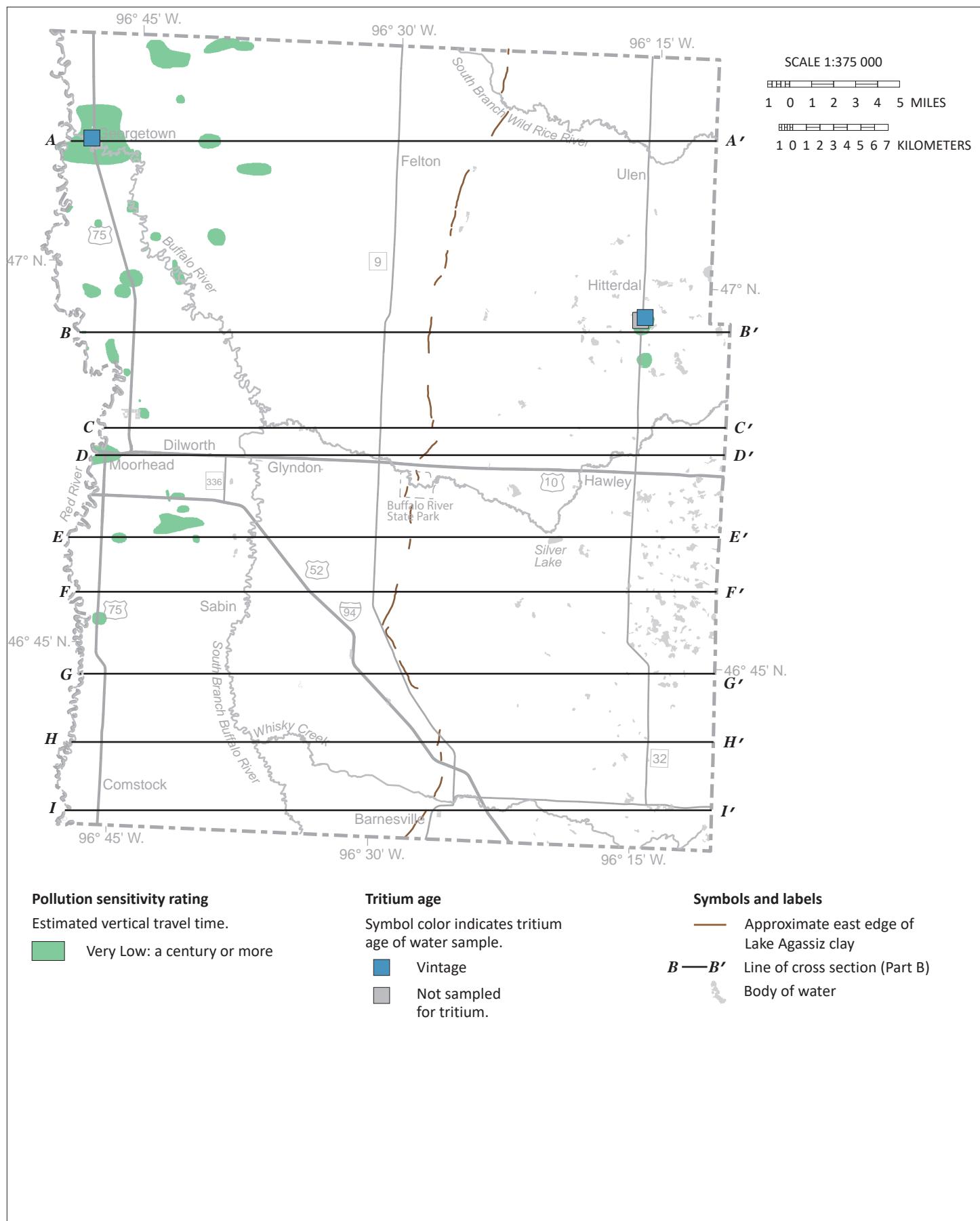


Figure 34. Pollution sensitivity of the bv/x aquifer group

This aquifer group exhibits very low pollution sensitivity. The depth to the top of this aquifer group ranges from approximately 130 to 250 feet.

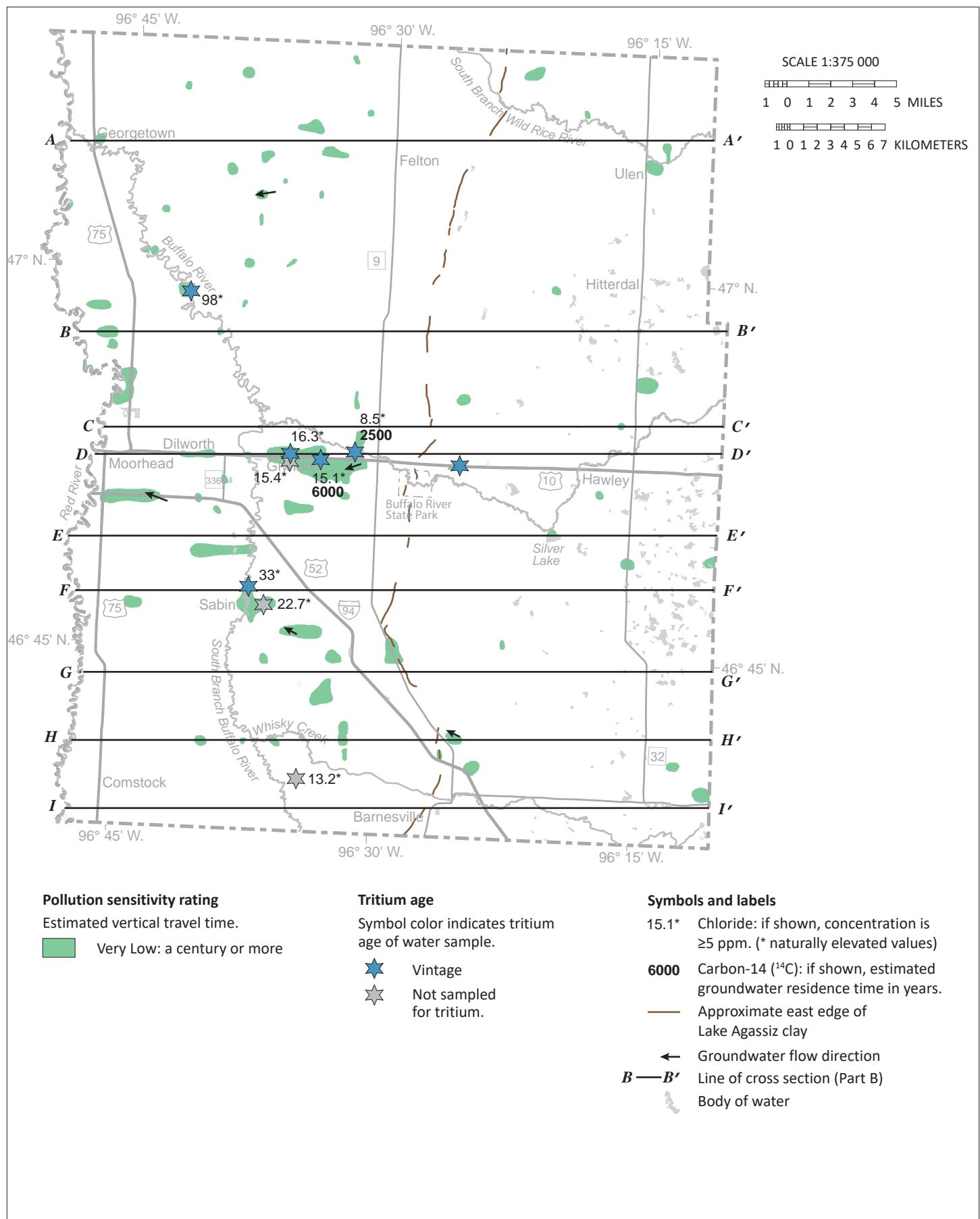


Figure 35. Pollution sensitivity of the qu aquifer group and groundwater flow directions

This aquifer group exhibits very low pollution sensitivity. The depth to the top of this aquifer group ranges from approximately 70 to 740 feet.

Hydrogeologic cross sections (Plates 7 and 8)

The hydrogeologic cross sections shown on Plates 7 and 8 illustrate the horizontal and vertical extent of aquifers and aquitards, groundwater residence time, and general directions of groundwater flow. These nine cross sections were selected from a set of 63 regularly spaced, west-to-east cross sections created by the MGS, to display the most chemistry data and to illustrate a variety of recharge examples.

These cross sections were constructed using a combination of well data from the County Well Index and the following sections of Part A of this atlas: Bedrock Geology (Plate 2), Surficial Geology (Plate 3), and Quaternary Stratigraphy (Plate 4). The well information for each cross section was projected onto the trace of the cross section from distances no greater than one-half kilometer.

Relative hydraulic conductivity

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

Glacial sediment layers that act as aquitards (till units) are shown in shades of gray on Plates 7 and 8. Lighter shades indicate aquitards with higher relative hydraulic conductivity. The percent sand in each of the aquitards is based on the average matrix texture of each glacial aquitard [or till].

Units with the lowest sand content include the Sherack and Brenna formations (sl and bl, 2 percent) and the upper member of the Red Lake Falls Formation (rpt, 24 percent). Till units with higher sand percentages include the New York Mills member of the Otter Tail River Formation (ont, 42 percent), the lower member of the New Ulm Formation and the Villard Member of the Otter Tail River Formation (ont and nvt, both 45 percent), Gardar Formation (dgt, 51 percent), Hewitt Formation (ht1, 52 percent), and the unnamed pre-Wisconsinan Rainy till (x3t, 56 percent).

Groundwater flow direction

Groundwater moves from areas with higher potential energy to areas with lower potential energy. The direction of groundwater movement is interpreted from the

equipotential contours constructed from measured water levels in wells. These contours can be used to identify the groundwater flow direction, recharge zones, and discharge zones.

The equipotential contours and flow arrows show that the groundwater flow is initially downward, then laterally toward the larger creeks and rivers. Groundwater recharge zones exist across broad areas of the county, however, smaller discrete groundwater recharge areas are identified in the following section based on occurrences of connected aquifers and geochemical data such as tritium, chloride, and nitrate.

Recharge and Discharge

The groundwater conditions first described on page 33 are also shown on the cross sections where water samples were collected as a way of interpreting how recharge water containing tritium entered the various aquifers. The following descriptions are grouped by groundwater condition to give a sense of general distribution and importance within the county.

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

An example of this condition is highlighted on the eastern portion of C-C' where recent tritium-age water was detected in the relatively shallow gss aquifer (gr aquifer group) by water that moved through the relatively thin overlying rlt aquitard. Similar recharge conditions can be found for the same aquifer group on the eastern portion of D-D', F-F' and G-G'; the nhga and nhs aquifers (nh aquifer group) in the southeastern portion of the county on H-H' and I-I', respectively; and the rgs aquifer (rlf aquifer group) on the western portion of F-F'.

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

Examples of this condition are shown on the eastern portion of F-F' where the mixed tritium-age water in the gss and gsg units (gr aquifer group) is probably the result of water from the overlying surficial sand leaking through the thin rlt aquitard. Similar recharge conditions can be found in the gss aquifer on the eastern portion of A-A'. In the southeastern part of the county condition 2 is shown on I-I' west of Deerhorn Creek in the nhs aquifer (nh aquifer group), and the eastern portion of I-I' in the osu aquifer (ot/nv aquifer group). Examples in the western part of the county are in the Buffalo aquifer (rgs) on C-C', E-E', and F-F'.

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

This condition appears to be relatively rare in the county. One example is shown on the eastern portion of B–B' where the overlying gsg aquifer (gr aquifer group) leaked groundwater with tritium through the underlying gst aquitard to the underlying hs1 aquifer. This type of recharge also occurs on the far eastern end of F–F' in the nvs aquifer (ot/nv aquifer group).

④ Groundwater flows laterally.

This classification is necessary due to the limiting assumption in the pollution sensitivity model of only vertical recharge. This classification is used where tritium detections occur in very low to low sensitivity areas. The likely source of water containing tritium is not from a direct vertical pathway, but from an upgradient (lateral) location.

Two examples of this condition are shown on the eastern part of B–B' for both the gr and h1 aquifer groups. The apparent sources of the groundwater with tritium in these aquifers are large areas of the relatively shallow gr aquifer group that exist upgradient from these locations. Other areas of lateral recharge for the gr aquifer group are shown on the eastern portion of E–E' and west of center on F–F'. Other examples of the L recharge condition for the hs1 and hs2 aquifers are shown on eastern C–C' along the Buffalo River. The Buffalo aquifer (rgs) shown on western D–D' has four examples where this aquifer is mostly covered by Lake Agassiz clay, suggesting the probable source of mixed tritium-age water is upgradient from these locations.

⑤ Groundwater flowpath is unknown.

The tritium detected in groundwater samples from these locations may be from unknown well conditions or unknown aquifer connections. This unknown designation is used when a recent or mixed classification can't be explained by any of the previously described recharge conditions. These anomalous conditions could be due to old corroded well casings that allow shallow recent water to leak directly into the well casing. In addition, sometimes older wells were not constructed to modern standards and lack a grout seal around the casing allowing recent tritium-age water to leak directly to the screened or open-hole portion of the well. Three examples of this condition are shown on the far eastern portions of cross sections C–C' (aquifer hs2), E–E' (aquifer hs3), and H–H' (aquifer hs2).

⑥ Groundwater discharges to a surface-water body.

Groundwater discharge to rivers, lakes, springs, and wetlands is a common occurrence in Minnesota. It supplies water vital to aquatic ecosystems. Discharge or baseflow is most likely to occur where an underlying aquifer is connected to surface water.

The groundwater discharge (gaining) or recharge from surface water (losing) of surface-water bodies can vary depending on seasonal or climatic cycles. Evaluating this variability was beyond the scope of this study. The following designations of discharge are meant to recognize that groundwater discharge to surface-water bodies is likely to occur for at least part of each year.

Even though the regional groundwater flow is toward the Red River, direct hydraulic connections through multiple stacked buried sand aquifers are rare or do not exist because of the thick Lake Agassiz clay layer beneath the river. However, the surficial sand aquifer (ss) does have a direct connection. Other rivers that appear to receive direct discharge include the south branch of the Wild Rice River (eastern A–A'), a western portion of the Buffalo River (A–A'), and the eastern portions of the Buffalo River (C–C' and D–D').

Aquifer characteristics and groundwater use

Aquifer specific capacity and transmissivity

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

Specific capacity is the pumping rate per unit depth of drawdown. It is typically expressed in gallons per minute per foot (gpm/ft) and is determined from short-term pumping or well-development tests performed after a well was drilled. To ensure that the specific capacity values reflect actual pumping (not air-lifting), the pumping-test data were obtained from the County Well Index for wells with the following conditions:

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

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

The specific capacity and transmissivity values in Table 2 show a wide range from approximately 1 to 230 gpm/ft, and 4,000 to 30,000 ft²/day, respectively, suggesting the productivity in these aquifers can be highly variable due to a wide range of aquifer material textures from relatively fine-grained sand to coarse sand and gravel mixtures.

Table 2. Specific capacity and transmissivity of selected wells

Aquifer	Specific capacity (gpm/ft)					Transmissivity (ft ² /day)		
	Casing diameter (inches)	Mean	Min	Max	Number of tests	Casing diameter (inches)	Average (ft ² /day)	Number of tests
Surficial sand and gravel (QWTA)								
ss	12	35	35	35	1	14	166960	1
Buried sand aquifer (QBUA or QBAA)								
rgs (Buffalo)	8–16	128	17	222	6	8–16	21339	4
gss	12–14	57	7	121	3	14	31549	1
gds	16	179	179	179	1	--	--	--
nhs	8–12	22	4	70	6	12	8304	1
osu	14	86	86	86	1	14	11364	1
nvs	4	1	1	1	1	--	--	--
dgs	12	11	11	11	2	8–14	4418	4
hs1, hg1	8–13	2	1	2	3	--	--	--
hs2	12	107	54	229	4	10–16	20691	2
hs3	12–14	16	6	23	3	12	4010	1
x3s	8	5	5	5	1	--	--	--
qsu1	12	8	7	8	3	6–12	5136	2

Specific capacity data was adapted from the County Well Index; gpm/ft (gallons per minute per foot). Transmissivity data are from MDH and the U.S. Geological Survey (USGS) tests compiled by the DNR; ft²/day (feet squared per day), -- means no data.

QWTA: Quaternary water-table aquifer; QBUA: Quaternary buried unconfined aquifer; QBAA: Quaternary buried artesian aquifer

Groundwater use

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

The reported water use for 2015 is categorized in Table 3 for all large-capacity users in the county by the type of aquifer (Figure 36) and type of use (Figure 37). The majority of permitted water use is for municipal and other public water supply (52 percent). This water is drawn mainly from the buried sand aquifers and to a lesser extent, surficial sand aquifers. Agricultural crop irrigation is the second most common use category (44 percent) with buried sand aquifers as the most important source. Others

use relatively small volumes of groundwater (less than 1 to 2 percent of total) from buried sand sources, including livestock watering, golf course irrigation, gravel washing, industrial processing, and lake level maintenance.

There are no reporting requirements in Minnesota for well owners that use quantities of groundwater less than 10,000 gallons per day or 1 million gallons per year. However, the aquifer being used can be determined in many cases by comparing the well constructions with the closely spaced cross sections produced by the MGS. Of the approximately 2,200 active wells in the county with identified aquifers, most are completed in the buried sand aquifers (95 percent) followed by the surficial sand aquifer (4 percent). Only 1 percent are completed in the bedrock or weathered bedrock aquifers. The large majority of wells are domestic wells (88 percent), followed by public supply (4 percent), irrigation (2 percent), commercial/industrial (1 percent), and other categories (6 percent).

Table 3. Reported 2015 water use from DNR appropriation permit holders

Use category	Surficial sand (QWTA)	Buried sand and gravel (QBAA, QBUA)	Unknown	Total (MGY)	Total (percent)
Municipal/public water supply	121	392	2	515	52
Agricultural crop irrigation	48	336	51	435	44
Livestock watering	--	22	--	22	2
Golf course irrigation	--	9	--	9	1
Sand and gravel washing	--	4	2	6	<1
Other industrial processing	--	1	--	1	<1
Basin (lake) level maintenance	--	--	<1	<1	<1
Total (MGY)	169	764	55	988	
Total (percent)	17	77	5		

Data from Minnesota Permitting and Reporting System (DNR, 2017b). MGY, million gallons per year: dash marks (--) indicate no use in those categories. Percentages do not total 100 due to rounding.

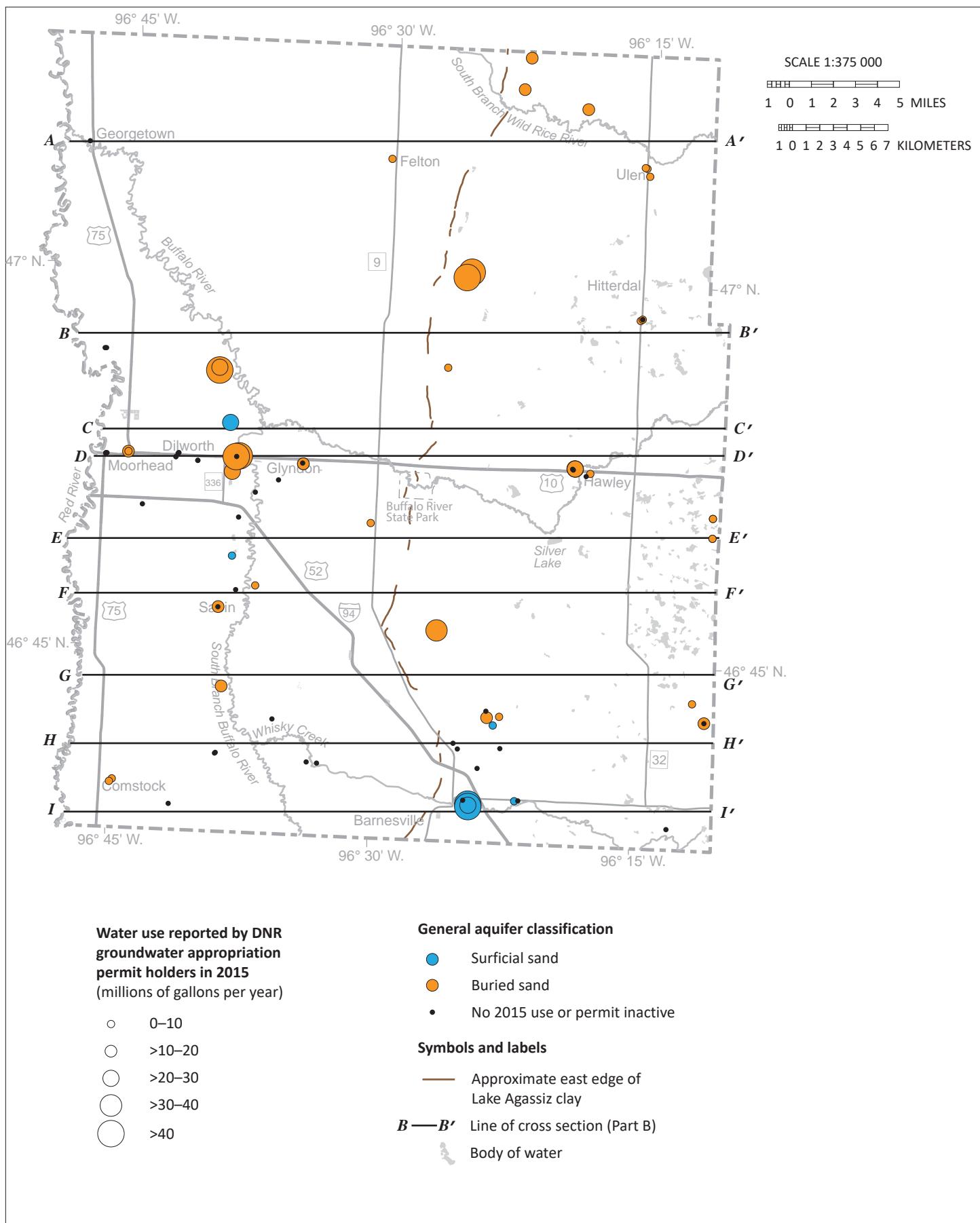


Figure 36. General aquifer classification of DNR appropriation permit holders
Buried sand aquifers are the most commonly used type of aquifer for high-capacity use.

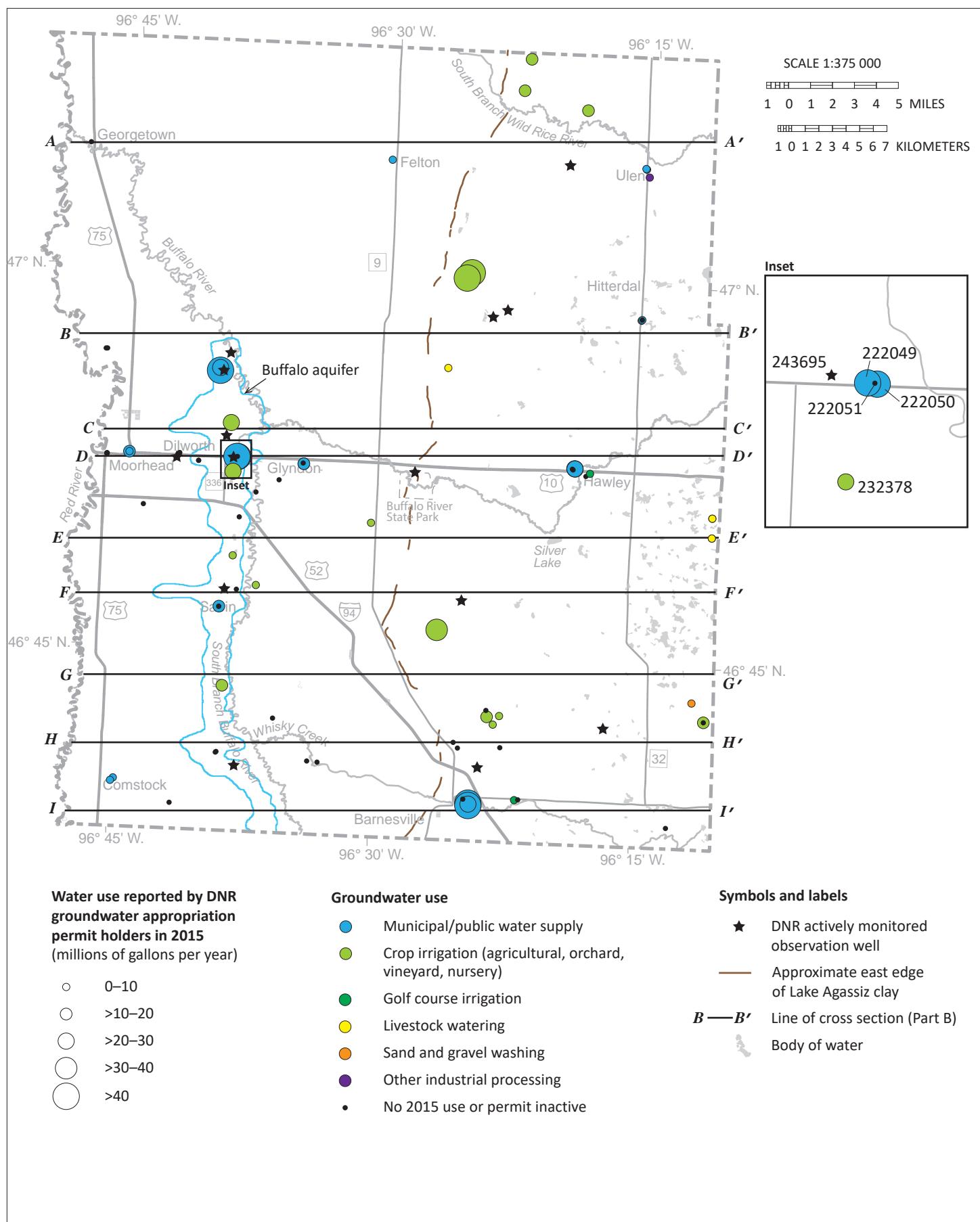


Figure 37. Groundwater use of DNR appropriation permit holders

Municipal and crop irrigation are the two most common types of high-capacity use in the county.

Groundwater level monitoring

The DNR maintains a statewide groundwater level monitoring program using observation wells for assessing groundwater resources, determining long term trends, interpreting impacts of pumping and climate, planning for water conservation, evaluating water conflicts, and otherwise managing water resources.

The Buffalo aquifer east of Moorhead has been monitored almost continuously since the beginning of its use in 1948. The data revealed the water-use challenges in this area and have helped in planning for sustainable long-term water supply.

The first major use was by Moorhead Public Service (MPS) in 1948 at the MPS South Well Field (Figure 37 inset). MPS began pumping water from the MPS North Well Field in January 1989 (Schoenberg, 1997).

The hydrograph of observation well 243695 (Figure 38, top) shows the long-term water level decline from 1946 to 1991 caused by withdrawals from the Buffalo aquifer. Schoenberg provided a detailed history of the transition from a confined aquifer at that location to unconfined because of groundwater withdrawal. Groundwater pumping from the aquifer reached its peak in 1988 and the aquifer water level reached its all-time low the following year.

To preserve the long-range viability of the aquifer, the DNR and MPS agreed to a reduced amount of groundwater withdrawal at that location (Figure 38, middle). The community transitioned to more surface water from the Red River and decreased annual pumping from the Buffalo aquifer. By 2004 the water levels within the aquifer returned to pre-1948 levels (DNR, 2017a).

The long-term strategy for the Buffalo aquifer is to maintain the current low-level pumping rates with the understanding that higher rates could be used during drought conditions. Except for some short term droughts, precipitation has shown a consistent pattern since the mid-1940s with a slight increase in the monthly average of approximately a half an inch (Figure 38, top).

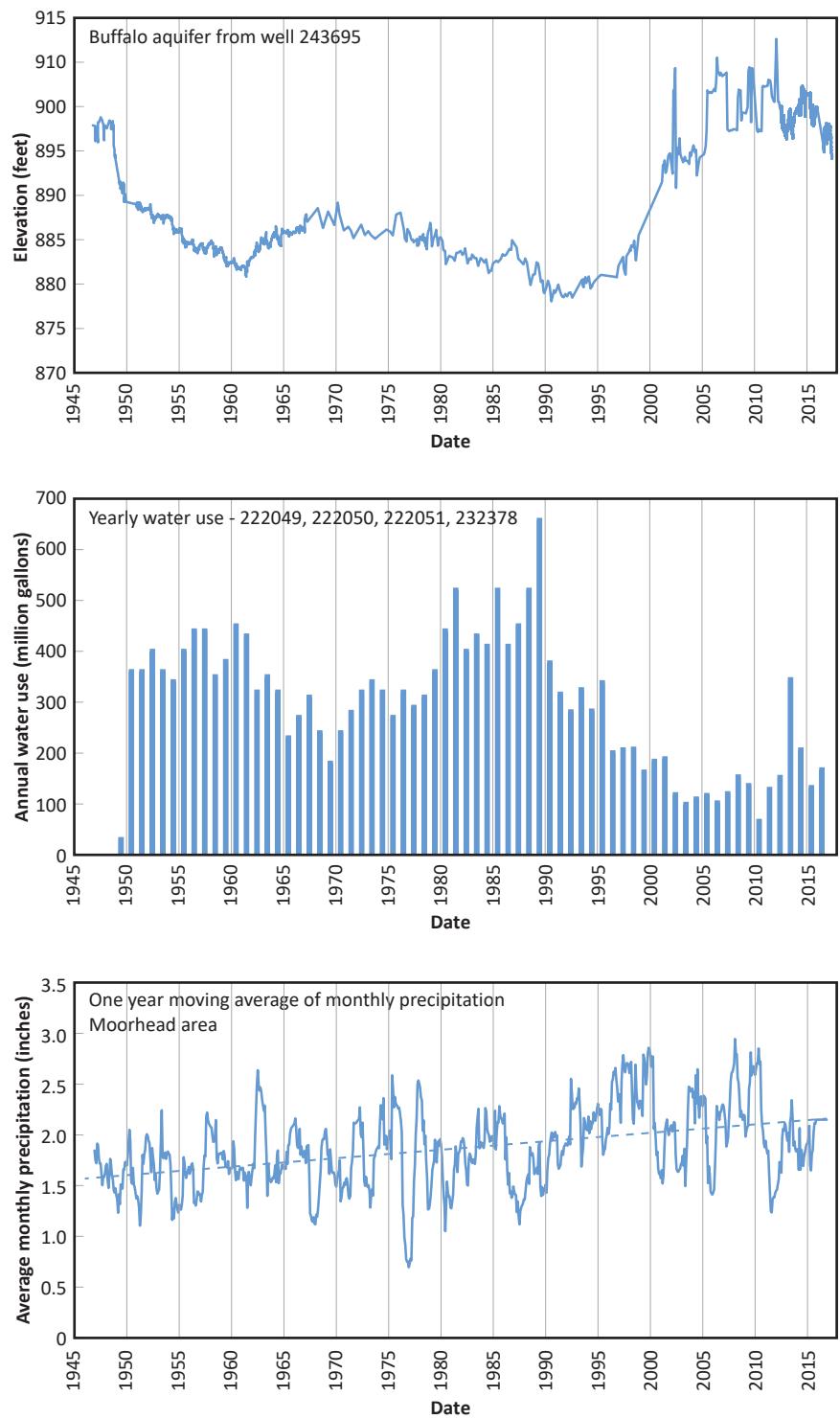


Figure 38. Hydrographs of the Buffalo aquifer area

Water levels, groundwater use, and precipitation. Hydrograph modified from Schoenberg, 1997.

Summary

Groundwater flow directions are westerly toward the Red River. Local water-table flow directions are toward tributaries of the Red River such as the Wild Rice and Buffalo rivers, and Whisky and Stony creeks. Water-table elevations cover a wide range of values ranging from high elevations in the eastern part of the county on the Alexandria moraine to lower values in the western half of the county (Red River valley).

Potentiometric surface maps of aquifers and aquifer groups show a general pattern of west and northwest flow toward the Red River. Some exceptions to this general pattern include complex local flow patterns because of groundwater pumping in the Buffalo aquifer and converging groundwater flow patterns in the Moorhead area apparent in the aquifer groups nh, ot/nv, dg/br, h1, and h2. Aquifer discharge to rivers also creates convergent flow toward rivers in the gr and nh aquifer groups, and ot/nv aquifer group in the northeastern part of the county along the South Branch Wild Rice River. Convergent groundwater flow created by groundwater discharge is also apparent along the Buffalo River in the east-central part of the county in the aquifer groups gr, ot/nv, h1, h2, and h3/h4.

Chemical characteristics of groundwater revealed important information regarding groundwater source, human health risk, residence time, and pollution sensitivity implications.

- **Surface water to groundwater connections** were revealed from stable isotope characteristics in 1 groundwater sample with an evaporative signature collected downgradient of Big Mud Lake. The aquifers overlain by thick impermeable Lake Agassiz clay have an isotopic signature characteristic of glacial meltwater. Samples of glacial meltwater or mixed glacial meltwater have carbon-14 residence times ranging from 30,000 to 40,000 years.
- **Chloride** is a contaminant in the Buffalo aquifer area and at scattered locations in the eastern part of the county. Of the 105 samples with elevated chloride, 21 percent also had an anthropogenic origin. Most of these were from the upper (shallowest) three buried sand aquifer groups (rlf, gr, and nh). In the western part of the county, the chloride was commonly from natural sources because the protective effect of the Lake Agassiz clay.
- **Nitrate** was found at elevated concentrations in 4 percent of the 159 groundwater samples tested. Most were detected in the eastern portion of the county in the relatively shallow gr and h1 buried sand aquifer groups

(well depths 45 to 78 feet) but also in deeper wells in the nh and h2 aquifers (117 to 264 feet, respectively) in the southeastern part of the county.

- **Arsenic** concentrations were above the method reporting limit for 88 percent of the 133 samples tested, indicating a natural water quality problem for the majority of well owners in the county. Elevated values were present in all sampled aquifers or aquifer groups, with the exception of the ss aquifer.
- **Manganese** concentrations equaled or exceeded the HBV (100 ppb) for 59 percent of groundwater samples, indicating a natural water quality problem for the majority of well owners in the county.
- **Carbon-14** data from 12 wells within the county showed that residence time in buried sand aquifers ranged from approximately less than 100 to 40,000 years, reflecting the wide range of groundwater conditions in the county.

Buried sand aquifer pollution sensitivity: The prf and rlf aquifers and the gr aquifer group are relatively sensitive to pollution with the exception of portions in the western part of the county where sensitivity can be very low to moderate. Recent or mixed tritium-age groundwater samples were common in the rlf aquifer and gr aquifer group. Most of the samples from the rlf aquifer contained anthropogenic chloride concentrations.

The underlying aquifers and aquifer groups typically have very low pollution sensitivity conditions. Exceptions include some eastern portions of the aquifer groups nh, ot/nv, and h1.

Water use: The majority of the permitted water use is for municipal and other public water supply (52 percent). This water usage is drawn mainly from the buried sand aquifers (QBAA and QBUA) and to a lesser extent, surficial sand (QWTA). Agricultural crop irrigation is the second most common use category (44 percent) with buried sand aquifers as the most important source.

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Appendix A

Groundwater field sample collection protocol

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

Samples were analyzed by DNR staff; the University of Minnesota, Department of Earth Sciences Laboratory (U of M); or the University of Waterloo Environmental Isotope Laboratory (Waterloo).

The well owners received a copy of the results and reference information.

For additional information, contact the County Geologic Atlas program.

Table A-1: Groundwater field sample collection and handling details

Parameter	Enriched Tritium	¹⁸ O ² H	Cations	Anions	Trace constituents	Alkalinity	¹⁴ C
Lab	Waterloo	Waterloo	U of M	U of M	U of M	DNR Staff	U of M
Sample container	500 ml HDPE	60 ml HDPE	15 ml, Fisherbrand BLUE cap	50 ml Argos BLACK bottle***	15 ml Sarstedt RED cap	500 ml plastic	30 gallon barrel
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
Preservative	no	no	1 drop 6N HCl	no	5 drops 15N HNO ₃	no	NH4OH added to adjust pH
Refrigeration	no	no	yes	yes	yes	Yes, if not analyzed onsite	no
Shelf life	long	long	2–3 weeks	2–3 weeks	2–3 weeks	24–48 hours	years
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	none	none
Field blank	none	none	1 for every 20****	1 for every 20****	1 for every 20****	none	none
Storage duplicate	yes	yes	no	no	no	no	no

*Sample bottle was rinsed three times with sample water prior to collecting the sample (filtered water if sample was filtered). Rinsing process was filling the bottle with sample water and then pouring the contents out over the cap.

**Rinsed the bottle three times with sample water prior to collecting the sample. Bottle was filled by submerging with cap in hand, and sealed submerged to ensure no remnant bubbles.

*** 50 ml anion bottle was filled, unless filtering was very difficult. All bottles were filled to at least 1/3 full.

****Deionized (DI) water was used for field blanks. DI water was poured into the back of filtering syringes when the plunger was removed. Bottles were filled by forcing water through filter.

Appendix B

Tritium values from precipitation and surface water

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

1. **Precipitation composites** were collected at a Minnesota DNR MNgage climatology monitoring station in Maplewood (Twin Cities metropolitan area). Samples were composited over the course of 30-day periods between spring and fall over the years 2012 through 2017.
2. **A lake-water sample** was collected at the surface several feet from shore. The relatively low TU value (3.8) may indicate a mixture of older, upwelling groundwater and lake water.

Visit the DNR County Geologic Atlas Program [page](#) (mndnr.gov/groundwatermapping) for more information.

For weather station information, visit the MNgage [page](#) (<https://climateapps.dnr.state.mn.us/HIDENsityEdit/HIDENweb.htm>).

Table B-1: Enriched tritium results

Sample date range	Tritium TU	Analytical error	Sample type
MNgage precipitation station			
05/21/2012–06/20/2012	8.7	0.7	Precipitation composite
09/30/2012–10/30/2012	6.7	0.7	Precipitation composite
05/09/2014–06/09/2014	7.0	0.7	Precipitation composite
10/01/2014–10/31/2014	6.7	0.7	Precipitation composite
05/01/2015–05/31/2015	5.3	0.6	Precipitation composite
08/17/2016–09/16/2016	8.3	0.8	Precipitation composite
04/01/2017–04/30/2017	8.1	0.7	Precipitation composite
09/06/2017–10/06/2017	6.5	0.6	Precipitation composite
Silver Lake, Clay County			
06/9/2015	3.8	0.5	Limnetic zone

Tritium age of historic groundwater samples

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

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

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

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

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

Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

hydraulic—relating to water movement.

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

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

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

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).

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

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.

saprolite—a residuum created from extensive chemical weathering of bedrock into clay minerals.

stable isotope—chemical isotopes that are not radioactive.

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

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

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

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

tritium (^{3}H)—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.

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



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