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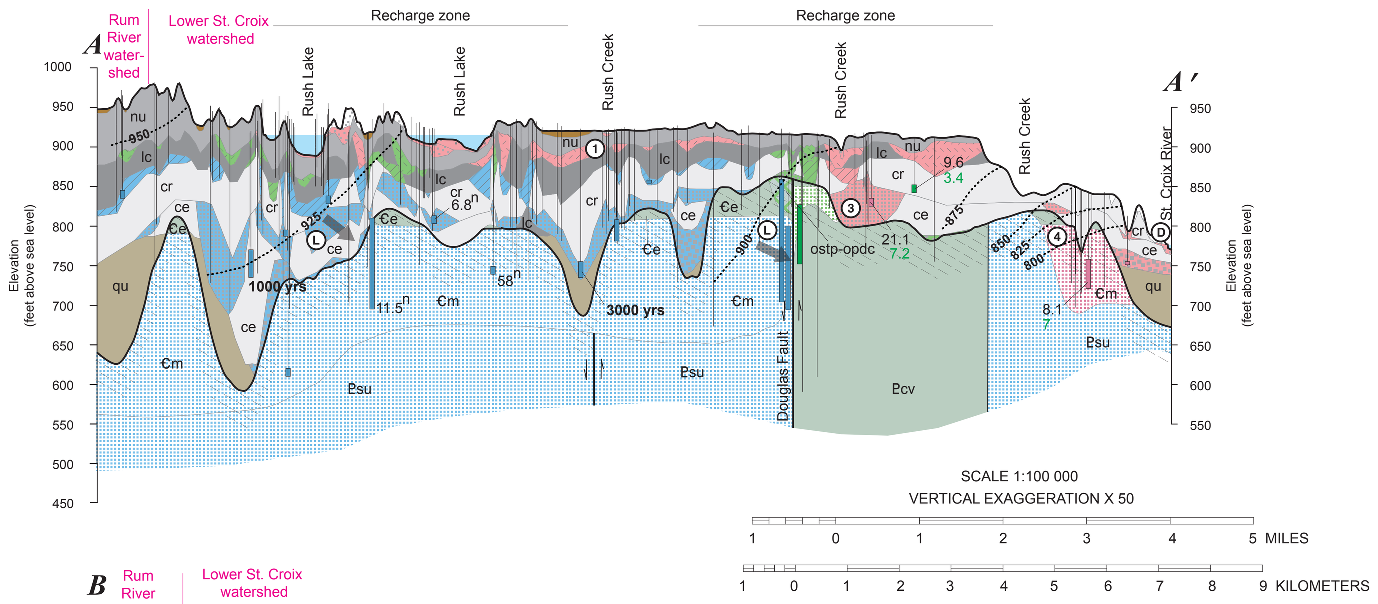
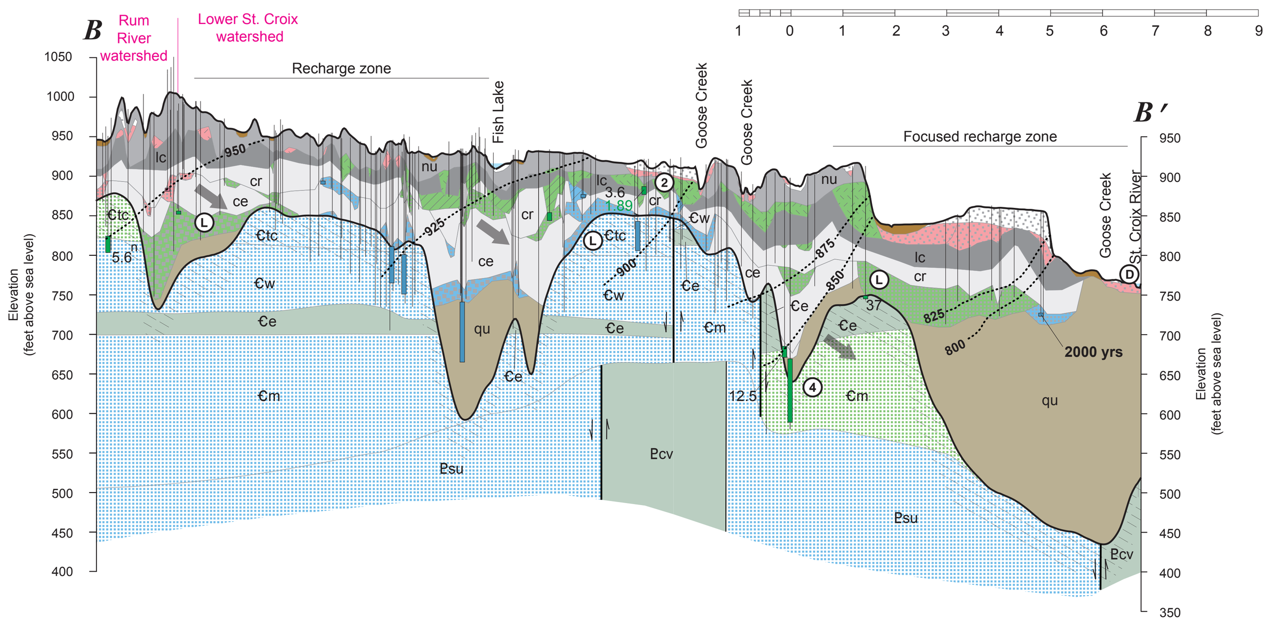
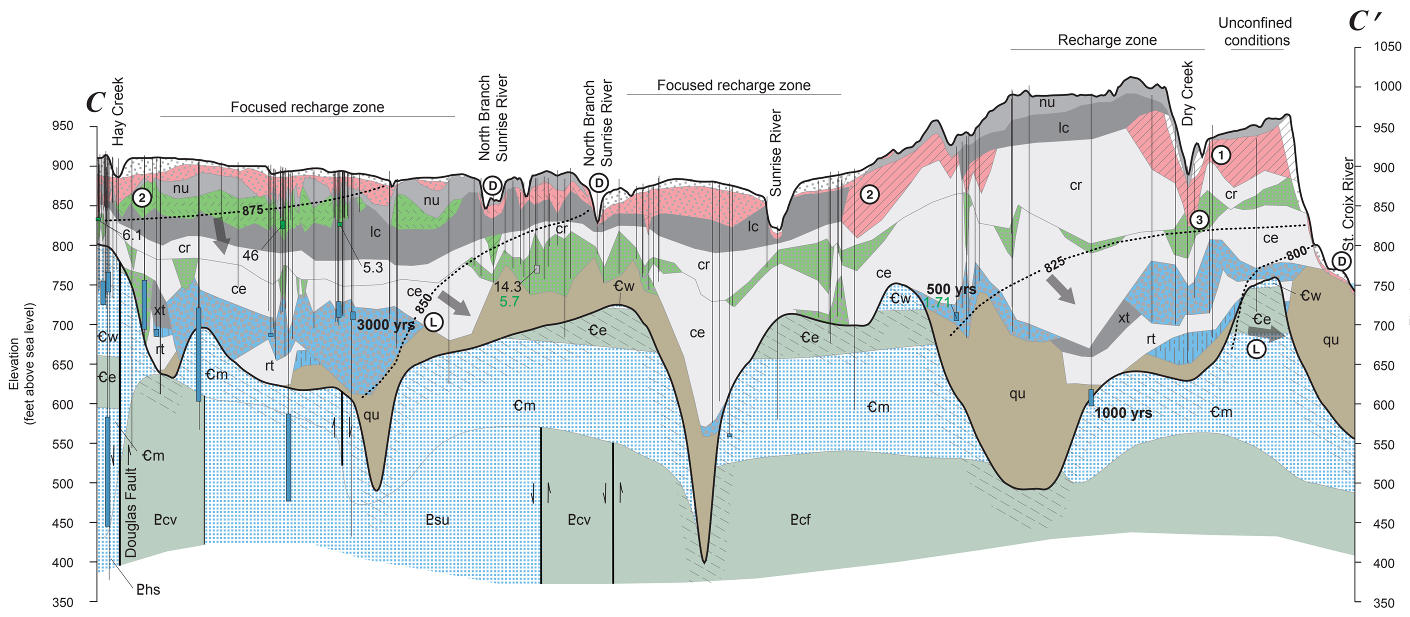
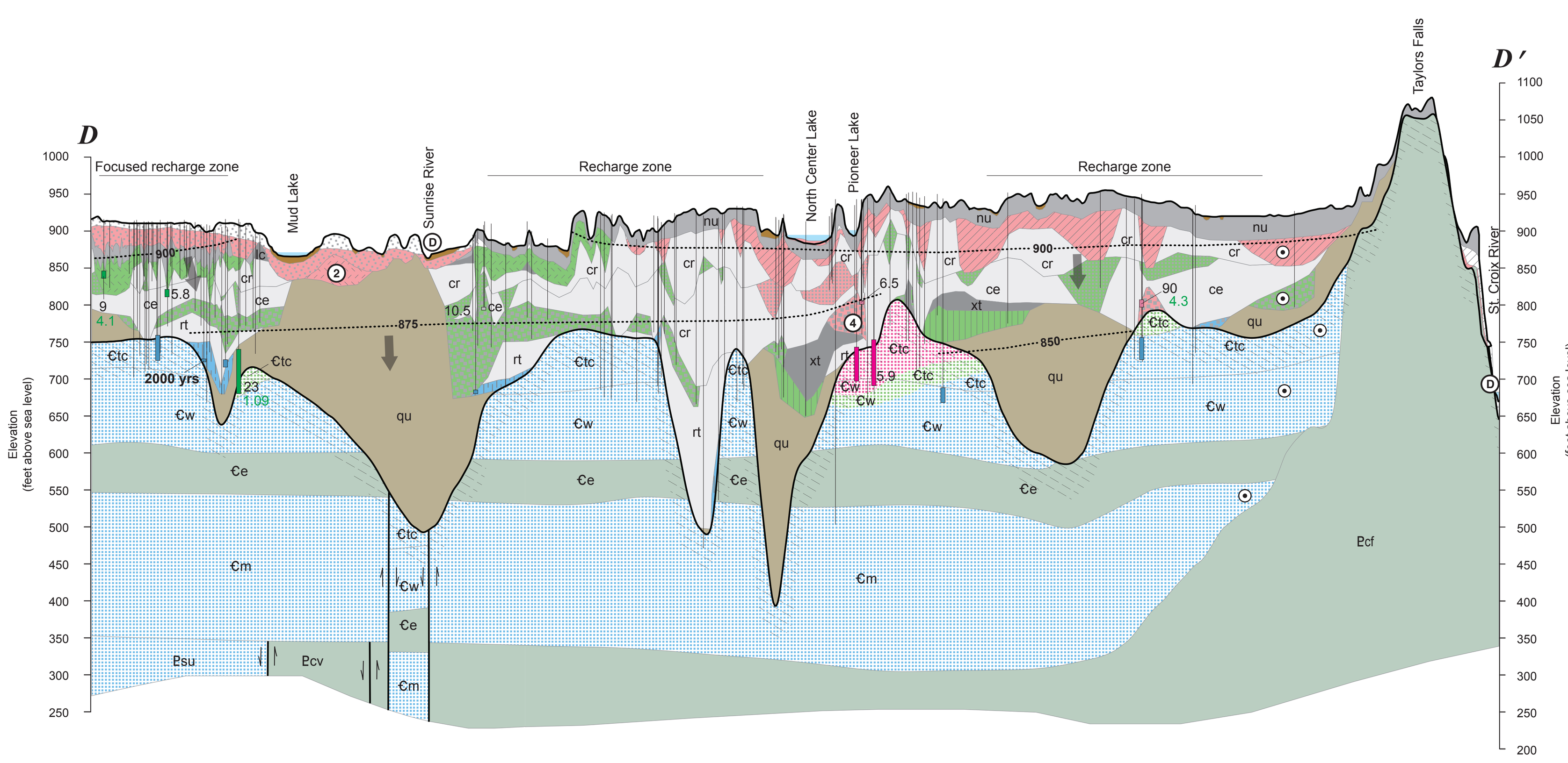
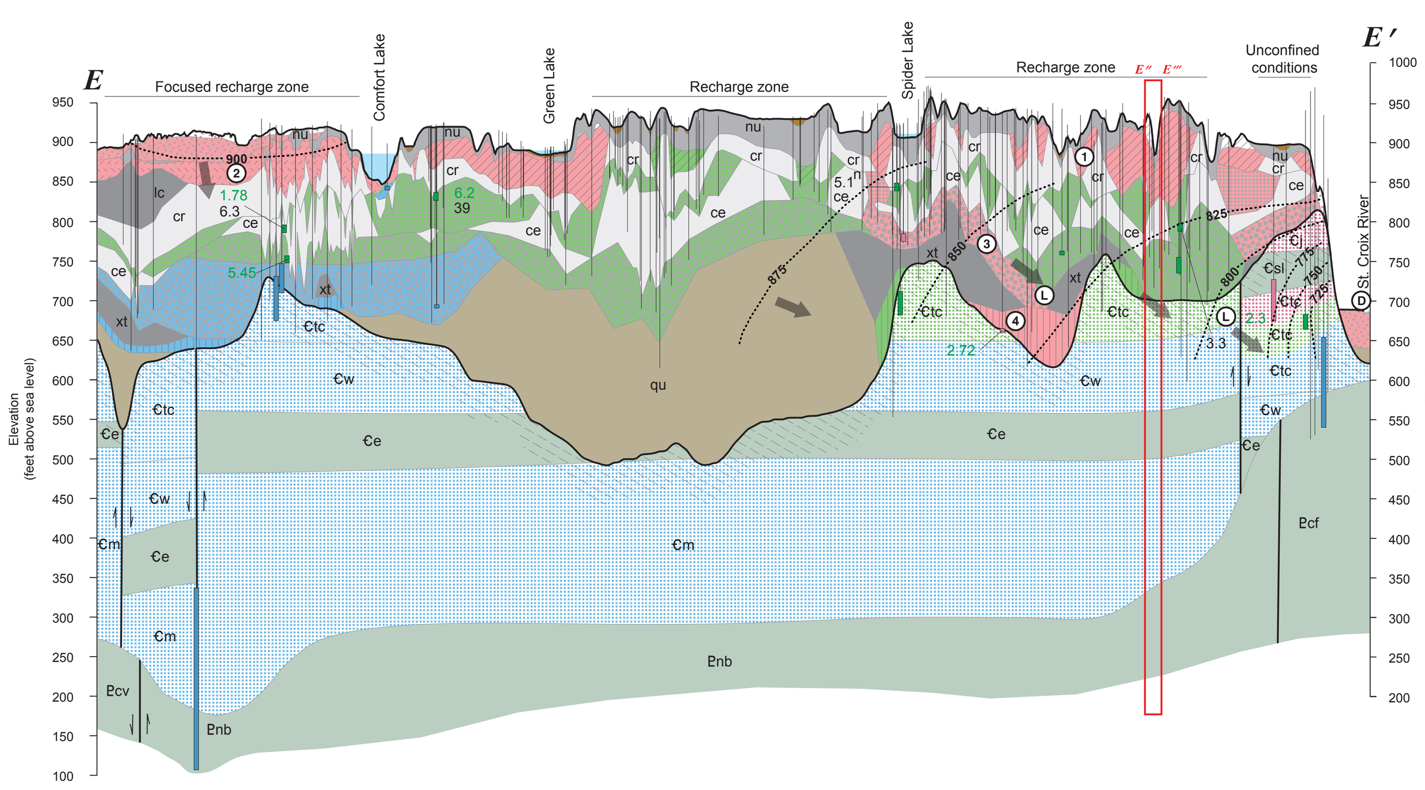






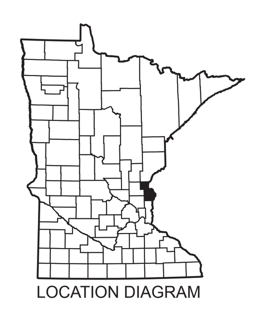




HYDROGEOLOGIC CROSS SECTIONS

By John D. Barry

2014



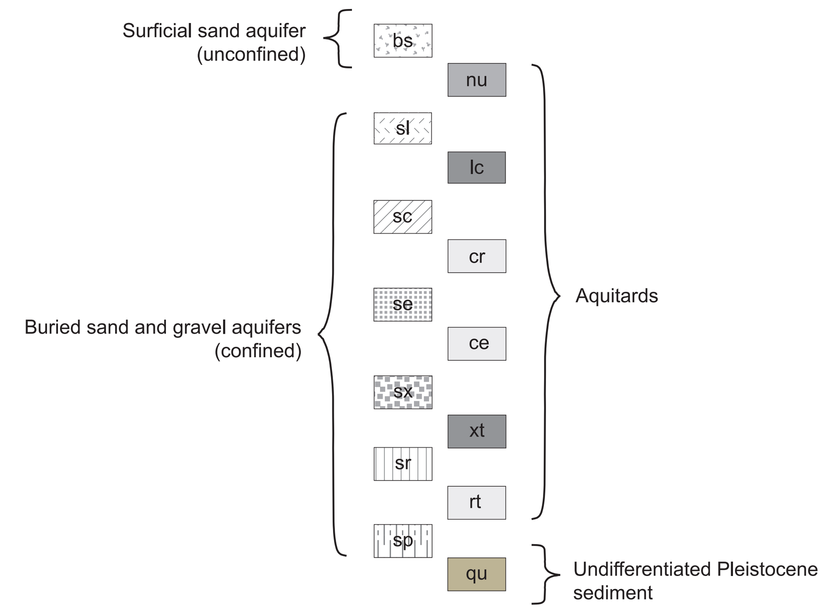


FIGURE 2. Stratigraphic relationship in Chisago County. Quaternary buried sand and gravel aquifers are shown as patterns, aquitard units are shown as shades of gray, and undifferentiated Pleistocene sediment is shown in brown. Aquitards are low-permeability till and other fine-grained units that restrict groundwater movement.

Geologic Unit		Hydrogeologic Unit	Hydrogeologic Unit Properties
Jordan Sandstone		Jordan aquifer	Relatively high intergranular permeability
			Relatively low permeability
St. Lawrence Formation			Relatively low permeability
Tunnel City Group	Mazomanie Formation	Upper Tunnel City aquifer	Relatively low intergranular permeability with high permeability bedding fractures
Tunnel City Group	Lone Rock Formation		Confining unit, not shown on cross sections; included with Ꞓtc aquifer unit
Tunnel City Group	Mazomanie Formation	Upper Tunnel City aquifer	Relatively low intergranular permeability with high permeability bedding fractures
Tunnel City Group	Lone Rock Formation		Confining unit, not shown on cross sections; included with Ꞓtc aquifer unit
Wonewoc Sandstone		Wonewoc aquifer	Moderate intergranular permeability
Eau Claire Formation			Relatively low permeability
Mt. Simon Sandstone		Mt. Simon aquifer	Moderate intergranular permeability
Mesoproterozoic Sedimentary Rock		Undifferentiated aquifer	Moderate intergranular permeability
Mesoproterozoic Volcanic Rock		Volcanic nonaquifer unit	Very low to low fracture permeability, very low yield

Aquifer, relatively high permeability
Aquitard, relatively low permeability
Volcanic nonaquifer, very low yield
High permeability bedding fracture

FIGURE 3. Sequence of bedrock geologic units, hydrogeologic units, and hydrogeologic unit properties in Chisago County.

INTRODUCTION

The five cross sections on this plate illustrate the horizontal and vertical extent of aquifers and aquitards commonly encountered in Chisago County. They also show groundwater residence time and the general direction of groundwater flow. These five were selected from a series of 50 west-to-east geologic cross sections constructed for Part A (Meyer, 2010). Figure 1 shows the location of the five cross sections which are coincident with those selected to show the Quaternary stratigraphy on Plate 4 of Part A. Each was slightly modified and combined with underlying bedrock geology to create the geological framework used. Select wells along these cross sections were sampled and analyzed for most of the groundwater chemistry data including major cations, anions, trace elements, stable isotopes, tritium, and carbon-14.

The hydrogeology of Chisago County is influenced by the extensive sandy surficial geologic deposits in the central part of the county and by the deeply incised St. Croix River valley that forms the eastern border of the county. Since the end of the last glaciation, the St. Croix River has downcut into the glacial sediments and bedrock units creating the St. Croix River valley. Regional groundwater flow of both the Quaternary and bedrock aquifers is primarily east towards the St. Croix River.

RELATIVE HYDRAULIC CONDUCTIVITY

This plate identifies 1 surficial sand aquifer, 6 Quaternary buried sand and gravel aquifers, and 5 bedrock aquifers in Chisago County. The Quaternary buried sand and gravel aquifers are adequate for domestic wells, but variability in their thickness and extent can make them inadequate for municipal or industrial supply wells that require higher pumping capacities. Most high-capacity wells are constructed in the bedrock aquifers. The hydraulic properties of the Quaternary buried sand and gravel aquifers and bedrock aquifers are discussed in more detail on Plate 8.

The correlation of Quaternary aquifers and aquitards is shown in Figure 2. The relative hydraulic conductivity of the laterally continuous aquitards across Chisago County is depicted by shades of gray in Figure 2 and on the cross sections. Lighter shades represent higher hydraulic conductivity and darker shades represent lower hydraulic conductivity. These hues were assigned using the percentage of sand relative to silt and clay found in the matrix texture of each till unit (Part A, Plate 4, Table 1). The percentage of fine-grained particles of unconsolidated glacial material is a key control on the ability of the material to transmit water (Stephenson and others, 1988). Generally, glacial materials with higher percentages of silt and clay have less pore space available to transmit water. The lightest shade depicts the glacial sediment of the St. Croix (cr), Emerald (ce), and pre-Emerald (rt) phases of the Superior lobe. The tills of these phases are roughly 65 percent sand and 35 percent clay and silt. A medium shade depicts the New Ulm Formation (nu) of the Des Moines lobe. The till of this formation has a roughly even distribution of fines (clay plus silt) and sand. Darker shades represent sediment of the Automba phase of the Superior lobe (lc) and much older Winnipeg provenance sediment (xt). The tills of these phases are roughly 65 percent fines and 35 percent sand. Each cross section shows deeply buried undifferentiated Pleistocene sediments (qu) that are poorly understood because no wells penetrate the sediments. The matrix texture of these sediments has not been adequately characterized; therefore, no relative hydraulic conductivity for the qu unit is presented.

The sequence of bedrock geologic units, hydrogeologic units, and hydrogeologic properties is shown in Figure 3. The bedrock aquifers generally have good horizontal and vertical permeabilities. The confining units generally have low vertical permeability but may have relatively high horizontal permeability along bedding fractures that provide sufficient yield for domestic wells. Groundwater movement through the Jordan, Mt. Simon, and older undifferentiated aquifers is primarily through intergranular flow. Groundwater in the Upper Tunnel City aquifer mainly moves through fractures. Groundwater movement in the Wonewoc aquifer is through a combination of intergranular and fracture flow. An enhanced-permeability zone is generally found in the uppermost 50 feet of all Paleozoic sedimentary bedrock units that are either exposed at the land surface or directly covered by glacial sediment (Runkel and others, 2006). This enhanced permeability is attributed to the presence of fractures developed or enlarged during weathering when the bedrock surface was the land surface. The fractures in this enhanced-permeability zone generally increase the yield of aquifers. In addition, they will usually increase the permeability of aquitards, compromising their confining character. These fractures can allow units such as Mesoproterozoic volcanic rock to be used as a water source.

GROUNDWATER RESIDENCE TIME

The pink, green, and blue areas on the hydrogeologic cross sections represent groundwater residence time. Groundwater residence time is the approximate time elapsed since precipitation infiltrated the land surface to when the water was extracted, either from a well or by natural discharge at a surface-water resource such as a spring. Groundwater residence time can be estimated by the amount of tritium (^3H) in the sampled water, as described on Plate 7.

Recent tritium-aged waters are commonly found nearest to the land surface and vintage tritium-age waters are commonly found at greater depths. Mixed tritium-age waters typically occur between shallow recent tritium-age waters and deeper vintage tritium-age waters, and are a blend of both. Cross section line E–E′ shows two circumstances that differ from this generalization. Vintage tritium-age water was found at a relatively shallow depth in a water sample from a well constructed in the sl aquifer near Comfort Lake. It is possible that this older water is flowing from the sandy cr aquitard that that occurs at a similar elevation to this well's screen. The occurrence of vintage tritium-age water at shallow depths in glacial sediments is not common, but does occur. In the vicinity of Spider Lake recent tritium-age water has migrated to depths not observed elsewhere in the county. In this vicinity, it appears that a steep groundwater gradient coupled with leaky aquitards has permitted recent tritium-age water to move to depths exceeding 250 feet below the ground surface.

The concentration of several ions in groundwater can also be used to help understand groundwater age and aquifer pollution sensitivity. Elevated levels of chloride and nitrate can be used as chemical indicators of recent human influences on groundwater, including the application of road salts or fertilizer and the use of water softeners.

Nitrate concentrations greater than 1 part per million (ppm) are greater than background conditions and indicate that an aquifer has *possibly* been affected by activities on the land surface (MDH, 1998 and Wilson, 2012). Nitrate concentrations greater than 3 ppm indicate that an aquifer *has been* affected by activities on the land surface (MDH, 1998). Chloride concentrations greater than 5 ppm can also be used to indicate that an aquifer has been impacted by activities on the land surface. However, some deep waters have naturally elevated levels of chloride. To differentiate, the ratio of chloride concentration to bromide concentration (Cl/Br) coupled with tritium results can be used to distinguish the chloride source (Davis and others, 1998; Panno and others, 2006). For this investigation, samples with chloride to bromide ratios below 270 have naturally elevated chloride concentrations and are denoted on map figures with a superscript n. Groundwater samples with chloride to bromide ratios greater than 270 are interpreted as having elevated chloride due to human activity.

The groundwater residence time of vintage tritium-age groundwater samples was further refined using carbon-14 (^{14}C) dating. This method uses the naturally occurring carbon-14 isotope and its half-life of 5730 years to estimate groundwater residence times from 100 to 40,000 years (Alexander and Alexander, 1989). Carbon-14 analysis was performed on 8 samples from this investigation and 8 previously collected for a joint investigation by the Minnesota Geological Survey and University of Minnesota Department of Earth Sciences (Lively and others, 1992). Of the 16 wells with modeled carbon-14 ages, 5 wells constructed in buried sand and gravel aquifers had groundwater ages ranging from 500 to 3,000 years, 8 constructed in the Mt. Simon aquifer had groundwater ages ranging from 500 to 7,000 years, 2 constructed in wells intersecting multiple bedrock aquifers had ages ranging from 200 to 2,000 years, and 1 sample provided a calibration value for recent tritium-age water. The ages determined through the carbon-14 dating of groundwater in Chisago County are relatively young for deep groundwater in Minnesota, indicating groundwater-flow systems that are recharged relatively quickly. This is consistent with the work of Berg and Pearson (2012), who found groundwater ages of the Mt. Simon aquifer to be generally younger in the northern Twin Cities metropolitan area west of Chisago County.

HYDROGEOLOGY ILLUSTRATED BY THE CROSS SECTIONS

Groundwater-flow Direction

Groundwater moves from areas with higher potential energy to areas with lower potential energy. Groundwater-flow direction is indicated by the gray arrows in the cross sections on this plate and is interpreted from the equipotential contours constructed from measured water levels in wells. In Chisago County, the primary control on groundwater-flow direction is the elevation of the St. Croix River. The river serves as a key discharge area for both the buried sand and gravel and bedrock aquifers, greatly influencing groundwater-flow direction and gradients. Groundwater flow is perpendicular to equipotential contours; flow in Chisago County is both east and downward. Equipotential contours depicted in cross section D–D′ are more horizontal than in the other cross sections indicating groundwater movement is mostly downward. The gradient through this area appears to be controlled by the influence of a thick succession of basalt in the vicinity of Taylors Falls. The basalt has very low hydraulic conductivity, causing it to act as an impoundment which limits lateral flow to the east. To flow around this natural obstacle, groundwater must flow to the northeast or southeast. This condition is shown in mapview on Plate 8, Figures 2 through 4 and Figures 6 through 8. Near Taylors Falls the potentiometric surfaces of the buried sand and gravel aquifers and the groundwater-elevation contours of bedrock aquifers show groundwater-flow direction is to the northeast and southeast around the volcanic basalt.

The scale selected to show the cross sections on this plate limits the ability to show groundwater-flow direction in the water table and perched groundwater systems of the county. Within these systems, groundwater flow is primarily influenced by surface landform and subsurface sediment texture characteristics. Localized groundwater-flow direction in these systems is typically toward secondary groundwater discharge areas such as smaller order streams, lakes, and wetlands.

Aquifer recharge

Precipitation is the source of recharge to the glacial sediments covering the county, which ultimately provides recharge to the deeper aquifers of the county. Recharge estimates to the surficial aquifers range from 3.4 to 8.6 inches per year (Lorenz and Delin, 2007). Recharge estimates to the buried sand and gravel aquifers and bedrock aquifers are generally less than one percent of average precipitation, or 0.3 inches per year (Delin and Falteisek, 2007). This recharge estimate varies and is dependent upon the matrix texture and thickness of the glacial sediment. Recharge rates can also be influenced by high-volume groundwater appropriation centers, which have the potential to locally steepen groundwater gradients and increase recharge.

Important recharge areas exist in the county where sandy surficial sediment allows higher infiltration rates. These recharge areas are primarily located in the central part of the county and are identified on the cross sections as focused recharge zones. Surficial geologic units with higher clay and silt content in other regions of the county limit recharge and are denoted on the cross sections as recharge zones. Recharge also occurs in the areas of the cross sections not delineated with recharge zone labels. Stable isotopic data was collected for this atlas to better understand the interaction of lakes and open-water wetlands with groundwater. Analysis of stable isotopic data has shown that the Chisago Lakes area serves as an important groundwater recharge area (Plate 7).

Aquifer discharge

The St. Croix River is the major groundwater discharge feature for the buried sand and gravel and bedrock aquifers of Chisago County. Groundwater is also discharged from aquifers to other surface-water bodies such as the Sunrise River, Rush Creek, Beaver Creek, Lawrence Creek, and some wetlands and lakes. Groundwater interaction with lakes and wetlands depends on the physical setting of these features. Rush Lake and Goose Lake, located in the northwestern region of the county, receive groundwater discharge that provides perennial surface water flow from these lakes. Large wetland complexes, primarily located along the St. Croix River, receive groundwater discharge that supports native plant communities. In each of these cases, groundwater is recharged at a higher elevation on the land surface and flows down gradient to these features. Groundwater discharge areas are identified on the cross section figures by Ⓓ.

Perched groundwater

The primary data used to create the water table map (Plate 7, Figure 1) is the minimum annual water depth from the Natural Resources Conservation Service (NRCS) soil survey for Chisago County. These data suggest that nearly the entire county has groundwater within 5 feet of the land surface. In some of these areas where groundwater is close to the land surface, it is likely present under perched conditions and is separated by unsaturated sediment or rock from the underlying regional water table. Perched groundwater conditions are very likely in eastern regions of the county where the land surface is much higher than the St. Croix River. Groundwater investigations in nearby Polk County, Wisconsin found evidence of water table mounding under lakes and the presence of dry conditions below lakes (Muldoon, 2000).

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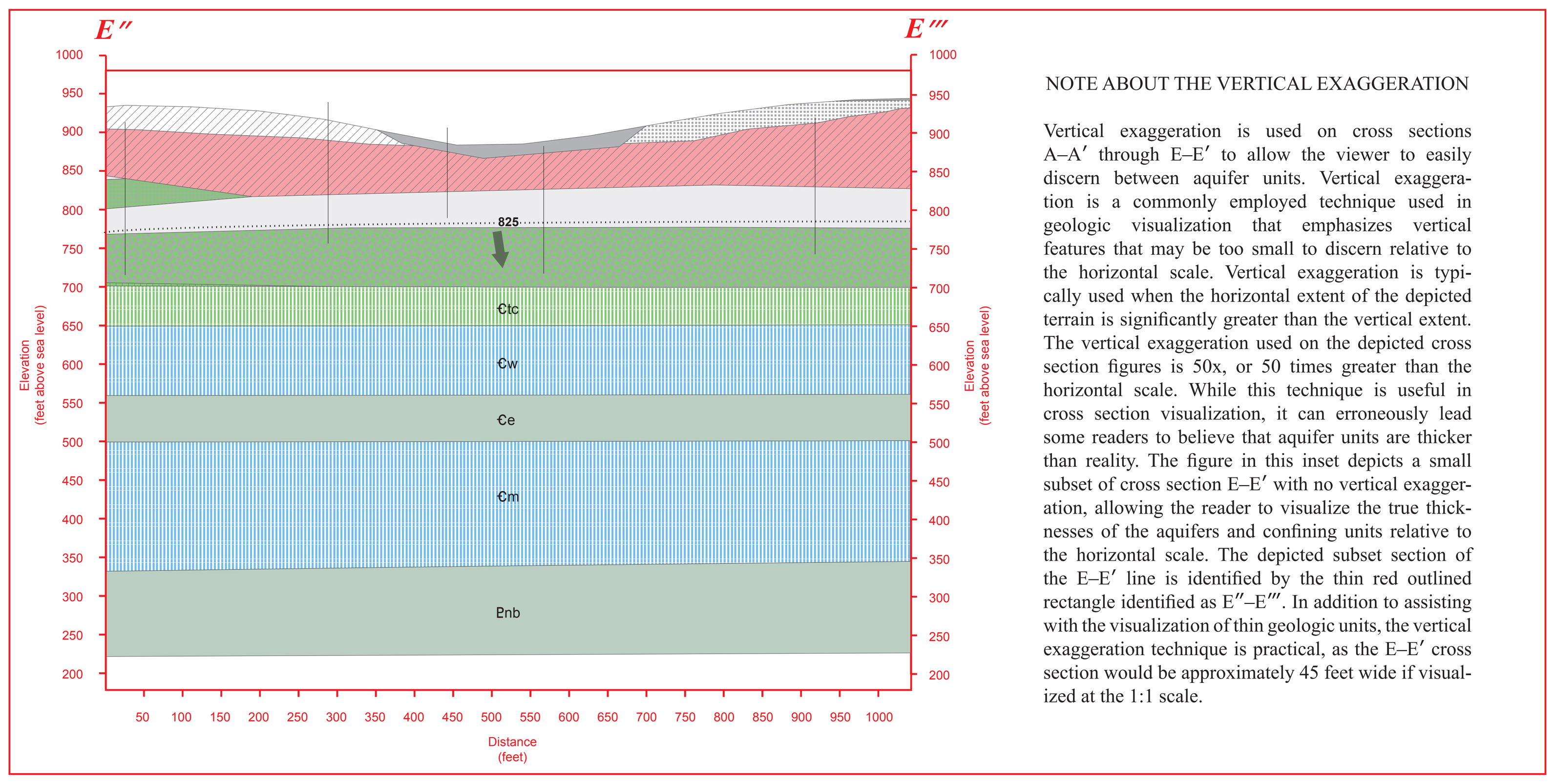

NOTE ABOUT THE VERTICAL EXAGGERATION

Vertical exaggeration is used on cross sections A–A′ through E–E′ to allow the viewer to easily discern between aquifer units. Vertical exaggeration is a commonly employed technique used in geologic visualization that emphasizes vertical features that may be too small to discern relative to the horizontal scale. Vertical exaggeration is typically used when the horizontal extent of the depicted terrain is significantly greater than the vertical extent. The vertical exaggeration used on the depicted cross section figures is 50x, or 50 times greater than the horizontal scale. While this technique is useful in cross section visualization, it can erroneously lead some readers to believe that aquifer units are thicker than reality. The figure in this inset depicts a small subset of cross section E–E′ with no vertical exaggeration, allowing the reader to visualize the true thicknesses of the aquifers and confining units relative to the horizontal scale. The depicted subset section of the E–E′ line is identified by the thin red outlined rectangle identified as E″–E‴. In addition to assisting with the visualization of thin geologic units, the vertical exaggeration technique is practical, as the E–E′ cross section would be approximately 45 feet wide if visualized at the 1:1 scale.

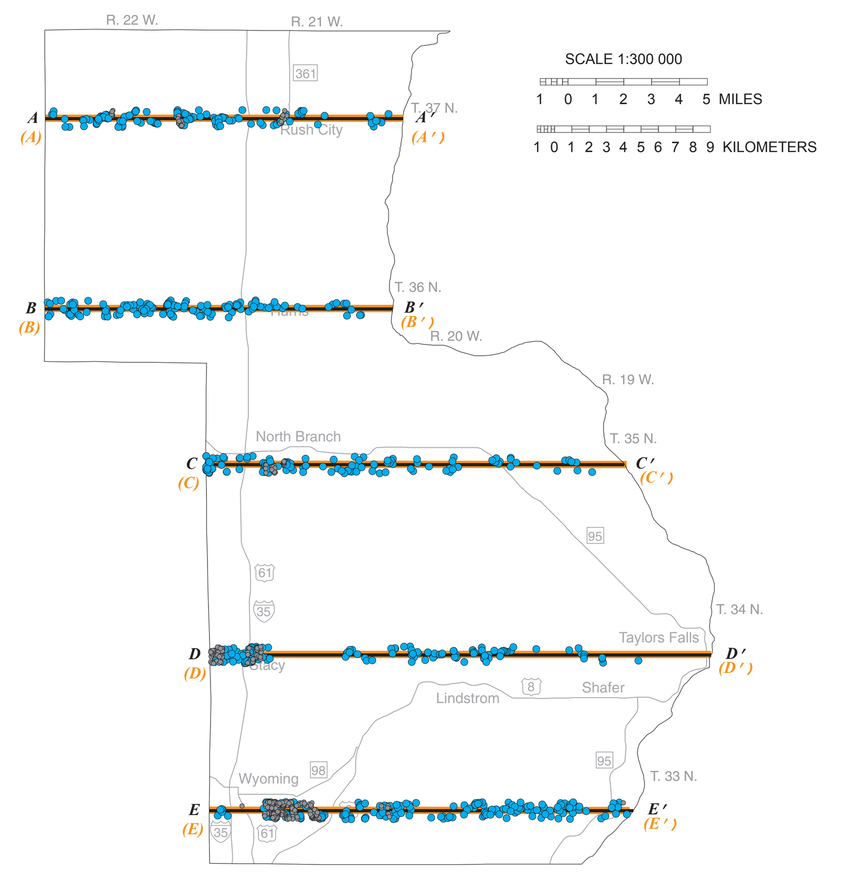

FIGURE 1. Location of hydrogeologic cross sections shown on this plate. The orange lines show the locations of the cross sections on this plate, which are coincident with the geologic cross section lines (shown in black) from Part A, Plate 4. Circles indicate the locations of wells used to generate the hydrogeologic cross sections. Blue circles indicate wells displayed in the cross sections. Gray circles indicate wells that are not shown in areas of high well density. These wells were removed to show underlying detail.

CROSS SECTION EXPLANATION

Symbols and labels

- 21.1 — If shown, chloride concentration equals or exceeds 5 parts per million. Naturally occurring chloride concentration greater than 5 parts per million is shown with a superscript n.
- 7.2 — If shown, nitrate-nitrogen concentration equals or exceeds 1 part per million.
- 3000 yrs — If shown, groundwater residence time in years, estimated by carbon-14 (^{14}C) isotope analysis
- General direction of groundwater flow
- 925 — Approximate equipotential contour
- Geologic contact
- Land or bedrock surface
- Lake
- Direction of fault movement, arrows indicate relative movement
- Peat

Tritium age

Darker color in small vertical rectangle (well screen symbol) indicates tritium age of water sampled in well. Lighter color indicates interpreted age of water in aquifer.

- Cold War era—Water entered the ground during the peak period of atmospheric tritium concentration during nuclear bomb testing, 1958–1959 and 1961–1972 (greater than 15 tritium units [TU]).
- Recent—Water entered the ground since about 1953 (8–15 TU).
- Mixed—Water is a mixture of recent and vintage waters (greater than 1 TU to less than 8 TU).
- Vintage—Water entered the ground before 1953 (less than or equal to 1 TU).
- Well was not sampled for tritium.

Aquifers grouped by stratigraphy

Interpreted tritium age is indicated by background color

Surficial aquifer

- Surficial sand

Buried sand and gravel aquifers

- sl
- sc
- se
- sx
- sr
- sp

Interpreted tritium age is indicated by pattern color

Sedimentary bedrock aquifers

- ** St. Peter/Prairie du Chien
- Ꞓj * Jordan
- Ꞓtc ** Upper Tunnel City
- Ꞓw * Wonewoc
- Ꞓm * Mt. Simon
- Ᵽsu * Undifferentiated Mesoproterozoic
- Enhanced-permeability zone
- * Primarily intergranular flow
- ** Intergranular and fracture flow

Aquitards and nonaquifers

Quaternary aquitards grouped by texture
Percent sand content indicates relative hydraulic conductivity (Plate 4, Table 1).

Aquitard	Percent sand
cr, ce, rt	Greater than 60
nu	Greater than 40 and less than or equal to 50
lc, xt	Greater than 30 and less than or equal to 40
qu	Undifferentiated Pleistocene sediment, texture and relative hydraulic conductivity unknown

Bedrock aquitards

- Ꞓsl St. Lawrence Formation
- Ꞓe Eau Claire Formation

Bedrock nonaquifer units

- Ᵽcf Mesoproterozoic Volcanic Rock–Clam Falls Volcanics
- Ᵽcv Mesoproterozoic Volcanic Rock–Chengwatana Group
- Ᵽnb Mesoproterozoic Volcanic Rock–North Branch Volcanics

Groundwater conditions

- ① Infiltration through a thin layer of overlying, fine-grained material to an underlying aquifer
- ② Groundwater recharge from an overlying surficial aquifer to a buried aquifer
- ③ Groundwater leakage from an overlying buried aquifer to an underlying buried aquifer
- ④ Groundwater leakage through multiple aquifers and fine-grained layers
- Ⓓ Groundwater discharge to surface-water body
- Ⓛ Lateral groundwater flow
- ⊙ Groundwater movement out of cross section

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This map was compiled and generated using Geographic Information Systems (GIS) technology. Digital data products, including chemistry and geophysical data, are available from the DNR Ecological and Water Resources Division at http://www.mndnr.gov/waters.

Base modified from Minnesota Geological Survey, Chisago County Geologic Atlas, Part A, 2010.

Project data compiled from 2010 to 2012 at a scale of 1:100,000. Universal Transverse Mercator projection, grid zone 15, North American Datum of 1983. Vertical datum is mean sea level.

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