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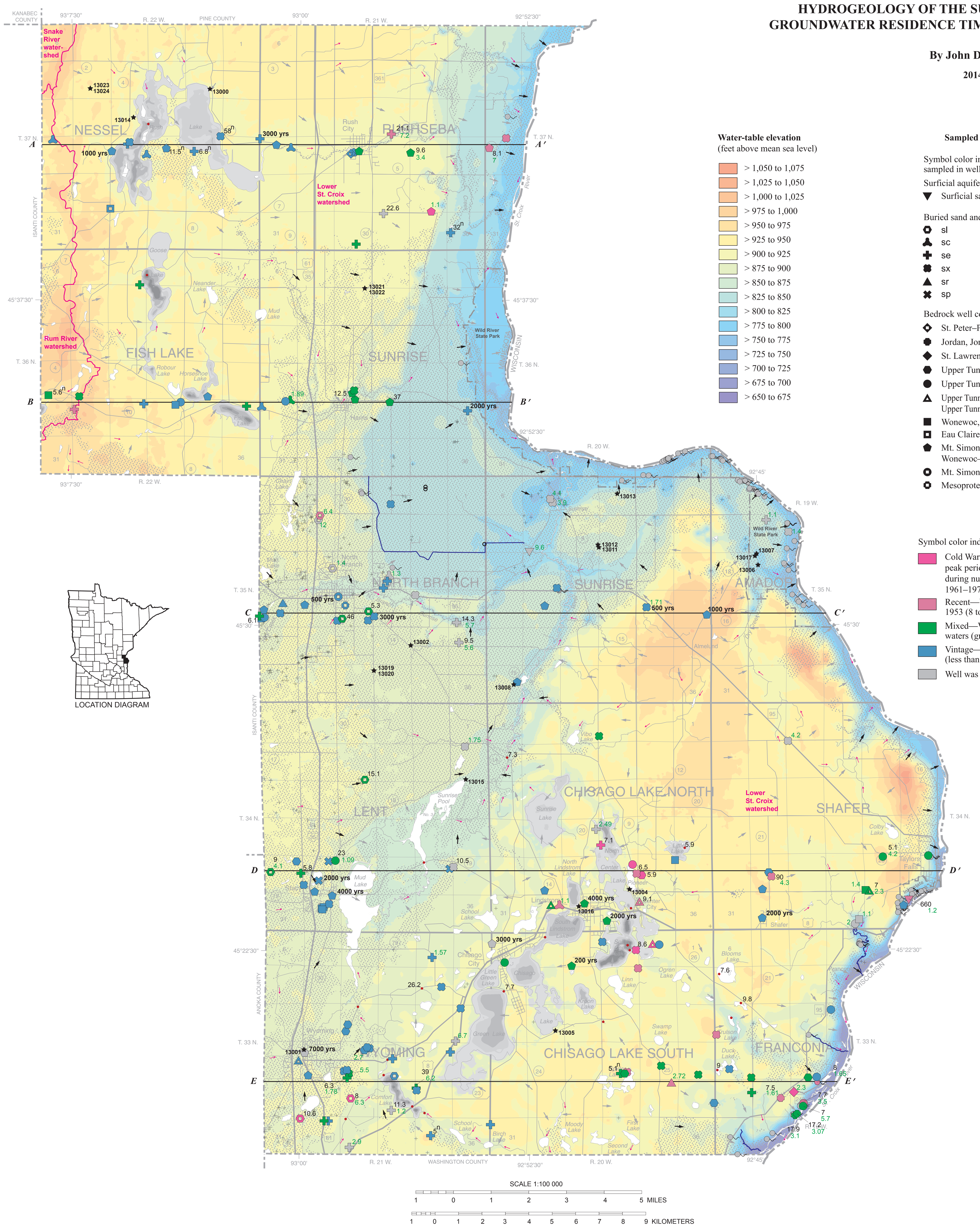
HYDROGEOLOGY OF THE SURFICIAL SAND AQUIFER, GROUNDWATER RESIDENCE TIME, AND ISOTOPIC SIGNATURE

By John D. Barry

2014



MAP EXPLANATION
Figures 1 and 5

Water-table elevation
(feet above mean sea level)

- > 1,050 to 1,075
- > 1,025 to 1,050
- > 1,000 to 1,025
- > 975 to 1,000
- > 950 to 975
- > 925 to 950
- > 900 to 925
- > 875 to 900
- > 850 to 875
- > 825 to 850
- > 800 to 825
- > 775 to 800
- > 750 to 775
- > 725 to 750
- > 700 to 725
- > 675 to 700
- > 650 to 675

Sampled well and aquifer symbols

Symbol color indicates tritium age of water sampled in well.

Surficial aquifer
- Surficial sand

Buried sand and gravel aquifers
- sl
- sc
- se
- sx
- sr
- sp

Bedrock well construction
- St. Peter–Prairie du Chien–Mt. Simon
- Jordan, Jordan–St. Lawrence
- St. Lawrence–Upper Tunnel City
- Upper Tunnel City
- Upper Tunnel City–Wonewoc
- Upper Tunnel City–Mt. Simon, Upper Tunnel City–Eau Claire
- Wonewoc, Wonewoc–Eau Claire
- Eau Claire
- Mt. Simon, Eau Claire–Mt. Simon, Wonewoc–Mt. Simon
- Mt. Simon–Fond du Lac
- Mesoproterozoic sedimentary

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
- Static (non-pumping) water level data from the County Well Index (CWI)
- Groundwater discharge (spring or seep); color indicates tritium age; gray symbols indicate not sampled for tritium.
- ★13002 — DNR groundwater level monitoring well. Label is well number.
- Surface-water sample
- Direction of groundwater flow at the water table in the surficial sand aquifer
- Direction of groundwater flow at the water table outside of the surficial sand aquifer
- Direction of streamflow
- Designated trout stream
- Surface watershed boundary
- Extent of surficial sand aquifer
- *E—E′* — Line of cross section
- Body of water

Tritium age

Symbol color indicates tritium age of water sampled in well.

- 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 to 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.

Water use from wells completed in the surfical sand aquifer reported by DNR groundwater appropriation permit holders for 2011
(millions of gallons per year)

- 0 to 15

Depth of selected lakes (feet)

- 0 to 10
- > 10 to 20
- > 20 to 30
- > 30 to 40
- > 40
- No data

FIGURE 1. Estimated water-table elevation in the surficial sediment of Chisago County. Data were assembled from elevations of rivers and streams, lakes and wetlands, regions identified as having groundwater-dependent plant communities, saturated soil conditions, and static water levels in wells completed in the surficial sand aquifer. Arrows show the generalized direction of groundwater flow at the water table: black arrows indicate flow direction within the surficial sand and gray arrows indicate flow direction in surficial sediments. Pink arrows indicate surface-water flow direction. Black hollow circles depict water use in permitted water-table wells for the year 2011 (concentrated in the northeast quadrant of North Branch Township). The locations of wells and surface waters that were sampled for general chemistry and isotope analysis, including samples collected from aquifers other than the surficial sand aquifer, are shown for convenience.

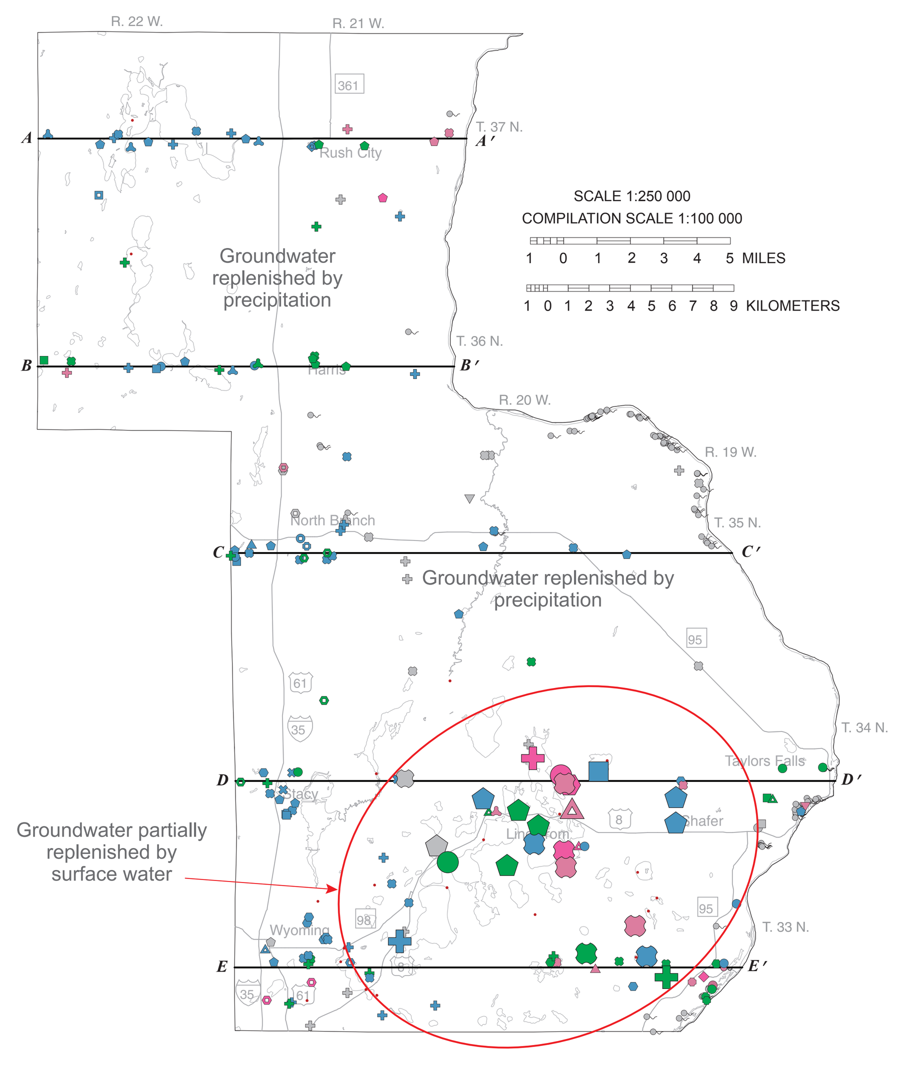
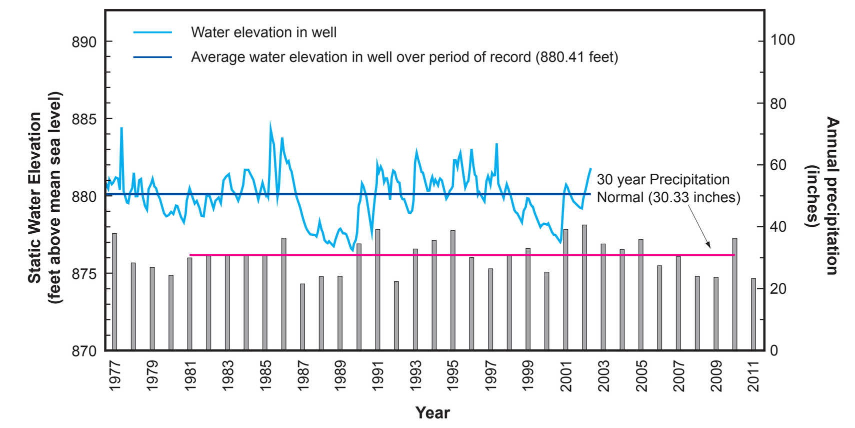
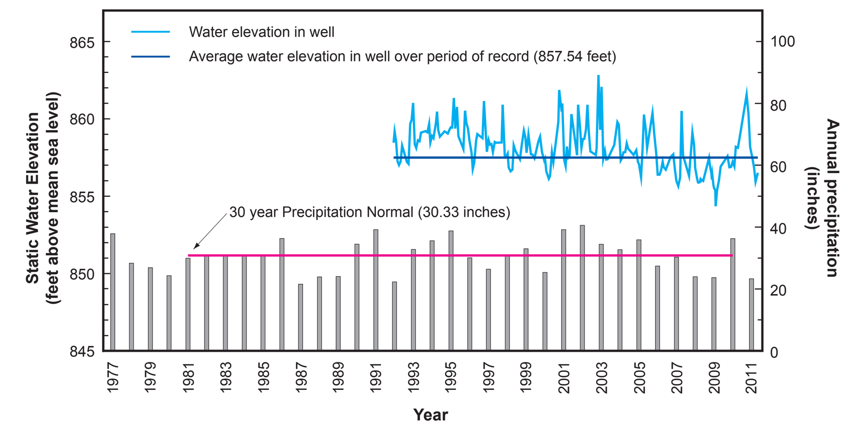


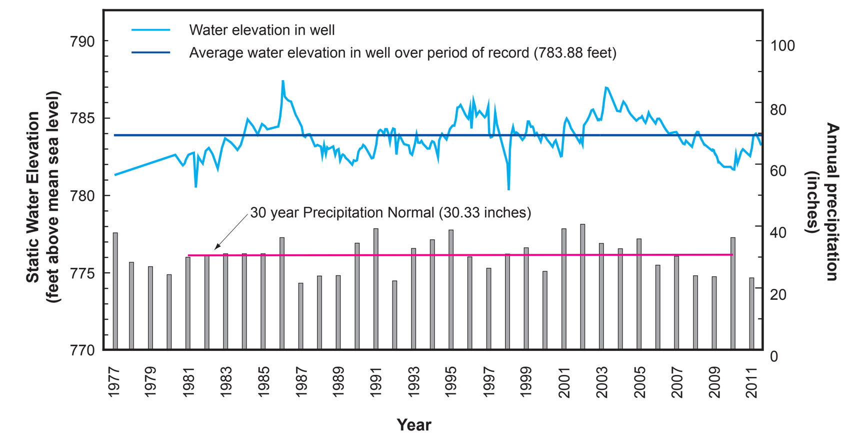
FIGURE 5. Stable isotopic signatures of the Chisago Lakes area. The majority of the groundwater samples collected within Chisago County appear to have originated as direct infiltration of modern precipitation (gray symbols plot near the North American meteoric water line in Figure 4). A subset of samples (within the red ellipse) represents groundwater partially recharged by infiltrated water from lakes and open-water wetlands. Groundwater samples with at least 50 percent of the maximum evaporative signature are denoted by a larger symbol size and are clustered in the Chisago Lakes area.



2a. Well 13002 (27 feet deep) in southeastern North Branch Township is constructed in the surficial sand aquifer. Water elevations track with precipitation.



2b. Well 13012 (17 feet deep) in central Sunrise Township is constructed in the surficial sand aquifer. Water elevation change in this shallow well varies with precipitation and appears to be directly influenced by short-term trends in precipitation.



2c. Well 13007 (110 feet deep) in Amador Township is constructed in the se aquifer, a sand and gravel aquifer that is under confined conditions elsewhere in the county. However, at this location the aquifer is unconfined and water levels are out of phase with precipitation.

FIGURE 2a–c. Comparison of groundwater hydrographs to precipitation. Three DNR groundwater level monitoring wells finished in the surficial sand aquifer in Chisago County were selected to illustrate the change of groundwater levels in response to precipitation. The three selected hydrographs show different groundwater-level responses depending on local conditions. Annual precipitation is shown by vertical gray bars. Precipitation was recorded from 1977–2011 at Wild River State Park (National Weather Service Station 218986).

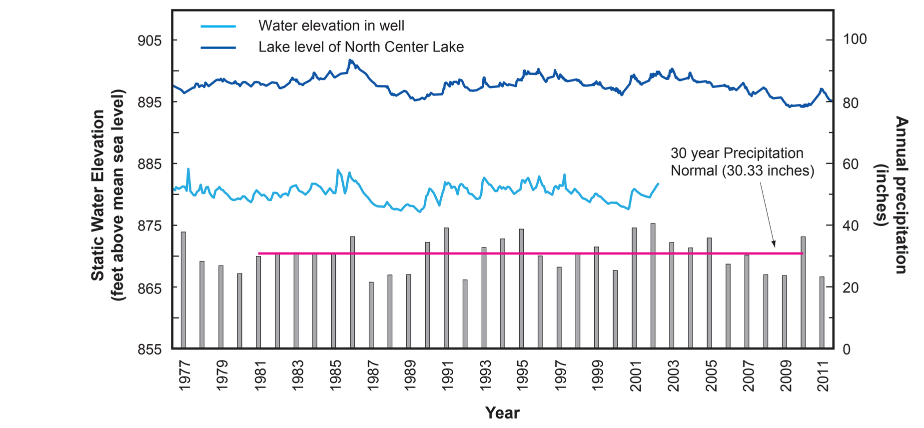


FIGURE 3. Comparison of a groundwater hydrograph to annual precipitation and water levels of North Center Lake. DNR monitoring well 13002 (26 feet deep) in southeastern North Branch Township is finished in the surficial sand aquifer. Precipitation was recorded from 1977–2011 at Wild River State Park (National Weather Service Station 218986). The graph shows groundwater elevations in the well track with precipitation and the water levels of North Center Lake. Comparison of groundwater levels in surficial sand aquifers and surface-water elevations of closed-basin lakes in the county shows similar relative changes in elevation over time suggesting that each is strongly influenced by annual precipitation.

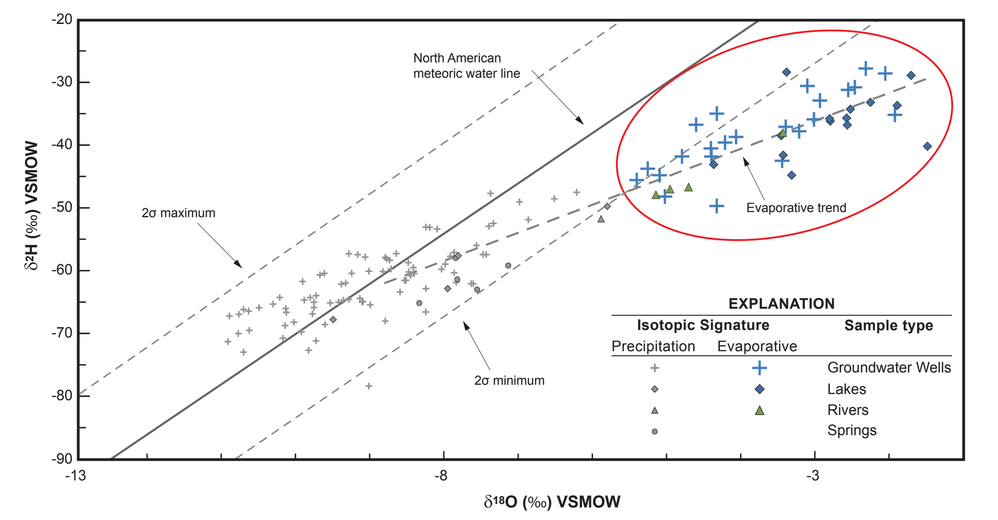


FIGURE 4. Graph of stable isotope values of groundwater, lakes, springs, and rivers sampled in the study area compared to the North American meteoric water line. Water samples analyzed for stable isotopes for this study generally fit into two types: (1) water samples that have an isotopic signature consistent with modern precipitation (gray symbols clustered near the North American meteoric water line) and (2) samples that were partially derived from preferentially evaporated surface water sources (primarily located within the red ellipse). Groundwater samples with at least 50 percent of the maximum evaporative signature are shown as blue crosses. The dashed "2σ" lines show the statistical variation of stable isotope precipitation values used to derive the North American meteoric water line (IAEA/WMO, 2014). The line is described by the following equation: $\delta^2H = 8.06\ \delta^{18}O + 9.45$. The local evaporative water line is described by the following equation: $\delta^2H = 4.46\ \delta^{18}O - 22.68$.

INTRODUCTION

The County Geologic Atlas program is a collaborative effort between the Minnesota Geological Survey (MGS) and the Minnesota Department of Natural Resources (DNR). It was developed to identify the distribution and character of geologic deposits and groundwater resources of Minnesota counties. The geologic components of an atlas are referred to as Part A and the hydrogeologic components as Part B. Together, atlases are developed to provide information and data to assist in uses such as sound land use and water resource planning.

The maps and data presented on these Part B plates show the extent and chemical and physical characteristics of the primary aquifers of Chisago County. Aquifers are geologic units that can store and transmit water at rates fast enough to supply water to wells (Fetter, 2000). The groundwater resources of Chisago County include a surficial sand aquifer, multiple buried sand and gravel aquifers, and several sedimentary bedrock aquifers. These aquifers are mapped and characterized from approximately 7,850 wells from the County Well Index (CWI), a database of wells in Minnesota described in Part A, Plate 1. This plate describes the hydrogeology of the surficial sand aquifer and describes the interaction of surface water and groundwater in the southeastern region of the county through the use of stable isotopes. Groundwater residence time, the time that has elapsed since water that fell on the surface was sampled from the aquifer, is also shown through the use of tritium analysis. The stippled area in Figure 1 delineates the extent of the surficial sand aquifer within Chisago County. The extent and thickness of the surficial sand deposits were determined by the MGS in the Part A Chisago County Geologic Atlas. The majority of the stippled area is an expression of the eastern extent of the Anoka Sand Plain (Meyer, 1998). Other areas shown with the stippled pattern include terrace deposits, ice contact deposits, and outwash areas.

WATER-TABLE ELEVATION

The water table is generally defined as the surface below which sediments are saturated with groundwater. The water table is present in sand and gravel, but it also exists in nonaquifer sediments such as silt and clay. Figure 1 represents the approximate elevation of the water table throughout the county. In general, the water table follows the surface topography of the county. The elevation of the water table is highest in the northwestern townships of Nessel and Fish Lake and in the southeast near the cities of Almelund and Taylors Falls. The water-table elevation is lower along the eastern border of the county near the St. Croix River and in the central region of the county near the city of Sunrise.

The estimated water-table elevation for the study area was developed using multiple data sources that were combined in a Geographic Information Systems (GIS) environment and interpolated to create a water-table grid. Data sources include the groundwater elevation from records of wells constructed in the Quaternary water-table aquifer and surface elevations of the following: rivers and perennial streams, the perimeter of large and small lakes, groundwater discharge locations such as springs and seeps, seepage soils as identified by the Natural Resources Conservation Service (NRCS), and locations of groundwater dependent plant communities from the Minnesota County Biological Survey (DNR, 2012a). The Quaternary water-table aquifer exists where surficial sand and gravel deposits are fully saturated and under unconfined conditions (surficial sand aquifer). To estimate the depth to the water table using wet soils these data were supplemented with a countywide 100-meter grid from the NRCS soil survey (NRCS, 2011).

The water-table elevation at each location in the combined dataset was calculated by subtracting the estimated depth to water from the surface elevation extracted from the county Light Detection and Ranging (LiDAR) grid. The countywide water-table elevation (Figure 1) was calculated by using the ArcGIS Topo to Raster tool (Esri, 2010) to simulate hydrologically correct flow. This approach assumes that streams, lakes, and perennial wetlands are surface expressions of the water table and uses groundwater-elevation data from wells in CWI collected over decades. Variability in the data coupled with assumptions used in this model creates some uncertainty in the estimated elevations shown on Figure 1. A generalized depth to water table grid and a separate map of the water table overlain on a shaded relief map are also available online with the project data, but are not shown in this report.

GROUNDWATER USE

The surficial sand and gravel aquifer is not a significant source of domestic potable water within Chisago County. At the time of this investigation, less than 4 percent of the nearly 7,850 wells in the county use the water-table aquifer for potable use. It is mainly used for sod irrigation, especially in the northeast region of North Branch Township (DNR, 2012b). It also provides groundwater discharge that is essential to sustain streams, lakes, and wetlands. In these areas, groundwater provides stable temperatures and nutrients for critical ecosystem functions that support biological communities such as macroinvertebrates and fish.

WATER-TABLE ELEVATION AND RESPONSE TO PRECIPITATION

Chisago County has 25 groundwater level monitoring wells that are managed by the DNR, of which 16 are actively being monitored (Figure 1). Eight of the active observation wells in the county were installed in 2012 and currently have limited periods of record. However, these newly installed wells are outfitted with continuous groundwater level recorders and are paired with a minimum of one shallow and one deep well at each site to provide improved insight to aquifer interaction, recharge, and drawdown and recovery. Figure 2 shows the hydrographs of water levels in three wells completed in the water-table aquifer. These three wells have a sufficient period of record to observe groundwater trends. The hydrographs illustrate the variability of groundwater levels in the water-table aquifer and show the relationship with annual precipitation. Groundwater level monitoring well 13002 is constructed to a shallow depth in the surficial sand and gravel aquifer and its water levels track with annual precipitation (Figure 2a). Groundwater level changes in this well also tend to be similar to changes in lake level elevations of closed basin lakes in the Lindstrom area. Monitoring well 13012 (Figure 2b) is also constructed to a shallow depth in the surficial sand and gravel aquifer; however, its hydrograph shows water-table elevation changes that are more variable and do not closely follow annual precipitation. Monitoring well 13007 (Figure 2c) is 110 feet deep and is constructed in the se aquifer. Water levels track with annual precipitation but with a response time that is out of phase. The hydrograph of this well, completed in coarse-grained terrace deposits near the St. Croix River, is very similar to a nearby Mt. Simon observation well (13006) and appears to be partially influenced by the water pressure of the Mt. Simon aquifer (Plate 8, Figure 10b). Figure 3 illustrates the relationship between annual precipitation, the surface-water elevation of North Center Lake, and the elevation of groundwater in a shallow water-table well. The nine observation wells in the Chisago well network that are no longer active are not in use due to a lack of connectivity with the aquifer or the presence of an active pump in the well.

GROUNDWATER CHEMICAL CHARACTERIZATION

Water samples were collected from 86 wells, 4 springs, and 4 lakes by DNR staff as part of this investigation. Samples were analyzed for natural ions, trace metals, stable isotopes, and enriched tritium. Carbon-14 age dating was performed on eight of the well samples. These data were combined with data collected by the Minnesota Department of Health's Source Water Assessment Unit, the Hydrogeology Working Group at the Department of Earth Sciences at the University of Minnesota, the Minnesota Pollution Control Agency's Groundwater Monitoring and Assessment Program, and the Minnesota Department of Agriculture's Monitoring and Assessment Unit. General water chemistry results of samples collected by the DNR are available through the DNR County Geologic Atlas and Regional Hydrogeologic Assessment Program on the Water Chemistry Data webpage (DNR, 2013). Data collected by others are included in the project GIS files.

GROUNDWATER AND SURFACE-WATER INTERACTION

Groundwater and surface water commonly interact throughout the landscape. They are key components of the hydrologic cycle that intermingle through space and time. The hydrologic cycle is made up of complex interactions that are dependent on a number of variables including, but not limited to, the texture of surficial materials, climatic conditions, groundwater hydraulic head, and groundwater hydraulic gradient. The groundwater level and flow direction are dynamic and are influenced by precipitation and groundwater withdrawal. Groundwater provides perennial discharge to many surface-water systems and surface water can provide an important source of recharge to groundwater. Stable isotopes are useful tools for determining groundwater and surface-water interaction. Isotopes of oxygen and hydrogen are commonly used in hydrologic studies as they are the essential elements of a water molecule (Kendall and McDonnell, 1998). The oxygen isotopes ^{18}O and ^{16}O and the hydrogen isotopes ^{2}H and ^{1}H have different masses. These mass differences cause isotopes to evaporate or condense at differing rates, resulting in an isotopic signature unique to the water. Precipitation that fell as rain has an isotopic signature different than precipitation that fell as snow. Precipitation that infiltrates rapidly has an isotopic signature different than water subjected to evaporation.

Figure 4 is a graph of stable isotope values of groundwater, lakes, springs, and rivers sampled in Chisago County. The term "δ" (delta) denotes the relative abundance of the heavier isotopes, ^{18}O and ^{2}H, to a standard (Vienna Standard Mean Ocean Water or VSMOW). Precipitation values for $\delta^{18}O$ and $\delta^{2}H$ generally plot along a line that is referred to as the meteoric water line. The North American meteoric water line (Figure 4) was developed using North American precipitation averages from stations available through the Global Network of Isotopes in Precipitation (IAEA/WMO, 2014). Water samples that plot near this line indicate water that has an isotopic signature consistent with rapidly infiltrated precipitation.

Lakes and open-water wetlands are subjected to evaporation that changes the isotopic signature of the water over time. This occurs when the lighter isotopic forms of water preferentially evaporate, leaving behind the heavier isotopes. Waters that have been subjected to evaporation have ratios of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ that plot along an evaporative water line, indicated by the bold dashed line in Figure 4. Water samples that are enriched in the heavier isotopes (^{18}O and ^{2}H) plot along the right side of the evaporative water line and represent the maximum evaporative isotopic signature. Water samples that plot at the intersection of the meteoric water line and the evaporative water line represent groundwater directly recharged by precipitation.

Water samples analyzed for stable isotopes for this study come from two primary data sets. One data set was collected in 1989–1991 during winter months. Roughly half of the other stable isotope data set was collected in fall of 2010, with the majority of the remainder collected in spring of 2011. The collection dates for these samples are relevant because the colder the ambient air temperature at the time of precipitation, the lighter the isotopic content of the water. Precipitation that occurs as snow is isotopically lighter than precipitation that falls in the summer. However, the ratio of $\delta^{18}O$ to $\delta^{2}H$ in precipitation collected in winter or summer is relatively constant; therefore plotting $\delta^{18}O$ versus $\delta^{2}H$ for precipitation tends to plot along the meteoric water line.

Groundwater samples located near the evaporative water line are interpreted as having mixed with a significant amount of water from lakes. The large symbols in Figure 4 and 5 represent those having greater than 50 percent of the maximum evaporitive signature for area lakes. Wells with this signature were mostly located in the Chisago Lakes area: although some wells with evaporative signature were noted east and southeast of the area. Lakes in this area are primarily in closed-basin settings with no perennial surface water outflow, whereas lakes in the northwestern region of the county exhibit perennial surface water outflow. These data demonstrate the connectivity of area lakes to the groundwater system, and highlight their importance in providing groundwater recharge to aquifers in this area, including deep bedrock aquifers.

GROUNDWATER RESIDENCE TIME

Groundwater residence time can be estimated by the amount of tritium (^{3}H) in the sampled water. The magenta, pink, green, and blue colors applied to the symbols in Figure 1 represent the relative age of groundwater. The gray symbols denote wells not sampled for tritium.

Groundwater residence time is the approximate length of time that has elapsed from the moment the water infiltrated the land surface to the time it was pumped from the aquifer or discharged at a spring. The presence of an elevated level of tritium indicates water that has infiltrated the land surface since the early 1950s. Tritium is a naturally occurring radioactive isotope of hydrogen. Concentrations in the atmosphere were greatly increased between about 1953 and 1963 by above-ground nuclear tests (Alexander and Alexander, 1989). Since tritium decays at a known rate (half-life of 12.32 years), the proportion of recently recharged water in a sample can be estimated by its tritium content.

Water samples with tritium concentrations of greater than 15 tritium units (TU) are classified as waters that entered the ground during the peak period of above-ground nuclear testing. In general, tritium in the atmosphere peaked in 1963 and has decreased since. Water samples ranging from 8 to 15 TU are classified as recent water that entered the ground since approximately 1953. Samples with 1 TU or less are classified as vintage water that entered the ground before approximately 1953. Samples with greater than 1 TU and less than 8 TU are considered mixed waters, as they are a mixture of vintage and recent waters. Figure 1 displays the groundwater residence time for all wells in Chisago County for which tritium data is available.

Groundwater samples from the combined dataset were analyzed to determine the groundwater residence time. In general, vintage tritium-age waters are present at depth across the entire county. Recent and mixed tritium-age waters are more prevalent within and down gradient of regions in the county where surficial sands are present. The relatively high transmission rate of sand appears to permit recent waters to penetrate to greater depths in these regions. Groundwater in the Chisago Lakes area and to the south-southeast is commonly recent and mixed in tritium age. In the Chisago Lakes area and in other municipal centers, recent tritium-age groundwater may be penetrating to greater depths from steep gradients caused by high-volume pumping. East and southeast of the Chisago Lakes area naturally steep groundwater gradients may provide the mechanism to transfer recent tritium-age waters to great depths.

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The DNR Information Center

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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.

GIS and cartography by John Barry, Shana Pascal, and Holly Johnson. Edited by Carrie Jennings, Ruth MacDonald, and Holly Johnson.