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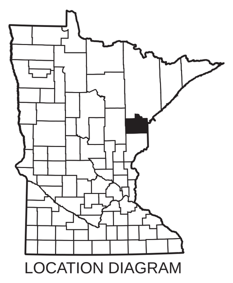

LOCATION DIAGRAM

POTENTIOMETRIC SURFACES OF BURIED AQUIFERS, STABLE ISOTOPE GEOCHEMISTRY, AND GROUNDWATER USE

By

James A. Berg

2011

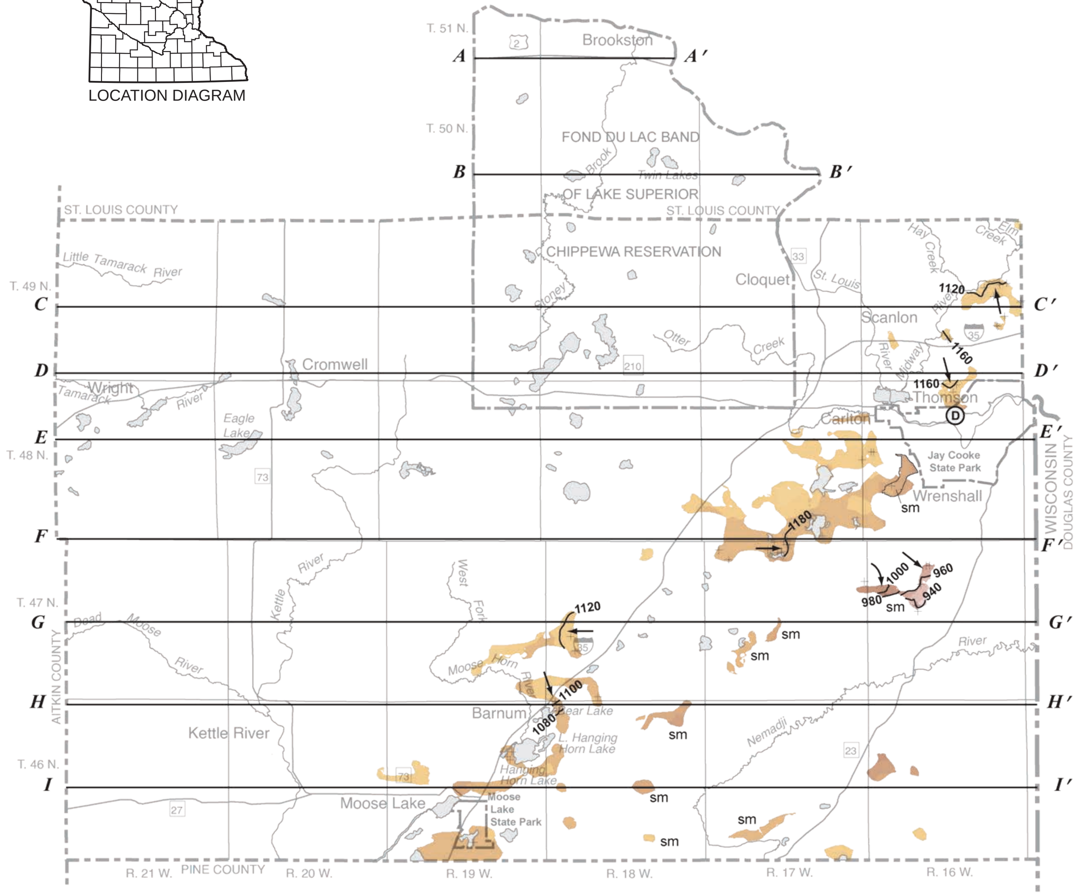

Figure 1. ***Potentiometric surface of sm and sl buried sand and gravel aquifers; sl aquifer unless labeled otherwise. Contour interval 20 feet.***

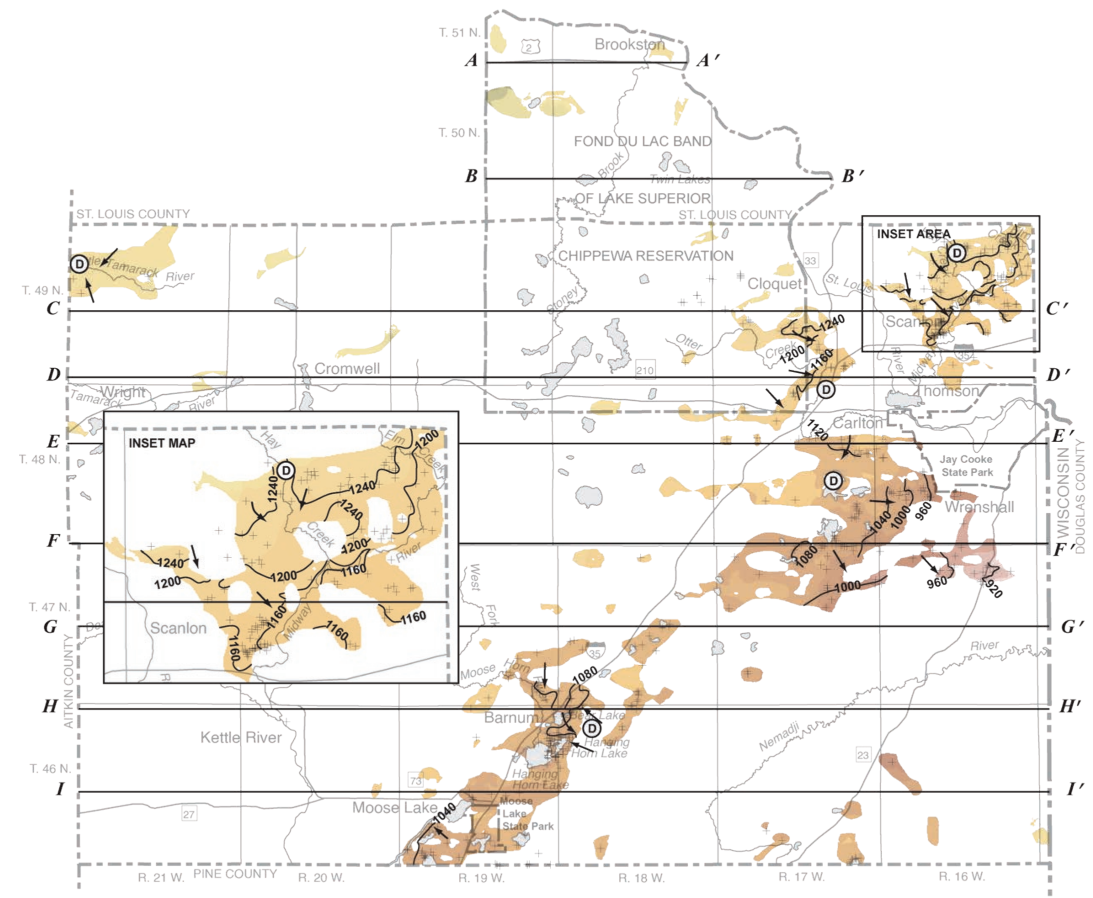

Figure 2. ***Potentiometric surface of the sc buried sand and gravel aquifer. Contour interval 40 feet.***

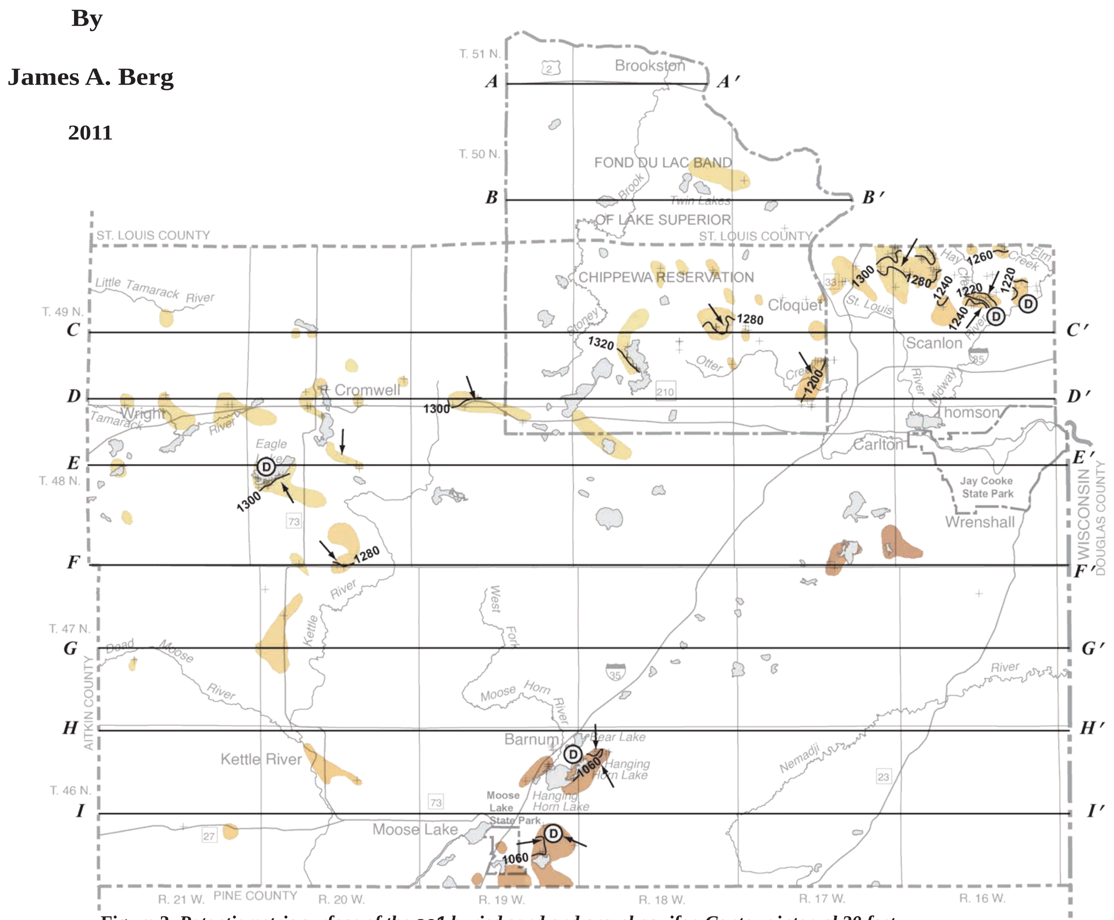

Figure 3. ***Potentiometric surface of the sc1 buried sand and gravel aquifer. Contour interval 20 feet.***

MAP EXPLANATION
Figures 1–5

Map symbols and labels

- Static water level data.
- Groundwater flow direction.
- 1220 Potentiometric surface contour. (feet above mean sea level)
- F F′ Line of cross section.
- Body of water.

Groundwater condition

- Groundwater discharge from a buried aquifer to a surface water body.

Elevation of top of aquifers (feet above mean sea level)

- > 1,450 to 1,500
- > 1,400 to 1,450
- > 1,350 to 1,400
- > 1,300 to 1,350
- > 1,250 to 1,300
- > 1,200 to 1,250
- > 1,150 to 1,200
- > 1,100 to 1,150
- > 1,050 to 1,100
- > 1,000 to 1,050
- > 950 to 1,000
- > 900 to 950
- > 850 to 900
- > 800 to 850
- > 750 to 800
- > 700 to 750
- 649 to 700

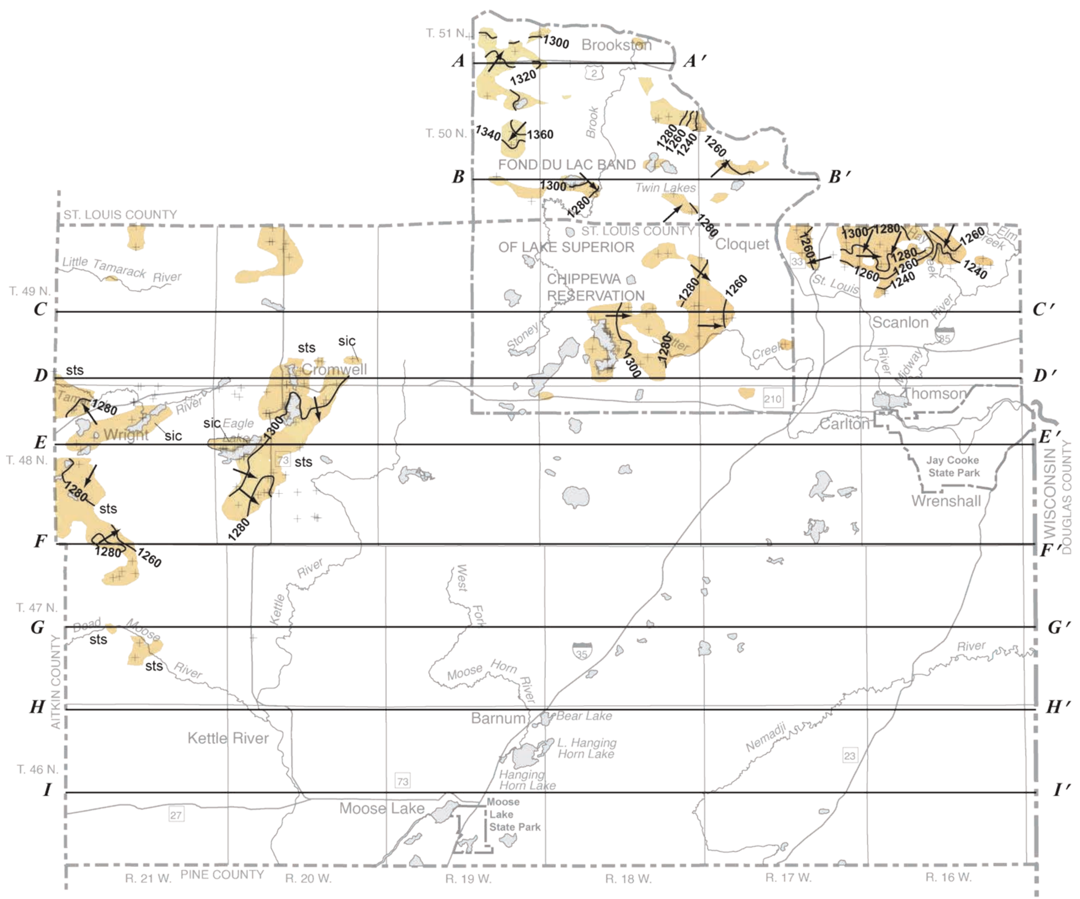

Figure 4. ***Potentiometric surface of sic and sts buried sand and gravel aquifers; sic aquifer unless labeled otherwise. Contour interval 20 feet.***

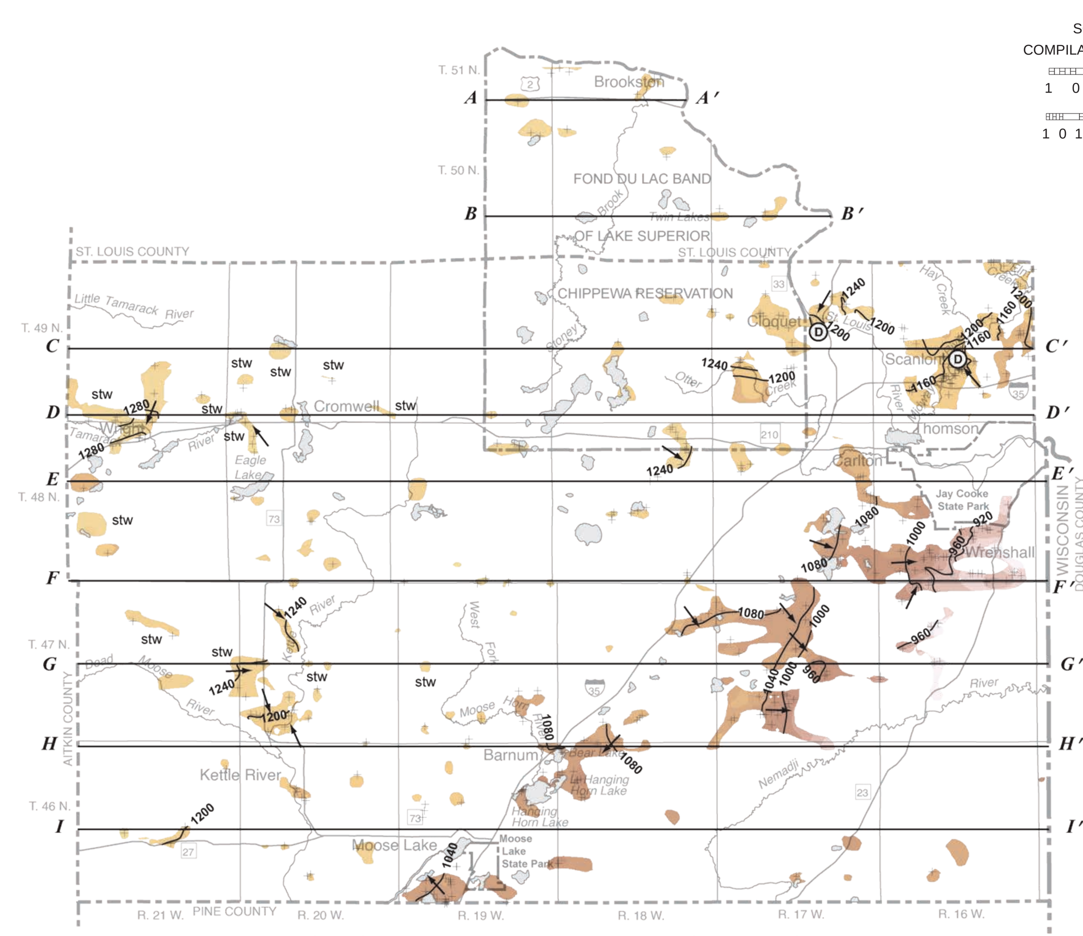

Figure 5. ***Potentiometric surface of stw and su buried sand and gravel aquifers; su aquifer unless labeled otherwise. Contour interval 40 feet.***

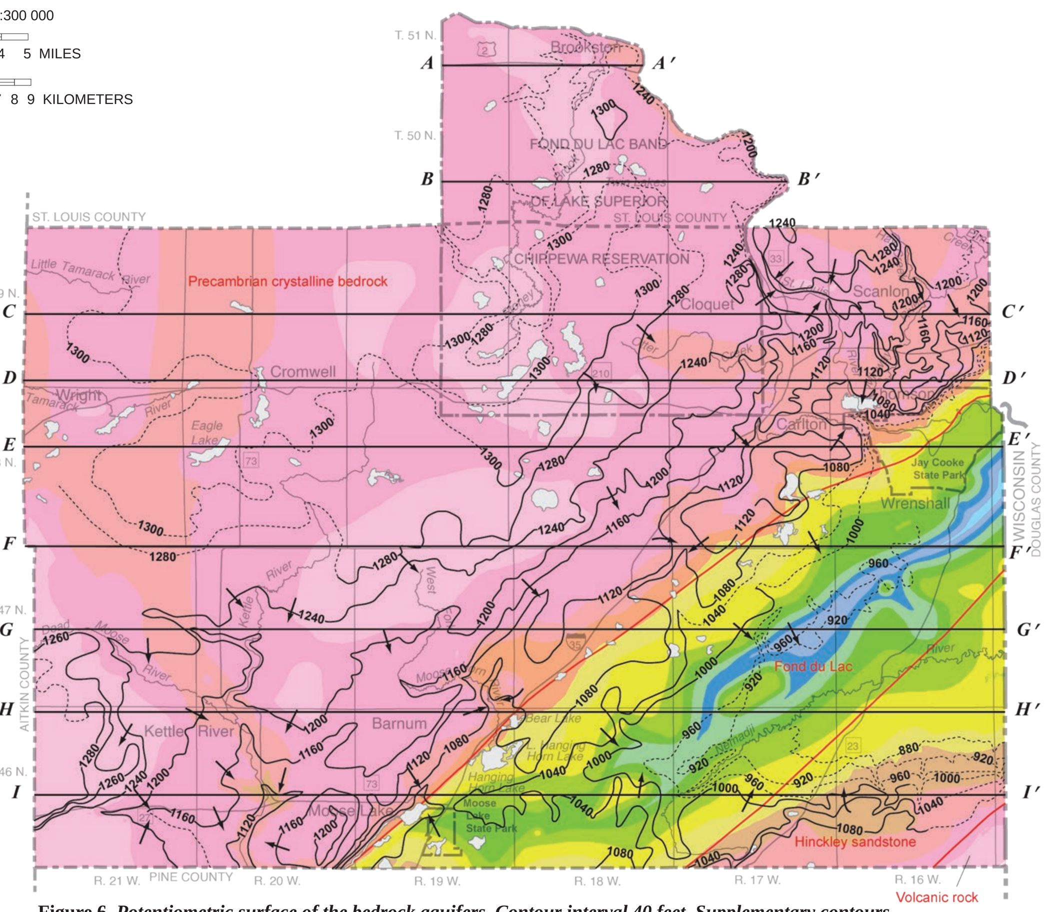

Figure 6. ***Potentiometric surface of the bedrock aquifers. Contour interval 40 feet. Supplementary contours with contour interval 20 feet shown in some areas.***

MAP EXPLANATION FOR FIGURE 6

Map symbols and labels

- Groundwater flow direction.
- 1200 Potentiometric surface contour (feet above mean sea level). Contour interval 40 feet. Supplementary contour with contour interval of 20 feet shown in some areas.
- 1300 Estimated potentiometric surface contour (feet above mean sea level). Contour interval 40 feet. Supplementary contour with contour interval of 20 feet shown in some areas.
- Major bedrock aquifer contact.
- F F′ Line of cross section.
- Body of water.

Bedrock elevation (feet above mean sea level)

- > 1,200 to 1,300
- > 1,100 to 1,200
- > 1,000 to 1,100
- > 900 to 1,000
- > 800 to 900
- > 700 to 800
- > 600 to 700
- > 500 to 600
- > 400 to 500
- > 300 to 400
- > 200 to 300
- 132 to 200

POTENTIOMETRIC SURFACES AND GROUNDWATER MOVEMENT

Potentiometric Surfaces

Water is usually moving into the aquifers (recharge), through the aquifers, and out of the aquifers (discharge) in complicated but definable patterns. It is rare for the water within aquifers and systems of aquifers to remain static or unchangeable. Three primary types of data are used by investigators to understand these water movement relationships: chemical data from collected water samples, aquifer test data gathered by pumping wells under controlled conditions, and static (non-pumping) water level data measured from wells and surface water bodies. Static water level data and groundwater movement are the primary focus of this plate. The chemical data from aquifers in this study area are discussed on the Pollution Sensitivity Plate (Plate 10). Available aquifer test data is discussed on Plate 7.

A potentiometric surface is defined as "a surface that represents the level to which water will rise in a tightly cased well" (Fetter, 1988). Static (non-pumping) water-level data from the County Well Index and measurements by personnel from the Department of Natural Resources were plotted and contoured to create the potentiometric contour maps on this plate. The contour lines illustrate the potentiometric surface; these lines are similar to the contour lines on a topographic map that provide a visual model of the ground surface. The potentiometric surface of an aquifer represents the potential energy that exists in a confined aquifer that is available to move groundwater. Low-elevation areas on the potentiometric surface above the elevation of coincident surface-water bodies may indicate discharge areas; when combined with other information, high-elevation areas on the potentiometric surface can indicate important recharge areas. As groundwater moves from higher to lower potentiometric elevations it flows perpendicular to the potentiometric elevation contours (flow directions shown as arrows). Groundwater flow paths from recharge areas through the aquifer to discharge locations are described by a wide continuum of depth, distance, and time. Flow into, through, and out of shallow aquifers can occur relatively quickly in days or weeks over short distances of less than a mile, whereas flow through deeper aquifers across dozens of miles may take centuries or millennia.

Buried Sand and Gravel Aquifers

The sm and sl aquifers shown in Figure 1 are some of the shallowest buried aquifers in the area. Direct connections to the surficial aquifers are common (central portion of the right side of F–F′ on Plate 8) and result in relatively rapid or focused recharge.

The sc aquifer (Figure 2 and right side of cross section D–D′ on Plate 8), shown west of Scanlon, also has direct connections and focused recharge conditions through the overlying surficial aquifer. Discharge to Otter Creek probably occurs at this location from the sc aquifer and may represent an example of a relatively rapid flow-through aquifer. Another shallow occurrence of the sc aquifer is shown on Figure 2 in the far northwestern portion of Carlton County and coincides with the Little Tamarack River. Similar rapid flow-through conditions to the river may exist in this area. Deeper portions of the sc aquifer that may be getting some focused recharge are shown west of Wrenshall (see right portion of cross sections E–E′ and F–F′ on Plate 8) and northeast of Moose Lake (see the central portion of cross section I–I′ on Plate 8). Groundwater flow in the sc aquifer in the area west of Wrenshall is generally south or easterly toward the Nemadji River basin. Groundwater flow in the sc aquifer northeast of Moose Lake and south of Barnum may discharge to Bear Lake, Hanging Horn Lake, and Little Hanging Horn Lake. Other deeper occurrences of the sc aquifer are shown in the far northeastern corner of Carlton County (Figure 2, inset map, and the right side of cross sections C–C′ and D–D′ on Plate 8). Groundwater flow in these areas is southerly with possible local discharge to Hay Creek, Elm Creek, and Midway River.

Recharge and discharge conditions and groundwater flow directions for the scattered and isolated sc1 aquifer occurrences are difficult to characterize (Figure 3) in a large, county-scale atlas project. However, possible discharge areas may include Eagle Lake, in western Carlton County south of Cromwell; Hay Creek, in northeastern Carlton County; and Hanging Horn Lake, in south-central Carlton County south of Barnum.

Most groundwater flow in the sic aquifer (Figure 4), which is restricted to the northern portion of the study area, is toward the St. Louis River. Most portions of this aquifer are too deep to have direct connections to sources of surface or near surface recharge. Exceptions include portions of the aquifer shown in the very northern part of the study area (see left side of cross section A–A′ on Plate 8); a small portion of the aquifer located west of Stoney Brook (see left side of cross section B–B′ on Plate 8); and a portion of the aquifer west of Cloquet (see right side of cross section C–C′ on Plate 8). Possible discharge from the aquifer to the St. Louis River appears to be limited to a small portion of the aquifer north of Twin Lakes in the northern part of the study area. Most of the sts aquifer of western Carlton County is also too deep for focused recharge or discharge to surface water bodies. Groundwater flow direction in the sts aquifer south of Cromwell is generally southeasterly toward the Kettle River.

The stw aquifer and much of the su aquifer appear to be too deep to receive any focused recharge (Figure 5). Groundwater flow through the stw aquifer in the Wright area (northwest Carlton County) is toward the Tamarack River. Groundwater flow in the stw and su aquifers along the Kettle River (southwestern portion of Carlton County) is toward the Kettle River. Groundwater flow in the su aquifer south of Wrenshall is southeasterly toward the Nemadji River. Possible su aquifer discharge conditions could occur at some locations in northeastern Carlton County to the St. Louis and Midway Rivers.

Bedrock Aquifers

The boundaries of the bedrock aquifers shown on Figures 6, 8, and 9 have been greatly simplified from the geologic units shown in Part A, especially for the complex assemblage of rock types that exist in the northwestern two-thirds of the study area. The bedrock in that portion of the study area consists of hard crystalline metamorphic and igneous rocks, with the metamorphic type as the most common. Since these types of rocks, and volcanic rock of the southeastern corner of the study area, have no intergranular porosity, groundwater moves primarily through fractures. While no production capacity information is available from these fractured crystalline rock aquifers, production capacities are probably low compared to other aquifers in the state. The southeastern third of the county is underlain mostly by two bedrock aquifers (Fond du Lac aquifer and Hinckley sandstone aquifer) and a small area of volcanic rock aquifer occupying the southeastern corner of the study area. Limited data were available regarding the specific capacity (a measure of production capacity) for the Fond du Lac aquifer (Table 1, Plate 7). These data and the lithology of the Fond du Lac Formation (mostly arkosic sandstone with interbedded mudstone and siltstone) suggest this formation also does not typically produce large amounts of water. The existence of many wells with long open-hole portions in both the Hinckley sandstone and Fond du Lac aquifers shown on the right side of cross sections H–H′ and I–I′ on Plate 8 suggest that the fractures in both of these aquifers have limited water-producing characteristics.

Compared to the spatially complex distribution of probable recharge areas described in the previous section for the buried sand and gravel aquifers, the area of likely rapid or focused bedrock aquifer recharge is a simpler zone that bisects the study area. Much of the recharge area of the bedrock aquifer can be defined with the simple depth to bedrock map shown in Part A, Plate 5. A zone of thin (less than 50 feet) glacial sediment bisects the study area along a southwest-northeast trend. Most groundwater samples with recent and mixed tritium age and elevated Cl/Br ratios obtained from the bedrock aquifers occur in this area (see Plate 10, Figure 8) and indicate relatively recent recharge.

The dominant groundwater flow directions in the bedrock aquifers (Figure 6) are toward the Kettle River in the southwestern portion of the study area, southeasterly toward the Nemadji River in the central portion, and toward the St. Louis River in the northeastern portion of the study area. Possible groundwater discharge to surface water may occur along extended reaches of the rivers and creeks that cross the area of thinly covered bedrock including: Split Rock River, Silver Creek, Gillespie Brook, Moose Horn River, King Creek, Little Otter Creek, Otter Creek, St. Louis River, Midway River, and Stoney Brook. Groundwater discharge to some limited segments of the Kettle River also appears likely.

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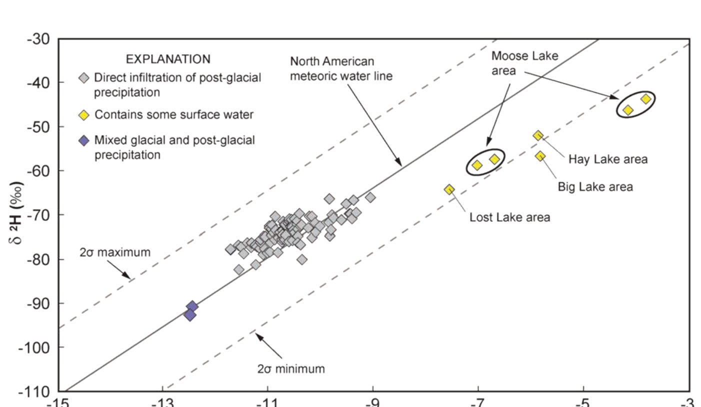

FIGURE 7. ***Graph of stable isotope values of groundwater sampled in the study area compared to the meteoric water line.*** *Groundwater samples analyzed for stable isotopes for this study can be classified into three general groundwater types: direct infiltration of post-glacial precipitation (gray symbols), samples that contain some water from surface water sources (yellow symbols), and mixed glacial and post-glacial precipitation (purple symbols). The dashed "2σ" lines show the statistical variation of stable isotope precipitation values used to derive the North American meteoric water line (IAEO/WMO, 2006).*

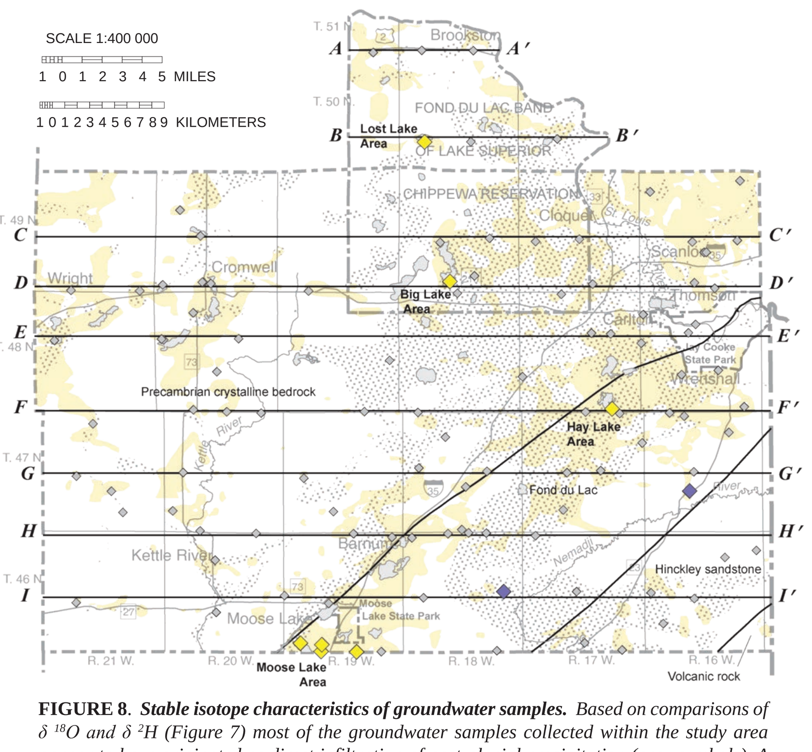

FIGURE 8. ***Stable isotope characteristics of groundwater samples.*** *Based on comparisons of δ ¹⁸O and δ ²H (Figure 7) most of the groundwater samples collected within the study area appear to have originated as direct infiltration of post-glacial precipitation (gray symbols). A group of samples (yellow symbols) represent groundwater that contains some infiltrated water from lakes and wetlands. A distinct group of samples with low (more negative) isotope values may be mixtures of glacial and post-glacial recharge (purple symbols).*

MAP EXPLANATION FOR FIGURE 8

Stable isotope characteristics

- Direct infiltration of post-glacial precipitation.
- Contains some surface water.
- Mixed glacial and post-glacial precipitation.

Map symbols and labels

- Major bedrock aquifer contact.
- Extent of surficial sand aquifer.
- Extent of mapped buried sand and gravel aquifers.
- F F′ Line of cross section.
- Body of water.

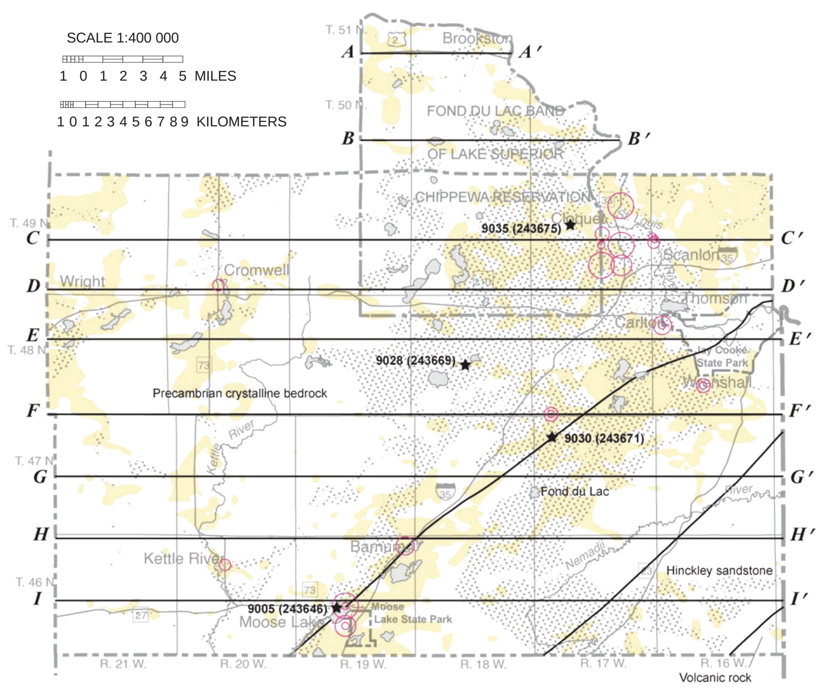

FIGURE 9. ***Locations of DNR groundwater appropriation permit holders in 2009 and DNR observation wells in the study area.***

MAP EXPLANATION FOR FIGURE 9

Water use reported by DNR groundwater appropriation permit holders for 2009 (millions of gallons per year)

- 0–2
- > 2–4
- > 4–8
- > 8–16
- > 16–32
- > 32–64
- > 64

Map symbols and labels

- 9035 DNR observation well number.
- (243675) CWI unique number.
- DNR observation well.
- Major bedrock aquifer contact.
- Extent of surficial sand aquifer.
- Extent of mapped buried sand and gravel aquifers.
- F F′ Line of cross section.
- Body of water.

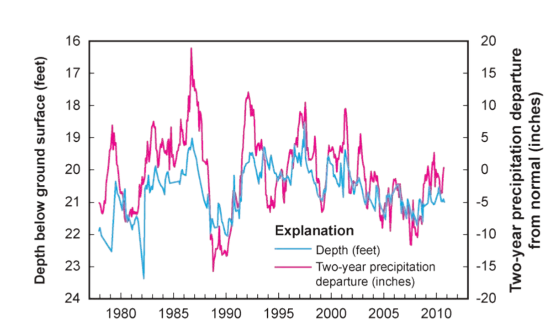

FIGURE 10. ***Hydrograph of water wable observation well 9028 (unique number 243669). The hydrograph also shows precipitation cumulative departure from normal.*** *This graph shows a close association between water table depth in the surficial sand aquifer and precipitation in the central portion of the study area.*

TABLE 1. Reported 2009 water use of DNR groundwater appropriation permit holders in the study area.
[Data from Minnesota Department of Natural Resources, State Water Use Data System; MGY, million gallons per year; dash marks (--) indicate no data available; QWTA, Quaternary water-table aquifer; QBAA, Quaternary buried artesian aquifer; CWI, county well index]

Use	Aquifer (CWI aquifer code)			Total (MGY)	Percent Use
	Surficial sand (QWTA)	Buried sand and gravel (QBAA)	Bedrock		
Municipal	130	366	67	563	90.8
Industrial/commercial	--	43	--	43	6.9
Non-crop irrigation	8	--	--	8	1.3
Golf course	--	4	--	4	0.6
Pollution containment	2	--	--	2	0.3
Total (MGY)	140	413	67	620	
Percent Use	22.6	66.6	10.8		

STABLE ISOTOPES OF OXYGEN AND HYDROGEN

Stable isotopes are used to understand water sources or the processes that have affected them. Isotopes commonly used for these purposes include oxygen (^{16}O and ^{18}O) and hydrogen (^{1}H and ^{2}H). The ^{2}H hydrogen isotope is called deuterium. All of the groundwater samples collected from the study area were analyzed for ^{18}O and deuterium ratios as an additional tool for characterizing the area groundwater.

Isotopes of a particular element have the same number of protons but different numbers of neutrons. Isotopes are called stable if they do not undergo natural radioactive decay. The mass differences between ^{16}O and ^{18}O or ^{1}H and ^{2}H can cause the concentrations of these isotopes to change (fractionate) during evaporation and precipitation, resulting in different $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios in rain, snow, rivers, and lakes. Figure 7 shows a plot of $\delta^{18}O$ and $\delta^{2}H$ values from groundwater samples collected in the study area. The value on the x-axis represents the ratio of ^{18}O to ^{16}O in the sample divided by the same ratio in a standard. The value on the y-axis represents the ratio of ^{2}H to ^{1}H in the sample divided by the same ratio in a standard. The diagonal line labeled "North American meteoric water line" is the trend line of $\delta^{18}O$ and $\delta^{2}H$ from precipitation in North America. Three types of information regarding the origin and history of these water samples can be interpreted from this graph: relative atmospheric temperature during precipitation, relative mixing of water from cold and warm sources, and evaporation from the body of water that is the source of the sample.

Source Water Temperature and Mixing

For the samples that plot along the same slope as the meteoric water line, the samples more depleted in heavy isotopes (samples that plot closer to the bottom left of the graph) suggest water that precipitated from a colder atmosphere. The two groundwater samples that cluster together in the lower left of the graph are somewhat exceptional in the study area and probably represent groundwater that is a mixture of glacial and post-glacial precipitation. Both of these samples (Figure 8) are from the Fond du Lac aquifer beneath the deep bedrock valley in the southeastern part of the study area (Figure 6).

Source Water Evaporation

Molecules of water with the more common hydrogen (^{1}H) and oxygen (^{16}O) are lighter and more readily evaporated, leaving the remaining water more concentrated in the heavier isotopes. Because of this fractionation effect lake water typically shows an evaporative signature, such as a higher concentration of the heavier isotopes than precipitation. Water that directly infiltrates the ground is not fractionated in this manner, so it has a meteoric signature that is a higher concentration of the lighter, more prevalent isotopes. The effect of evaporative fractionation is isotopic values that plot with a slope less than the slope of the meteoric water line (Ekman and Alexander, 2002; Kendall and Doctor, 2003).

On Figure 7 the samples that show isotopic evidence of surface water evaporation are shown on the upper right portion of the graph. These seven groundwater samples were collected from areas around four lakes (Figure 8). Four of these seven samples were from the Moose Lake area in the southern part of the study area. The apparent surface water source for these samples is the cluster of lakes south of the City of Moose Lake including Sand Lake in Carlton and Pine Counties, and Island Lake in Pine County. The aquifers in this area containing lake water that has undergone evaporation include not only the relatively shallow sc and sc1 aquifers, but also the deeper su and Fond du Lac aquifers. The su aquifer and Fond du Lac aquifer samples from this group had the youngest ^{14}C residence time estimates of all samples collected in the study area, both with a value of 1000 years.

Other locations with lake water sources and infiltration to aquifers include the sic aquifer beneath Lost Lake and Big Lake in the northern part of the study area (left side of cross section B–B′ and center of cross section D–D′ on Plate 8, respectively), and the sc aquifer beneath Hay Lake in the east-central part of the study area (right side of cross section F–F′ on Plate 8).

The majority of samples plotted in the center portion of the graph along the meteoric water line (Figure 7) suggest sources from post ice-age precipitation (normal rain and snow melt water) that infiltrated directly into the subsurface and did not reside for long periods in lakes or other surface water bodies.

GROUNDWATER USE AND MONITORING

A water use (appropriation) permit from the Minnesota DNR is required for all users, with some exceptions, for withdrawing more than 10,000 gallons of water per day or 1 million gallons per year. The categories of large capacity users in the study area and reported water use by use category for 2009 from the three main types of aquifers are shown in Table 1. A generalized map of all mapped aquifers in the study area and permitted users is shown in Figure 9. The large majority of water use in the area is for municipal water purposes (Table 1). The main aquifer for this use, and also the next highest category of use (industrial/commercial), is the buried sand and gravel aquifer (QBAA). Unlike many other counties in Minnesota, irrigation uses a very small percentage of water in the study area.

Of the approximately 3500 wells in the study area, the majority (56%) pump water from buried sand and gravel aquifers, followed by crystalline bedrock sources (27%), the surficial sand aquifer (8%), the sedimentary bedrock aquifers (5%), and other minor categories (4%). The large majority of wells in the study area are domestic wells (88%), followed by public supply (5%), and other minor categories (4%).

To monitor the cumulative effect of groundwater appropriation across the state, the DNR maintains and monitors approximately 700 observation wells. There are four active observation wells in the study area (Figure 9). All of these wells monitor water table levels in the surficial sand aquifer. Figure 10 shows a typical hydrograph from DNR observation well 9028 in the central part of the study area. This figure shows that the water table levels (blue) in the surficial sand aquifer have risen and fallen over time in response to changes in area precipitation (red).

This map was compiled and generated using geographic information systems (GIS) technology. Digital data products, including chemistry and geophysical data, are available from DNR at mndnr.gov/groundwatermapping.

This map was prepared from publicly available information only. Every reasonable effort has been made to ensure the accuracy of the factual data on which this map interpretation is based. However, the Department of Natural Resources does not warrant the accuracy, completeness, or any implied uses of these data. Users may wish to verify critical information; sources include both the references here and information on file in the offices of the Minnesota Geological Survey and the Minnesota Department of Natural Resources. Every effort has been made to ensure the interpretation shown conforms to sound geologic and cartographic principles. This map should not be used to establish legal title, boundaries, or locations of improvements.

Base modified from Minnesota Geological Survey, Carlton County Geologic Atlas, Part A, 2009.

Project data compiled from 2009 to 2010 at a scale of 1:100,000. Universal Transverse Mercator projection, grid zone 15, 1983 North American datum. Vertical datum is mean sea level.

GIS and cartography by Jim Berg, Greg Massaro, and Shana Pascal. Edited by Neil Cunningham.