HYDROGEOLOGY OF THE BURIED AQUIFERS

By

James A. Berg

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INTRODUCTION

The majority (62 percent) of the approximately 2,600 wells in Pope County are used for domestic water supply. Irrigation is the other major use category representing 27 percent of the wells in the county. The combination of industrial, commercial, municipal, and public supplies account for 3 percent of the wells in the county. Buried aquifers are the major source of water for most of the domestic, industrial, municipal, and public supply wells. The surficial aquifers described on Plate 6 are used mainly for irrigation, but many irrigation wells also use the buried aquifers as a water source.

Although the buried aquifers may be the most important ground-water resource in the region, they are often the most difficult to map and predict. Our knowledge of these aquifers primarily depends on drill hole information, and the reliability of the aquifer maps depends on the spatial density of that information. Subsurface aquifer maps can be created and interpreted by several different methods; therefore, a brief description of the assumptions and methods used for this atlas is provided to help the user understand the strengths and limitations of these maps.

Quaternary Stratigraphy, Mapping Methods, and Lithology Database

The Quaternary stratigraphy used in this atlas was derived from surficial geologic mapping (Part A). In addition, drill hole information was derived from shallow (5 feet to 25 feet) augered holes and deeper (150 feet to 200 feet) rotosonic cores from the Traverse-Grant Regional Hydrogeologic Assessment, Part A (in press). The regional assessment contains some revisions of similar information presented in the Pope County Geologic Atlas, Part A (Plate 4). "Quaternary" is the geologic age since the beginning of the ice age to the present. This is the period during which all the important aquifer sediments were deposited in Pope County by advancing and receding glaciers. "Stratigraphy" describes the sequence of the various layers in these sediments, which ultimately helps us map the aquifers and describe the ground-water flow conditions.

Information from the rotosonic cores (locations shown as black stars on the maps) was important for determining the deeper stratigraphy in the area. This information, however, was also limited with only three cores used to assess the entire county. For the county-scale mapping shown in this atlas, the lithology data from the County Well Index (CWI) database were used for estimating the boundaries of the stratigraphic units. "Lithology" refers to descriptions by drillers and geologists about the types of geologic materials (sand, clay, and silt) that they have recorded from drill hole and outcrop samples. Sand and gravel layers and oxidized till samples (usually described as yellow or brown) were correlated and interpreted to create 39 closely spaced (1 kilometer) west-east cross sections with stratigraphic information extrapolated from the three core locations and the surface geology map on Plate 3 of Part A. This large set of cross sections was used to help create the aquifer maps shown in this atlas by employing a variety of three-dimensional geographic information system (GIS) methods.

Quaternary History and Depositional Models

The following geologic sequence of events summarizes the late glacial history of Pope County, as described in the Traverse-Grant Regional Hydrogeologic Assessment (in press), and focuses on the deposition of the three buried aquifers mapped for this atlas. Other aquifers are present beneath these but could not be mapped across the county because of a lack of data. The late glacial history of west-central Minnesota is generally a story of sediment deposition from ice lobes that repeatedly moved into and retreated from the region from two sources in Canada: the Keewatin dome, from which ice lobes flowed into Minnesota from the northwest, and the Labradoran dome, from which ice lobes entered the area from the northeast (Figures 1 and 2).

The depositional model for the CW aquifer (Figure 2c) assumes a general southwestern movement of sand and gravel in the northeastern portion of the county from ice lobes that were receding to the northeast. Sediment transport took a more southerly orientation in the western and southern portions of the county (Part A, Plate 3). The depositional model for the earlier BROW aquifer (Figure 2a) and later OT aquifer (Figure 2e) assumes general sediment transport directions to the southwest and south. The ice lobes that created the OT and BROW aquifers receded to the northwest and possibly acted as western barriers during sediment transport and deposition in some areas.

THICKNESS AND DEPTH OF BURIED SAND AND GRAVEL DEPOSITS

The most common thickness values for all three buried sand and gravel deposits range from 20 feet to 40 feet. Locally, the deposits can be 80 feet thick or greater. Notably thick portions of the OT aquifer (Figure 3a) include an area north of Starbuck and another area west of the Little Chippewa River in the northwestern portion of the county (also shown near the left end of cross section C–C′, Plate 8). The most common depths to the top of this aquifer range from 40 feet to 80 feet with a total range of 0 to 120 feet.

The thickest portion of the CW aquifer (Figure 3b) also includes an area near Starbuck (shown just west of Lake Minnewaska on cross section D–D′, Plate 8) where the thickness can exceed 100 feet. The most common depths to the top of this aquifer range from 40 feet to 100 feet with a total range of 20 feet to 200 feet.

Very thick portions of the BROW aquifer seem to be rare; however, this map may be less representative of actual conditions because of limited well information for these greater depths (Figure 3c). The most common depth range to the top of this aquifer is 80 feet to 120 feet with a total range of 0 to 240 feet.

All three aquifers are generally saturated and confined. The elevations for the tops of these aquifers are shown on Plate 8, Figures 2b, 2c, and 2d.

GROUND-WATER MOVEMENT, RECHARGE, AND DISCHARGE IN BURIED SAND AND GRAVEL AQUIFERS

Introduction

Two general hydrogeologic tools were used to help determine the movement of ground water in these aquifers: the potentiometric surface map and the distribution of distinctive ground-water chemical constituents. A potentiometric surface is defined as "a surface that represents the level to which water will rise in a tightly cased well" (Fetter, 1988). The potentiometric surface of a confined aquifer (aquifer under pressure) occurs above the top of an aquifer where an overlying confining layer (low-permeability layer) exists. Static (nonpumping) water-level data from the CWI and measurements by personnel from the Department of Natural Resources were plotted and contoured to create the potentiometric contour maps. Low-elevation areas on the potentiometric surface that could be above confined sand and gravel bodies may indicate discharge areas; high-elevation areas, combined with other sources of information, can be identified as important recharge areas. Ground water moves from higher to lower elevations perpendicular to the potentiometric elevation contours (flow directions shown as arrows). Geochemical indicators that can be related to ground-water recharge and movement were used in this study for two general purposes: to estimate residence time or age of ground water (based on tritium and carbon-14) and to determine whether anthropogenic (human-created) constituents or contaminants (elevated nitrate values and high ratios of chloride to bromide) are present in the ground water.

Indicators of Ground-Water Residence Time

Recent tritium values (shown as dark pink well symbols on the Figure 3 maps) are important indicators of water that has infiltrated the land surface within the past 50 years. Tritium (^3H) is a radioactive isotope of hydrogen that naturally occurs in the atmosphere. However, atmospheric testing of hydrogen bombs from 1953 to the early 1960s greatly increased the concentrations of atmospheric tritium. This tritium combines with atmospheric water molecules, precipitates as rain or snowfall, and enters aquifers through surface infiltration. The presence of tritium at more than 10 tritium units (TU) in a water sample indicates recent water (recharged since 1953). Samples with tritium values of 1 or below are interpreted as vintage water (recharged before 1953). Tritium values between 1 and 10 are mixtures of recent and vintage water. Recent tritium values were found in samples from several locations in the OT and CW aquifers; water can travel rather easily and quickly from the land surface to these aquifers because of shallow conditions or connections with surficial aquifers (see Plate 9 for detailed discussion).

Several water samples were tested for carbon-14 (^{14}C), which is a method useful for estimating ground-water residence times from approximately 100 years to 40,000 years (Alexander and Alexander, 1989). The age range of the nine ground-water samples tested for carbon-14 was from 100 years to 3000 years. The oldest age-dated sample was from a well in the BROW aquifer in the southern corner of the county northwest of Brooten.

Anthropogenic Indicators

Nitrate concentrations in ground water above approximately 1 part per million (ppm) are usually caused by anthropogenic sources such as fertilizer application and septic or sewage systems (Minnesota Pollution Control Agency, 1998). None of the samples collected within the county from the buried aquifers had nitrate concentrations above this background value. All samples but one were collected from buried or confined aquifers where reducing conditions (absence of dissolved oxygen) predominate. Dissolved nitrate is naturally removed by bacteria under these conditions, which may account for the lack of elevated nitrate values.

Ratios of chloride to bromide (Cl/Br) from water samples have been used in previous ground-water studies (Berg, 2004) as an indicator of chloride contamination from human activities (see Figures 6 and 7, Plate 9). Samples containing high Cl/Br ratios (above 175) were found throughout the county from all three aquifers. Three samples with high Cl/Br ratios came from the OT aquifer in the western part of the county (Figure 3a) in areas where the OT aquifer is very shallow or connected to surficial sand (note the sample near the left edge of C–C′, Plate 8). An example of one of the four high-ratio Cl/Br samples from the CW aquifer (Figure 3b) is shown near the right edge of cross-section H–H′ where the CW aquifer is connected to the overlying shallow OT aquifer. The high Cl/Br ratios in four samples from the BROW aquifer in the eastern portion of the county (Figure 3c) also appear to be attributable to multiple aquifer connections that allow relatively recent recharge water to infiltrate to this aquifer.

Recharge and Discharge

The process of water penetrating the land surface and infiltrating into aquifers is a widespread occurrence for most portions of the aquifers described on these plates. However, the rate of recharge can vary considerably from values that are almost imperceptible to values that are easily measured by conventional methods. This discussion and other references to recharge on the sensitivity plate (Plate 9) will concentrate on areas thought to have the most rapid or focused recharge. The term "rapid" means no evidence of water age older than several decades (recent and mixed tritium). Focused recharge areas for these complex, connected buried aquifers and younger glacial sediments were determined by regional examination of well tritium and the potentiometric surfaces. Recharge conclusions using this stratigraphic approach were supported in many areas by chemical evidence of recharge: recent or mixed tritium values and elevated Cl/Br ratios.

Direct evidence of buried aquifer discharge to surface-water bodies was not collected as part of this atlas. Discharge was suspected where the buried aquifer potentiometric surface could be above the elevation of a surface-water body at the possible discharge area.

OT aquifer. Insufficient data were available for the OT aquifer to construct a potentiometric surface; however, some flow directions are shown on Figure 3a where clusters of data existed. Most of this aquifer probably recharges rapidly because many portions are relatively shallow. However, half the tritium values of ground-water samples collected from this aquifer were vintage, indicating that some portions are somewhat isolated. Probable discharge areas include intersections with the Chippewa River valley in the northwestern corner of the county (left end of cross-sections B–B′ and C–C′, Plate 8) and the same valley in the west-central portion of the county (area between cross-sections F–F′ and G–G′).

CW aquifer. Recharge to this aquifer typically occurs by leakage from the overlying OT aquifer and surficial aquifers. Rapid leakage into this aquifer seems common except for much of the north-central and northwestern areas. Focused recharge occurs in three areas: south of Cyrus, in and around Glacial Lakes State Park, and portions of the aquifer in the northeastern part of the county where it is directly connected to the Belgrade-Glenwood sand plain. At two locations in the western portion of the county (west of Farwell and south of Lake Emily), mixed tritium values and an elevated Cl/Br ratio were detected that cannot be explained by leakage from connected sand deposits. These samples may represent samples that were affected by leakage through a corroded casing or leakage from shallower sand and gravel deposits that have not been accounted for because of limited well log data.

Possible discharge areas for this aquifer include three areas around Lake Minnewaska: a wetland area due west of the lake, an area along the southwestern shore, and the Glenwood area (cross-section C–C′, Plate 8). Other possible discharge locations occur in the south-central portion of the county at county ditch no. 15 (cross-section H–H′, Plate 8) and the East Branch of the Chippewa River (cross-section I–I′, Plate 8).

BROW aquifer. Most recharge to the BROW aquifer, the stratigraphically lowest of the mapped aquifers, appears to be indirect based on tritium values in water samples and stratigraphic associations. Evidence of recharge to this aquifer includes a north-south cluster of three mixed tritium samples south of Lake Amelia and west of Sedan (cross-sections D–D′, E–E′, and F–F′, Plate 8), as well as a west-east trend including a cluster of two mixed tritium samples from southwest of Villard to Westport (cross-section B–B′, Plate 8). In both of these areas, a hydrologic connection from the surficial aquifer through the CW aquifer to the BROW aquifer can be seen. Only one water sample collected from this aquifer (southeast of Sedan) yielded a recent tritium value. The stratigraphic connection that could explain this occurrence is not apparent from existing well data. The remainder of the recharge evidence is from mixed tritium values and stratigraphic associations.

Possible discharge areas for this aquifer include four locations around Lake Minnewaska, the Long Beach and Glenwood areas, and two locations along the south shore. Three other discharge areas are Outlet Creek west of Glacial Lakes State Park, the Scandinavian Lake area, and a wetland area northeast of Simon Lake (cross-section I–I′, Plate 8).

Arsenic

A previous large-scale study (Minnesota Department of Health, 2001) of naturally occurring arsenic in well-water samples from western Minnesota has shown that more than 50 percent of 900 private drinking water wells had arsenic concentrations that exceeded the federal drinking water standard of 10 parts per billion (ppb) or 10 micrograms per liter (µg/L). The elevated ground-water arsenic values appeared to be more common from wells in glacial sediment deposited by a sequence of ice lobes that moved into Minnesota from the northwest (Des Moines lobe till). The Des Moines lobe till contains approximately 10 percent to 50 percent shale (Traverse-Grant Regional Hydrogeologic Assessment, Part A, in press) as a proportion of the sand size fraction. This relatively abundant shale fragment component contains finely disseminated pyrite (an iron sulfide mineral), which may be the dominant source of arsenic and the reason for the association of Des Moines lobe till and elevated arsenic in well water samples. Erickson and Barnes (2005) confirmed through statistical analysis that this spatial relationship is valid and conjectured that the significant characteristics of these Des Moines lobe sediments that contribute to elevated arsenic in ground-water samples include a high proportion of fine-grained material (clay and silt) and sufficient entrained carbon from wood and plant debris. In addition to this till composition factor, elevated arsenic values are only found in ground water that has little or no dissolved oxygen (reducing conditions).

Pope County is within the boundaries of these Des Moines lobe glacial sediments (Plate 3, Figures 2 and 3, Part A), and 45 percent of ground-water samples collected for this project contained arsenic concentrations that exceeded 10 ppb. Arsenic values are shown on the aquifer maps (Figures 3a, 3b, 3c) according to the associated aquifer, and together on Figure 4 symbolized by aquifer with the size of the symbol proportional to the arsenic concentration. Figure 4 shows that elevated arsenic values exist throughout the county. Elevated arsenic values were not found in the OT aquifer probably because it is typically shallow and commonly contains oxidized water that prevents mobilization of arsenic. The arsenic (S) stratification labels on Figure 4 highlight pairs of wells, within a radius of approximately 1.5 miles, where one of the wells is screened in the CW aquifer and the other well is screened in the underlying BROW aquifer. In six of seven well pairs, the overlying CW aquifer, which has direct contact with Des Moines lobe till (Otter Tail River group), has a higher arsenic value than the BROW aquifer well of the same pair. These vertical stratigraphic relationships are consistent with the previously referenced mapped relationships (Minnesota Department of Health, 2001; Erickson and Barnes, 2005) and suggest that the Des Moines lobe sediments are the source of naturally occurring arsenic. These relationships also suggest that in some locations drilling and constructing a deeper well could locate ground water with lower concentrations of arsenic.

REFERENCES CITED

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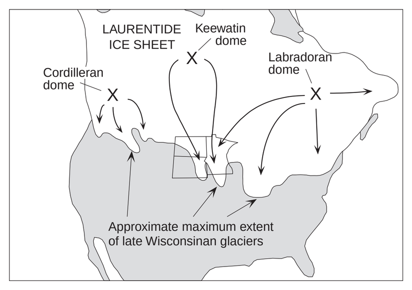
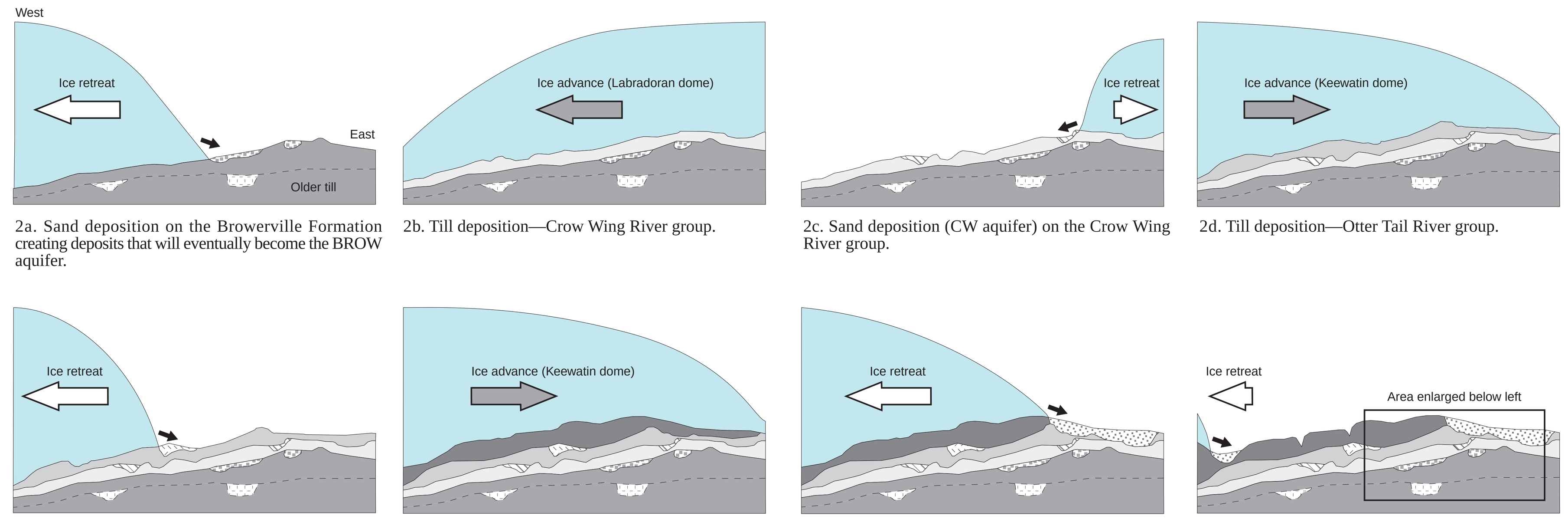


FIGURE 1. *Glacial ice sources.* Approximate extent of a portion of the Laurentide ice sheet about 15,000 years ago. Arrows indicate possible ice lobe flow paths (modified from Plate 3, Part A).

FIGURE 2. *Schematic cross sections summarizing the late glacial history of Pope County since the deposition of the Browerville Formation.* Figure 2a shows deposition of sand and gravel on top of the Browerville Formation from an ice lobe that melted and receded to the north and northwest. These sand and gravel deposits eventually were buried by the fine-grained material of subsequent ice advances, which created the buried BROW aquifer shown on this plate. The source location of glacial ice subsequently shifted to the northeast (Labradoran dome). Another ice lobe moved into the area from the northeast (Figure 2b). Most of the Crow Wing River group was deposited during this southwestern ice lobe advance. The overlying sand and gravel (CW aquifer) was deposited during ice lobe recession to the northeast (Figure 2c). The glacial ice source shifted again to the north or northwest (Keewatin dome). Advancing ice deposited most of the Otter Tail River group (Figure 2d) followed by deposition of the overlying sand and gravel (OT aquifer) as this ice lobe receded to the northwest (Figure 2e). The OT deposits were subsequently buried in the western two-thirds of the county by till of the Lower Goose River group deposited by another ice advance from the north or northwest (Keewatin dome) (2f). Sand and gravel of the Belgrade-Glenwood sand plain was subsequently deposited in eastern Pope County from the melting ice lobe (2g). Till of the Upper Goose River group on the far western edge of the county was deposited during the final ice lobe advance from the northwest (Figure 2h), followed by sand and gravel deposition in the Chippewa River valley as that ice lobe melted (2h). Figure 2i summarizes the stratigraphy of these geologic units in Pope County.



2a. Sand deposition on the Browerville Formation creating deposits that will eventually become the BROW aquifer.

2b. Till deposition—Crow Wing River group.

2c. Sand deposition (CW aquifer) on the Crow Wing River group.

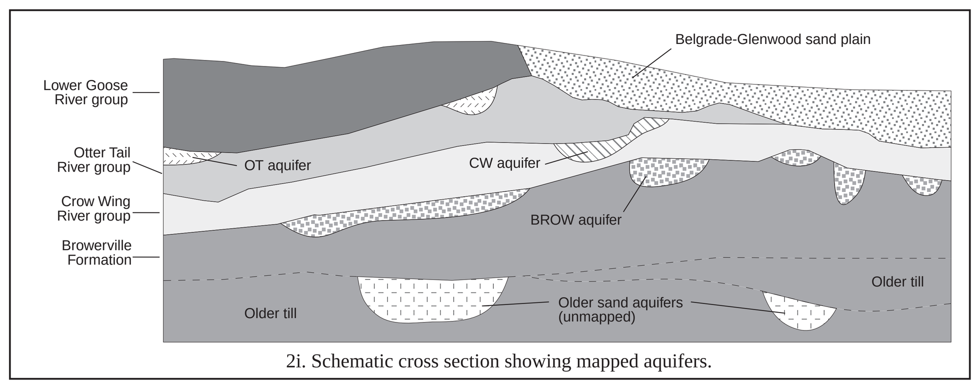
2d. Till deposition—Otter Tail River group.

2e. Sand deposition (OT aquifer) on the Otter Tail River group.

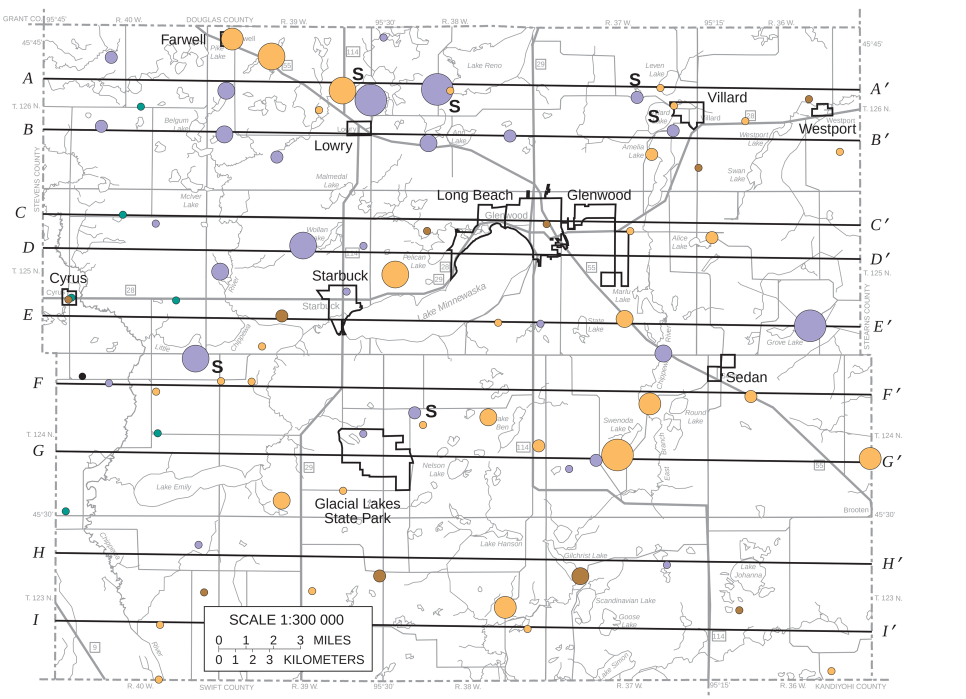
2f. Till deposition—Lower Goose River group.

2g. Sand deposition—Belgrade-Glenwood sand plain.

2h. Sand deposition—Chippewa River sand plain.



2i. Schematic cross section showing mapped aquifers.



Well symbols by aquifer

- Surficial sand and gravel
- OT
- CW
- BROW
- Older sand aquifer

Symbol size indicates arsenic concentration (in parts per billion).

- 0–10
- 10–20
- 20–30
- 30–40
- 40–50
- Greater than 50

S Stratification of arsenic. A pair of wells in the CW and BROW aquifers with high arsenic concentrations in the overlying CW aquifer.

FIGURE 4. *Summary of arsenic values from ground-water samples.* Arsenic values are symbolized by aquifer with the size of the symbol proportional to the arsenic concentration. Forty-five percent of ground-water samples collected for this project had arsenic concentrations that exceeded the federal drinking water standard of 10 parts per billion. Elevated arsenic values exist throughout the county. The stratification of arsenic (S) labels highlights pairs of wells, within a radius of approximately 1.5 miles, where one of the wells is screened in the CW aquifer and the other well is screened in the underlying BROW aquifer. In six of seven well pairs, the CW aquifer, which has direct contact with the overlying Des Moines lobe till (Otter Tail River group), had a water sample with a higher arsenic value than the water sample from the BROW aquifer well of the same pair.

MAP EXPLANATION

Figures 3a, 3b, 3c

Well symbols

- Well sampled for water chemistry.
- Static (nonpumping) water-level data from the County Well Index (CWI).
- Well or boring log.

6.65, 208, **2000** Well water sample data:
- If shown, ground-water age in years estimated by carbon-14 isotope analysis.
- Chloride to bromide ratio.
- Arsenic concentration in parts per billion.

Color of well symbol indicates tritium age

- Recent—Water entered the ground since about 1953 (10 or more tritium units).
- Mixed—Water is a mixture of recent and vintage waters (greater than 1 tritium unit to less than 10 tritium units).
- Vintage—Water entered the ground before 1953 (less than or equal to 1 tritium unit).

Map symbols and labels

- Rotosonic drill log.
- Arrow indicates the general direction of ground-water movement.
- F F′ Line of cross section.
- Eastern limit of the Lower Goose River group.
- Boundary of buried aquifer.
- Uncertain boundary of buried aquifer.
- 1200 Approximate potentiometric contour of buried aquifer in feet above mean sea level—Contour interval is 20 feet.
- Hachures toward lower elevation of potentiometric surface.

Thickness of buried sand and gravel deposit (in feet)

- 0–20
- 20–40
- 40–60
- 60–80
- 80–100
- 100–120
- Data insufficient or deposit not present

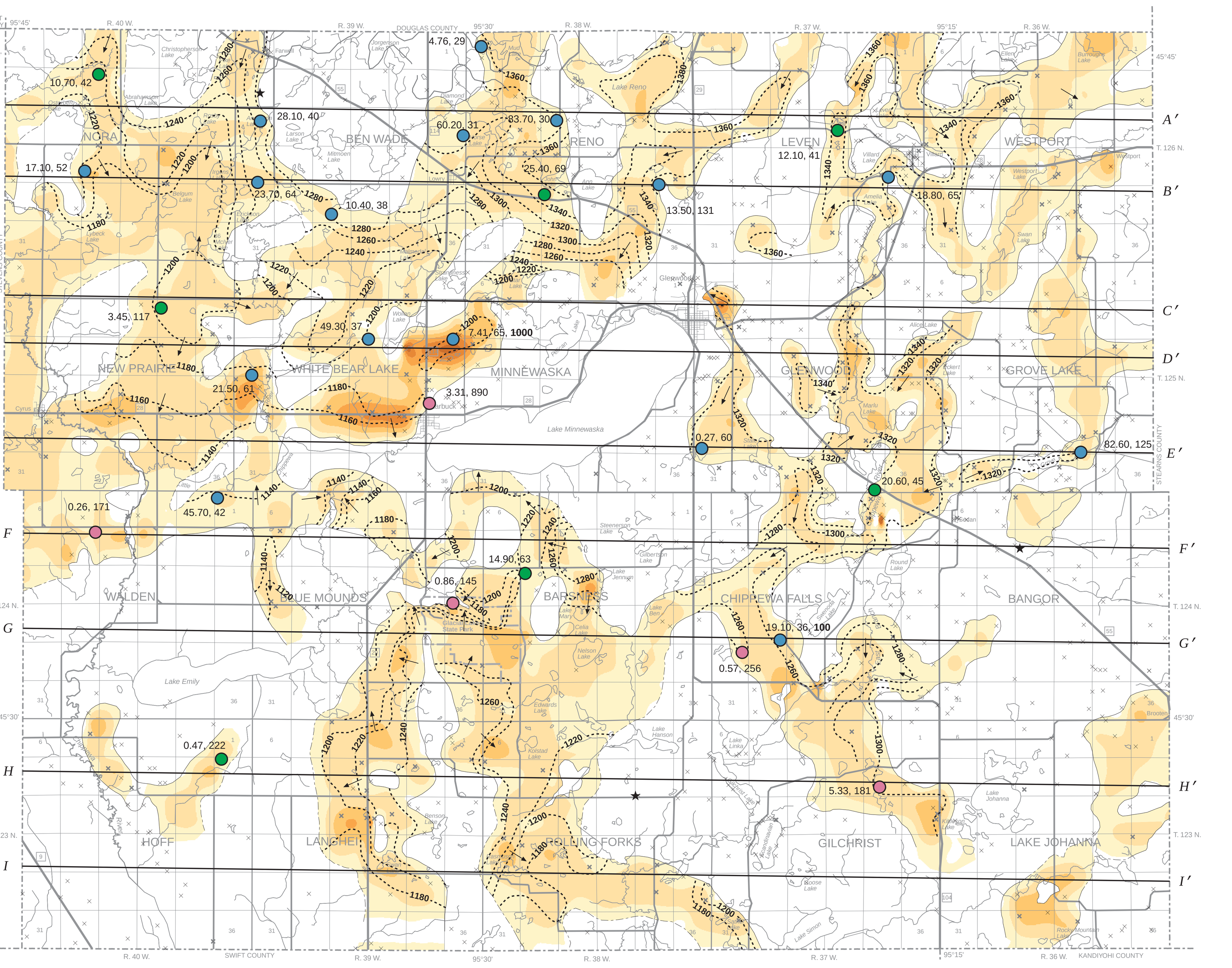
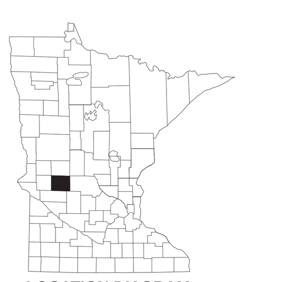


FIGURE 3b. *Thickness of sand and gravel deposits (CW aquifer) on top of the Crow Wing River group and potentiometric surface of the CW aquifer.* The thickest portion of the CW aquifer includes an area near Starbuck (shown just west of Lake Minnewaska on cross section D–D′, Plate 8) where the thickness can exceed 100 feet. Focused recharge to the aquifer occurs in three areas: south of Cyrus, in and around Glacial Lakes State Park, and portions of the aquifer in the northeastern part of the county where it is directly connected to the Glenwood-Brooten sand plain. Possible discharge areas for this aquifer include three areas around Lake Minnewaska: a wetland area due west of the lake, an area along the southwestern shore, and the Glenwood area (cross-section C–C′, Plate 8). Other possible discharge locations occur in the south-central portion of the county at county ditch no. 15 (cross-section H–H′, Plate 8) and the East Branch of the Chippewa River (cross-section I–I′, Plate 8).

SCALE 1:150 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 6 7 8 KILOMETERS



LOCATION DIAGRAM

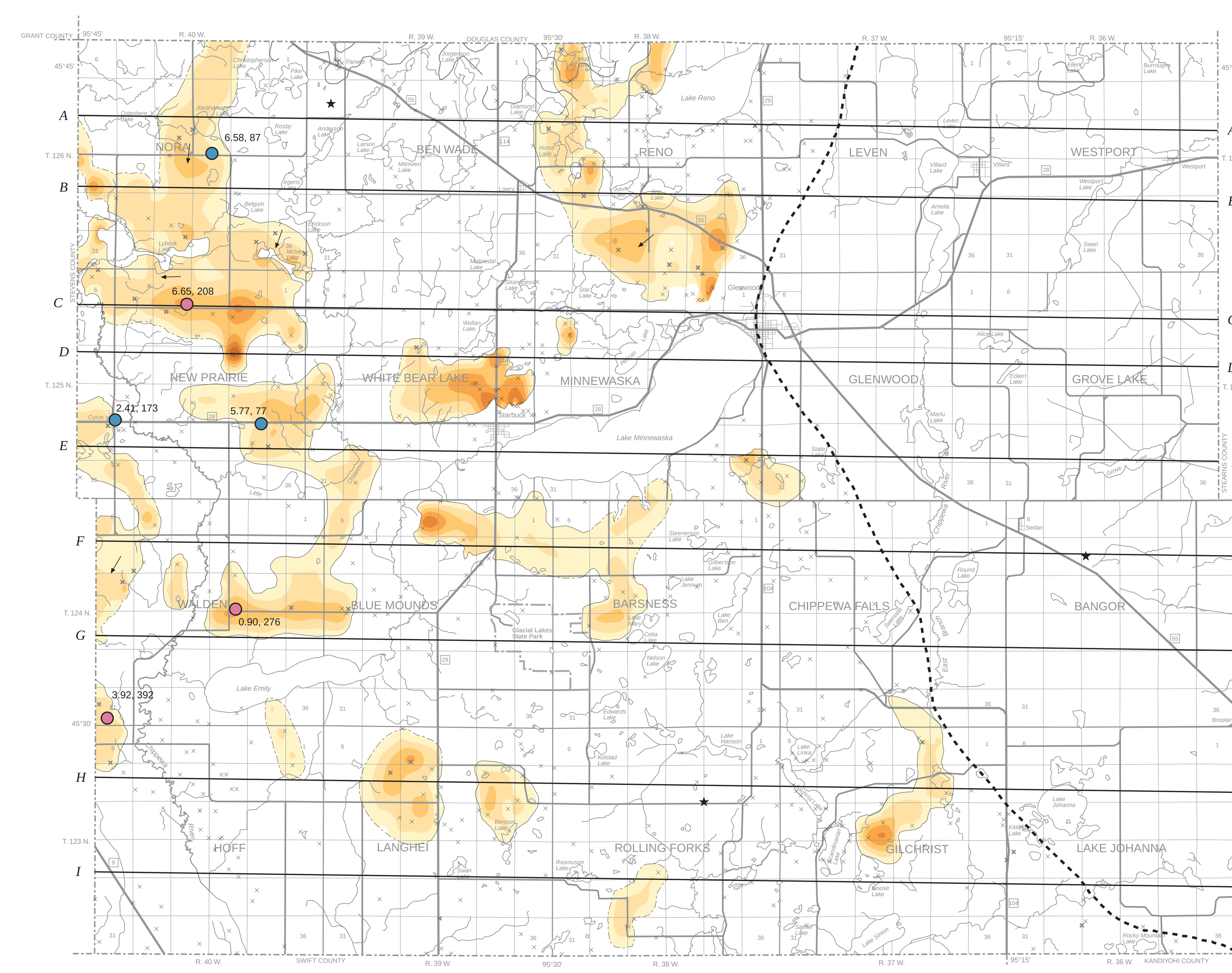


FIGURE 3a. *Thickness of sand and gravel deposits (OT aquifer) on top of the Otter Tail River group.* The notably thick portions of the OT aquifer include an area north of Starbuck and another area west of the Little Chippewa River in the northwestern portion of the county (also shown near the left end of cross-section C–C′, Plate 8). The dashed line at the eastern edge of the mapped units shows the eastern limit of the overlying Lower Goose River group. Water-level data were very limited for the OT aquifer, but a few ground-water flow directions are shown where clusters of data exist.

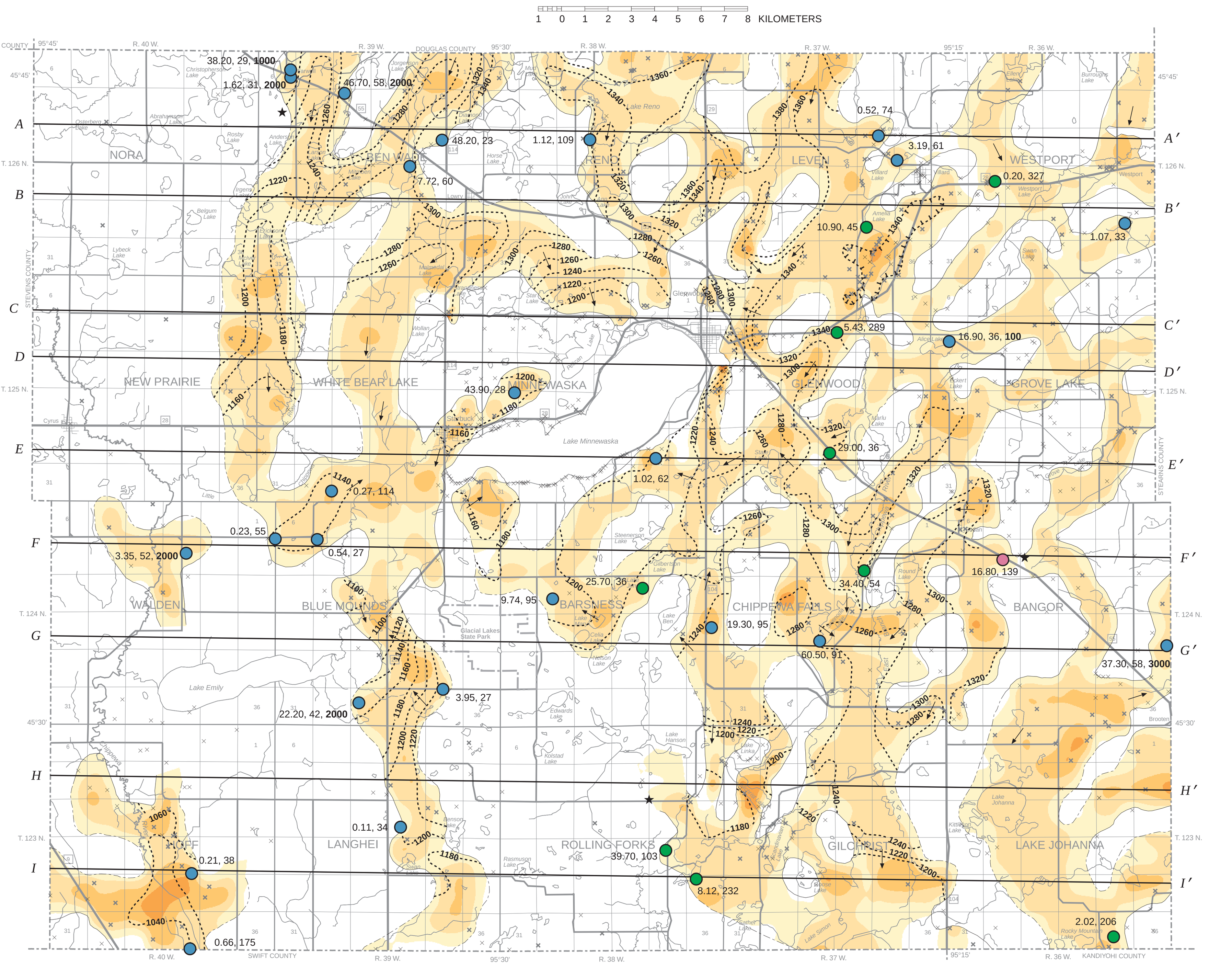


FIGURE 3c. *Thickness of sand and gravel deposits (BROW aquifer) on top of the Browerville Formation and potentiometric surface of the BROW aquifer.* The largest recharge areas of this aquifer are indicated by a north-south cluster of three mixed tritium samples south of Lake Amelia and west of Sedan (cross-sections D–D′, E–E′, and F–F′) and a west-east trend including a cluster of two mixed tritium samples from southwest of Villard to Westport (cross-section B–B′). Possible discharge areas for this aquifer include four locations around Lake Minnewaska, the Long Beach and Glenwood areas, and two locations along the south shore. Three other discharge areas are Outlet Creek west of Glacial Lakes State Park, the Scandinavian Lake area, and a wetland area northeast of Simon Lake (cross-section I–I′).

This map was compiled and generated using geographic information systems (GIS) technology. Digital data products, including chemistry and geophysical data, are available from DNR Waters at http://www.dnr.state.mn.us/waters.

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.

Digital base composite:
Roads and county boundaries - Minnesota Department of Transportation GIS Statewide Base Map (source scale 1:24,000)
Hydrologic features - U.S. Geological Survey Digital Line Graphs (source scale 1:100,000)
Digital base annotation - Minnesota Geological Survey
Project data compiled from 2004 to 2005 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 and Greg Massaro. Edited by Nick Kroska.