STATE OF MINNESOTA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATERS

COUNTY ATLAS SERIES
ATLAS C–15, PART B, PLATE 6 OF 9
Hydrogeology of the Surficial Aquifers

HYDROGEOLOGY OF THE SURFICIAL AQUIFERS

By

James A. Berg

2006

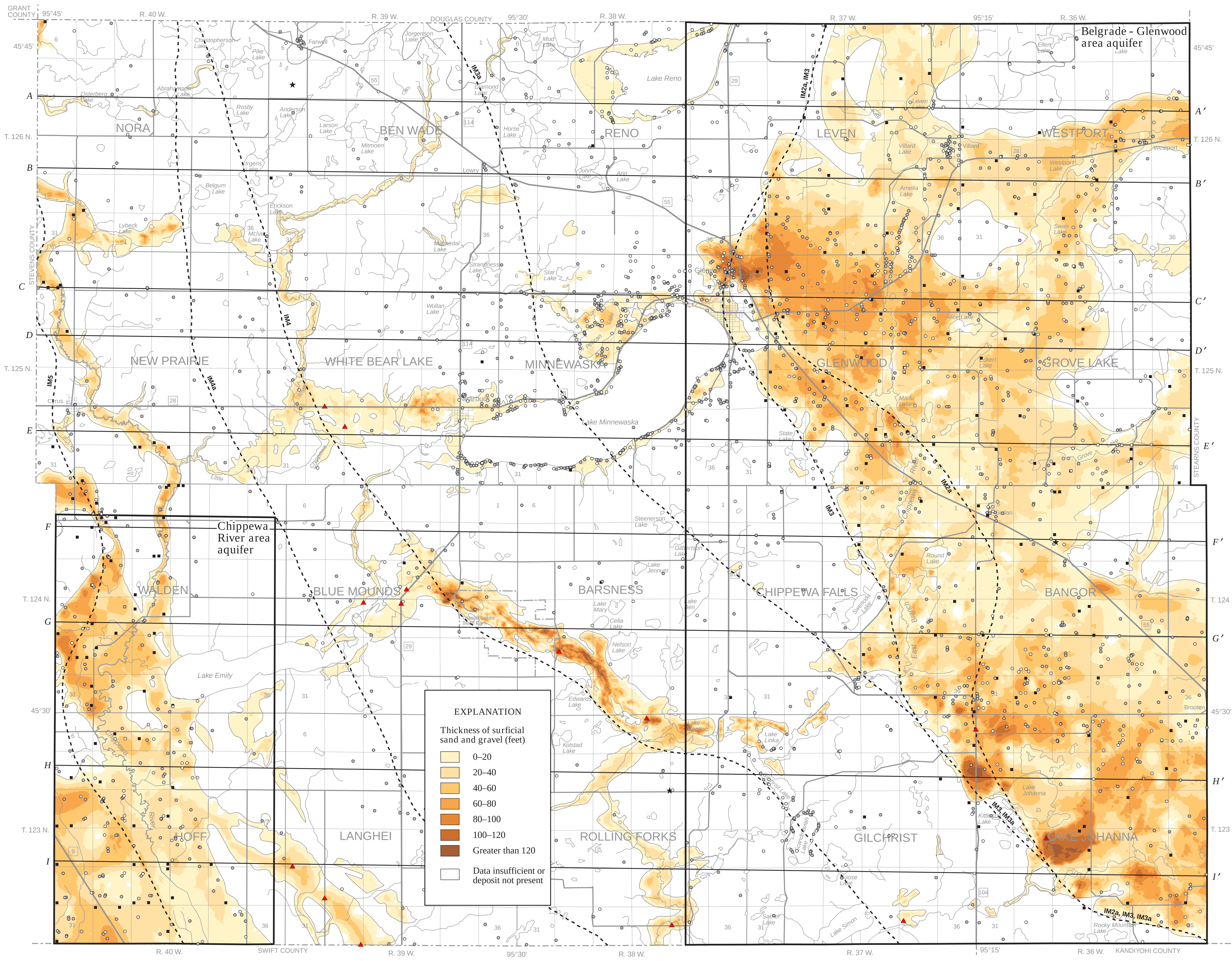

FIGURE 1. *Surficial sand and gravel thickness.* This map shows the thickness and distribution of surficial sand and gravel deposits in Pope County. With a few exceptions, the boundaries of these deposits are the same as the geologic map units delineating sand and gravel shown on Plate 3 in Part A. These surficial aquifers are the most important source of water for irrigation in the county. Irrigation is common in the eastern and southwestern portions of the county where the surficial aquifer is laterally extensive and relatively thick in many areas.

Most of the sand and gravel was deposited by meltwater from glaciers as they receded to the west and north. The ice margin lines (from Part A, Plate 3) show the approximate edges of two different ice lobes at various stages of recession (Lower Goose River group, ice margin [IM] 2a through IM4a, and Upper Goose River group, IM5). At these ice margins, the edge of the ice lobes, which was the source of the meltwater and sediment, remained long enough to create the patterns of distribution and thickness variations that are shown on this map.

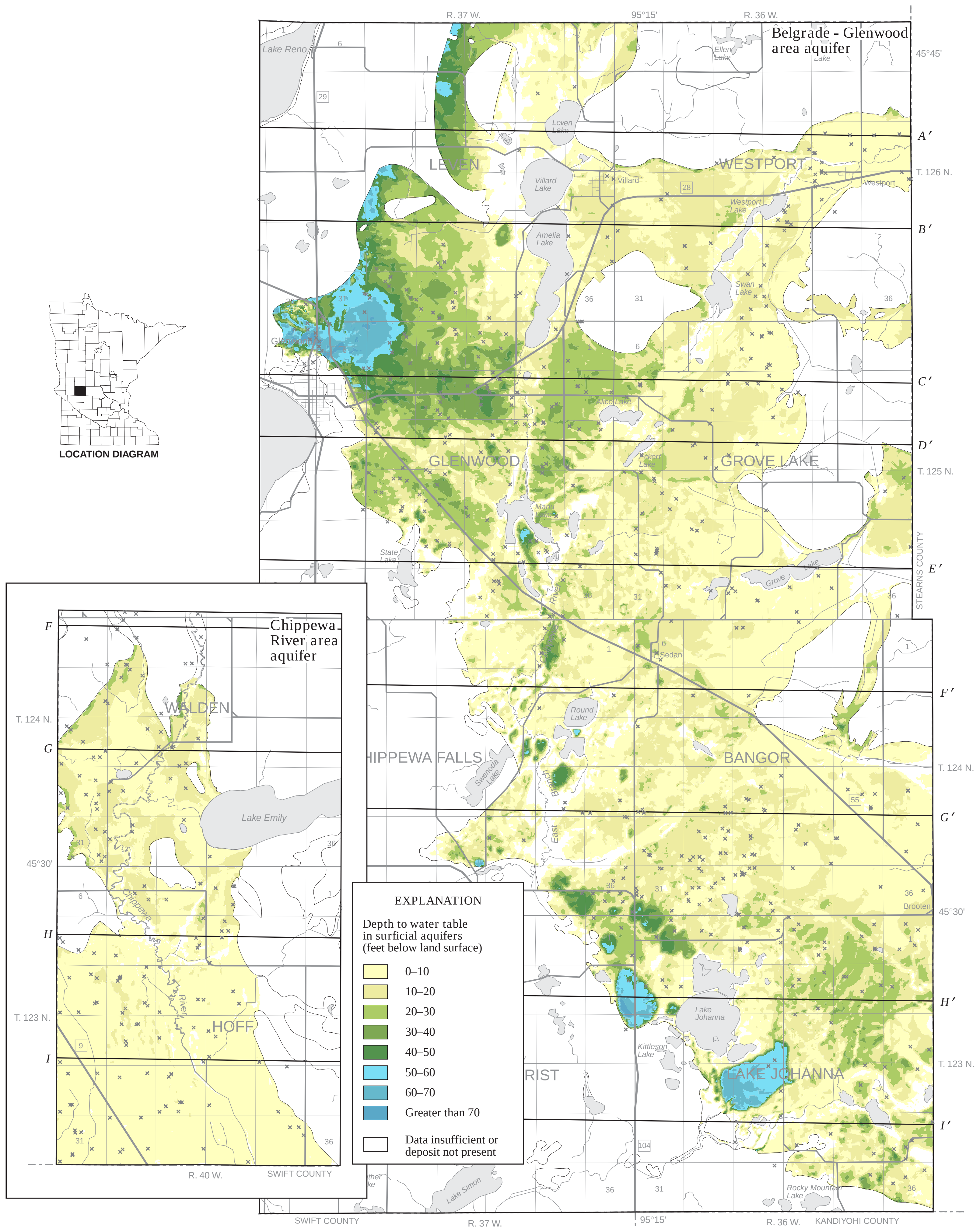

FIGURE 2. *Depth to water table from the land surface in the surficial aquifers.* The water table aquifers are generally not used as a drinking water source except in a few older wells. Where the water table is shallow, contaminants may reach the water table faster compared to the deep water table areas. The deep water table areas near Glenwood and Lake Johanna in southeastern Pope County generally correspond to areas of thickest sand and gravel (Figure 1). Shallow water table conditions generally prevail in the southwestern and east-central parts of the county.

INTRODUCTION

Like ground water in most counties in western and central Minnesota, most ground water in Pope County is pumped from unconsolidated bodies of sand and gravel. Eastern Pope County is dominated by a portion of one of the largest surficial sand deposits in the state: the Belgrade-Glenwood sand plain, which is a major source of irrigation water in the region (Figure 1, Belgrade-Glenwood area aquifer). The northern Chippewa River sand plain in southwestern Pope County is another important irrigation district in the region (Figure 1, Chippewa River area aquifer). Beneath these surficial aquifers are complex, layered glacial deposits that contain other important ground-water supplies for the county (Plate 7).

The purpose of this atlas is to provide data and maps showing the distribution and physical characteristics of the most important aquifers in the county (Plates 6 and 7); to describe the ground-water flow patterns, flow directions, aquifer connections, and important ground-water chemical characteristics (Plates 6, 7, and 8); and to assess sensitivity to pollution of the surficial and buried aquifers (Plate 9). This atlas is designed for units of government and citizens to use in planning for land use, water supply, and pollution prevention.

DATA SOURCES

Much of the information used to produce the maps, cross sections, and tables of this atlas came from well records: the database of well logs (County Well Index [CWI]) maintained by the Minnesota Geological Survey (MGS) and the Minnesota Department of Health (MDH), as well as well logs from holes that were drilled for several previous hydrogeolgical investigations of this region by the U.S. Geological Survey (USGS) (Van Voast, 1971a; Van Voast, 1971b; Wolf, 1976; Soukup and others, 1984; Delin, 1986a; Delin, 1986b; Delin, 1988; Delin, 1991). An additional information source was electrical resistivity data collected by DNR Waters staff for this report.

The CWI data include descriptions by drillers that are made as the well is drilled. Most of these well locations are verified in the field by staff from the MGS or MDH. The dataset also contains well logs with unverified locations. Unverified data were used in the maps and cross sections of this atlas; however, some of the unverified data were ignored if the information seemed inconsistent with other more reliable information.

The electrical resistivity data (red triangles shown on Figure 1) were particularly useful where drill hole data were rare or absent and an estimate of the thickness of sand and gravel deposits was important. The sand and gravel was detected by its resistivity difference from other material. The base of the surficial sand and gravel deposit is interpreted as an abrupt change between the higher electrical resistivities of the sand and gravel and the lower resistivities of the clay and silt of the underlying fine-grained glacial materials (generally glacial till).

CHARACTERISTICS OF SAND AND GRAVEL AQUIFERS

Depositional Characteristics of Surficial Aquifers

Figure 1 shows the thickness and distribution of two major surficial sand and gravel deposits and other surficial sand and gravel deposits in the county. The geologic history of surficial sand deposition is derived from descriptions on Plate 3, Part A. Several advances and recessions of ice lobes, which moved into Minnesota from the northwest through the area that is now occupied by the Red River, dominate the late glacial history of the county. The ice margins shown as dashed lines on Figure 1 represent the approximate positions that the ice lobe edges occupied long enough for huge volumes of meltwater and associated sand and gravel to be discharged in some areas from the melting ice.

The largest and thickest deposit from glacial meltwater in the county is the Belgrade-Glenwood sand plain in the eastern portion of the county, which is part of the Brooten-Belgrade sand plain that extends into Stearns County. This deposit is really a composite derived from two different areas as suggested by the two distinct north and south areas with thick sand and gravel. The northern area deposits appear to have been transported through the Lake Minnewaska area to a location north of Glenwood. The southern area deposits appear to have been derived from a topographically low area near Lake Simon through locations north and south of Lake Johanna. Sand and gravel thicknesses range from less than 10 feet in the east-central portion of the county, in the vicinity of Sedan and Round Lake, to 100–140 feet in the two thick sand areas previously described.

A thick surficial sand and gravel deposit along the western margin of the county is associated with the Chippewa River and ice margin 5 (IM5). This sand and gravel was deposited along the eastern edge of a major ice lobe to the west. The broadening of this deposit south of cross-section F–F′ and west of Lake Emily to the southwestern corner of the county represents deposits from a delta that was associated with Glacial Lake Benson that existed to the south in Swift and Chippewa counties (Patterson and others, 1999). The thickness of this deposit is fairly well known from drill hole data except for an eastern channel branch near the southern portion of the county. The sand and gravel in this Chippewa River area commonly is 20–40 feet thick; the thickest portion (40–60 feet) occurs generally west of Lake Emily.

In south-central Pope County, a large sand and gravel deposit extends northwest from the Linka and Gilchrist lakes area in the east to Glacial Lakes State Park. This deposit is parallel to ice margin 4 (IM4). The relatively high topographic relief of this area, along with drill hole and electrical resistivity data, suggests that the thickness of this deposit is highly variable. In some places, the deposit is 100–120 feet thick.

Two smaller surficial sand deposits exist in the central portion of the county around the Lake Minnewaska-Starbuck area and around Lake Reno in the north-central portion of the county. The thicker portions of the Lake Minnewaska-Starbuck deposit consist of small areas of glacial outwash combined with thinner postglacial (Holocene) lakeshore deposits. The thin sand around Lake Reno is interpreted to be mostly Holocene lakeshore deposits.

Hydrogeologic Characteristics of Surficial Aquifers

Estimating the yield of ground water from an aquifer requires information about an aquifer's extent and thickness, hydraulic conductivity (an aquifer's ability to transmit water), and other data sources. The maps of the surficial aquifers on this plate (Figures 1, 2, and 3) provide information about basic aquifer extent and thickness. Data used for estimating aquifer yields are obtained by pumping water from a well at a constant rate for a certain period of time. Table 1 shows a data summary from CWI of the simplest test of this type called a specific capacity test. This test is defined as well discharge, which is measured in gallons per minute divided by feet of water-level drawdown (gpm/ft) in the pumped well. High specific capacity values indicate that large amounts of ground water can be withdrawn with slight water-level drawdown in the well. In addition, high specific capacity values usually indicate high values of hydraulic conductivity.

The specific capacity values of wells in the surficial (water table or unconfined) aquifers differ from the specific capacity values of wells in the buried (confined) aquifers in the county (Plate 7). Extensive networks of buried sand and gravel aquifers were deposited by meltwater from earlier episodes of glacial advances, subsequent melting, and associated sand and gravel deposition. These aquifers are described in more detail on Plates 7 and 8. Wells in the surficial aquifers have higher specific capacities than wells in the buried aquifers with mean values of 38 gpm/ft and 77 gpm/ft for the eastern and western sand plains, respectively (Table 1). Wells in the buried aquifers have lower mean values (20–21 gpm/ft) because the aquifers are generally confined, thinner, and more limited in areal extent. The range of specific capacity values of wells in the surficial aquifers shows much greater variability than the values from the buried aquifers. This greater variability of specific capacity values of wells in the surficial aquifers is probably due to the greater range of aquifer thickness values and wider range of aquifer boundary conditions. As a result, specific capacities of wells in the surficial aquifers generally will be higher but less predictable than the buried aquifers.

Water table depth, elevation, and ground-water flow direction. The water table depth and elevation characteristics of the eastern and western surficial aquifers are shown in Figures 2 and 3 (the water table extends into adjoining nonaquifer materials that are not shown). These maps are generalized estimates and are mostly useful for comparisons of water table depth and elevation across the county. The data used to derive these maps were collected periodically each year during various climatic conditions from the 1960s to 2005. Water table depth varies seasonally and yearly according to precipitation conditions. Water table depth is useful to determine the type of septic system that might be needed for a new dwelling or development or to evaluate the sensitivity of the surficial aquifer to other potential pollutant sources besides the septic system.

The water table elevation maps are useful for depicting ground-water flow directions. Since much of the water in the lakes and streams in sand plain areas is ground-water discharge, the ground-water source areas of those surface-water bodies can be identified from these maps. This information can assist local units of government in managing these water bodies. In addition, ground-water flow gradients can be derived from these maps, which can be used along with other information, to estimate ground-water flow velocity. For all of these applications, additional site-specific information would be required to make accurate determinations.

Chippewa River area aquifer (western sand plain surficial aquifer). The water table of the western surficial aquifer (Figure 2) is mostly shallow (0 to 10 feet below land surface) except in the area west of Lake Emily. Nowhere is the water table deeper than approximately 30 feet below land surface in this area. The water table elevation map (Figure 3) shows that most shallow ground-water flow converges toward the Chippewa River and provides some portion of its discharge. The water table in this area has a relatively low gradient.

Belgrade-Glenwood area aquifer (eastern sand plain surficial aquifer). A broad range of water table depths are shown on Figure 2 in the eastern surficial aquifer area. Relatively shallow water table depths, ranging from 0 to 20 feet below land surface, characterize most of the central portion of the sand plain. Much greater depths (40 feet to 80 feet below land surface) are found in the thicker and topographically higher portions of the sand plain east of Glenwood and beneath the hills surrounding Lake Johanna in southeastern Pope County.

The Belgrade-Glenwood area aquifer straddles the boundaries of three major Minnesota watersheds: the Chippewa River to the west, the North Fork Crow River to the southeast, and the Sauk River to the northeast (Figure 3). In sandy, shallow water table areas, the ground-water flow directions are often similar to the surface-water flow directions. Therefore, the flow network of the surface-water system (Minnesota Department of Natural Resources, 2006) and the water table flow directions are shown together to create a comprehensive picture of shallow ground-water and surface-water movement in this area.

Shallow ground-water movement in the northeastern portion of the sand plain converges on the Swan-Westport chain of lakes. Surface- and ground-water discharges to Ashley Creek and subsequently flows east from the county. In the east-central portion of the sand plain, ground-water flow converges on Grove Lake and the North Fork Crow River and leaves the county to the east. South of the Grove Lake area, ground-water flow converges on Sedan Brook and an unnamed wetland and creek northwest of Brooten. This water also leaves the county to the east.

Most of the northwestern portion of this sand plain is dominated by surface drainage and ground-water flow through the Leven-Villard-Amelia chain of lakes. Surface water from this lake chain discharges to the East Branch of the Chippewa River that also captures most of the shallow ground-water discharge in this portion of the sand plain. Beyond the sand plain, the East Branch of the Chippewa River drains southwest to Linka and Gilchrist lakes. For a small portion of the western part of this sand plain, in an area around Glenwood, the ground water flows west toward Lake Minnewaska.

In summary, ground-water movement through the eastern sand plain area can be understood by dividing the aquifer into the three major surface watersheds, following the ground-water flow to the major surface drainage features, and tracking the surface-water flow to the edge of the study area.

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SCALE 1:100 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 6 7 8 KILOMETERS

MAP EXPLANATION
Figures 1, 2, 3

Well symbols

× Static (nonpumping) water-level data from the County Well Index (CWI).

● Verified well.

○ Unverified well.

■ U.S. Geological Survey well or test hole.

Map symbols and labels

★ Rotosonic drill log.

▲ Resistivity test.

← Arrow indicates the general direction of ground-water movement.

↩ Arrow indicates the downstream direction of streamflow.

F F′ Line of cross section. See Plate 8, Hydrogeologic Cross Sections.

IM3 Ice margin (IM) boundary.

Surface watershed boundary.

Extent of mapped surficial sand and gravel.

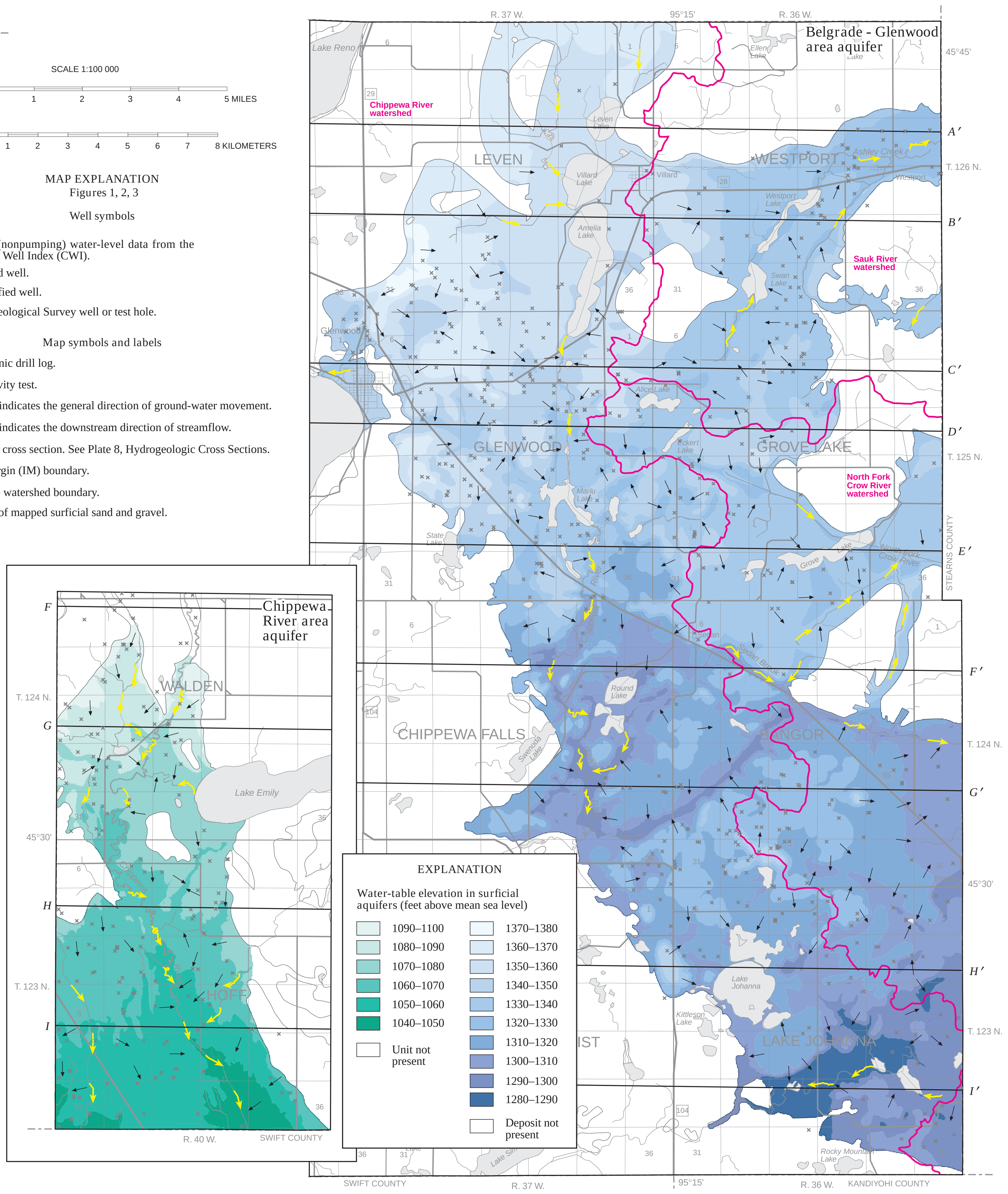

FIGURE 3. *Water table elevation in the surficial aquifers, flow directions of ground water at the water table, and discharge direction of surface water.* The flow network in the Chippewa River area aquifer (southwestern Pope County) is relatively simple with flow converging toward the river and ultimately discharging south. The flow network in the Belgrade-Glenwood area aquifer in eastern Pope County is complicated because water flows toward topographic low features (lakes, wetlands, small ponds), especially in the southern portion, and because water flow in the area is split by three major watersheds.

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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 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.

TABLE 1. Specific capacity of selected large-capacity wells*.

Aquifer	Well diameter range (inches)	Specific capacity (gpm/ft)			Number of tests
		Mean	Minimum	Maximum	
Surficial (see this plate)					
Belgrade-Glenwood (eastern surficial)	5–24	38	1	129	147
Chippewa River (western surficial)	12–24	77	13	500	108
Combined	5–24	58	1	500	255
Buried (see Plate 7)					
CW	5–16	20	2	67	31
BROW	5–16	21	2	230	78
Combined	5–16	20	2	230	109

*Specific capacity was measured by well discharge in gallons per minute per foot (gpm/ft) of water-level drawdown. Tests conducted on wells with large-capacity rates (greater than 100 gallons per minute). Data adapted from the County Well Index.

GEOLOGIC ATLAS OF POPE COUNTY, MINNESOTA

STATE OF MINNESOTA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATERS

COUNTY ATLAS SERIES
ATLAS C–15, PART B, PLATE 7 OF 9
Hydrogeology of the Buried Aquifers

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 interpretations were 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 both 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 these 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 coincident surface-water 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 southeastern 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 portion 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 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 mapping clear or probable connections between overlying aquifers. 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 dominant 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.

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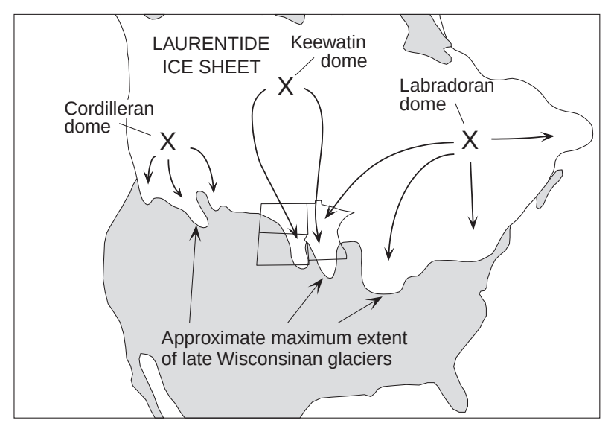
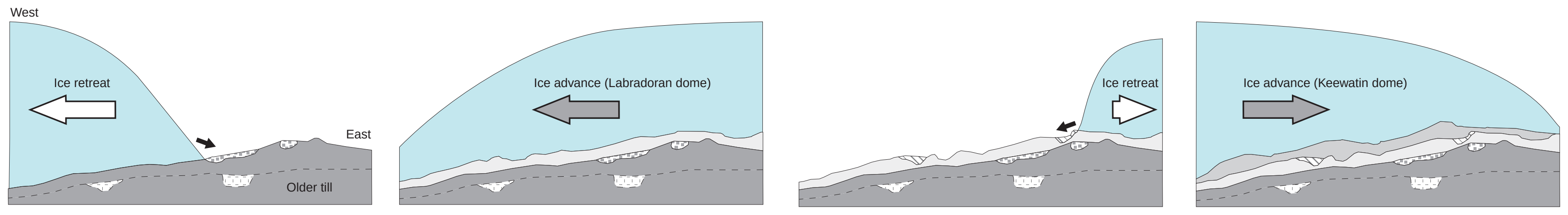


FIGURE 1. ***Glacial ice sources.*** Approximate extent of a portion of the Laurentide ice sheet about 15,000 years ago. Arrows indicate possible ice lobe flow paths (modified from Plate 3, Part A).

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.

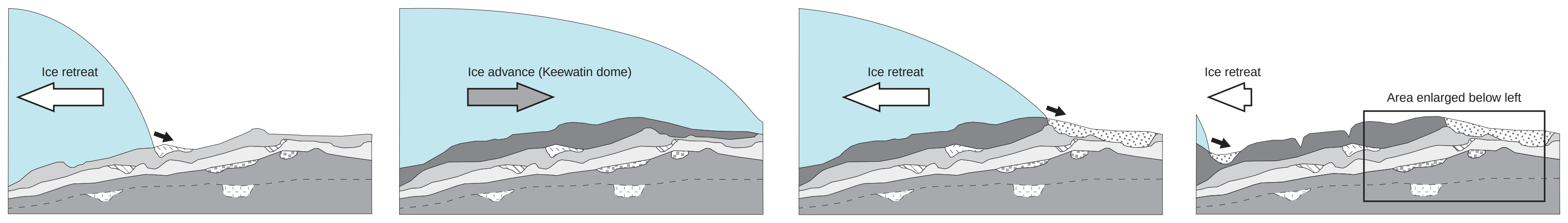


2a. Sand deposition on the Browerville Formation creating deposits that will eventually become the BROW aquifer.

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.

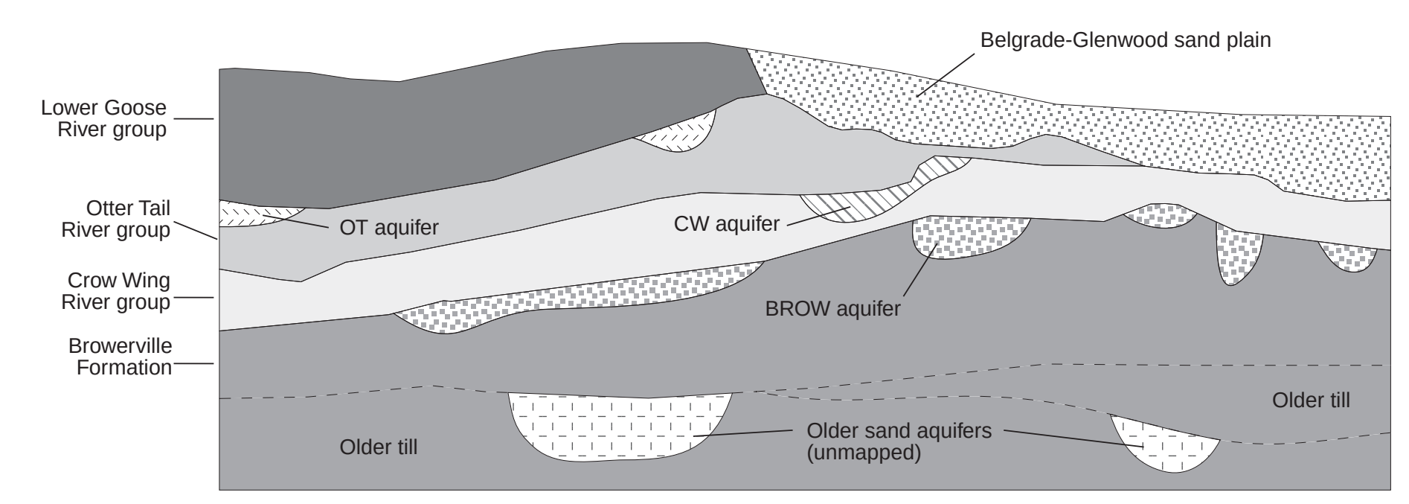


2e. Sand deposition (OT aquifer) on the Otter Tail River group.

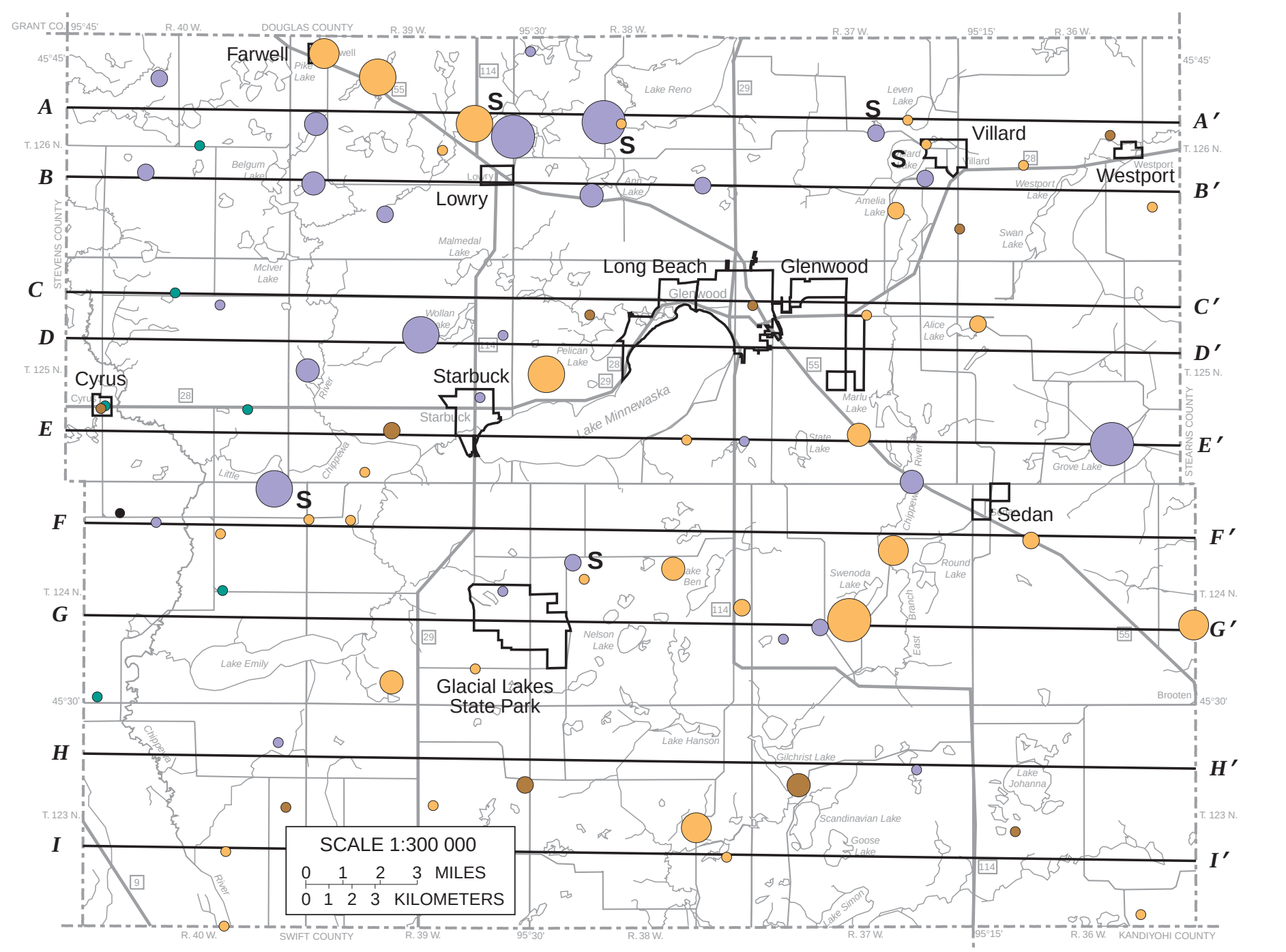
2f. Till deposition—Lower Goose River group.

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

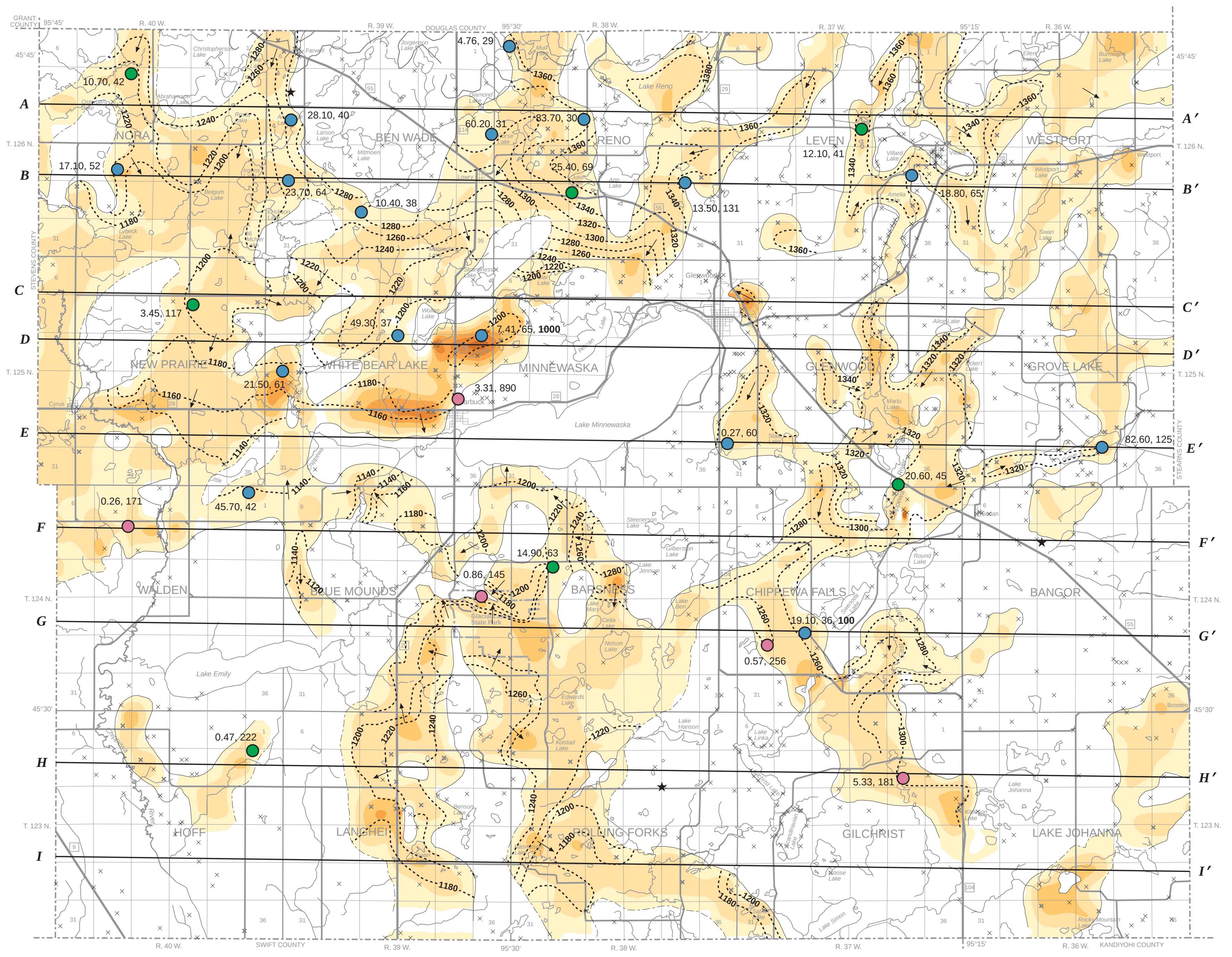


FIGURE 3b. ***Thickness of sand and gravel deposits (CW aquifer) on top of the Crow Wing River group and potentiometric surface of the CW aquifer.*** The thickest portion of the CW aquifer includes an area near Starbuck (shown just west of Lake Minnewaska on cross section D–D′, Plate 8) where the thickness 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

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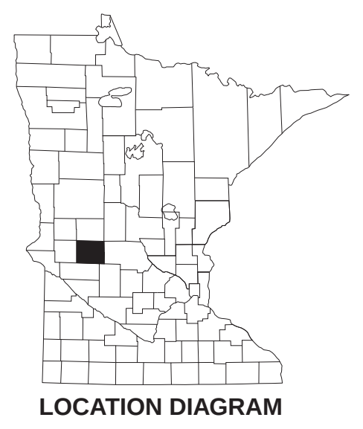
1 0 1 2 3 4 5 6 7 8 KILOMETERS



LOCATION DIAGRAM

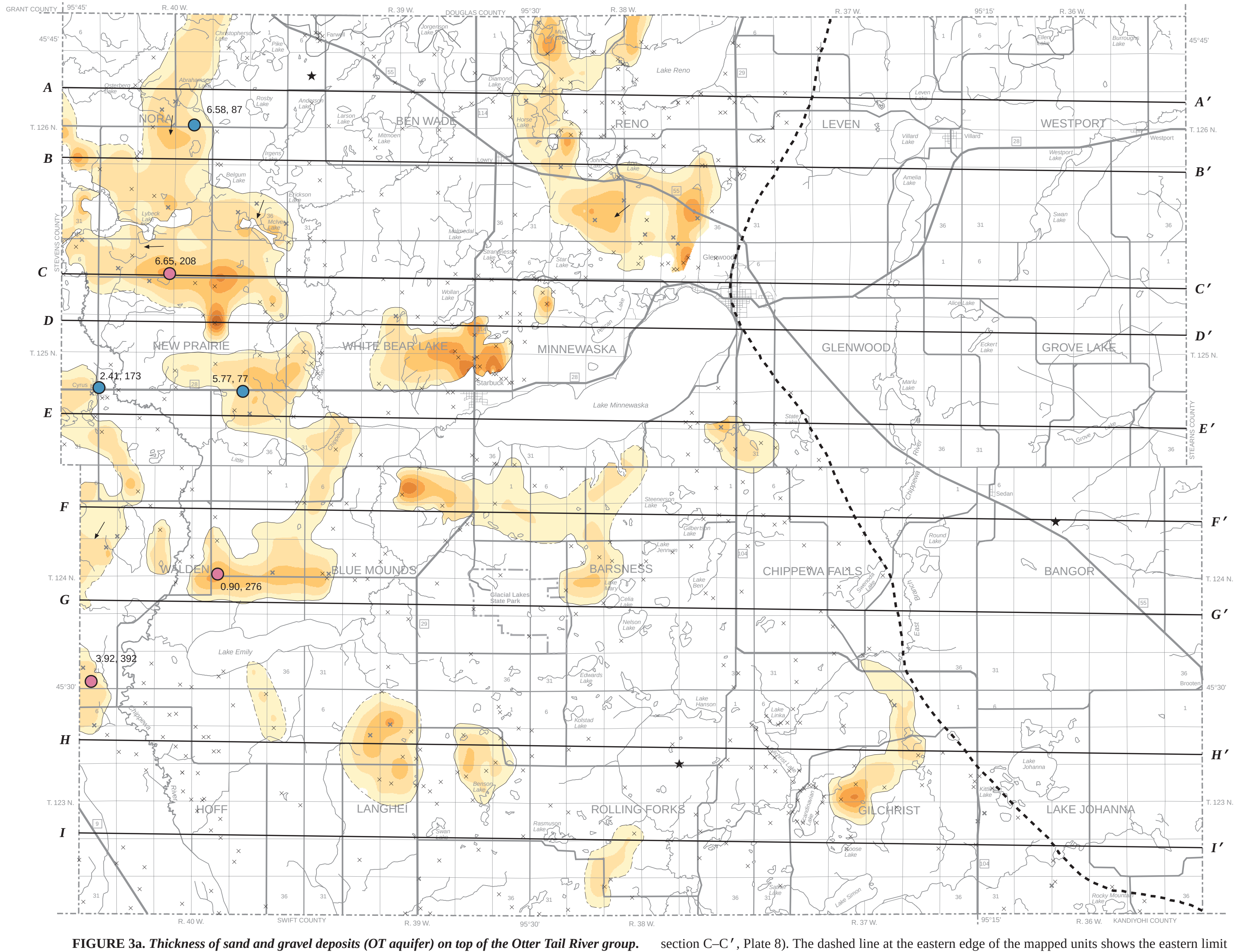


FIGURE 3a. ***Thickness of sand and gravel deposits (OT aquifer) on top of the Otter Tail River group.*** The notably thick portions of the OT aquifer include an area north of Starbuck and another area west of the Little Chippewa River in the northwestern portion of the county (also shown near the left 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.

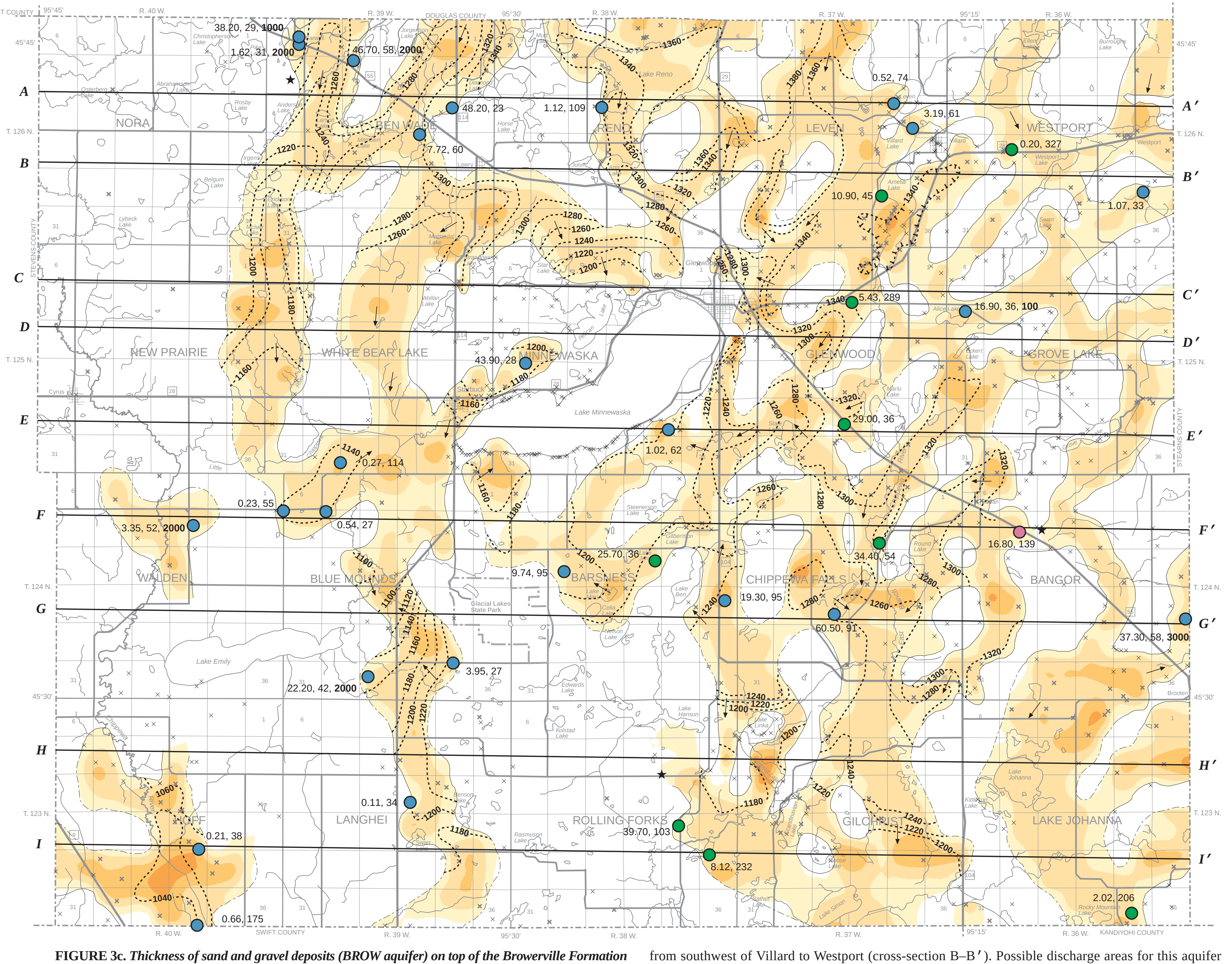


FIGURE 3c. ***Thickness of sand and gravel deposits (BROW aquifer) on top of the Browerville Formation and potentiometric surface of the BROW aquifer.*** The largest recharge areas of this aquifer are indicated by a north-south cluster of three mixed tritium samples south of Lake Amelia and west of Sedan (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′).

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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.

GEOLOGIC ATLAS OF POPE COUNTY, MINNESOTA

STATE OF MINNESOTA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATERS

COUNTY ATLAS SERIES
ATLAS C-15, PART B, PLATE 8 OF 9
Hydrogeologic Cross Sections

HYDROGEOLOGIC CROSS SECTIONS

By

James A. Berg

2006

INTRODUCTION

The nine hydrogeologic cross sections shown on this plate illustrate the horizontal and vertical extent of hydrogeologic units (aquifers and confining units), ground-water residence time, water table, and general ground-water flow directions. The cross sections shown on this plate were selected from a set of 39 regularly spaced, west-to-east cross sections. The cross sections were constructed using a combination of well data from the County Well Index (CWI), surface resistivity data, information from the surficial geology map of the Traverse-Grant Regional Hydrogeologic Assessment (in press), and information from Quaternary stratigraphy (Plate 4) and the bedrock topography map (Plate 2) of Part A. The well information for each cross section was projected onto the trace of the cross section from distances no greater than a half kilometer with a few exceptions.

PURPOSE AND METHOD OF CONSTRUCTING THE CROSS SECTIONS

The 39 cross sections were constructed to enable extrapolation of glacial stratigraphy from known areas to the rest of Pope County. The cross sections include the upper five stratigraphic units in the county (Upper Goose River, Lower Goose River, Otter Tail River, and Crow Wing River groups and Browerville Formation). Figure 1 depicts an oblique view of the county with three of those stratigraphic units separated below the land surface layer, which mostly consists of the Upper and Lower Goose River groups and sand and gravel outwash. The cross sections were also used as the primary tools for plotting and interpreting the three-dimensional distribution of surficial and buried sand deposits. The stratigraphic boundaries were correlated not only from west to east along the cross section by the conventional method of matching presumed stratigraphic unit tops, but also north to south by overlaying adjacent digitized cross sections with geographic information system (GIS) software to check for correlation discrepancies. The sand thickness information from each stratigraphic unit was then transferred to a map of the same scale, and the sand unit boundaries were drawn using geographical assumptions derived from a general understanding of the unit's depositional history and regional paleogeography. The sand unit boundaries on the cross sections on this plate were adjusted to match the boundaries of the maps on Plates 6 and 7.

The digital characteristics from the set of 39 cross sections were used to help create the aquifer maps shown in this atlas using a variety of GIS methods. As a GIS object, a curved line consists of many straight-line segments that are connected with small angular deviations in combinations sufficient to create the desired curved shape. The connections between these small straight-line segments (vertices) in a GIS cross section can contain information that can be used for three-dimensional mapping. This information (attributes) needed for the three-dimensional mapping process includes the three-dimensional coordinates of the vertex (x, y, and z) and its stratigraphic association. By using a custom extension (GIS tool), the three-dimensional coordinates for each stratigraphic surface were extracted from the set of 39 cross sections and interpolated using a spline-tension method. The resulting surfaces define the top and bottom elevations of the sand units and associated stratigraphic groups. The thickness maps shown on Plates 6 and 7 were derived by subtracting the appropriate surfaces.

HYDROGEOLOGIC FEATURES AND DATA

Relative hydraulic conductivity. The lithologic units (types of sediment) are shown on these cross sections with patterns and shades of gray to reflect broadly defined categories of inferred hydraulic conductivity. As such, the layers and other features of the cross sections are meant to represent hydrogeologic units. The cross-section explanation on this plate for the Quaternary units shows an inferred continuum of hydraulic conductivity, or the water-transmitting capacity of the hydrogeologic unit, from low to high. The till of the Goose River group (shown as the darkest gray) has the lowest average sand content (23 percent to 33 percent [Traverse-Grant Regional Hydrogeologic Assessment, in press]) and probably the lowest hydraulic conductivity. The Otter Tail River group and Browerville Formation (shown as the medium light and dark grays, respectively) are in the middle of the continuum (sand content from 43 percent to 48 percent). The Crow Wing River group till (shown as the lightest gray) is probably the most permeable with sand content ranging from 54 percent to 57 percent.

The sand and gravel aquifers (OT, CW, and BROW) are shown with stipple or line patterns on the cross sections and the reference maps (Figures 3a, 3b, and 3c) to the right. These patterns are provided to help the reader identify the aquifers on both the cross sections and the reference maps. The elevations above sea level for the top surface of the aquifers may help the reader identify an aquifer by depth or elevation at a specific location.

Ground-water residence time. The pink, green, and blue overlays shown on these cross sections represent the relative age of the ground water, also known as ground-water residence time. This is the approximate time that has elapsed since the water infiltrated the land surface to when it was pumped from the aquifer for this investigation. Ground-water residence time is closely related to the aquifer pollution sensitivity concept described on Plate 9. In general, short residence time suggests high pollution sensitivity, whereas long residence time suggests low sensitivity.

Tritium (^3H) is a naturally occurring isotope of hydrogen. Concentrations of this isotope in the atmosphere were greatly increased from 1953 through 1963 by above-ground detonation of hydrogen bombs (Alexander and Alexander, 1989). This isotope decays at a known rate, with a half-life of 12.43 years. Water samples with tritium concentrations of 10 or more tritium units (TU) are considered recent water (mostly recharged in the past 50 years, shown in pink). Concentrations of 1 TU or less are considered vintage water (recharged prior to 1953, shown in blue). Water samples with tritium concentrations greater than 1 TU and less than 10 TU are considered a mixture of recent and vintage and are referred to as mixed (shown in green).

Ground-water age for the vintage samples can be estimated with the carbon-14 (^{14}C) isotope. This isotope, which also occurs naturally, has a much longer half-life than tritium (5,730 years). Carbon-14 is used to estimate ground-water residence within a time span from about 100 years to 40,000 years.

HYDROGEOLOGY ILLUSTRATED BY THE CROSS SECTIONS

All of the aquifers shown on the cross sections that contain or are thought to contain ground-water tritium values greater than 1 TU (recent or mixed water) are marked with a code (1 through 4) indicating the types of recharge. A *1* indicates infiltration through a thin layer of overlying fine-grained material to an underlying aquifer. A *2* shows areas where ground water from an overlying surficial aquifer has recharged the underlying buried aquifer through leakage or a direct connection. Areas labeled with a *3* indicate ground-water leakage from the OT aquifer to the underlying CW aquifer. Areas labeled with a *4* indicate ground-water leakage through multiple aquifers and till. The other codes include *L* where lateral flow of ground water is suspected, *D* where ground-water discharge from buried aquifers probably occurs, *U* where the source of the recent or mixed ground water is unknown, and *S* where arsenic stratification occurs as defined by Figure 4, Plate 7. That figure provides a map summary of arsenic values from ground-water samples classified by aquifer. Where water samples were taken from wells near each other in the CW and BROW aquifers, higher arsenic concentrations typically were found in samples from the CW aquifer than in samples from the underlying BROW aquifers. These codes are also shown for comparison on the small-scale reference maps (Figures 3a–3c) of each buried aquifer at locations where residence time has been confirmed with tritium data. Figure 2 shows the distribution of the surficial aquifers in the county for comparison.

Infiltration through thin, overlying, fine-grained layers (*1*) is typical for the OT aquifer (Figure 3a) with examples shown on the left side of C–C′, F–F′ between Outlet Creek and Steenerson Lake, and all the OT aquifer shown on cross section H–H′. Leakage from surficial aquifers (*2*) appears to be most common in the CW aquifer (Figure 3b). Examples of this type of recharge are shown on all cross sections, with CW aquifer occurrences particularly common on the right portions of cross-sections A–A′ through E–E′. Four confirmed examples are shown on Figure 3b: two of them are beneath the Belgrade-Glenwood sand plain in eastern Pope County, one is at Glacial Lakes State Park, and another is in western Pope County in the Chippewa River valley. Leakage from the OT aquifer to the CW aquifer (*3*) occurs at scattered locations in the western two-thirds of the county (Figure 3b) with confirmed examples shown on the left side of cross-section C–C′ west of the Little Chippewa River and on the right side of H–H′ in the Nilson Lake area. Infiltration through multiple aquifers and intervening fine-grained layers (*4*) is very common in eastern Pope County (Figure 3c) with the recharge from the surficial aquifer through the CW aquifer to the BROW aquifer as the usual occurrence. Examples of this type of recharge are shown on most of the cross sections with a confirmed occurrence shown on the middle portion of cross-section I–I′ in the Coates Lake area and two occurrences on E–E′: west of Starbuck in a sand and gravel aquifer in the older unmapped sand aquifer and on the right side of E–E′ west of the East Branch Chippewa River.

Examples of discharge (*D*) from the OT aquifer are shown near the left edge of cross-sections B–B′ and C–C′ (Chippewa River valley) and the left portion of H–H′ (unnamed creek). Discharge examples from the CW aquifer include the Glenwood area (cross-section C–C′) and the East Branch Chippewa River (center of I–I′). Probable BROW aquifer discharge examples are shown in the Long Beach area (center of cross-section C–C′), the Glenwood area (center of cross-section D-D′), and on the right portion of cross-section I–I' to an unnamed wetland area. Two examples of arsenic stratification (*S*) are shown on the center and right portions of cross section A–A′ at locations in the Reno Lake and Levan Lake areas, respectively.

SUMMARY

The OT aquifer in central and western Pope County is commonly recharged through direct surface leakage although some portions of the aquifer appear to be isolated (protected) from direct recharge. Recharge to the CW aquifer through surficial aquifers in eastern, central, and southwestern Pope County appears to be the most common mode of water infiltration. Ground-water leakage from the overlying OT aquifer to the CW aquifer represents another important recharge mode at scattered locations in the western two-thirds of the county. Ground-water leakage through multiple aquifers and fine-grained units is the dominant recharge mode for the generally deeper BROW aquifer. This type of recharge is especially common in eastern Pope County beneath the Belgrade-Glenwood sand plain.

Probable ground-water discharge locations from the buried aquifers include the Chippewa River in northwestern Pope County, Lake Minnewaska, East Branch Chippewa River, and several unnamed creeks and wetlands.

REFERENCE CITED

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ACKNOWLEDGEMENTS

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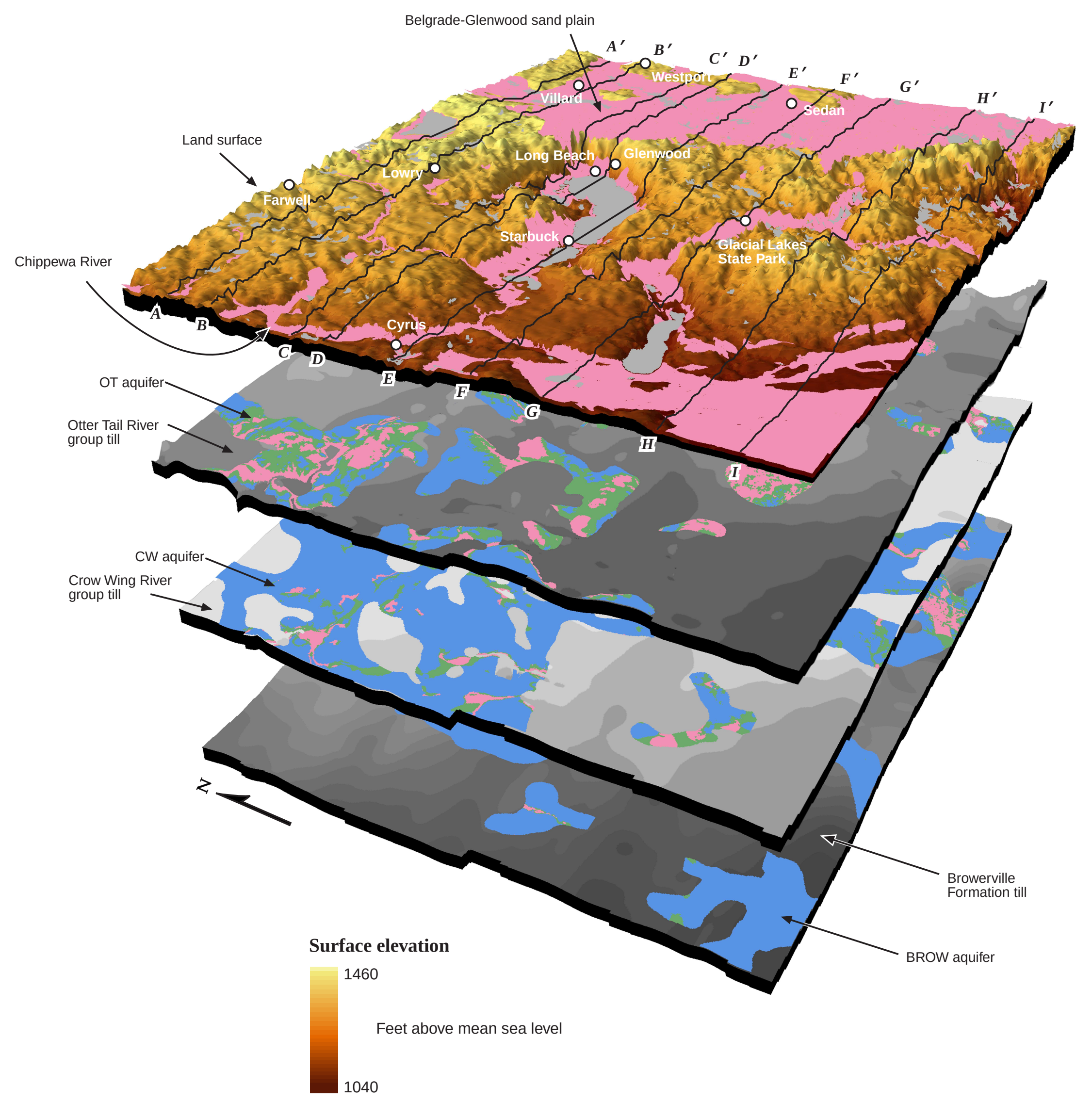
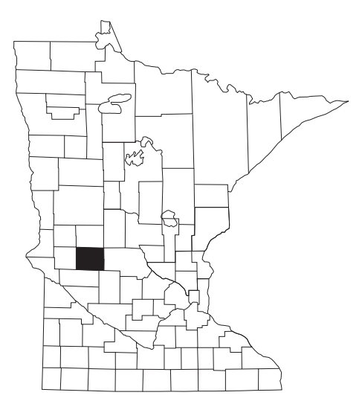


FIGURE 1. ***Exploded, three-dimensional oblique view of the uppermost glacial sediment layers.*** This diagram depicts an oblique three-dimensional view of the county separated into four layers. The land surface layer and surficial aquifers are separated from the underlying three mapped aquifers and the underlying till associated with those aquifers. The lowest layer, BROW aquifer and Browerville Formation till, overlies about 50 feet to about 350 feet of older till. The aquifers are colored with the same color scheme used on the cross sections according to ground-water residence time.

The diagram is meant to illustrate three general concepts. The main purpose is to show the layered or stacked nature of the aquifers. Also by comparing the amount of pink and green in each aquifer (indicating recent and mixed water), a decrease in the amount of recent and mixed water becomes apparent; the decrease suggests less recent recharge to the deeper aquifers and greater protective cover. Finally, the relative elevations of the top of each till surface are shown by the darker shades of gray indicating the lower elevations on each layer. The lowest part of each surface, including the land surface, is in the southwestern portion of the county. The elevations generally increase toward the northeast.



LOCATION DIAGRAM

The DNR Information Center

Twin Cities: (651) 296-6157
Minnesota Toll Free: 1-888-646-6367
Telecommunication Device for the
Hearing Impaired (TDD): (651) 296-5484
TDD Minnesota Toll Free: 1-800-657-3929
DNR Web Site: http://www.dnr.state.mn.us

This information is available in an alternative format on request.

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.

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.

EXPLANATION

Cross sections and figures

Symbols and labels

①	Infiltration through a thin layer of overlying, fine-grained material to an underlying aquifer.
②	Ground-water recharge from overlying surficial sand plain to buried aquifer.
③	Ground-water leakage from the OT aquifer to the underlying CW aquifer.
④	Ground-water leakage through multiple aquifers and fine-grained layers.
Ⓛ	Lateral ground-water flow.
Ⓓ	Ground-water discharge.
Ⓤ	Unknown source of recent or mixed ground water.
Ⓢ	Stratification of arsenic.

Color indicates tritium age. Vertical rectangle indicates well screen or open hole of well.

🟥	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).
▯	Well not sampled for tritium.
0.21 38	If shown, arsenic concentration in parts per billion (top) and chloride to bromide ratio (bottom).
2000	If shown, ground-water age in years, estimated by carbon-14 isotope analysis.
- - - -	Water table surface in surficial aquifer.
- - - -	Unit contact line.
←	General direction of ground-water flow.

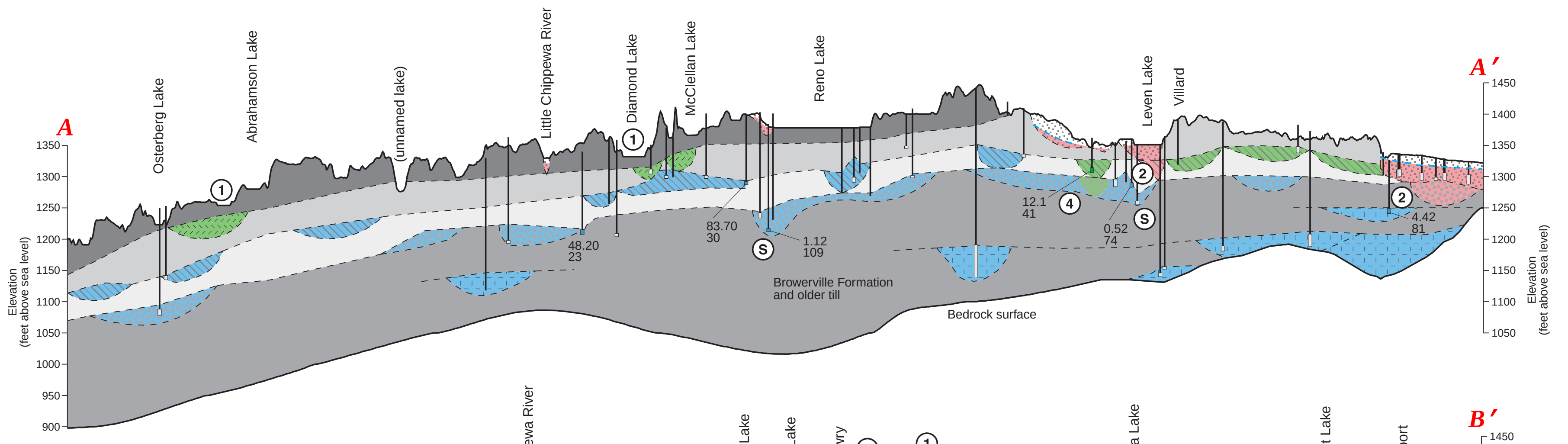
Geologic and hydrogeologic units

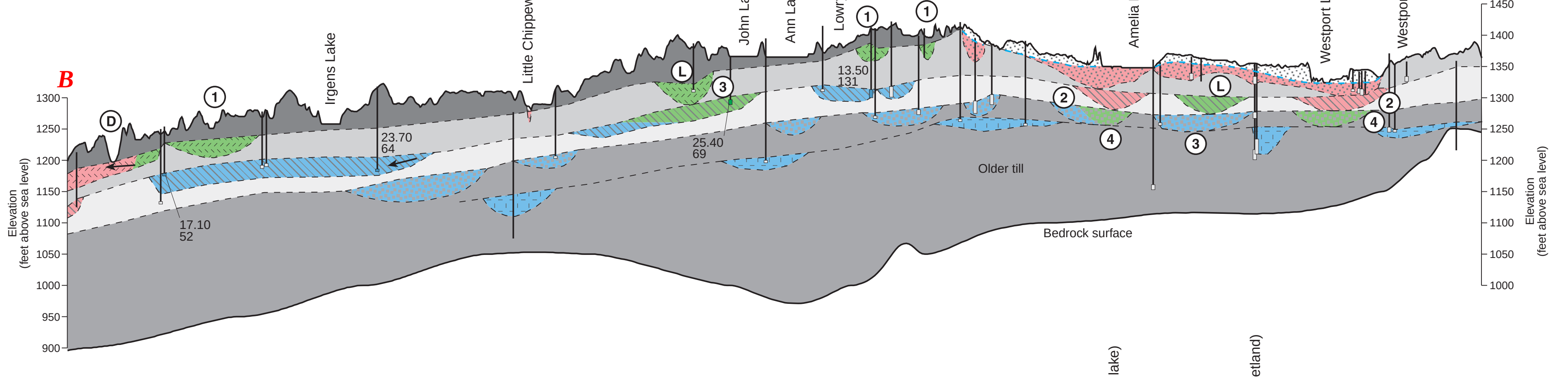
▨	Surficial sand and gravel (water-table aquifer). Uncolored where unsaturated.	■	Upper and Lower Goose River groups. Dashed line is contact between groups.
▨	OT aquifer.	■	Otter Tail River group.
▨	CW aquifer.	□	Crow Wing River group.
▨	BROW aquifer.	■	Browerville Formation and older till (lower part).
▨	Older sand aquifers.		

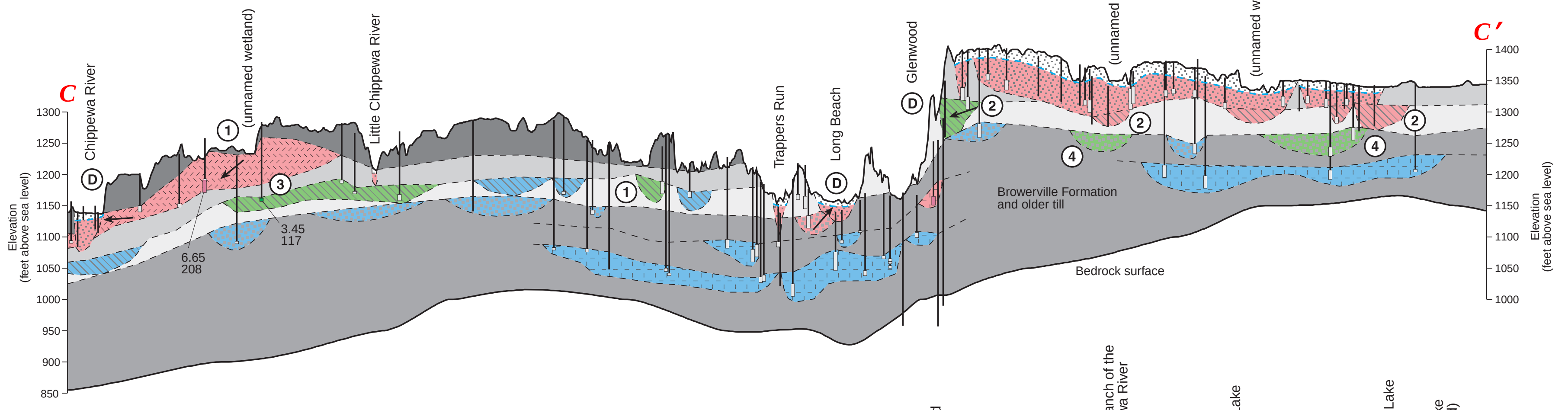
VERTICAL EXAGGERATION X 70

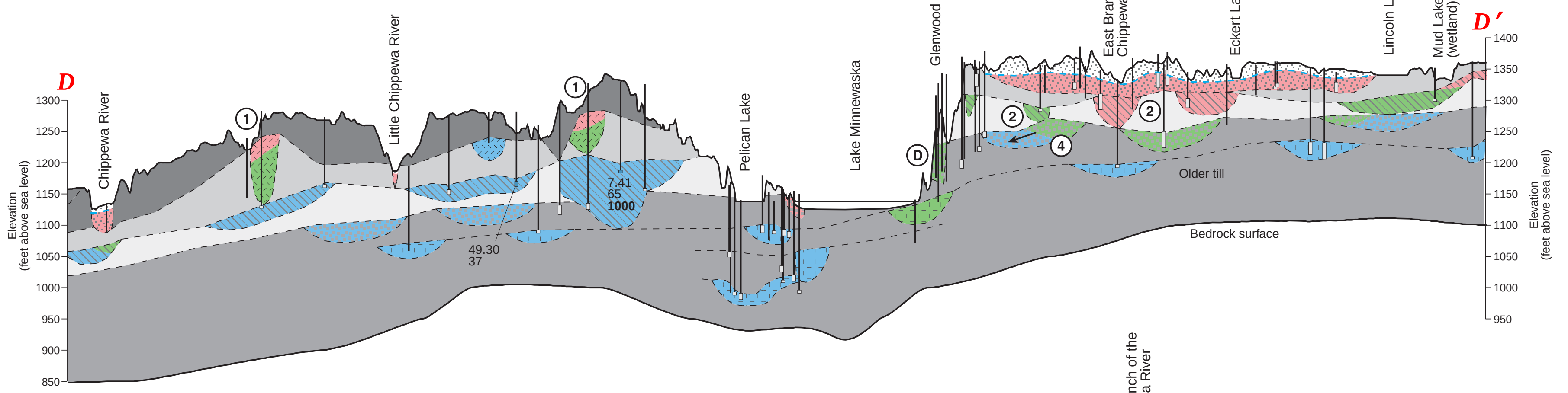
1 0 1 2 3 4 5 MILES

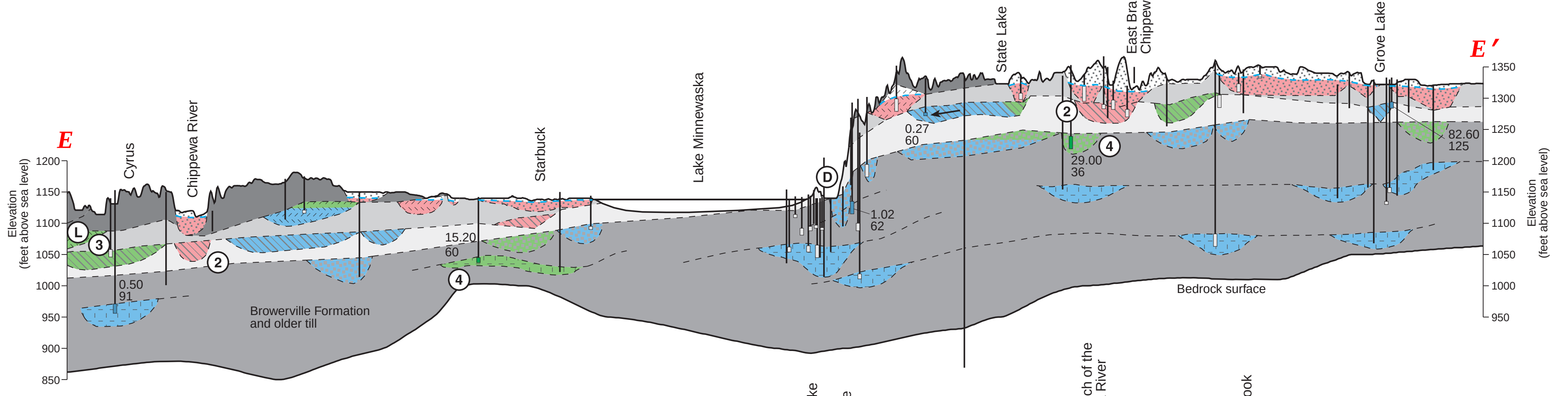
1 0 1 2 3 4 5 6 7 8 KILOMETERS

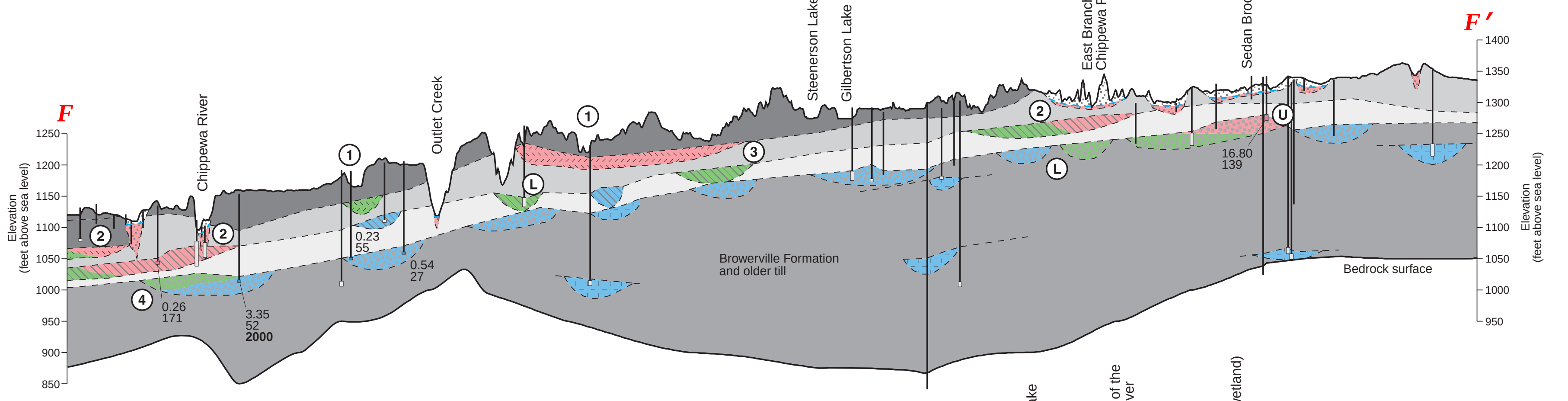


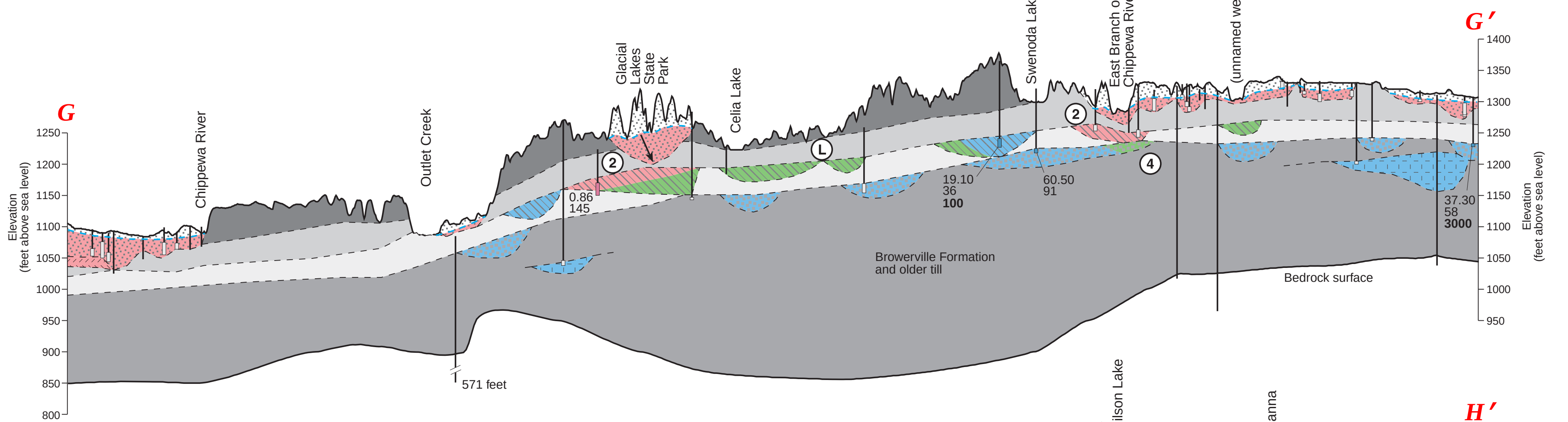


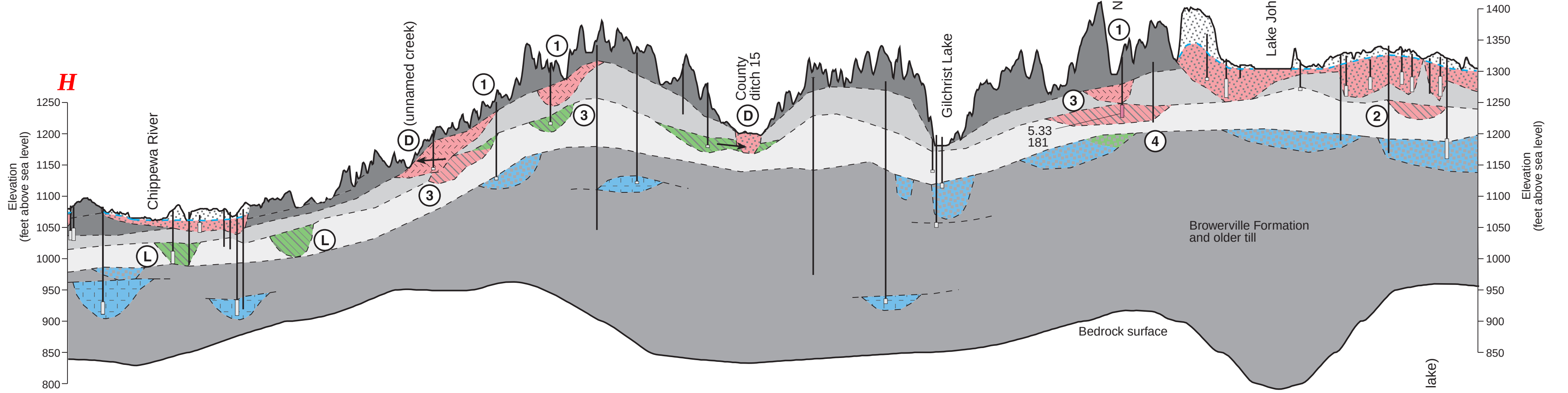


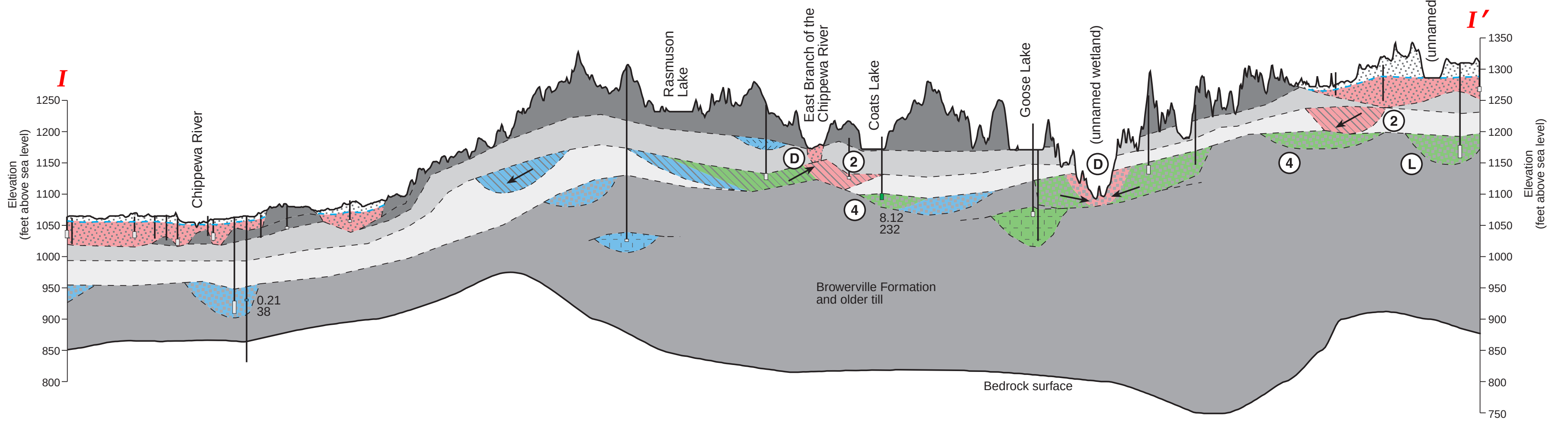












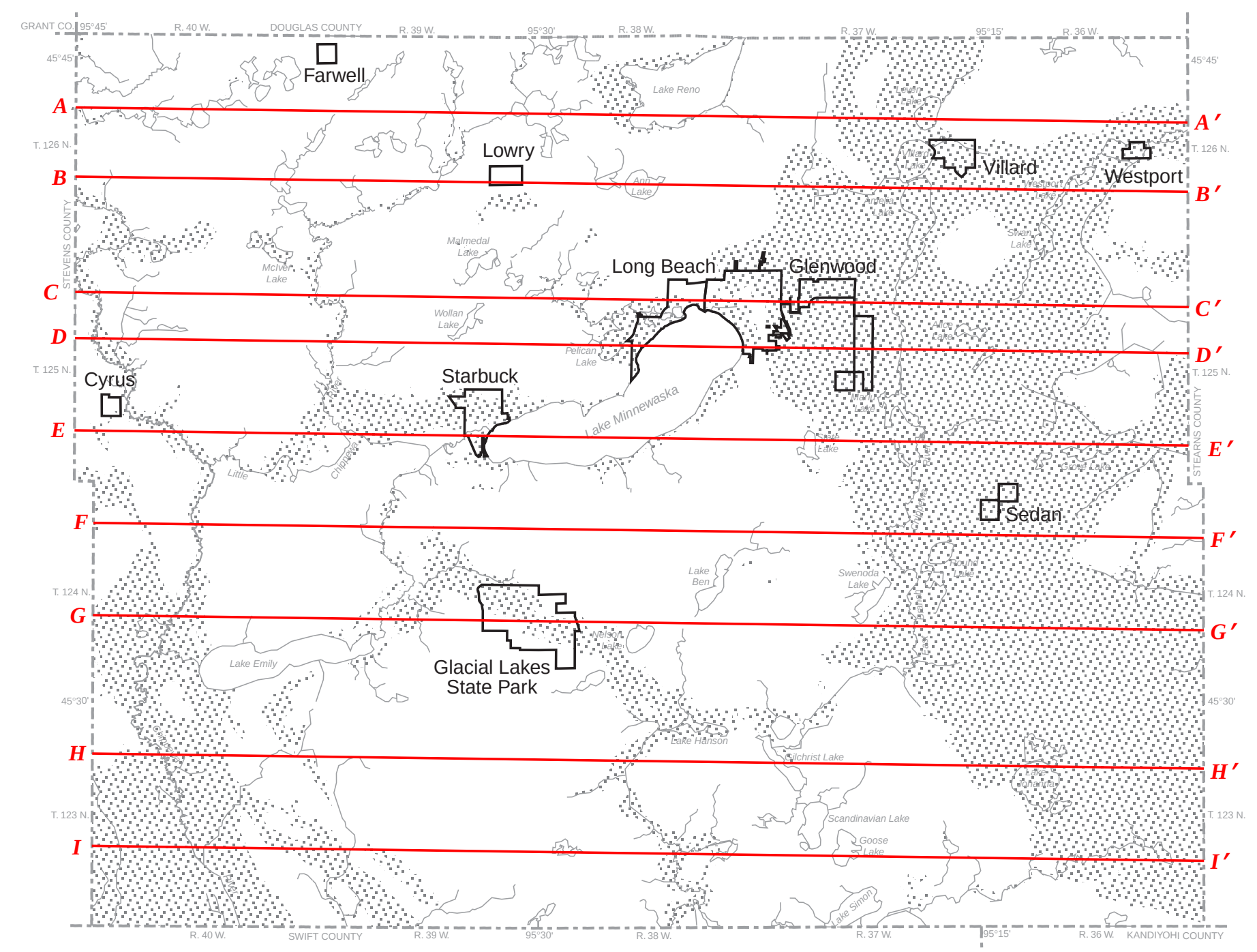


FIGURE 2. *Extent of surficial aquifers. See Plate 6 for more information.*

SCALE 1:300 000

1 0 1 2 3 4 5 MILES

1 0 1 2 3 4 5 6 7 8 KILOMETERS

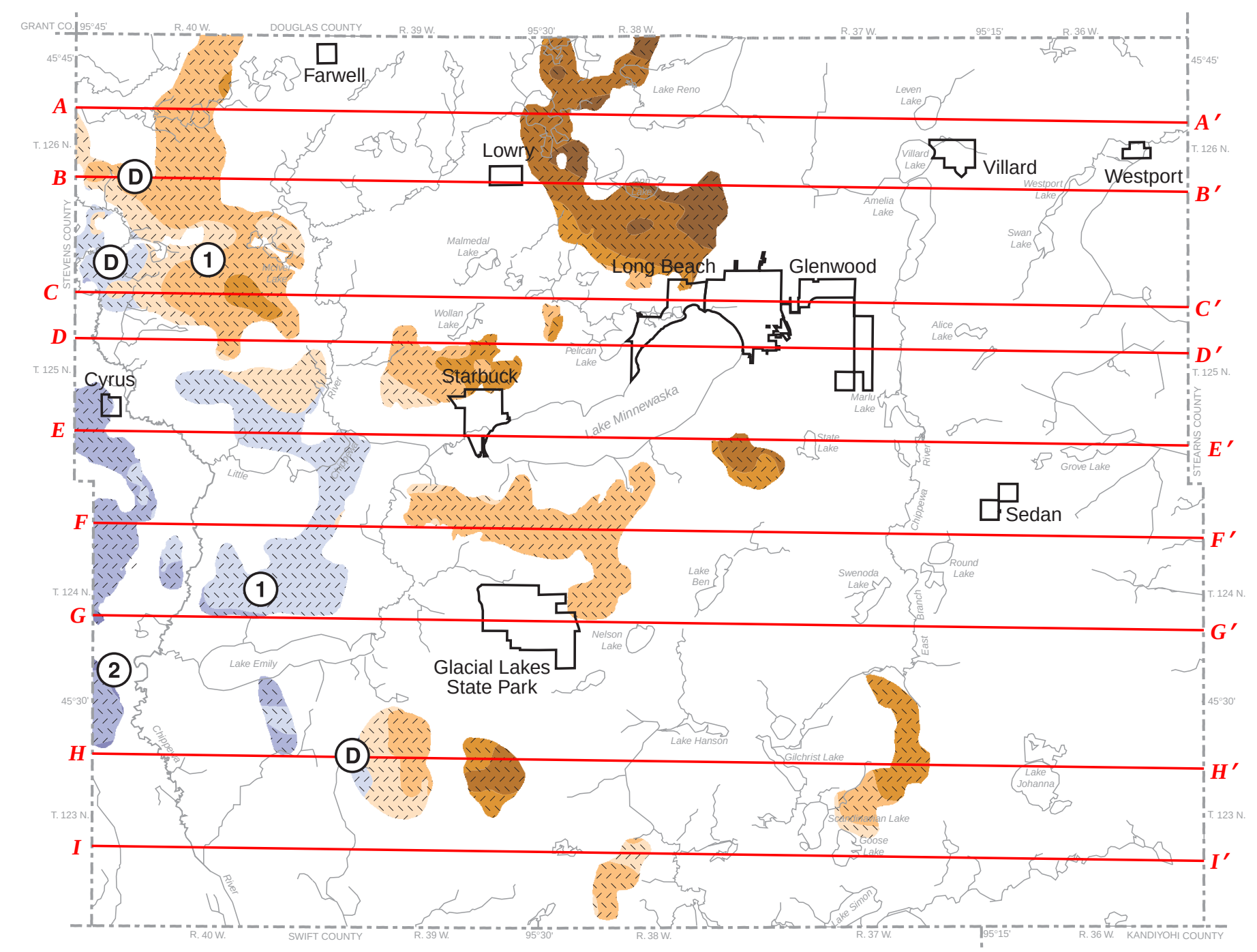


FIGURE 3a. *Aquifer conditions and elevation of the top of the OT aquifer. See also Plate 7, Figure 3a.*

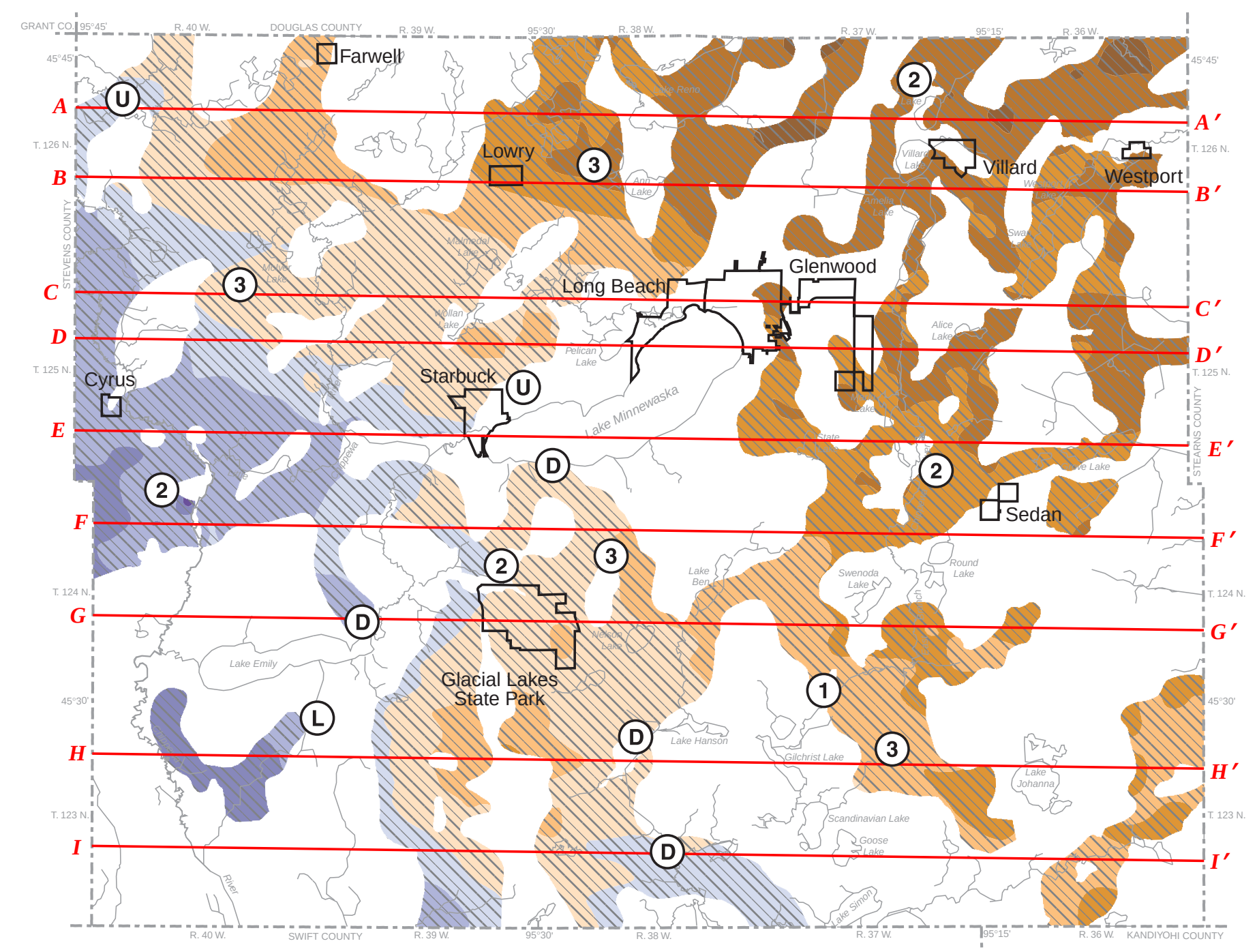


FIGURE 3b. *Aquifer conditions and elevation of the top of the CW aquifer. See also Plate 7, Figure 3b.*

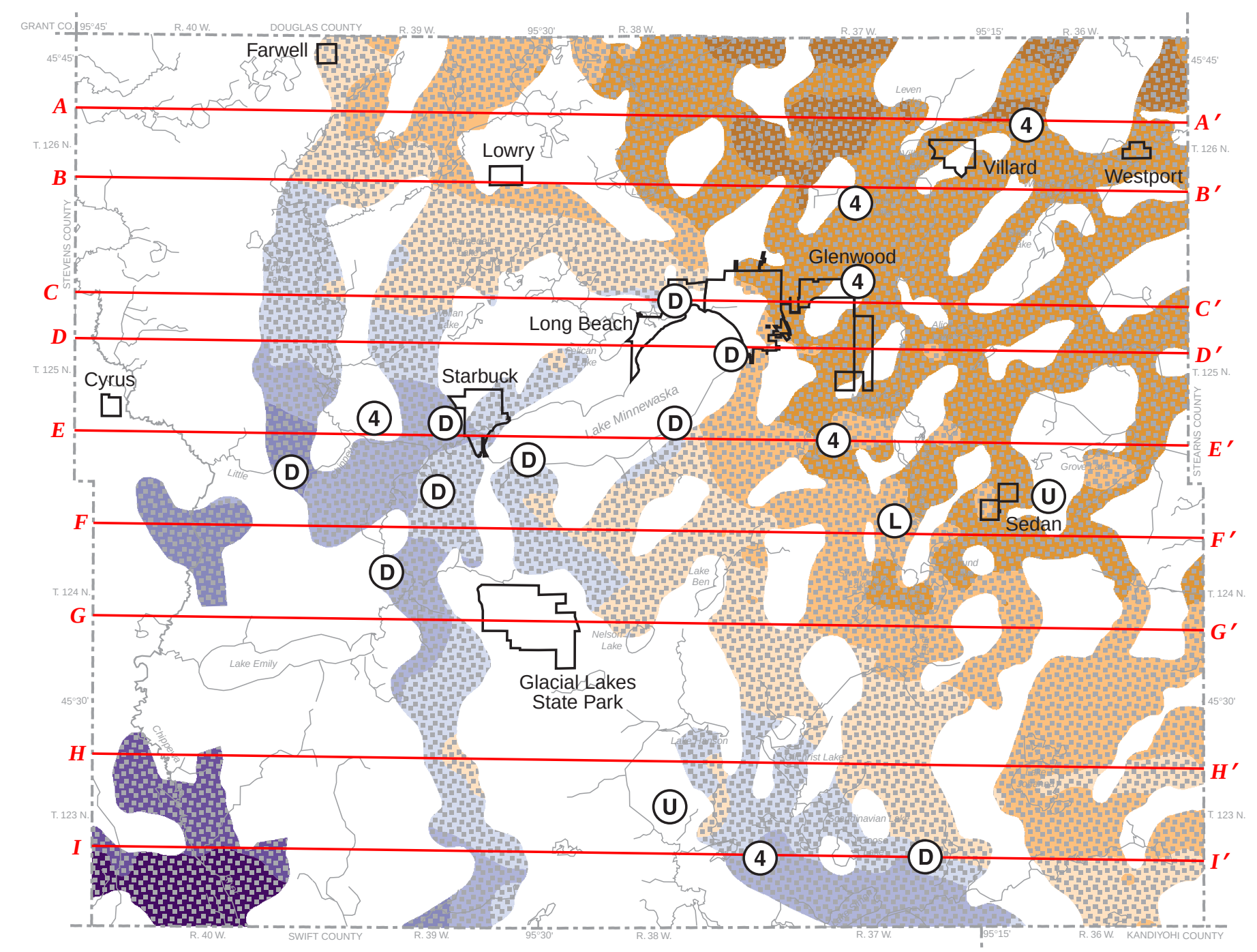


FIGURE 3c. *Aquifer conditions and elevation of the top of the BROW aquifer. See also Plate 7, Figure 3c.*

EXPLANATION

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

■	1350–1400	□	1100–1150
■	1300–1350	■	1050–1100
■	1250–1300	■	1000–1050
■	1200–1250	■	950–1000
□	1150–1200	■	900–950
□	Data insufficient or deposit not present		

GEOLOGIC ATLAS OF POPE COUNTY, MINNESOTA

STATE OF MINNESOTA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATERS

COUNTY ATLAS SERIES
ATLAS C–15, PART B, PLATE 9 OF 9
Sensitivity to Pollution of the Buried Aquifers

SENSITIVITY TO POLLUTION OF THE BURIED AQUIFERS

By

James A. Berg

2006

INTRODUCTION

This plate describes the relative sensitivity of the surficial aquifers and the uppermost, buried sand and gravel aquifers in Pope County to surface or near-surface releases of contaminants. Sensitivity to pollution is defined as the ease with which a surface contaminant moving with water might travel to and enter a subsurface water source. The maps are intended to assist Pope County in protecting and managing its ground-water resources. The surficial aquifers described on Plate 6 include the Belgrade-Glenwood and Chippewa River area aquifers, as well as smaller, scattered aquifers between them. The uppermost, buried sand and gravel aquifers, as shown on Plates 7 and 8, include the generally shallow OT aquifer in the western two-thirds of the county and the CW and BROW aquifers that underlie much of the county. These aquifers are the primary sensitivity targets for the following discussion.

The migration of contaminants in or with water through earth materials is a complex phenomenon that depends on many factors. A countywide evaluation of sensitivity to contaminants requires some simplifying assumptions. For this report, the permeability factor (the ability of earth materials to transmit water) was only evaluated qualitatively. Additionally, this evaluation was based on the assumption of vertical ground-water transport, although horizontal flow may dominate in many settings. Finally, the sensitivity ratings are based on vertical travel time of water (Figure 1), not the behavior of specific contaminants.

The pollution sensitivity of the surficial aquifers is shown in Figure 2. Since these aquifers have little or no laterally extensive protective cover, they were assumed to be highly or very highly sensitive almost everywhere in the county. No geochemical data were collected to verify directly the sensitivity of surficial aquifers. The surficial aquifer distribution and thickness, however, are important considerations in the following pollution sensitivity evaluation of buried sand and gravel aquifers. They are the primary factors controlling recharge water infiltrating to the buried aquifers.

DEVELOPMENT OF BURIED AQUIFER SENSITIVITY MODEL AND MAPS

The goals of the sensitivity modeling and mapping process were to calculate the thickness of protective material overlying each aquifer and interpret protective thickness as different levels of pollution sensitivity. The sensitivity modeling and mapping process has three steps. The first step is mapping and defining the aquifers and fine-grained confining or protective material as three-dimensional geographic information system (GIS) surfaces. The second step is representing aquifer recharge as a series of related elevation surfaces that can be used in the protective layer thickness calculations. The third step is interpreting the protective thickness calculations as pollution sensitivity.

In the first step, the top and bottom elevation surfaces that define aquifers and till layers are created as described on Plates 6, 7, and 8. These surfaces are represented in three dimensions on Figure 1, Plate 8, and in two dimensions on Figure 3 of this plate as the boundaries between the various layers. These elevation surfaces of aquifers and till layers are GIS grid layers (Figure 4) that are used in the GIS grid calculations. The calculations, described below, define recharge surface elevations and the thickness of protective layers overlying the aquifers.

The second step for creating the sensitivity maps is to develop a simplified three-dimensional model that describes how water from precipitation, which first infiltrates the surficial aquifers, can directly recharge portions of the first underlying aquifer and, indirectly, portions of deeper aquifers. The central concept of this process has been previously referred to as focused (relatively rapid) recharge on Plate 7. This is the concept that portions of the aquifers overlap and are connected by complex three-dimensional pathways that allow surface water to penetrate into even the deepest aquifers in some areas. The sensitivity model for the buried aquifers uses this idea by dividing this focused recharge into discreet surfaces at the base of each aquifer, which will be called recharge surfaces. Each buried aquifer receives focused recharge from the base of the overlying aquifer if the confining layer separating those aquifers is thin or absent. For the purposes of this model and the process of determining the elevations of the recharge surfaces, "thin" is considered to be 10 feet. The path of water for a stack of aquifers typical of Pope County is shown in Figure 3. That figure shows a generalized cross section of the principal aquifers mapped in the county and considered in the sensitivity evaluation: the surficial aquifers (details on Plate 6) and the buried OT, CW, and BROW aquifers (details on Plates 7 and 8).

The path of water from precipitation at the land surface to buried aquifers crosses recharge surfaces of the buried aquifers. On Figure 3, the surfaces are labeled *1* (generally shallow), *2* (generally intermediate depth), and *3* (generally deep). In this conceptual model, all the recent recharge water enters the buried aquifer system (pink arrow) at recharge surface 1 (red dotted line). In thick sand and gravel areas, the generally shallow recharge surface 1 is at the base of the sand and gravel. Where little or no sand or gravel exists at the surface, recharge surface 1 is the same as the land surface. If the protective, fine-grained layer (till) between the base of recharge layer 1 and the top of the underlying buried aquifer is 10 feet or less, recent recharge water infiltrates to the next underlying aquifer (pink arrow) and moves downward to recharge surface 2 (black dotted line). Where no OT buried aquifer exists in eastern Pope County, recharge surface 2 is the same as recharge surface 1. If the same criteria are applied at recharge surface 2 (underlying protective layer thickness of 10 feet or less), recent or mixed water (split pink and green arrow) infiltrates to the next underlying aquifer and so on until a limited amount of recent or mixed water reaches recharge surface 3 for the deepest aquifer.

Just as the aquifer and till layer surfaces were created as elevation grid layers, the recharge surfaces were also created in this same GIS file format. Each recharge surface was produced through a series of GIS calculations (described above) starting with the land surface elevation grid and proceeding stepwise downward to the top of the BROW aquifer (Figure 3). With each succeeding step, the deepest portion of the recharge surface becomes progressively smaller, thereby mimicking a general reduction of recharge with depth that occurs in the natural system. The calculated elevation surfaces for all the aquifers, till layers, and recharge surfaces are used in the third step to generate pollution sensitivity maps for each buried aquifer.

In the final step of the sensitivity evaluation, the thickness of the fine-grained or protective sediment (till) that covers each aquifer is calculated and a sensitivity rating is applied. The sensitivity of the aquifer is inversely proportional to the thickness of that protective layer. The protective layer thickness is calculated by subtracting the elevation of the top of the aquifer from the elevation of the adjacent overlying recharge surface. Figure 5 shows the model for interpreting the pollution sensitivity of the buried aquifers according to the calculated protective layer thickness. The resulting pollution sensitivity evaluations for each buried aquifer (OT, CW, and BROW) are shown on figures 8, 9, and 10, respectively.

EVALUATION OF BURIED AQUIFER SENSITIVITY MAPS

The results of a valid pollution sensitivity model should generally correspond to the distribution of ground-water residence time indicators. The most important indicators for the buried aquifers were the values and spatial characteristics of tritium in collected ground-water samples. The carbon-14 residence time values from collected ground-water samples were also useful for portions of the buried aquifers that have a predicted very low sensitivity. The chloride to bromide ratios (Cl/Br) as an anthropogenic indicator of recent industrial age activity were useful evidence of recent water infiltration and an evaluation tool of areas with a moderate to very high pollution sensitivity classification (Figures 6 and 7).

OT aquifer. Figure 8 shows good agreement between the tritium age of samples from the OT aquifer and pollution sensitivity classifications for the OT aquifer. Of the six ground-water samples collected from this aquifer, three had recent values and three had vintage values. All the recent values were from locations that were mapped with moderate to very high pollution sensitivity ratings. The Cl/Br ratios of these samples were all above 175, which suggests that some of the Cl was probably introduced by human activities (Figure 6). The three vintage values were all located in areas with very low pollution sensitivity classifications, and the corresponding Cl/Br values were all below the 175 threshold.

CW aquifer. Figure 9 also shows good agreement between ground-water residence time indicators and pollution sensitivity classifications for the CW aquifer with a few exceptions. Of the 28 ground-water samples collected from this aquifer, 16 samples had vintage tritium values. All of these vintage sample locations were in areas classified as low to very low sensitivity with one exception: a sample in eastern Pope County near Grove Lake (right end of cross-section E–E′, Plate 8). This sample was from an area classified as high sensitivity. Two of the samples analyzed for carbon-14 age were collected from this aquifer: a sample of 1000-year-old ground water collected northeast of Starbuck and a sample of 100-year-old ground water collected west of Lake Swenoda (right side of cross-section G–G′, Plate 8). Both of these samples were collected at locations classified as very low sensitivity.

Seven of the 28 samples from the CW aquifer had mixed values. Six of the seven mixed values were associated with low or very low sensitivity areas, which would not normally be the expected tritium age range. Four of these six mixed values (from areas south of Lake Minnewaska, south of Lake Emily, northeast of Cyrus, and northwest of Villard) are near and possibly downgradient of high-sensitivity areas, which may be the source of mixed water that moved laterally through the CW aquifer to the sample locations. The other two mixed values associated with very low sensitivities may have stratigraphic and hydraulic connections that cannot be determined with the existing data. One of the seven mixed value samples (from west of Sedan along the East Branch of the Chippewa River) is associated with an area rated as very high pollution sensitivity. This valley may be a discharge area for buried aquifers. The mixed tritium value of the ground-water sample may be the result of physical mixing of deep, upward-moving vintage water with near-surface recent water.

Five of the 28 samples from the CW aquifer had recent tritium values. One of the five samples, collected within Glacial Lakes State Park, is associated with a high-sensitivity area, which is consistent with the recent tritium value. The remaining four of this set of five samples were collected from an area west of the Chippewa River, near Starbuck, north of Lake Linka, and west of Lake Johanna. The sample sites are near and possibly downgradient of high-sensitivity areas that may be the source of the recent water through lateral migration. The two samples with recent values collected in southeastern Pope County also had elevated Cl/Br ratios indicating a nearby chloride contaminant source.

BROW aquifer. This aquifer has mostly been classified with low and very low sensitivity ratings with most of the moderate and high ratings at scattered locations in the eastern portion of the county beneath the Belgrade-Glenwood sand plain and the eastern portion of the CW aquifer (Figure 10). Of the 35 samples collected from this aquifer, 25 of the samples were vintage and nine were mixed. These results are consistent with the relatively protected geologic setting of this aquifer. All samples of vintage age were from areas classified as very low sensitivity. Most of the samples collected for carbon-14 analysis were from this aquifer. Six of the seven samples had ages in the 1000- to 3000-year-old range with one 100-year-old sample in the eastern Belgrade-Glenwood sand plain area. All these samples of 100- to 3000-year-old ground water were collected in areas of very low sensitivity.

All nine of the samples with mixed tritium values from the BROW aquifer are located in areas of low to very low sensitivity. Five of this set of nine samples (all located in eastern or northeastern Pope County) are near moderate to high sensitivity areas that may have been the source of mixed water moving laterally to the sampling locations. Four mixed value samples (three located in the southeastern portion of the county and one located near the center of the county east of Lake Jennum) have no apparent source of mixed water. The origin of these tritium values cannot be determined using the existing data. The one recent value (located southeast of Sedan) is consistent with the moderate pollution sensitivity classification at that location.

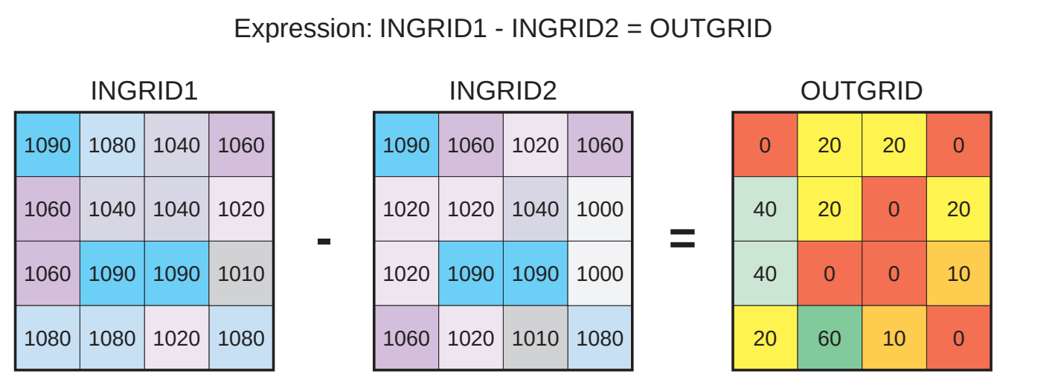
Older, unmapped aquifers. Ten samples were collected from older aquifers that were not mapped (Figure 10). Eight of the samples had either vintage or mixed values (five vintage, three mixed), which are also generally consistent with older and deeper aquifers. One mixed-age sample (from an area west of Starbuck, left side of cross-section E–E′, Plate 8) is from a portion of one of these older aquifers that may have an indirect recharge pathway through multiple aquifers. One recent-age sample, which also has an elevated Cl/Br ratio, was collected from a municipal well in Glenwood (cross-section C–C′, Plate 8). The recent tritium age of the sample and elevated Cl/Br ratio are difficult to understand using available information. Since this well is relatively old (drilled in 1978), the recent water may be due to surface leakage through a corroded casing.

Summary. The most sensitive portions of the buried aquifers in Pope County underlie the central and western parts of the county for the OT aquifer and the eastern part of the county for the CW and BROW aquifers. The OT aquifer in central and western Pope County is sensitive to pollution mostly because it is generally shallow. The sensitive Belgrade-Glenwood surficial aquifer intersects or is generally close to the top of the CW aquifer in eastern Pope County. That proximity creates pathways for relatively rapid infiltration to buried aquifers. The BROW aquifer is sensitive at scattered locations but is relatively protected from rapid recharge.

A comparison of ground-water residence time indicators and pollution sensitivity ratings shows a general consistency with some exceptions. The exceptions mainly consist of mixed or recent tritium age samples collected from areas that were rated as low or very low sensitivity. Most of these occurrences may be attributed to lateral ground-water movement from areas where geologic conditions allow infiltration of recent water.

REFERENCE CITED

Geologic Sensitivity Workgroup, 1991, Criteria and guidelines for assessing geologic sensitivity of ground water resources in Minnesota: St. Paul, Minnesota, Department of Natural Resources, Division of Waters, 122 p.


Expression: INGRID1 - INGRID2 = OUTGRID

INGRID1

1090	1080	1040	1060
1060	1040	1040	1020
1060	1090	1090	1010
1080	1080	1020	1080

-

INGRID2

1090	1060	1020	1060
1020	1020	1040	1000
1020	1090	1090	1000
1060	1020	1010	1080

=

OUTGRID

0	20	20	0
40	20	0	20
40	0	0	10
20	60	10	0

FIGURE 4. ***GIS grid calculations used to create pollution sensitivity maps.*** The recharge surfaces and the till layer surfaces used to calculate protective layer thickness were created as geographic information system (GIS) grid layers. A grid layer is a type of GIS file consisting of regularly spaced squares or cells. The cell size scale can vary depending on the type of resolution that is appropriate for a given application. Each cell has a numerical value. The grids can be simply added or subtracted to obtain layers of new information. In this example, a hypothetical "INGRID2" is subtracted from "INGRID1" to yield the "OUTGRID" array of values. Grid calculations used for this sensitivity evaluation included subtracting the thickness values of the surficial sand and gravel deposits from the grid values of land surface elevations. The result created an elevation grid of recharge surface 1 shown in Figure 3.

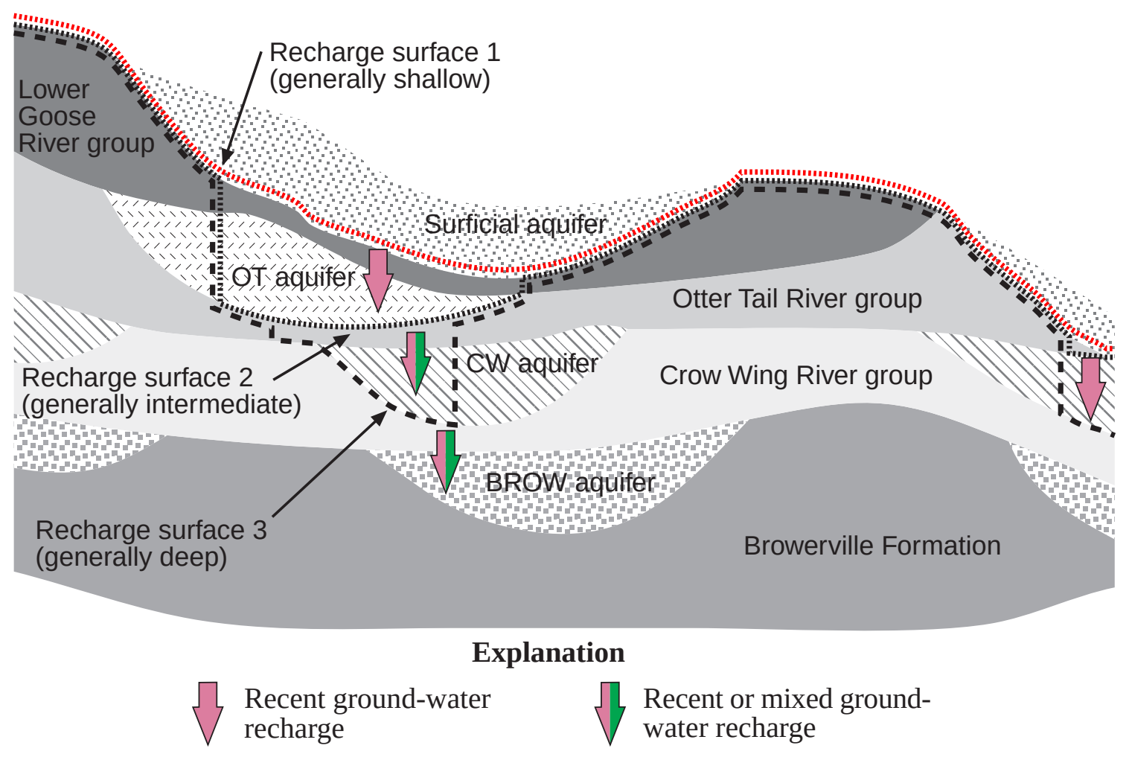
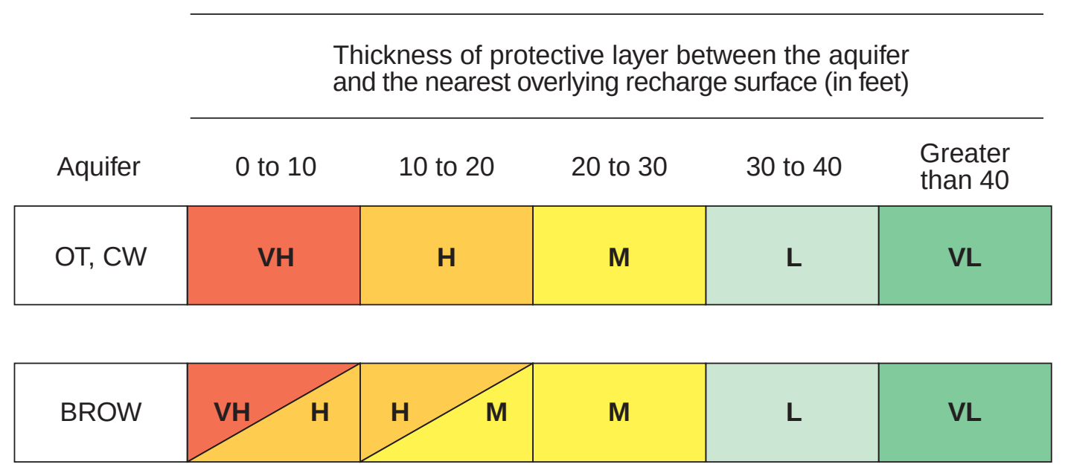


FIGURE 3. ***Generalized cross section showing recharge concepts for the three buried aquifers considered in the sensitivity evaluation.*** The source of recent water from precipitation is divided into three recharge surfaces. In this conceptual model, all the recent recharge water enters the buried aquifer system (pink arrows) at the generally shallow recharge surface 1 (red dotted line). If the protective, fine-grained layer (till) between the base of recharge surface 1 and the top of the underlying buried aquifer is 10 feet or less, recent water recharges the underlying aquifer (pink arrow) then moves downward to recharge surface 2 (black dotted line). Where no OT aquifer exists in eastern Pope County, recharge surface 2 is the same as recharge surface 1. If the same protective layer conditions exist at the next deeper recharge surface (underlying protective layer thickness 10 feet or less), recent or mixed water recharges the BROW aquifer. The thickness of the protective layer between the top of the aquifers and the nearest overlying recharge surface was used to estimate pollution sensitivity.



Aquifer	Thickness of protective layer between the aquifer and the nearest overlying recharge surface (in feet) 0 to 10	10 to 20	20 to 30	30 to 40	Greater than 40
OT, CW	VH	H	M	L	VL
BROW	VH / H	H / M	M	L	VL

FIGURE 5. ***Pollution sensitivity model.*** Pollution sensitivity is inversely proportional to the thickness of the protective layer between the top of the aquifer and the adjacent overlying recharge surface as defined in Figure 3. The OT and CW aquifers mostly receive recharge either directly from the land surface or through a surficial aquifer (recharge surfaces 1 and 2). Because most of the BROW aquifer is indirectly recharged through overlying aquifers (recharge surface 3), the BROW aquifer was assigned lower sensitivity for the thickness ranges of 0 to 10 feet and 10 feet to 20 feet (high and moderate sensitivity, respectively). One portion of the BROW aquifer in southeastern Pope County apparently is recharged directly through a thin layer of cover material. Therefore, very high and high sensitivity ratings are shown in that area for the thickness ranges of 0 to 10 feet and 10 feet to 20 feet, respectively.

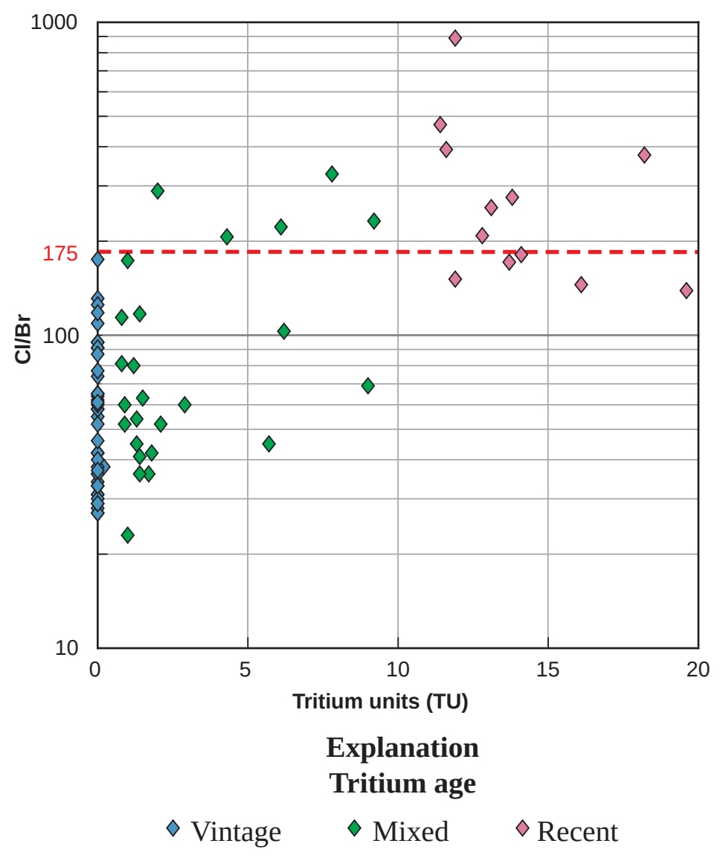


FIGURE 6. ***Chloride to bromide ratio versus tritium in ground-water samples.*** This graph compares the ratio of chloride to bromide (Cl/Br) concentrations to tritium concentrations from 80 wells. The samples came from the three mapped buried aquifers and older unmapped aquifers. Mineral sources of chloride (Cl), such as salt used in water softeners, on roads, or in mineral fertilizers, are depleted in bromide (Br) relative to chloride and have high Cl/Br ratios. None of the samples with Cl/Br ratios above 175 have vintage tritium age values. This suggests that ratios of Cl/Br above approximately 175 appear to be partly attributable to human activities.

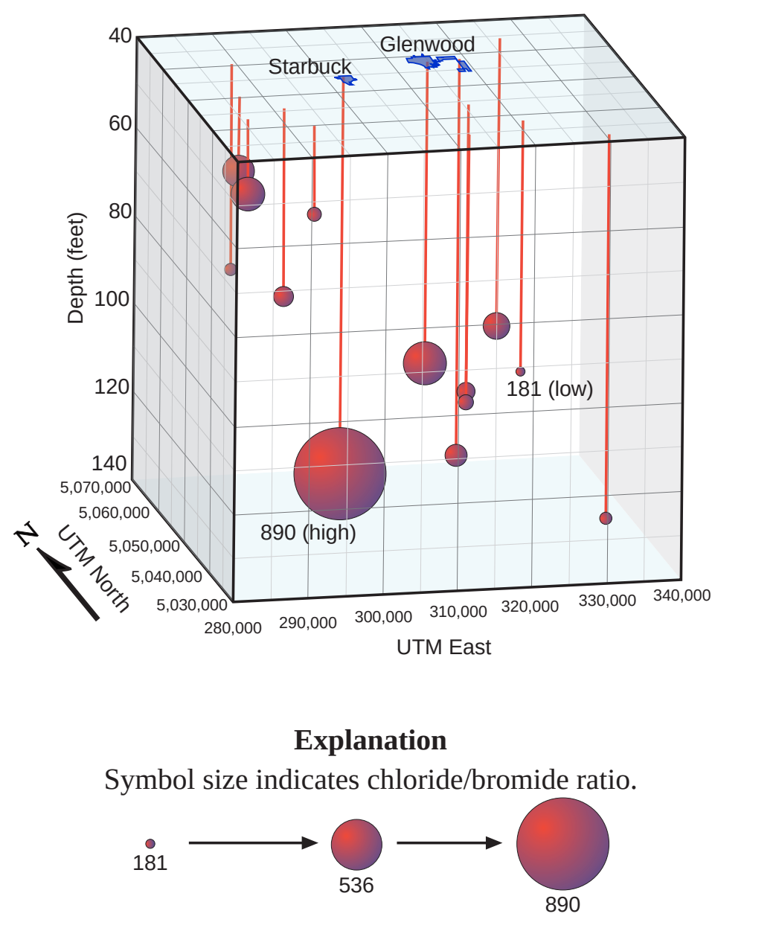


FIGURE 7. ***Three-dimensional bubble plot of elevated chloride to bromide ratios.*** This graph shows only the results of samples from buried aquifers with chloride to bromide (Cl/Br) ratios that exceeded the threshold of approximately 175 indicating the presence of some human-produced chloride (anthropogenic chloride). The area represented by the graph is most of the county. The size of the spheres or "bubbles" is proportional to the Cl/Br ratio. The bubbles are plotted in three-dimensional space with the vertical axis representing depth from land surface. The other axes were used to plot the map location of the well using Universal Transverse Mercator (UTM) coordinates (zone 15). The plot shows a general tendency for the anthropogenic chloride to occur at shallow depths in western Pope County and greater depths in eastern Pope County. The extensive Belgrade-Glenwood surficial aquifer and common recharge pathways to the underlying aquifers in the east allow deeper penetration of anthropogenic constituents.

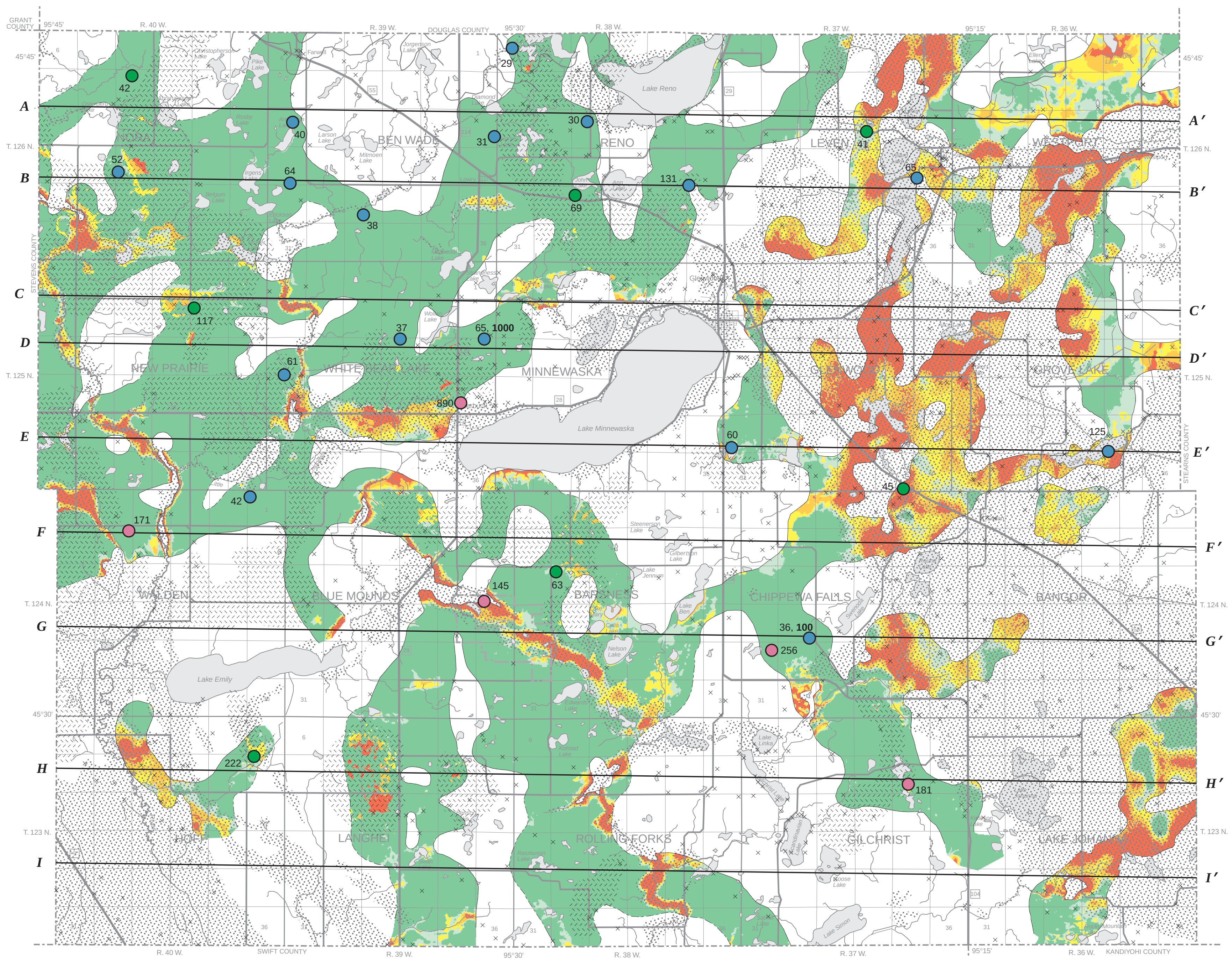


FIGURE 9. ***CW aquifer pollution sensitivity.*** The CW aquifer is relatively sensitive in eastern Pope County where it is typically the first buried aquifer beneath the sensitive Belgrade-Glenwood surficial aquifers. Elsewhere in the county, the aquifer is rated as mostly very low sensitivity. A generally good agreement exists between ground-water residence time indicators and pollution sensitivity classifications for the CW aquifer. Most of the vintage sample locations were in areas that were classified as low to very low sensitivity. Two of the samples analyzed for carbon-14 age were collected from this aquifer: a 1000-year-old sample collected northeast of Starbuck (middle of cross-section D–D′, Plate 8) and a 100-year-old sample collected west of Lake Swenoda (right side of cross-section G–G′, Plate 8). Both of these samples were collected at locations classified as very low sensitivity. Most of the samples with mixed and recent tritium values that were associated with lower than expected sensitivity ratings are near and possibly downgradient of high-sensitivity areas, which may be the source of mixed water that moved laterally through the CW aquifer to the sample locations. The distribution of the overlying surficial sand aquifers and OT aquifer is shown for comparison.

MAP EXPLANATION
Figures 8, 9, 10

Sensitivity ratings

Estimated vertical travel time for water-borne surface contaminants to enter the aquifers (sensitivity targets).

VH	**Very High**—Hours to months.
H	**High**—Weeks to years.
M	**Moderate**—Years to decades
L	**Low**—Decades to a century. or more.
VL	**Very Low**—A century or more.

Well symbols and labels

▲	Sample from surficial aquifer.
●	Sample from buried aquifer.
■	Sample from older, unmapped aquifer.
×	Well or boring log.
87	Chloride to bromide ratio.
1000	If shown, ground-water age in years, estimated by carbon-14 isotope analysis.

Tritium age

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

Patterns shown as overlying stratigraphically older units.

▨	Surficial aquifer.
▨	OT aquifer.
▨	CW aquifer.
F—*F′*	Line of cross section.
- - - -	Eastern limit of the Lower Goose group.
——	Buried aquifer boundary.
— · — · —	Buried aquifer boundary—uncertain.

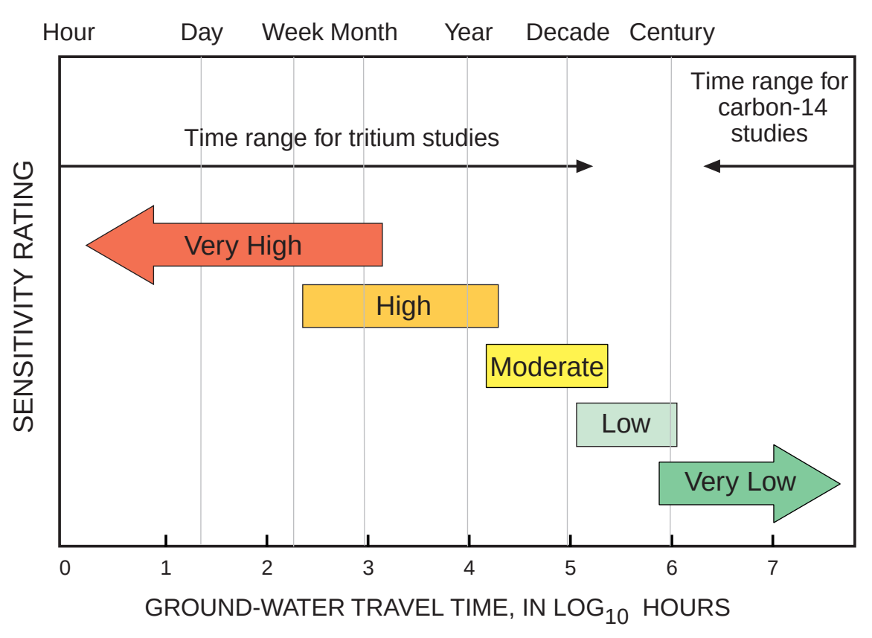


FIGURE 1. ***Geologic sensitivity rating as defined by vertical travel time (Geologic Sensitivity Workgroup, 1991).*** Ratings are based on the time range required for water at or near the surface to travel vertically into ground water of interest or a pollution sensitivity target. For Pope County, the pollution sensitivity targets are the surficial aquifers (Figure 2) and the uppermost buried sand and gravel aquifers (Figures 8, 9, and 10). Tritium and carbon-14 studies indicate the relative ages of ground water.

SCALE 1:150 000
1 0 1 2 3 4 5 MILES
1 0 1 2 3 4 5 6 7 8 KILOMETERS

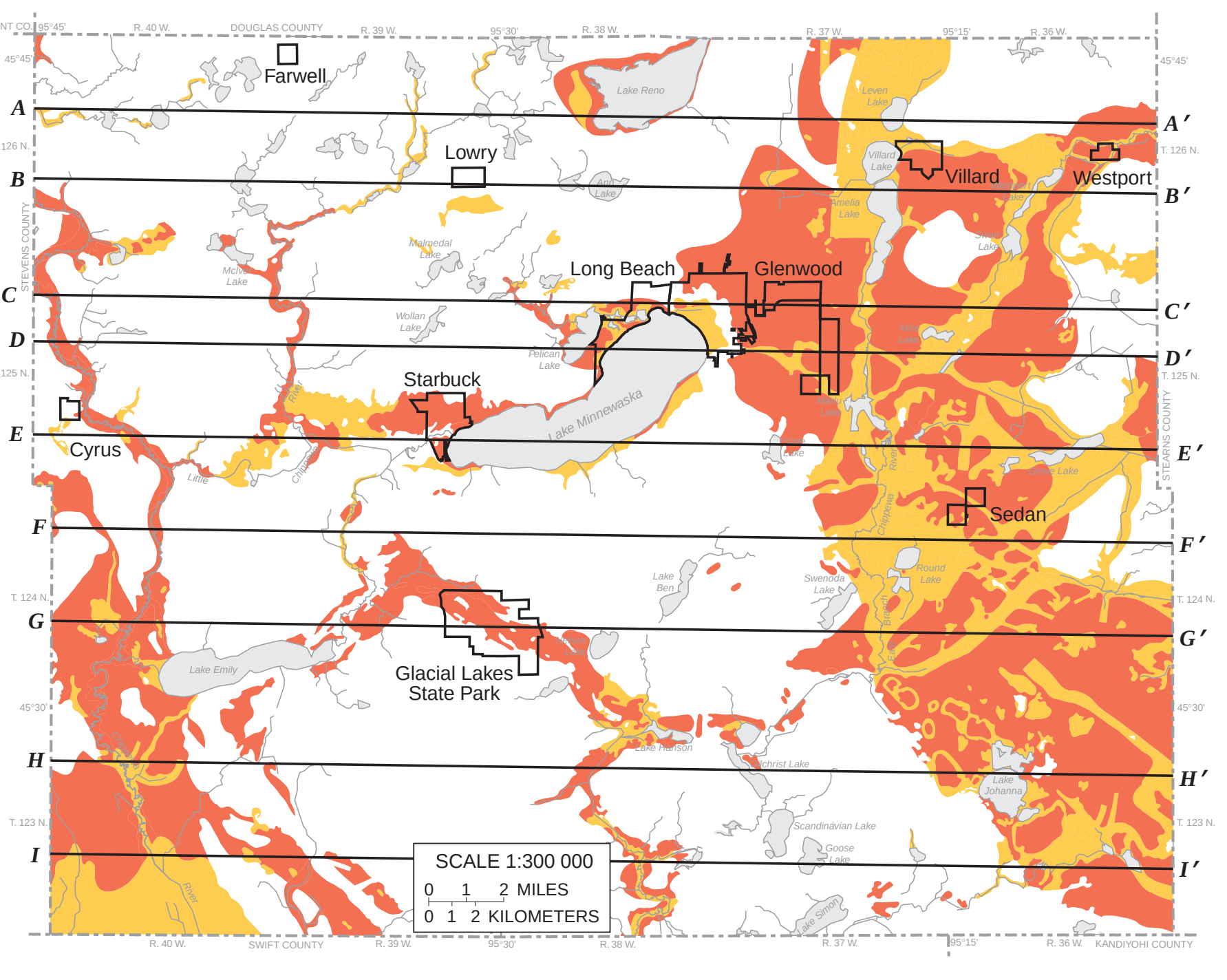
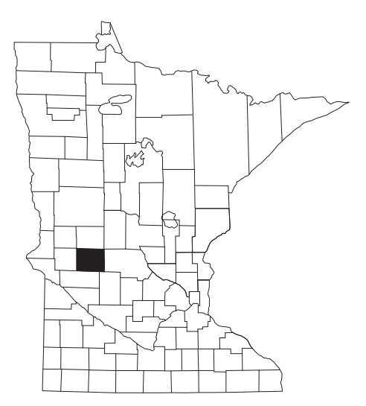


FIGURE 2. ***Pollution sensitivity of surficial aquifers.*** The surficial aquifers described on Plate 6 are relatively sensitive to pollution. The sensitivity rating (Figure 1) of these aquifers is based mainly on the relative content of fine- and coarse-grained sediments in the aquifers. The sediment descriptions of the updated map units in the Traverse-Grant Regional Hydrogeologic Assessment, Part A (in press), were evaluated according to the described sediment texture. The coarsest sediments that consist mainly of sand and gravel were rated as very high sensitivity. These map unit codes include bd, bsl, hc, hsl, lgo, lgc, ogs, ogo, ogc, and qc. The map units containing sand, silt, and clay were rated as high and include bns, ha, ho, hns, lgd, olw, and ugd. In selected areas, map units that generally consist of a thin cover (less than a few feet) of fine-grained material such as clay, silt, and organic material or till but are underlain by sand or sand and gravel were also included in the high sensitivity category. These map units include hp, hs, lgp, and op. Finally, based on well logs and other mapping considerations, small areas of some other units were included in the high sensitivity category.



LOCATION DIAGRAM

Caution: The information on these maps is a generalized interpretation of the sensitivity of ground water to contamination. The maps are intended to be used for resource protection planning and to help focus the gathering of information for site-specific investigations.

The DNR Information Center

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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.

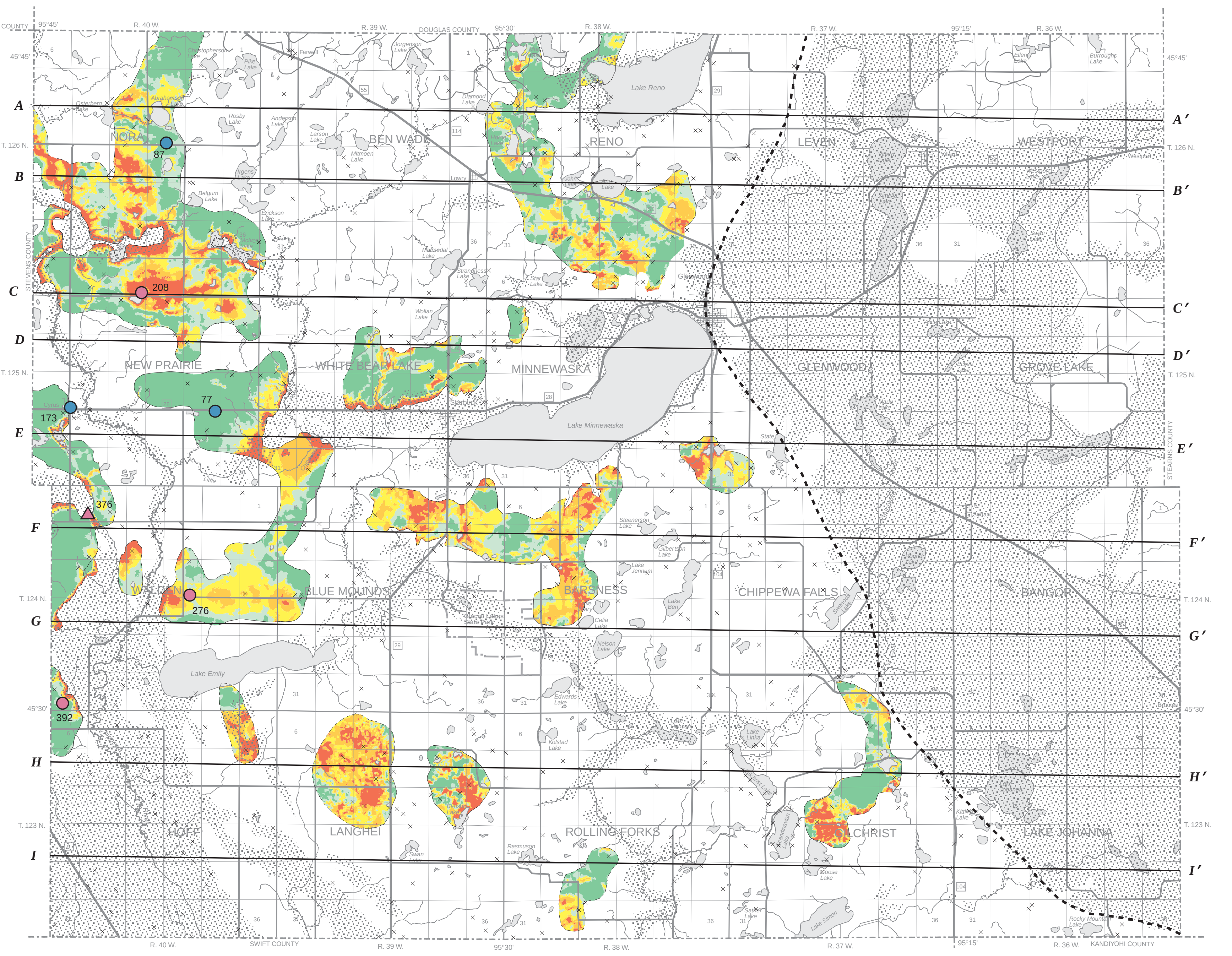

FIGURE 8. ***OT aquifer pollution sensitivity.*** In central and western Pope County, the generally shallow OT buried aquifer has scattered sensitive areas interspersed with lower sensitivity areas. This figure shows good agreement between the tritium values and pollution sensitivity classifications for the OT aquifer. All the recent values were from locations that were mapped with moderate to very high sensitivities. The chloride to bromide (Cl/Br) ratios of these samples were all above the 175 value that was estimated as the threshold indicating some of the Cl was probably introduced by human activities (Figure 6). The three vintage values were all located in areas with very low pollution sensitivity classifications, and the corresponding Cl/Br values were all below the 175 threshold. The distribution of the overlying surficial sand aquifers is shown for comparison.

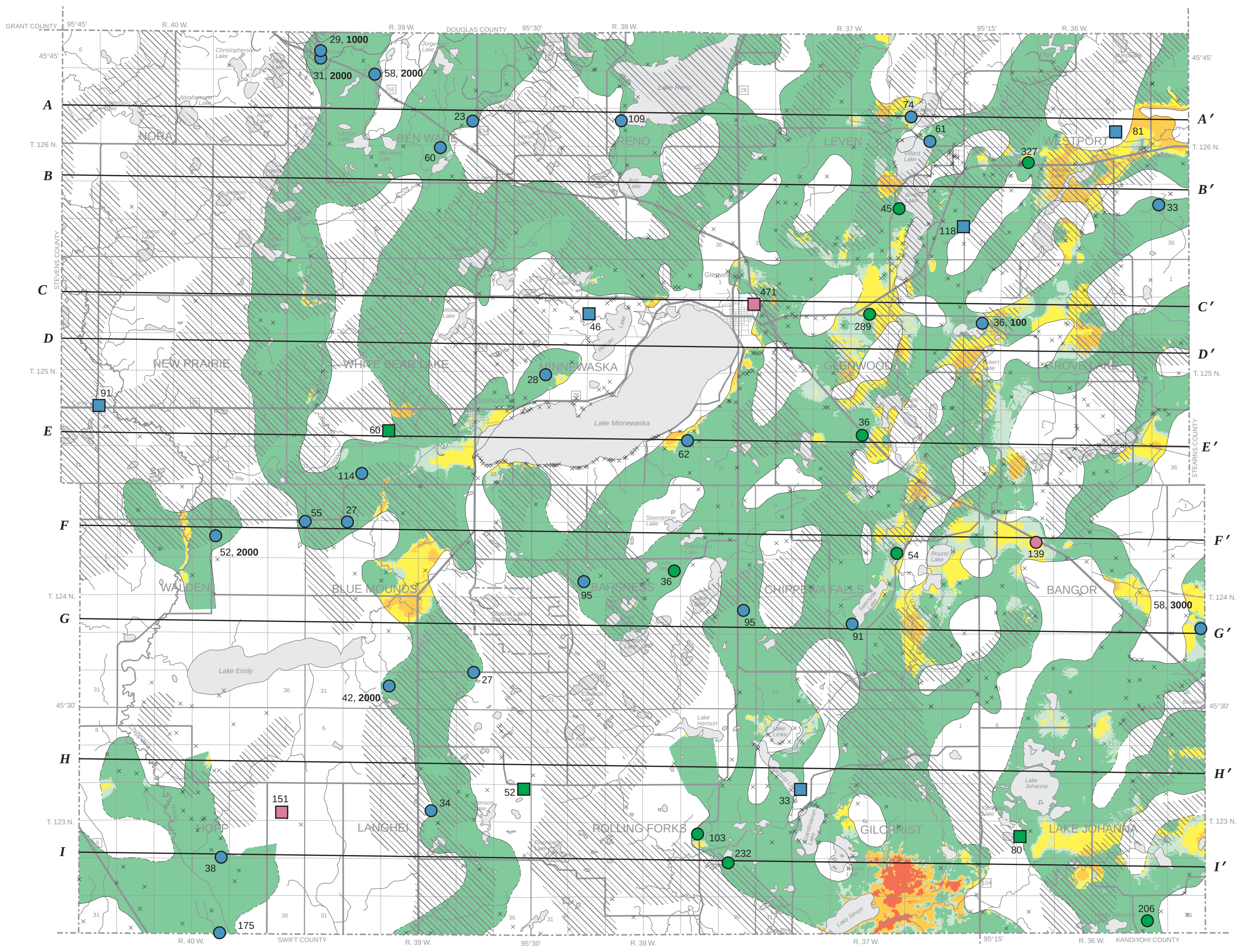

FIGURE 10. ***BROW aquifer pollution sensitivity.*** This aquifer has mostly been classified with low and very low sensitivity ratings with most of the moderate and high ratings at scattered locations in the eastern portion of the county beneath the Belgrade-Glenwood sand plain. Of the 35 samples collected from this aquifer, 25 of the samples were vintage and nine were mixed, which is consistent with the relatively protected geologic setting of this aquifer. All of the vintage samples were located in areas that are classified as very low sensitivity. All of the samples analyzed for carbon-14 age dating had ages ranging from 100 years to 3000 years, and all were collected in areas of very low sensitivity. Most of the mixed values that were associated with lower than expected sensitivity ratings are near and possibly downgradient of high-sensitivity areas, which may be the source of mixed water that moved laterally through the BROW aquifer to the sample locations. Ten samples were collected from older aquifers that were not mapped. Most of the samples had either vintage or mixed values, which are also generally consistent with older and deeper aquifers. The distribution of the overlying CW aquifer is shown for comparison.

GEOLOGIC ATLAS OF POPE COUNTY, MINNESOTA