STATE OF MINNESOTA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATERS

SENSITIVITY TO POLLUTION OF THE BURIED AQUIFERS

By

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2008

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.

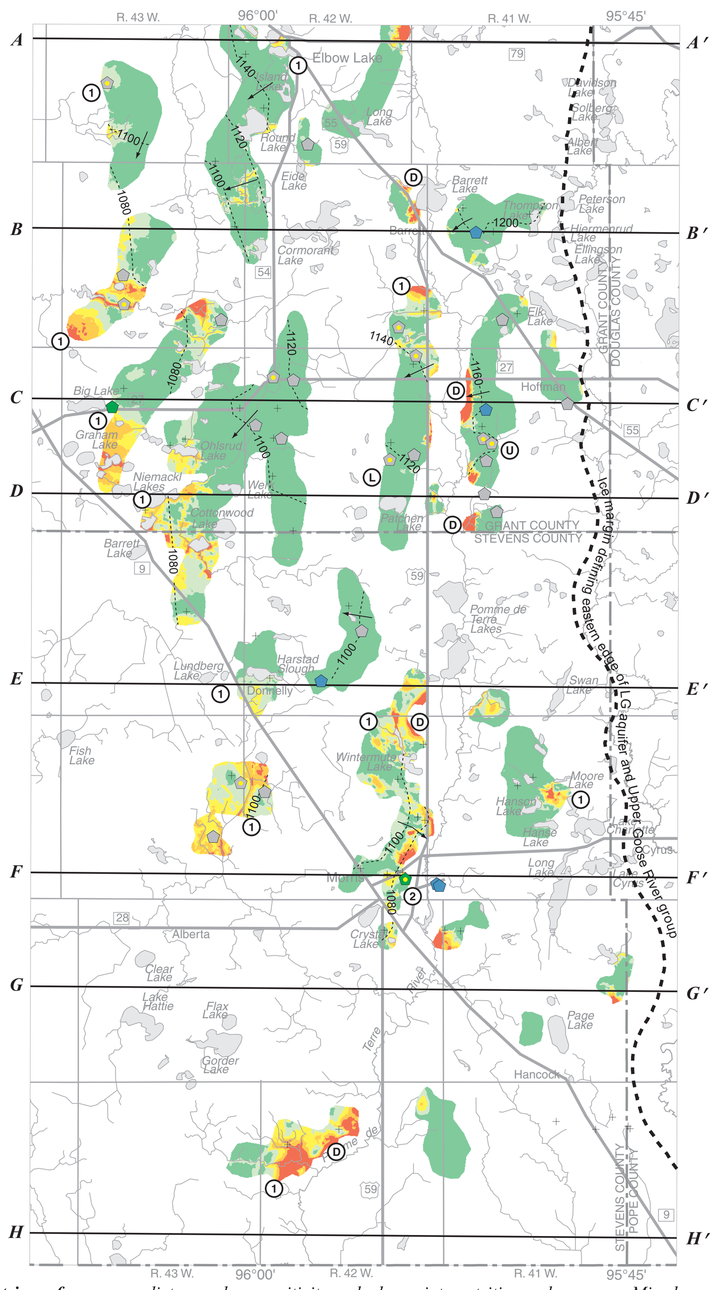
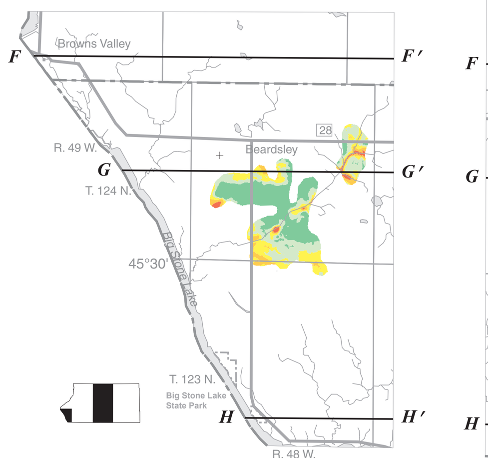

FIGURE 4. ***LG aquifer—pollution sensitivity and potentiometric surface.*** *The limited-extent LG aquifer in the central and southwestern portion of the study area mostly has very low pollution sensitivity, except where a thin layer of fine-grained material covers the aquifer. This figure shows good agreement between the portions of this aquifer where the sensitivity model predicts very low sensitivity and where vintage tritium values occur. Mixed tritium values and most elevated Cl/Br values occur in areas modeled as low to moderate sensitivity. Except for a few locations near the Pomme de Terre River, the directions of regional ground-water flow are generally to the west and southwest.*

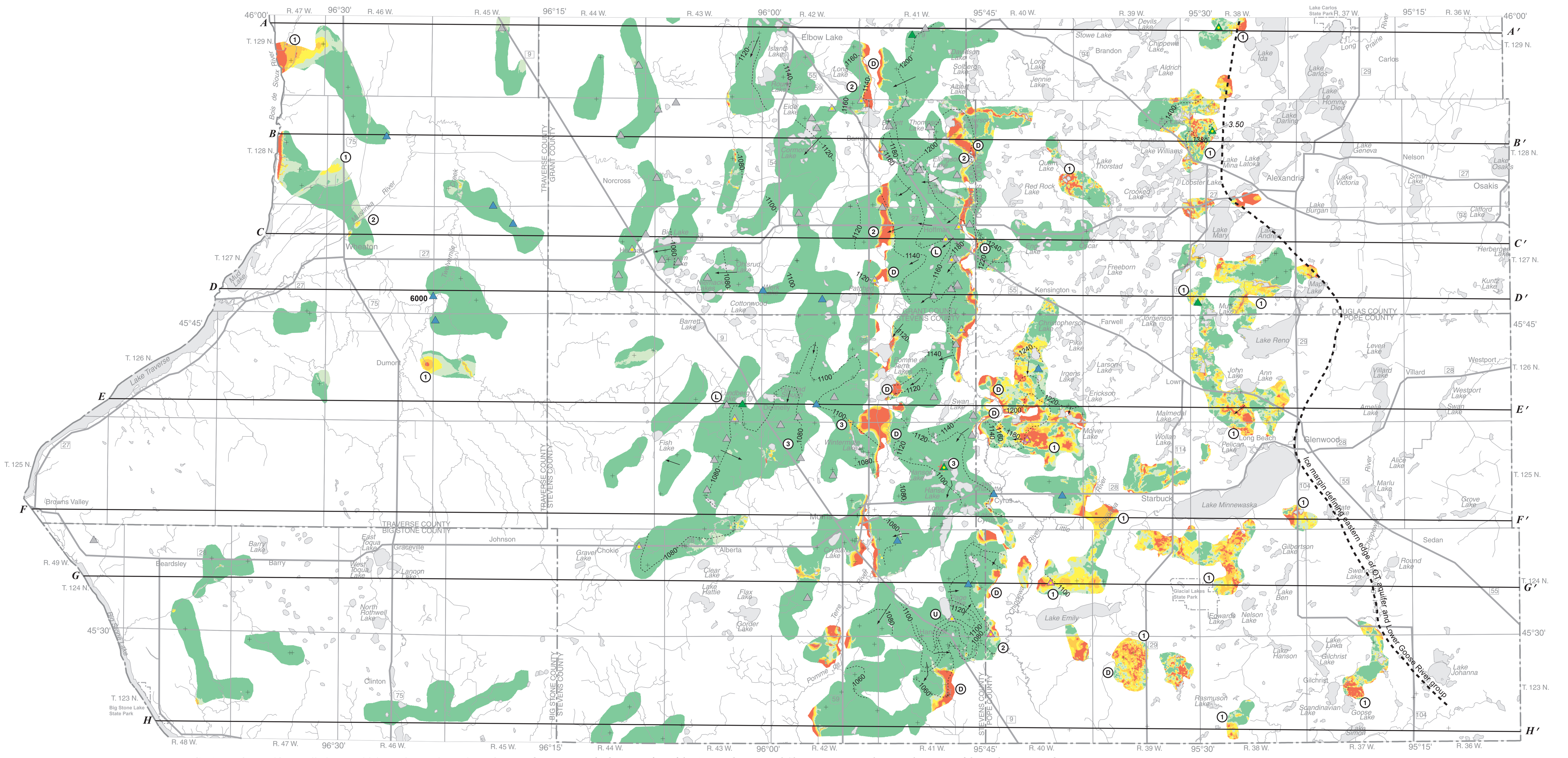

FIGURE 5. ***OT aquifer—pollution sensitivity and potentiometric surface.*** *Moderate to very high pollution sensitivity conditions are common for this aquifer in the eastern portion of the study area where the aquifer is covered by a thin layer of fine-grained material. With a few exceptions, this aquifer is shown with very low pollution sensitivity in the western portion of the study area where it is mostly covered by thicker layers of fine-grained material. Discharge to the surficial sand and gravel aquifers of the Pomme de Terre and Chippewa rivers in the central portions of the study area is probably a common occurrence. All the vintage tritium values occur in locations that were modeled as very low sensitivity. Most mixed and recent values occur in areas modeled as moderate to very high sensitivity. The west and southwest directions of regional ground-water flow are complicated locally by the Pomme de Terre and Chippewa rivers and associated tributaries.*

INTRODUCTION

This plate describes the relative sensitivity of the uppermost, buried sand and gravel aquifers in the study area 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 help local units of government protect and manage their ground-water resources. The uppermost, buried sand and gravel aquifers, as shown on Plates 4 and 5, include the generally shallow LG aquifer in the central portion of the study area; the OT aquifer, which is also relatively shallow in the eastern one-third of the study area (most of Pope and Douglas counties); the CW aquifer and aquifer 1, which were mapped only for the eastern two-thirds and half of the study area respectively; and the western aquifer, which was mapped for only the western one-third of the study area. 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 regional 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 dominates in many settings. Finally, the sensitivity ratings are based on vertical travel time of water (Figure 1), not the behavior of specific contaminants.

The surficial aquifers were assumed to be highly or very highly sensitive almost everywhere in the study area because these aquifers have little or no laterally extensive protective cover (see Figure 4 on Plate 3). No geochemical data were collected to verify directly the sensitivity of surficial aquifers. The surficial aquifer distribution and thickness, however, are important factors 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 POLLUTION SENSITIVITY MODEL AND MAPS OF BURIED AQUIFERS

The goals of the pollution 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 pollution sensitivity modeling and mapping process has three steps. The first step is mapping and defining the aquifers and low-permeability geologic units (protective layers) 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 along with 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 the low-permeability till layers are created as described on Plates 3, 4, and 5. These surfaces are represented in three dimensions in Figure 1 of Plate 8 in the Pope County Geologic Atlas, Part B (Berg, 2006a), and in two dimensions on Figure 2 of this plate as the boundaries between the various layers. These elevation surfaces of aquifers and till layers are GIS grid layers 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 pollution 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 is focused (relatively rapid) recharge. In focused recharge, portions of the aquifers overlap and are connected by complex three-dimensional pathways that allow surface water to penetrate into even the deepest mapped 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 are called recharge surfaces (Berg, 2006b). 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 or less.

The vertical recharge path of water for a stack of aquifers typical of Pope and Douglas counties is shown in Figure 2. That figure shows a generalized cross section of the principal aquifers mapped in the eastern portion of the study area. Similar stacks of different aquifer combinations exist throughout the study area. The vertical path of water from precipitation at the land surface to buried aquifers crosses recharge surfaces of the buried aquifers. On Figure 2, the recharge 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, low-permeability layer (till) between the base of recharge surface 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 aquifer exists in eastern Pope and Douglas counties, 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 starting with the land surface elevation grid and proceeding stepwise downward to the top of aquifer 1 or the lowest mapped aquifer. 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 protective 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 3 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 (LG, OT, CW, aquifer 1, and western aquifer) are shown on Figures 4, 5, 6, 7, and 8, 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. In general, the recent and mixed tritium values should correspond to areas of very high to low sensitivity, whereas, the vintage values should correspond to areas of low to very low sensitivity. The carbon-14 residence time values from collected ground-water samples were also useful for corroborating sensitivity for portions of the buried aquifers that have a predicted very low sensitivity. The chloride to bromide ratios as an anthropogenic indicator of recent industrial age activity were useful evidence of recent water infiltration and an evaluation tool for areas with very high to low pollution sensitivity classifications.

The distribution of chemical constituents in ground water can help establish ground-water movement. Chemical data such as tritium and carbon-14 are used to estimate ground-water residence time or age, and high ratios of chloride to bromide (Cl/Br) indicate anthropogenic (human-created) influence on ground water (Berg, 2006b). These chemical data can be indicators of ground-water recharge and movement.

A map of the potentiometric surface can also help portray ground-water movement. 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 (low-permeability) layer exists. Static (nonpumping) water-level data from the County Well Index and measurements by personnel from the Department of Natural Resources were plotted and contoured to create the potentiometric contour maps. Low-elevation areas on the potentiometric surface that could be above the coincident surface-water bodies may indicate discharge areas; when combined with other information sources, high-elevation areas on the potentiometric surface can be identified as important recharge areas. Ground water moves from higher to lower potentiometric elevations perpendicular to the potentiometric elevation contours (flow directions shown as arrows).

LG aquifer. Of the 16 ground-water samples collected from the LG aquifer that were analyzed for tritium or exhibited elevated Cl/Br concentrations, all but a few samples had values that matched the expected range of sensitivity classifications (Figure 4). Two exceptions were elevated Cl/Br values in samples taken from wells located in eastern Grant County, southwest of Hoffman. Both locations are near an unnamed tributary of the Pomme de Terre River, which could have created a pathway for surface infiltration to the LG aquifer in that area.

OT aquifer. Figure 5 shows good agreement between the tritium age of samples from the OT aquifer and corresponding pollution sensitivity classifications. Thirty-three ground-water samples collected from this aquifer were analyzed for tritium or exhibited elevated Cl/Br ratios. All three samples with recent tritium values, which were located in Pope County, occurred in areas mapped with moderate to very high pollution sensitivity ratings. The 13 samples with vintage tritium values were located in areas with very low sensitivity classifications. One sample with a vintage value, found in Traverse County southeast of Wheaton, had a carbon-14 value of 6000 years (Plate 5, left side of cross-section D–D′). Five samples with mixed tritium values were located in areas with low to very high sensitivity. One mixed tritium value in north-central Stevens County just west of Donnelly and a nearby elevated Cl/Br value are associated with a very low sensitivity area. However, these samples were collected from locations downgradient of Lundberg Lake, which is a possible pathway for surface-water infiltration. Two other elevated Cl/Br values in Stevens County (east of Chokio and north of Hancock) also are associated with a very low sensitivity area. These locations are downgradient from small surface-water bodies that may have acted as infiltration pathways. Three elevated Cl/Br values in the Hoffman area, west of the Chippewa River in eastern Grant County (left of center, cross-section C–C′), appear to be the result of lateral migration of anthropogenic chloride from the Chippewa River.

CW aquifer. Figure 6 also shows good agreement between ground-water residence time indicators and pollution sensitivity classifications for the CW aquifer with a few exceptions. Fifty-three ground-water samples collected from this aquifer were analyzed for tritium or exhibited elevated Cl/Br values. All 28 of the samples with vintage tritium are associated with areas rated as low to very low sensitivity except for one sample in eastern Pope County near Grove Lake, an area rated as high sensitivity. Five of the vintage samples were analyzed for carbon-14 age with values ranging from 100-year-old ground water collected west of Lake Swenoda in eastern Pope County to a 1700-year-old ground water collected west of Kensington in southeastern Grant County (center of cross-section D–D′). Fifteen of the 53 samples from the CW aquifer had mixed tritium values. Four samples with mixed values and three with elevated Cl/Br values are associated with very low sensitivity areas, which is not the expected sensitivity classification. Some of these mixed values and some of the elevated Cl/Br values that seem inconsistent with the sensitivity model are near or 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. One of the mixed value samples (from west of Sedan along the East Branch of the Chippewa River in Pope County) 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 have resulted from deep, upward-moving vintage water mixing with near-surface recent water.

Seven samples from the CW aquifer had recent tritium values. Six samples with recent values were located in Pope County. Two samples were collected in Glacial Lakes State Park and are associated with high-sensitivity areas, which is consistent with the recent tritium values. The remaining recent tritium samples were collected from areas west of the Chippewa River, near Starbuck, north of Lake Linka and west of Lake Johanna. These sample sites are near and possibly downgradient of high-sensitivity areas that may be the source of the recent water through lateral migration.

Aquifer 1. Most of the 71 samples collected from this aquifer for tritium analysis had vintage or mixed tritium values. These results are consistent with the relatively protected geologic setting of this aquifer. All samples with vintage age are associated with areas rated as very low sensitivity. Eight of the vintage samples were also analyzed for carbon-14 age. Seven of the carbon-14 samples had ages in the 1000- to 3000-year-old range, and a 100-year-old sample came from the eastern portion of the Belgrade-Glenwood sand plain. All eight carbon-14 samples are associated with areas of very low sensitivity.

Most samples with mixed tritium values from aquifer 1 are associated with areas of low to very low sensitivity. Eight of these samples were located in eastern or northeastern Pope County and southeastern Douglas County (right side of cross-section C–C′) 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 southeastern Pope County and one located near the center of the Pope 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. One sample with a vintage tritium value was located west of Carlos in Douglas County and is associated with a high sensitivity area in the Long Prairie River valley. It may have a similar setting to the sample from the CW aquifer described in the previous section. This valley may be a discharge area for buried aquifers. The mixed tritium value may have resulted from deep, upward-moving vintage water mixing with near-surface recent water.

Most samples with recent tritium values from aquifer 1 occurred in the Alexandria area. Seven of the 10 recent values in the Alexandria area are clustered southeast of Lake Darling in areas rated as low or very low sensitivity. A couple possible source locations for lateral migration of recent water exist in this area. Three of the 10 samples with recent tritium values are located inside the south portion of the Alexandria municipal boundaries, west of Lake Burgan. These three ground-water sampling locations are downgradient from possible source locations of recent water to the south. Two samples with recent tritium values that occurred near the northern edge of Lake Carlos are also both are associated with very low sensitivity areas. These occurrences are difficult to explain with existing information and may be the result of conditions beyond the project area. A sample with recent tritium values located southeast of Sedan in Pope County was consistent with the low to moderate pollution sensitivity classification at that location.

Western aquifer. Seven samples collected from the western aquifer were analyzed for tritium or exhibited elevated Cl/Br values. Two of the samples, which are associated with very low sensitivity areas in the southwestern portion of the study area in Big Stone County, did not contain detectable concentrations of tritium, indicating vintage residence time conditions. Both samples were also analyzed for carbon-14 with ages ranging from 200 years to 3000 years. The locations of the four samples with elevated Cl/Br values were scattered across the western portion of the study area in areas associated with very low sensitivity and cannot be explained with existing information.

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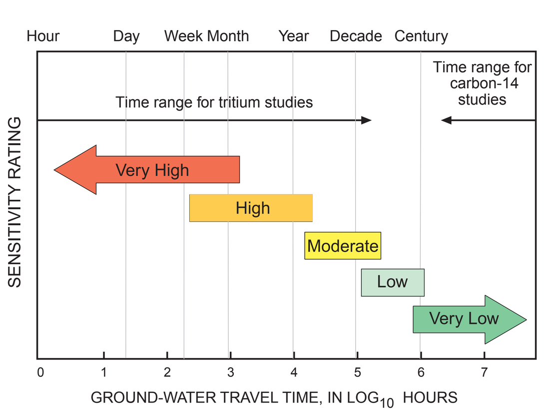

FIGURE 1. ***Geologic sensitivity rating as defined by vertical travel time*** *(Geologic Sensitivity Workgroup, 1991). Ratings are based on the time range required for water at or near the surface to travel vertically into the ground water of interest or a pollution sensitivity target. Tritium and carbon-14 studies indicate the relative ages of ground water.*

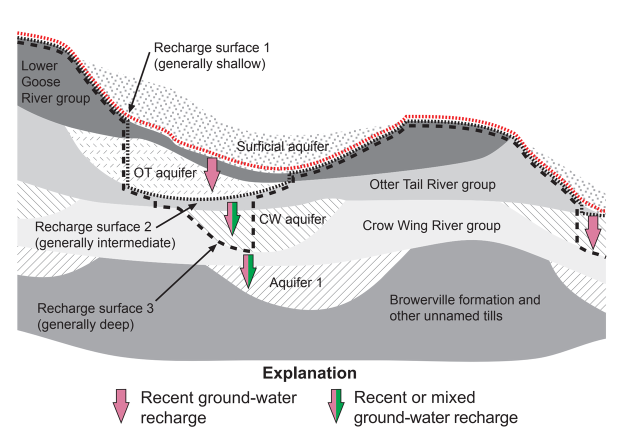

FIGURE 2. ***Generalized cross section showing recharge concepts for buried aquifers considered in the sensitivity evaluations.*** *In this conceptual model of the eastern part of the study area, all recent recharge enters the buried aquifer system at recharge surface 1 (red dotted line). Recharge surface 1 is considered to be at the land surface where till is present, at the bottom of surficial sand deposits and at the bottom of surface water bodies where surficial sand is not present. If less than 10 feet of fine-grained sediment (clay or till) exists between recharge surface 1 and the shallowest underlying buried aquifer, then recent recharge is assumed to move to the bottom of that aquifer to form recharge surface 2. The process and criteria are repeated stepwise for deeper aquifers (recharge surface 3).*

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
VH	H	M	L	VL

FIGURE 3. ***Pollution sensitivity rating matrix.*** *Pollution sensitivity is inversely proportional to the thickness of a protective layer between the top of the aquifer and the nearest overlying recharge surface. Any buried aquifer with less than a 10-foot-thick protective layer between it and an overlying recharge surface is rated very high sensitivity because there is little fine-grained material to increase the time of travel. A thicker overlying protective layer provides additional protection to the aquifer, and sensitivity ratings are determined based on the thickness of this layer.*

MAP EXPLANATION

Sensitivity ratings

Estimated vertical travel time for water-borne contaminants to enter an aquifer (pollution sensitivity target).

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

Tritium age

Color indicates tritium age of water sampled in well.

- Recent—Water entered the ground since about 1953 (10 or more tritium units [TU]).
- Mixed—Water is a mixture of recent and vintage waters (greater than 1 TU to less than 10 TU).
- Vintage—Water entered the ground before 1953 (less than or equal to 1 TU).
- Well not sampled for tritium, but sampled for chloride and bromide.

Well and buried aquifer symbols

- LG aquifer
- OT aquifer
- CW aquifer
- Aquifer 1
- Western aquifer

Map symbols and labels

- 1080 Potentiometric contour line. Contour interval is 20 feet.
- General direction of ground-water flow.
- Static (nonpumping) water-level data.
- 6.08 If shown, nitrate as nitrogen concentration equals or exceeds 3 parts per million.
- 2000 If shown, ground-water age in years, estimated by carbon-14 isotope analysis.
- If shown on well symbol, chloride to bromide ratio greater than 175.
- Ice margin.
- Body of water.
- F F′ Line of cross section.
- 1 Infiltration through a thin layer of overlying, fine-grained material to an underlying aquifer.
- 2 Ground-water recharge from overlying surficial aquifer to buried aquifer.
- 3 Ground-water leakage from an overlying buried aquifer to an underlying buried aquifer.
- 4 Ground-water leakage through multiple aquifers and fine-grained layers.
- D Ground-water discharge from a buried aquifer to surface-water body.
- L Lateral ground-water flow.
- U Unknown source of recent or mixed ground water.

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COMPILATION SCALE 1:100 000
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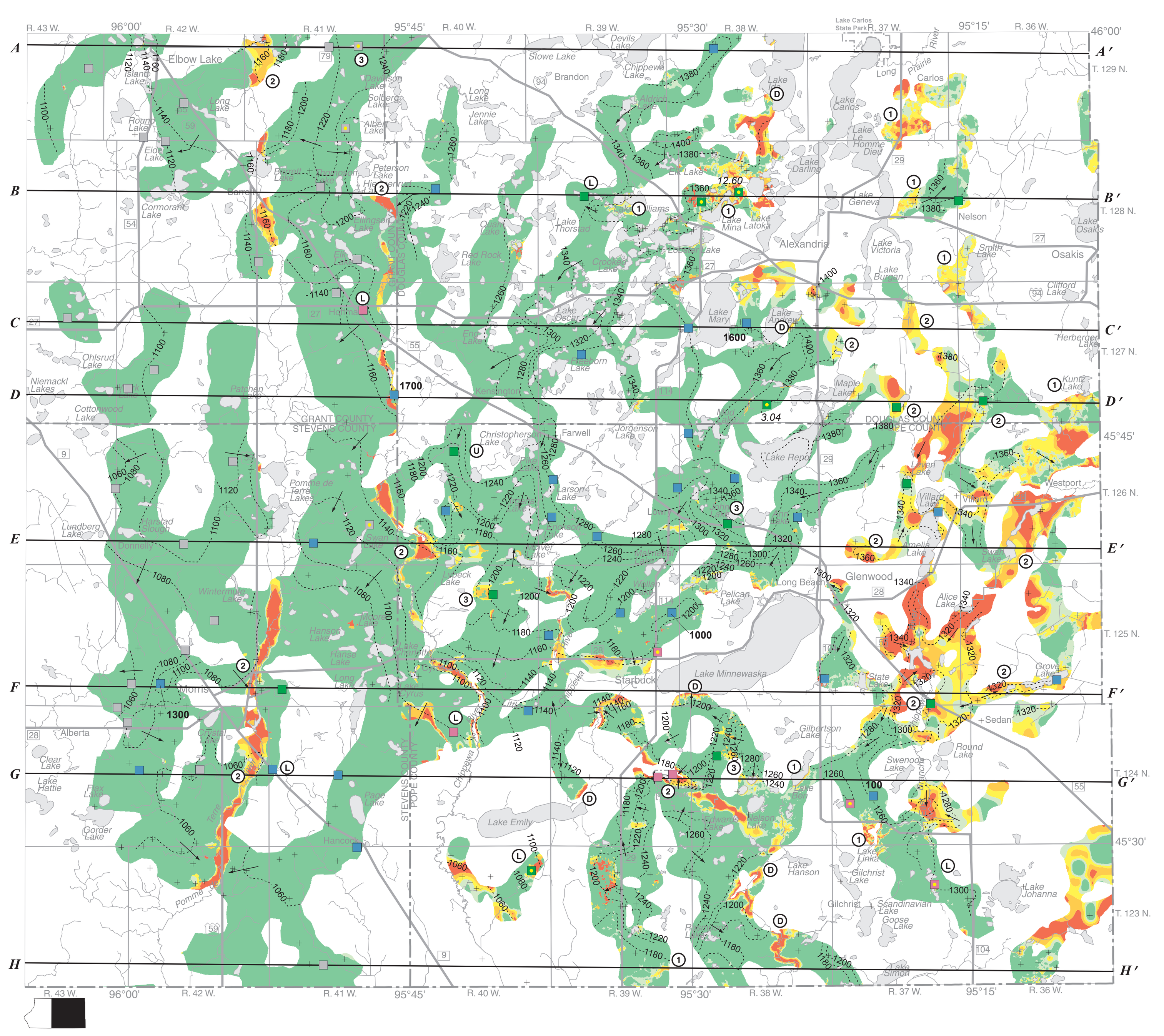

FIGURE 6. ***CW aquifer—pollution sensitivity and potentiometric surface.*** *The CW aquifer is relatively sensitive in eastern Pope and Douglas counties where it is typically the first buried aquifer beneath the sensitive surficial aquifers in that portion of the study area. Smaller sensitive areas exist in other parts of the study area, especially in areas associated with the Pomme de Terre and Chippewa rivers where thick surficial aquifers are present and ground-water leakage from the surficial aquifers to the CW aquifer may be common. Indicators of ground-water residence time generally agree with the pollution sensitivity ratings for the CW aquifer. Most vintage tritium values occur in areas that were modeled as low to very low sensitivity. Five of these vintage samples were also analyzed for carbon-14 age with values ranging from 100 years to 1700 years. Most occurrences of mixed and recent tritium probably resulted from one of the five leakage mechanisms shown on the figure. A regional ground-water divide in eastern Douglas County and northeastern Pope County splits the ground-water flow directions within this aquifer. East of the divide, flow is to the east; flow west of this divide is generally to the southwest with many local complexities created by discharge to local depressions such as Lake Minnewaska and the valleys of the Pomme de Terre and Chippewa rivers.*

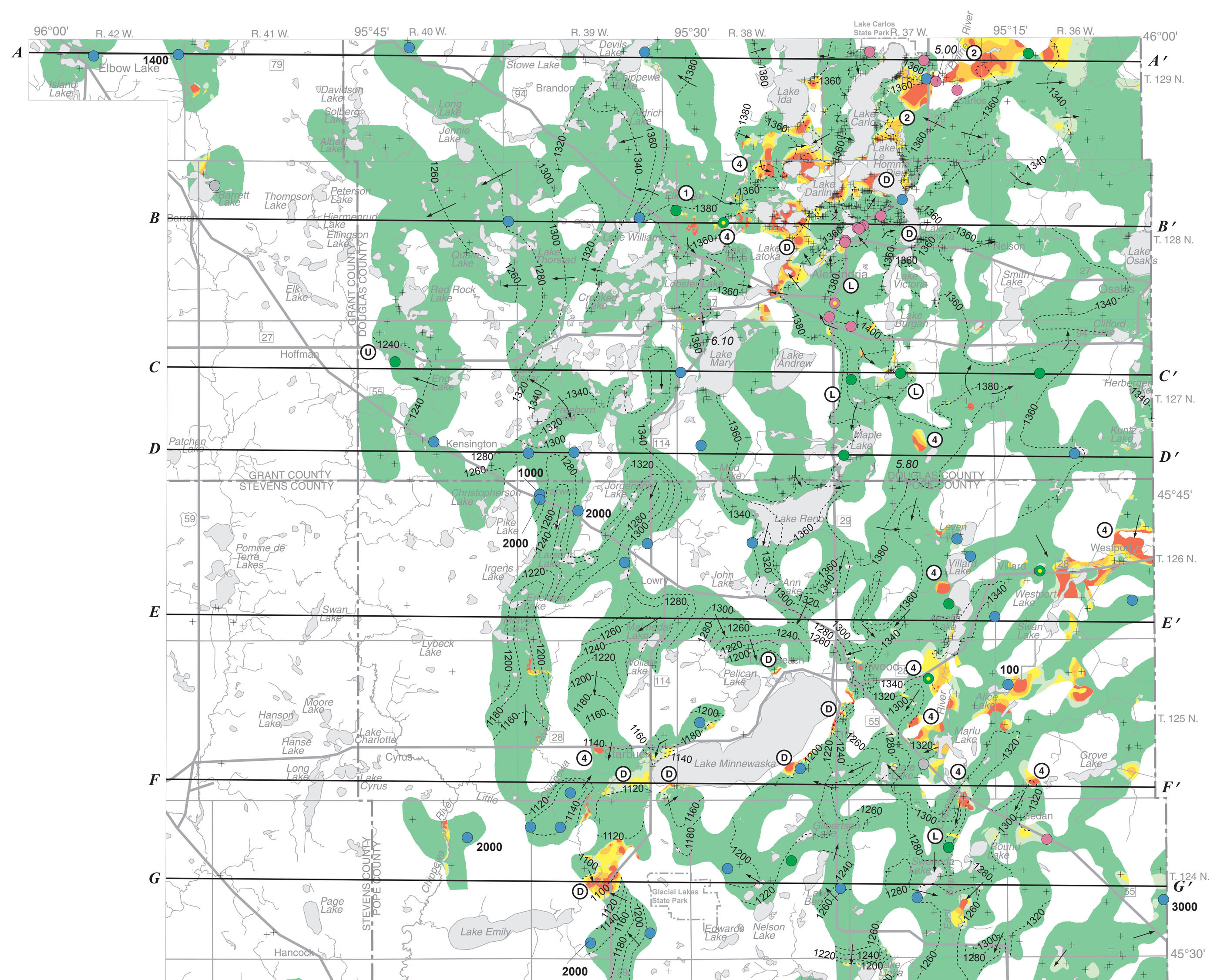

FIGURE 7. ***Aquifer 1—pollution sensitivity and potentiometric surface.*** *This aquifer was mostly rated as low and very low pollution sensitivity. Most areas of moderate and high sensitivity occur at scattered locations in the eastern portion of the study area beneath the Belgrade-Glenwood area aquifer and the eastern portion of the CW aquifer. In these more sensitive areas, leakage through multiple aquifers appears to be the most common mechanism. Most of the vintage tritium values occur in areas rated as low or very low sensitivity. Vintage samples analyzed for carbon-14 age had values ranging from 100 years to 3000 years. Most of the mixed or recent tritium values that were associated with lower than expected pollution sensitivity ratings occur downgradient from areas of higher sensitivity.*

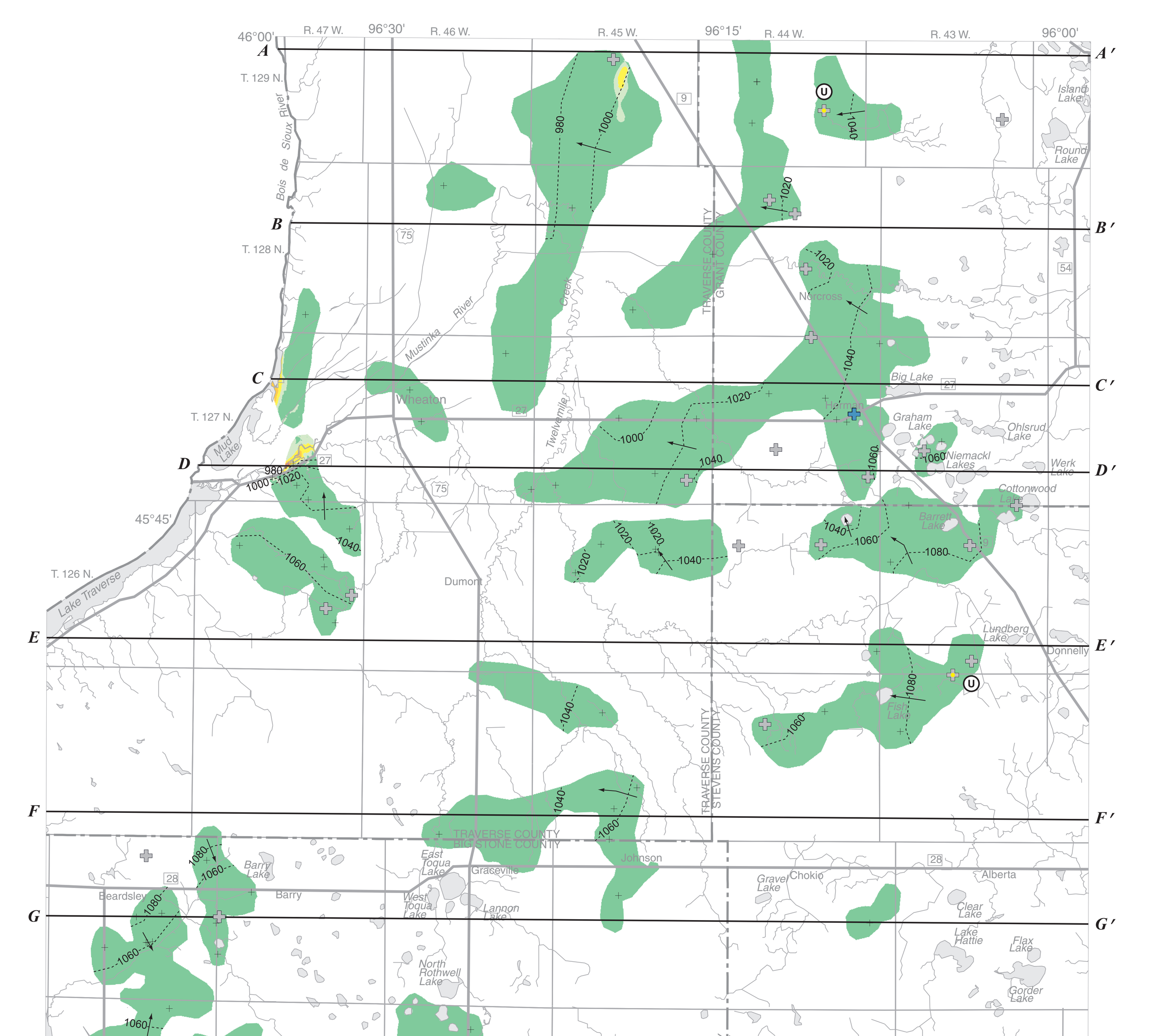

FIGURE 8. ***Western aquifer—pollution sensitivity and potentiometric surface.*** *The mapped area for this aquifer in the western portion of the study area does not have deep or extensive surficial aquifers and the overlying buried aquifer (mostly the OT aquifer) generally has limited extent and thickness. As a result of those conditions, few direct recharge pathways to the western aquifer exist. The few samples from this aquifer that were analyzed for tritium were vintage age and all occurred in areas rated as very low sensitivity. Two of the vintage samples from Big Stone County that were also analyzed for carbon-14 age had values of 200 years and 3000 years. Ground water generally flowed to the west with some local exceptions.*

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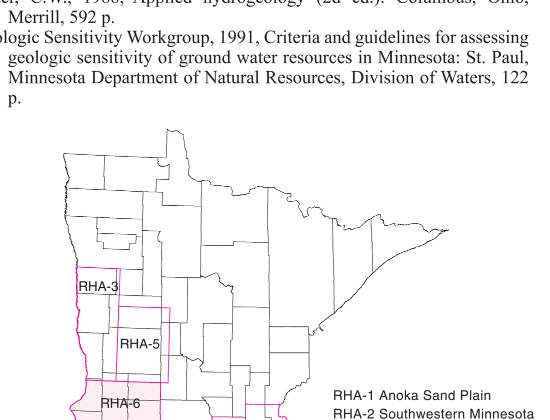
Base modified from Minnesota Geological Survey, Traverse–Grant Area Regional Hydrogeologic Assessment, Part A, 2006.

Project data compiled from 2004 to 2007 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.



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