SENSITIVITY TO POLLUTION OF THE BURIED AQUIFERS

By

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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 sensitivity areas may have stratigraphic and hydraulic connections that cannot be determined with the existing data. One of the seven mixed values (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 of the vintage samples 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 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 southwestern 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 four 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.

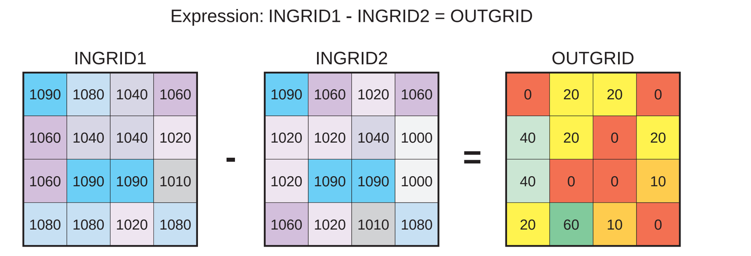

FIGURE 4. *GIS grid calculations used to create pollution sensitivity maps.* The recharge surfaces and the till layer surfaces used to calculate protective layer thickness were created as geographic information system (GIS) grid layers. A grid layer is a type of GIS file consisting of regularly spaced squares or cells. The cell size 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.

Aquifer	0 to 10	10 to 20	20 to 30	30 to 40	Greater than 40
	Thickness of protective layer between the aquifer and the nearest overlying recharge surface (in feet)				
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 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.

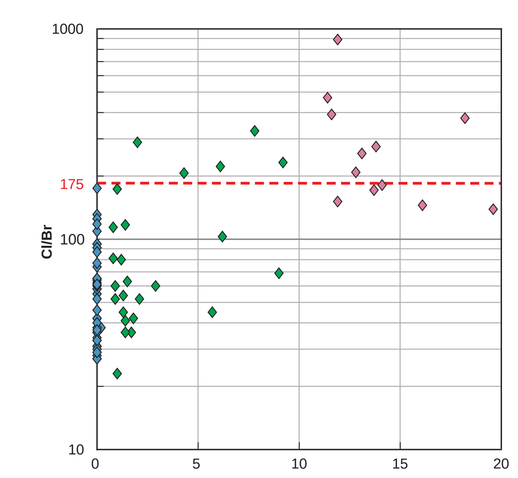

FIGURE 6. *Chloride to bromide ratio versus tritium in ground-water samples.* This graph compares the ratio of chloride to bromide (Cl/Br) concentrations to tritium concentrations from 80 wells. The samples came from the three mapped buried aquifers and older unmapped aquifers. Mineral sources of chloride (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.

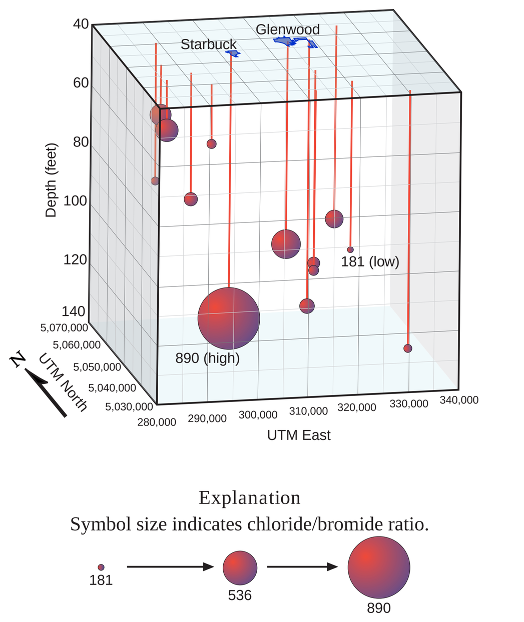

FIGURE 7. *Three-dimensional bubble plot of elevated chloride to bromide ratios.* This graph shows only the results of samples from buried aquifers with chloride to bromide (Cl/Br) ratios that exceeded the threshold of approximately 175 indicating the presence of some human-produced chloride (anthropogenic 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 at 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.

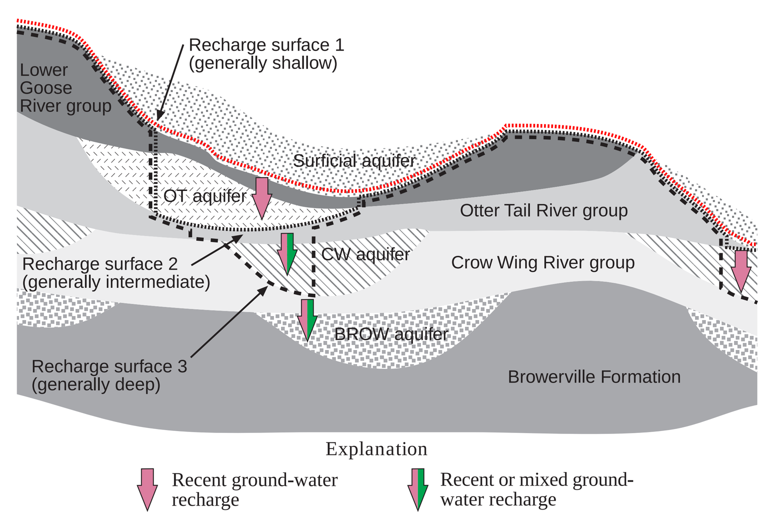

FIGURE 3. *Generalized cross section showing recharge concepts for the three buried aquifers considered in the sensitivity evaluation.* The source of recent water from precipitation is divided into three recharge surfaces. In this conceptual model, all the recent recharge water enters the buried aquifer 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.

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.

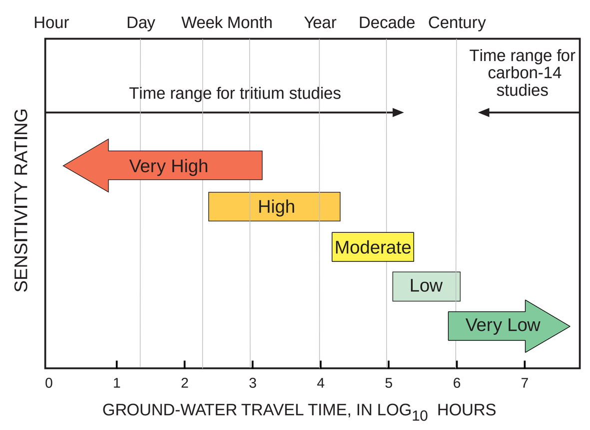

FIGURE 1. *Geologic sensitivity rating as defined by vertical travel time (Geologic Sensitivity Workgroup, 1991).* Ratings are based on the time range required for water at or near the surface to travel vertically into ground water of interest or a pollution sensitivity target. For Pope County, the pollution 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.

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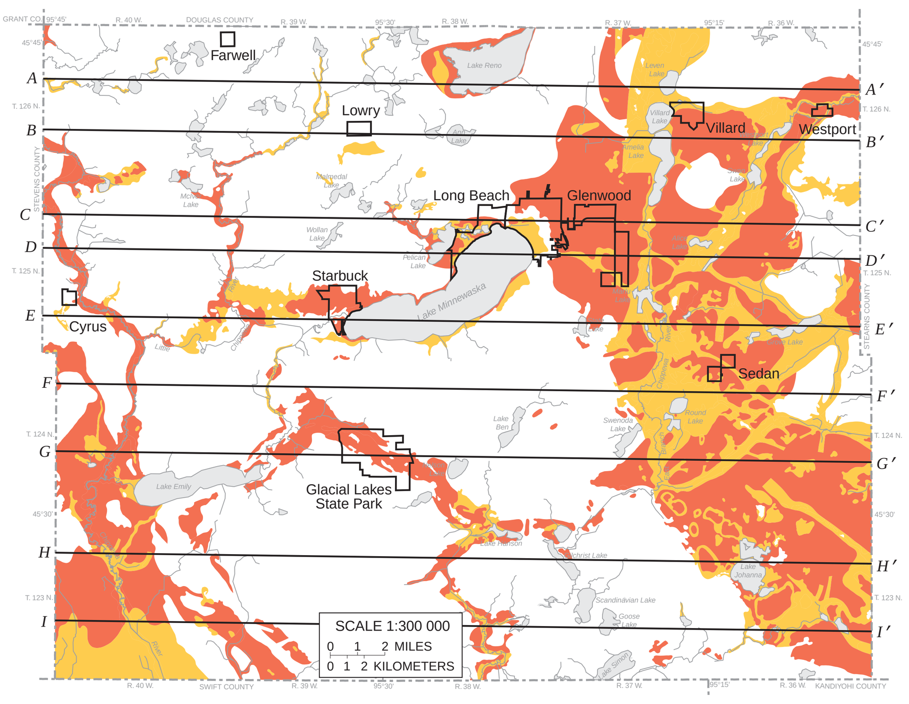


FIGURE 2. *Pollution sensitivity of surficial aquifers.* The surficial aquifers described on Plate 6 are relatively sensitive to pollution. The sensitivity rating (Figure 1) of these aquifers is based mainly on the relative content of fine- and coarse-grained sediments in the aquifers. The sediment descriptions 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 td, 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, ow, 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.

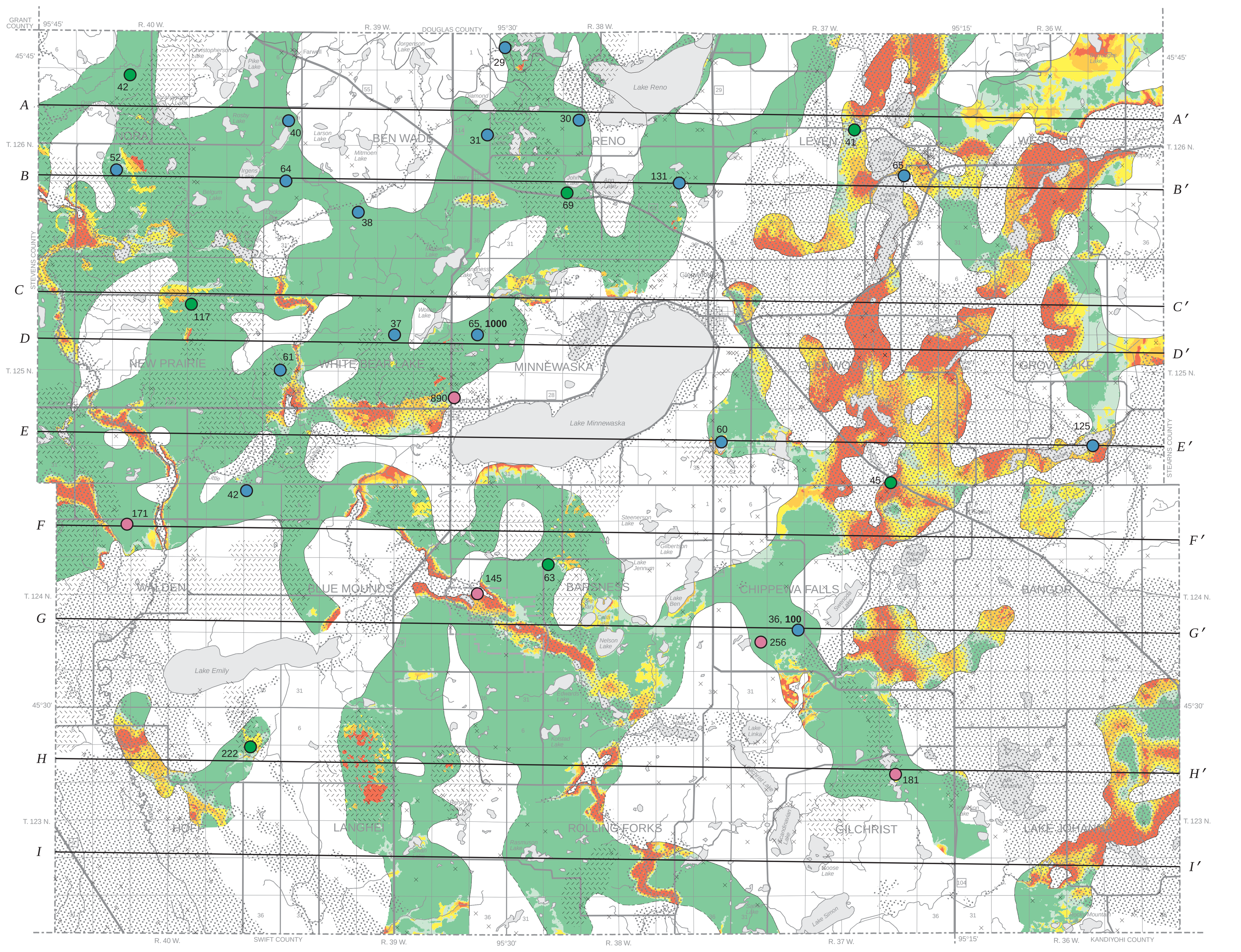
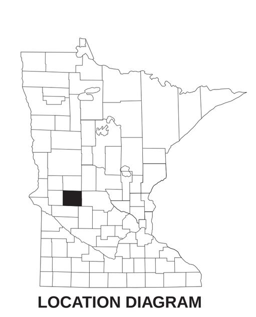


FIGURE 9. *CW aquifer pollution sensitivity.* The CW aquifer is relatively sensitive in eastern Pope County where it is typically the first buried aquifer beneath the sensitive Belgrade-Glenwood surficial aquifers. Elsewhere in the county, the aquifer is rated as mostly very low sensitivity. A generally 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 are 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 near areas that are rated as very low sensitivity 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.



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.

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.

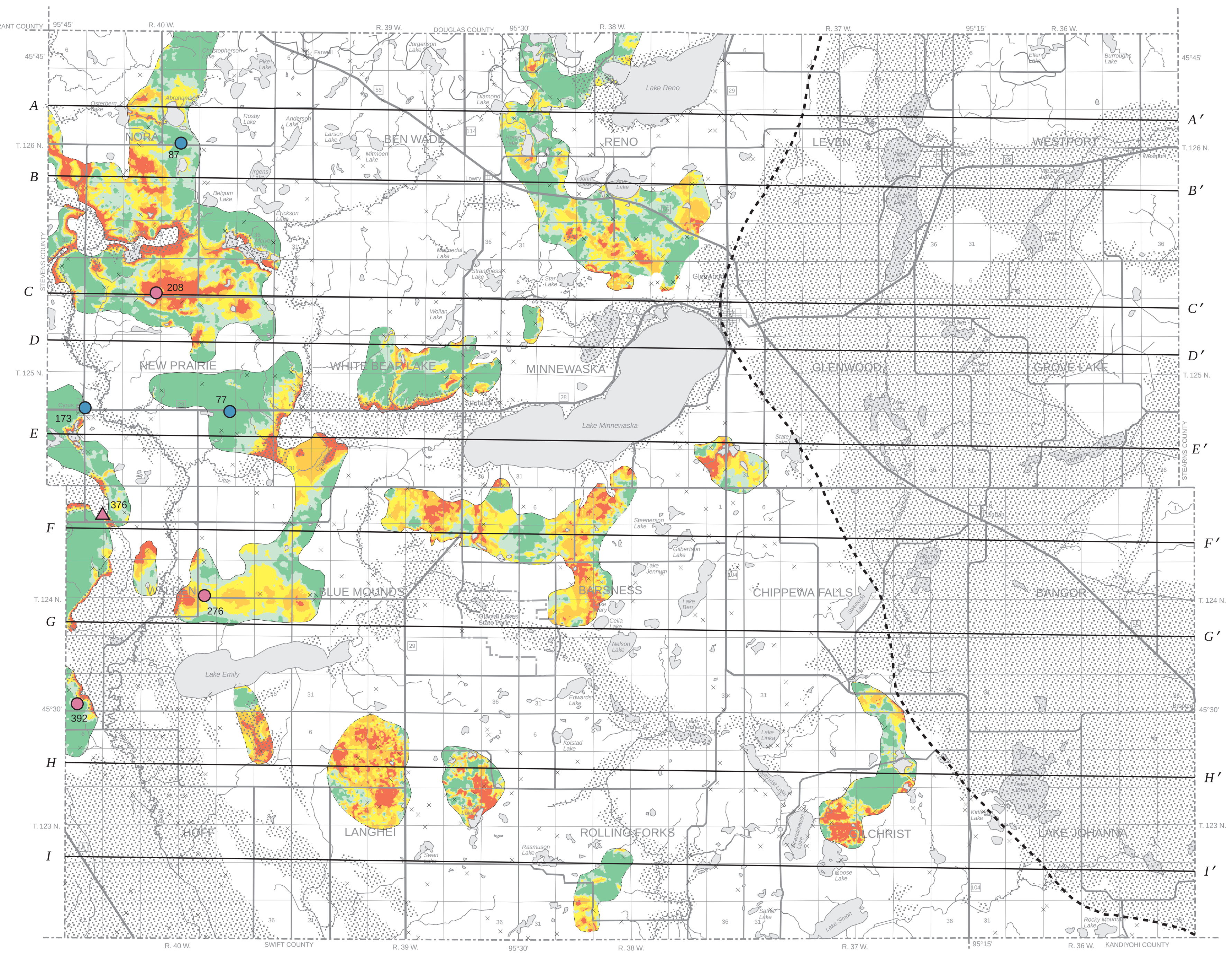


FIGURE 8. *OT aquifer pollution sensitivity.* In central and western Pope County, the generally shallow OT buried aquifer has scattered sensitive areas interspersed with lower sensitivity areas. This figure shows good agreement between the tritium values and pollution sensitivity classifications for 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 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 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.

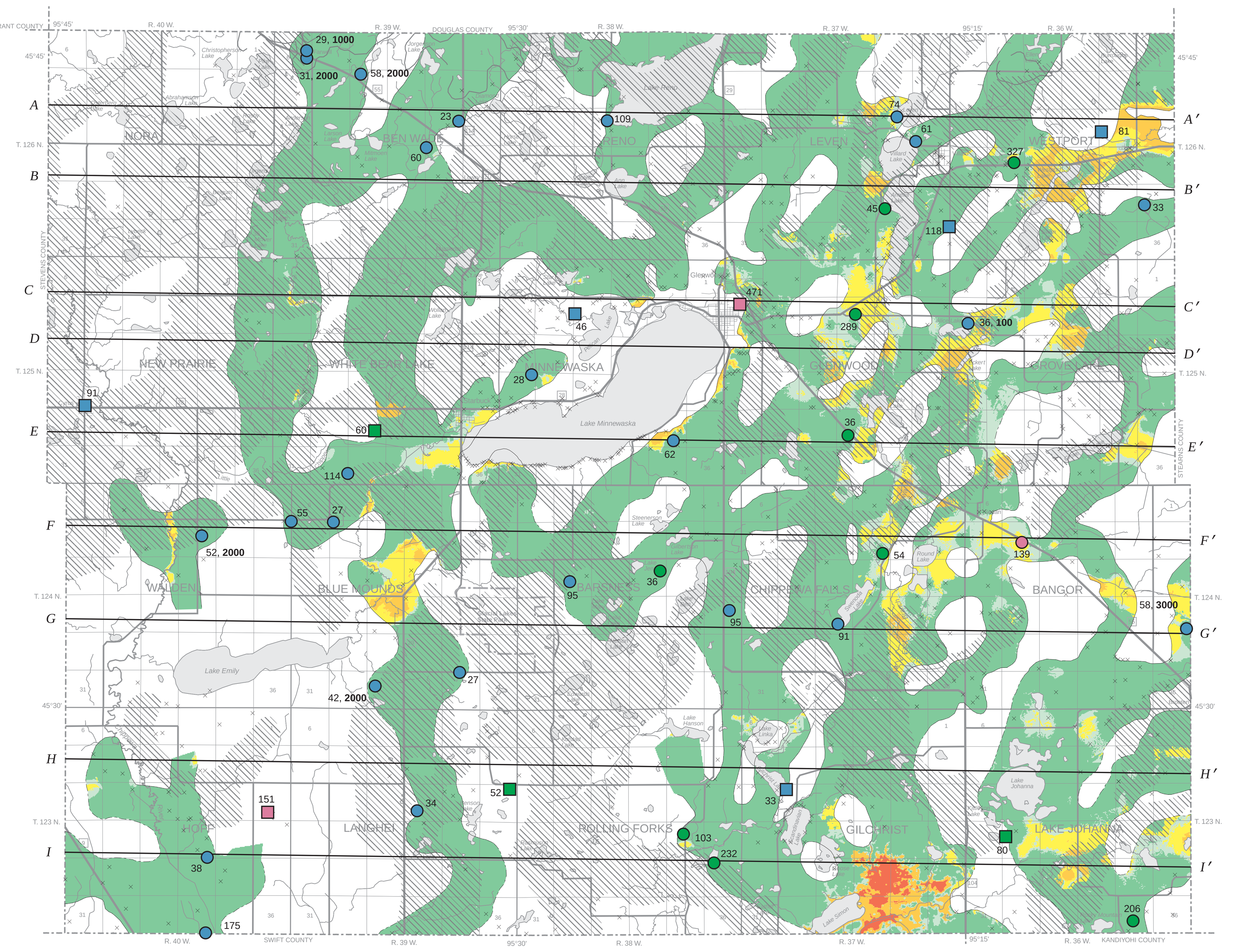


FIGURE 10. *BROW aquifer pollution sensitivity.* This aquifer has mostly been classified with low and very low sensitivity ratings with most of the moderate and high ratings at scattered locations in the eastern portion of the county beneath the Belgrade-Glenwood sand plain. Of the 35 samples collected 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 sample were collected from older aquifers that were not mapped. Most of the samples had either vintage or mixed values and are also generally consistent with older and deeper aquifers. The distribution of the overlying CW aquifer is shown for comparison.