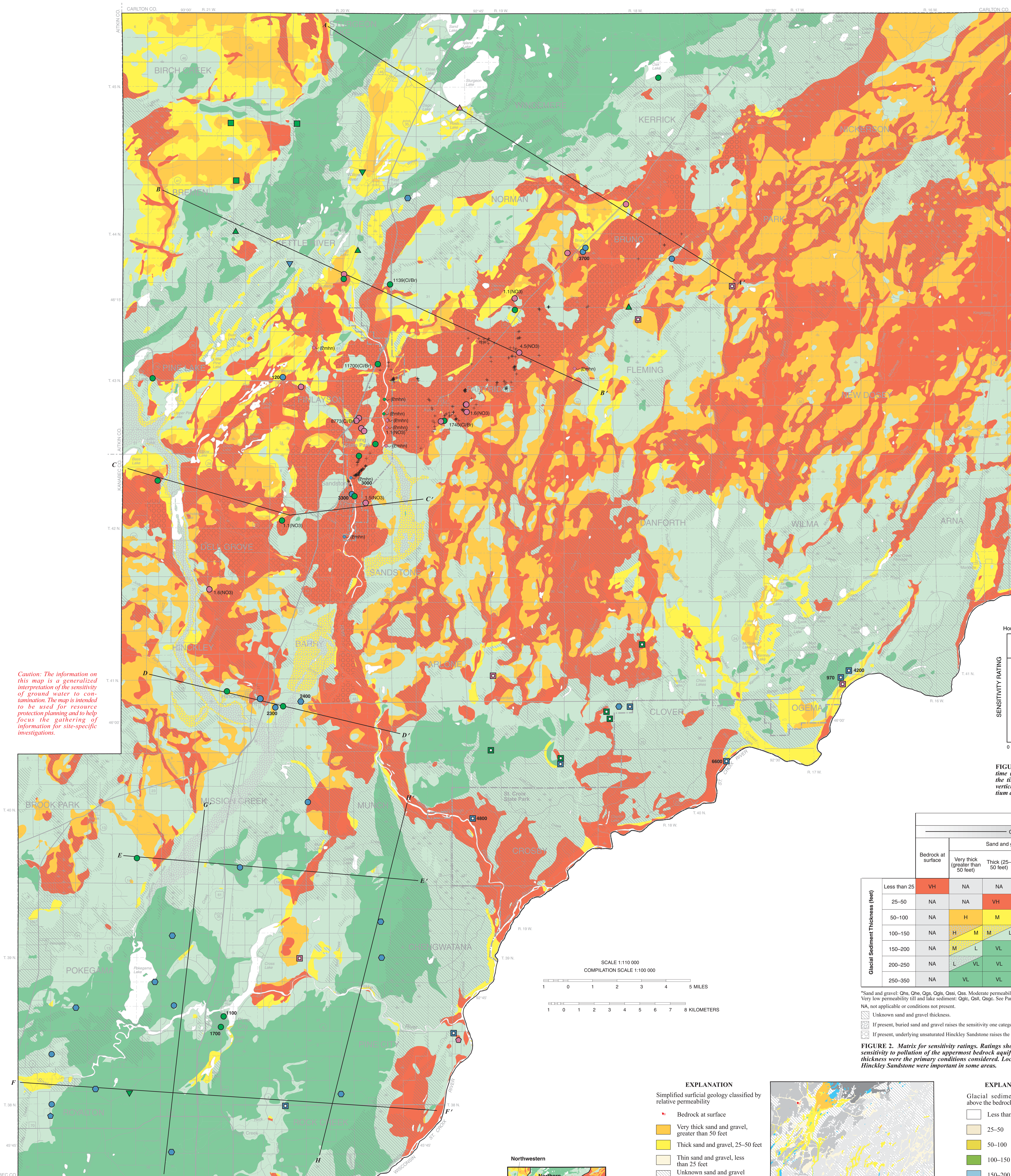

Caution: The information on this map is a generalized interpretation of the sensitivity of ground water to contamination. The map is intended to be used for resource protection planning and to help focus the gathering of information for site-specific investigations.

SCALE 1:110 000
COMPILATION 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

Sensitivity ratings

Estimated vertical travel time for water-borne surface contaminants to enter the uppermost bedrock aquifers (target zone).

- 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

Permeability and local geologic factors

- Unknown sand and gravel thickness
- Buried sand and gravel indicated by aeromagnetic geophysics
- Unsaturated Hinckley Sandstone, possibly associated with karst

Well symbols and labels

Shape indicates aquifer.

- Quaternary
- Paleozoic sandstone
- Hinckley sandstone
- Fond du Lac
- Hinckley sandstone–Fond du Lac
- Volcanic rock
- Metamorphic rock

Color indicates tritium age.

- Recent—Water entered the ground since 1953 (10 or more tritium units).
- Mixed—Water is a mixture of recent and vintage waters (0.8 to less than 10 tritium units).
- Vintage—Water entered the ground before 1953 (less than 0.8 tritium unit).

1740 (Cl/Br) If shown, chloride to bromide ratio equals or exceeds 1000

4.5 (NO3) If shown, nitrate-nitrogen concentration equals or exceeds 1 part per million

2400 If shown, ground-water age in years, estimated by carbon-14 isotope analysis

Map symbols

- Ground-water sample from spring collected for chemical analysis; color indicates tritium age. If shown, Ꞓmhn indicates spring from Hinckley sandstone.
- + Sinkhole
- Lakes or rivers
- Wetlands, marsh
- F F′ Line of cross section (see also Plate 9)

SENSITIVITY TO POLLUTION OF THE UPPERMOST BEDROCK AQUIFERS

By

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2004

INTRODUCTION

This plate shows the relative sensitivity of the uppermost bedrock aquifers to surface or near-surface releases of contaminants. Sensitivity is defined as the ease with which a surface contaminant moving with water might travel to and enter a bedrock drinking water source. The map is intended to assist Pine County in protecting and managing its ground-water resources. As shown on Plates 8 and 9, the uppermost bedrock aquifer includes the metamorphic rock and Fond du Lac aquifers in the northwest, the Hinckley sandstone aquifer in the central and southwestern portions, and the volcanic rock and Mesoproterozoic sandstone aquifers in the eastern and southeastern portions. Isolated areas of the Paleozoic sandstone aquifer exist in the southern portion of the county. These aquifers will be considered the sensitivity target for the following discussion. The sensitivity of the Quaternary buried sand and gravel aquifers in southern Pine County was discussed on Plate 8, Figure 2.

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 is 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 criteria (Figure 1), not the behavior of specific contaminants.

RATINGS MATRIX AND MAP DEVELOPMENT

The sensitivity assessment shown on the map is based on geologic factors that influence the travel time of water from the land surface to the sensitivity target, which is the uppermost bedrock aquifers. The effect of these geologic factors is interpreted in Figure 2. In Pine County, the two most important geologic factors were the relative permeability of the surficial geologic units (Figure 3a) and the thickness of glacial sediment (Figure 3b). Local geologic factors that also influence rates of ground-water infiltration (discussed below) are represented on Figure 3c. With geographic information system (GIS) technology, the information from these three maps was combined into a composite map that retains the geologic factors. The composite map and three factors then became the basis (vertical and horizontal axes) of the sensitivity matrix (Figure 2). Each combination of permeability, glacial sediment thickness, and local geologic factors was represented as a cell or portion of a cell in the matrix. Each matrix cell was then interpreted for pollution sensitivity (very low to very high) using some broad hydrogeologic assumptions, such as thick glacial sediment contributes to low pollution sensitivity conditions or permeable surficial geologic units contribute to high sensitivity conditions. These assumptions that relate geologic conditions to travel time were tested with chemistry data from ground-water samples taken from wells and springs in the target aquifers. The matrix and the map were subsequently adjusted to ensure consistency with the chemistry data.

The simplified surficial geology map (Figure 3a) was derived primarily from Part A, Plate 4, with textural information from Part A, Plate 5. The thickness of some of the sand and gravel units was determined based on well log data from the County Well Index and surface resistivity data. The model assumes that overall permeability increases as sand and gravel thickness increases and till thickness decreases in areas of equal glacial sediment thickness. Figure 3a shows large but discontinuous areas of low and very low permeability in the northwestern, north-central, and southern portions of the county. The southwestern-northeastern area across the central portion of the county is generally covered by moderate permeability till with smaller areas covered by very low permeability units (thick, clayey glacial lake sediments) and sand and gravel deposits of various thicknesses. Large areas of surficial sand and gravel that have unknown thickness characteristics are shown with a diagonal line pattern.

The glacial sediment thickness map (Figure 3b) shows thick areas in the northern, southern, and eastern portions of the county and thin areas in the central and northeastern portions of the county. This map was a composite of the Depth to Bedrock map on Plate 6 and the Bedrock Aggregate map on Plate 7 from Part A.

The local geologic factors map (Figure 3c) shows several factors relevant to the pollution sensitivity evaluation that could not be included with the two axes of the matrix. Two of these factors are extensive subsurface features: buried valley sand and gravel deposits and a mostly buried, clayey lake deposit (glacial Lake Lind) (Johnson and others, 1999). The buried valley sand and gravel deposits were first noticed as thin, sinuous aeromagnetic anomalies (Part A, Plate 3). The valleys were later confirmed with refraction seismic investigations. The protective value of the glacial sediment layer is reduced if a large portion of it consists of sand and gravel. Therefore, the pollution sensitivity classifications at these buried valley locations were increased one class, usually from very low to low (Figure 2). The sensitivity classifications were only modified in this manner to a point just south of cross section E–E′. Despite substantial buried sand and gravel in the southern portion of the county (Plate 8, Figures 2a and 2b), vintage tritium values predominate. The very low permeability sediments of glacial Lake Lind occur in the southeastern portion of the county (dashed line on Figure 3c and cross sections E–E′, F–F′, G–G′, and H–H′ on Plate 9). Although the layer is thin, the clayey lake sediments probably slow vertical infiltration that might otherwise travel more rapidly through the buried sand and gravel layers. This buried lake sediments layer may extend farther west and provide an effective protective layer and very low pollution sensitivity conditions despite the presence of buried sand and gravel in the area. Because of the presence of the glacial Lake Lind sediments, the low to very low sensitivity interpretation of the southern part was not increased as it was in the western portion of Pine County where unprotected, thick buried sand and gravel is present.

Unsaturated Hinckley Sandstone is another local factor that influences sensitivity (Figure 3c). East of the Kettle River, this area closely matches the distribution of known sinkholes and may be related either as a cause or an effect. In limestone karst areas, sinkholes can be very common if the till cover is less than 50 feet thick (Alexander and others, 2003). Much of the area underlain by unsaturated Hinckley Sandstone has less than 50 feet of glacial sediment cover. Shade (2002) also noted an apparent relationship between thin glacial sediment and sinkhole occurrences in Pine County. Areas where unsaturated Hinckley Sandstone was covered with less than 50 feet of till were given a sensitivity classification of very high because of a high potential for sinkholes. In some places where unsaturated Hinckley Sandstone occurs beneath sand or gravel of unknown thickness, the unsaturated Hinckley Sandstone conditions were assumed to supercede the overlying conditions.

SENSITIVITY MAP EVALUATION

Evaluation data. Three general areas emerge after combining the previously described sensitivity conditions and layers and applying the sensitivity ratings. These three general areas are the moderate to very high sensitivity of the central and northwestern areas, the very low to low sensitivity of the southern area covered by thick glacial sediment, and the northern area with both high and low sensitivity characteristics (Figure 4). The matrix (Figure 2) represents a conceptual model that was tested with chemical and isotope data from ground-water samples. The model and associated sensitivity map should be able to predict generally the age of the ground water and the distribution of some common contaminants in these three areas. For evaluation purposes, the data considered were associated with the target aquifer (uppermost bedrock aquifers), along with vintage age ground-water data from the Quaternary aquifer.

Ground-water age data (tritium and carbon-14) were used in this and other pollution sensitivity studies as a means of verifying the sensitivity ratings. These data help to characterize the likely speed of infiltrating contaminants through various protective layers of differing thickness.

The concentrations of commonly occurring contaminants, nitrate-nitrogen and chloride, in ground-water samples were used to indirectly evaluate the sensitivity model. Nitrogen from fertilizers and sewage effluent may raise nitrate concentrations in ground water above background levels and indicate some level of sensitivity. However, this chemical is not a very good age indicator because the general timing of large-scale applications is mostly unknown. Furthermore, the distribution of these substances is uneven and the rate of nitrate degradation can vary considerably.

The presence of chloride from human activities (road salt, fertilizer, septic tank effluent, or water softening salt) may indicate recent recharge of ground water (Ekman and Alexander, 2002). Because natural ground water in Pine County may contain high concentrations of chloride, elevated chloride concentration alone may not indicate infiltration of contaminated water. The chloride to bromide (Cl/Br) ratio is a better indicator. Salt derived from halite deposits typically has very high Cl/Br values. In water samples collected from the target (uppermost bedrock) aquifers discussed on this plate, the Cl/Br values mostly were less than 1000 (Plate 8, Figure 3) with a few values exceeding that threshold. The high ratio values (greater than 1000) were all associated with recent or mixed tritium concentrations. These values were considered to indicate an anthropogenic origin and are shown on the pollution sensitivity map.

Evaluation of central and northwestern areas. These areas have the highest sensitivity ratings mostly because of thin glacial sediment cover. In these areas, 47 ground-water samples were collected for tritium analysis. Most of these samples had mixed or recent tritium values (24 recent and 16 mixed) supporting the higher sensitivity interpretation for these areas. Vintage tritium was found in 7 of the 47 samples. Three samples with vintage tritium occurred along the Kettle River in the central area and represent evidence of the deep, upwelling conditions created by that river. Three other vintage samples (two in Bruno and one in Finlayson) were from deep wells (110 feet to 345 feet) that pump water from beneath the relatively shallow recent and mixed ground-water layer that is characteristic of this area (cross-sections A–A′, B–B′, and C–C′, Plate 9). The remaining sample of this vintage group came from an 85-foot-deep well east of Bruno where locally thick glacial sediment occurs (cross-section A–A′, right side).

Elevated nitrate and Cl/Br values from the target aquifers were mostly found in the central area. These occurrences were mostly limited to the very sensitive area between the cities of Sandstone and Bruno.

Evaluation of southern area. The southern area has the lowest sensitivity ratings, typically in the low to very low range, because the bedrock water supply aquifer is relatively well protected from contaminant releases. In this area, 40 samples (10 from Quaternary buried aquifers and 30 from bedrock aquifers) were collected for tritium analysis. All 10 samples from Quaternary buried aquifers had vintage tritium values. In most cases, the deeper bedrock aquifer will have a longer ground-water residence time than the shallower Quaternary buried aquifer and, consequently, lower pollution sensitivity. Therefore, the Quaternary buried aquifer samples with vintage tritium values were considered to be minimum values for the ground-water residence time of the target aquifer and are shown on the sensitivity map.

In 37 of the 40 samples, mixed (10) or vintage (27) tritium values were found, and none of the samples contained high (greater than 1000) Cl/Br values. These characteristics support the interpretation of the southern area's generally low sensitivity. Two of the three water samples with recent tritium values, one from a well northeast of Pine City and the other from a well east of Pine City near the St. Croix River, occur in some of the small, local areas where the glacial sediment is thin and permeable. The other water sample with a recent tritium value in this area, located near the northeastern corner of St. Croix State Park, is in a small area with relatively thick, permeable glacial sediment.

Evaluation of northern area. The northern area has mostly low and very low sensitivity ratings, although it includes an area of moderate and high sensitivity. The low to very low sensitivity areas are covered with thick, clayey glacial sediments. The central part of this area, located around Sturgeon Lake and Willow River, has moderate to high sensitivity characteristics due to locally very thick sand and gravel deposits that allow relatively rapid recharge of the underlying Fond du Lac aquifer (left side of A–A′, Plate 9). Eight ground-water samples were collected in the northern area. All six of the samples collected in the low to very low sensitivity part had vintage or mixed tritium values (two vintage and four mixed). The two samples from the moderate to high sensitivity portion had mixed and recent tritium values.

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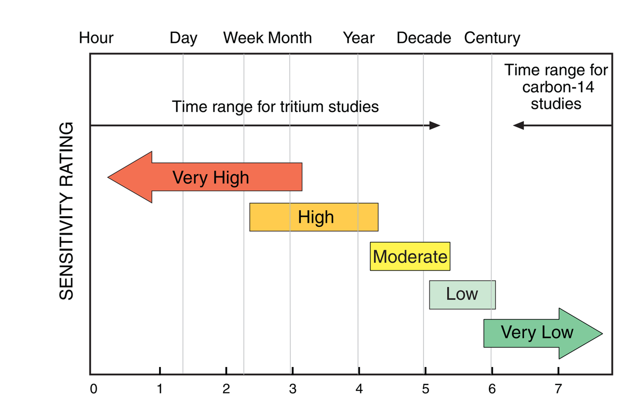


FIGURE 1. *Geologic sensitivity rating as defined by vertical travel time (Geologic Sensitivity Workgroup, 1991). Ratings are based on the time range required for water at or near the surface to travel vertically into the uppermost bedrock aquifers (sensitivity target). Tritium and carbon-14 studies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

Glacial Sediment Thickness (feet)	Surface Material (Generally decreasing permeability →): Bedrock at surface	Sand and gravel thickness*: Very thick (greater than 50 feet)	Sand and gravel thickness*: Thick (25–50 feet)	Sand and gravel thickness*: Thin (less than 25 feet)	Sand and gravel thickness*: Unknown	Till and lake sediment type*: Moderate-permeability till	Till and lake sediment type*: Low-permeability till	Till and lake sediment type*: Very low permeability till and lake sediment
Less than 25	VH	NA	NA	NA	VH	VH	VH / H	H
25–50	NA	NA	VH	VH	VH	VH / H	M	L
50–100	NA	H	M	L	L	L	L	VL
100–150	NA	H / M	M / L	M / L	M / L	M / L	L / VL	L / VL
150–200	NA	M / L	VL	L / VL	VL	L / VL	L / VL	VL
200–250	NA	L / VL	VL	L / VL	VL	L / VL	L / VL	L / VL
250–350	NA	VL	VL	VL	L / VL	VL	L / VL	VL

*Sand and gravel: Qhs, Qhe, Qgs, Qgls, Qssi, Qss. Moderate permeability till: Qssm, Qsgw, Qsgs, Qglf. Low-permeability till: Qsfm, Qsgf, Qgm, Qggm. Very low permeability till and lake sediment: Qglc, Qsll, Qsgc. See Part A, Plate 4, for detailed descriptions of units.

NA, not applicable or conditions not present.

Unknown sand and gravel thickness.

If present, buried sand and gravel raises the sensitivity one category.

If present, underlying unsaturated Hinckley Sandstone raises the sensitivity one category.

FIGURE 2. ***Matrix for sensitivity ratings. Ratings show the influence of combinations of geologic conditions on the sensitivity to pollution of the uppermost bedrock aquifers. The permeability of surface material and glacial sediment thickness were the primary conditions considered. Local geologic factors of buried sand and gravel and unsaturated Hinckley Sandstone were important in some areas.***

EXPLANATION

Simplified surficial geology classified by relative permeability

- Bedrock at surface
- Very thick sand and gravel, greater than 50 feet
- Thick sand and gravel, 25–50 feet
- Thin sand and gravel, less than 25 feet
- Unknown sand and gravel thickness
- Moderate-permeability till
- Low-permeability till
- Very low permeability till and lake sediment
- Surface water

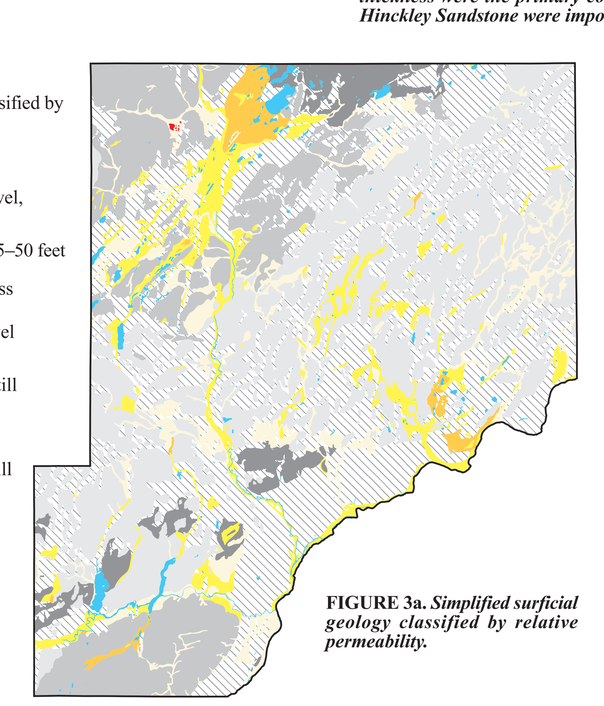


FIGURE 3a. ***Simplified surficial geology classified by relative permeability.***

EXPLANATION

Glacial sediment thickness above the bedrock surface (feet)

- Less than 25
- 25–50
- 50–100
- 100–150
- 150–200
- 200–250
- 250–300
- 300–350

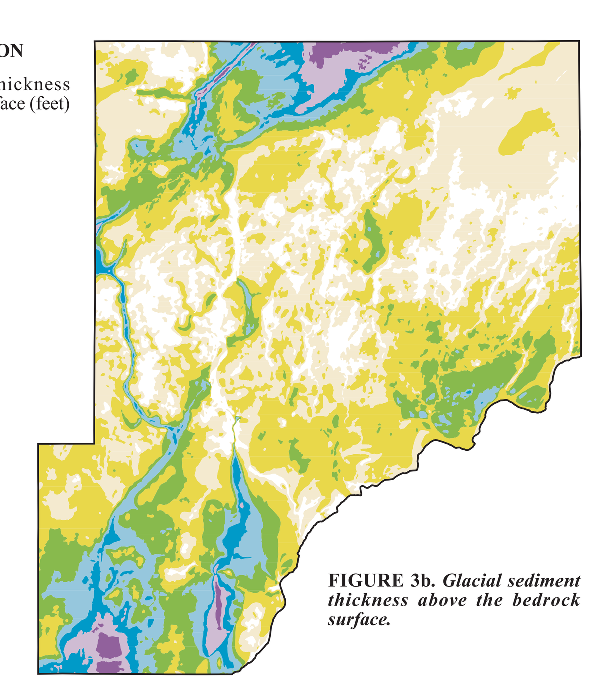


FIGURE 3b. ***Glacial sediment thickness above the bedrock surface.***

EXPLANATION

Local geologic factors

- Buried sand and gravel indicated by aeromagnetic geophysics
- Unsaturated Hinckley Sandstone, possibly associated with karst
- Approximate northern limit of clayey sediments of glacial Lake Lind
- Major river

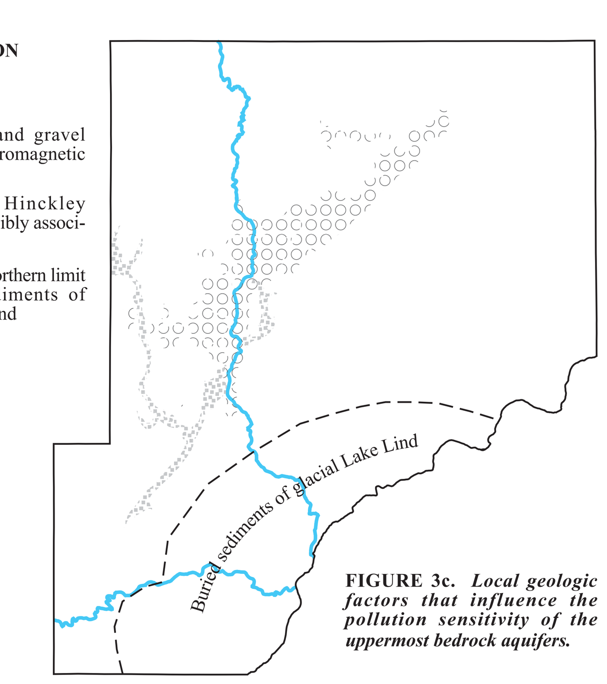


FIGURE 3c. ***Local geologic factors that influence the pollution sensitivity of the uppermost bedrock aquifers.***

FIGURE 3. ***Geologic conditions in Pine County considered in the sensitivity model.*** This figure shows the distribution of geologic conditions that were considered most important in rating the pollution sensitivity of the uppermost bedrock aquifers. These maps and the associated data were combined according to the sensitivity matrix (Figure 2) to produce the pollution sensitivity map.

The simplified map of surficial geology in Figure 3a was a major source of information for the sensitivity matrix and sensitivity map. The surficial sediment units from Part A, Plate 4, were reclassified to represent areas of relatively higher or lower permeability. The model assumes that overall permeability increases as sand and gravel thickness increases and till thickness decreases in areas of equal glacial sediment thickness. If the thicknesses of these materials were equal, the till and lake sediment areas would provide the most protection; conversely, the areas with sand and gravel would provide the least. The thickness of these materials, however, varies throughout the county.

The variation in sediment thickness was accounted for in the model with the map shown in Figure 3b representing glacial sediment thickness. This map was created by combining data from the Depth to Bedrock map (Part A, Plate 6) and data indicating very thin glacial sediment (less than 25 feet) from the Bedrock Aggregate map (Part A, Plate 7). The thick areas generally provide better protection than the thin areas, except for areas in the north-central portion of the county where the glacial sediment is mostly sand and gravel.

Certain local geologic factors within the county also have an important effect on pollution sensitivity. These factors (Figure 3c) include the unsaturated portion of the Hinckley Sandstone and associated karst conditions; thick, buried valley deposits of sand and gravel in west-central Pine County; and buried, clayey sediments of glacial Lake Lind in the southeast (Johnson and others, 1999). The unsaturated Hinckley Sandstone and the buried valley deposits of sand and gravel, if present, were assumed to increase pollution sensitivity. The buried sand and gravel aquifers in southern Pine County (Plate 8, Figure 2) protected beneath the glacial Lake Lind sediments were not considered in the sensitivity model.

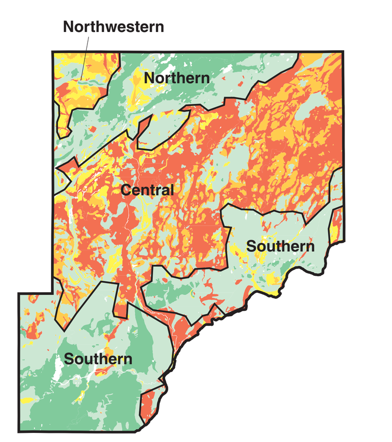
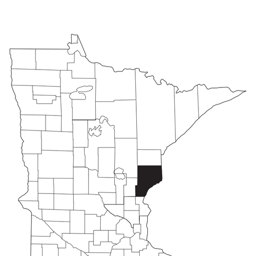


FIGURE 4. *Map of Pine County sensitivity areas discussed in the text.*



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://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 2001 to 2003 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, Mike Tronrud, and Greg Massaro. Edited by Nick Kroska.