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DEPARTMENT OF NATURAL RESOURCES
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COUNTY ATLAS SERIES
ATLAS C-19, PART B, PLATE 10 OF 10
Sensitivity of Groundwater Systems to Pollution

POLLUTION SENSITIVITY OF THE NEAR-SURFACE MATERIALS, BURIED SAND AND GRAVEL AQUIFERS, AND BEDROCK AQUIFERS

By

James A. Berg

2011

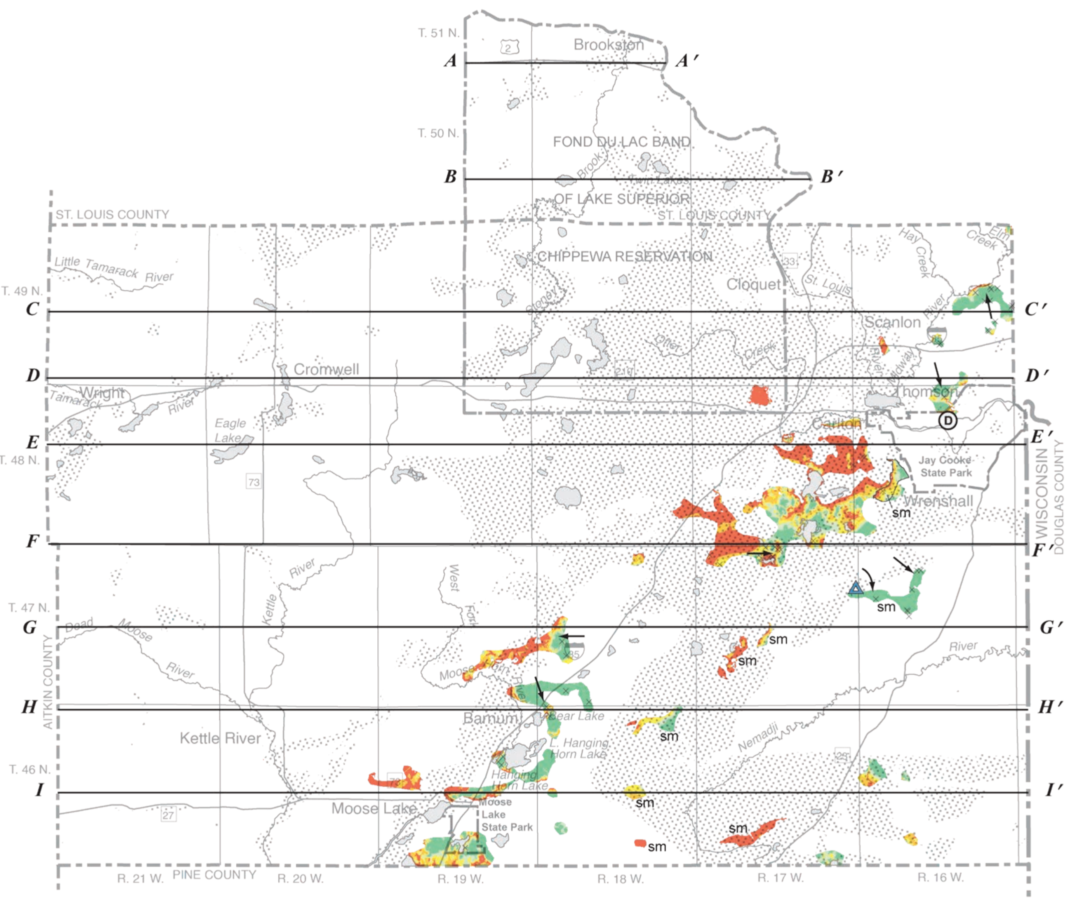

FIGURE 3. *Pollution sensitivity of the sm and sl buried sand aquifers; sl aquifer unless labeled otherwise.*

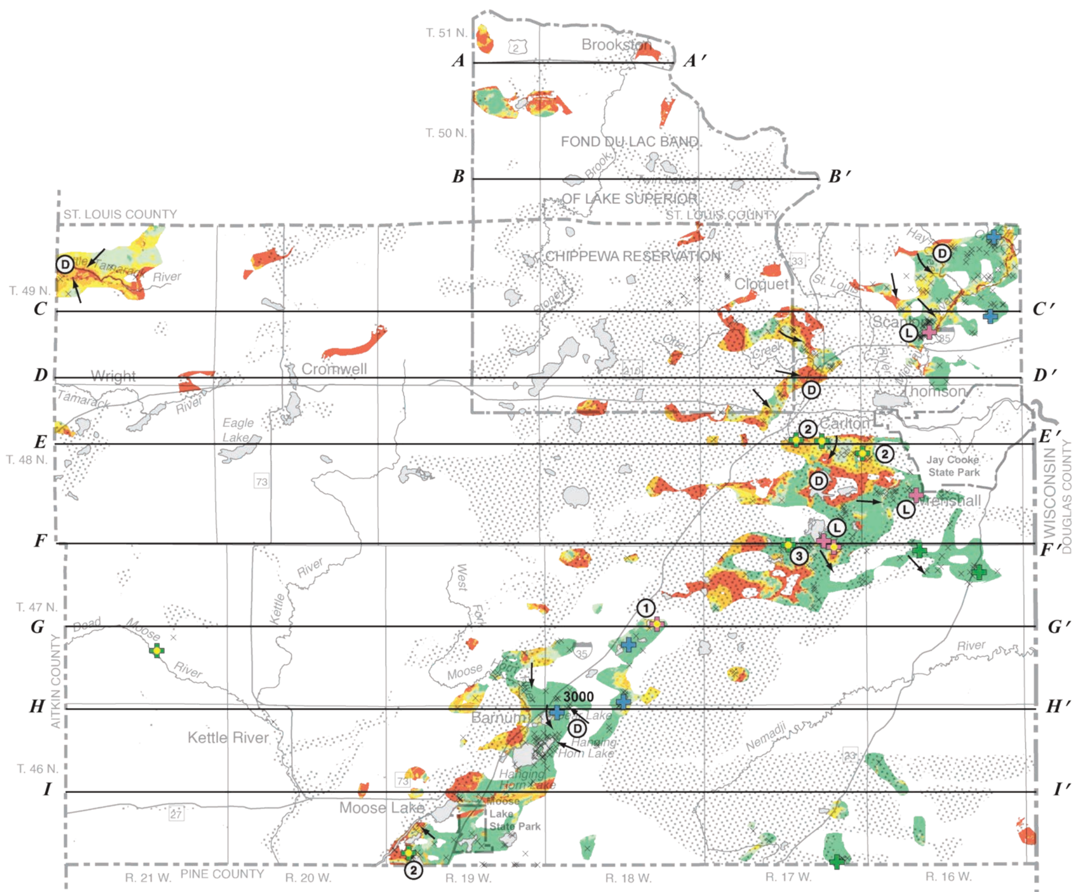

FIGURE 4. *Pollution sensitivity of the sc buried sand aquifer.*

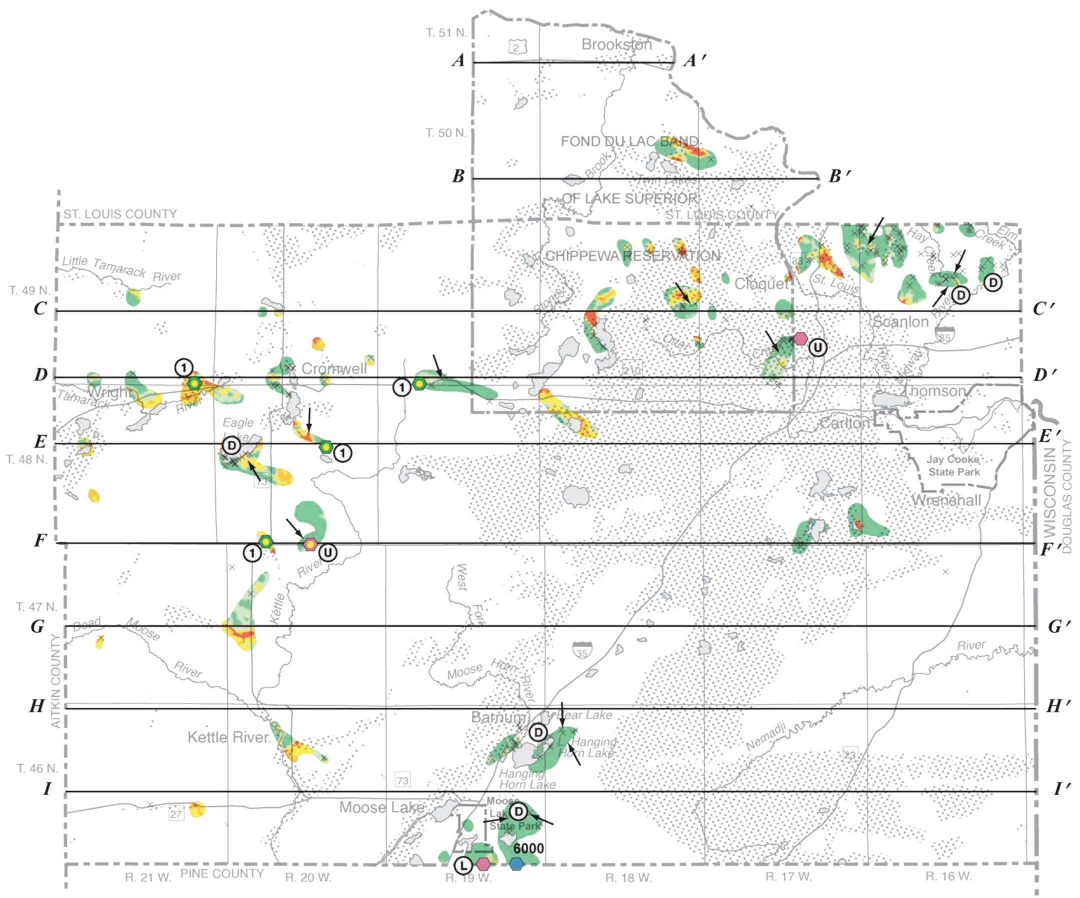

FIGURE 5. *Pollution sensitivity of the sc1 buried sand aquifer.*

Caution: The information on these maps is a generalized interpretation of the sensitivity of groundwater 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.

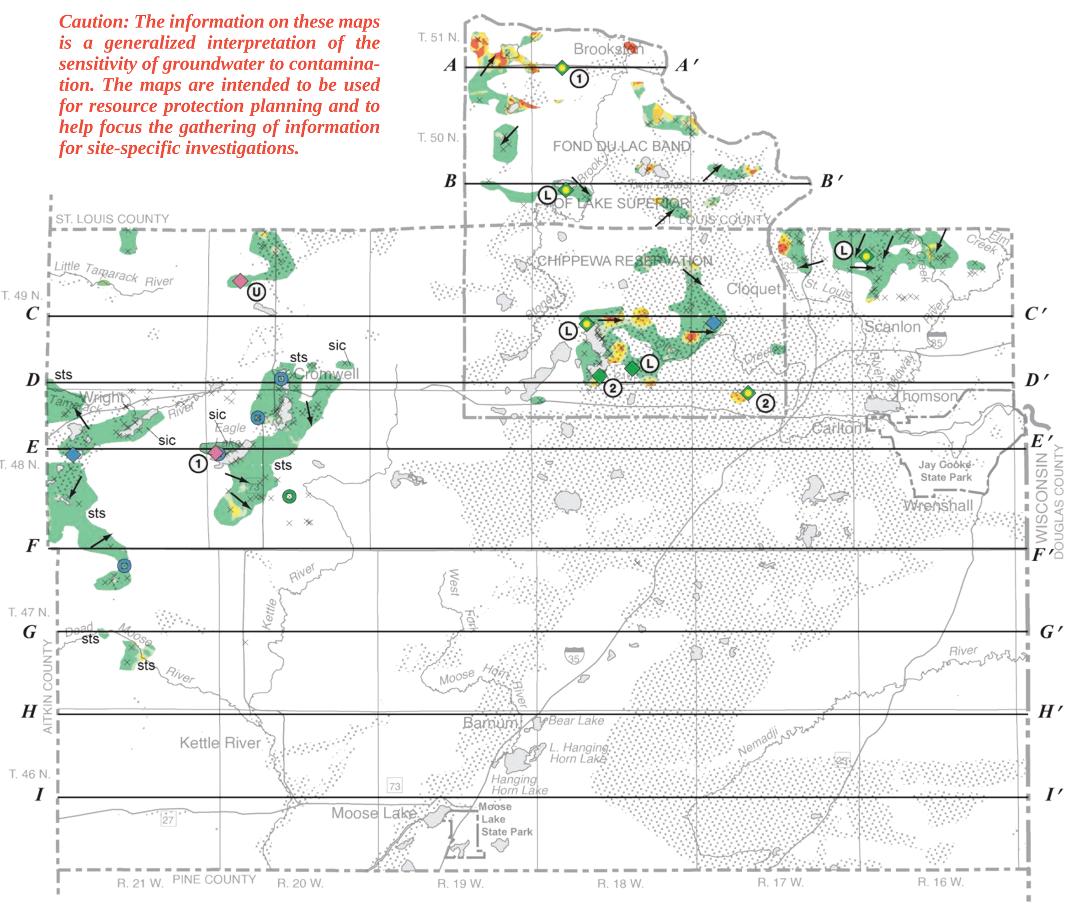

FIGURE 6. *Pollution sensitivity of the sic and sts buried sand aquifers; sic aquifer unless labeled otherwise.*

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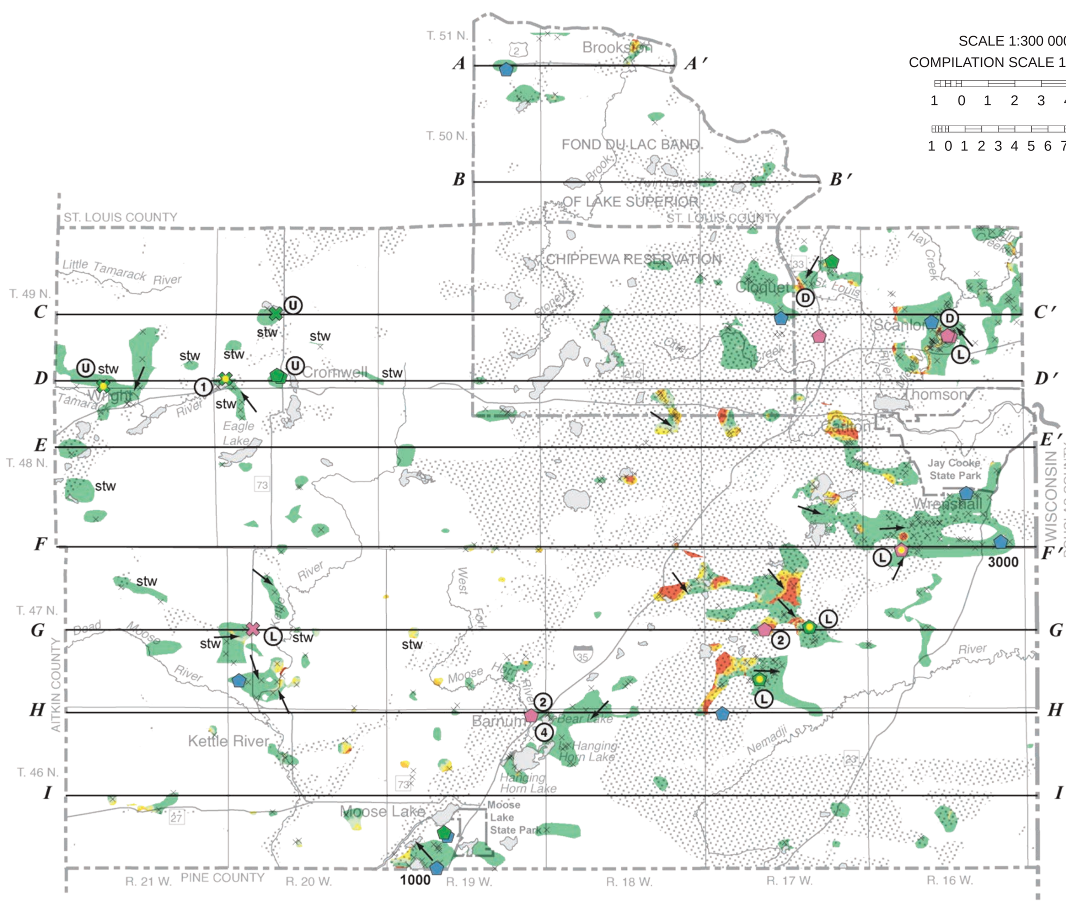

FIGURE 7. *Pollution sensitivity of the stw and su buried sand aquifers; su aquifer unless labeled otherwise.*

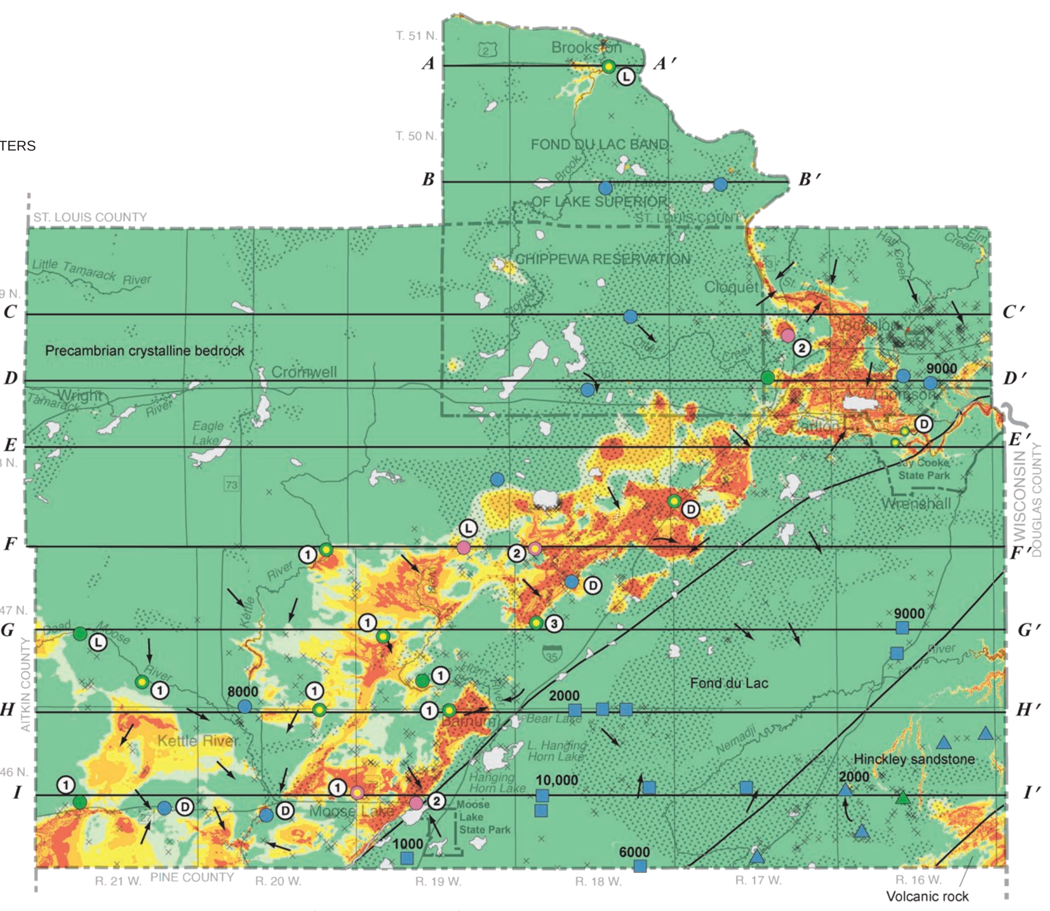

FIGURE 8. *Pollution sensitivity of the bedrock aquifers.*

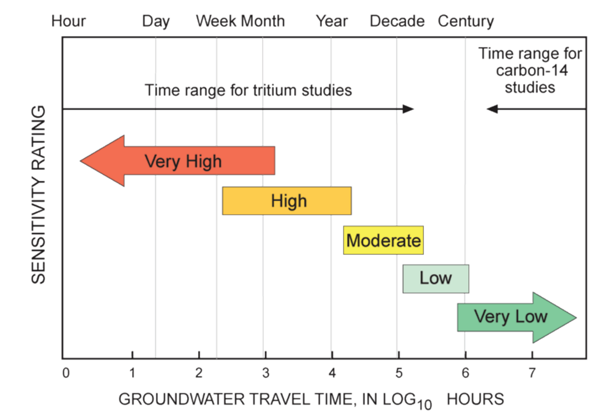

FIGURE 2. ***Geologic sensitivity rating for the buried sand and gravel aquifers and the bedrock aquifers as defined by vertical travel time (Geologic Sensitivity Workgroup, 1991).*** *Ratings are based on the time range required for water at or near the surface to travel vertically into the groundwater of interest or a pollution sensitivity target. Tritium and carbon-14 studies indicate the relative ages of groundwater.*

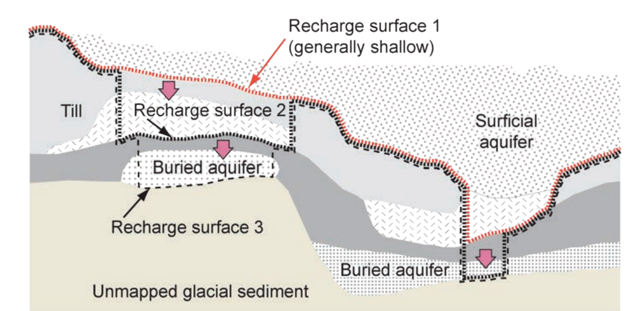

FIGURE 9. ***Generalized cross section showing recharge concepts for buried aquifers considered in the sensitivity evaluations.*** *In this model, all recent recharge enters the buried aquifer system at recharge surface 1 (red dotted line). Recharge surface 1 is considered to be at the land surface where till is present or at the bottom of surficial sand deposits. 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 reach and move to the bottom of the aquifer which is defined as recharge surface 2. A second deeper buried aquifer that has less than 10 feet of clay or till between it and the overlying buried aquifer is also assumed to allow further penetration of recent recharge. In that case, recharge surface 3 is defined at the bottom of this next deeper aquifer. The pink arrows indicate groundwater recharge of recent tritium age through a recharge surface.*

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 10. ***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 as defined in Figure 9. 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 above it to retard downward groundwater movement. A thicker overlying protective layer provides additional protection to the aquifer, and sensitivity ratings are assigned based on the thickness of this layer. In areas where the depth from the land surface to the top of the aquifer exceeds 100 feet, the very high and high classifications may be overestimates if vertical gradients and hydraulic conductivities are low.*

MAP EXPLANATION
Figures 3–8

Pollution sensitivity rating

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).

Sampled well and aquifer symbols

Buried sand and gravel aquifers
- sm
- sc
- sc1
- sic
- sts
- stw
- su

Bedrock aquifers
- Hinckley sandstone
- Fond du Lac Formation
- Precambrian crystalline bedrock

Symbols and labels

- If shown on well symbol, chloride to bromide ratio greater than 190.
- Groundwater sample from spring collected for chemical analysis; color indicates tritium age.
- Well log used to map aquifer
- Groundwater flow direction
- 2000 If shown, groundwater age in years, estimated by carbon-14 (^{14}C) isotope analysis.
- Extent of surficial sand aquifer.
- Major bedrock aquifer contact (Figure 8 only).
- F F′ Line of cross section.
- Body of water.

Groundwater conditions

- ① Infiltration through a thin layer of overlying, fine-grained material to an underlying aquifer.
- ② Groundwater recharge from overlying surficial aquifer to buried aquifer.
- ③ Groundwater leakage from an overlying buried aquifer to an underlying buried aquifer.
- ④ Groundwater leakage through multiple aquifers and fine-grained layers.
- Ⓓ Groundwater discharge from a buried aquifer to surface-water body.
- Ⓛ Lateral groundwater flow.
- Ⓤ Unknown source of recent or mixed groundwater.

INTRODUCTION

This plate describes the sensitivity to pollution of the buried sand and gravel aquifers, the bedrock aquifers in the study area, and of the near-surface materials by estimated infiltration travel time of a contaminant that moves conservatively with water. For the purpose of this study, the near-surface is defined as land surface to a depth of 10 feet.

Migration of contaminants dissolved in water through unsaturated and saturated sediments is a complex process. It is affected by biological degradation, oxidizing or reducing conditions, contaminant density, and other factors. Large-scale assessments of pollution sensitivity require some generalizing assumptions. For example, flow paths from the land surface through the soil and underlying sediments to an aquifer are assumed to be vertical; horizontal flow paths may be important in specific instances, but they have not been adequately mapped and are not considered in this sensitivity model. Permeability of the sediments is evaluated only qualitatively. The sensitivity assessment is an empirical method that estimates the time of travel for water from infiltration at the land surface to the pollution sensitivity target.

The geologic sensitivity rating of the near-surface materials (Figure 1) shows geologic sensitivity corresponding to an estimate of travel time from the land surface to a depth of 10 feet. The focus of this near-surface sensitivity rating estimate is travel in the vadose zone, which is the unsaturated zone between the land surface and the water table. The time of travel through this thin surface layer in the study area varies from hours to approximately a year. Areas with relatively short travel times (hours to weeks) are rated high or very high. Areas with longer travel times (months to a year) are rated low or very low.

Figure 2 shows the rating for geologic sensitivity that corresponds to an estimate of travel time to mapped buried sand and gravel aquifers and bedrock aquifers. The aquifer sensitivity rating has the same categories as the near-surface sensitivity rating, but the ratings represent significantly longer travel times; to distinguish the ratings applied to these two different pollution sensitivity targets, the two sensitivity ratings are shown in different colors.

The buried sand and gravel aquifer and the bedrock aquifer sensitivity ratings are based on vertical travel times defined by the Geologic Sensitivity Workgroup (1991). The travel times to these aquifers vary from days to thousands of years. Areas with relatively short travel times of less than a few years are rated high or very high. Areas with estimated travel times of decades or longer are rated low or very low.

SENSITIVITY TO POLLUTION OF THE BURIED SAND AND GRAVEL AQUIFERS AND THE BEDROCK AQUIFERS

Development of Sensitivity Model and Maps

The pollution sensitivity modeling and mapping process involved calculating the thickness of protective material overlying each aquifer and interpreting 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 the protective layers for the underlying aquifers 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.

The geologic maps and associated stratigraphic information created for Plates 3, 4, and 5 of Part A were the basis for all the hydrogeologic maps and cross sections shown in this Part B and represent the first step of the pollution sensitivity modeling process. For this report, some of the information from Part A was reclassified and reinterpreted to separate the surficial water table aquifer from the buried sand and gravel units that are most commonly treated as hydrologically confined aquifers. Thus, the extent and thickness of sand and gravel units Qsm, Qsl, and Qsc shown in Figures 5, 6, and 7, respectively, on Plate 5 of Part A have been modified. These three geologic map units are shown in this report as the less extensive corresponding buried sand and gravel aquifers sm, sl, and sc; the surficial portions of these units have been reclassified and incorporated into the surficial sand aquifer map. In addition, the sc1 aquifer (Figure 5) that had not been mapped as part of the set of sand and gravel units on Plate 5 of Part A was mapped for this report as an additional buried aquifer. The remaining buried sand and gravel aquifer maps (Figures 6, 7, and 8) are unchanged from corresponding geologic map units in Part A. The relationship between geologic map units and aquifers is illustrated in Figure 2 on Plate 8.

Once these modifications to the digital maps were completed, a method using three-dimensional GIS surfaces that has been used for previous atlases (Berg, 2006; Tipping 2006; Petersen, 2007; Berg, 2008; Peterson, 2010) was used to create the pollution sensitivity evaluation shown on this plate. This model predicts how water from precipitation, which first infiltrates the surficial aquifers, directly recharges portions of the first underlying aquifer and, subsequently, portions of deeper aquifers. The central concept of the model is focused recharge, or 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 simplifies this concept by dividing focused recharge into discrete surfaces at the base of each aquifer, which are called recharge surfaces (Berg, 2006). 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, a thin protective layer is considered to be 10 feet or less in thickness.

The vertical recharge path of water for a stack of aquifers typical of the study area is shown in Figure 9. The figure shows a generalized cross section of the principal aquifers mapped in a 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. In Figure 9, 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 or clayey lake sediment) 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). If the same criteria are applied at recharge surface 2 (underlying protective layer thickness of 10 feet or less), recent or mixed water 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 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 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 or aquitard 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 10 shows the rating matrix for interpreting the pollution sensitivity of the buried aquifers according to the calculated protective layer thickness. The resulting pollution sensitivity evaluations for each buried sand and gravel aquifer are shown on Figures 3 through 7. The same process was conducted to produce the bedrock aquifers pollution sensitivity map in Figure 8.

Comparison of Sensitivity Model to Groundwater Chemistry Data from the Buried Sand Aquifers

The results of a valid pollution sensitivity model should generally correspond to the distribution of groundwater residence time indicators. The most important indicators for the buried aquifers were the values and spatial characteristics of tritium in collected groundwater samples. In general, the groundwater samples with recent and mixed tritium age should correspond to areas of very high to moderate sensitivity, and the groundwater samples of vintage tritium age should correspond to areas of low to very low sensitivity. The ^{14}C residence time values from collected groundwater samples were also useful for corroborating sensitivity ratings for portions of the buried aquifers that have a predicted very low sensitivity. The chloride to bromide (Cl/Br) ratios as an anthropogenic (created by humans) 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 ratings.

Buried sand and gravel aquifers. The sm and sl aquifers are both shown on Figure 3. Moderate to very high sensitivities are very common for both of these aquifers due to generally shallow conditions and overlying surficial sand in many areas. Only one groundwater sample was collected from the sm aquifer located southwest of Wrenshall. The vintage tritium age of the sample at that location is consistent with the associated very low sensitivity rating.

Moderate to very high sensitivities were also common along the northwestern edge of the sc aquifer (Figure 4) extending from south-central to northeast Carlton County where the aquifer is typically shallower and overlain by surficial sand. Most of the groundwater samples had recent and mixed tritium age and are consistent with the pollution sensitivity ratings with the exception of three samples with recent tritium age from the sc aquifer (one sample east of Scanlon, and two samples southwest of Wrenshall) in an area of the sc aquifer rated very low sensitivity. Lateral groundwater movement from nearby recharge areas or well construction problems may account for these inconsistencies. Most of the groundwater samples from this aquifer that had recent and mixed tritium age also had elevated Cl/Br values consistent with contaminant sources. The ^{14}C residence time of 3000 years of the sample east of Barnum is consistent with the very low sensitivity rating in that area.

Similar to the previously described aquifers, the sc1 aquifer shows a mixture of sensitivity ratings from very high to very low (Figure 5). Most of the groundwater samples with recent and mixed tritium age in the western part of the study area associated with moderate to very high sensitivity ratings are due to infiltration through thin overlying fine-grained layers (glacial till). The groundwater sample with recent tritium age west of the Kettle River is in a portion of the sc aquifer rated very low sensitivity and may be due to poor well construction. The two groundwater samples collected from the south-central portion of the study area show that local variations in the overlying stratigraphy can have a significant effect on groundwater residence time. The recent tritium age of the western sample is likely due to infiltration through overlying sand layers. In contrast, just over a mile to the east of the recent-age sample, a water sample from the aquifer had vintage tritium age and had a ^{14}C groundwater age of 6000 years.

The pollution sensitivity of the sic and sts aquifers is shown on Figure 6. Most areas of both aquifers have a very low sensitivity rating due to greater depth of burial and lack of overlying surficial sand. Two groundwater samples were collected west of Eagle Lake (located in the western part of Carlton County and the left side of cross section E-E′). The sample from the shallower sic aquifer had a recent tritium age and the sample from the deeper sts aquifer had vintage tritium age. The seven samples with mixed tritium age in the north central and northeastern parts of the study area reflect a range of conditions including infiltration through thin overlying protective layers (groundwater condition ①), lateral groundwater movement from nearby recharge areas (condition Ⓛ), and leakage from the surficial aquifer (condition ②).

The stw and su aquifers (Figure 7) generally have very low sensitivity ratings due to thick overlying protective layers. Most of the areas rated moderate to very high sensitivity are in the eastern part of the study area where the su aquifer is overlain by thick surficial sand. Apparent lateral groundwater flow from nearby recharge areas accounts for several samples with recent and mixed tritium age in the eastern part of the study area. A sample with recent tritium age collected from a location in the southwestern part of the study area may represent another example of this condition.

Bedrock aquifers. Shallow bedrock conditions, with depth to bedrock of less than 150 feet, is very common in the study area with the exception of the deep bedrock valley in the southeastern part of the study area and portions of the northwestern study area. Most of the area of the bedrock aquifer rated moderate to very high sensitivity has generally shallow bedrock conditions and consequently limited overlying protective layers. The most common infiltration condition in the southwestern part of the more sensitive area is infiltration through a thin layer of overlying, fine-grained material to an underlying layer (condition ①). In the northeastern part of this area, where shallow bedrock conditions coincide with the presence of surficial and buried aquifers, direct and indirect recharge from the surficial sand aquifer to the bedrock aquifers is evident (conditions ② and ③). At several locations across this more sensitive area near rivers and streams, groundwater samples of mixed and vintage tritium age indicate probable upwelling conditions or groundwater discharge locations (condition labeled as Ⓓ) as deeper, older water is brought to the surface by upward gradients. Samples with recent or mixed tritium age that do not match the local pollution sensitivity ratings, such as groundwater samples of recent tritium in low to very low sensitivity areas, are probably due to lateral groundwater movement (condition Ⓛ).

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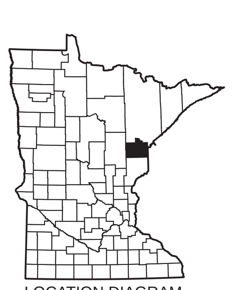

LOCATION DIAGRAM

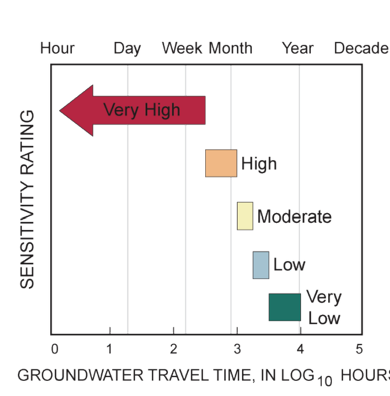

FIGURE 1. ***Geologic sensitivity rating for the near-surface materials as defined by vertical travel time.*** *Ratings are based on the time range required for water at the land surface to travel vertically 10 feet through the vadose zone to the water table. Because the water table is not well mapped everywhere, it is assumed to be at 10 feet below land surface for this calculation.*

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Base modified from Minnesota Geological Survey, Carlton County Geologic Atlas, Part A, 2009.
Project data compiled from 2009 to 2010 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, Greg Massaro, and Shana Pascal. Edited by Neil Cunningham.

TABLE 1. Infiltration rates used to assess pollution sensitivity rating of near-surface materials. Minimum transmission rates for NRCS hydraulic groups (2009a) and surficial geology map units are from Tipping (2006) using similar ranges of soil and sediment textures.

NRCS hydraulic group rating	Texture	Minimum transmission rate (inches per hour)	Surficial geology map unit (Plate 3 of Part A)	Texture	Minimum transmission rate (inches per hour)
A, AD	muck, sandy loam, loamy sand	0.3	Qai, Qao, Qci, Qco, Qd, Qli, Qlo, Qmi, Qmo, Qt, Qwg	sand and gravel	0.5
B, BD	sandy loam, silt loam	0.15	Qal, Qcc, Qct, Qha, Qit, Qll, Qws	sandy loam	0.3
C, CD	loam, very fine sandy loam, silt loam, fine sand	0.05	Qhp, Qlc, Qlt, Qul, Qac, Qmc	loam to silty loam, peat	0.15
D	clay, loam, fine sandy loam, peat, silty clay	0.01	Qab, Qat, Qmt, Qmw	loam to clay loam	0.05
			Qkt, Qwf	clay loam	0.01

SENSITIVITY TO POLLUTION OF THE NEAR-SURFACE MATERIALS

The sensitivity to pollution assessment for near-surface materials estimates the time of travel for water to travel from the land surface to a depth of ten feet, and is shown in Figure 11. Soil properties are used to estimate the travel time from land surface to a depth of three feet and surficial geology properties are used to estimate the travel time from a depth of three feet to ten feet. The near-surface materials sensitivity assessment was developed by estimating infiltration rates through soils and surficial geologic units based on the Natural Resources Conservation Service (NRCS) hydraulic rating (NRCS, 2009a) for soils and the geologic unit texture of deeper parent materials from Plate 3 of Part A, Surficial Geology. Estimates of infiltration rates are shown in Table 1. The NRCS defines hydraulic groups primarily based on the soil unit's texture and the presence or absence of dense, low permeability layers.

Hydraulic group A soils are more than 90 percent sand and gravel, and water is freely transmitted through the soil. Group B soils are less permeable than group A soils, but water transmission is unimpeded through the soil. In group C soils, water transmission is somewhat restricted. In group D soils, water movement is restricted or very restricted. Tipping (2006) estimated minimum transmission rates for these four soil hydraulic groups based on an NRCS web publication that is no longer available. Estimated minimum transmission rates for the surficial geologic units from Tipping (2006) were also used for this assessment.

The near-surface materials sensitivity rating is determined by using the minimum transmission rates for the soil and surficial geologic units to calculate the estimated travel time to the assumed water table depth of 10 feet. The GIS polygons from the soil survey of St. Louis County (NRCS, 2006), the soil survey of Carlton County (NRCS, 2009b), and the surficial geologic map (and the corresponding transmission rates) were combined; the total travel time to 10 feet was calculated using the soil rate for the upper three feet and the surficial geologic material rate for the lower seven feet.

The combined estimate from both layers is shown in Figure 11 as the near-surface materials geologic sensitivity. Most of the study area has an estimated infiltration travel time of 10 to 60 days (very high to moderate pollution sensitivity rating) since sand, sandy loam, and sandy till are common materials at the surface to near-surface depths, especially in the northwestern two-thirds of the study area. Estimated infiltration travel times of 61 to 510 days (low to very low pollution sensitivity rating) are very common in the southeastern portion of the study area where clay soil, and till or clayey lake sediment are the primary near-surface material. Some abrupt discontinuities of sensitivity ratings along the Carlton-St. Louis County border are due to discrepancies in the respective county soil surveys that were created at different dates by different investigators.

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COMPILATION SCALE 1:100 000
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1 0 1 2 3 4 5 6 7 8 9 KILOMETERS

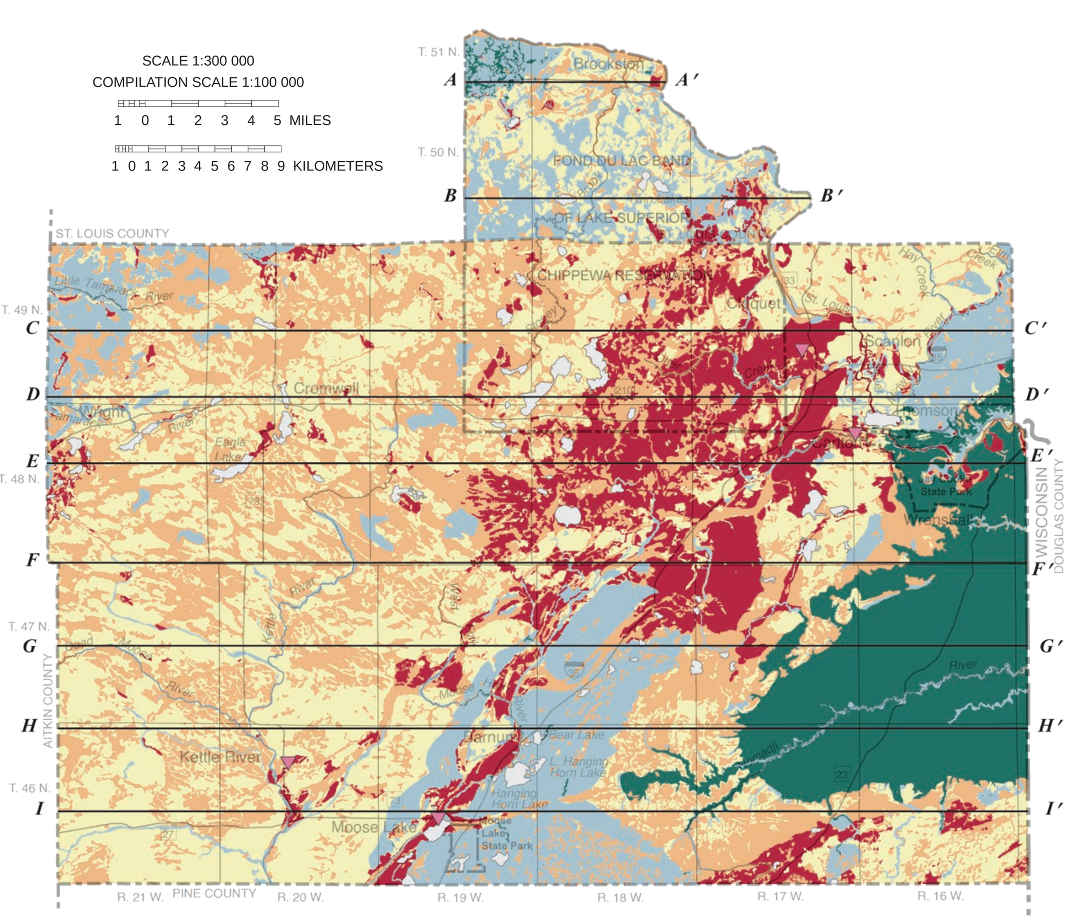

FIGURE 11. *Pollution sensitivity of the near-surface materials.*

MAP EXPLANATION FOR FIGURE 11

Pollution sensitivity ratings for near-surface materials

Estimated vertical travel time for water-borne contaminants to move from the land surface to a depth of 10 feet.

- VH Very High—Hours to weeks.
- H High—Weeks to a month.
- M Moderate—A month.
- L Low—Several months.
- VL Very Low—Months to a year.

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]).

Well and aquifer symbols

- Surficial sand aquifer.

Symbols and labels

- F F′ Line of cross section.
- Body of water.