STATE OF MINNESOTA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATERS—Surface Ground Water

REGIONAL HYDROGEOLOGIC ASSESSMENT SERIES
RHA-4, PART B, PLATE 4 OF 4
Geologic Sensitivity to Pollution of Near-Surface Ground Water

GEOLOGIC SENSITIVITY TO POLLUTION OF NEAR-SURFACE GROUND WATER

By
Randy Bradt
2000

INTRODUCTION

Prevention of ground-water contamination is an important part of water resource management. An important first step is to recognize where ground water is particularly sensitive to pollution. The 1989 Minnesota Groundwater Protection Act requires the Minnesota Department of Natural Resources (DNR) to map geographic areas defined by natural features where there is a significant risk of ground-water degradation from activities conducted at or near the land surface. This plate describes the sensitivity to pollution of the shallow portion of near-surface ground-water systems, including surficial aquifers. The sensitivity map depicts the relative potential for ground-water contamination by using categories of travel time. The travel time categories, ranging from Very High to Very Low, describe the time needed for water-borne contaminants to travel from the land surface to the shallow portion of the near-surface ground water. The map shows that areas mapped as sand and gravel at or near the surface are more susceptible to rapid transport of contaminants than are areas mapped as glacial till and lake sediments. The information on this plate allows planners to include ground-water quality concerns in land-use decisions. The pollution sensitivity map is also useful for directing fiscal resources to areas of greatest potential for ground-water contamination.

GEOLOGIC SENSITIVITY

DNR Geologic Sensitivity Guidelines

Geologic sensitivity as described in the DNR guidelines (Geologic Sensitivity Workgroup, 1991) is used to assess pollution sensitivity and prepare maps depicting areas sensitive to pollution. The guidelines focus on travel time: the time it takes for water-borne contaminants to vertically travel from the land surface to the water table. Travel time primarily depends on the permeability and thickness of geologic materials between the land surface and the water table. Geologic materials with the lowest vertical permeability are assumed to have the greatest capacity to retard the vertical movement of contaminants, resulting in the longest travel times. Conversely, geologic materials with the highest vertical permeability are assumed to be least capable of retarding the vertical movement of contaminants, resulting in the shortest travel times. The geologic sensitivity criteria are shown in Figure 1. There are five overlapping classes of travel times. Each class is assigned a relative geologic sensitivity rating from Very High to Very Low. The ranges of travel time for each class overlap because of the uncertainty of travel-time estimates. Short travel times do not mean that ground water is or will be contaminated, and long travel times do not ensure that ground water in these areas is or will remain uncontaminated.

Assessing geologic sensitivity requires several simplifying assumptions: (1) contaminants are chemically inert and move with the water, (2) contaminants are released at or near the land surface and move vertically downward, (3) estimates of permeability can be made based on the general knowledge of saturated permeabilities for broad groups of geologic materials, and (4) surficial geologic map units from Plate 1 in Part A are representative of the geologic materials from the land surface to the water table.

Modifications of Vertical Travel Time Concept

Ground-water flow occurs through voids (pores) in the geologic material, which are categorized as either primary or secondary porosity. Primary porosity represents the pore space between grains already present when the glacial sediments were deposited, and secondary porosity is the pore space resulting from fractures, joints, worm burrows, and root traces that developed after the sediments were deposited.

Estimates of travel times to the water table are based on an assumption that flow rates through unsaturated geologic materials are equal to or slower than flow rates through the same materials under saturated conditions. The presence of secondary porosity, however, makes this assumption inaccurate. Several studies from the Midwest and Canada (Alexander and Alexander, 1989; Ruland and others, 1991) have shown that fractures in till allow water to move at or near the land surface and move vertically downward, then travel laterally through higher permeability sediments until discharging into nearby lakes, wetlands, and streams.

The presence of secondary porosity significantly decreases or disappears below the water table. In this study, geologic sensitivity is defined as the time it takes water-borne contaminants to travel vertically from the land surface to a target zone, a zone extending from the water-table surface to a depth of 20 feet below the water table (Figure 2). The objective for extending the sensitivity target depth an additional 20 feet below the water table was to ensure that the target zone included geologic material that is not influenced by secondary porosity.

Well drillers and geologists have noted that there is a color change in glacial till sediments at depth. As shown in Figure 2, the upper oxidized zone has lighter brown, yellow, or gold sediments that overlie unoxidized darker gray, blue, or black sediments. As water containing dissolved oxygen enters the till, various minerals in the till are oxidized causing the till color to change. Much of the color change probably can be attributed to the oxidation of iron. As the water moves through the till, microbes remove oxygen from the water. The dissolved oxygen content decreases as water moves deeper into the till until no oxygen is available to oxidize minerals. An approximate median oxidized zone thickness was determined to be 22 feet for this study area based on well log information from the County Well Index (CWI) data base maintained by the Minnesota Geological Survey.

The significance of the oxidized zone is that till fractures are associated with that zone. Studies by Ruland and others (1991), Hendry (1988), and others have used parameters such as isotopes, general water chemistry, water level measurements, and pump test data to evaluate the hydrogeology of glacial tills. The studies show that the oxidized zone can be orders of magnitude more transmissive than the underlying unoxidized till. A study by Grisak and others (1976) determined that fractures could increase a till's ability to transmit water by approximately two orders of magnitude. Fracture density appears to decrease with depth. The fractures may extend into the unoxidized zone, but their numbers and effectiveness for transmitting water are significantly reduced.

An analysis of depth to water information from the CWI database shows that for most of the study area, the water table probably occurs in the oxidized zone. Because of the presence of fractures in the oxidized zone, there is concern that contaminants could be rapidly transmitted from the surface to the water table and below. However, the role of fractures in ground-water hydrology decreases significantly a few feet below the water table; therefore, a depth of 20 feet below the water table was chosen to define the maximum depth of the target sensitivity zone.

PREPARATION AND INTERPRETATION OF THE SENSITIVITY MAP

The surficial geologic map units from Plate 1 in Part A are the source of geologic information for the sensitivity map. Important textural information can be found in the detailed descriptions of the surficial geologic map units. Additionally, the "Correlation of Map Units" groups various geologic map units according to their mode of deposition and geologic age.

The first group, "ice deposits," contains the following eight mapped glacial till deposits: Qtrd, Qtmd, Qbad, Qfd, Qtld, Qtqd, Qtfr, and Qtbr. The texture of these mapped units ranges from loam to clay. The textures vary because the various mapped till units but also within each mapped till unit. The percentage of clay in tills in the study area, reported in Table 1, Part A, ranges from 10 to 40 percent with most tills averaging more than 20 percent. A clay content of 15 to 20 percent was determined to mark a threshold above which hydraulic conductivities are uniformly low (Stephenson and others, 1988). The term hydraulic conductivity refers to the geologic material's ability to transmit water. In a ground-water study involving 12 aquifer tests near the Pomme de Terre and Chippewa rivers, Delin (1986) reported an average vertical hydraulic conductivity for glacial till of 0.025 foot per day. Additionally, a review of water-level data from wells in the region shows that vertical hydraulic gradients are commonly 0.3 or less. Ground-water flow occurs through the pores, which constitute an estimated volume of 30 percent of the total till matrix. If these values are representative of tills in the study area, the calculated flow rate of water through till probably ranges from a few inches to as much as 10 feet per year. The travel time for contaminants moving with water from the land surface to the lower part of the target zone would best be described by a Moderate sensitivity rating for these sediments. This fact means that water-borne contaminants would take from several years to a decade to travel from the surface to the lower part of the target zone. These estimated flow rates are several orders of magnitude slower than flow rates through sand and gravel deposits.

The second group of deposits, "stream deposits," includes the following six geologic map units: Qssd, Qsd, Qsld, Qdb, Qsw, and Qsh. These are generally sorted sand, gravel, and silt-sized sediments that are capable of transmitting water from tens to hundreds of feet per day. Horizontal hydraulic gradients in areas not under the influence of pumping wells are generally low; therefore, actual flow rates are more likely to be from inches to a few feet per day, with most flow moving horizontally. Most of these deposits were rated Very High sensitivity, which means contaminants could reach the lower part of the target zone within a month and possibly within a few hours or days.

Not all of the stream sediments are simply sand and gravel deposits; other factors were considered when assigning a geologic sensitivity rating. Some of the mapped stream deposits are associated with unsorted or fine-grained sediments that are interbedded with or overlie the mapped stream sediments. For example, map unit Qsld is overlain by up to 10 feet of clay, silt, fine sand, and organic deposits. These deposits provide some additional protection, so the sensitivity rating was reduced from Very High to High. Additionally, if Qoh (organic deposits) overlies or is adjacent to stream sediments, a Very High sensitivity rating was assigned. There are also sand and gravel deposits that may be locally unsaturated. For example, map unit Qssd is interpreted as stream sediment that was deposited in channels walled by glacial ice. After the ice melted, these deposits remained as ridges of sand and gravel, which may be unsaturated as a result of gravity drainage. Another stream sediment that may also be locally unsaturated is the glacial River Warren (Qsw) sand and gravel that primarily forms terrace deposits along the Minnesota River. Since insufficient information is available to determine whether a water table is present for all mapped Qsw and Qssd sediments, the water table was assumed to occur within these mapped units, and they were assigned a geologic sensitivity rating of Very High.

The mapped stream sediments, which compose approximately 25 percent of the study area, were all classified as either Very High or High sensitivity. Where these sediments occur, contaminants could rapidly move into the subsurface and contaminate ground water. In some places, a potential pathway for contaminants could exist where a hydraulic connection exists between surficial and buried sand and gravel deposits. Another concern is lateral migration of contaminants. Even though transport of contaminants is vertically restricted by underlying, lower permeability material, they could move laterally through higher permeability sediments until discharging into nearby lakes, wetlands, and streams.

In the third group, four geologic map units (Qgl, Qib, Qih, and Qoh) make up the "lake deposits" category. The most widespread deposits are associated with glacial Lake Benson (Qib), which consists of clay, silt, and some fine sand. The texture of Qoh does not significantly restrict ground-water movement. However, where Qoh occurs within other lake deposits or glacial till, it was assigned a Moderate sensitivity rating. This rating was based on the assumption that the surrounding geologic material also underlies Qoh and best represents the degree of protection provided to shallow ground water. Insufficient information is available concerning the hydrologic characteristics for the remaining three map units (Qgl, Qib, and Qih). The textures of these sediments are generally fine grained; therefore, they were assumed to provide a degree of protection similar to the glacial tills in the study area and were thus rated a Moderate geologic sensitivity.

The fourth group is characterized by one map unit (bA), the "bedrock" category. Outcrops of these rocks are found in the Minnesota River valley where removal of overlying sediment and weathered rock has exposed various granite and gneiss bedrock. These rock units are characterized by very little primary porosity. Most of the water found in these rocks occurs where fracturing has created secondary porosity. Because the rocks have the potential to rapidly transmit contaminants through fractures and because these rocks are found close to stream sediment (Qsh), they were rated a Very High geologic sensitivity.

USING THE POLLUTION SENSITIVITY MAP

The sensitivity map portrays information that is generalized according to the scale at which it is shown. Enlarging the map could result in a false indication of precision. The sensitivity map does not account for changes in sensitivity as a result of human activities, such as improperly constructed or abandoned wells that may accelerate transport of contaminants to the water table. Additionally, map unit boundaries are a product of the geologic sensitivity assessment model and do not represent absolute differences in sensitivity. Each map unit represents a predominant sensitivity rating; therefore, this map should not be considered a substitute for site-specific information.

EVIDENCE SUPPORTING THE SENSITIVITY INTERPRETATIONS

The pollution sensitivity map is divided into regions having a range of estimated time required for contaminants to travel from the land surface to the lower part of the target zone. Verifying the mapped ratings directly is difficult, so measurements of ground-water residence time and water quality are used as indirect tests. Residence time is the approximate time that ground water has resided below the land surface until it is discharged or pumped from an aquifer. Radiometric dating using isotopes of hydrogen or carbon provides estimates of ground-water residence times (Alexander and Alexander, 1989). Tritium (^{3}H), as discussed on Plate 3, is an isotope of hydrogen that is an indicator of recently recharged precipitation. If a ground-water sample has no detectable tritium, the sample is dominated by precipitation that entered the subsurface prior to 1954. Conversely, samples containing detectable tritium have some component of post-1953 recharge.

The wells sampled in this study are plotted on the sensitivity map along with their aquifer type and interpreted tritium results. The tritium information is useful for estimating how deeply water has vertically infiltrated during the last 45 years. The thickness and permeability of geologic materials between the land surface and the aquifer significantly affect the vertical flow rates. Labels posted for each well on the map include the sampling interval, confining score, and depth to the aquifer. This additional information is necessary to clarify the role of various geologic materials in providing protection for aquifers in the study area.

The sampling interval represents the depth to the top and bottom of the well screen through which the sampled water enters the well. The confining score is a calculated value that represents the cumulative thickness of low-permeability material between the land surface and the top of the aquifer. When each well was drilled, the driller recorded the thickness and type of geologic materials and other well construction information on a well log. To calculate a confining score, a value of 1 was assigned for every foot of low-permeability sediment (clay, shale, or till). Sand and gravel offer little protection and were assigned a zero value. Therefore, the confining score is the sum of the low-permeability material above the sampled aquifer. The last value reported on the label is the depth to feet below land surface to the top of the aquifer.

Mapped surficial sand and gravel deposits in the study area were interpreted as either Very High or High sensitivity. Several residents with wells completed in these deposits have reported rapid water-level changes that are occasionally associated with muddied water soon after a rain event. Additionally, water samples from these surficial aquifers generally have rather low concentrations of dissolved solids, elevated levels of dissolved oxygen, and detectable tritium. Surficial aquifers are also more likely to have elevated nitrate concentrations. All of these observations indicate rapid infiltration and support the Very High and High geologic sensitivity ratings.

BURIED AQUIFER SENSITIVITY

Most of the wells in the study area are completed in buried aquifers that are usually located more than 20 feet below the water table. The pollution sensitivity map does not specifically address vertical travel times to these aquifers. In general, most of the buried aquifers are overlain by a sufficient thickness of low-permeability geologic material to be assigned a Moderate or Low sensitivity rating. Carbon-14 age dates ranging from 1,500 to 8,000 years before present support a Very Low sensitivity rating for aquifers more than 100 feet below land surface. The samples were collected from nine wells completed in Quaternary or Cretaceous deposits between 109 and 453 feet deep. As previously mentioned, if vertical flow rates at only 1 foot per year are assumed to be constant with depth, the oldest water from the sampled wells should be 453 years old. The carbon-14 age dates, however, are much older. One explanation for this disparity may be that lateral flow becomes increasingly important with depth. Shallow aquifers may be part of local or intermediate flow systems that have shorter ground-water residence times because recharge and discharge occur over relatively short distances. Deeper wells are probably located within regional ground-water flow systems that have a much longer residence time because of slower movement and longer flow paths from recharge to discharge areas.

Figure 3 is a schematic illustration showing the relationship between the vertical distribution of tritium and representative hydrogeologic conditions for the upper Minnesota River basin study area. The tritium sample results collected from buried aquifers within till suggest that tritium in till probably extends from the land surface to an average depth of approximately 50 feet. This is also where local and intermediate flow systems are found. From 50 to 100 feet deep is a transition zone representing the maximum depth that post-1954 water has infiltrated. Samples from aquifers below 100 feet are rarely found to have tritium; these aquifers are interpreted to be part of the regional flow system.

Figure 3 also shows four conditions in which local geologic and well construction factors could enhance water's ability to travel to the water table or to an aquifer. Condition 1 represents unmapped, localized zones of more permeable geologic materials within till providing a preferential pathway for water to enter the subsurface. Condition 2 shows how an aquifer could appear to be well protected by thick till in one location; however, in other locations the till is thin or absent, thus allowing more rapid recharge at those sites. Following recharge, horizontal ground-water movement transports the recently recharged water to other locations in the aquifer. Condition 3 shows an improperly constructed well acting as a conduit for water to enter from the surface or for water to move from one aquifer to another. Condition 4 is an example of fractures that are likely to be present in glacial tills or lake sediments (modified from Ruland and others, 1991). These fractures can allow water to move more quickly than expected.

REFERENCES CITED

Alexander, S.C., and Alexander, E.C., Jr., 1989, Residence times of Minnesota groundwaters: Journal of the Minnesota Academy of Science, v. 55, no. 1, p. 48-52.

Bradt, R., 1997, Surficial hydrogeology, Plate 3 of Faltesek, J., ed. and project supervisor, Regional hydrogeologic assessment, southwestern Minnesota: Minnesota Department of Natural Resources, Regional Hydrogeologic Assessment Series RHA-2, Part B, scale 1:200,000.

Delin, G.N., 1986, Hydrogeology of confined-drift aquifers near the Pomme de Terre and Chippewa rivers, western Minnesota: U.S. Geological Survey Water-Resources Investigations Report 86-4098, 70 p.

Geologic Sensitivity Workgroup, 1991, Criteria and guidelines for assessing geologic sensitivity of ground water resources in Minnesota: St. Paul, Minn., Minnesota Department of Natural Resources, Division of Waters, 122 p.
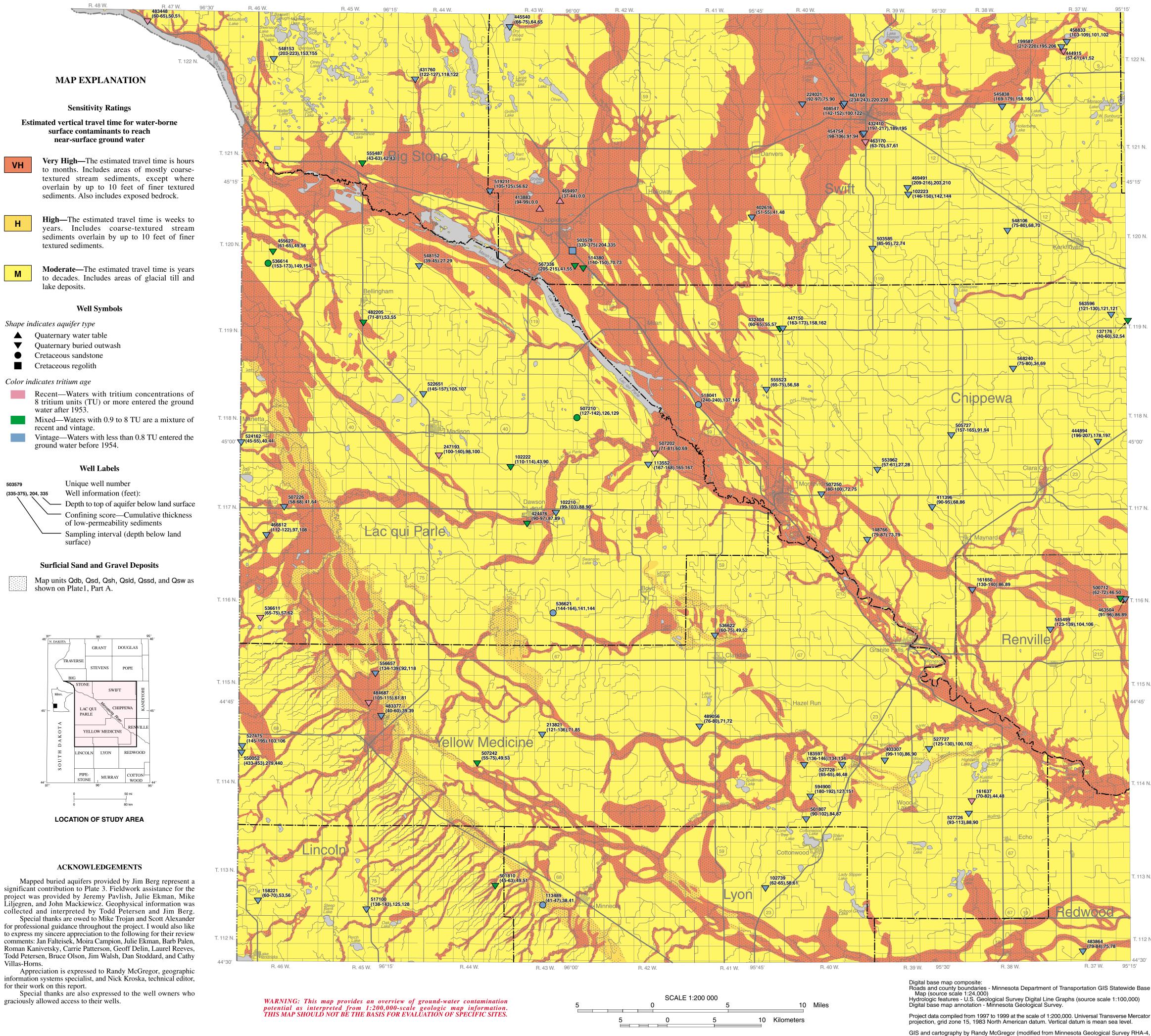
Grisak, G.E., Cherry, J.A., Vonhof, J.A., and Blumele, J.P., 1976, Hydrogeologic and hydrochemical properties of fractured till in the interior plains region, in Legget, R.F., ed., Glacial Till: The Royal Society of Canada, Special Publications, no. 12, p. 304-335.

Hendry, M.J., 1988, Hydrogeology of clay till in a prairie region of Canada: Ground Water, v. 26, no. 5, p. 607-614.

Ruland, W.W., Cherry, J.A., and Feenstra, Stan, 1991, The depth of fractures and active ground-water flow in a clayey till plain in southwestern Ontario: Ground Water, v. 29, no. 3, p. 405-417.

Stephenson, D.A., Fleming, A.H., Mickelson, D.M., 1988, Glacial deposits, in Back, W., Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: Boulder, Colo., Geological Society of America, The Geology of North America, v. O-2, p. 301-314.

ACKNOWLEDGEMENTS

Mapped buried aquifers provided by Jim Berg represent a significant contribution to Plate 3. Fieldwork assistance for the project was provided by Jeremy Pavlish, Julie Ekman, Mike Liljegren, and John Mackiewicz. Geophysical information was collected and interpreted by Todd Petersen and Jim Berg.

Special thanks are owed to Mike Trojan and Scott Alexander for professional guidance throughout the project. I would also like to express my sincere appreciation to the following for their review comments: Jan Falteisek, Moira Campion, Julie Ekman, Barb Palen, Roman Kanivetsky, Carrie Patterson, Geoff Delin, Laurel Reeves, Todd Petersen, Bruce Olson, Jim Walsh, Dan Stoddard, and Cathy Villas-Horns.

Appreciation is expressed to Randy McGregor, geographic information systems specialist, and Nick Kroska, technical editor, for their work on this report.

Special thanks are also expressed to the well owners who graciously allowed access to their wells.

LOCATION OF STUDY AREA

MAP EXPLANATION

Sensitivity Ratings

Estimated vertical travel time for water-borne surface contaminants to reach near-surface ground water

VH — Very High—The estimated travel time is hours to months. Includes areas of mostly coarse-textured stream sediments, except where overlain by up to 10 feet of finer textured sediments. Also includes exposed bedrock.

H — High—The estimated travel time is weeks to years. Includes coarse-textured stream sediments overlain by up to 10 feet of finer textured sediments.

M — Moderate—The estimated travel time is years to decades. Includes areas of glacial till and lake deposits.

Well Symbols

Shape indicates aquifer type

▲ Quaternary water table
▽ Quaternary buried outwash
■ Cretaceous sandstone
● Cretaceous regolith

Color indicates tritium age

Recent—Waters with tritium concentrations of 8 tritium units (TU) or more entered the ground water after 1953.

Mixed—Waters with 0.9 to 8 TU is a mixture of recent and vintage.

Vintage—Waters with less than 0.8 TU entered the ground water before 1954.

Well Labels

503579 — Unique well number
(335-375), 204, 335 — Well information (feet):
— Sampling interval (depth below land surface)
— Depth to top of aquifer below land surface
— Confining score—Cumulative thickness of low-permeability sediments

Surficial Sand and Gravel Deposits

Map units Qdb, Qsd, Qsh, Qsld, Qssd, and Qsw as shown on Plate1, Part A.

FIGURE 1. Geologic sensitivity rating as defined by ground-water travel time. Ratings are based on the time required for water at or near the surface to travel vertically to the water table or other ground water of interest. Longer travel times imply a lower sensitivity to pollution. Dye trace, tritium, and carbon-14 studies can indicate the relative ages of ground water.

FIGURE 2. Schematic illustration of target zone of geologic sensitivity. The target zone extends from the water table downward 20 feet. Fractures and joints in till are illustrated in the close-up view. Arrow points and blue dashed line indicate water table surface.
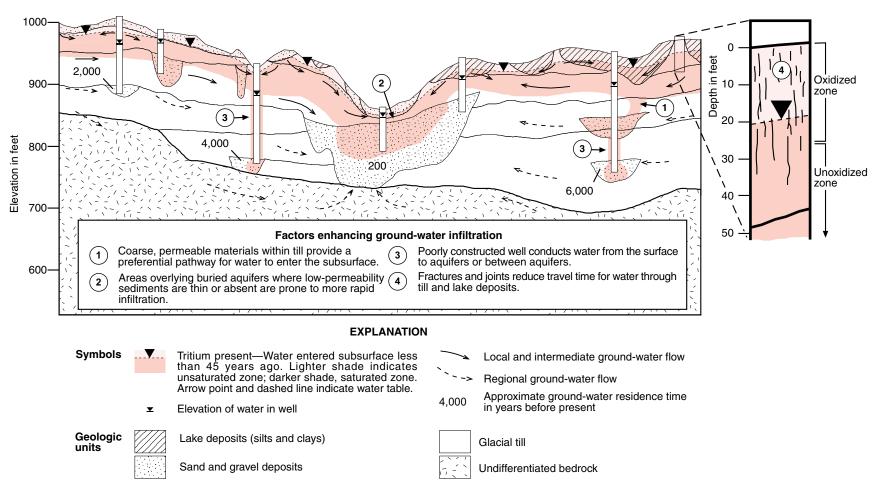
FIGURE 3. Schematic illustration of subsurface conditions in the upper Minnesota River basin. The illustration shows the vertical distribution of tritium and the factors that may reduce travel time and enhance ground-water recharge. Modified from cross section A–A', Plate 2, Part A. Not drawn to scale.

WARNING: This map provides an overview of ground-water contamination potential as interpreted from 1:200,000-scale geologic map information. THIS MAP SHOULD NOT BE THE BASIS FOR EVALUATION OF SPECIFIC SITES.

SCALE 1:200 000

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 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 hydrogeology and sound cartographic principles. This map should not be used to establish legal title, boundaries, or locations of improvements.

Equal opportunity to participate in and benefit from programs of the Minnesota Department of Natural Resources is available to all individuals regardless of race, color, national origin, sex, sexual orientation, marital status, status with regard to public assistance, age, or disability. Discrimination inquiries should be sent to: Minnesota DNR, 500 Lafayette Road, St. Paul, Minnesota 55155-4031; or the Equal Opportunity Office, Department of the Interior, Washington, DC 20240.

©2000 State of Minnesota,
Department of Natural Resources, and the
Regents of the University of Minnesota