GROUND-WATER FLOW IN BEDROCK AQUIFERS

By

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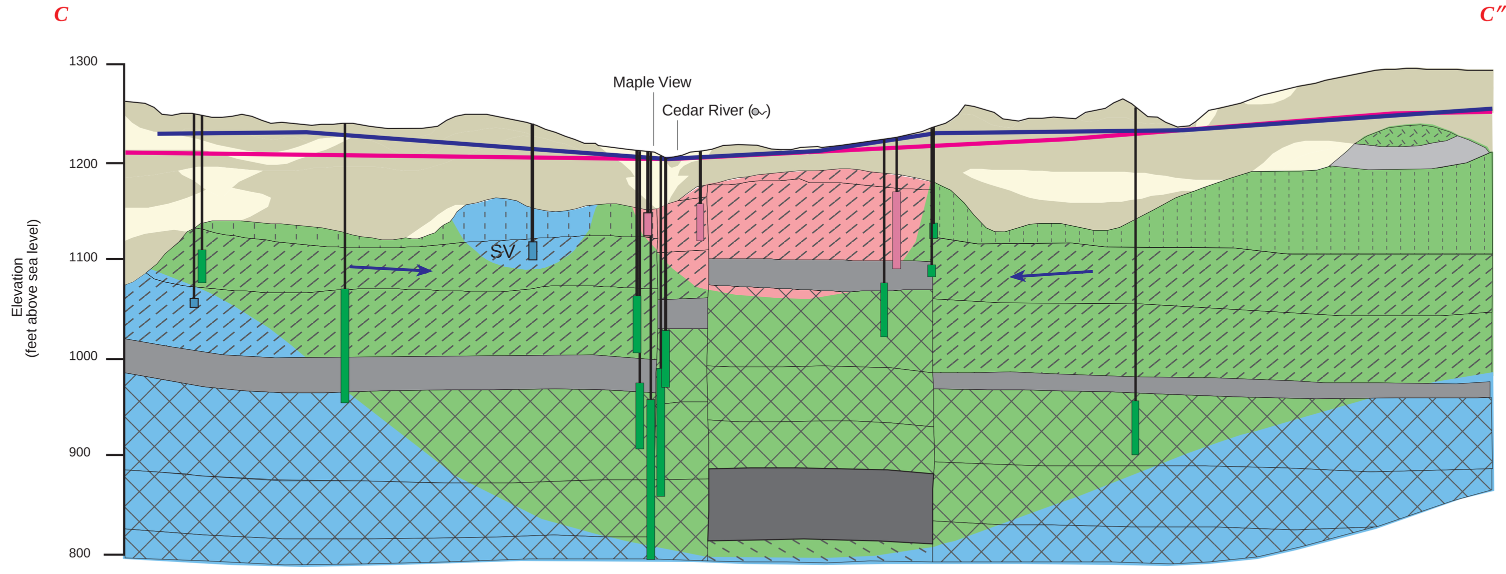

FIGURE 1. *Enlarged portion of cross-section C–C″ north of Austin. The cross section shows faults, displacement of aquifer and confining units, and numerous wells projected onto the cross section in this location. Some data show an inconsistent overall pattern of residence time in relation to depth and faults. The cross section shows that samples from some wells in the upper portions of the aquifer have recent water, and other wells in the aquifer have vintage water. Mixed waters occur below both water types.*

0 1 2 3 MILES
VERTICAL EXAGGERATION X 40

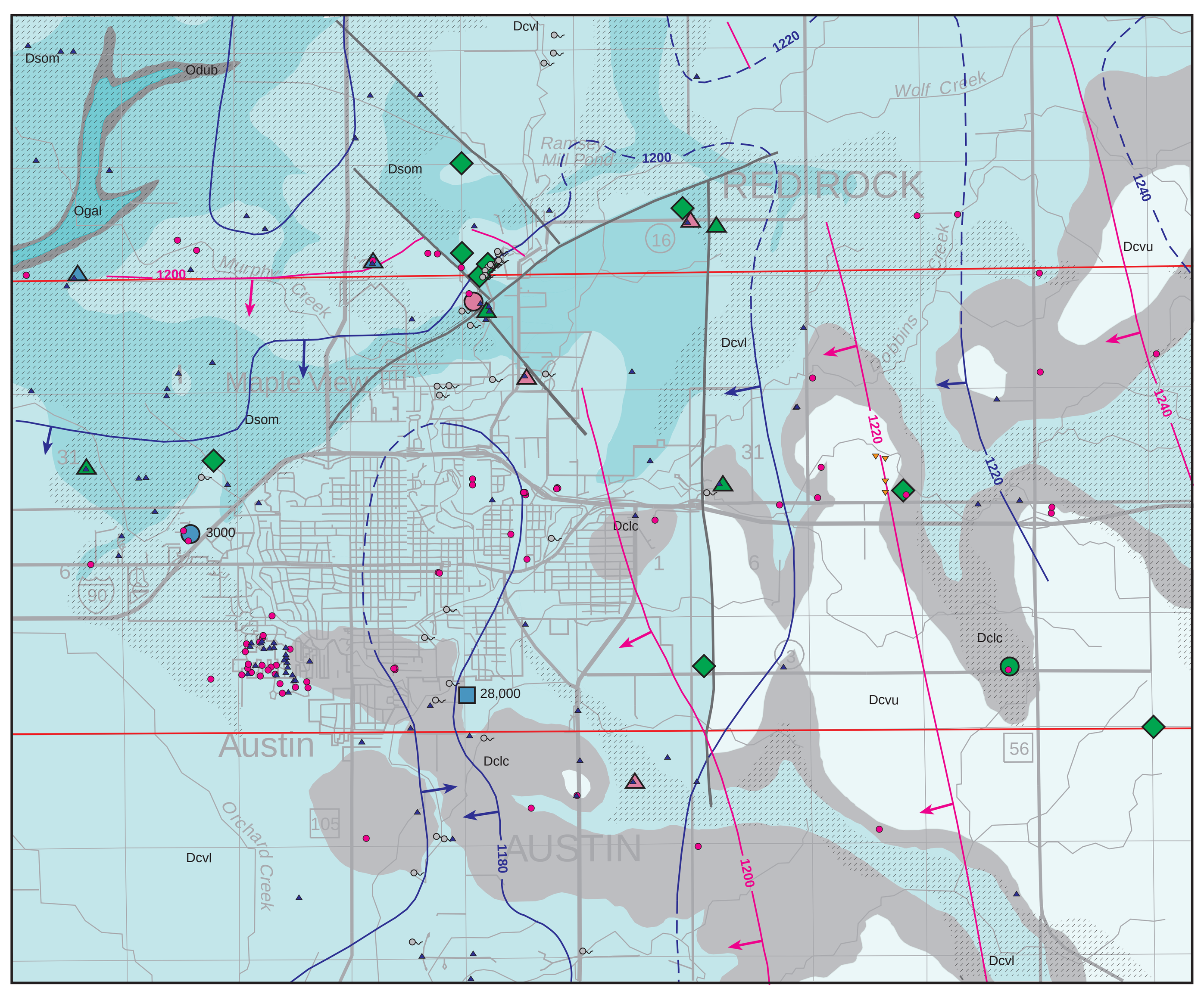

FIGURE 2. *Enlarged map view of Austin area. Austin is the largest population center in the county and the density of data is highest here. Faulting is shown north and east of Austin. Residence time data show various age dates within the Lower Cedar Valley and the Spillville-Maquoketa aquifers.*

0 1 2 3 MILES
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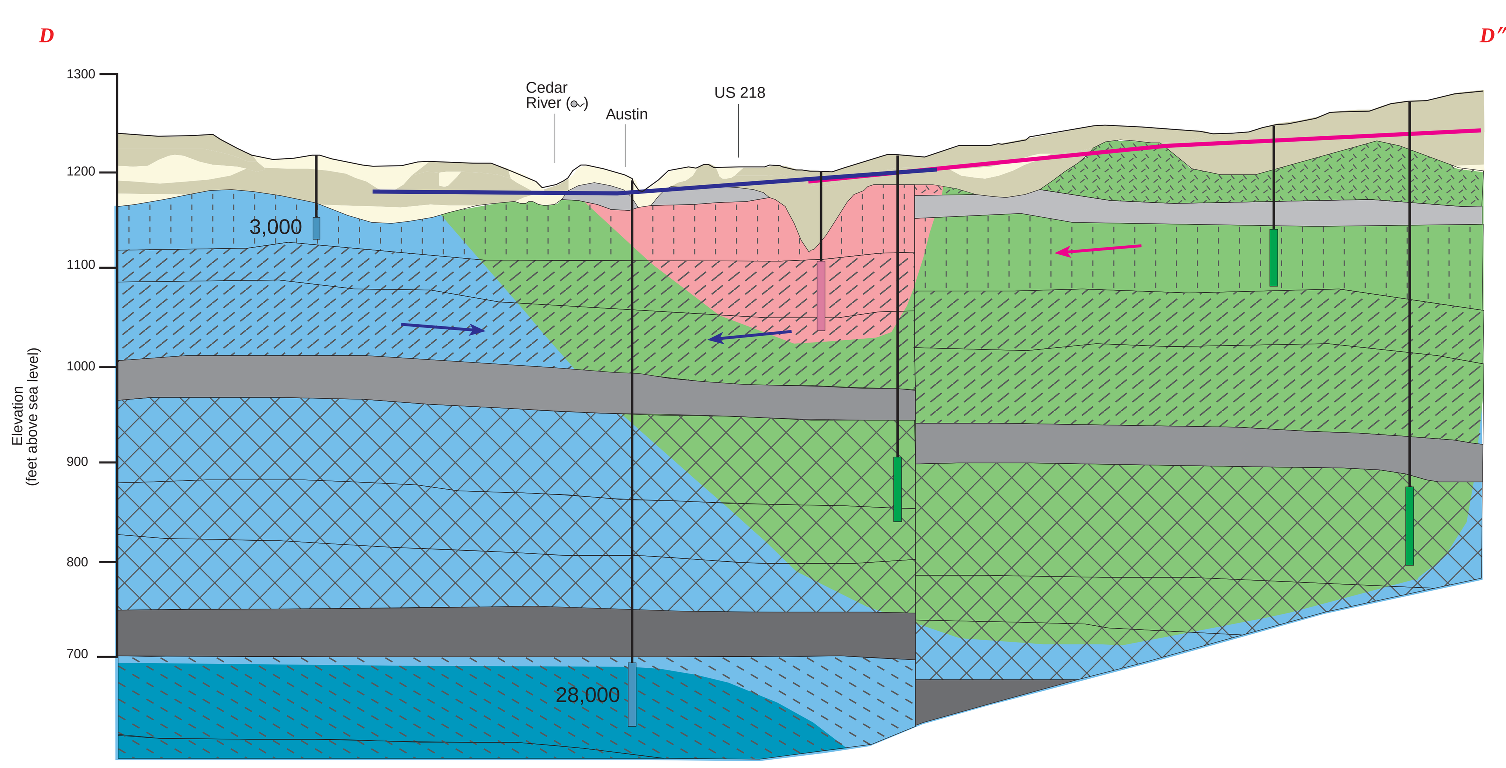


FIGURE 3. *Enlarged portion of cross-section D–D″ south of Austin. The cross section shows one mapped fault, displacement of aquifer and confining units, and fewer wells than cross section C–C″. This area shows a predictable pattern of recent water near the land surface at the fault with progressively older water below and to the east and west. This cross section also shows the presence of very old water under the Decorah-Platteville-Glenwood map unit.*

0 1 2 3 MILES
VERTICAL EXAGGERATION X 40

CROSS-SECTION EXPLANATION

Recent—Water entered the ground since 1953 (10 or more tritium units). Well screen color shows recent water.

Mixed—Water is a mixture of recent and vintage waters (0.8 to less than 10 tritium units). Well screen color shows mixed water.

Vintage—Water entered the ground before 1953 (less than 0.8 tritium units). Well screen color shows vintage water.

Very old—Water with carbon-14 age greater than 10,000 years before present. Well screen color shows vintage water.

Ground-water flow—Lower Cedar Valley aquifer

Ground-water flow—Spillville-Maquoketa aquifer

Potentiometric Contour

In feet above mean sea level. Contour interval is 20 feet.

Lower Cedar Valley

Spillville-Maquoketa

Cross-Section Symbols

18,000 If shown, ground-water age in years, estimated by carbon-14

SV Vintage water shallower than mixed water

Spring associated with stream

Geologic Units and Aquifers

Sand and gravel deposits

Undifferentiated till

Upper Cedar Valley aquifer

Chickasaw shale

Lower Cedar Valley aquifer

Spillville-Maquoketa aquifer

Dubuque Formation

Galena Group aquifer

Decorah-Platteville-Glenwood map unit*

St. Peter-Prairie du Chien-Jordan aquifer

*The Decorah Shale and Glenwood Formation both act as confining units, but the intervening Platteville Formation is a thin aquifer. Combined, these units are treated as a confining unit.

MAP EXPLANATION

Well Symbols

Shape indicates aquifer type

Lower Cedar Valley

Spillville-Maquoketa

Galena Group

St. Peter-Prairie du Chien-Jordan

Color indicates tritium age

Recent—Waters with tritium concentrations of 10 tritium units (TU) or more entered the ground water since 1953.

Mixed—Waters with 0.8 to 10 TU are a mixture of recent and vintage.

Vintage—Waters with less than 0.8 TU entered the ground water before 1953.

Well Label

30,000 If shown, ground-water age in years, estimated by carbon-14

Map Symbols

Fault

Spring

Uppermost Bedrock Aquifers and Confining Units

Aquifer or confining unit	Symbol
Greater than 75 feet of till cover	
Upper Cedar Valley aquifer	Dcvu
Chickasaw Shale	Dclc
Lower Cedar Valley aquifer	Dcvl
Spillville-Maquoketa aquifer	Dsom
Dubuque Formation	Odub
Galena Group aquifer	Ogal

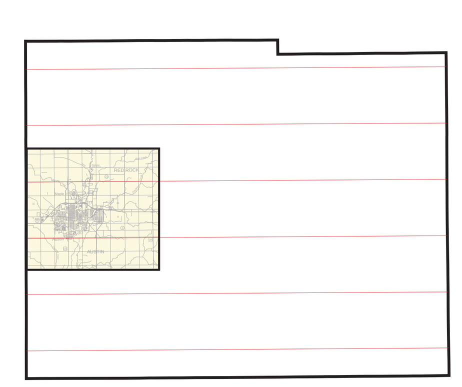
Potentiometric Contour

Lower Cedar Valley
Spillville-Maquoketa

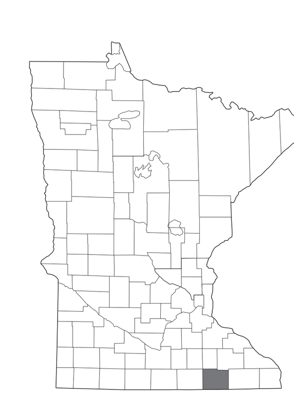
Potentiometric contour of aquifers in feet above mean sea level—Contour interval is 20 feet. Dashed where contour is uncertain. Arrow indicates general direction of ground-water movement.

Upper Cedar Valley
Lower Cedar Valley
Spillville-Maquoketa

Wells measured for static water level



LOCATION OF AUSTIN AREA INSET



LOCATION DIAGRAM

RESIDENCE TIME AND GEOLOGIC FEATURES

This plate describes the details of ground-water flow in Mower County. Ground-water flow was determined using water-level measurements, radiometric dating, and dye trace tests. Water-level measurements of wells were used to create potentiometric surfaces. Radiometric dating was conducted on water samples to estimate ground-water residence times. Where carbonate aquifers were at the surface, dye trace tests identified local points of ground-water recharge and discharge.

Plate 7 shows the potentiometric surfaces of three bedrock aquifer units in Mower County based on available water-level information. The results of radiometric dating of all wells are also shown on the Plate 7 map, and the cross sections illustrate the distribution of recent, mixed, vintage, and very old waters. Ground-water dye tracing is described under "Fracture and Conduit Flow in Carbonate Aquifers". Dye tracing was also used in the karst mapping efforts for this project (Plate 10).

Residence Time and Radiometric Dating. Radiometric dating involves the measurement of radioactive isotopes and is used to estimate residence time and indicate ground-water flow. Large quantities of tritium (^{3}H), a naturally occurring radioactive isotope, were dispersed into the atmosphere during atmospheric nuclear bomb testing, which started in 1953 and ended in the early 1960's. Since then, increased tritium concentrations have been incorporated into precipitation, and the presence of tritium in ground water indicates contact with the atmosphere since 1953. The presence of carbon-14 (^{14}C), another naturally occurring radioactive isotope, in ground water also indicates that the water has had contact with the atmosphere. The amount of carbon-14 in a water sample is also used to estimate how much time has elapsed since the water infiltrated the land surface. These dating techniques are used together to determine where water has reached an aquifer in less than 50 years (short residence time indicates water with detectable tritium), has not had contact with the atmosphere within the last 50 years (longer residence time indicates water without detectable tritium), and may have been in an aquifer for thousands or tens of thousands of years (a very old residence time indicates an age date greater than 10,000 years based on carbon-14 concentration). This information helps identify areas where land use practices with potential to contaminate ground water pose the greatest risk. See Plate 9 for more information on areas sensitive to pollution.

Relationship between Faulting and Waters with Detectable Tritium. The data indicate that residence time of the water is related to the geologic features interpreted to have influenced the movement of ground water. The potentiometric surface derived using water level measurements does not readily indicate the impact of important geologic features. These geologic features are local conditions, and residence time information from ground-water samples is required to characterize ground-water flow in the county.

The area around Austin has been enlarged on this plate for clarity (Figures 1, 2, 3). This area has the most data, as well as some of the most complicated geology and hydrogeology in the county. The enlarged map (Figure 2) displays the dense distribution of wells in this location more clearly than Plate 7 does. The cross-section enlargements (Figures 1 and 3) show many sampled wells in areas where rock units are discontinuous because of faulting. The map shows recent and vintage waters in samples from wells completed in the Lower Cedar Valley aquifer. Samples of recent, mixed, and vintage waters were taken from wells completed in the Spillville-Maquoketa aquifer.

Figures 1 and 3 show bedrock faults north and east of Austin. Faults disrupt the continuity of the aquifers and low-permeability units. Separate analysis of the hydrogeology of each aquifer in this area was not feasible. The cross sections show a shallow area of recent water (tritium concentration greater than 10 tritium units [TU]) close to the faults and a wider and deeper area of mixed water (tritium concentration from 0.8 TU to 10 TU) surrounding the recent water in the same location. The zones of mixed ground water appear on the cross sections as transition areas between recent and vintage water. In this faulted area and south of Austin, recent and mixed waters are found in wells completed to greater depths than elsewhere in the county. Vintage water (no detectable tritium) is shown underneath and to the east and west of this zone of water with detectable tritium. Very old waters are found under the Decorah-Platteville-Glenwood map unit in Figure 3.

Samples from wells in the faulted areas shown on Figures 1 and 3 indicate that faulting may have increased permeability because of great fracturing density and subsequent development of conduits. Worthington (1999) describes similar conditions in carbonate aquifers with triple porosity. Triple porosity is a term to characterize carbonate aquifers in which three types of porosity occur: matrix porosity—spaces between grains (primary porosity); fracture porosity— discontinuous planar spaces related to bedding, fractures, and faults (secondary porosity); and conduit porosity—integrated channel network related to solution features (secondary porosity). Figure 4 is an illustration modified from Worthington (1999) and describes two types of porosity, fracture and conduit, found in the carbonate aquifers of Mower County.

Pumping and multiaquifer wells contribute to the presence of tritium at these depths. However, the presence of pumping and multiaquifer wells in areas without deep tritium penetration suggests that these influences cannot completely account in all areas for the presence of tritium.

In Figure 1, shallow vintage water is present above waters with detectable tritium. In this area, till inhibits the vertical infiltration of water from the surface directly above the well. However, ground water entering an aquifer near the land surface at another location can flow long distances within an aquifer underneath a zone of more slowly moving vintage water. This lateral-flowing water moves faster through integrated, solution-enhanced conduits. The well west of the faults in cross-section C–C″ is one of several places in the county where vintage water occurs in the bedrock aquifer directly beneath the glacial sediments but above areas in the aquifer that contain water with detectable tritium. This condition may indicate that the carbonate aquifers here have fracture and conduit porosity. (See description of ground-water flow in "Fracture and Conduit Flow in Carbonate Aquifers".)

In summary, the area around Austin clearly shows the association between faulting and ground water with detectable tritium deep in an aquifer. The remainder of this plate describes the other important features displayed on the cross sections on Plate 7 and provides a more detailed explanation of ground-water flow in fractured carbonate aquifers.

Zones of Mixed Water. The cross sections on Plate 7 show that the most extensive areas of mixed water are in western and southeastern Mower County where it persists to 500 feet deep in some places. Because of the association between these deep, mixed waters and the faults found around Austin and Le Roy, the presence of unmapped faults south of Austin is inferred. There were not enough well logs to map faults south of Austin; however, tritium data indicate that faults may be present here also. This is an example of ground-water data providing detail to identify local geological features where other data are sparse.

Cross-sections A–A′, B–B′, D–D′, and F–F′ on Plate 7 show that recent and mixed waters have not infiltrated very deeply into the bedrock aquifers under thick till. In some places where the till is thick, recent and mixed waters have reached the aquifer. This situation occurs under one of two conditions. First, as seen in the Austin area, ground water can move laterally at greater velocity through areas in the aquifers with fracture- and solution-enhanced permeability (in the eastern portion of cross-sections B–B′, C–C′, and F–F′) than it can move vertically from the surface through the till. Second, there are places in the glacial cover containing large quantities of sand and gravel (in the center of cross-sections A–A′ and C–C′). These sand and gravel deposits provide porous material with high permeability through which the ground water flows from the surface, bypassing the tills, into the bedrock aquifer.

Wells with mixed concentrations of tritium may be drawing vintage water from small, unconnected fractures in the aquifer and recent water from larger, more well-connected fractures intersected by the well bore. This mixing occurs within the well bore but cannot be shown in detail at the scale of this map. Additionally, identifying where mixing is occurring requires discrete sampling of the fractures in a well and was beyond the scope of this study.

Zones of Vintage and Very Old Water. Most cross sections on Plate 7 show that where the till is thick, water with detectable tritium has not reached the deep parts of the aquifer. Cross-sections D–D′ and E–E′ show extensive areas of vintage water directly under the till.

Samples with very old carbon-14 dates were found in wells in the northeastern and southwestern parts of the county. These are shown on the eastern portion of cross-sections A–A′, B–B′, and C–C′ and the western portion of cross-sections D–D′ and E–E′. All samples with carbon-14 dates greater than 10,000 years were taken from the aquifers under the Decorah and Glenwood shales.

Yield and Movement of Ground Water. The aquifers in Mower County are part of the Paleozoic Hollandale Embayment, a series of carbonates, sandstones, and shales that cover southeastern Minnesota. These aquifers are the largest in the state and provide high yields and good quality water. The aquifers in Mower County consist of carbonate bedrock separated by shale units. Availability of ground water in these carbonate aquifers depends on the density of fractures and solution-enhanced permeability (see "Fracture and Conduit Flow in Carbonate Aquifers"). The abundance of fractures and conduits is greatest near the bedrock surface (Runkel and others, 2003). Important fracture systems may also transport large quantities of water at depths of hundreds of feet, but these are not as abundant as the fractures and conduits nearer the bedrock surface (Jeffrey Green, oral commun, 2000; Robert Tipping, Anthony Runkel, oral communs., 2001). Well yields in these aquifers depend on how many fractures are intersected by the well. Water supplies are most available near the bedrock surface where fracture density is greatest.

Wells completed close to the bedrock surface usually have high yield, but they can be susceptible to contamination from distant sources even if till cover is present. The state well code requires that some low-permeability material be present over a bedrock aquifer to be used for a well. In Mower County, 75 feet of till over bedrock will generally retard flow from land surface to the aquifer. If little or no till is at the surface, a low-permeability bedrock unit at depth offers some protection to an underlying aquifer from direct infiltration from the land surface. However, water can enter the ground-water system where the till cover is thin or absent and quickly travel laterally through solution-enhanced fractures and conduits to a location where the aquifer is covered by till.

Conclusion. Although all details of fracture and conduit flow may not be clear, residence-time results indicate that multiple types of porosity occur in the carbonate aquifers of Mower County. The effects on water resources and the implications for land use are described in more detail on Plates 9 and 10.

REFERENCES CITED

Green, J. A., Mossler, J. H., Alexander, S. C., and Alexander, E. C., Jr., 1997, Karst hydrogeology of Le Roy Township, Mower County, Minnesota: Minnesota Geological Survey Open-File Report 97-2, 2 pls., scale 1:24,000.

Runkel, A. C., Tipping, R. G., Alexander, E. C., Jr., Green, J. A., Alexander, S. C., 2003, Hydrogeology of the Paleozoic bedrock in southeastern Minnesota: Minnesota Geological Survey, Report of Investigation 61, 105 p., 2 pls.

Worthington, S. R. H., 1999, A comprehensive strategy for understanding flow in carbonate aquifers, *in* Palmer, A. N., Palmer, M. V., and Sasowsky, I. D., eds., Karst modeling, Karst Waters Institute Special Publication 5, Proceedings of the symposium, February 24–27, 1999, Charlottesville, Va.: Charles Town, W. Va., Karst Waters Institute.

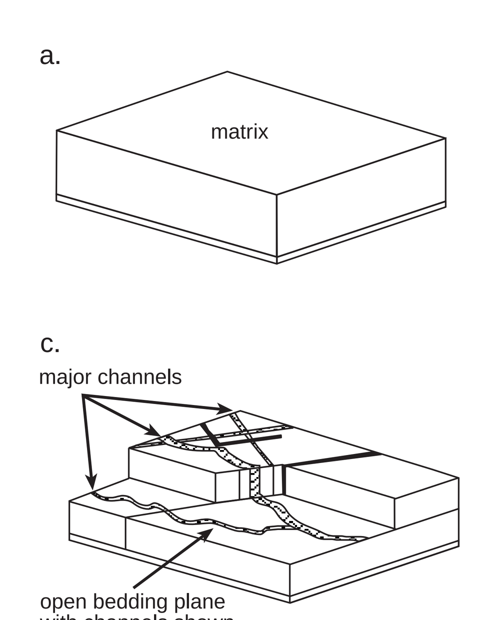


FIGURE 4. *Elements of triple porosity in a carbonate aquifer. a. Diagram showing matrix porosity. This is the same as intergranular porosity in a porous media aquifer. b. Diagram showing matrix and planar elements. Planar elements can be joints, fractures, or bedding planes. Ground water flows through intergranular spaces, as well as planar elements. c. Diagram showing matrix, planar, and conduit elements. Conduit elements are linear solution features resulting in an integrated network of channels. Conduits result from solution where water flows through a path of least resistance. Because more water flows within the conduits and there is a greater opportunity for solution, larger channels grow at the expense of smaller ones. (modified from Worthington, 1999)*

FRACTURE AND CONDUIT FLOW IN CARBONATE AQUIFERS

Aquifers of carbonate or crystalline rock transmit water very differently than aquifers of granular media transmit water. Granular media aquifers store water primarily in the spaces between grains in the rock. Referred to as primary porosity, it is created at the same time as the rock. Secondary porosity develops after the rock has been formed. Examples of secondary porosity include fractures, joints, and solution features, as well as cavities left from tree roots and worm and animal burrows. Permeability is defined as the capacity to transmit water through the connections between pore spaces. If the connections between grains in a granular aquifer are consistent and quantifiable, they provide information about ground-water flow. In contrast, the flow of ground water in an aquifer of carbonate or crystalline rock is governed more by the fractures and other secondary porosity features than by the pore spaces between grains. Carbonate aquifers often have solution features that result in multiple porosities and permeabilities. These characteristics make flow behavior more difficult to describe than flow behavior in more homogeneous granular aquifers.

Worthington (1999) describes ground-water behavior in carbonate aquifers in terms of triple porosity: intergranular (primary) porosity, fracture porosity, and conduit porosity (Figure 4). The ground-water behavior in the carbonate bedrock aquifers in Mower County is dominated by the two types of secondary porosity (fracture and conduit). Primary porosity of the carbonate bedrock in Mower County is negligible.

Multiple types of porosity in carbonate aquifers result in flow behavior that is difficult to characterize because the porosity and permeability vary throughout the aquifer. The variable characteristics require use of special techniques to describe the aquifer adequately. The fractures are two-dimensional planar features that occur as bedding planes, joints, or faults. These planar features can be examined using borehole tools like down-hole video, down-hole flow meter, packer tests, and slug tests. Conduits (see Figure 4) develop along fractures or other places where the aquifer is susceptible to solution. The conduits have the greatest permeability and the least volume of the porosity elements. Figure 5 shows photographs of conduits from two of the uppermost carbonate aquifers in Mower County. Figure 5a is a photograph of a rock sample taken from the Spillville Formation, which clearly shows an integrated network of channels. Figure 5b shows a single conduit in the Galena Group emerging into Spring Valley Cavern in Fillmore County. The ground water flowing from this conduit may have flowed through several smaller conduits upgradient from this location.

Further evidence to support the presence of fracture and conduit flow in the aquifers of Mower County comes from the distribution of tritium data based on wells sampled throughout the county. These data indicate that velocities of vertical and lateral ground-water flow in these aquifers are greater than velocities of ground-water flow through aquifers formed by granular sediments. First, the western portions of cross-sections C–C′, D–D′, E–E′, and F–F′ and the eastern portions of E–E′ and F–F′ (Plate 7) show wells with detectable tritium very deep in the subsurface. The presence of tritium at these depths is associated with faulting in the area. Where there is faulting, fracture density and the opportunity for conduits to develop through solution processes increase. Second, several wells in the eastern portion of C–C′ have recent water. West of Grand Meadow, till becomes quite thick, and recent water beneath the till indicates rapid lateral flow (another characteristic of fracture and conduit flow) from the east. Third, on A–A′ there are areas marked SV that show vintage water at shallow depths above mixed water. Worthington (1999) reports that this is a common feature in triple-porosity aquifers.

Residence Time. Figure 6 is a schematic diagram that illustrates various water-flow and residence-time conditions that occur in a multiple-porosity carbonate aquifer. The diagram shows that the bedrock surface has abundant fractures regardless of rock type, which is a condition observed throughout southeastern Minnesota (Runkel and others, 2003). Both limestone and shale are extensively fractured and, when not covered by glacial material, allow water to infiltrate rapidly into the aquifer. The distribution of the recent water on the diagram shows that water quickly reaches the aquifer where there is no low-permeability material covering it. Within the bedrock aquifer, recent ground water flows toward a regional discharge point. The diagram illustrates that dye introduced at a sinkhole has a short flowpath before discharging at a nearby spring. The portion of the aquifer covered by till is protected from water flowing rapidly into the aquifer from the land surface. The exception occurs where sand and gravel provides a high-permeability zone by which water from the land surface can rapidly enter the underlying aquifer. Although sand and gravel does not allow water to reach the aquifer as quickly as limestone without till cover, it still provides a pathway for water to travel from the surface to the aquifer without the protective benefits of the till. Several wells displayed on the diagram show the effects of multiple porosity on residence time results, as described in the figure caption.

Karst Systems. High ground-water velocities have physical and chemical impacts on karst aquifers, like those found in Mower County. If sufficient velocity occurs and pore spaces are larger than 2 millimeters, turbulent ground-water flow can result. Water molecules under turbulent flow conditions move erratically, like water in a stream. Turbulent flow allows material to be carried from the aquifer through conduits and increases the amount of void space in the aquifer. High velocities also allow great volumes of water to move through the aquifer and may dissolve the aquifer material and enlarge pore spaces.

Large volumes of water can be drained directly from the surface into a carbonate aquifer that has solution-enhanced permeability. As a result, when a carbonate aquifer is at the land surface, the landscape has very few surface water features. Water from the surface drains directly into an aquifer through features like sinks and losing streams and may discharge at the surface only at seeps and springs. Drainage occurs within the aquifer. This internal drainage is typical of a karst system.

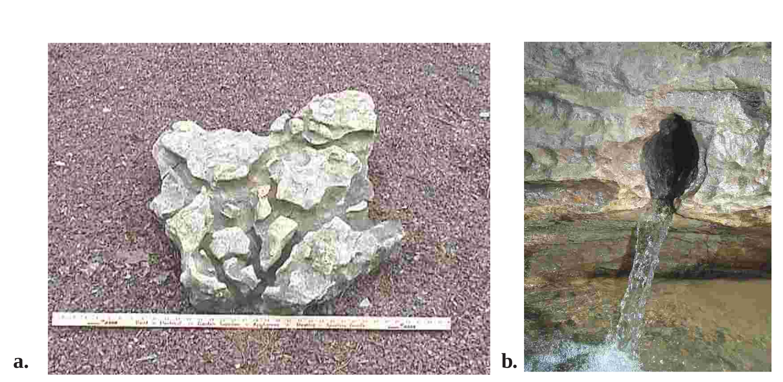
Karst features in eastern and southeastern Mower County have less topographic relief than in many other karst areas because the glacial advances through Minnesota smoothed the landscape. Additionally, glacial cover obscures karst features on the land surface. However, the subtlety of the features or lack of surface expression does not diminish the impact on ground-water flow characteristics or ground-water management issues. Tracer tests have been conducted in Mower County at locations of identified surface karst features and have been used to determine ground-water flow directions and velocities.

Dye Trace Tests in Karst Systems. Karst limestone aquifers typically have high ground-water flow rates, which can be as rapid as several miles per day. Artificial tracers introduced into the ground-water system allow flow times to be measured. Fluorescent dyes are the most common tracers used for karst hydrology investigations. Figure 7 represents the results of a dye trace done at Le Roy in southeastern Mower County.

Dye was poured into a stream sink on the Minnesota-Iowa border and recovered at a large spring complex on the east side of Le Roy. The leading edge of the dye cloud in the ground water traveled to springs A12 and A20 in approximately 15 hours. The dye concentrations peaked after about 20 hours. Dye continued to emanate from the springs for at least 40 days. The straight-line distance between the stream sink and the springs is 4,200 feet. Other dye traces in the Le Roy and Grand Meadow areas yielded similar results. The leading edge of the dye traveled at a rate of 1 mile to 2 miles per day. Extended sampling at the springs demonstrated that dye flows through the system for weeks to months.

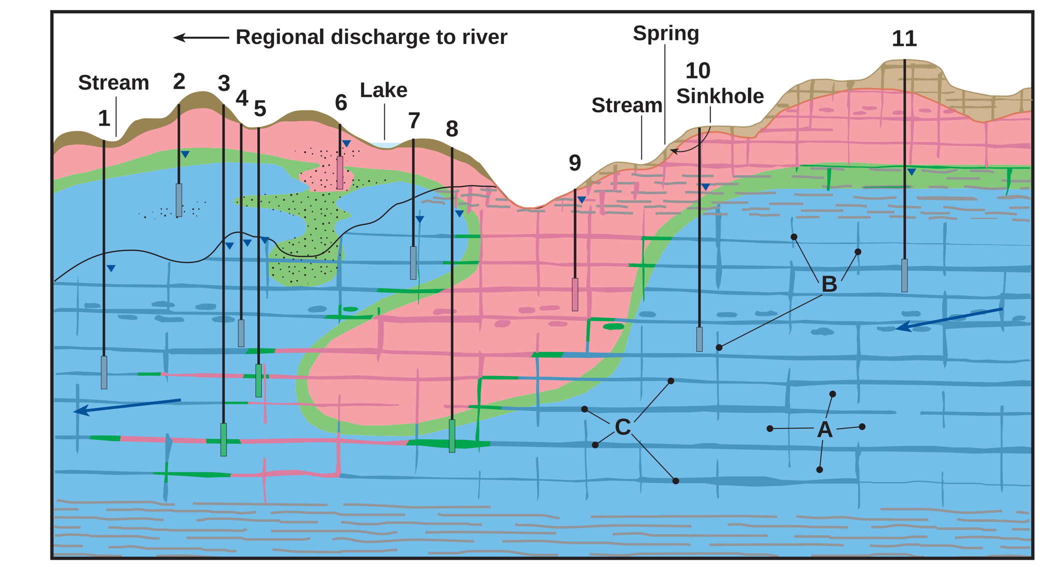
A working hypothesis is that a leading edge of dye flows through the largest and most integrated part of the fracture and conduit network while the rest of the dye moves through progressively less transmissive flow paths. The most developed parts of the flow system are labeled conduits, which are horizontal and vertical channels that have been altered by the solution of the bedrock. Rock samples from horizontal conduits show channels carved into them whose sinuosity resembles surface water streams (Figure 5a). These channels are capable of transmitting ground water at the rapid rates observed during dye tracing. The long tail on the dye trace curve is consistent with ground-water flow though a network of smaller, less-developed fractures that can only transmit water at a rate slower than in the more well-developed channels.

A challenge in Mower County is that glacial material obscures the landscape features associated with the underlying karst system. Where glacial sediments cover the aquifers, only borehole data could be gathered, and conclusions are general. Because of the overlying sediment, identifying all of the karst features that are present in the county was impossible.



a. b.

FIGURE 5. *Examples of conduits in aquifers. a. Dolostone sample from Spillville Formation taken from Osmundson Quarry near Grand Meadow, Mower County, shows a network of conduits. Photograph by E. Calvin Alexander, Jr. b. Conduit discharges ground water from the Galena Group aquifer into Spring Valley Caverns, Fillmore County. Photograph by Allen and Chris Lewerer.*



EXPLANATION

Regional ground-water flow

Static water level in well

Shale

Dye trace path

Sand and gravel

Carbonate bedrock

Unsaturated carbonate bedrock

Unsaturated till

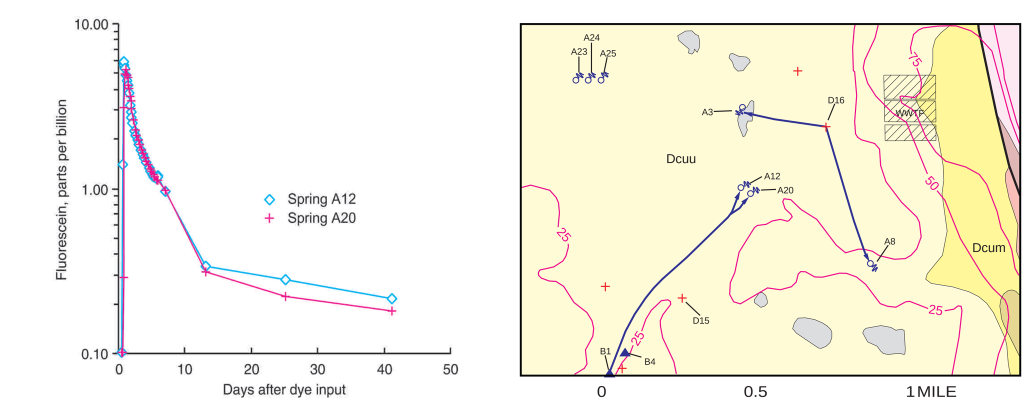
Saturated till

Recent—Water entered the ground since 1953 (10 or more tritium units). Well screen color shows recent water.

Vintage—Water entered the ground before 1953 (less than 0.8 tritium units). Well screen color shows vintage water.

Mixed—Water is a mixture of recent and vintage waters (0.8 to less than 10 tritium units). Well screen color shows mixed water.

FIGURE 6. ***Schematic diagram illustrating ground-water flow through a carbonate aquifer with multiple types of porosity. Numbered wells have screen colors that indicate the presence of recent, mixed, and vintage ground water.***
A. Matrix—water held in tight voids within the rock; flow is slow.
B. Fractures—discontinuous planar features, often vertical.
C. Conduits—part of network extending from recharge point to discharge point, often horizontal; flow is fast.
1, 11. Vintage wells—intermediate and shallow within aquifer; beneath zone of water containing tritium; receives vintage water from conduits and matrix.
2. Vintage well—within shallow isolated sand and gravel lens in glacial material; beneath recent water zone.
3, 5. Mixed wells—deep and intermediate within aquifer; recent conduit water and vintage matrix water mixes in the well.
4, 10. Vintage wells—intermediate depth within aquifer; vintage water comes from matrix only.
6. Recent well—in shallow sand and gravel deposit within the glacial materials.
7. Vintage well—shallow, completed in upper part of carbonate aquifer; receives vintage conduit and matrix waters; protected by till from infiltration from above, and not as deep as highly transmissive zone with recent water.
8. Mixed well—deep within aquifer; receives mixture of vintage matrix water and mixed conduit water.
9. Recent well—intermediate depth within aquifer; fractured and weathered shale unit provides limited protection from surface infiltration.



EXPLANATION

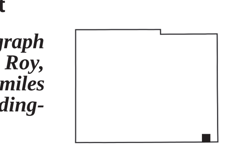
Stream sink

Spring

Line of equal depth to bedrock Contour interval 25 feet

Sinkhole

FIGURE 7. ***Results of tracer test (Green and others, 1997) November 1997 in the Lithograph City Formation (DCUU) from Stateline Sink (MN50:B1) about a mile south of Le Roy, Minnesota, to Liftstation Spring (MN50:A12) and Gihon Spring (MN50:A20) about 1.5 miles away on the Upper Iowa River, east of Le Roy. The breakthrough curve documents leading-edge velocities typical of conduit flow (miles per day).***



LOCATION OF TRACER TEST

Digital base map 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 map annotation—Minnesota Geological Survey.

Project data compiled from 1997 to 2001 at the scale of 1:100,000. Universal Transverse Mercator projection, grid zone 15, 1983 North American datum. Vertical datum is mean sea level.

Modified from Minnesota Geological Survey County Geologic Atlas Series; Atlas C–11; Part A; Plates 2, 3, 4, 5.

GIS data and metadata available through the DNR Waters website:
http://www.dnr.state.mn.us/waters