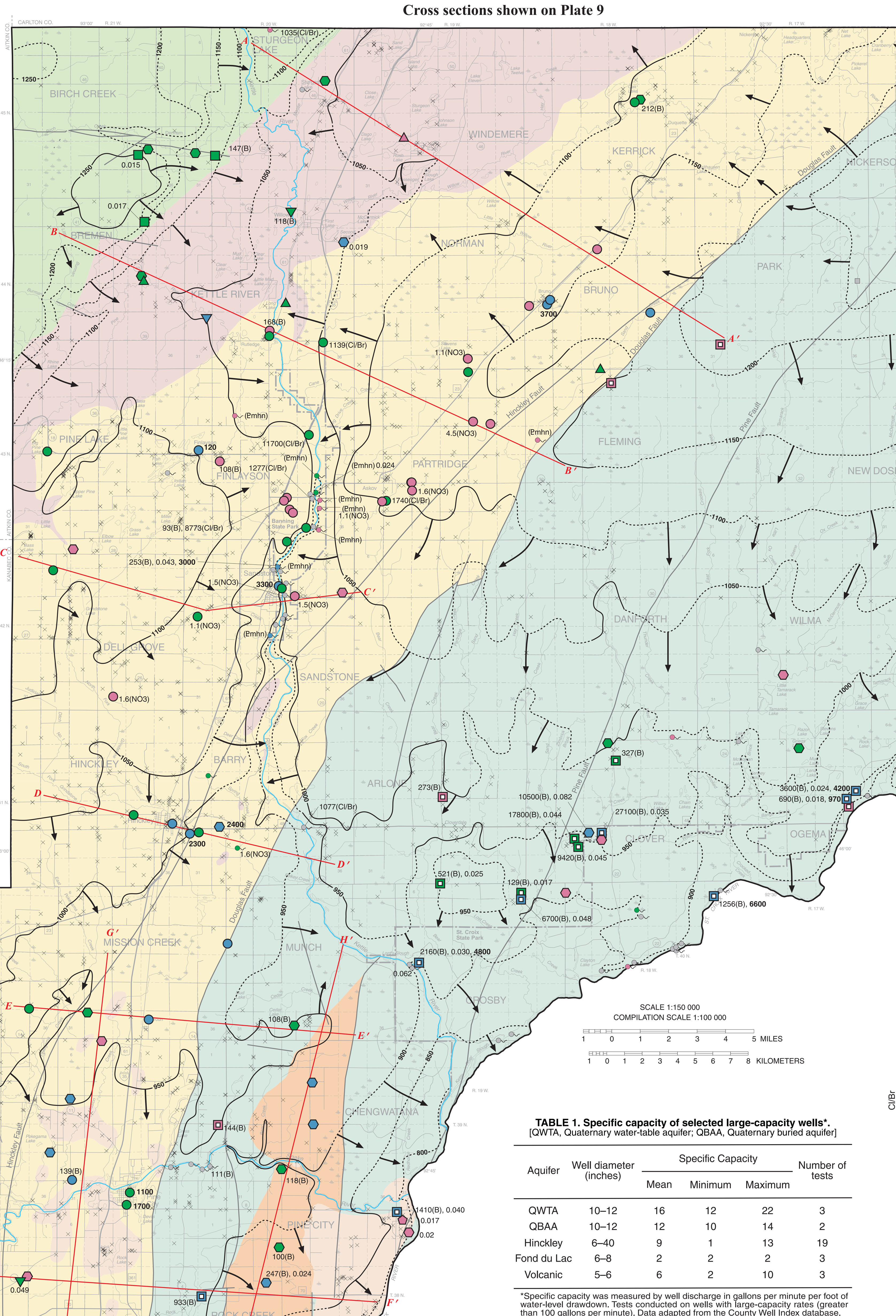
BEDROCK HYDROGEOLOGY

Cross sections shown on Plate 9



MAP EXPLANATION

Potentiometric contour

Potentiometric contour of uppermost water-supply bedrock aquifer in feet above mean sea level—Contour interval is 50 feet. Line is dashed where uncertain.

Arrow indicates the general direction of ground-water movement.

Static water-level data from the County Well Index.

Bedrock aquifers

- Paleozoic sandstone (Ꞓzu)
- Hinckley sandstone (Ꞓmhn)
- Fond du Lac (Ꞓmfl)
- Mesoproterozoic sandstone (Ꞓmsu)
- Volcanic rock (Ꞓmmv, Ꞓmbu, Ꞓmcb, Ꞓmcp)
- Metamorphic rock (Ꞓps, Ꞓdam, Ꞓdms, Ꞓdmv, Amc)

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).
- Boring or spring not tested for tritium.

327 (B) — If shown, boron concentration exceeds 95 parts per billion

0.024 — If shown, strontium to magnesium ratio equals or exceeds 0.015

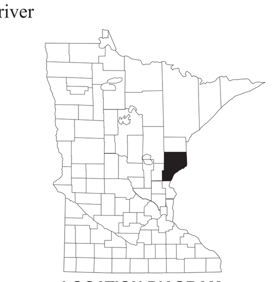
1740 (Cl/Br) — If shown, chloride to bromide ratio equals or exceeds 1000

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.
- Ground-water sample from boring collected for chemical analysis
- F—F′ Line of cross-section
- Fault
- Major river



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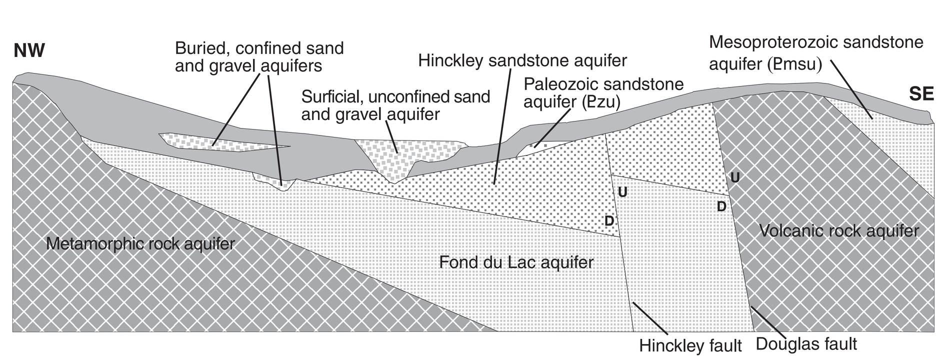

FIGURE EXPLANATION

Geologic Unit	Hydrologic Condition	Aquifer Porosity Type
Quaternary		
Fine-grained sediments (mostly glacial till and glacial lake sediments).	Confining or leaky confining unit.	
Sand, sand and gravel, or gravel (glacial outwash and glacial lake sediments).	Aquifer, confined and unconfined. Confined units can occur in complex, layered networks in the northern and southern portions of the county.	Water flows between sand grains (matrix porosity).
Paleozoic		
Paleozoic sandstone (Ꞓzu). Thin, isolated occurences may include equivalents of the Mt. Simon Sandstone to the St. Peter Sandstone. Occurs on the Hinckley Sandstone, volcanic formations, and Mesoproterozoic sandstone (Ꞓmsu).	Aquifer, mostly confined.	Fracture and matrix.
Mesoproterozoic		
Hinckley Sandstone (Ꞓmhn).	Aquifer, mostly confined.	Fracture, karst, and matrix.
Fond du Lac Formation (Ꞓmfl) and Mesoproterozoic sandstone (Ꞓmsu).	Aquifer, mostly confined. Used in northwestern portion of county.	Fracture and matrix.
Volcanic rocks. Mostly basalt rocks, including the Minong volcanic sequence (Ꞓmmv), the Chengwatana Volcanic Group (Ꞓmcb, Ꞓmcp), and undifferentiated basalt (Ꞓmbu).	Aquifer, mostly confined. Used in eastern portion of county.	Fracture and permeable zones between flow layers.
Paleoproterozoic and Late Archean		
Metamorphic rocks (pelitic schist and metagraywacke [Ꞓps]), including the Denham Formation (Ꞓdam, Ꞓdms, Ꞓdmv) and McGrath Gneiss (Amc).	Aquifer, mostly confined. Used in northwestern portion of county.	Fracture.

FIGURE 1. *Schematic cross section from the northwestern corner to the southeastern corner of Pine County. The characteristics of the confining units and aquifers are described above.*

TABLE 1. Specific capacity of selected large-capacity wells*.
[QWTA, Quaternary water-table aquifer; QBAA, Quaternary buried aquifer]

Aquifer	Well diameter (inches)	Specific Capacity			Number of tests
		Mean	Minimum	Maximum	
QWTA	10–12	16	12	22	3
QBAA	10–12	12	10	14	2
Hinckley	6–40	9	1	13	19
Fond du Lac	6–8	2	2	2	3
Volcanic	5–6	6	2	10	3

*Specific capacity was measured by well discharge in gallons per minute per foot of water-level drawdown. Tests conducted on wells with large-capacity rates (greater than 100 gallons per minute). Data adapted from the County Well Index database.

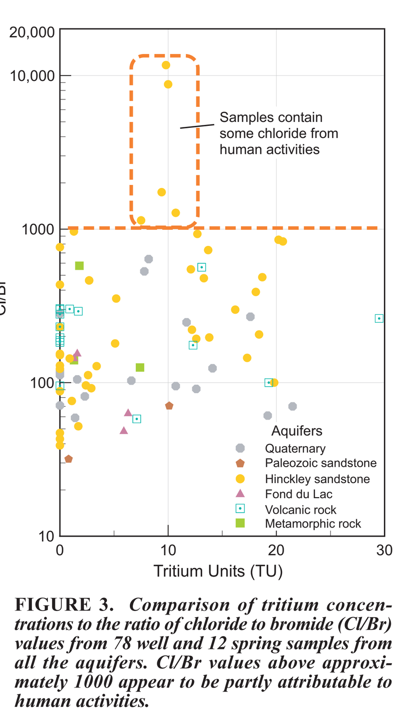

FIGURE 3. *Comparison of tritium concentrations to the ratio of chloride to bromide (Cl/Br) values from 78 well and 12 spring samples from all the aquifers. Cl/Br values above approximately 1000 appear to be partly attributable to human activities.*

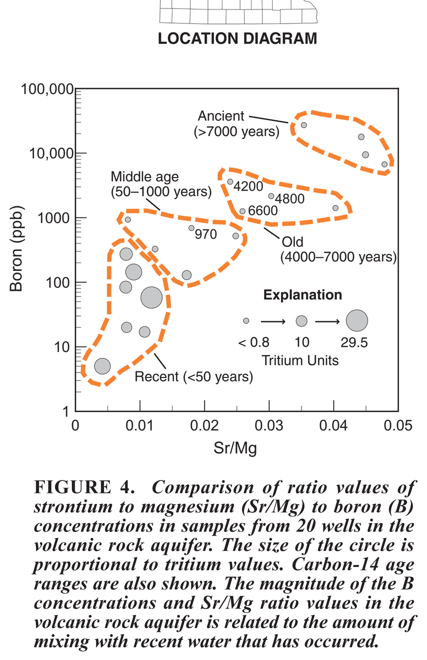

FIGURE 4. *Comparison of ratio values of strontium to magnesium (Sr/Mg) to boron (B) concentrations in samples from 20 wells in the volcanic rock aquifer. The size of the circle is proportional to tritium values. Carbon-14 age ranges are also shown. The magnitude of the B concentrations and Sr/Mg ratio values in the volcanic rock aquifer is related to the amount of mixing with recent water that has occurred.*

HYDROGEOLOGY OF THE UNCONSOLIDATED AND BEDROCK AQUIFERS

By

James A. Berg

2004

INTRODUCTION

Ground-water supplies in Pine County are pumped from six different bedrock aquifers and complex networks of buried and unconfined sand and gravel deposits (Figure 1). The bedrock aquifers, which supply ground water to 57 percent of the county's wells, consist of fractured volcanic (basalt) and metamorphic rock aquifers, as well as thick sandstone units. Unconsolidated sand and gravel aquifers, which account for the remaining 43 percent of wells, are clustered mostly in the southern and northern portions of the county where the glacial sediment is thickest. Bedrock aquifer wells are evenly distributed across most of the county except in the sparsely populated eastern portion. Typically, bedrock aquifer wells pump water from the first bedrock unit encountered beneath the glacial sediments. Well drillers rarely drill deeper than the uppermost bedrock aquifer.

The main features of this plate include a summary diagram of aquifer types in the county (Figure 1), maps of the three buried Quaternary sand and gravel aquifers in the southern portion of the county (Figures 2a, 2b, and 2c), and information on ground-water chemistry and ground-water flow directions within the bedrock aquifers (Bedrock Hydrogeology map to the left). This project was closely preceded by a University of Minnesota masters thesis (Shade, 2002) that focused on the hydrogeology of the Sandstone to Bruno area. Since this study had similar goals and methods, the project data from the thesis have been included in the following figures, maps, and discussions.

CHARACTERISTICS OF THE MAJOR AQUIFERS

Aquifer yields can be estimated and compared through various tests that involve pumping water from a well at a constant rate for a certain time period. Table 1 shows the results from the County Well Index (CWI) of the simplest test of this sort called a specific capacity test. This test is defined as well discharge (measured in gallons per minute [gpm]) divided by the water-level drawdown in the pumped well. High specific capacity values are advantageous for the well owner because large amounts of ground water can be withdrawn with a small amount of water-level drawdown in the well. In addition, high specific capacity values usually indicate high values of hydraulic conductivity (the aquifer's ability to transmit water). Based on limited data, water-table sand and gravel aquifers (QWTA), buried sand and gravel aquifers (QBAA), and the Hinckley sandstone aquifer appear to have the highest specific capacities; the Fond du Lac and volcanic rock aquifers appear to have the lowest capacities. The Hinckley sandstone and the volcanic rock aquifers appear to have the greatest variability of specific capacity values, which may reflect the high variability of permeability conditions within these aquifers. All these results seem consistent with the physical characteristics of these units that are discussed in the following sections.

Quaternary sand and gravel aquifers. These aquifers are mostly restricted to the northern and southern portions of the county and represent an important ground-water resource for the county. These aquifers were separated into three overlying units in the southern portion of the county (Figures 2a, 2b, and 2c) and labeled S1, S2, and S3 ("S" for different depositional episodes of Superior lobe glaciers; see also cross sections on Plate 9). The aquifers consist of generally high-permeability sand and gravel in buried valleys trending north and south. The S1 aquifer is locally a surficial water-table aquifer north of the Snake River and a buried confined aquifer most other places in the southern portion of the county. The water-table portion of the S1 aquifer (Figure 2a) is continuous with and has a strong hydraulic connection to the underlying buried aquifers at many locations (for example, Plate 9, cross-section F–F′ left of middle). Similar connections exist between the various buried aquifers at numerous locations across the county (Plate 9, F–F′ left side; G–G′ left side; H–H′ right side) and with the underlying bedrock aquifers (A–A′ through G–G′ at many locations).

Hinckley sandstone aquifer. Municipalities in the county most commonly use this aquifer because it exists beneath most of the large population centers, has good physical aquifer properties, and is very thick (approximately 500 feet along its eastern edge). It has solution-enhanced fractures and high content of quartz sand. Most of the Hinckley Sandstone is a fine- to medium-grained sandstone composed of about 96 percent quartz (Part A, Plate 2). Quartz sandstones tend to retain good primary porosity characteristics. Large portions of this aquifer in an area from Sandstone to Bruno contain karst features, such as sinkholes (Plate 10) and solution-enhanced fractures, that are similar to features in carbonate aquifers in southeastern Minnesota (Part A, Plate 6). Sandstone karst features may also exist in other parts of the county.

Fond du Lac aquifer and similar Mesoproterozoic sandstone aquifer. The Hinckley sandstone aquifer is directly underlain by the Fond du Lac aquifer that has a similar geometry: a vast wedge that is thick in the southeast and thins to the northwest (Part A, Plate 2). However, the Fond du Lac aquifer is very thick (approximately 2100 feet) along its eastern boundary. Although it consists of a medium- to coarse-grained sandstone, a lower content of quartz sand and the presence of siltstone and shale beds result in low hydraulic conductivity. Karst features have not been found in this aquifer and are thought not to exist due to high feldspar content that probably precludes karst processes (Shade, 2002).

In the southeastern portion of the county, an unidentified wedge of Mesoproterozoic sandstone similar to the Fond du Lac aquifer directly overlies the volcanic rocks. However, since it is physically separated from the Fond du Lac aquifer, its stratigraphic relationship remains unknown.

Volcanic rock and metamorphic rock aquifers. The volcanic rock sequence of southeastern Pine County and the metamorphic rocks in the northwest corner of the county are types of crystalline bedrock. These rocks have a matrix that is essentially impermeable to ground-water movement; therefore, ground-water movement is limited mostly to fractures in the rock. The volcanic rock aquifer consists mainly of basalt (Part A, Plate 2). These sequences include the Minong volcanic sequence (Ꞓmmv), an associated basalt sequence (Ꞓmbu), and the Chengwatana volcanic group basalt (Ꞓmcb). One of these basalt units, the Chengwantana volcanic group basalt (Ꞓmcb), contains thin interflow conglomerates (layers of cobbles and gravel) that separate individual lava flows. These layers are hydraulically significant because they provide pathways for ground-water movement in rocks that would otherwise have limited primary permeability. Because of the lack of outcrop and drilling information, it is not known whether the other volcanic sequences contain similar layers of interflow conglomerates. Therefore, all the volcanic sequences have been grouped as one aquifer for the purposes of this report.

Other permeability and porosity features within the volcanic rock aquifer include amygdaloidal flow tops (voids in the rock created by gas bubbles in the lava) and two types of fractures. Localized fracture zones were created by ancient tectonic activity (earth movements), and widespread joint or stress relief fractures were created by slow, gradual, vertical movements of the earth's crust in response to surface loading and unloading of glacial ice (Runkel and others, 2002). These two types of fractures also create most of the permeability and porosity within the metamorphic rock aquifers in northwestern Pine County. Since permeability in these rocks is limited to the fracture zones, wells completed in these aquifers tend to be deeper than equivalent wells completed in the other aquifers, and have longer open-hole (uncased) sections (Plate 9, cross-sections A–A′, B–B′, D–D′, E–E′, and F–F′). The long open-hole sections intercept more fractures, which produce more water for the well. The deep well also acts as a reservoir or cistern for the well owner.

RECHARGE, DISCHARGE, AND GROUND-WATER MOVEMENT IN BEDROCK AQUIFERS

Introduction. Two general hydrogeologic tools can be used to help understand the movement of ground water in aquifers: the potentiometric surface map and the distribution of distinctive ground-water chemical constituents. A potentiometric surface is defined as "a surface that represents the level to which water will rise in a tightly cased well" (Fetter, 1988). The potentiometric surface of a confined aquifer (aquifer under pressure) occurs above the top of an aquifer where an overlying confining layer (low permeability layer) exists. Static (nonpumping) water-level data from CWI and DNR measurements were plotted and contoured to create the potentiometric contour map. Low-elevation areas on the potentiometric surface represent discharge areas; high-elevation areas, combined with other sources of information, can be identified as important recharge areas. Ground water moves from higher to lower elevations perpendicular to the potentiometric elevation contours (flow directions shown as arrows on the Bedrock Hydrogeology map). Geochemical indicators used in this study have three general purposes: estimate residence time or age of ground water (based on tritium and carbon-14), determine whether anthropogenic (human-created) constituents or contaminants (elevated nitrate values and high ratios of chloride to bromide) are present in the ground water, and identify ground water from basalt rock source areas (boron and strontium to magnesium ratios).

Indicators of ground-water residence time. Recent tritium values (shown as dark pink well and spring symbols on the Bedrock Hydrogeology map and Figure 2 maps) are important indicators of water that has infiltrated the surface within the past 50 years. Tritium (^{3}H) is a radioactive isotope of hydrogen that naturally occurs in the atmosphere. However, atmospheric testing of hydrogen bombs from 1953 to the early 1960's greatly increased the concentrations of atmospheric tritium. This tritium combines with atmospheric water molecules, precipitates as rain or snowfall, and enters aquifers through surface infiltration. The presence of tritium at more than 10 tritium units (TU) in a water sample indicates recent water (recharged since 1953). No detectable tritium means vintage water (recharged before 1953). Tritium values in between are mixtures of recent and vintage water. Recent values are common in the Hinckley sandstone aquifer in the central portion of the county because water can travel rather easily and quickly from the land surface to the uppermost water-supply aquifer for that portion of the county (see Plate 10 for detailed discussion).

A few water samples were tested for carbon-14 (^{14}C), which is a method useful for estimating ground-water residence times from approximately 200 years to 40,000 years (Alexander and Alexander, 1989). The age range of the 12 ground-water samples tested for carbon-14 was from 120 years to 6600 years. The oldest sample was from a well in the volcanic rock aquifer in St. Croix State Park.

Anthropogenic indicators. Nitrate concentrations in ground water above approximately 1 part per million (ppm) are usually from anthropogenic sources such as fertilizer application and septic or sewage systems (Minnesota Pollution Control Agency, 1998). Slightly elevated concentrations of nitrate were common in ground-water samples from wells completed in the Hinckley sandstone aquifer between Hinckley and Bruno. None of the samples collected within the county had nitrate concentrations that exceeded the health risk limit of 10 ppm by the Minnesota Department of Health.

Elevated chloride concentrations have been used in other parts of Minnesota as a measure of contamination from road salt or fertilizer application (Berg, 2003). However, remnants of residual brine from ancient seas that contain high concentrations of chloride still exist within Pine County (Shade, 2002). Therefore, chloride alone cannot be used as an indicator of human activities influencing ground-water contamination in the county. Mineral sources of chloride (Cl), such as salt used in water softeners or road salt, are depleted in bromide (Br) relative to chloride and have high Cl/Br ratios. Comparisons of tritium concentrations to Cl/Br ratios from ground-water samples (Figure 3) indicate that none of the samples with Cl/Br ratios above 1000 have vintage tritium values. This relationship suggests that Cl/Br ratios above approximately 1000 in samples appear to be partly attributable to human activities. Four samples collected from the Hinckley aquifer in the Sandstone-Askov area had elevated Cl/Br ratios. Two other samples of this type were collected, one east of Hinckley and one near the northern border of the county.

Source area indicators of basalt rock. The basalt formations of eastern Pine County are part of a larger group of volcanic rocks created during the midcontinent rift episode (Allen and others, 1997). High concentrations of boron and strontium are characteristic of ground water that has been in contact with these rocks (Shade, 2002). A comparison of the ratio of strontium to magnesium (Sr/Mg) to boron concentrations in water well samples collected from the volcanic rock aquifer shows a good correlation indicating a common source (Figure 4). Adding age data (tritium and carbon-14) to this graph to create a bubble plot (tritium values proportional to the size of the circles) reveals a continuum of ground-water types ranging from recent waters with low boron concentrations and Sr/Mg ratios to ancient waters with high boron concentrations and Sr/Mg ratios. The magnitude of boron concentrations and Sr/Mg ratio values in the volcanic rock aquifer is related to the amount of mixing with recent water that has occurred.

The Minnesota Department of Health recommends that drinking water should contain boron at concentrations no greater than 1000 parts per billion (ppb) (Anne Kukowski and Helen Goeden, Minnesota Department of Health, written communs., February 12, 2004). Figure 4 shows that portions of the volcanic rock aquifer that have remained relatively isolated from recent-age recharge waters, as shown by detectable tritium, can have boron concentrations exceeding 1000 ppb. Eight ground-water samples collected from wells around the perimeter of St. Croix State Park had boron values that exceeded 1000 ppb. The potential exists for more occurrences of elevated boron in well samples across the eastern portion of the county where the volcanic rock aquifer is the water source.

Slightly elevated concentrations of boron and Sr/Mg ratios in nonvolcanic rock aquifers indicate ground water that has mixed with water that has been in contact with basalt rocks. Values of boron greater than 95 ppb and Sr/Mg ratios greater than 0.015 in the nonvolcanic aquifers suggest some amount of ground-water contribution from the basalts. The basalt occurrences that supply these constituents to the nonvolcanic aquifers are located in the eastern (volcanic aquifer) and northwestern (metamorphic rock aquifer that contains some basalt rock intrusions) portions of the county.

Bedrock recharge. Recharge to the bedrock aquifers is supplied by precipitation through the overlying glacial sediments. Bedrock aquifer recharge, therefore, occurs throughout the county but at different rates according to the infiltration characteristics and ground-water flow dynamics of the surficial material. In Pine County, bedrock aquifer recharge is influenced primarily by the thickness and composition of the surficial material. Thick glacial sediment with a high proportion of fine-grained sediment (silt and clay) limits ground-water infiltration. The thickness of the surficial material is shown and discussed on Plate 10. Identifying the high recharge rate areas is an important first step for understanding the pollution sensitivity of the bedrock aquifers. High-elevation areas on the potentiometric surface map, combined with anthropogenic chemical constituents and recent or mixed tritium values, are indicative of recharge areas to bedrock aquifers. Extensive and important recharge areas include most of the Hinckley Sandstone subcrop (where the Hinckley sandstone is the uppermost bedrock aquifer) from the City of Hinckley to the northern border of the county.

Another potentiometric high area, in the northwestern corner of the county, is also an area of thin glacial sediment. This area may be an important recharge area for the metamorphic rock aquifer and the Fond du Lac aquifer. Four samples of ground water with basalt source indicators from the northwestern portion of the county provided additional evidence of ground-water recharge to this area and lateral, southeasterly ground-water movement within the metamorphic rock and Fond du Lac aquifers. All these locations are west of the Kettle River ground-water divide and are hydraulically separated from the volcanic rock aquifer in the eastern part of the county. The highest indicator value within this group (147 ppb boron) was from a well in the Denham Formation that contains a metamorphosed basalt unit. This unit may be the source of these basalt ground-water indicators. Aeromagnetic data (Part A, Plate 3) for this portion of the county indicated possible mafic dikes within the bedrock. These dikes may be another source of ground water with basalt-contact indicators. A ground-water sample with mixed tritium from a deep well near the left side of cross-section B–B′ (Plate 9) also suggested lateral recharge to the Fond du Lac aquifer from this area.

Almost no chemical data were available in the northeastern portion of the county. Since this is a topographically high area of the county and the glacial sediment is relatively thin and moderately permeable (Plate 10, Figures 3a and 3b), this is probably an important recharge area for the volcanic rock aquifer.

Bedrock discharge. Bedrock aquifer discharge in Pine County is dominated by the Kettle River in the west-central portion of the county and the St. Croix River in the southeast. The major ground-water flow directions within the county are controlled by these two drainages. The Kettle River is such a strong ground-water discharge feature that two Hinckley sandstone springs located along the river near the City of Sandstone discharge vintage ground water in an area that would otherwise be expected to discharge recent ground water because of rapid infiltration conditions (see Plate 10). One of these springs also contained chemical indicators from the underlying volcanic rock aquifer (high boron and Sr/Mg values). In addition, three bedrock wells along the Kettle River north of the City of Sandstone contained water with indicators of volcanic rock aquifers. These spring and well data indicated the deep, upwelling ground-water flow conditions shown on cross-section C–C′ (Plate 9). This upwelling occurs within the Hinckley sandstone aquifer along the Kettle River from the City of Sandstone to Willow River. Notable secondary ground-water discharge conditions are created by the lower Snake River, East Pokegama Creek southeast of Brook Park, North Fork Grindstone River southwest of Pine City, and Sand Creek south of Bruno.

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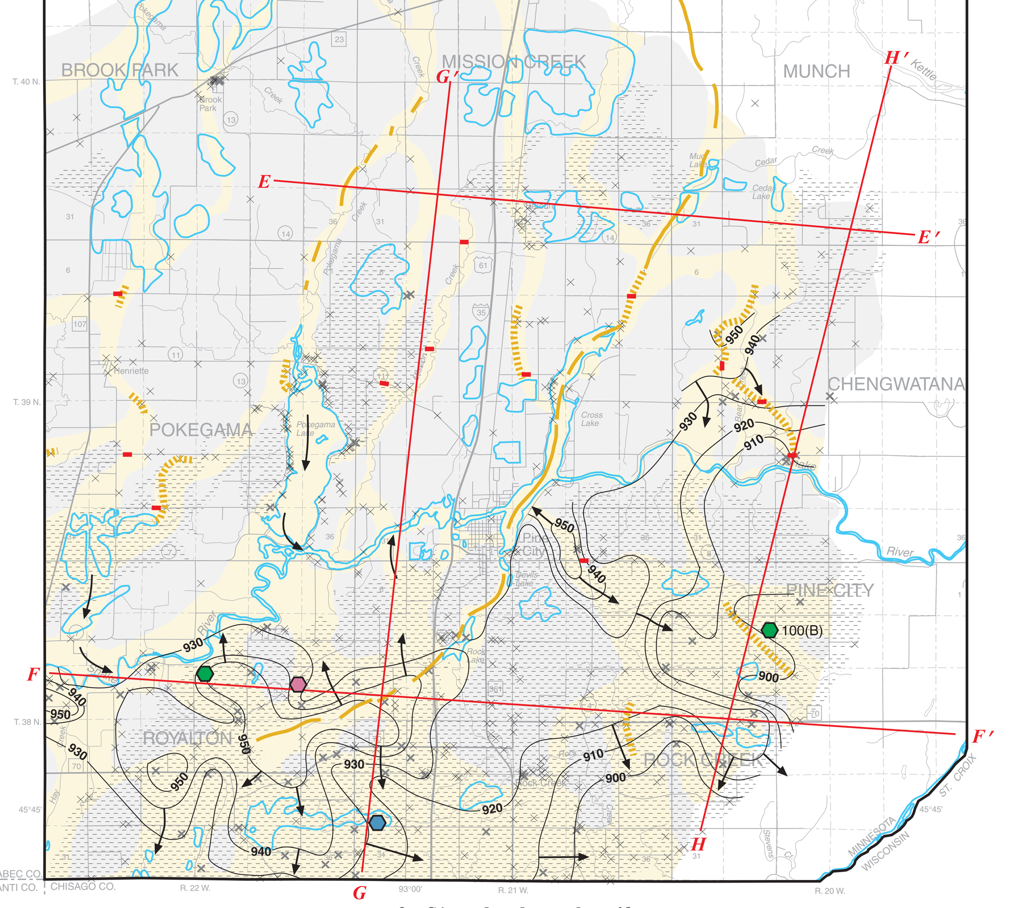
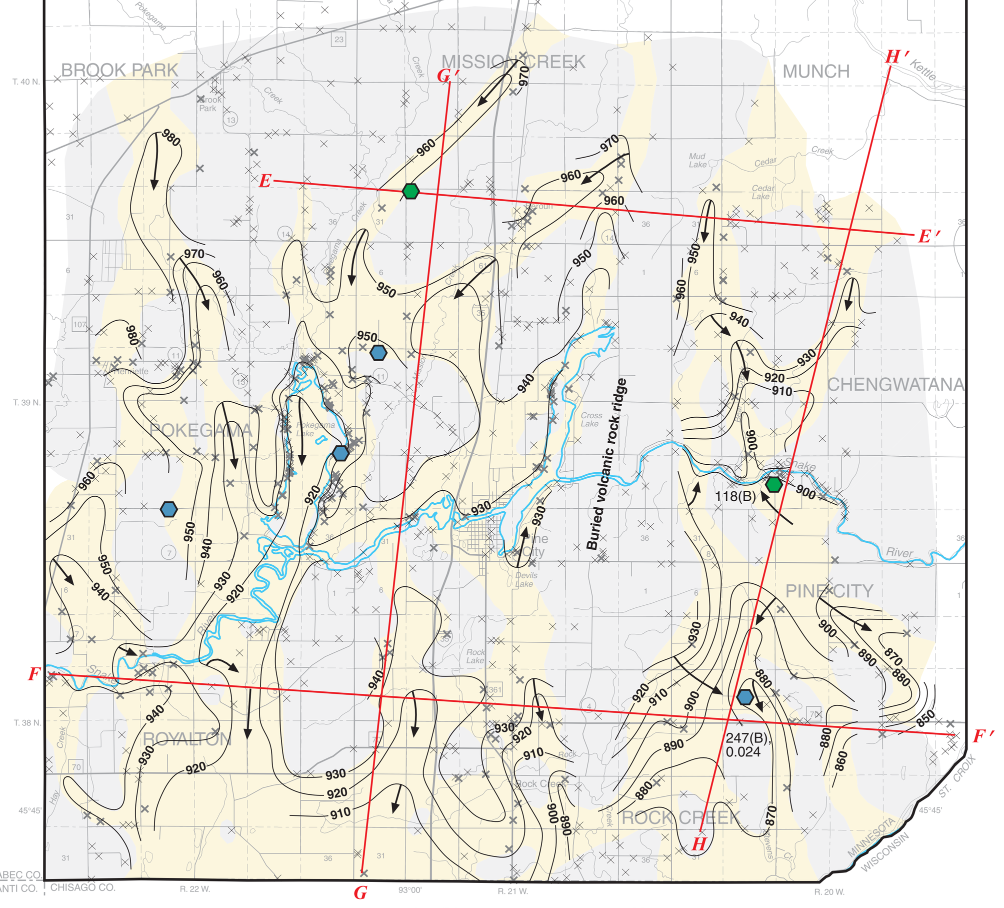


2a. S1 sand and gravel aquifer
Elevation of top of the S1 unit: 860–1000 feet above mean sea level



2b. S2 sand and gravel aquifer
Elevation of top of the S2 unit: 830–940 feet above mean sea level

2c. S3 sand and gravel aquifer
Elevation of top of S3 unit: 700–860 feet above mean sea level

FIGURE EXPLANATION

- 900 — Contour of potentiometric surface in feet above mean sea level.
- General direction of ground-water movement.
- Aquifer 20 feet or more thick
- Aquifer absent or less then 20 feet thick
- Overlying clayey units: Grantsburg till and glacial Lake Grantsburg sediment
- Quaternary well, recent tritium age
- Quaternary well, mixed tritium age
- Quaternary well, vintage tritium age
- 247(B) If shown, boron concentration exceeds 95 parts per billion
- 0.024 If shown, strontium to magnesium ratio equals or exceeds 0.015
- Well log data point
- Static water level data point
- F—F′ Line of cross-section
- Esker
- Buried esker
- Resistivity line
- Major river
- Lakes and wetlands

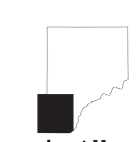


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FIGURE 2. *Quaternary sand and gravel aquifers of southern Pine County.* Buried sand and gravel deposits are the most important source of ground water for domestic and agricultural use in southern Pine County. Most of the sand and gravel was deposited by meltwater from glaciers receding northward. Three depositional units, called S1, S2, and S3, were mapped using approximately 1000 drillers' logs in the County Well Index (CWI), surficial geologic features, and surface resistivity image data. The well logs were correlated with a network of 10 stratigraphic cross sections. The positions of four cross sections (E–E′, F–F′, G–G′, H–H′) are shown on Figures 2a, 2b, and 2c, and the corresponding cross-section diagrams are shown on Plate 9. Sand and gravel descriptions from the logs were classified by comparison with the cross sections. The approximate elevation ranges of the upper surfaces of units were the following: S1—860 feet to 1000 feet, S2—830 feet to 940 feet, and S3—700 feet to 860 feet. Where known or possible sand and gravel deposits in the S1, S2, and S3 units were 20 feet or more thick, these deposits were considered aquifers and are shown in yellow as the S1, S2, and S3 aquifers on Figures 2a, 2b, and 2c, respectively. The gray areas show where the aquifers are thin (less than 20 feet) or where no sand or gravel was encountered for the network at its characteristic elevation at that location. These aquifers are shown on cross-section diagrams E–E′ through H–H′ on Plate 9.

The S1 sand and gravel unit was deposited in two phases. The initial phase consisted of deposition of sand and gravel in subglacial valleys (tunnel valleys) as north-south oriented, linear ridge deposits called eskers. Some of these eskers are exposed at the surface and are shown on Plate 4 of Part A and on Figure 2a of this plate. This subglacial valley formation and deposition of the eskers for this unit probably occurred mostly during the St. Croix and Automba phases of the Superior lobe (Part A, Plate 5, Figures 1A through 1C). A second phase of sand deposition began after the southern portion of the county was covered by glacial Lake Lind (Part A, Plate 5, Figures 1D through 1F). Fine-grained deltaic sand was deposited into glacial Lake Lind from the receding Superior lobe to the northeast apparently filled in the existing tunnel valleys with fine-grained sand from lake deltas. The lake basin was deepest in the southern portion of the area. Therefore, the fine lake sand is thicker and more laterally continuous south of the Snake River than in areas to the north where the fine lake sand is mostly limited to the tunnel valleys. Unit S1 is a composite of these two depositional phases.

The stippled overlay pattern on the S1 aquifer map (Figure 2a) shows the overlying protective layers that were deposited during a subsequent glacial ice advance from the south (Grantsburg sublobe) and associated glacial lake episode (glacial Lake Grantsburg; see Part A, Plate 5, Figure 1I). Thick, clayey glacial deposits cover much of the aquifer south of the Snake River. However, an extensive, irregularly shaped ground-water mound and the presence of tritium in ground-water samples shown in the southwestern corner of the S1 map indicated substantial local recharge to the buried S1 aquifer in this area through the partially buried esker deposits. The elevated boron concentration (greater than 95 parts per billion) near the southeastern corner of the S1 map was evidence that the aquifer is connected to a buried volcanic ridge located a few miles to the west (Plate 9, cross-section F–F′). North of the Snake River, most of the S1 aquifer has thin or no cover. For more information on boron indicators, see "Volcanic rock and metamorphic rock aquifers" and "Source area indicators of basalt rock" in the text block above.

The S2 and S3 units (Figures 2b and 2c) have a distribution like the S1 unit. This suggests a similar history of glacial sand and gravel deposition in discrete valleys. Since these units are deeper than the S1 unit, the buried volcanic ridge in the eastern portion of the area acted as a depositional divide forcing sediment into two sub-basins. This ridge also acts as a ground-water divide separating each of the S2 and S3 aquifers into eastern and western ground-water basins that ultimately converge at the St. Croix River. Recent and mixed tritium values were found in ground-water samples along the northern fringe of both the S2 and S3 aquifers, suggesting lateral recharge through buried valley deposits or shallow bedrock areas. In approximately the southern half to three-quarters of the area, vintage tritium values from the S2 and S3 aquifers indicate less direct or slower recharge and lower pollution sensitivity. Elevated boron concentrations or magnesium ratios from water samples in the eastern portion of the area indicate a strong hydraulic connection to the buried volcanic ridge to the west (Plate 9: cross-sections E–E′ and F–F′, and label 6).

East of Pine City, ground water from both the S2 and S3 aquifers enters the Snake River from the north and south. West of Pine City, much of the southerly S2 and S3 ground-water flow may bypass the Snake River on its way to the St. Croix River. Both of these aquifers have similar potentiometric surfaces at Pokegama Lake suggesting that these two sand and gravel aquifers have coalesced at that location.

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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.
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GEOLOGIC ATLAS OF PINE COUNTY, MINNESOTA