Hydrogeology and Simulation of Groundwater Flow in Sauk County, Wisconsin

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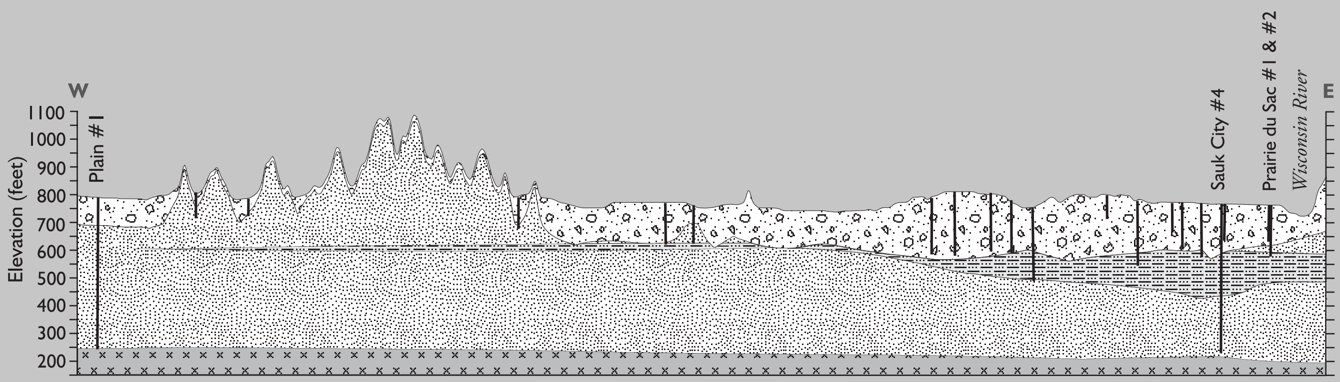

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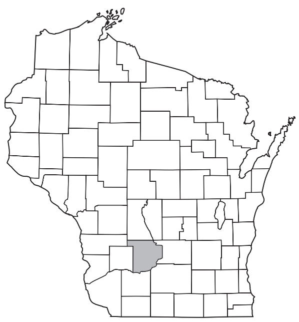

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FIGURES

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Hydrogeology and Simulation of Groundwater Flow in Sauk County, Wisconsin

Madeline B. Gotkowitz, Kurt K. Zeiler, Charles P. Dunning, Judith C. Thomas, and Yu-Feng Lin

ABSTRACT

In this report we describe the regional hydrogeology and groundwater resources of Sauk County, Wisconsin, and the regional groundwater flow model we developed for the county. Important regional hydrostratigraphic units include the unlithified aquifer, the sandstone aquifer, the Eau Claire aquitard, and the quartzite aquifer.

- *The unlithified aquifer consists of deposits that range in composition from sand and gravel to clayey till and lake sediment. This aquifer is absent in much of the uplands of western Sauk County, but consists of more than 200 ft of permeable sand and gravel deposits in the Wisconsin River valley bottom.*
- *The sandstone aquifer consists of most of the saturated Paleozoic bedrock units above the Precambrian rock. The sandstone aquifer underlies the unlithified aquifer where the unlithified aquifer is present and is the uppermost aquifer in upland areas where the bedrock is shallow and the surface deposits are unsaturated.*
- *Interbedded fine-grained facies of the Eau Claire Formation range in thickness from zero to more than 235 ft in southeastern Sauk County. The facies thin to the west and are not present over much of the county. Where present, the facies are an aquitard, restricting vertical flow between the unlithified and sandstone aquifers. In areas of the county where the Eau Claire aquitard is not present, the sandstone aquifer is in good hydraulic contact with the overlying unlithified aquifer.*
- *A relatively low-hydraulic conductivity quartzite aquifer supplies small volumes of water to domestic and park wells in the areas of the Baraboo Hills that have no overlying sandstone or unlithified aquifer. The hydraulic conductivity of the quartzite is low and water flows to wells predominantly through fractures. The quartzite is characterized as the bottom boundary of the sandstone aquifer because of the relative differences of the hydraulic conductivity of the two units.*

The two-dimensional regional groundwater flow model presented here is adequate for simulating groundwater flow to wells where flow is predominantly horizontal, such as areas of the county where wells are completed in a thick sequence of the sandstone aquifer. The model indicates that almost all the groundwater pumped in Sauk County originates as recharge within the county. Steady-state zones of contribution limited by travel times of 50 years show that most of the municipal wells produce water that originates as recharge within approximately 2 miles of a given well.

On the basis of estimates of groundwater use and groundwater recharge, sufficient groundwater is available to meet current and probable future demand. However, groundwater withdrawal from particular wells can decrease flow to nearby streams and springs. Although natural groundwater quality in Sauk County wells is good, nitrate and pesticide residues originating at the land surface have affected the groundwater quality throughout Sauk County.

INTRODUCTION

Background

In 1998 personnel from the Sauk County Departments of Health, Land Conservation, and Planning and Zoning, and the University of Wisconsin–Extension formed the Sauk County Groundwater Working Group. Recognizing the lack of information regarding regional groundwater and surface-water flow systems in the county, the group developed the Sauk County Groundwater Project, a joint project of the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS).

Sauk County has recently experienced a rapid increase in population: In 2002 the county population was 55,225, an increase of 17 percent since 1990 and 49 percent since 1960 (Sauk County Development Corporation, 2003). Accompanying this increase in population are an increase in residential building, a decrease in land in agricultural production, and an increase in road capacity from major population centers in adjacent Dane County. These changes have heightened awareness among citizens and public officials of a need to manage and preserve the water resources of Sauk County.

Purpose and scope

In this report we describe the regional hydrogeologic framework and groundwater flow systems in Sauk County and summarize the geologic features relevant to the hydrogeology. We provide compilations and summaries of various groundwater-use and groundwater-quality datasets. We also document the development and results of a two-dimensional computer model used to simulate regional groundwater flow and several three-dimensional submodels developed for areas of the county that are more hydrogeologically complex. The models can be used to assess current and proposed groundwater withdrawals and to evaluate effects of proposed groundwater-management programs. The information provides a basis to assess the susceptibility of groundwater to drawdown from pumping and contamination from land-use practices.

One of the primary purposes for developing the computer model of groundwater flow was to identify the zones of contribution (ZOCs) for municipal wells in the county. A ZOC encompasses that part of the land surface over which recharging precipitation enters a groundwater system and eventually flows to a well; identifying ZOCs helps determine potential contamination sources to a well and provides a scientific basis for delineating wellhead-protection areas.

Physical setting

Sauk County encompasses 837.7 mi^2 in south-central Wisconsin. Most population centers are along the Wisconsin and Baraboo Rivers (fig. 1); other parts of the county are largely agricultural. The county includes three geologically and geographically distinct physiographic regions: the glaciated area, the Baraboo Hills, and the Driftless Area (fig. 2; Clayton and Attig, 1990). Each of these regions has topographic and geomorphic features that are the result of the complex geologic history of the area.

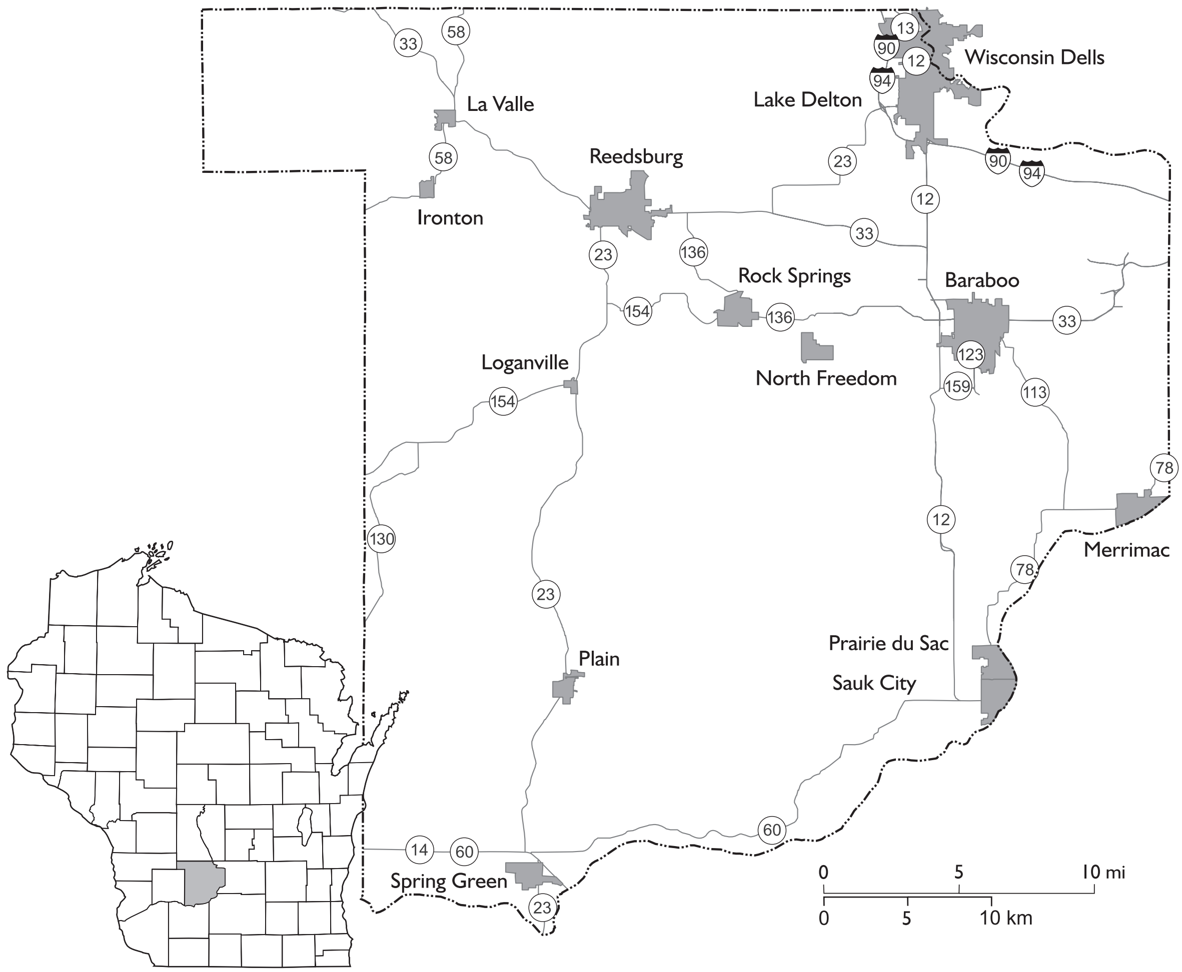


Figure 1. *Location of Sauk County, Wisconsin, and its population centers.*

The eastern part of Sauk County is covered by material deposited during the last part of the Wisconsin Glaciation. The outermost moraine (fig. 2) marks the maximum extent of the glacial ice, and the area east of this moraine consists of thick deposits (up to 400 ft) of glacial and stream sediment. Glacial lake sediment deposited in several basins (fig. 2) and outwash sediment covers a large part of the land surface west of the moraine. The outwash plain, with sediment deposits up to approximately 250 ft thick, consists primarily of sand and gravel and extends in broad terraces along the Wisconsin River. Lake sediment, which typically underlies modern stream valleys, consists primarily of sand with interbedded silt and clay. The complex layering of glacial, lake, and outwash deposits in Sauk County is illustrated in the cross sections of Clayton and Attig (1990) and Dalziel and Dott (1970).

The Baraboo Hills, in the east-central part of the county, consist of Precambrian quartzite that forms a complex arrangement of plunging synclines and anticlines. The surface expression of the syncline forms the South and North Ranges of the Baraboo Hills, which trend east–northeast over approximately 15 miles. The South Range is fairly continuous and has relatively flat summit plateaus. It rises approximately 800 ft above the surrounding valleys to elevations more than 1,580 ft above sea level. The North Range

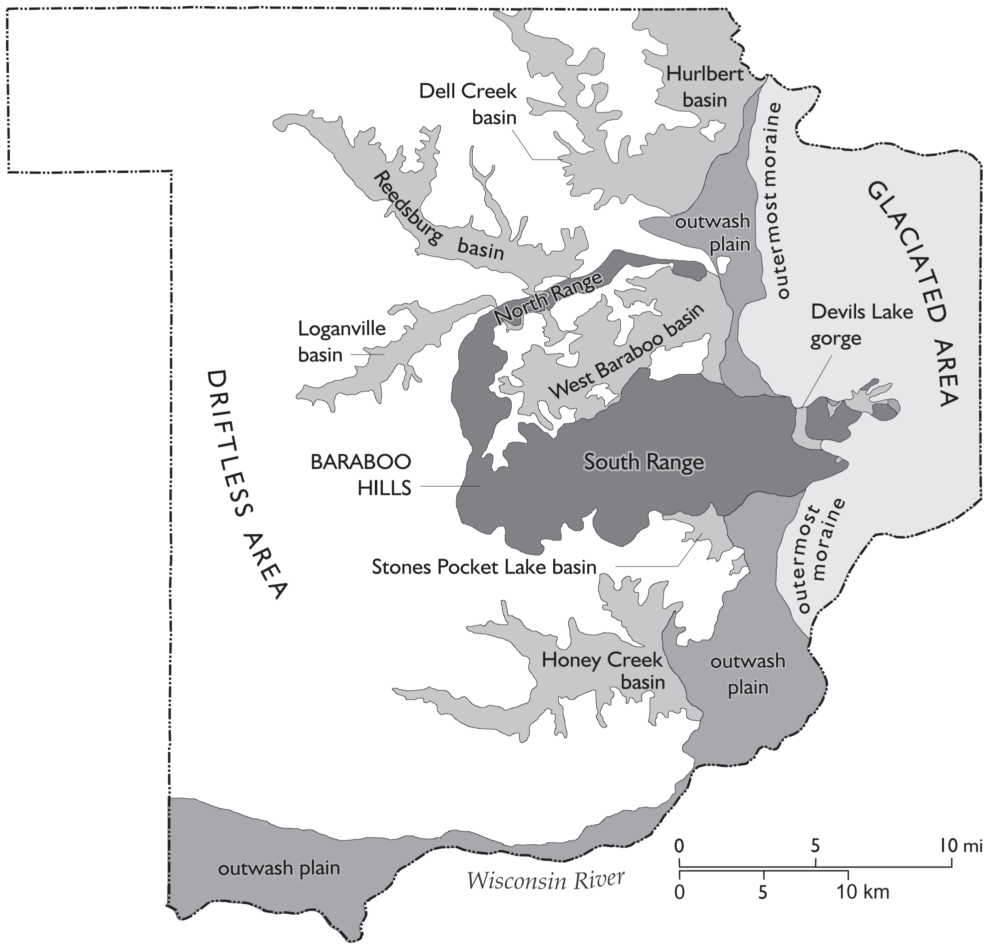


Figure 2. *Sauk County physiographic regions and glacial features. Lake and stream basins indicate areas where fine-grained sediments deposited during glacial periods may be present within unlithified deposits. (Modified from Clayton and Attig, 1990.)*

is smaller and more discontinuous. A thin soil layer covers the Baraboo Hills; the depth to bedrock is generally less than 25 ft (Gotkowitz and Zeiler, 2003a). Glacial lake sediment in the West Baraboo basin (fig. 2) overlies Cambrian sandstone of the bedrock Baraboo basin, which is bounded by the Baraboo Hills. The relatively impermeable quartzite surrounding Baraboo basin sandstone creates a complex hydrogeologic setting.

Extensive parts of northern, southern, and western Sauk County lie within the Driftless Area, a region of Wisconsin not covered by glaciers in the geologic past (Clayton and Attig, 1990). The Driftless Area consists of narrow uplands with relatively flat ridgetops surrounded by steep-sided valleys. Ridgetops and valley bottoms are used for pasture and row crops, and the hillslopes are typically wooded. The elevations of the ridgetops vary from approximately 1,100 to 1,300 ft, up to 400 ft above nearby valley bottoms. In the uplands, surficial deposits are typically less than 25 ft thick, although in isolated areas the depth to bedrock can be up to 100 ft. The areas of thicker surficial deposits in the uplands are probably the result of increased mineral weathering (clay and soil formation) or windblown deposition of glacial loess. Nearly flat-lying Paleozoic sand, sandstone, siltstone, and dolomite are exposed along the valley walls. The valley bottoms contain tens of feet of Pleistocene sediment overlying layers of sandstone and dolomite. The high topographic relief and layering of various types of sedimentary rocks that have contrasting permeabilities constitute a hydrogeologic setting distinct from other regions within the county.

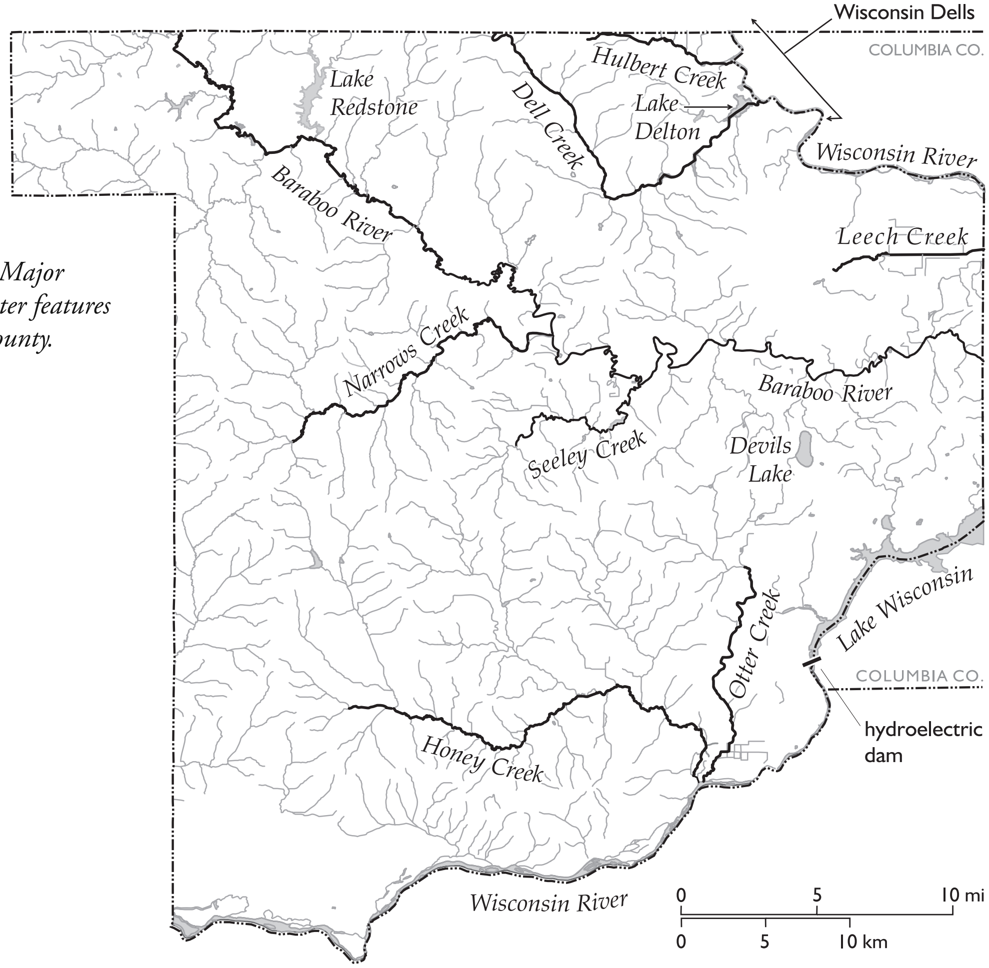


Figure 3. *Major surface-water features of Sauk County.*

The Wisconsin River extends along the northeast, southeast, and southern borders of Sauk County (fig. 3). In the Wisconsin Dells, the river valley is narrow and steeply downcut into sandstone formations. To the south and southeast of the Dells, the valley broadens as it passes through broad and flat outwash plains. The river stage drops approximately 38 ft across the hydroelectric dam at the southern end of Lake Wisconsin.

The Baraboo River traverses the width of Sauk County, flowing from the northwest through the Driftless Area and across the glaciated region (figs. 2 and 3), ultimately discharging to the Wisconsin River in Columbia County. Four dams that once spanned this river in Sauk County were removed between 1997 and 2001. Other stream systems, including Honey Creek, Narrows Creek, and Dell Creek, occupy glacial lakebeds and the valleys of the Driftless Area (fig. 3). Flow in creeks that originate in the Baraboo Hills (such as Otter and Seeley Creeks) is influenced by the distinctly different hydrologic settings encountered as the creeks flow from the Baraboo Hills to discharge into the Baraboo or Wisconsin Rivers. Several large lakes are in the northern part of the county, including Lakes Redstone and Delton, which are manmade, and Devils Lake, which is a natural feature (fig. 3).

On the basis of measurements collected at the Baraboo Water Works, the average annual precipitation in Sauk County is 33.8 inches. Seventy percent of this precipitation falls from April to September. The average annual air temperature is 43.4° F. The maximum

Table 1. *Municipal wells and pumping rates.*

Well	Local well number	Wisconsin unique well number	Aquifer type	2000 average pump rate (in gpm)	Pump capacity (in gpm)	Modeled pump rates for calibration (in gpm)	Modeled pump rates for ZOC determinations (in gpm)
Baraboo	2	BG928	sandstone	229	650	229	325
Baraboo	4	BG929	sandstone	403	1100	403	550
Baraboo	6	BG931	sandstone	413	1000	413	500
Baraboo	7	AR322	unlithified	523	1300	523	650
Baraboo	8	RX387	sandstone	not in use	1000	0	799
Ironton	1	EP387	sandstone	13	550	13	275
La Valle	1	BG932	sandstone	26	182	26	91
Lake Delton	1	BG951	sandstone	58	340	58	170
Lake Delton	2	EJ765	sandstone	114	450	114	225
Lake Delton	3	EJ766	sandstone	305	750	305	375
Lake Delton	4	EJ767	sandstone	132	600	132	300
Lake Delton	5	OH433	sandstone	not in use	950	0	475
Loganville	1	BG933	sandstone	18	220	18	110
Merrimac	1	BG934	unlithified	22	450	22	225
North Freedom	2	BG936	sandstone	30	300	30	150
Plain	1	BG937	sandstone	18	145	18	73
Plain	2	BG938	sandstone	44	345	44	173
Prairie du Sac	2	BG939	unlithified	114	1375	114	688
Prairie du Sac	3	AY370	sandstone	145	535	145	268
Reedsburg	1	BG941	sandstone	not in use	305	0	153
Reedsburg	2	BG942	sandstone	not in use	285	0	143
Reedsburg	3	BG943	sandstone	662	500	662	761[1]
Reedsburg	4	BG944	sandstone	719	700	719	827[1]
Reedsburg	5	BG945	sandstone	not in use	580	0	290
Reedsburg	6	CB345	sandstone	485	1060	485	530
Rock Springs	1	BG946	sandstone	0.03	150	0.03	75
Sauk City	4	BG954	sandstone	141	1290	141	645
Sauk City	5	CN884	sandstone	127	1200	127	600
Sauk County Health	2	BG901	sandstone	0.14	not available	0.14	0.14[1]
Sauk County Health	3	BG902	sandstone	15	not available	15	18[1]
Spring Green	1	BG949	sandstone	46	430	46	215
Spring Green	2	BG950	unlithified	179	900	179	450
Wisconsin Dells	1[2]	BF378	sandstone	69	580	69	290
Wisconsin Dells	2[2]	BF379	sandstone	not in use	450	0	225
Wisconsin Dells	3[2]	BF380	sandstone	125	600	125	300
Wisconsin Dells	4	BG952	sandstone	102	600	102	300
Wisconsin Dells	5	BG953	sandstone	93	1000	93	500
Wisconsin Dells	6[2]	AC717	sandstone	62	500	62	250

[1] Pumping rate used for ZOC determination was 15 percent greater than the 2000 average rate. All other pumping rates used for ZOC determinations are equal to one-half the pump capacity.

[2] Well owned and operated by city of Wisconsin Dells, but located in Columbia County.

average temperature of 82.9° F occurs in July, and the average minimum temperature of 1.6° F occurs in January (Wisconsin State Climatology Office, 2004).

Water use and pumping centers

Information about water use in Sauk County is compiled every 5 years by the USGS, based partly on information collected by state agencies and partly on estimates of population and water-use rates (Ellefson and others, 2002). Groundwater is the primary source of water: Ninety-nine percent of the approximately 13.86 million gallons per day (gpd) of water used in the county is groundwater. Approximately 41 percent of the groundwater used supplies industrial facilities; 23 percent is pumped for domestic use; agricultural use (including irrigation) accounts for 16 percent of the total; commercial use totals 9 percent. The remaining 11 percent is attributed to use at public facilities such as schools, parks, and hospitals and pipe losses from water-supply systems.

Fourteen municipal water-supply systems in Sauk County serve population centers in Reedsburg, Baraboo, Sauk City–Prairie du Sac, Wisconsin Dells–Lake Delton, and smaller communities throughout the county (fig. 1). Total pumping from municipal wells was approximately 7.8 million gpd in 2000; more than 90 percent of this use occurred in these four population centers. Average pumping rates during 2000 at the wells maintained by these systems varied widely (table 1). Groundwater is also withdrawn by privately owned wells serving homes, mobile home parks, hotels, water parks, schools, hospitals, agricultural needs, and commercial and industrial businesses.

Previous work

Clayton and Attig (1990) provided an extensive characterization of the complex geologic history of Sauk County, including descriptions of surficial deposits and bedrock units, a geologic map, and cross sections. Dalziel and Dott (1970) focused on the geology of the Baraboo Hills and the Baraboo basin.

Although no single publication contains comprehensive information about the hydrogeology of Sauk County, several reports contain site-specific hydrogeologic information compiled for well siting or contamination investigations (for example, Mid-State Associates, 1992; U.S. Army Environmental Center, 1993). Zeiler (2002) reported on a three-dimensional groundwater flow and transport model developed for the Badger Army Ammunition Plant, which is in the outwash plain along the Wisconsin River.

Many studies have been conducted in some of the unique hydrologic settings found within Sauk County. Pfeiffer (2001) studied the hydrologic system on the Wisconsin River floodplain at Cambell Bottoms, in southwest Sauk County. She determined that groundwater recharge on nearby bluffs and local recharge to the river terraces are sources of water to the lowland savanna environment. Her work characterized recharge and discharge at the scale of the ridge and swale topography within the floodplain, groundwater–surface water interactions in the floodplain, and changes in flooding patterns along the Wisconsin River since the construction of major reservoirs in the 1940s. Hunt (1987) examined the hydrogeochemistry in the wetland setting at the Leopold Memorial Reserve. Boorse (1999) compared two prairie pothole wetlands in the glaciated region of the county that differ in their hydrologic and groundwater conditions. The work of Patlak (1983) includes an evaluation of groundwater flow at a prairie wetland in eastern Sauk County.

Hindall and Borman (1974) and Devaul and Green (1971) provided atlas-type summary maps of groundwater and surface-water resources as well as water budgets for the central and lower Wisconsin River basins. Weidman and Schultz (1915) identified flowing wells, providing a historical perspective on groundwater elevations and water use in the county. Harr and others (1978) described the groundwater resources of neighboring Columbia County. Bradbury and others (1999) and Krohelski and others (2000) characterized the hydrogeology and developed a groundwater flow model of nearby Dane County.

An investigation of the hydrogeology of La Crosse County in southwest Wisconsin provided insight to the groundwater flow system in the physiographic region of the Driftless Area (Chapel and others, 2003). Juckem (2003) evaluated groundwater recharge in the Coon Creek watershed, which is in the Driftless Area. Juckem concluded that recharge occurs primarily along hillslopes, rather than on ridgetops, and that the contrasts between the rock properties within the Paleozoic section in the uplands of the Driftless Area may result in perched groundwater conditions.

METHODS AND DATA SOURCES

Our study relied primarily upon existing hydrologic and geologic data. Much of these data was organized in geographic information system coverages and database formats (Gotkowitz and Zeiler, 2003a, 2003b). The database includes records of more than 1,200 municipal, commercial, industrial, irrigation and private drinking-water wells.

Subsurface records

Wisconsin Department of Natural Resources (DNR) well construction reports provided information about the thickness and characteristics of unlithified materials and bedrock units, depth to groundwater, and specific capacity of wells. The locations of these wells were determined to within 50 to 1,000 ft by cross-checking information from the reports with plat maps, aerial photographs, and USGS 7.5-minute series topographic maps (1962–83). Depth to water measurements recorded on the reports were converted to groundwater elevations using estimates of land-surface elevation from the National Elevation Dataset (U.S. Geological Survey, 2001) digital elevation model (DEM), 30 m grid.

WGNHS geologic logs, which are based on examinations of samples of drill cuttings from well boreholes, contain detailed descriptions of lithology and stratigraphy. Approximately 270 of these logs provided estimates of the top and bottom elevations of the hydrostratigraphic units in Sauk County. Geologic logs from neighboring counties, the geologic map and cross sections compiled by Clayton and Attig (1990), and maps of hydrostratigraphic units for a regional groundwater model of Dane County developed by Krohelski and others (2000) were also considered in developing these regional-scale maps of the hydrostratigraphic units.

Subsurface data collected during the study include borehole geophysical logs (natural gamma radiation, electric, and caliper) at a well in Baraboo and a well in the village of Lake Delton. We conducted two surface resistivity surveys in the uplands of western Sauk County to evaluate thickness of geologic strata and water-table elevation.

Hydrologic data

Existing hydrologic data were compiled from well construction records and records of pumping tests and specific capacity tests on file at the WGNHS. The TGUESS computer program (Bradbury and Rothschild, 1985) was used to estimate horizontal hydraulic conductivity of aquifer sediments from specific capacity tests.

Long-term records of water levels for two monitoring wells, one in Sauk County and one in nearby Dane County, are contained in the database of the Groundwater Observation Network, which is maintained by the USGS (http://wi.water.usgs.gov/public/gw/). Streamflow records used in this project are also in a database maintained by the USGS (http://nwis.waterdata.usgs.gov/wi/nwis/discharge). We measured flow at several streams in Sauk County to provide additional information for calibration of the groundwater flow models. We also conducted field surveys to locate some stream headwaters and springs to verify parts of the water-table map.

Water-table elevations

We estimated water-table elevations in Sauk County from the elevations of surface-water features such as streams, lakes, and wetlands and from the depth to water recorded on well construction reports. We also used the USGS digital data for hydrography (derived from U.S. Geological Survey, 2001), topographic quadrangles (U.S. Geological Survey 7.5-minute series, digital raster graphics, 1996–97), and the DEM as aids in estimating these elevations. Gotkowitz and Zeiler (2003b) produced a water-table map for the county at a scale of 1:100,000, which we generalized for this report.

The accuracy of the map varies throughout the study area, increasing near surface-water bodies and where a greater density of wells could be reliably located. The water-table elevation was inferred from topography where data were scarce.

Table 2. *Non-municipal wells included in model and their permitted pumping rates.*

Well name	Pumping rate (in thousand gpd)
Badger Army Ammunition Office	86.4
Blackhawk Elementary School	3.6
Bluffview A	1.2
Bluffview B	172.9
Christmas Mt. Hotel/Chalet	9.6
Christmas Mt. Oak Villas	86.4
Cooperative Service Center	86.4
Dellwood Mobile Home Park	86.4
Devils Head Resort Lodge	518.6
Fairfield Center Elementary School	3.6
Foremost Farms Baraboo	431
Foremost Farms Reedsburg A	540.2
Foremost Farms Reedsburg B	660.3
Foremost Farms Sauk City	431
Hartje Lumber	86.4
Koenecke Ford Mercury	86.4
Living Hope Academy	86.4
Loganville Elementary School	3.6
Lower Dells Estate 1	86.4
Lower Dells Estate 2	86.4
Lower Dells Estate 3	86.4
Maple Park	86.4
Merrimac Mobile Home Park	86.4
Mueller Sports Medicine	3.6
Oak Ridge Estates Mobile Home Park	86.4
Spring Brook Falls	86.4
Summer Oaks Cove	57.6
Tower Rock Elementary School	3.6
U.S. Department of Agriculture Dairy Forage Research Center	115.3
Weston Elementary School	3.6
Weston High School	3.6
46 irrigation wells, various locations	86.4
9 school wells	3.6
6 Badger Army Ammunition Plant remediation wells	718.3
5 Badger Army Ammunition Plant remediation wells	316
19 commercial, industrial, and park wells	86.4
Total (other than municipal pumping in regional model)	4,173.1

The use of water levels from well construction reports to create the water-table map is a likely source of inaccuracy. Water-supply wells are not ideal measuring points for determining the water-table elevation because most of these wells are open to the aquifer over long intervals that extend far below the top of the saturated zone. However, this well design provides a good measurement of depth to groundwater in low-lying areas, such as the outwash plains, where groundwater flow is predominantly horizontal. At higher elevations and in areas of steep terrain, groundwater flow may have a large vertical component. In such areas, the water level measured in a well may be lower than the water-table elevation. For this reason, it is difficult to determine accurately the water-table elevation on ridgetops in the uplands.

Well locations and pumping rates

The DNR provided locational information for municipal wells and their monthly pumping rates from the year 2000; we used the monthly rates to calculate an average pumping rate (table 1). We verified the locations and pumping rates for a majority of the municipal wells by contacting water-utility personnel from each town or city. We determined locations of other high-capacity wells (wells that are permitted by the DNR to pump in excess of 70 gallons per minute [gpm]) and their permitted pumping rates from information on file at the WGNHS and the DNR (table 2). We did not verify pumping rates at these wells with owners or operators.

HYDROGEOLOGY

Regional geology

Paleozoic bedrock formations in the Driftless Area of Sauk County are composed of up to 900 ft of nearly flat-lying, alternating layers of sand, sandstone, shale, siltstone, and dolomite underlain by Precambrian igneous and metamorphic rock. In the Baraboo Hills, the predominant bedrock is Precambrian quartzite of the Baraboo Formation. A generalized stratigraphy of Sauk County and corresponding units of hydrogeologic significance is shown in figure 4.

Age		Group	Formation	Description		Hydrostratigraphic unit
Cenozoic			Rountree, Horicon, and others	sandy clay and glacial sediment		unlithified aquifer
Paleozoic	Ordovician	Ancell	St. Peter	sandstone	Parfreys Glen	sandstone aquifer
		Prairie du Chien	Oneota	dolomite		
	Cambrian	Trempealeau	Jordan	sandstone		
			St. Lawrence	siltstone, sandstone, and dolomite		
			Tunnel City	sandstone		
		Elk Mound	Wonewoc	sandstone		
			Eau Claire	sandstone or shale/ siltstone		aquitard
			Mount Simon	sandstone		sandstone aquifer
Precambrian			Baraboo	predominantly quartzite		quartzite aquifer/aquitard

Figure 4. *Generalized stratigraphy and hydrostratigraphy for geologic units in Sauk County (modified from Clayton and Attig, 1990).*

Precambrian units

Igneous and metamorphic rock of Precambrian age is exposed at the land surface in the Baraboo Hills and underlies Cambrian sedimentary rock in other areas of the county. The elevation of the surface of the Precambrian rock (fig. 5) is well documented in the Baraboo Hills and parts of the Baraboo basin, where there are large surface exposures and where many wells are drilled in Precambrian rock. Logs from wells in Spring Green, at the Badger Army Ammunition Plant, and northwest of La Valle provide constraints on the elevation of the Precambrian surface in other areas of the county. The surface elevation of the Precambrian rock in Sauk County ranges from less than 200 to more than 1,400 ft above sea level (fig. 5); most of this extreme topographic relief is in the vicinity of the Baraboo Hills.

Paleozoic units

The Cambrian Elk Mound Group, which includes the Mount Simon, Eau Claire, and Wonewoc Formations, is laterally extensive in all parts of the county except the Baraboo Hills. The Mount Simon Formation is a fine- to medium-grained quartz sand and sandstone, bounded by the Precambrian surface at the base and overlain by the Eau Claire Formation. The Mount Simon can be seen in the vertical cliffs of the Wisconsin River gorge at the Wisconsin Dells. It reaches a maximum thickness of 500 ft north of the Baraboo Hills and varies from approximately 0 to 200 ft thick south of the Hills. In the Baraboo Hills area, the Mount Simon and other sandstones of the Elk Mound Group abut conglomeratic sandstone of the Parfreys Glen Formation (fig. 6).

Several classifications of Eau Claire Formation in Sauk County have been proposed (Clayton and Attig, 1990). With respect to the hydrogeologic considerations, sandstone facies of this formation are difficult to distinguish from the underlying Mount Simon or overlying Wonewoc Formations. A shale zone that is up to 10 ft thick in southeastern Juneau County (Clayton, 1989) may be a part of this unit; however, Clayton and

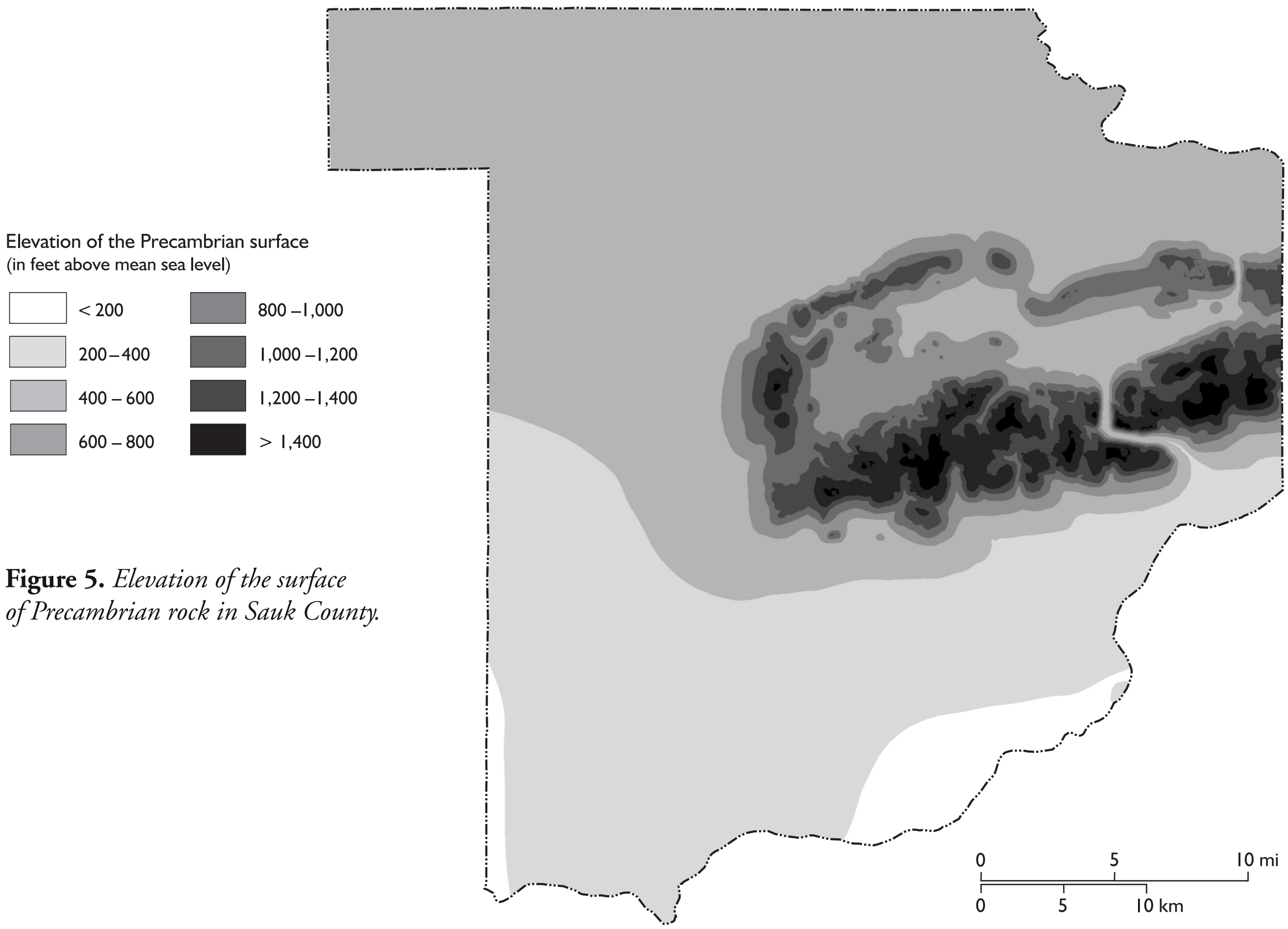


Figure 5. *Elevation of the surface of Precambrian rock in Sauk County.*

Attig (1990) reported only minor occurrences of siltstone, on the order of several millimeters, in northeastern Sauk County. In southeastern Sauk County, the Eau Claire is entirely in the subsurface and is reported on various geologic logs to consist of dolomitic sandstone with considerable siltstone, shale, and sandy dolomite. Although individual shale beds up to 65 ft thick are noted in several geologic logs in the area, the combined thickness of shale and siltstone ranges up to 250 ft in a well at the Badger Army Ammunition Plant (WGNHS geologic log 570005). Shale does not appear in deep wells drilled in Spring Green or Plain in southwestern Sauk County; however, shale up to 75 ft thick has been encountered in the Eau Claire Formation in Arena, Wisconsin, on the south side of the Wisconsin River in Iowa County (WGNHS geologic logs 250102 and 250003). Bradbury and others (1999) found that the shale facies of the Eau Claire Formation vary widely across Dane County, thinning from up to 120 ft in western parts of the county to less than 10 ft in eastern Dane County.

The Wonewoc Formation consists of quartz sand and sandstone, similar to the Mount Simon and Eau Claire Formations. The overlying Tunnel City Formation, generally a glauconite-rich sandstone, ranges from approximately 90 to 135 ft thick. Several geologic logs near Loganville, in northwest Sauk County, report approximately 10 ft of shale at the base of the Tunnel City Formation (WGNHS geologic logs 570108, 570129, and 570020).

The Cambrian Trempealeau Group comprises the St. Lawrence and Jordan Formations. The St. Lawrence Formation contains approximately 30 to 70 ft of siltstone, very fine-grained sandstone, and some shale and dolomite. It is overlain by the Jordan Formation, which consists of fine- to coarse-grained sandstone up to 70 ft thick.

Ordovician strata include the Prairie du Chien and Ancell Groups. The youngest extensive bedrock formation in Sauk County is the Oneota Formation of the dolomitic Prairie du Chien Group. The Oneota is up to 70 ft thick and forms the relatively flat upland plateaus of the county. The St. Peter Formation of the Ancell Group overlies the Oneota at few locations in the county and does not affect the regional hydrogeologic setting.

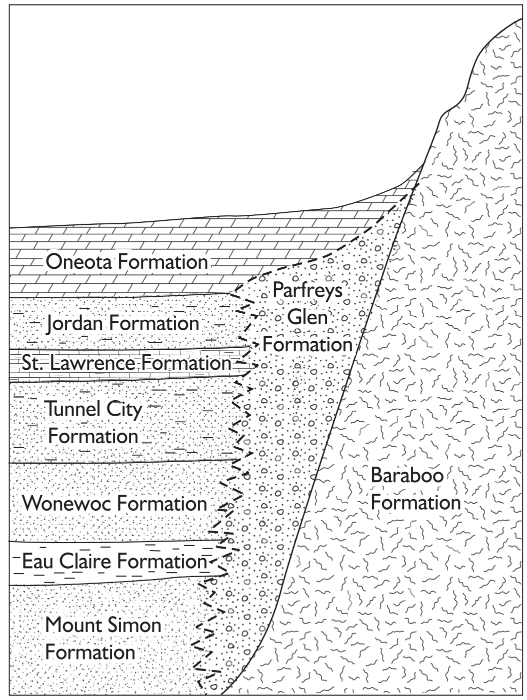


Figure 6. *Generalized cross section of sandstone aquifer units and the Baraboo Formation (modified from Clayton and Attig, 1990).*

The Tunnel City, St. Lawrence, Jordan, and Oneota Formations have been eroded from most river valleys, but these units form the valley walls and ridgetops in the Driftless Area. The thickness of the Cambrian–Ordovician sequence ranges up to 900 ft; the thickest intervals of this sequence are in the uplands of the Driftless Area (fig. 7). The elevation of the top of the Cambrian–Ordovician bedrock surface varies as dramatically as the land-surface topography, with elevations of up to 1,310 ft above sea level in northwestern Sauk County (fig. 8).

Cenozoic units

The Rountree Formation is a nearly continuous sheet of clay, sandy clay, and clayey sand that overlies the Oneota Formation in the uplands of the western part of the county. Its average thickness is estimated to be approximately 30 ft in the middle of the upland plateaus, thinning toward the edges of the plateaus and absent on the hillslopes. The age of the Rountree is not known, but it may in part be as old as early Cenozoic (Lee Clayton, Wisconsin Geological and Natural History Survey, verbal communication, 2004).

Quaternary deposits in Sauk County formed approximately 20,000 years ago as the Green Bay Lobe advanced during the Wisconsin Glaciation. The westernmost advance is marked by the outermost moraine (fig. 2), which forms a north–south ridge. In most places, an outwash plain adjoins the moraine to the west. The outwash plain consists primarily of sand and gravel deposits. Several modern stream basins contained lakes during glacial periods, such as the Reedsburg, Dell Creek, and Honey Creek Basins (fig. 2). These basins are areas where fine-grained lake sediment may be found within the unlithified deposits.

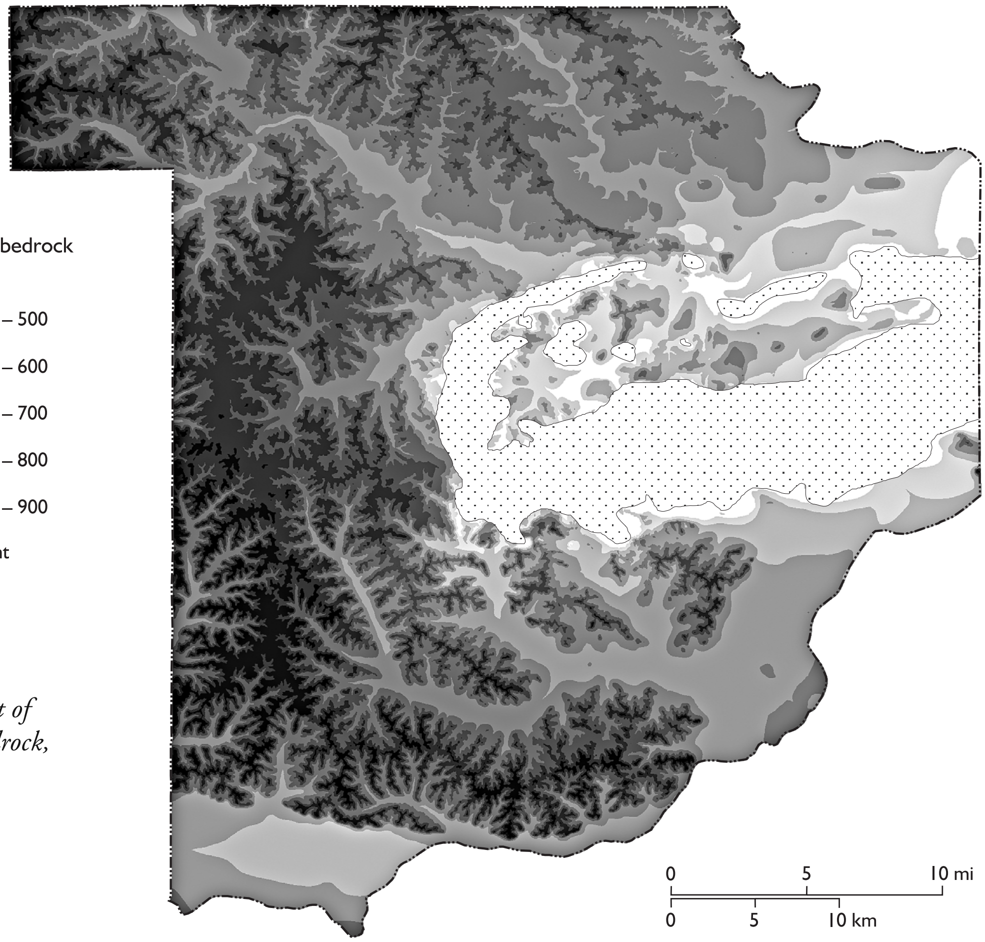


Figure 7. *Thickness and extent of the Cambrian–Ordovician bedrock, which constitutes the sandstone aquifer.*

The till found on the moraine, the thinner till deposits east of the moraine, and collapsed glacial stream or lake sediment east of the moraine are primarily part of the Horicon Formation. Clayton and Attig (1990) described the lakebed sediments as a complex arrangement of sand, silt, and clay. Where till is present, it is accompanied by a complex layering of meltwater-stream sand and gravel, poorly sorted sand and gravel deposited in esker tunnels, interbedded till deposits, and supraglacial sediment that is poorly sorted and gravelly. The till itself typically consists of approximately 5 to 10 percent clay, 15 to 30 percent silt, 60 to 75 percent sand, and approximately 10 percent gravel.

Hydrostratigraphic units

Hydrostratigraphic units are partial or entire geologic formations or several formations lumped together that have similar hydraulic properties. Aquifers are hydrostratigraphic units that can store and transmit water at rates sufficient to supply groundwater to wells; aquitards are hydrostratigraphic units that are relatively impermeable to the flow of groundwater. The definition of hydrostratigraphic units depends upon the scale at which the groundwater system is being evaluated. For example, although a particular interval of shale within a sandstone aquifer may alter flowpaths to a nearby well, the shale facies may not have a lateral extent sufficient to constitute an aquitard within the regional groundwater system.

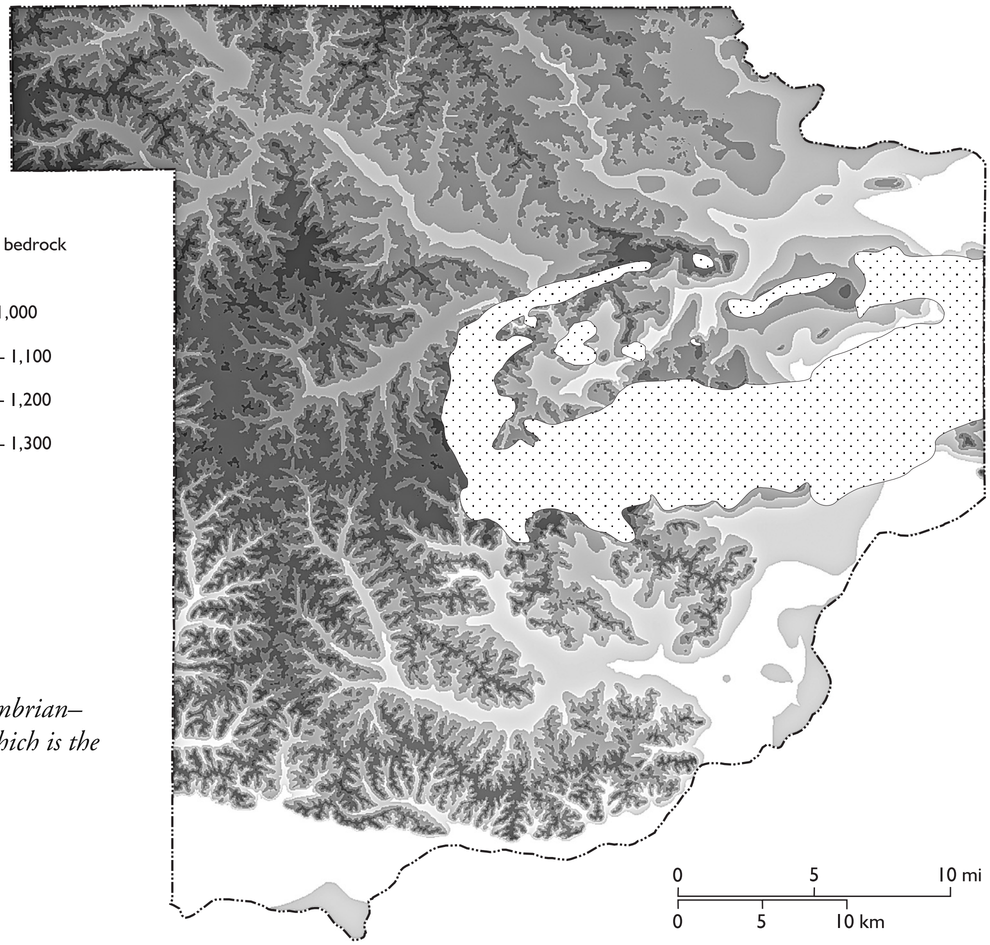


Figure 8. *Elevation of the Cambrian–Ordovician bedrock surface, which is the top of the sandstone aquifer.*

Four hydrostratigraphic units are important for regional groundwater flow in Sauk County (fig. 4). There are two primary aquifers, the unlithified and the sandstone aquifers, and one primary aquitard, the Eau Claire aquitard. The fourth hydrostratigraphic unit, the Precambrian quartzite, yields sufficient flow to a relatively small number of domestic wells within the Baraboo Hills. However, the Precambrian formations constitute an aquitard over most of Sauk County, forming the base of the sandstone aquifer, due to the very low hydraulic conductivity of the Precambrian rock compared to that of the Cambrian sandstone that overlies it. The thicknesses of these hydrostratigraphic units vary across the county with changes in the topographic and geologic setting, as is illustrated in a series of hydrostratigraphic cross sections (fig. 9A–F). This delineation of aquifers and aquitards is appropriate for the regional scale of this study; site-specific studies may require further consideration of local conditions.

Unlithified aquifer

The unlithified aquifer is the uppermost aquifer everywhere it is present. It consists of glacial and alluvial materials that vary in composition from sand and gravel outwash to clayey till and lake sediment. The aquifer consists of more than 200 ft of permeable sand and gravel deposits in the Wisconsin River valley bottom. The extent and thickness of unlithified deposits are shown in figure 10; figure 11 illustrates areas in the county where these deposits are typically sufficiently thick and permeable to constitute an aquifer. This aquifer is absent in the uplands of the Driftless Area, where the unlith-

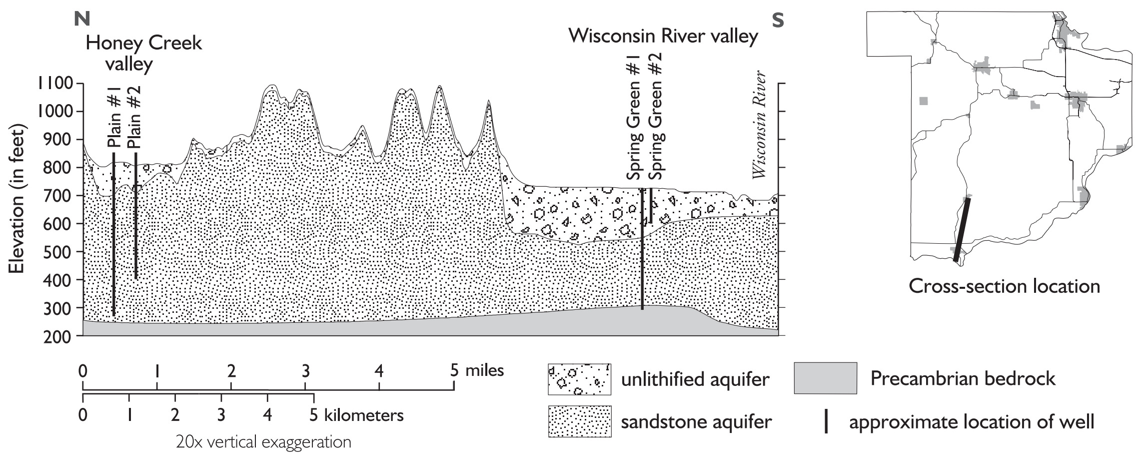


Figure 9A. *North–south cross section from Plain through Spring Green.*

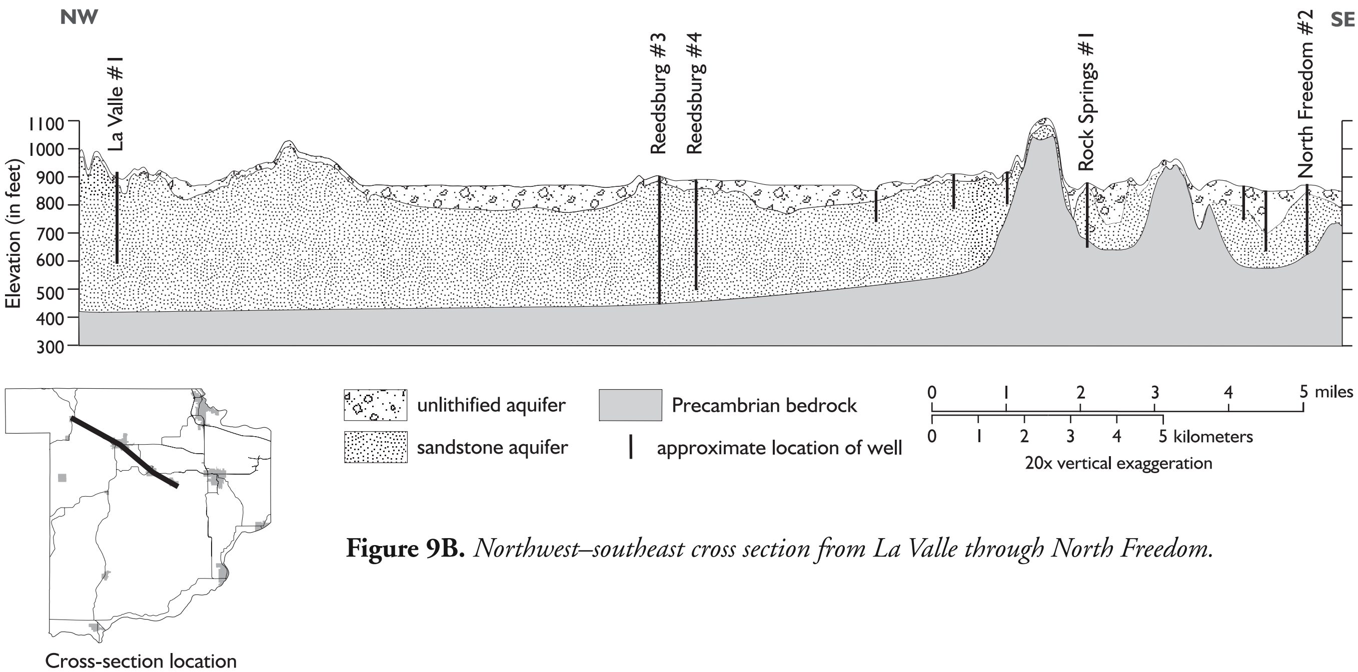


Figure 9B. *Northwest–southeast cross section from La Valle through North Freedom.*

ified deposits are thin, typically unsaturated, and consist primarily of sandy clay of the Rountree Formation. The unlithified aquifer is thick and very permeable in outwash plains and the major river valleys (fig. 9A–F). Data from specific capacity tests conducted at 46 wells completed in this aquifer yield estimates of horizontal hydraulic conductivity ranging from 55 to 976 feet per day (ft/day), with a geometric mean of 162 ft/day. The hydraulic conductivity of the unlithified aquifer decreases in areas where it consists primarily of glacial lakebed sediment or till deposits, but in those areas it may still be sufficient to supply domestic wells. Several municipal wells located in the outwash plain or alluvial valleys pump exclusively from the unlithified aquifer (table 1).

Sandstone aquifer

The sandstone aquifer underlies the unlithified deposits and consists of all saturated bedrock units above the Precambrian rock, with the exception of the parts of the Eau Claire Formation that act as an aquitard (discussed in the next section, *Eau Claire aqui-*

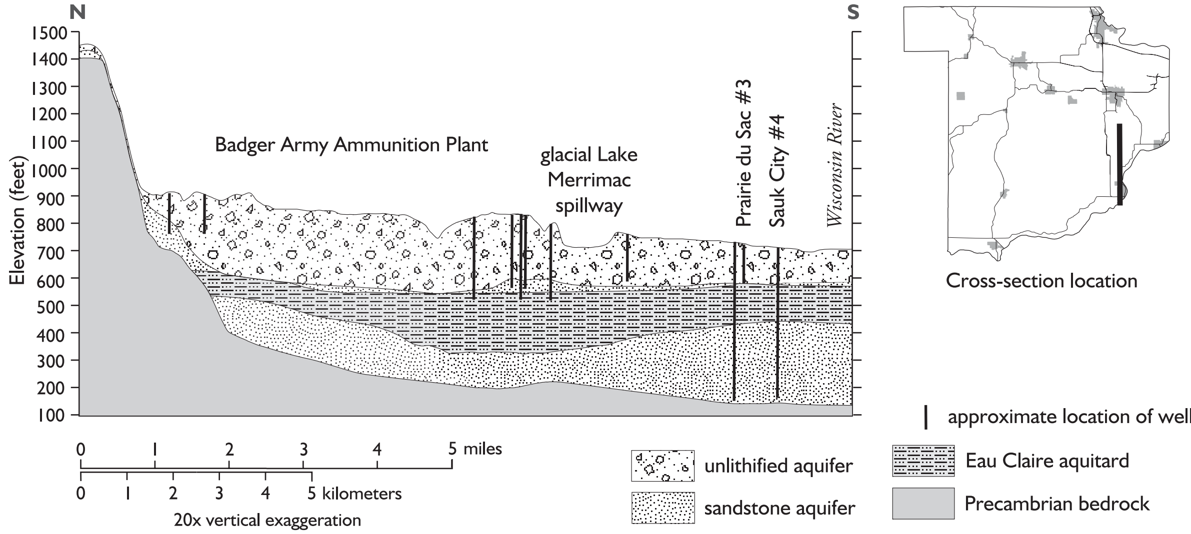
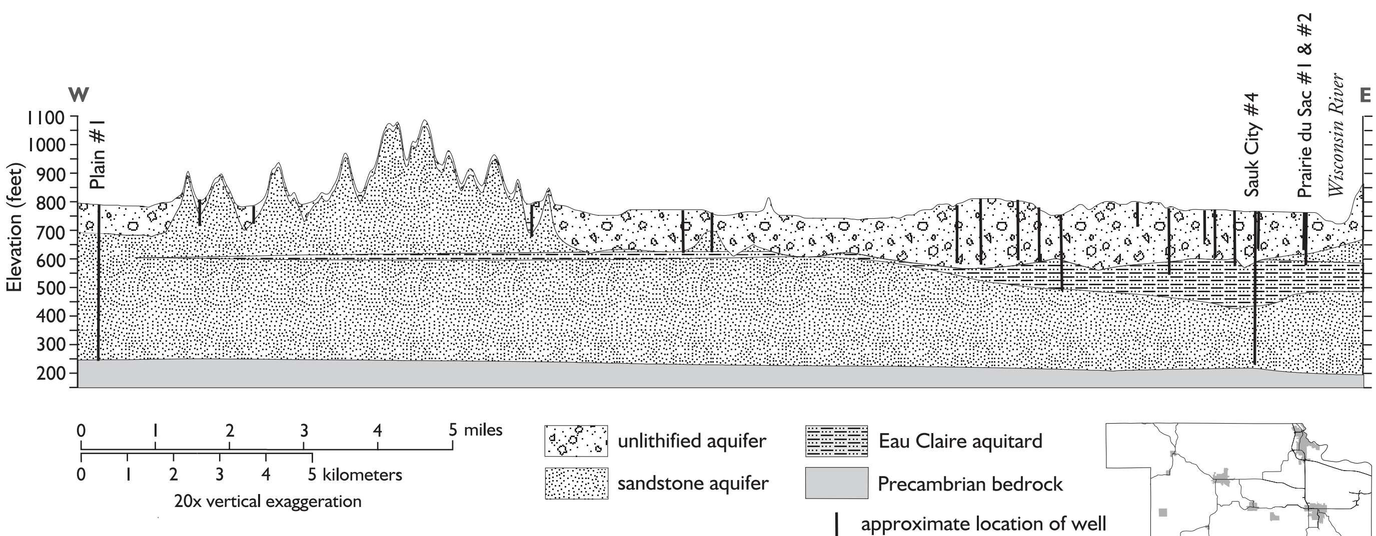


Figure 9C. *North–south cross section through Prairie du Sac area.*



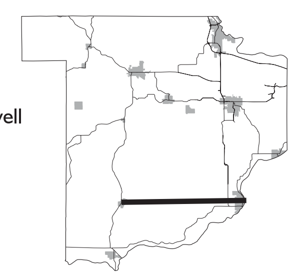


Figure 9D. *West–east cross section from Plain to Prairie du Sac area.*

tard). Where the water table is in bedrock, the water table defines the top of the aquifer. Where the water table is in unlithified materials, the Cambrian–Ordovician bedrock surface defines the top of the sandstone aquifer (fig. 8). In many areas of the county, such as Spring Green, no aquitard separates the unlithified and sandstone aquifers, and they function as a single aquifer with heterogeneous hydraulic properties. Areas of Sauk County where the sandstone is the primary aquifer used by high capacity and domestic wells are illustrated in figure 11. Data from specific capacity tests conducted at 46 municipal and private high capacity wells completed in the sandstone aquifer yield estimates of horizontal hydraulic conductivity ranging from 1 to 153 ft/day, with a geometric mean of 8 ft/day.

Most municipal wells in Sauk County are drilled through and open to sandstone of the Elk Mound Group. Lithologic descriptions on geologic logs from these wells indicate that the sandstone is primarily fine to medium grained. Geophysical logs collected in

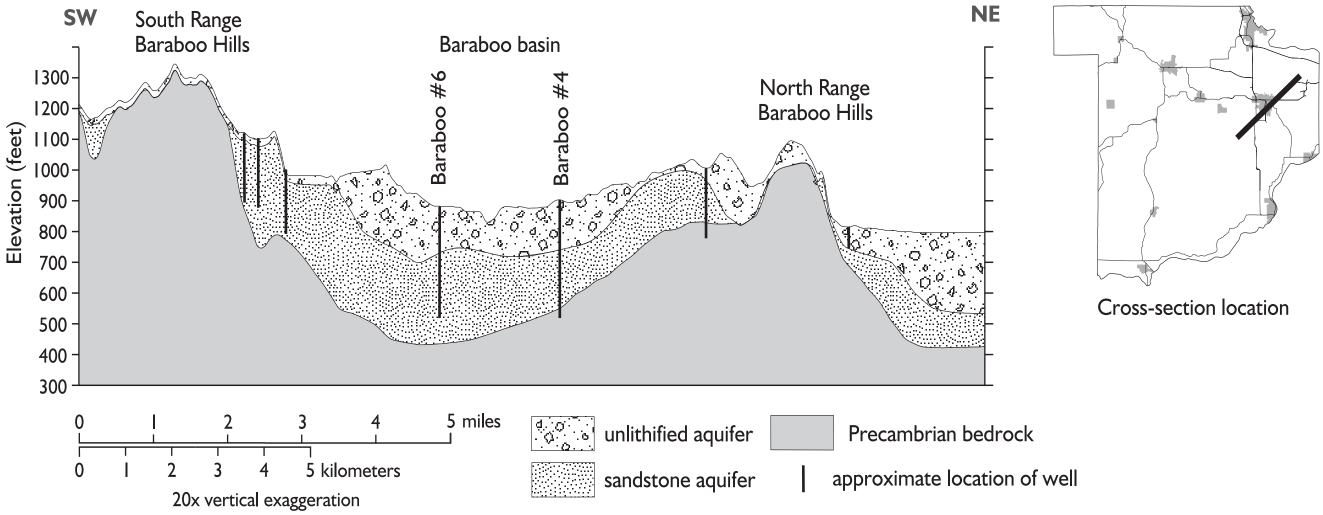


Figure 9E. *Southwest–northeast cross section through the Baraboo basin.*

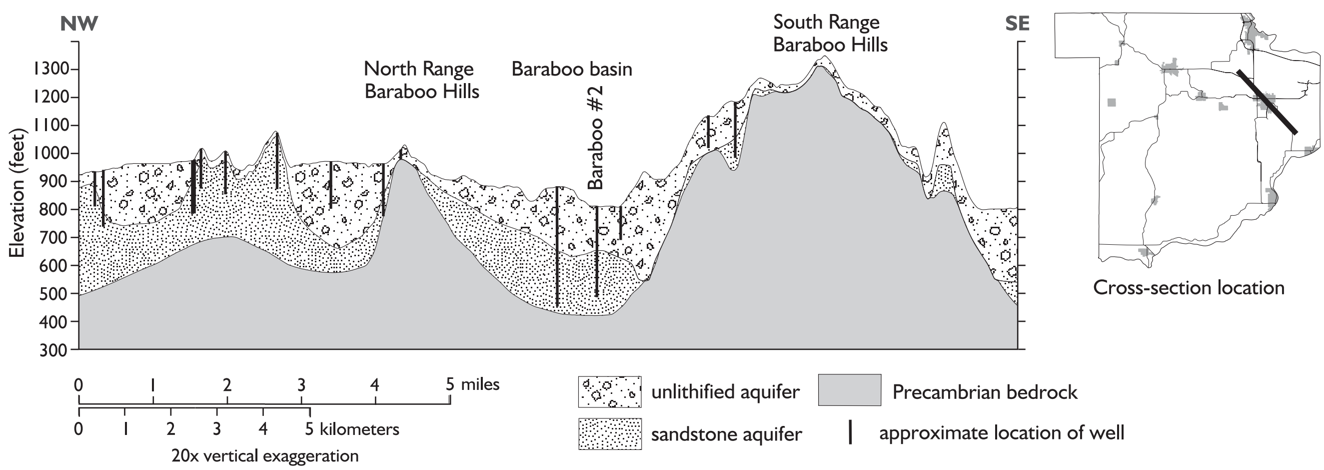


Figure 9F. *Northwest–southeast cross section through the Baraboo basin.*

wells in Lake Delton (WGNHS log 570433) and Baraboo (WGNHS log 570431) show uniform properties of the Elk Mound formations. Of particular interest is the lack of any fine-grained units at elevations and stratigraphic intervals that would correlate to the Eau Claire Formation, confirming the absence of the Eau Claire aquitard at these locations.

Little is known about the hydrogeologic properties of the Ordovician and late Cambrian dolomite, siltstone, and sandstone that constitute the upland ridges in Sauk County. Although many domestic wells are completed in dolomite of the Oneota Formation, most municipal wells in the county are in areas stratigraphically below this unit, in valleys where the Ordovician and late Cambrian formations are absent. Therefore, no data are available to assess hydraulic gradients within and between these formations. Vertical and horizontal fractures are commonly observed in the Oneota dolomite in Sauk County (Lee Clayton, Wisconsin Geological and Natural History Survey, verbal communication, 2003) and in La Crosse County (Chapel and others, 2003). Specific capacity data from domestic wells completed in the Oneota indicate that the overall yield of the formation is low. It is likely that flow to the wells occurs primarily through second-

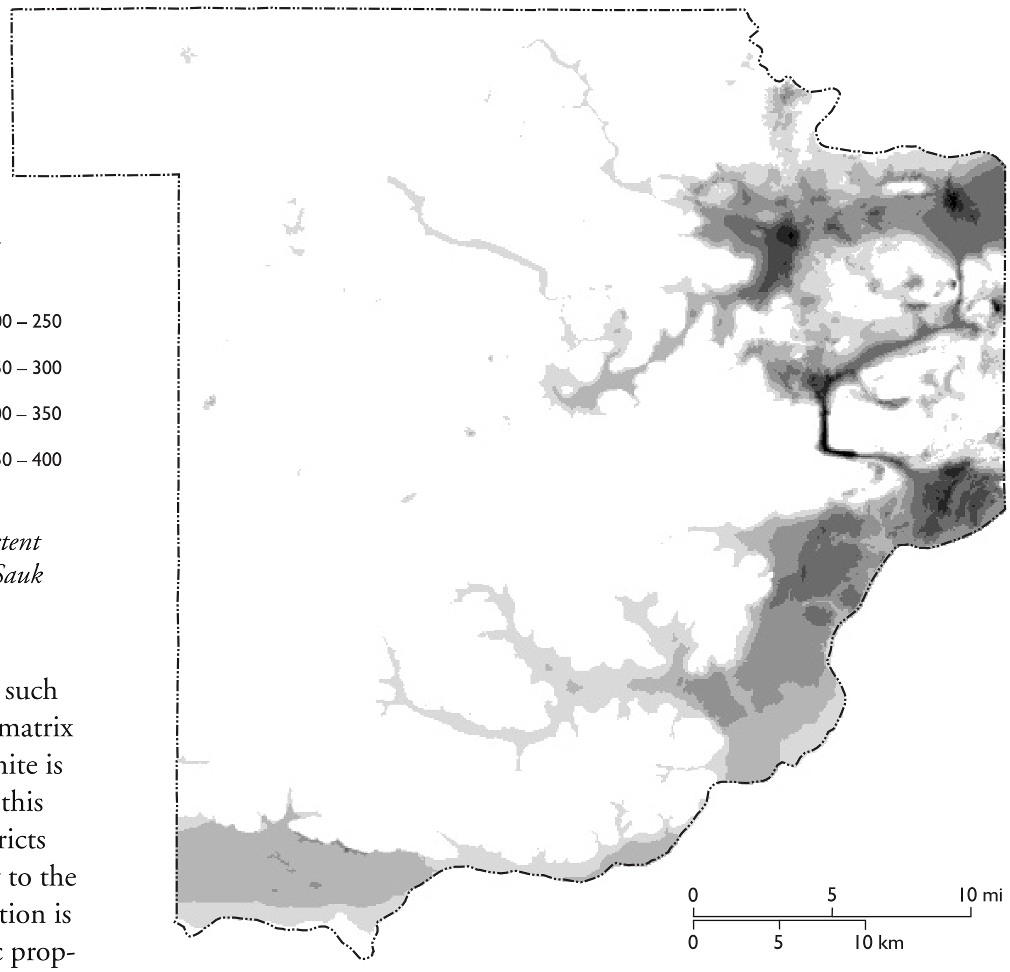


Figure 10. *Thickness and extent of the unlithified aquifer in Sauk County.*

ary permeability features, such as fractures, and that the matrix permeability of the dolomite is low. The extent to which this formation permits or restricts vertical groundwater flow to the underlying Jordan Formation is unknown. Hydrogeologic properties of the Oneota in western Wisconsin and eastern Minnesota are discussed in detail by Chapel and others (2003) and by Runkel and others (2003).

The fine- to coarse-grained sandstone of the Jordan Formation may constitute a regionally extensive aquifer underlying the Oneota. Underlying the Jordan, the predominantly fine-grained lithology in the St. Lawrence Formation and occasional fine-grained sequences within the Tunnel City Formation likely restrict vertical movement of groundwater. Juckem (2003) suggested that in Coon Valley in the Driftless Area, the Jordan sandstone may be under perched conditions due to the overall confining properties of the overlying Oneota dolomite and the underlying St. Lawrence Formation.

Low hydraulic conductivity strata at the base of the Tunnel City Formation confine, or at least partially confine, underlying sandstone of the Elk Mound Group. At a few locations in northwestern Sauk County, the wells reach the base of the Tunnel City Formation. Ten to 15 ft of shale within the Tunnel City has been reported in well logs at Loganville (WGNHS geologic log 570129), the Sauk County Health Care Center (WGNHS geologic log 570108), and the village of Ironton (WGNHS geologic log 570389). Static water levels reported by drillers for the Loganville and Heath Care Center wells, which are both cased through the shale, are higher than the elevation of the shale, indicating that the shale confines (or partially confines) the underlying sandstone. Work by Swanson (2001) in Dane County suggested that bedding-plane fractures and

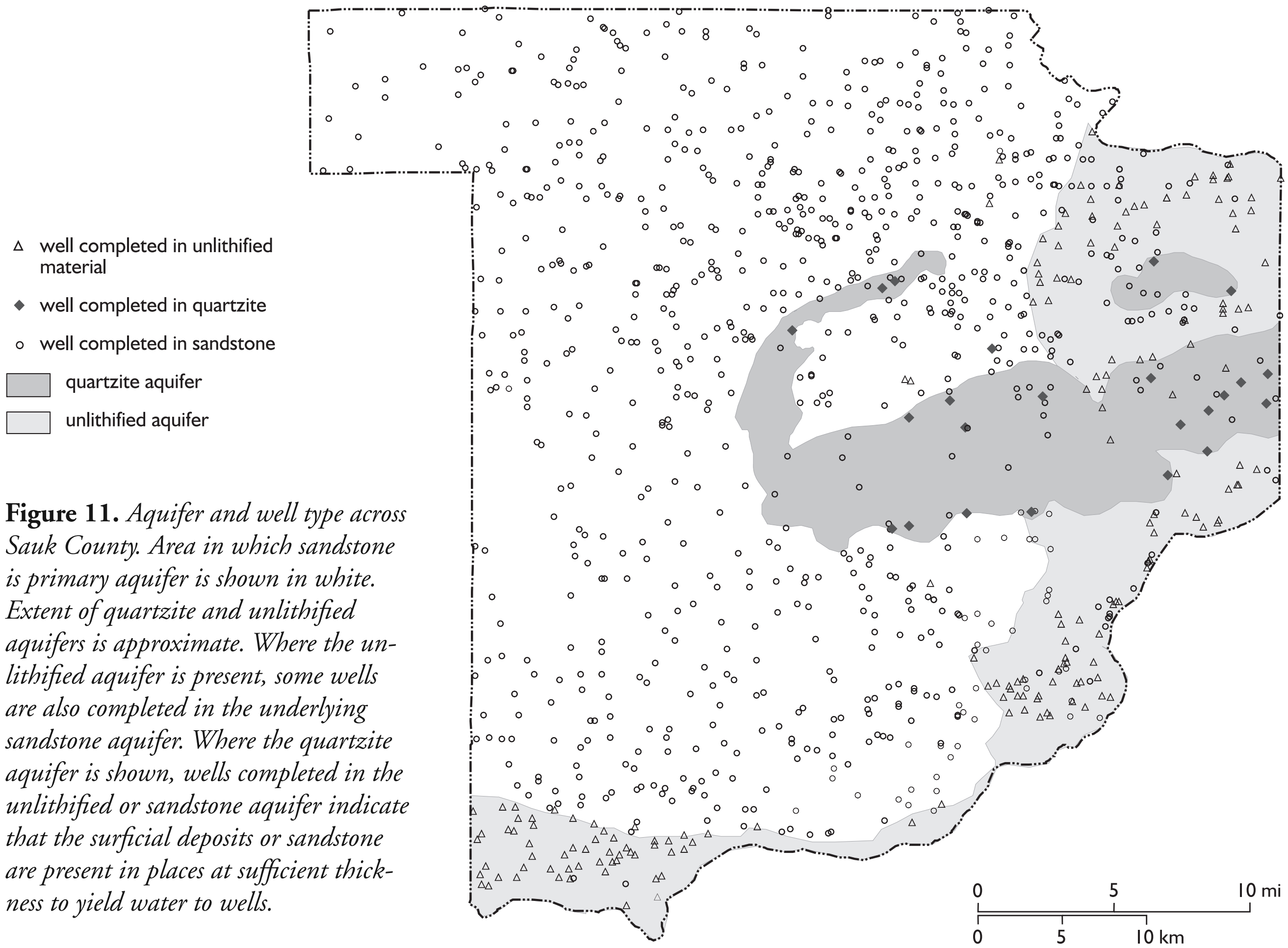


Figure 11. *Aquifer and well type across Sauk County. Area in which sandstone is primary aquifer is shown in white. Extent of quartzite and unlithified aquifers is approximate. Where the unlithified aquifer is present, some wells are also completed in the underlying sandstone aquifer. Where the quartzite aquifer is shown, wells completed in the unlithified or sandstone aquifer indicate that the surficial deposits or sandstone are present in places at sufficient thickness to yield water to wells.*

complex layering of glauconite-rich and coarser grained intervals in the Tunnel City cause horizontal flow rates within the formation that are much higher than vertical flow rates across the formation. This leads to the development of springs at outcrops and subcrops of the Tunnel City.

Eau Claire aquitard

In Sauk County the Eau Claire aquitard consists of interbedded shale, siltstone, dolomite, and shaley sandstone. This lumping of relatively fine-grained lithologies captures the full thickness of deposits that likely have low hydraulic conductivity in relation to the overlying unlithified aquifer and the underlying sandstone aquifer. The mappable extent of this aquitard in Sauk County is limited to south of the Baraboo Hills, where it is present at sufficient thickness to form a regional aquitard (fig. 12). Hydraulic information also indicates the confining properties of this unit: Sauk City and Prairie du Sac municipal wells that are cased through the siltstone–shale facies and open to the lower Eau Claire and Mount Simon Formations have static water levels at or very near the land surface. This interpretation is consistent with the hydrostratigraphic interpretation offered by Bradbury and others (1999) in northwestern Dane County.

Where the Eau Claire aquitard is present (fig. 12), little to no sandstone overlies it. In areas where the number of wells available is sufficient to fully characterize the Cambrian sequence, the aquitard typically constitutes the uppermost bedrock and separates

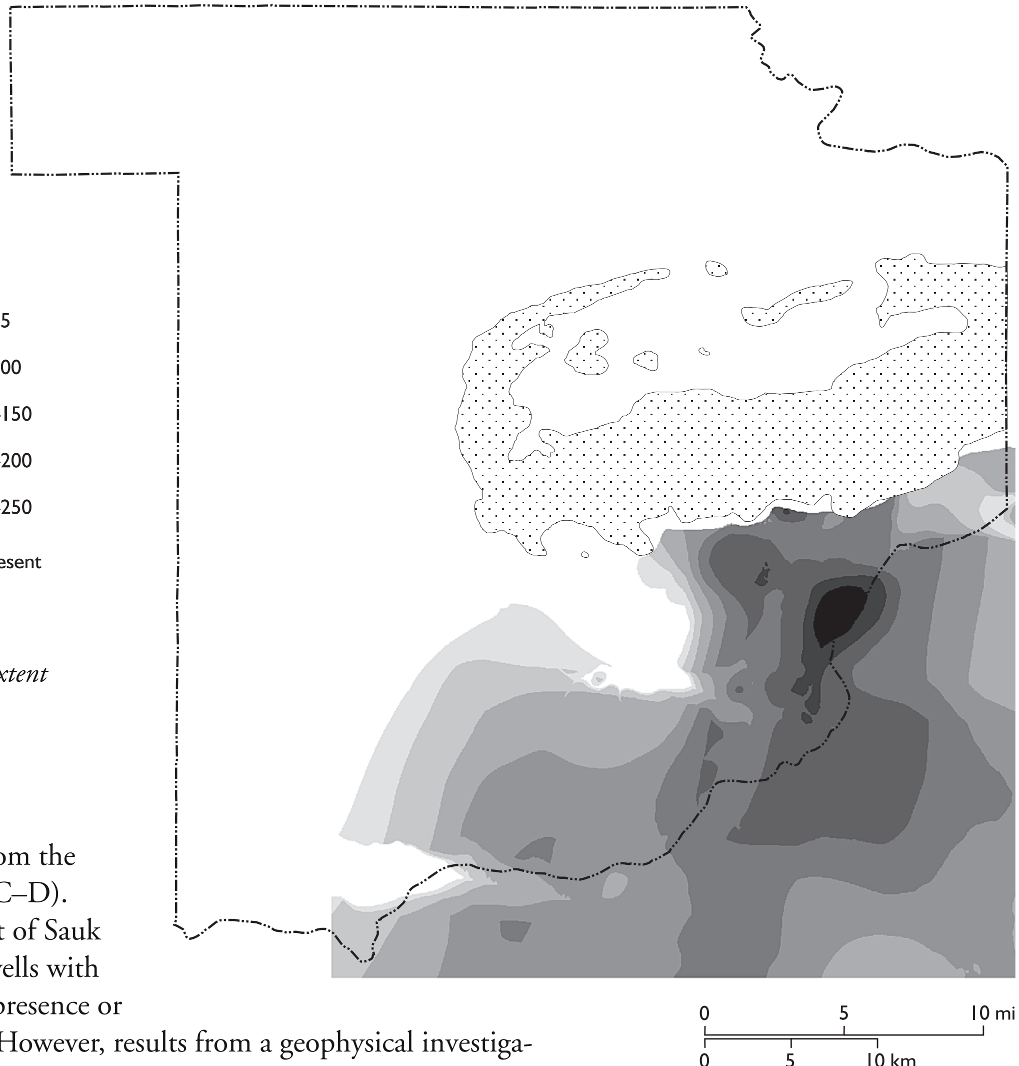


Figure 12. *Thickness and extent of the Eau Claire aquitard.*

the unlithified aquifer from the sandstone aquifer (fig. 9C–D). In the Driftless Area west of Sauk City, there are no deep wells with which to determine the presence or absence of the aquitard. However, results from a geophysical investigation conducted between Plain and Sauk City confirmed the thickness and extent of the aquitard as depicted in figures 9D and 12 (Hart and Thomas, 2005). No data are available from which to estimate the vertical hydraulic conductivity of the aquitard in Sauk County. Krohelski and others (2000) assigned a vertical hydraulic conductivity of 0.0006 ft/day to this aquitard in the Dane County groundwater flow model.

Quartzite aquifer

Over most of Sauk County, the Precambrian quartzite forms an aquitard that underlies the sandstone aquifer. However, in the Baraboo Hills region, where the unlithified and sandstone aquifers are very thin or absent, the relatively impermeable quartzite is considered an aquifer because it yields sufficient water for domestic and park wells (fig. 11). Wells drilled several hundred feet deep into the quartzite yield very small amounts of water, with specific capacities on the order of less than 0.1 gallon per minute per foot of drawdown. Flow to these wells is primarily through fractures, and the matrix permeability of the quartzite is expected to be very low. Figure 11 also shows that several wells within the mapped extent of the quartzite aquifer are completed in sandstone. These wells indicate the locations of discontinuous deposits of sandstone (Parfreys Glen Formation) within the Baraboo Hills that are large enough to supply domestic wells.

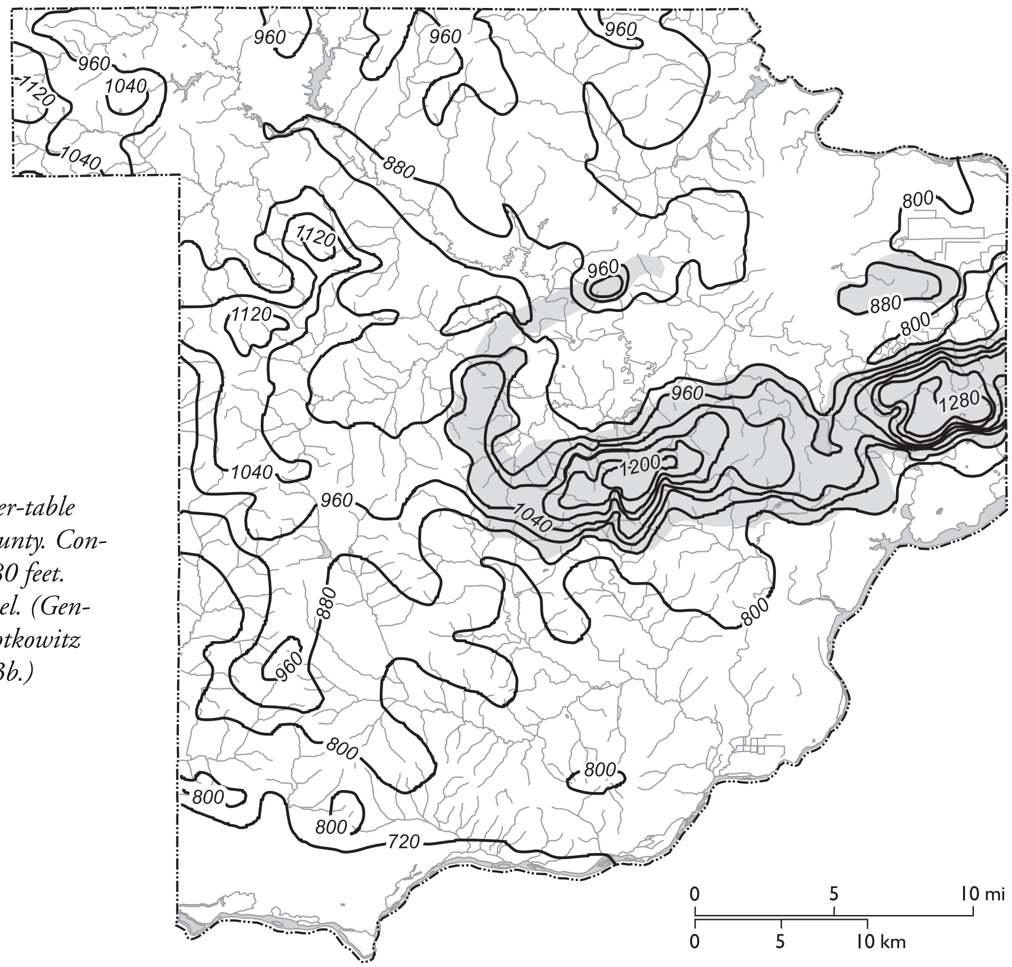


Figure 13. *Water-table map of Sauk County. Contour interval is 80 feet. Datum is sea level. (Generalized from Gotkowitz and Zeiler, 2003b.)*

The Precambrian rock is not considered an aquifer where Cambrian sandstone is present at sufficient thickness and continuity to constitute a mappable unit and aquifer. There, the Precambrian rock is assumed to form the base of the sandstone aquifer because of its very low hydraulic conductivity in contrast to the sandstone. The highly irregular surface elevation of the Precambrian units creates a geometrically complex boundary to the sandstone aquifer. This is particularly true within the Baraboo basin, where the sandstone aquifer is underlain by quartzite and is essentially contained between the North and South Ranges (fig. 9E–F).

Regional groundwater flowpaths

At a regional scale, groundwater flows through aquifers from recharge to discharge areas. The natural direction of groundwater flow in an unconfined aquifer is in response to gravity, from areas of higher to lower water-table elevation. The water table is typically a subdued reflection of the topography. The water-table map of Sauk County (fig. 13) depicts the highest groundwater elevations in the Baraboo Hills and uplands of the Driftless Area. General directions of shallow groundwater flow are toward major groundwater discharge features, such as the Baraboo and Wisconsin Rivers and Honey and Dell Creeks (figs. 3 and 13). Gotkowitz and Zeiler (2003b) provided a more detailed water-table map of the county (scale 1:100,000).

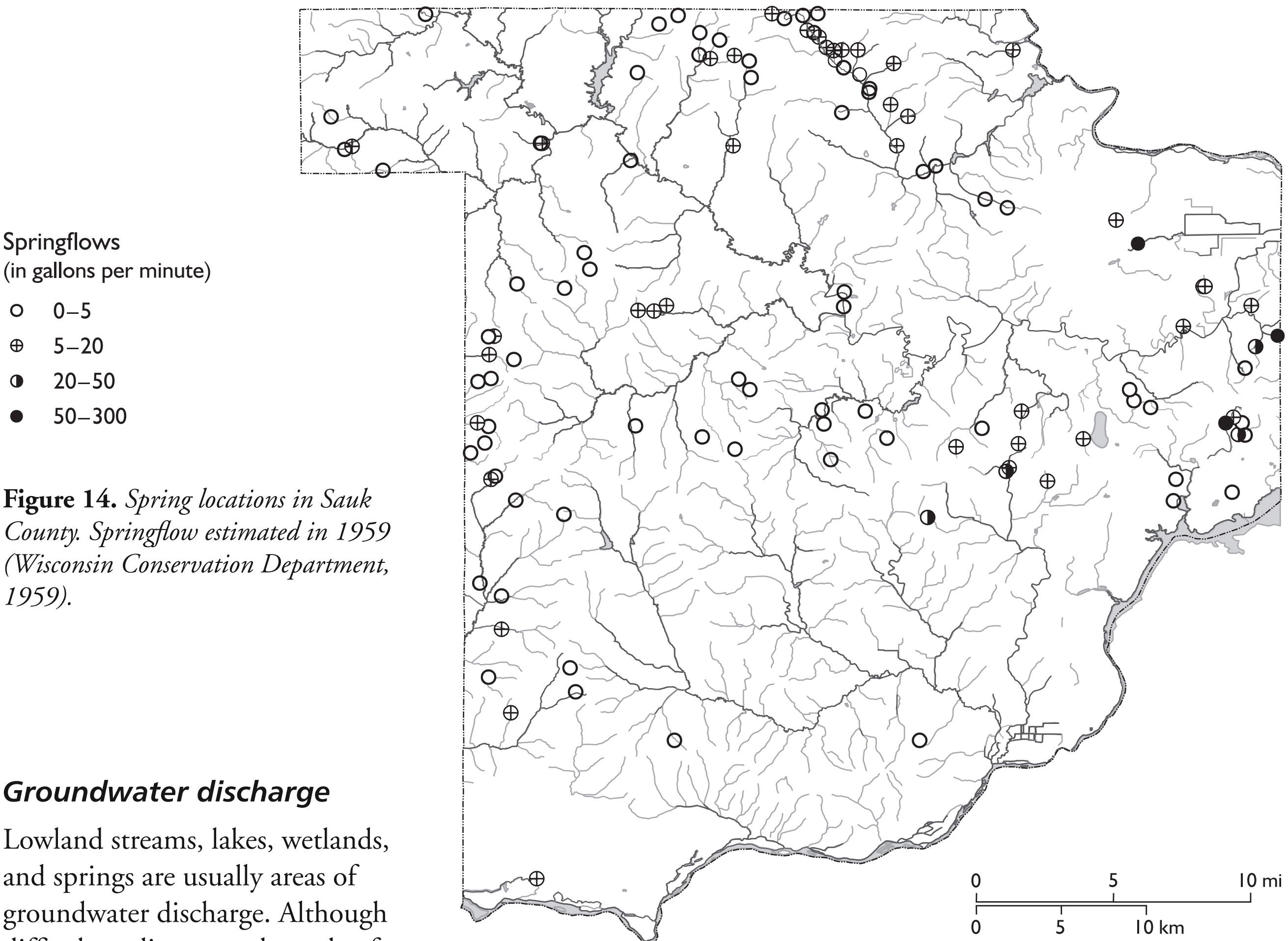


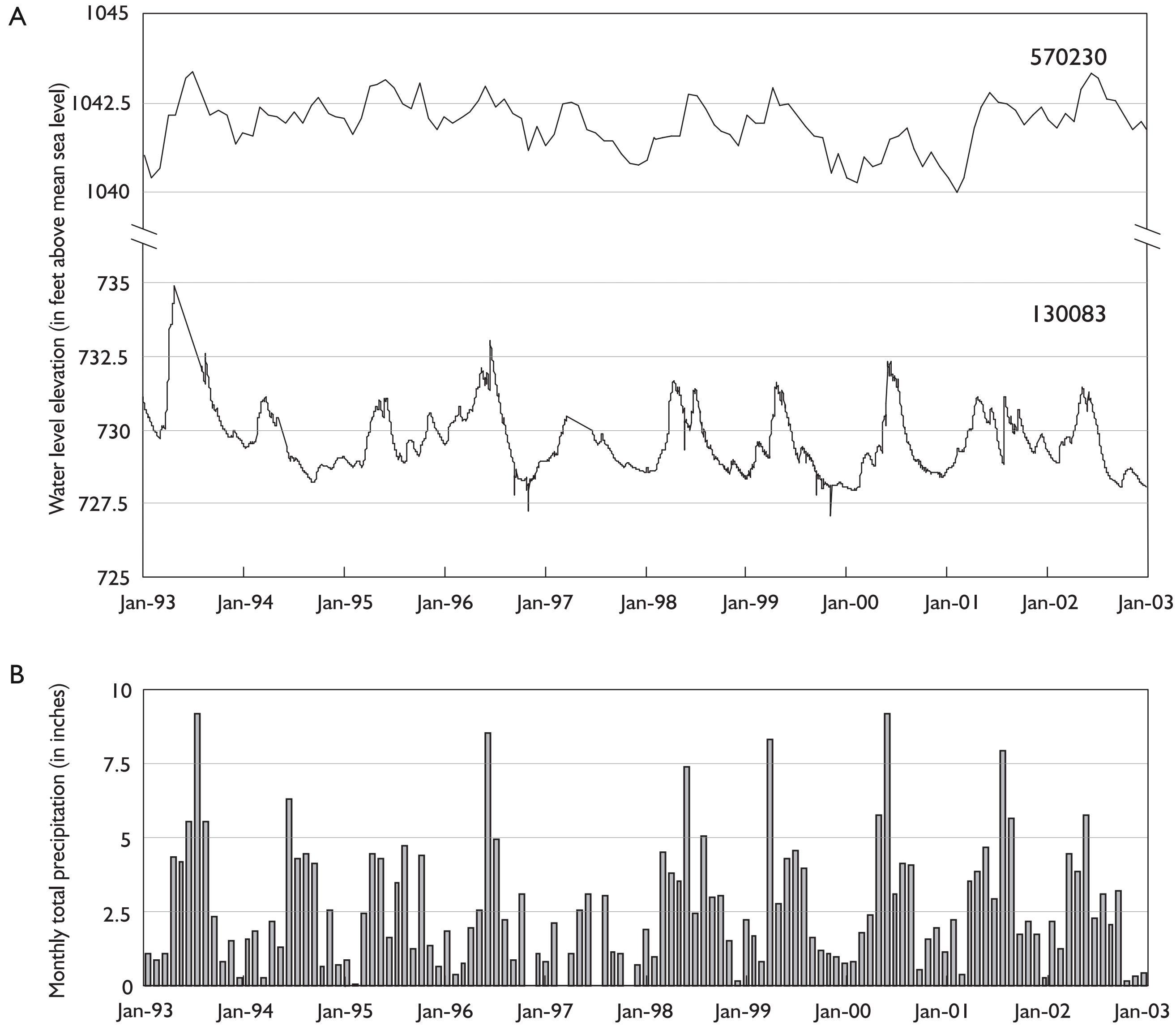
Figure 14. *Spring locations in Sauk County. Springflow estimated in 1959 (Wisconsin Conservation Department, 1959).*

Groundwater discharge

Lowland streams, lakes, wetlands, and springs are usually areas of groundwater discharge. Although difficult to discern at the scale of figure 13, local-scale flowpaths contribute groundwater discharge to many small stream systems as well as major rivers. In upland areas, groundwater discharge to these small stream systems may be along shallow flowpaths where relatively recent recharge flows through saturated, unlithified deposits. Precipitation that falls on the glacial outwash or alluvial plains along the major river valleys in Sauk County, such as the Baraboo and Wisconsin River valleys, recharges the unlithified aquifer and follows relatively short flowpaths to discharge as base flow to the rivers. These rivers also receive discharge from longer regional flowpaths in the sandstone aquifer, as discussed by Pfeifer (2001).

Other points of groundwater discharge are the numerous springs found throughout Sauk County. A survey (Wisconsin Conservation Department, 1959) identified 120 springs in Sauk County (fig. 14), although many more springs are likely present. The discharge to the springs measured for that study ranged from less than 2 to more than 200 gpm, with an average flow of 10 gpm. Measured flow at three of the springs exceeded 50 gpm, and the total flow from all mapped springs exceeded 1,175 gpm.

Many springs in Sauk County are contact springs, which form where permeable material overlies a rock type of lower hydraulic conductivity. For example, springs are commonly seen along the bedrock walls of the valleys of the Driftless Area. These springs form in the Cambrian bedrock units where saturated sandstone overlies a less perme-



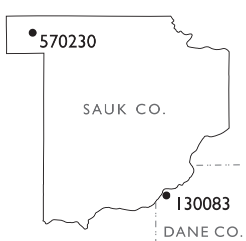


Figure 15. *A: Long-term water levels in sandstone well (570230) and unlithified aquifer well (130083). (Monitoring well locations are shown in inset map, left.) B: Precipitation record for Prairie du Sac, Wisconsin (L.J. Anderson, Wisconsin State Climatology Office, written communication, 2003).*

able bed of siltstone or shale (for example, at the contact of the Jordan and St. Lawrence Formations). Contact springs are also found in Rock Springs, where the edge of the Cambrian sandstone aquifer overlies the less permeable quartzite of the Baraboo Formation.

Other springs are found where the water table intersects a depression in the topography, as at the headwaters of Leech Creek. There, permeable glacial outwash deposits at a relatively high position in the landscape to the west of the headwaters probably serve as a recharge area to springs that discharge in the sandy bottom of the creek headwaters. Springs found high in the landscape in the Baraboo Hills are likely the result of discharge along the top of the bedrock surface, where water runs off the top of impermeable quartzite.

Groundwater recharge

Recharge of precipitation and snowmelt to groundwater does not occur uniformly over the landscape, but rather is affected by variables such as soil properties, vegetation, ground-surface slope, aquifer type, and the timing and magnitude of precipitation and snowmelt events. In Sauk County, recharge to the regional groundwater flow system is likely greater where the unlithified aquifer consists of very porous sand and gravel (for example, outwash plains and alluvial valleys). Less recharge probably occurs where finer-grained glacial lake sediment is present. Little groundwater recharge is expected to occur in the Baraboo Hills. Precipitation generally drains off the Baraboo Hills through the thin soil cover or other surface deposits, or discharges to local ephemeral stream systems high in the landscape. This runoff recharges groundwater where the unlithified or sandstone aquifers are in contact with the quartzite of the Baraboo Hills.

In the Driftless Area, the clayey Rountree Formation and the dolomitic Oneota Formation probably restrict recharge of precipitation to the underlying geologic units. This leads to increased runoff of precipitation to streams high in the landscape (J.W. Attig, Wisconsin Geological and Natural History Survey, verbal communication, 2003).

At high elevations in the landscape, some surface-water features recharge groundwater. For example, in the Baraboo Hills, Devils Lake recharges the groundwater system over parts of the lakebed (Krohelski and Batten, 1995). Similarly, complex groundwater–surface water interactions are established as streams traverse the distinct geologic settings in the county. Otter Creek is a gaining stream where it flows within the Baraboo Hills; however, the creek loses flow to the groundwater system as it encounters higher hydraulic conductivity sediment in the Stones Pocket lake basin and on the outwash plain (figs. 2 and 3) (Zeiler, 2002).

For the purpose of this report, rates of groundwater recharge were estimated in two ways. The first method relates changes in the water-table elevation to recharge events. The total rise in the water-table elevation over a year is multiplied by an assumed value of specific yield of aquifer sediment or rock. Hydrographs (fig. 15) of water levels in a monitoring well completed in the sandstone aquifer in northwestern Sauk County and from a monitoring well completed in the unlithified aquifer near the Wisconsin River in Dane County provided recharge estimates for the sandstone aquifer and the unlithified aquifer. Specific yield of the sand and gravel in the outwash plain is estimated at 23 to 28 percent (Zheng and Bennett, 1995). For estimating recharge to the sandstone aquifer in northwestern Sauk County, a specific yield of 15 to 24 percent was used, representing the soil–water capacity of the soil overlying the sandstone in this area of the county (U.S. Department of Agriculture, 1980). We estimated recharge for each year from 1993 to 2002. For the unlithified aquifer, recharge ranged from 5.8 to 17.6 inches per year (in/yr), with an average value of 12.4 in/yr. Estimates of recharge to the sandstone aquifer ranged from 2.7 to 10 in/yr, with an average of 5.6 in/yr.

We also estimated recharge through calibration of the regional groundwater flow model, which is further discussed in the next section of this report, *Simulation of the regional groundwater flow system*. We delineated areas within the model domain expected to have similar recharge rates on the basis of the rock type of the uppermost aquifer. The calibrated values of recharge are very similar to those estimated by the water-table elevation method. The rate assigned to areas of unlithified deposits was 10.2 in/yr; all other areas of the county were assigned a rate of 5.2 in/yr.

SIMULATION OF THE REGIONAL GROUNDWATER FLOW SYSTEM

Our regional groundwater flow model is a single-layer model that can be refined in the vicinity of municipal wells where the underlying assumption of horizontal groundwater flow is valid. The regional model also serves as a screening tool to develop boundary conditions for three-dimensional submodels in areas of Sauk County where the hydrogeologic setting is complex. We have simplified our interpretation of the natural flow system as much as possible while retaining sufficient complexity to adequately simulate groundwater flow to municipal wells. Our understanding of the geologic and hydrostratigraphic conditions in the county served as a framework for development of the numerical models. We refined this framework throughout the modeling process as we gained insight into the hydrogeologic system.

Methods

Computer codes

We used the GFLOW computer code (Haitjema, 1995) to develop a two-dimensional analytic element model encompassing the Sauk County region. We calibrated this regional model by adjusting model parameters, such as hydraulic conductivity and recharge, to provide a good match between simulated and measured groundwater elevations and streamflows. For cases in which the two-dimensional approach of the regional model was deemed to adequately represent local hydrogeologic conditions, we delineated ZOCs for municipal wells with the GFLOW model. For municipalities in more hydrogeologically complex settings, the regional GFLOW model provided a basis for developing three-dimensional finite difference models with the MODFLOW code (Harbaugh and McDonald, 1996). Hunt and others (1998) discussed the use of analytic element models in conjunction with more complex finite-difference models. The types of models we used and the areas for which the models were constructed are listed in table 3.

We selected the GFLOW code for the regional model because hydrologic features can be easily added to or modified in the model to test hypotheses or add detail in an area of interest. The area of interest is represented in the “near field” of the model, where features that affect groundwater flow (wells, streams, lakes, and local changes in hydraulic conductivity or recharge) are represented in detail by mathematical equations. The

Table 3. *Summary of groundwater flow models for Sauk County.*

Areas in model domain	Model code	Dimensions	Simulated hydrogeologic units: Sandstone aquifer	Unlithified aquifer	Eau Claire aquitard
Sauk County region	GFLOW	2-D	X	X	
Merrimac	GFLOW	2-D		X	
Sauk City–Prairie du Sac	MODFLOW	3-D	X	X	X
Reedsburg	GFLOW	2-D	X		
Spring Green–Plain	MODFLOW	3-D	X	X	
Baraboo–North Freedom–Rock Springs	MODFLOW	3-D	X	X	
La Valle	GFLOW	2-D	X		
Lake Delton–Wisconsin Dells	GFLOW	2-D	X		
Ironton	GFLOW	2-D	X		
Loganville	GFLOW	2-D	X		

"far field" of the model includes a much coarser mathematical representation of regional hydrologic features. These far-field features effectively set the boundary conditions for the near field of the model by controlling the simulated regional flow field. A computer was used to solve the mathematical equations in the model, producing a simulation of groundwater elevations and streamflow across the model domain. The GFLOW code is limited with respect to simulating vertical flow of groundwater, and it is not suitable for simulating flow in areas where vertical gradients are important in relation to horizontal gradients. Haitjema (1995) and Strack (1989) provided detailed descriptions of the mathematical and practical applications of the method.

We calibrated the GFLOW model with the computer code UCODE (Poeter and Hill, 1998). UCODE provides a statistically rigorous method for estimating model parameters, such as hydraulic conductivity and recharge, to find a best fit between the model simulation and calibration targets (for example, groundwater elevations and streamflows). In the work presented here, we have relied heavily upon the guidance in Hill (1998) and the example provided by Hunt and others (2000) in using UCODE to optimize the regional GFLOW model.

We used MODFLOW96 (Harbaugh and McDonald, 1996) to simulate three-dimensional steady-state flow to wells in areas of Sauk County where aquifer complexity was not sufficiently represented by the regional GFLOW model. We developed three MODFLOW models, covering 1) the Sauk City–Prairie du Sac area; 2) the Baraboo–North Freedom–Rock Springs area; and 3) the Spring Green–Plain area (table 3). We used the results of the regional GFLOW model, including the model-simulated location of water-table divides and particle tracking to wells, to determine appropriate boundaries for these MODFLOW submodels. Gotkowitz and others (2002) described these submodels; we included conclusions derived from the submodels in this report.

Delineation of zones of contribution

We determined ZOCs for 5- and 50-year times of travel for each municipal well. The DNR developed a formula to calculate the well pumping rates used in the ZOC simulations, taking future water-use increases into account. This formula assigned the

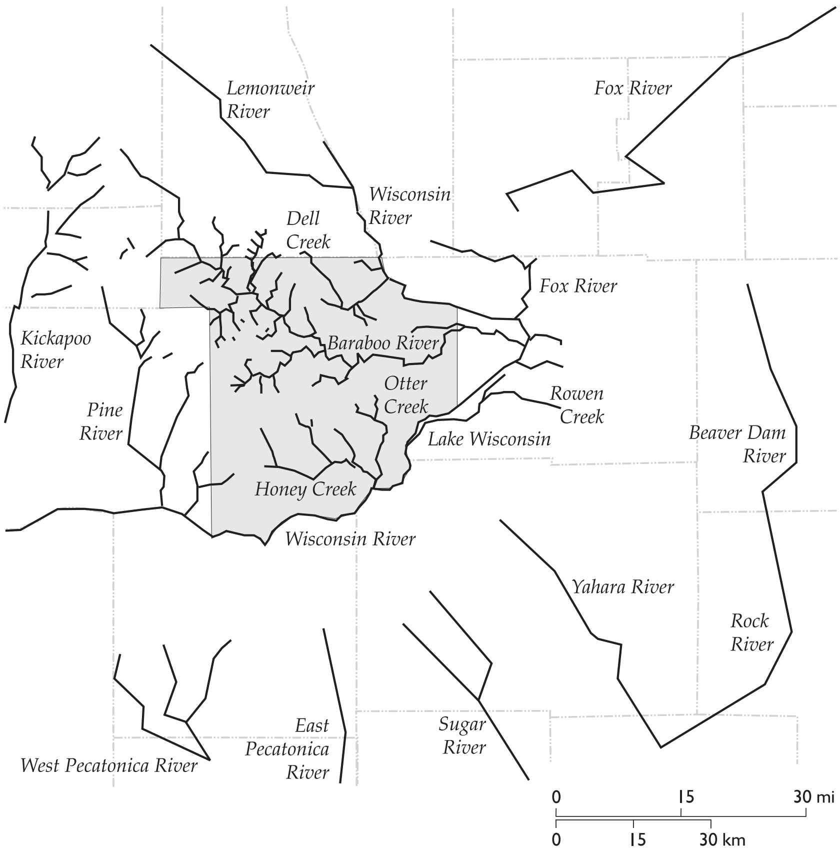


Figure 16. *Far-field and near-field features represented in the groundwater model. All streams shown within Sauk County are in the near field of the model.*

average pumping rate from the year 2000 at each municipal well, with the exception of the well for which the ZOC was delineated. For that well, the model used the greater of half the operational pump capacity or the year 2000 average rate plus 15 percent. In most cases, the use of a rate equal to half of the operational capacity leads to a simulated ZOC that is larger than the simulated ZOC for the actual pumping rate of the well. Table 1 presents actual and simulated pumping rates.

We used steady-state model simulations to determine the ZOCs because groundwater withdrawal in Sauk County is relatively limited and does not cause large decreases in water levels over time. This conclusion is based on historic and current water-level records and on long-term hydrographs from two monitoring wells completed in the sandstone aquifer in Sauk County.

Particle tracking is a modeling technique that mathematically follows the path of an imaginary particle along groundwater flow lines. Reverse particle tracking from the wells identified groundwater flowpaths to the wells for 5- and 50-year travel times. Particles were started at the top and bottom of the open interval of the well to determine the starting elevation that would yield the largest ZOC. Forward particle tracking was performed to verify the results of the backward method.

Although the ZOC is a technically defined area based on groundwater hydraulics, in some cases the results in this report include more land surface in the ZOC than that over which recharging precipitation flows to the well. This occurs because the results of a three-dimensional model are projected to a two-dimensional map of the land surface. The endpoints of the flowpaths (which in some cases defined a three-dimensional, irregularly shaped volume) were projected to a map of the ground surface, resulting in a two-dimensional ZOC. For municipal wells in Sauk County that have deep casings, the actual land surface contributing recharge may be physically distant from the well itself and may not encompass the well. Franke and others (1998) provided a discussion of this issue. For the purposes of wellhead protection and this report, the ZOC includes the land surface over which precipitation that recharges the well enters the groundwater system plus the surface projection of the three-dimensional flowpaths between the recharge area and the well.

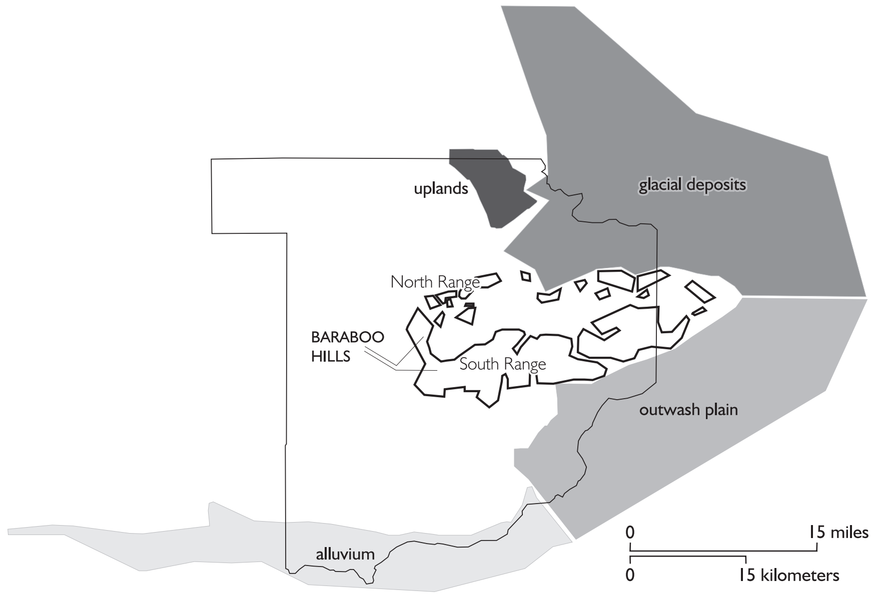


Figure 17. *Areas assigned global rates of hydraulic conductivity and recharge (polygons shown with no pattern) and those assigned specific rates (screened polygons) determined by type of material. See table 4 for values of hydraulic conductivity and recharge.*

Model construction

The regional GFLOW model simulates the sandstone aquifer over the parts of the model domain where the unlithified aquifer is absent or very thin. In other parts of the model domain, the regional model represents flow in the unlithified and sandstone aquifers. In these areas, where the model represents both aquifers, it simulates an average of the properties of the two aquifers. The regional model is isotropic, two-dimensional, and does not simulate vertical flow within the aquifer. The simplifying assumption, that flow is predominantly horizontal, is reasonable where the aquifer is regionally isotropic and away from boundaries that induce strong vertical gradients. The Eau Claire aquitard is not explicitly represented in this model. The Baraboo Hills are represented as a no-flow boundary; the model does not simulate flow in the quartzite aquifer.

Table 4. *Modeled rates of hydraulic conductivity and recharge, by area.*

Model area	Hydraulic conductivity (in ft/day)	Recharge (in in/yr)
Near and far fields[1]	13.2	5.2
Wisconsin River valley alluvium	112.1	10.2
Glacial deposits north of Baraboo Hills	38.7	10.2
Outwash plain south of Baraboo Hills	310.1	10.2
Uplands northwest of Wisconsin Dells	2	5.2

[1] Global rates

The far-field elements are major rivers outside of Sauk County (fig. 16). These elements are regional hydraulic boundaries. The near field of the model, which includes all Sauk County, is the primary area of interest and is simulated with much greater detail than the far field.

Aquifer base elevation, horizontal hydraulic conductivity, and recharge are the global parameters defined for the entire model domain. We assigned a base elevation of 450 ft, which is the average elevation of the base of the Cambrian sandstone. Inhomogeneities, regions within the domain that are assigned a unique value for one or more of the parameters, were added to the model where necessary to achieve a reasonable simulation of the water table. We defined these inhomogeneities on the basis of mapped geologic units (Clayton and Attig, 1990); they include alluvial and outwash deposits in the Wisconsin River valley and south of the South Range of the Baraboo Hills and glacial deposits (primarily till) north of the North Range of the Baraboo Hills (fig. 17; table 4). We also assigned an inhomogeneity to the Driftless Area uplands northwest of the

Wisconsin Dells, where water levels reported on well construction reports suggest that the hydraulic conductivity of the sandstone aquifer is lower than in other regions. We assigned recharge and hydraulic conductivity values to these various areas of the model during calibration, as described below.

The model simulates streams and rivers in the near field by specifying four parameters for each stream segment: beginning and ending stream stage elevations, streambed resistance, and streambed width. Resistance is calculated by dividing the streambed-sediment thickness by an assumed value of its vertical hydraulic conductivity. For example, a 5-ft sediment thickness with a vertical conductivity of 5 ft/day would be assigned a resistance of 1 day. In the model, streambed-sediment resistances were set within the range of 0.25 to 5 days. Sensitivity analysis demonstrated that model results were affected very little by changes in streambed resistance, so these values were fixed for all model runs. We assigned the width of the stream on the basis of field observations and stream order; it ranges from 2 to 25 ft, with the exception of the Wisconsin River, which was assigned a width of 500 ft. The model tabulates the amount of water captured from and lost to the groundwater system by the near-field stream network, allowing simulated streamflows to be compared to measured streamflows during model calibration.

Areas in the model that represent the Baraboo Hills are assigned zero hydraulic conductivity and act as no-flow boundaries. Two large polygons represent the south limb of the Baraboo Hills, and 17 smaller polygons represent the north limb of the Hills (fig. 17). To account for the impact of precipitation runoff on recharge to the sandstone aquifer, we assigned the perimeters of no-flow areas a rate of recharge using the runoff coefficient (0.30) calculated by Krohelski and Batten (1995).

Input to the model also included the locations and pumping rates of all municipal wells in the county and at 116 other high capacity wells (tables 1 and 2). Model pumping rates at municipal wells were the average rates calculated from monthly pumping records in the year 2000. Pumping rates assigned to other wells in the model were based on the normal rates reported on the high-capacity well permits. We did not verify these pumping rates with well operators, and the rates we used may overestimate actual pumping rates. This is important because, as discussed in later sections of this report, simulated groundwater flow directions at several municipal wells are affected by the pumping rates assigned to nearby high-capacity wells. Pumping from residential wells was not represented in the groundwater flow models developed for this project. The relatively low water use from domestic wells and the likelihood that homes with wells also have on-site septic systems suggest that the groundwater flow field will not be greatly altered by pumping from these wells at the scale of this model.

Model calibration

We used an iterative process to develop and calibrate the regional model. As hydrologic detail was added to the GFLOW model, a UCODE run was completed to identify

Table 5. *Streamflow calibration targets, in cubic feet per second (cfs).*

Station name (number)	Q_{50} (in cfs)	Q_{80} (in cfs)	UCODE weight (covariance)	Simulated flux (in cfs)
Baraboo River near Baraboo (05405000) [1]	290	197.1	0.01	222
South Branch Baraboo River near Hillsboro (05404116)	15.4	9.9	0.2	5.7
Hulbert Creek near Wisconsin Dells (05403630)	4.3	3.4	0.2	1.5
Dell Creek near Lake Delton (05403700)	24.2	18.8	0.01	17.4
Narrows Creek near Loganville (05404200)	5.1	3.9	0.01	3.8
Honey Creek near Sauk City (05406300) [2]	73.6	53.7	0.2	57.5
Leech Creek north of Baraboo[3]	7.9	5.8	0.05	4.7

[1] Using last 30 years of record only.
[2] Honey Creek Q_{80} was estimated using miscellaneous measurements on July 27, 1964 and October 9, 1975 and the long-term discharge record from the Baraboo River near Baraboo station.
[3] Leech Creek Q_{80} is 0.73 of Q_{50}, which was taken as the 7.9 cfs measured on April 6, 2001 and June 29, 2001.

parameter values that provided the optimal match to calibration targets (groundwater elevations and stream fluxes). Groundwater-elevation targets included depth to groundwater reported on 582 well construction reports. We selected these from the larger dataset used to construct the water-table map, on the basis of our confidence in the accuracy of the well locations and to provide a good spatial distribution across the county.

We selected seven streamflow targets from USGS streamflow data to include in the regional model calibration (table 5). We used measured streamflow to estimate 50 and 80 percent flow duration (the flow rate that is equaled or exceeded 50 percent [Q_{50}] or 80 percent [Q_{80}] of the time) for each site. Baseflow in Wisconsin streams is generally assumed to fall between the Q_{50} and Q_{80} (for example, Krohelski and others, 2000). Because the GFLOW model is a steady-state simulation, simulated streamflows represent baseflow conditions. We selected Q_{80} data as the targets for the final optimization and calibration runs because initial results indicated that they could be simulated using rates of hydraulic conductivity and recharge that resulted in a better match to groundwater-elevation targets.

To optimize the model calibration with UCODE, we assigned each calibration target a weight based on the uncertainty associated with the measurement. Targets with higher uncertainty received lower weights. By weighting the calibration targets, those measurements that are more accurate are given greater consideration as UCODE calculates the values of model parameters that yield the best fit of the simulated results to observed conditions. Hill (1998) provided a detailed explanation of assigning target weights and the statistical methods used to evaluate model sensitivity to parameters. We assigned all groundwater-elevation targets a weight of 0.1; we assigned the stream-flux targets a weight of 0.01, 0.05, or 0.2 (table 5).

Preliminary UCODE runs indicated that model calibration was not sensitive to changes in the aquifer-base elevation or streambed resistance, so these parameters were not varied in the model runs. Hydraulic conductivity and recharge values optimized with UCODE are reported in table 4. We assigned the same recharge value to the three

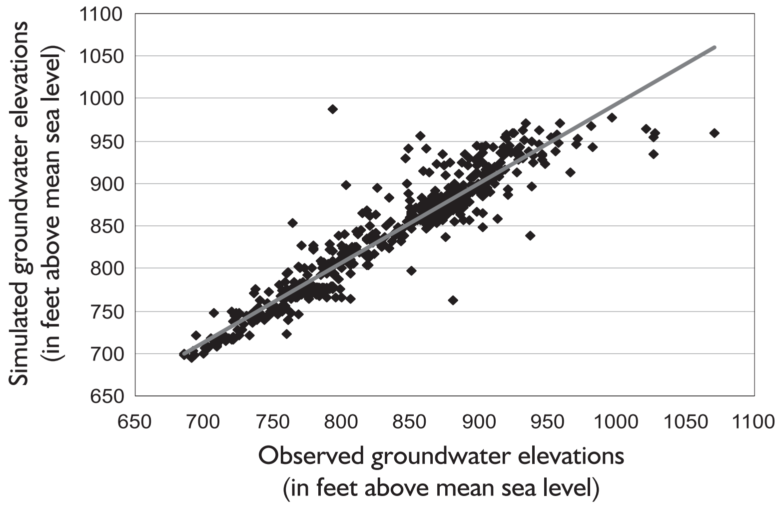


Figure 18. *Simulated versus observed groundwater elevations. These results show that the model consistently underestimates the highest measured water levels.*

inhomogeneities that represent parts of the unlithified aquifer to preserve the simple framework appropriate for this regional screening model. The hydraulic conductivity values are within the range of values determined from specific capacity and pumping test data from wells in Sauk County.

The recharge rates arrived at through model calibration agree very well with those calculated for the sandstone and unlithified aquifers, and they are similar to those used in modeling studies in similar settings. The regional recharge rate arrived at by UCODE optimization, 5.2 in/yr, is similar to the average recharge rate of 5 in/yr applied in a model of Dane County (Krohelski and others, 2000). The higher recharge rate of 10.2 in/yr applied to areas representing the unlithified aquifer is comparable to the 12.7 in/yr determined for sand and gravel deposits in Rock County by Gaffield and others (2002).

The calibrated model provides a good match to measured conditions. The root mean square difference (or the standard deviation) between measured and simulated water levels is 23.6 ft, which is only 7 percent of the total range in water levels across the domain. Simulated water-table elevations are generally well distributed around the measured values; however, the model underestimates the highest water-level measurements (fig. 18). This may be due to the two-dimensional nature of this model, which represents the sandstone aquifer sequence as a single hydrogeologic unit (discussed further in the *Limitations of the model* section of this report). A good match between simulated and estimated Q_{80} flow duration was also obtained for the flux targets (table 5). The match to the estimated streamflow may have been improved by increasing recharge; however, this would in turn require an increase in hydraulic conductivity to match groundwater-elevation targets.

Results: Zones of contribution

The primary uses of this model were to determine ZOCs for municipal wells in Sauk County where the two-dimensional approach of the regional model was appropriate and to serve as a starting point for development of three-dimensional MODFLOW models in the hydrogeologically complex areas of the county. (Gotkowitz and others [2002] presented documentation for each MODFLOW model, including descriptions of development, calibration, and results.) Figure 19 shows the 5- and 50-year ZOCs for all municipal wells. The ZOCs differ in shape and size as a result of the varied hydrogeologic setting, well construction, and pumping rates at each location.

In the village of Merrimac, the model indicates that the primary source of groundwater to the single municipal well is relatively recent recharge to the aquifer northwest of Merrimac and that Lake Wisconsin does not contribute water to the well. The ZOC of this well intersects the water table at a travel time of approximately 14 years, indicating that very recent recharge is the primary source of water to the well.

Reedsburg, La Valle, Ironton, and Loganville wells have similarly shaped ZOCs because these wells are completed in the sandstone aquifer in an area assigned uniform properties in the model. The size of these ZOCs varies because of the higher pumping rates assigned to some wells. The ZOCs for the Reedsburg municipal wells intersect in complex patterns because of their relative proximity to each other and to two industrial high-capacity wells. The simulated ZOCs for the municipal wells are affected by the pumping rates at these industrial wells.

Flow between the unlithified and sandstone aquifers was simulated in the three-dimensional submodel developed for the area encompassing Plain and Spring Green. The model showed that flow to the two municipal wells in Plain is from the northwest and that there are strong upward gradients from the sandstone aquifer to the overlying alluvium. Model simulations showed that both wells (which are cased through the alluvial aquifer) receive all their water from the sandstone aquifer because the pumping rates at these wells do not induce vertical gradients sufficient to reverse the upward gradient from the sandstone to the overlying unlithified aquifer.

In Spring Green, the two municipal wells (one completed in the unlithified aquifer and the other in the sandstone aquifer) receive groundwater from substantially different flowpaths. Much of the flow to the well completed in the unlithified aquifer originates from the unlithified aquifer. Due to the strong upward vertical gradients from the sandstone to the unlithified aquifer in the Wisconsin River valley, some of the water pumped from the well may originate from the sandstone aquifer. The ZOC simulated for the municipal well that is open to the sandstone aquifer is very sensitive to the pumping rate used in the model. At a pumping rate equal to half of the pump capacity, the upward vertical gradient from the sandstone to the unlithified aquifer is reversed, and the well receives some groundwater from the unlithified aquifer. Groundwater flow rates in the unlithified aquifer are rapid, resulting in the long tail to the north on the ZOC (fig. 19). The model does not simulate a reversal of vertical gradients when this well is assigned its actual average pumping rate, which is much lower than the half-capacity rate (table 1). Under typical use, all flow to the well is from the sandstone aquifer. The model demonstrated that the upper and lower aquifers are hydraulically well connected, but that under typical pumping rates the Spring Green municipal wells receive water from different aquifers.

Flow between the unlithified aquifer, the Eau Claire aquitard, and the deep sandstone aquifer was considered in the three-dimensional submodel of the Sauk City–Prairie du

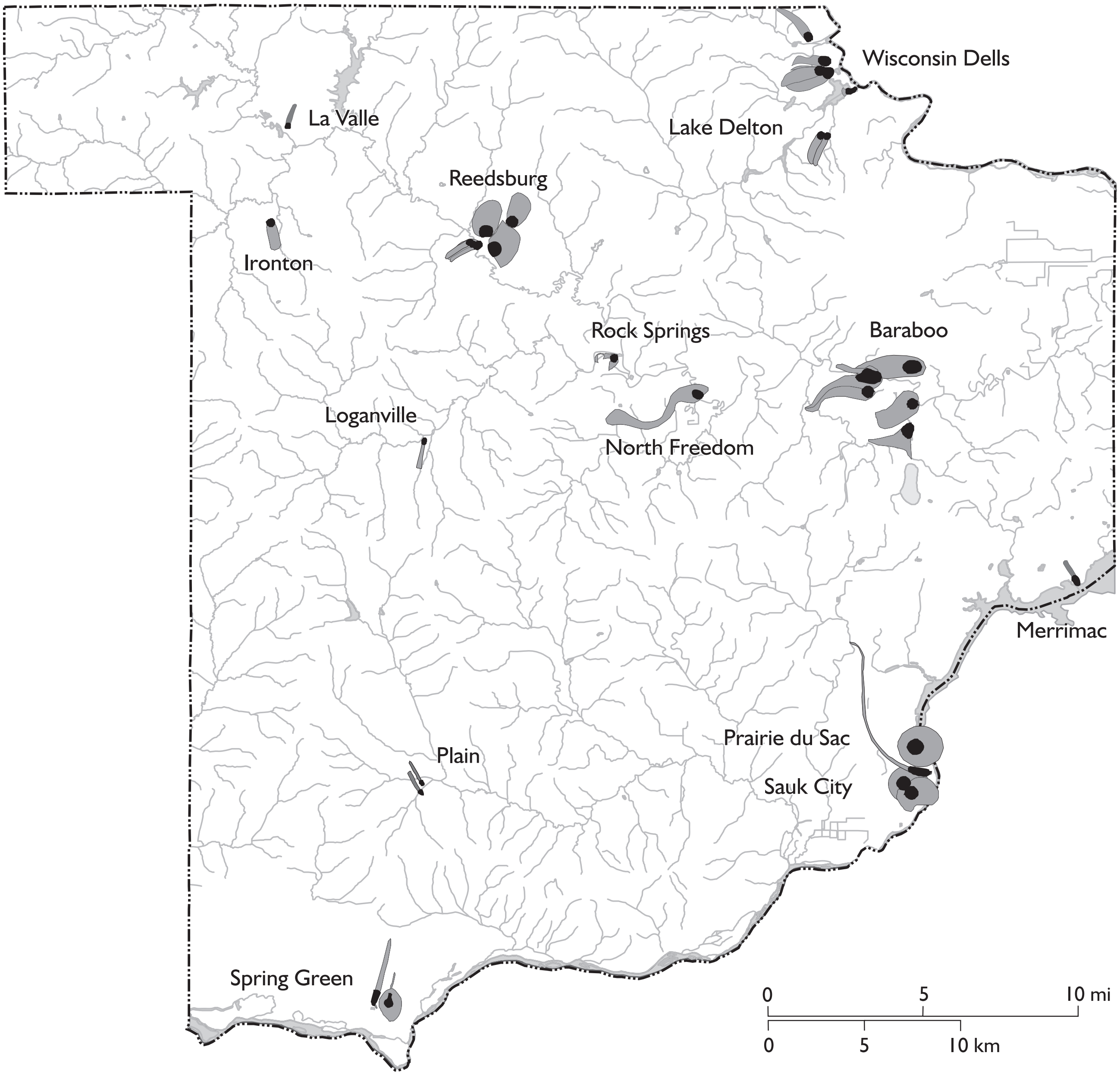


Figure 19. *Zones of contributions for 5- and 50-year travel times in Sauk County. Five-year travel time are shown as dark area; 50-year travel time are shown in gray.*

Sac area. Model simulations demonstrated that the aquitard restricts upward flux of water from the deep sandstone aquifer to the Wisconsin River and that some groundwater in the deep sandstone underflows the Wisconsin River from east to west. Sauk City well #5 is cased through the aquitard and receives all its water within the 50-year travel-time delineation from the sandstone aquifer. Groundwater flow to Prairie du Sac well #3 and Sauk City well #4, which are open to part of the Eau Claire aquitard as well as the deep sandstone aquifer, is predominantly from the sandstone aquifer. A small part of flow to these wells may be from the aquitard. Prairie du Sac well #2 is completed in the unlithified aquifer and receives most of its water from the northwest (fig. 19). This ZOC also extends east of the well because the model simulates some vertical discharge from the underlying aquitard to the unlithified aquifer.

We used a three-dimensional model to determine the ZOCs for the Baraboo–North Freedom–Rock Springs area because the flow field is complex where the municipal wells are near the Baraboo Hills. Similar to the regional flow model, this model represents the Baraboo Hills as no-flow boundaries that have enhanced recharge to the aquifer. The ZOCs indicate that flow to these wells is generally from the west and southwest. However, the 50-year ZOCs for some of these wells are strongly influenced by the location of the Baraboo Hills (no-flow boundaries) in relation to the wells. The results for Baraboo wells #7 and #4 and wells in North Freedom and Rock Springs are constrained by the representation of the Baraboo Hills, which is based on limited data regarding the spatial extent of the Baraboo Hills and the rate of runoff from them. The groundwater flow directions toward the North Freedom well are extremely sensitive to the pumping rate assigned to the well; this is also because of the proximity of the well to the no-flow boundary.

We used the regional GFLOW model to determine ZOCs for the municipal wells in the Wisconsin Dells–Lake Delton area. All these wells are located where the unlithified aquifer is thin or absent and are completed in the sandstone aquifer. Groundwater flowpaths to Wisconsin Dells well #4 originate from the northwest. Flow to the wells north of Lake Delton is from the west or northwest. Wells south of the lake receive groundwater from the south. Backward particle tracking from Lake Delton #4, at the eastern end of Lake Delton, showed that flowpaths originate from within the area under the lake. This suggests that in addition to the sandstone aquifer underlying the lake, Lake Delton itself may be a source of water to this well. Field investigation would be necessary to confirm gradients between the lake and underlying aquifer prior to using the model to estimate the extent to which Lake Delton recharges the aquifer and ultimately provides water to the well.

Limitations of the model

The Sauk County regional GFLOW model is a simplification of the real system, and there are limitations to its applicability and use. The regional model is two-dimensional and does not simulate vertical flow within the aquifer. This restricts its utility where the groundwater flow system has a relatively strong vertical component, such as areas where pumping wells are close to the relatively low hydraulic conductivity quartzite of the Baraboo Hills. Similarly, because the GFLOW model does not explicitly represent the Eau Claire aquitard, it cannot be used to evaluate flow patterns between the unlithified and sandstone aquifers where the aquitard is present. Three-dimensional models developed for more hydrogeologically complex areas of the county (table 3; Gotkowitz and others, 2002) overcome some of these limitations of the GFLOW model.

The GFLOW model may simulate groundwater flow patterns more accurately in the lower-lying areas of the county than in the uplands because of the selection of groundwater-elevation-calibration targets. The primary purpose of this model was to simulate flow to municipal wells to delineate their ZOCs. Therefore, we chose to calibrate to groundwater-elevation targets selected from the project database that reflect the properties of the deeper sandstone units rather than calibrate to the shallow water-table map (fig. 13). The water-table map incorporates groundwater elevations from many domestic wells completed in the Oneota Formation and surface-water elevations of upland streams. Although this is probably an accurate depiction of the water table in the uplands, the two-dimensional nature of the GFLOW code requires that either inhomogeneities be put into the model to explicitly represent areas such as the uplands, where the hydraulic conductivity of the shallow bedrock units may be different than the deeper sandstone units, or that the overall hydraulic conductivity used in the model be adjusted to represent a composite of hydraulic conductivities expressed in the calibration targets.

An additional constraint on simulation of flow in the uplands of the Driftless Area is the complex nature of the hydrogeology and the relative scarcity of data from the region. Seasonal perched water conditions in the Driftless Area may occur within the Rountree Formation, which consists of clay and sandy clay. Confining conditions may be locally present in low-conductivity formations within the bedrock (for example, within the Oneota and St. Lawrence Formations). Neither seasonal perched water conditions nor local confining conditions were simulated in the regional GFLOW model. This model may do a poor job of simulating flow to wells and streams in the uplands of the Driftless Area, where lower hydraulic conductivity units (for example, the Oneota Formation) that are located higher in the stratigraphic sequence of the sandstone aquifer are not explicitly represented in the model.

GROUNDWATER QUALITY

Although the scope of this project did not include groundwater sampling and chemical analysis, we compiled data about the water quality in Sauk County's aquifers from the DNR water-quality database and from the Central Wisconsin Groundwater Center. This information about nitrate, pesticide residues, and inorganic constituents provides a brief overview of groundwater quality in the county. These data indicate that groundwater in Sauk County is naturally of good quality, but that impacts from anthropogenic contaminants are widespread.

Groundwater quality is similar in the unlithified and sandstone aquifer wells (table 6). The water is calcium–magnesium–bicarbonate type, and both aquifers yield water that is very hard. Some sandstone aquifer wells have elevated concentrations of iron. High iron in groundwater may indicate low oxygen conditions and is more likely found in deeper aquifers where groundwater is typically depleted in oxygen. No health hazards

Table 6. *Groundwater quality at municipal wells. Source of data is Wisconsin Department of Natural Resources Bureau of Remediation and Redevelopment database of contaminated lands. All concentrations reported in milligrams per liter (mg/L), except radioactivity, which is reported in picoCuries per liter (pCi/L). Detection limit was variable for many constituents; lowest detection limit is reported here.*

	Unlithified aquifer					Sandstone aquifer				
Constituent	Number of wells	Minimum	Maximum	Mean	Standard deviation	Number of wells	Minimum	Maximum	Mean	Standard deviation
Alkalinity (total $CaCO_3$)	4	127	256	199	58.2	27	73	284	167	69.3
Nitrogen (NO_3+NO_2)	4	0.18	7.34	3.5	3.6	27	<0.01	4.3	1.2	1.5
Hardness as $CaCO_3$	4	144	313	235	74	27	82.2	320	177	75
Calcium	4	31.9	68.5	50.6	15.7	27	17.8	68.3	38.7	16.0
Magnesium	4	15.6	34.5	26.4	8.4	27	9.17	36.4	19.8	8.6
Sodium	4	< 0.004	14	6.4	7.4	27	<0.004	12	3.2	3.8
Chloride	4	1.69	34	155	16	27	<0.6	22.2	5.2	6.7
Sulfate	3	16.1	23.5	20	3.7	16	<0.02	16.8	8	5.1
Iron	4	< 0.01	0.132	0.033	0.066	27	<0.01	4.04	21	0.78
Fluoride	4	0.063	0.094	0.084	0.014	27	<0.002	1.2	229	0.32
Manganese	4	< 0.004	0.076	0.019	0.038	27	<0.004	2.6	0.104	0.499
Nickel	4	< 0.02	<0.02	—	—	26	<0.02	0.0037	0.0003	0.0008
Zinc	4	< 0.002	0.049	0.013	0.024	26	<0.002	3.15	0.163	0.633
Arsenic	4	<0.001	<0.001	—	—	29	<0.001	0.0014	0.00005	0.0003
Barium	4	0.0318	0.031	0.018	0.008	27	0.0007	0.072	0.017	0.016
Radioactivity	4	<0.8	<0.8	—	—	26	<1.4	5.7	1.5	1.6

are associated with iron; however, consumers may dislike the color and staining associated with it. All Sauk County municipal wells have water that is low in naturally occurring contaminants, such as arsenic and natural radioactivity. Nitrate levels are elevated at some municipal wells in the shallow and deep aquifers, although none exceed the enforcement standard of 10 parts per million (ppm).

Because groundwater originates from precipitation that percolates down from the land surface, any water-soluble material or liquid that comes into contact with the percolating water has the potential to be transported to the water table. Pollutants that originate from a point source, such as an underground storage tank or a landfill, migrate through groundwater as a plume, affecting groundwater quality along a discrete flowpath. The DNR Bureau of Remediation and Redevelopment database of contaminated lands (available at <http://dnr.wi.gov/org/aw/rr/brrts/>) identifies more than 230 leaking underground-storage-tank sites, and more than 80 sites where spills have occurred in Sauk County. Constituents of gasoline and other fuels impact a majority of these sites.

Another category of contaminants to groundwater is that of nonpoint-source contaminants, so called because compounds are spread along the ground surface. Nitrogen (typically applied as a fertilizer) and pesticides from agricultural sources are nonpoint sources of contaminants. Nonpoint sources tend to affect broader areas of aquifers than point-source contaminants and are therefore virtually impossible to remediate in any way other than the alteration of land-use practices. (Septic systems are also sources of nitrate to groundwater, but they are point sources.)

Table 7. *Nitrate and atrazine groundwater concentrations across Sauk County. Drinking water standard is 10 ppm for nitrate and 3 ppb for atrazine.*

Constituent	Number of wells	Average	Median	Maximum	Percentage exceeding enforcement standard
Nitrate (in ppm)	1,430	4.9	3.0	58	14.5
Atrazine (in ppb)	488	0.65	0.0	61.4	4

Wells sampled for nitrate included residential wells and wells that serve facilities open to the public, such as restaurants, hotels, and parks. These types of wells tend to be completed at shallower depths than municipal wells because they are used to pump smaller volumes of groundwater. Therefore, groundwater samples from these wells are generally representative of shallow groundwater quality; samples collected from municipal wells (such as those reported in table 6) may be representative of deeper groundwater or groundwater that is mixed over a long open interval in a well. These data indicate that more than 14 percent of wells in the county have nitrate levels exceeding the enforcement standard of 10 ppm (table 7). Nitrate contamination of groundwater is widespread across the county (fig. 20A).

The DNR also maintains records of wells sampled for residues of atrazine, which is an herbicide typically used on corn crops. Approximately 4 percent of the wells tested in Sauk County exceed the enforcement standard for atrazine residues of 3 parts per billion (ppb) (table 7). Wells in various regions of the county are affected (fig. 20B). Although the nitrate and atrazine residue datasets were collected over time (for example, wells were tested for nitrate from 1987 to 2002), the data are not sufficient to determine whether water quality is improving or declining. However, the datasets indicate that contamination by these constituents is widespread and poses a concern to groundwater resources over a large part of the county.

CONCLUSIONS

The two-dimensional regional groundwater flow model presented here is adequate for simulating groundwater flow to wells where path lines are predominantly horizontal, such as areas of the county where wells are completed in a thick sequence of the sandstone aquifer. This model may do a poor job of simulating flow to wells and streams in the uplands, where lower hydraulic conductivity units (for example, the Oneota Formation) that are located higher in the stratigraphic sequence of the sandstone aquifer are not explicitly represented in the two-dimensional model. Three-dimensional models developed for hydrogeologically complex areas of the county are useful to simulate flow in the vicinity of Baraboo, Spring Green, and Sauk City–Prairie du Sac (Gotkowitz and others, 2002).

Almost all the groundwater pumped in Sauk County originates as recharge in the county. Steady-state ZOCs limited by travel times of 50 years show that most of the

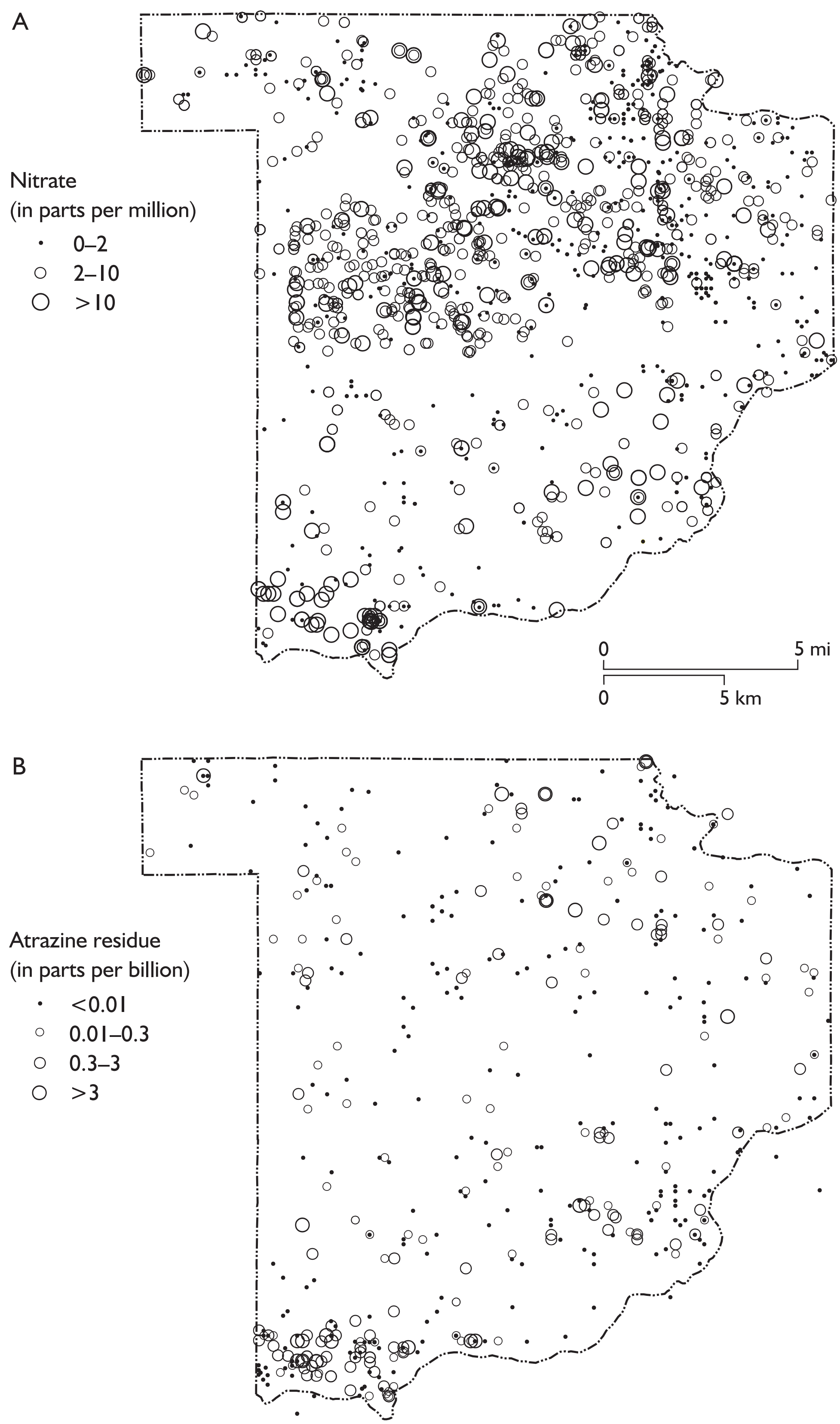


Figure 20. *Concentrations of nitrate (A) and atrazine residue (B) in groundwater in Sauk County.*

municipal wells produce water that originates as recharge within approximately 2 miles from a given well. The ZOCs should be useful for delineating source water assessment areas and for wellhead-protection planning. For example, the ZOCs could be used by water-resource managers to identify areas over which the application of fertilizers and pesticides should be restricted.

The amount of groundwater pumped in the county, almost 14 million gpd, is small compared to the average recharge to aquifers that is estimated to occur in Sauk County (more than 240 million gpd). However, groundwater withdrawal from particular wells can decrease flow to nearby streams and springs. Because more than 90 percent of the groundwater used is pumped from the four populations centers (Reedsburg, Baraboo, Lake Delton–Wisconsin Dells, and Prairie du Sac–Sauk City), these areas may eventually be susceptible to drawdown of water levels because of the concentrated nature of groundwater withdrawal. The locations of new wells can be selected to reduce the potential for well interference from existing high capacity wells. Groundwater use in the Baraboo basin may be affected by the complexity of the sandstone aquifer. The impermeable Precambrian rock that bounds the aquifer surrounds the basin, and patterns of recharge and discharge in the sandstone are highly affected by the location of the Precambrian–Cambrian contact.

Natural groundwater quality in Sauk County wells is good, although it is relatively hard. Nitrate and pesticides applied at the land surface have affected the groundwater quality across all Sauk County. Where the Eau Claire aquitard is present, the sandstone aquifer is protected from these contaminants. In these areas, wells should be cased through the aquitard. In other areas of the county, where no aquitard is between the unlithified and sandstone aquifers, the sandstone aquifer is highly susceptible to contamination in areas of downward vertical gradients.

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COVER: West–east cross section from Plain to Prairie du Sac area.