HYDROGEOLOGY OF DANE COUNTY, WISCONSIN

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K Bradbury, 10/1/99

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Abstract

This summary and analysis of the hydrogeology of Dane, County, Wisconsin is based on work conducted between 1992 and 1997, and provides a framework for an understanding of groundwater resources in the county.

For the purposes of describing and modeling regional groundwater conditions the geologic units present in the county consist of four hydrostratigraphic units: three aquifer units and one aquitard. The Mount Simon aquifer is the most important aquifer in Dane County for the purposes of water supply to high capacity wells. This aquifer consists of sandstones of the Mount Simon and lower Eau Claire Formations. Rocks of Precambrian age form the bottom of the aquifer system. An important leaky confining unit, here called the Eau Claire aquitard, covers much of Dane County and, where it occurs, impedes the exchange of water between the Mount Simon aquifer and overlying aquifers. The Eau Claire aquitard consists of shale and siltstone facies of the upper part of the Eau Claire Formation. The aquitard appears to be thin and partially absent in the central Yahara lakes area, where the preglacial bedrock surface is believed to have been eroded deeply into the underlying Mount Simon Formation. The upper Paleozoic aquifer consists of all saturated Paleozoic rocks between the top of the Eau Claire aquitard and the bedrock surface. The thickness of the upper Paleozoic aquifer ranges from zero, where it is absent beneath the Yahara lakes, to over 200 ft in the western part of the county. The uppermost aquifer in Dane County is the unlithified aquifer, consisting of saturated unlithified materials primarily of Quaternary age. These materials range in lithology from clayey lake sediment to sand and gravel.

All groundwater in Dane County originates as precipitation (rainfall and snowmelt) in or just outside of the county. In general, the water table is a subdued reflection of the county's topography. The depth to groundwater in the county ranges from zero at the fringes of lakes and wetlands to over 200 ft beneath the ridges in the southwest. The water table is highest (over 1000 ft above sea level) in the western part of the county near Mount Horeb and Blue Mounds, and is lowest (less than 840 ft) along the Yahara River in the southeast. Several groundwater divides cross Dane County and separate shallow groundwater into basins analogous but not identical to surface-water basins. Shallow groundwater moves radially away from groundwater divides.

The elevation of the potentiometric surface of the Mount Simon aquifer ranges from about 800 feet above sea level in central Madison to over 900 ft near Verona and in western Dane County near Blue Mounds. A significant low in the potentiometric surface beneath Madison results from long-term pumping of municipal wells there. In this area the potentiometric surface has been lowered until it is below the level of the Yahara lakes.

Shallow and deep groundwater systems are well connected in Dane County. Where the water table is higher than the potentiometric surface the vertical hydraulic gradient is downward, and groundwater moves downward to recharge to Mount Simon aquifer. Where the potentiometric surface is above the water table the vertical gradient is upward, and groundwater moves upward from the Mount Simon aquifer into overlying units. The presence or absence of the Eau Claire aquitard and the hydraulic properties of the shallow Paleozoic rocks largely control the rate of vertical movement.

Numerous springs occur in Dane County and serve as natural points of groundwater discharge. The largest springs occur at low topographic elevations near major surface water bodies and probably discharge groundwater from regional groundwater flow systems. Many small springs occur at higher elevations, particularly in the driftless part of the county, and probably receive local flow from the upper Paleozoic aquifer.

Groundwater withdrawals from high-capacity wells are focused near the Madison metropolitan area, with smaller withdrawals at outlying communities. In 1992, total groundwater consumption was about 51 million gallons per day, and the City of Madison was the largest single consumer. Delineation of areal zones of contribution for municipal wells in Dane County illustrates horizontal groundwater movement to these wells. The source for groundwater produced by municipal wells in Dane County is local, and for almost every well the steady-state zone of contribution lies entirely within the county. Wells located near the Yahara Lakes may be deriving significant quantities of water from downward leakage from the lakes themselves. Groundwater moves downward from surface water to groundwater along much of the shoreline of Lakes Mendota and Monona. Municipal wells located near the Yahara lakes could draw roughly 25 percent of their water from such downward leakage.

Both numerical particle tracking and tritium isotopes provide estimates of groundwater age. Groundwater produced by wells in Dane County ranges in age from less than five years to over 3,000 years.

A groundwater susceptibility map shows a wide range of groundwater contamination susceptibility across the county. In general, areas of shallow bedrock or shallow groundwater are most susceptible, including large parts of the driftless area of western Dane County. Moraine areas just west of Madison are less susceptible to contamination. In other areas of the county the contamination susceptibility varies spatially over small distances as local conditions vary.

Introduction

Background and purpose

This summary and analysis of the hydrogeology of Dane County, Wisconsin is based on work conducted between 1992 and 1997 as part of the Dane County Regional Hydrologic Study. The Dane County Regional Hydrologic Study is a cooperative effort between the Wisconsin Geological and Natural History Survey (WGNHS), the United States Geological Survey (USGS) and the Dane County Regional Planning Commission (DCRPC). The overall objectives of the Dane County Regional Hydrologic Study are (DCRPC, 1991):

- To improve the basic information base and understanding of groundwater and surface water resources and their relationship in order to ascertain existing and potential resource impacts from urban development, groundwater use, and water diversion;
- to establish a hydrogeologic framework for future or more detailed studies, and identify shortcomings in the data base;
- to develop and refine management tools (conceptual and computer models) that will be useful in water management decision making in the county on a continuing basis; and
- to use these tools to evaluate proposed management applications to prevent or minimize adverse impacts caused by urbanization, groundwater withdrawals, and water diversion.

This report is one product of the regional study, and summarizes the hydrogeology of the county. A related report (Krohelski and others, 1999) describes a three-dimensional groundwater flow model constructed for the county. Other products of the regional study include the work of Swanson (1996), who examined groundwater recharge in Dane County, and Fritz (1996), who developed a map of aquifer susceptibility to contamination in the county. In addition, Bradbury and others (1995) developed water table maps for the county and the DCRPC (1996) summarized the results of various proposed future water management scenarios. In a related study, Bradbury and others (1996) used the three-dimensional groundwater flow model to delineate zones of contribution for all municipal wells in the county for wellhead protection purposes.

Scope

This report is intended to describe the framework of the regional hydrogeology of Dane County, and is based on a regional analysis of available data. It addresses large-scale groundwater movement, recharge, and discharge; groundwater withdrawals by wells; groundwater interactions with major surface-water bodies; and regional aquifer characteristics. We hope this report will provide a regional context and starting point for site-specific investigations, but it is not intended as a replacement for such investigations.

Physical setting

Dane County is located in south central Wisconsin (fig. 1) and straddles the boundary between the

Driftless area of southwestern Wisconsin and the area covered by the Laurentide Ice Sheet during the Wisconsin Glaciation (Clayton and Attig, 1997). As a result, there is a diversity of geomorphic settings within the county. The western part of the county is located within the Driftless Area, so called because there is no evidence that this region was directly affected by glacial ice. The landscape of the Driftless Area is typified by dissected uplands and a well-developed drainage system. Hills are generally flat topped and are commonly used for pasture-land and growing row crops. Slopes are steep and commonly are forested. In contrast, the eastern two-thirds of the county was glaciated and the topography is rolling and moderately hilly. The drainage system is not as well developed and the region contains many lakes and marshes. The eastern part of the county contains numerous drumlins.

The average annual precipitation in Dane County, as measured at the Madison airport, is 30.88 in. The mean annual air temperature is 45.2° F, with an average maximum of 82.4° F in July and an average minimum of 7.2° F in January. Sixty percent of annual precipitation falls in the five months of May through September.

Land use in Dane County is predominately agricultural, with most activity directed toward dairy farming and row crops. The centrally-located Madison metropolitan area, composed of the city of Madison along with the adjacent cities of Monona, Middleton, and Fitchburg, is the largest population center in the county. Based on 1994 estimates, the total population of Dane County is 389,700, and 238,600, or about 61 percent of Dane County residents, live in the Madison metropolitan area (Wisconsin Legislative Reference Bureau, 1995).

Previous work

Over thirty years have passed since publication of the last comprehensive analysis and description of groundwater flow in Dane County. That report (Cline, 1965) addresses water resource issues based on data available in the early 1960's and emphasizes issues related to water supply. Previously, Cline (1963) also reported on the hydrology of the upper Black Earth Creek Basin, with a discussion of groundwater conditions in the basin. Olcott (1972) completed a comprehensive study of the bedrock geology in the county that included mapping the depth to bedrock, the elevation of the bedrock surface, and the bedrock geology. An updated map of the bedrock geology is currently (1999) being compiled at the Wisconsin Geological and Natural History Survey. McLeod (1975a, 1975b) later developed digital computer models for simulating drawdowns in the sandstone aquifer and for estimating the hydrologic changes to the aquifer system in the county. These models were adequate and useful in their day, but were based on now-antiquated computer hardware and software and are no longer capable of addressing many current groundwater issues.

Other recent groundwater studies in Dane County were the result of the detection of the pesticide atrazine in many private wells in southern Wisconsin in the late 1980's. Bradbury and McGrath (1992) studied the movement of atrazine in groundwater in part of the Driftless area near Mt Horeb, and Levy (1993) investigated atrazine movement in the glaciated terrain near Wanaukee. Muldoon and others (1994) examined correlations between atrazine contamination, hydrogeologic features, and land use practices throughout the county.

Early reports of the Quaternary geology in the study area include Alden's (1918) study of southeastern Wisconsin. The soils were originally mapped in 1915 (Geib and others, 1915). McCartney (1979) described the statistical reliability of a surficial materials map in western Dane County that was generated using the 1915 soil survey information, however the soils map and descriptions have been updated in the Soil Survey of Dane County (Glocker and Patzer, 1978) since that time. Oelkers (1995) studied the relationship between the glacial landforms mapped on the *Glacial Map of Dane County* (Mickelson and McCartney, 1979) and the hydraulic conductivity of the surficial glacial deposits with which the landforms are associated. Rayne and others (1996) investigated the hydraulic properties of sandy till of the Horicon Formation, which occurs near the land surface over much of eastern Dane County. Clayton and Attig (1997) recently completed a new map and report describing Dane County's glacial geology.

Acknowledgments

Many people and organizations contributed to the Dane County hydrologic study, and to the preparation of this report. We particularly thank Bill Lane, Paul Gempler, and Mike Kakuska of the Dane County Regional Planning Commission for supporting this project. Staff and students of the Wisconsin Geological and Natural History Survey who contributed to this report include Maureen Muldoon, Bill Batten, Matt Menne, Kate Barrett, Mike Czechanski, Eric Oelkers, David Misky, Todd Rayne, Mark Strobel, Reed Ruck, and Tim Eaton. Dane County, the Madison Metropolitan Sewerage District, the City of Middleton, the Dane County Regional Planning Commission, and the Wisconsin Department of Natural Resources provided additional funding for this project.

Methodology and Data Sources

Subsurface records

This report contains previously unpublished information about groundwater levels, subsurface stratigraphy, and the hydrogeologic properties of the geologic units present in Dane County. Most of these interpretations were developed from the study of various subsurface geologic records available for Dane County and surrounding counties. These records include WGNHS geologic logs, well construction reports, and long-term water level measurements.

WGNHS geologic logs

WGNHS geologic logs consist of detailed subsurface stratigraphic records prepared by examination of well cuttings submitted to the WGNHS by drilling contractors. Most such samples are from high-capacity wells. WGNHS geologists examine the well cuttings in a laboratory, prepare stratigraphic descriptions, and interpret formation contacts. Most logs also contain well construction details and water level information, and some contain additional hydraulic information. In general, the geologic logs are the most accurate and detailed data available from wells in Dane County. The WGNHS maintains a computerized database containing information from the geologic logs. Figure 2 shows the distribution of geologic logs in Dane and surrounding counties.

Well construction reports

Compilation of a computerized database of information taken from well construction reports was a critical step in the hydrologic study. Well construction reports (WCRs) are standardized records of basic well construction information submitted to the Wisconsin Department of Natural Resources by well drillers whenever a domestic water well is constructed in Wisconsin. The records include such information as well depth, depth to water, specific capacity test results, and geologic materials encountered. The WGNHS maintains paper files of these records, which date back to the mid-1940's. Thousands of such records exist for Dane County, but the records are of little use unless the data they contain can be efficiently searched and located in space. An early part of Dane County Hydrologic Study consisted of selecting representative WCRs, identifying the actual wells associated with each WCR, plotting the well location on a topographic map, determining digital coordinates for the well's location, and entering the WCR data into a computerized relational database. The goal of this process was the construction of a spatially-coordinated digital database for rapid manipulation of the WCR data.

Data were compiled at a scale of 1:24,000, using U. S. Geological Survey quadrangles (7.5-minute series, topographic) as base maps. The well construction reports were examined and checked against historical plat books, U. S. Geological Survey ortho-photographs (1987), and maps of subdivision plots in order to determine locations. Wells were located to at least the nearest quarter-quarter section. For some areas, particularly newer subdivisions, the locations of the wells were field checked before they were plotted onto the base maps. Data density varies across the county, with fewer data points in the rural portions of the county and more data points in urban areas. Land surface elevations of the wells were determined from USGS quadrangle maps. The topographic contour interval on the base maps is 10 ft, therefore elevations determined from the maps are assumed to be accurate to within $\pm$ ½ the contour interval. In some cases, the elevations were field-measured using an altimeter. Altimeter measurements are accurate to within $\pm$ 3 feet. The elevations of approximately 150 wells were measured with the altimeter. After plotting the data, each well was assigned a unique identification number. The locations were digitized and the information from the well construction report, or geologic log and the water elevation, was entered into a database for Dane County.

The current WCR database for Dane County contains information from over 4,000 domestic wells distributed about evenly across the county (fig. 2). Each well has a unique identification number and is located in space using the Dane County UTM coordinate system.

Long-term water level measurements

Long-term records of groundwater levels are available from 13 wells in the county as part of the Wisconsin groundwater observation-well network (Zaporozec, 1996), a cooperative activity between the WGNHS and USGS. Figure 2 shows the locations of these wells. Water levels are measured either continuously (4 wells), weekly (1 well), or monthly (8 wells), and records extend back as far as 1946. Water level records are stored in a computer database at the USGS offices in Middleton, WI.

RPC well survey

In order to collect up-to-date information on well construction and groundwater use, the Dane County Regional Planning Commission (RPC) prepared and distributed a well construction/water use questionnaire which was sent to all known owners of high-capacity wells in Dane County. The pumping and well construction information on these forms was cross-checked with other existing RPC, WGNHS, and USGS records. As a result, several previously-unlisted high-capacity wells were added to the database.

Preparation of contour maps

The contour maps of various parameters (water table, potentiometric surface, aquifer thickness, etc) presented in this report were prepared using automatic computer contouring using the Surfer version 6 contouring package (Golden Software, Inc, 1995) followed by manual interpretive editing and smoothing. In this approach, digital point data (for example, water levels in individual wells) were interpolated to a regular grid using either the inverse distance or kriging interpolators available in Surfer. The resulting grid was initially contoured by computer. These computer-generated contours were then manually smoothed and edited to honor known data points and to reflect professional judgement in areas of sparse data.

Collection of field data

Test well and geophysical logging

Although an extensive hydrogeologic field program was beyond the scope of this study, one new test well was installed specifically for the project. Analyses of existing data showed a lack of deep stratigraphic data northwest of Madison, and the numerical model (described below) suggested that hydraulic data in this vicinity would be important to understanding groundwater flow there. Accordingly, well DN-1371 was drilled near Springfield Corners (fig. 2) for the purpose of determining subsurface stratigraphy and hydraulic properties. The well was drilled to 460 ft using standard air-rotary techniques. A series of borehole geophysical logs were obtained from this well using a portable downhole logger. In addition, the USGS conducted a series of hydraulic tests on this well using inflatable straddle packers.

Stream seepage and vertical gradient survey

In order to improve the understanding of groundwater-surface water exchange in Dane County, a stream seepage and vertical gradient survey was undertaken during the summer of 1995. The goal of this survey was to measure the direction (upward or downward) and rate of groundwater seepage through the beds of selected streams in the county and to attempt to quantify the vertical hydraulic conductance of the streambed materials. The survey was conducted using a combination of minipiezometers (Lee and Cherry, 1978) and current meter measurements along short stream reaches under baseflow conditions. The total flow along the stream reach is measured using a current meter at cross sections at its upper and lower ends. Assuming base flow conditions (no contribution from runoff), and negligible evaporation, differences in stream discharge between the upper and lower cross sections must be due to groundwater flux. Using this flux and the measured vertical gradient, Darcy's law gives the vertical hydraulic conductivity of the streambed sediments.

We also used a minipiezometer survey to measure vertical hydraulic gradients at a series of locations along the shore of lakes Mendota and Monona.

Isotopic analyses of water samples

Water samples were collected from various sites in Dane County for analysis of isotopes of hydrogen and oxygen as an aid in determining groundwater age and source areas. Samples were collected from public supply wells, monitoring wells, and springs, and tested for oxygen-18 (^{18}O), tritium (^{3}H), and deuterium (^{2}H). Samples were analyzed by the isotope laboratory at the University of Waterloo, in Waterloo, Ontario, Canada.

Groundwater flow modeling

Modeling methodology

One of the prime objectives of the Dane County Hydrologic Study was the construction of a three-dimensional computerized groundwater flow model for Dane County. Krohelski and others (1999) describe the construction and implementation of this model. The model uses data on aquifer properties, hydraulic head distributions, and recharge developed in this report, and is an important tool for integrating diverse data sets. This model represents a significant improvement over McLeod's (1975 a,b) earlier flow models of Dane County because it is calibrated to current hydraulic heads, it includes groundwater-surface water exchange, and it includes spatially-variable recharge to the water table. The model uses the well-known USGS MODFLOW modeling code (McDonald and Harbaugh, 1988). The finite-difference grid used in the model has equally-spaced nodes about 1300 ft on a side. Model boundaries are set at hydrogeologic boundaries outside of the political boundaries of Dane County. Major internal surface water bodies, including the Yahara lakes, the Yahara River, and other rivers and streams are simulated using the MODFLOW river package, which can calculate simulated groundwater discharge to or recharge from surface water bodies.

Model use

As described by Krohelski and others (1999), the Dane County groundwater flow model has multiple uses. In the context of this report the model is used to integrate the hydrogeologic data sets (hydrostratigraphy, hydraulic heads) constructed for Dane County in order to understand and visualize three-dimensional groundwater flow paths, recharge/discharge relationships, groundwater-surface water interactions, and drawdown due to pumping. The model is also used to test various water management scenarios involving the placement and pumping rates of proposed future wells around Dane County (Dane County RPC, 1996) . Also, the model has been used to delineate groundwater flow paths and zones of contribution for all municipal wells in Dane County (Bradbury and others, 1996) for wellhead protection planning.

Hydrogeology

Regional geologic setting

A series of dolomite and sandstone units overlying crystalline rock composes the bedrock geology of Dane County (table 1). The bedrock geology of Dane County is described in detail by Cline (1965) and Ostrom (1967) and is also discussed by Mickelson (1983), Kammerer (1995), Clayton and Attig (1997), and Brown and others (in preparation). Figure 3 shows the general arrangement and approximate relative thicknesses of bedrock geologic units across Dane County.

Precambrian units

Igneous and metamorphic rocks of Precambrian age are the lowermost rocks under all of Dane County and are not exposed at the surface anywhere in the county. The Precambrian surface is irregular, ranges in elevation from about 220 ft below sea level to 200 ft above sea level as measured in 43 deep wells where it was penetrated in the county. The surface of the Precambrian rocks is highest in the northeastern and northwestern corners of Dane County (fig. 4), and lowest in the southern part of the county. Deep wells are rare in the southern part of the county, particularly in the southwest, and the elevation of the Precambrian surface is poorly known in these areas.

Little is known about the hydrogeologic properties of the Precambrain rocks in Dane County. These crystalline igneous and metamorphic rocks are thought to have little primary porosity and very low hydraulic conductivity. Some groundwater movement may occur through fractures in these rocks, but it is unlikely to be significant to the regional hydrogeology of the county. Due to the excellent water-yielding characteristics of the younger sandstones and dolomites the Precambrian rocks have never been exploited as a source of groundwater in the county. We assume, as have other investigators, that the Precambrian rocks in Dane County act as an aquitard and form an effective base to the aquifer system.

Cambrian units

The lowermost Paleozoic rocks in Dane County consist of sandstone and shale of the Elk Mound Group, which contains (from oldest to youngest) the Mount Simon, Eau Claire, and Wonewoc Formations. The Mount Simon Formation ranges from about 200 to 450 ft thick in the county, and consists of well-cemented, coarse to medium-grained sandstone. Its base is the irregular surface of the underlying Precambrian rocks. The overlying Eau Claire Formation contains fine- to medium-grained dolomitic sandstone and shale. The base of the Eau Claire commonly grades imperceptively into the Mount Simon (Cline, 1965), and the contact between the two is difficult to distinguish in well records. The upper part of the Eau Claire contains significant shale and siltstone. The overlying Wonowoc Formation contains medium to fine-grained sandstone. Only the upper part of the Elk Mound Group is exposed in northwestern Dane County, just above the level of the Wisconsin River (Clayton and Attig, 1997).

The Tunnel City Formation, which contains glauconitic sandstone, and the St Lawrence Formation, composed of sandy dolomite, overlie the Elk Mound Group. These units were called the Franconia Sandstone and Trempleau Formation in previous reports (for example, Cline , 1965). They are exposed around the lower flanks of highlands in the northwestern part of the county (Clayton and Attig, 1997). The youngest Cambrian rocks in the county is the yellow to reddish, coarse- to fine-grained, dolomitic sandstone of the Jordan Formation. The Jordan is classified in older reports as the upper part of the Trempleau Formation (for example, Cline, 1965). The Jordan Formation ranges from zero to about 70 ft thick, and outcrops in steep slopes surrounding Prairie du Chien plateaus in the northwest part of the county (Clayton and Attig, 1997).

Sandstones of the Elk Mound Group are a major source for water for wells throughout Dane County. Groundwater in these sandstones moves through interconnected pore spaces, along bedding planes, and through fractures (Cline, 1965). The Mount Simon and Wonowoc Formations contain less silt, shale, and dolomite than the Eau Claire and yield more water than the other Cambrian sandstones. Although much of the thickness of the Eau Claire yields moderate amounts of water, the shaley facies near its upper part yields little water and is an impediment to vertical groundwater movement. We discuss this shaley facies in more detail below.

The Tunnel City and St Lawrence Formations yield less water to wells than the other late Cambrian sandstones. Locally, these units may form a leaky aquitard above the Wonowoc Formation. Two pumping tests (RMT, Inc, 1994, 1995) one using a well (DN-947) located on west side of Madison, and a second using a well (DN-119) located on the east side of Madison suggest that the Tunnel City and St Lawrence act hydraulically as a leaky confining bed in the Madison area. Sufficient data are not available to determine the hydraulic properties of these units in other parts of the county.

Cenozoic Era	Holocene Epoch	unnamed units		
Cenozoic Era	Pleistocene Epoch	Kieler Fm.	Holy Hill Fm.	Horicon Member
				other members?
		other formations?		
	?	Rountree Formation		
Paleozoic Era	Ordovician Period	Maquoketa Formation		
		Sinnipee Group	Galena Formation	
			Decorah Formation	
			Platteville Formation	
		Ancell Group	Glenwood Formation	
			St. Peter Formation	
		Prairie du Chien Group		
	Cambrian Period	Jordan Formation		
		St. Lawrence Formation		
		Tunnel City Formation		
		Elk Mound Group	Wonewoc Formation	
			Eau Claire Formation	
			Mount Simon Formation	
Precambrian eras		various unnamed units		

Table 1. Stratigraphic section for Dane County (from Clayton and Attig, 1997).

Ordovician units

Above the Cambrian age rocks are dolomite, sandstone and shale of Ordovician age. From the oldest to youngest, the four units in the Ordovician are the Prairie du Chien Group, Ancell Group, Sinnipee Group, and Maquoketa Formation (Kammerer, 1995; Ostrom, 1967). Rocks of the Prairie du Chien Group, exposed in the Black Earth Creek Valley, are light gray to buff colored sandy dolomite with chert nodules (Cline, 1965). The Ancell Group consists of the St. Peter Formation, which is composed of coarse- to fine-grained quartz sandstone and the overlying thin (0-2 ft thick) Glenwood Formation, made up of dolomitic sandstone, shale and siltstone (Kammerer, 1995; Ostrom, 1967; and Cline, 1965). The St. Peter lies unconformably on the eroded surface of the Prairie du Chien, and its thickness, which ranges from zero to over 200 ft, can vary rapidly over short horizontal distances. The St. Peter commonly outcrops in or below scarps surrounding dolomite plateaus in the southwest part of the county (Clayton and Attig, 1997).

Rocks of the Prairie du Chien Group yield small to moderate amounts of water to wells. Most groundwater movement in the Prairie du Chien rocks is through fractures, joints, and minor solution features. Accordingly, yields to wells can vary widely over short distances. Locally, large fractures and solution openings have been reported in wells. The water table occurs in the Prairie du Chien mainly in the southwest part of Dane County; the rocks are above the water table in northwestern and central Dane County (Cline, 1965). Sandstone of the St Peter Formation generally has moderately high hydraulic conductivity, but this formation yields only small amounts of water to wells because it is often thin and frequently occurs above the water table. Locally, the thin Glenwood Formation forms an aquitard above the St Peter, but subsurface data on the Glenwood are insufficient to trace it across the county.

Above the Ancell Group, the Sinnipee Group consists of dolomite of the (from oldest to youngest) Platteville, Decorah, and Galena Formations. Much of the Sinnipee Group was eroded from Dane County, and the entire sequence occurs only near Blue Mounds, where the rocks are nearly 300 ft thick. Parts of the lower Sinnipee Group are exposed at many locations in the southwestern part of the county, and have a highly variable appearance in outcrop. In some localities, they are highly fractured, and in other parts of the county the rock is massive (B. Brown, WGNHS, verbal communication, 1995). The Maquoketa Formation, a blue-gray shale, is the youngest Paleozoic rock in Dane County and is exposed at East Blue Mound (Cline, 1965; Clayton and Attig, 1997).

Rocks of the Sinnipee Group occur above the water table over most of Dane County. These rocks are saturated only in the western part of the county between Mt Horeb and Blue Mounds (Cline, 1965). Locally, perched water tables have been reported in the Sinnipee Group west of Madison. Few wells in Dane County obtain adequate supplies of water from the Sinnipee Group. The overlying Maquoketa Formation is unsaturated where it occurs in Dane County.

Pleistocene units

Deposits of the Wisconsin glaciation cover the northern and eastern two-thirds of the county (fig. 1) and are described by numerous geologists, including Alden (1918), Mickelson (1983), and Clayton and Attig (1997). The maximum extent of glacial ice is marked by a hummocky moraine zone that trends northwest to southeast across the county. According to Clayton and Attig (1997), the moraine is composed of till of the Horicon Member of the Holy Hill Formation, which was deposited by the Green Bay Lobe during the Late Wisconsin glaciation. East of the hummocky moraine zone is the Yahara River valley, an area dominated by Lakes Mendota, Monona, Waubesa, and Kegonsa. The glacial deposits in the valley consist of sand, silt, and clay typically three to 50 ft thick, and in places is overlain by several feet of post-glacial silt, clay and peat (Clayton and Attig, 1997). The northern and eastern parts of the county are characterized by northeast - to - southwest trending drumlins with marshy lowlands or gently rolling diamicton-covered land between them. Sand and gravel deposited by glacial meltwater occurs as outwash plain or valley train deposits. Sand and gravel also occurs as floodplain deposits along modern rivers.

Windblown silt, or loess, was deposited over all of Dane County during the Wisconsin Glaciation but was subsequently eroded from many areas (Attig and Clayton, 1997). Today on flat uplands the remaining loess is about 3 ft thick. Most loess has been removed from steep hillslopes and has been either removed or reworked in geologically active areas such as stream valleys.

The thickness of unlithified deposits in the county ranges from zero to nearly 200 ft thick based on the Dane County Soil Survey (Glocker and Patzer, 1978) and well construction. The thickest sand and gravel deposits are in the Wisconsin River Valley in the northwest part of the county. Diamicton is generally at least a few feet thick and is thickest in the moraine zone and thinner in the east (Clayton and Attig, 1997).

Major aquifers and confining units

For the purpose of describing and modeling regional groundwater conditions in Dane County we have chosen to divide the geologic units present in the county into four hydrostratigraphic units: three aquifer units plus one aquitard. In making these generalizations we have grouped geologic units having similar hydraulic characteristics into single hydrostratigraphic units. While we believe these subdivisions are adequate from a regional standpoint they may not be appropriate for site-specific studies where local conditions vary from our county-wide interpretations. In this report, and in the accompanying regional groundwater flow model (Krohelski and others, 1999), the major hydrogeologic units are the Mount Simon aquifer, the Eau Claire aquitard, the upper Paleozoic aquifer, and the unlithified aquifer. The following section describes these hydrogeologic units from bottom to top in the geologic section.

Mount Simon aquifer

The Mount Simon aquifer is the most important aquifer in Dane County for the purposes of water supply to high capacity wells. This aquifer consists of sandstones of the Mount Simon and lower Eau Claire Formations. The lower boundary of the aquifer is the Precambian surface. The upper boundary is the bottom of the shaley facies of the Eau Claire. The aquifer ranges in thickness from about 100 ft to over 700 ft. It is thickest in south-central Dane County and thinnest in the northwest, where the underlying Precambrian surface rises. The average thickness of the aquifer is about 500 ft. The Mount Simon is a confined aquifer everywhere it occurs in Dane County.

Eau Claire aquitard

An important leaky confining unit, here called the Eau Claire aquitard, covers much of Dane County and, where it occurs, impedes the exchange of water between the Mount Simon aquifer and overlying aquifers. The Eau Claire confining unit consists of the shale and siltstone facies of the upper part of the Eau Claire Formation. This material has not been identified as a separate stratigraphic unit, and in fact may not be one continuous layer of material. However, we identified shale or siltstone material at about the same stratigraphic position in 103 WGNHS geologic logs from western, central, and southern Dane County. This material ranges in thickness from over 60 ft in northwestern Dane County to being absent in the northeast, where it was either never deposited or was subsequently removed by erosion (fig. 5). The Eau Claire aquitard appears to be patchy and partially absent in the central Yahara lakes area, where the preglacial bedrock surface is believed to have been eroded deeply into the underlying Mount Simon Formation.

Some of the best evidence for the Eau Claire aquitard comes from test well DN-1371, installed for this project near Springfield Corners, (Section 9, T8N, R8E), about 10 miles northwest of Madison (fig. 2). This well is 467 feet deep, and penetrates about 100 ft into the Mount Simon Formation. Figure 6 shows data from this well. Notice the gamma signature corresponding to the observed location of the Eau Claire confining bed noted in drill cuttings. This is the only significant gamma response in the entire stratigraphic section penetrated by well DN-1371, and is typical of gamma logs from other Dane County wells.

The Eau Claire aquitard has a significant influence on hydraulic head at well DN-1371. The graph on the left side of figure 6 shows results of straddle packer tests. Inflatable straddle packers were used to isolate various sections of the borehole while hydraulic heads in the borehole were measured using pressure transducers. A significant drop in total head of nearly 50 ft occurs across the shaley Eau Claire facies. This head drop is convincing evidence that the shaley facies acts as a major aquitard at this location.

The hydraulic properties of the Eau Claire aquitard are very poorly known. Krohelski and others (1999) assigned a vertical hydraulic conductivity of 0.0006 ft/d to this unit, based primarily on a literature review of similar materials, and the regional groundwater model calibrates acceptably with this value. Identification and correlation of the Eau Claire aquitard across Dane County is somewhat problematic because of its poor representation in most available sets of well cuttings, the scarcity of deep wells outside the Madison metropolitan area, and the lack of data beneath the Yahara lakes. However, the analyses here and in the regional flow model (Krohelski and others, 1999) suggest that the presence or absence of the Eau Claire aquitard is an important control on vertical groundwater movement between shallow and deep bedrock aquifers in Dane County. The absence of the aquitard in central Dane County, where pumping stresses are greatest, allows pumping to have much more effect on shallow groundwater and surface water resources than might otherwise occur. Collection of additional data on the occurrence and properties of this aquitard should be one focus of future hydrogeologic studies in Dane County.

Upper Paleozoic aquifer

The upper Paleozoic aquifer consists of all saturated Paleozoic rocks between the top of the Eau Claire aquitard and the bedrock surface. Where the water table is in bedrock the top of this aquifer is the water table. Where the water table is in Quaternary materials the top of this aquifer is the bedrock surface. We recognize that the upper Paleozoic aquifer thus contains a variety of materials ranging in lithology from sandstone to siltstone to dolomite, and that the hydraulic properties of these materials may be somewhat dissimilar. However, on a regional scale all these units appear to be hydraulically interconnected. In addition, there are currently insufficient subsurface hydraulic data available to make any more-detailed hydrogeologic subdivisions of the upper Paleozoic rocks across the county. The thickness of the upper Paleozoic aquifer ranges from zero, where it is absent beneath the Yahara lakes, to over 200 ft in the western part of the county. Where it is covered by saturated clay-rich unlithified materials, the upper Paleozoic aquifer usually behaves as a confined aquifer. Where the water table occurs in bedrock, as it does throughout most of southwestern Dane County, the aquifer is unconfined.

Unlithified aquifer

The uppermost aquifer in Dane County is the unlithified aquifer, consisting of saturated unlithified materials primarily of Quaternary age. These materials range in lithology from clayey lake sediment to sand and gravel. The bottom of this aquifer unit is the bedrock surface, and the top of the aquifer unit is the water table. The saturated thickness of these materials ranges from zero to over 200 feet. Due to the heterogeneity of these materials in Dane County it was necessary to further subdivide the materials into several aquifer types. Fritz (1996) undertook a detailed delineation of the properties of the unlithified aquifer, which she divided into three types. Plate 1 shows the distribution of these three aquifer types across the county. Type 1 consists of well-sorted sand and gravel deposited as stream sediment, type 2 consists of moderately- to poorly-sorted sand, gravel, and silt deposited as sandy diamicton and well sorted offshore glacial lake sediment, and type 3 consists of well- to moderately-well-sorted sand and gravel overlain by silty or clayey lake sediments. The type 1 aquifer includes areas mapped as stream or outwash sediment. Such areas are in the Sugar River Valley, Wisconsin River Valley, and Black Earth Creek Valley, for example. The type 2 aquifer is present in the glaciated northern and eastern part of the county. The type 3 aquifer is a unit of sand and gravel overlain by lake sediments.

Type 3 aquifers are located beneath the surface of what was Glacial Lake Middleton, Deansville Marsh, and in parts of the Yahara River Basin. In these regions, there is enough evidence from well construction reports and field evidence (J. Attig, WGNHS, verbal communication, 1996) to indicate that fine-grained lake sediments are thick enough and laterally extensive enough to be considered a confining or partially confining bed. Therefore, aquifer types 1 and 2 are hydraulically unconfined, while aquifer type 3 is confined or partially confined.

Hydraulic Properties

Mount Simon aquifer

Hydraulic conductivity and transmissivity data for the Mount Simon aquifer are based on 14 aquifer pumping tests conducted in the Madison area (table 2). Most of these aquifer tests date from the 1960's. Local consulting firms conducted additional tests during the period of this study (RMT, 1994, 1995; Woodward-Clyde, 1994); these estimates are consistent with earlier values. The geometric mean value of hydraulic conductivity determined for the Mount Simon (10 ft/day) was used in the regional groundwater flow model (Krohelski and others, 1999). There are few pumping tests outside the Madison metropolitan area, and data are insufficient to reveal any regional trends in the hydraulic conductivity of the Mount Simon.

Upper Paleozoic aquifer

Table 2. Summary of pumping test results for the Mount Simon aquifer in Dane County. T: transmissivity, K: hydraulic conductivity, S: storage coefficient.

Well	Tn	Rn	Sec	Well name	T, ft^2/day	thickness, ft	K, ft/day	S	Reference*
Dn-50	7	10	6	Madison #3	8640	500	17.3	3.0E-04	RMT (1995)
DN-96	7	9	32	Madison #10	6019	565	10.7	1.8E-04	USGS (1957)
DN-96	7	9	32	Madison #10	6523	565	11.5	3.4E-04	CLINE (1965)
DN-144	7	9	30	Madison #12	5875	540	10.9	--	CLINE (1965)
DN-144	7	9	30	Madison #12	6048	540	11.2	3.5E-04	USGS (1957)
DN-301	9	10	17	DeForest #2	4637	500	9.3	1.5E-04	USGS (1960)
DN-316	6	8	22	Verona #2	4752	630	7.5	4.9E-07	USGS (1959)
DN-316	6	8	22	Verona #2	7546	630	12.0	1.8E-10	USGS (1959)
DN-316	6	8	22	Verona #2	3686	630	5.9	8.2E-07	USGS (1959)
DN-900	5	11	5	Stoughton #4	6077	610	10.0	6.9E-07	USGS (1963)
DN-900	5	11	5	Stoughton #4	3499	610	5.7	6.1E-04	USGS (1963)
DN-921	7	8	12	Middleton #5	5285	480	11.0	8.5E-07	USGS (1964)
Dn-935	7	9	13	Madison #17	16400	525	31.0	--	Woodward-Clyde (1994)
Dn-947	7	8	24	Madison #16	5040	545	9.2	1.2E-04	RMT (1994)

Statistics

Statistics	T, ft^2/day	thickness, ft	K, ft/day	S
Min	3499	480	6	1.8E-10
Max	16400	630	31	8.4E-04
Mean	6356	565	11	2.2E-04
Geom Mean	5899	563	10	--

* USGS references refer to unpublished data in USGS files

Estimates of the hydraulic conductivity for the upper Paleozoic aquifer in Dane County are based on specific capacity tests on over 1500 water wells completed in this aquifer in the county and included in the WCR database. Most of these wells are domestic water supply wells open to several geologic units. The program TGUESS (Bradbury and Rothschild, 1985) was used to estimate hydraulic conductivity and transmissivity of the upper Paleozoic aquifer based on specific capacity tests.

Wells that were completed above the Eau Claire and below the Pleistocene were selected from the WCR database for specific capacity analysis. From this data set, wells having reasonable values for the specific capacity parameters (open interval, drawdown, pumping rate, etc) were selected. Because the Eau Claire Formation is not identified in every WCR, approximate values for the aquifer bottom were estimated using a spatial trend function. The resulting specific capacity data set included 1554 wells. Estimated values of hydraulic conductivity ranged from $9x10^{-2}$ to 500 ft/day, with a geometric mean of 4 ft/day. There was no spatial trend in either hydraulic conductivity or transmissivity of the upper Paleozoic aquifer identified in these data, although lateral variations in the properties probably occur locally.

Unlithified aquifer

The unlithified aquifer consists of various materials ranging from fine-grained lacustrine sediment to coarse-grained sand and gravel. Accordingly, the hydraulic properties of the unlithified aquifer vary widely across the county. Swanson (1996) estimated saturated vertical and horizontal hydraulic conductivity of these materials by grouping the surficial materials into distinct hydrogeologic units based on existing hydraulic conductivity data. She then used the vertical distribution and areal extent of these hydrogeologic units to calculate composite estimates of vertical and horizontal hydraulic conductivity.

Swanson (1996) recognized three distinct unlithified material types found within the county, including silt and clay deposits of lacustrine origin, sandy diamicton (till of the Horicon Formation) and sand and gravel deposits (outwash and stream deposits). Table 3 presents the geometric mean (mean of log-transformed values) of hydraulic conductivity for each of the material types.

The three unlithified hydrogeologic units show high variability of hydraulic conductivity. Hydraulic conductivity ranges over approximately 4 orders of magnitude for the sand and gravel deposits, approximately 3.5 orders of magnitude for the silt and clay deposits, and approximately 5 orders of magnitude for the sandy diamicton.

Geomorphic settings were used to determine the areal extent and vertical distribution of the three unlithified hydrogeologic units over six geomorphic settings based on the *Glacial Map of Dane County, Wisconsin* (Mickelson and McCartney, 1979). The six settings include ground and end moraine, outwash plains and fans, pitted outwash plains and valleys, alluvial valleys, former lake beds, and landforms associated with ice-contact stratified deposits such as kames and eskers.

Results from a field investigation by Oelkers (1995) support the correlation between the mapped glacial geology (Mickelson and McCartney, 1979) and sediments in the county. The glacial map units provide a reasonable estimate of the lithologic characteristics of the first unit of sediments beneath the loess or colluvium. Well Constructor's Reports (WCRs) and geologic logs from residential and private wells provide additional information about vertical distribution of materials, or hydrogeologic units, within each geomorphic setting.

Swanson (1996) assumed that areas mapped as ground and end moraine consist primarily of sandy diamicton (Horicon till) over bedrock. The Horicon till is vertically homogeneous and probably isotropic with respect to hydraulic conductivity. Areas mapped as outwash fans and plains probably consist almost entirely of sand and gravel deposits, and are also probably isotropic. Areas mapped as pitted outwash plains and valleys contain an average of 51% sand and gravel and 49% sandy diamicton. Ice-contact stratified deposits contain an average of 53% sand and gravel and 47% sandy diamicton. Alluvial valleys contain an average of 56% silt and clay and 44% sandy diamicton. Pitted outwash plains and valleys, alluvial valleys, and ice-contact stratified deposits were thus assigned grouped hydraulic conductivities based on these percentages.

Table **3**. Hydraulic conductivity (K) estimates for the three distinct unlithified hydrogeologic units in Dane County (from Swanson, 1996)

Hydrogeologic unit	**Log K**	**K, ft/d Geom Mean (std dev)**
Sand and Gravel	0.15	1.4 (1.04)
Sandy Diamicton	-0.22	0.6 (1.23)
Silt and Clay	-1.0	0.1 (0.98)

The former beds of Glacial Lakes Yahara and Middleton cover a large area in central Dane County (Clayton and Attig, 1997). Deposits in the lake basins consist primarily of sandy diamicton deposited in a preglacial bedrock valley, overlain by lacustrine deposits (Mickelson, 1983). Because till occupies the deeper portion of the bedrock valley, and the unlithified materials are assumed to be relatively flat-lying, the percentage of lacustrine deposits in a vertical sequence in the center of a valley (low bedrock elevation) may be less than the percentage of lacustrine deposits on the edge of a valley (high bedrock elevation) where less sandy diamicton was previously deposited beneath the lacustrine deposits. Swanson (1996) established statistical correlations between percentages of lacustrine deposits and bedrock elevations, and used these correlations to estimate the vertical distribution of lacustrine deposits and sandy diamicton within the former lake bed areas. The spatially variable vertical distribution of materials was used to estimate vertical and and horizontal conductivities of the unlithified deposits in the former lake beds.

The estimated spatial distribution of saturated horizontal and vertical hydraulic conductivity values for the unlithified surficial materials in the county is based on a generalized form of the *Glacial Map of Dane County, Wisconsin* (Mickelson and McCartney, 1979). Table 4 presents the hydraulic conductivity estimates that were assigned to materials that are associated with the geomorphic settings.

Table **4.** Geomorphic settings and corresponding saturated vertical and horizontal hydraulic conductivity estimates (estimates in former lake beds vary with position in bedrock valley).

Geomorphic setting	**K_H (ft/d)**	**K_V (ft/d)**
pitted outwash plains/valleys	1.0	0.8
alluvial valleys	0.3	0.2
landforms associated with ice-contact stratified deposits	1.0	0.8
ground/end moraine	0.6	0.6
outwash plains/valleys	1.4	1.4
former lake bed	0.1 - 0.4	0.1 - 0.3

Groundwater Flow Systems

The hydrogeology of Dane County fits within the overall framework of a groundwater flow system, where groundwater moves continuously from areas of recharge to areas of discharge. As classically understood (e.g. Toth, 1963; Freeze and Cherry, 1979) for humid-climate settings such as southern Wisconsin, the main controls on flow systems include surface topography, surficial recharge variations due to soils and climate, stresses due to pumping, and subsurface heterogeneity. A conceptual model of groundwater movement in Dane County fits well within the flow system concept.

Groundwater Recharge

All groundwater in Dane County originates as precipitation (rainfall and snowfall) in or just outside of the county. Groundwater recharge is the addition of water to the water table, and knowledge of the location of groundwater recharge areas and the rates of groundwater recharge is essential for groundwater flow models and for water resources planning.

Precise measurement and mapping of groundwater recharge is extremely difficult. Controls on recharge include precipitation timing and intensity, topography, vegetative cover, surface roughness, and soil properties, and these parameters are rarely known in detail over large areas. Previous estimates of average recharge rates in Dane County range from 6 to 11 in/yr. Cline (1965) estimated a county-wide average of 6 in/yr based on a water-budget analysis. McGrath (1991) based estimates of 9 to 11 in/yr on baseflow analyses from streams in the Driftless Area of western Dane County. Using a water-balance model, Levy (1993) estimated recharge to be about 5.6 in/yr at a site just west of the Village of Waunakee.

The recharge map included in this report (fig 7) is based on a combination of inverse groundwater modeling and soil moisture budget analyses (Swanson, 1996). Swanson used a county-wide inverse groundwater flow model to delineate *areas* of groundwater recharge and discharge, following the methodology of Stoertz and Bradbury (1989). By assuming that a combination of hydraulic conductivity and recharge or discharge rates controls the configuration of the water table, this method accounts for recharge flux to regional and local groundwater flow systems. It delineates recharge *areas* which are consistent with regional groundwater flow, but tends to produce poor estimates for recharge *rates* because of a high correlation between recharge rates and hydraulic conductivity.

Estimates of *rates* of recharge to the water table throughout the county were based on a soil water balance model (Swanson,1996). This procedure assumes that groundwater recharge is approximately equal to deep drainage, or percolation, through a soil column, and thus varies seasonally in response to precipitation, snowmelt, evapotranspiration, runoff, and changes in soil moisture. Swanson (1996) modified Thornthwaite and Mather's (1957) soil water balance method and applied it to each soil map unit (Glocker and Patzer, 1978) in Dane County. Recharge estimates produced by the soil moisture budget method are similar to previous estimates, and range from 0.3 to 6.8 inches per year. However, this method, based primarily on soils data, does not conform to the groundwater flow system and does not account for runoff water routed across the land surface. Accordingly, it was expected to underestimate the absolute recharge rates while producing a reasonably accurate relative distribution of rates.

The final distribution of recharge in Dane County was created by overlaying the distribution of recharge areas with the distribution of relative recharge rates, and then scaling the estimated recharge rates upward by a factor of about 2, giving an average recharge rate of 5 in/yr and a range of rates of 0.2 to 13.3 in/yr (Krohelski and others, 1999). The upward scaling was needed to achieve calibration of the regional hydrologic model.

Recharge varies widely across the county (fig 7), with recharge areas occurring over about 52% of the landscape. Recharge usually occurs in the higher parts of the landscape, along the crests and flanks of broad ridges, and along steep wooded slopes (Potter and others, 1995). Lower areas of the landscape, including broad floodplains, wetlands, and stream valleys, are more often areas of groundwater discharge. However, the highest recharge rates in the county occur along the Wisconsin River floodplain near Mazomanie, where broad sand plains allow little runoff and rapid infiltration.

Shallow groundwater flow

Configuration of the water table

The depth to groundwater in Dane County ranges from zero at the fringes of lakes and wetlands to over 200 ft beneath the ridges in the southwest. Plate 1 shows the configuration of the water table in Dane County. This map (at a scale of 1:100,000) was compiled from individual water-table maps for all USGS 7.5 minute topographic quadrangles in the county constructed by Bradbury and others (1995). These maps are an interpretation of all available data, including water levels on well construction reports, surface water elevations, WGNHS geologic logs, and miscellaneous water levels available from the files of the WGNHS and WDNR. Bradbury and others (1995) describe the map construction process, which included study of over 4000 well construction reports and geologic logs. Data density varies across the county, with fewer data points in the rural portions of the county and more data points in urban areas. Map accuracy increases in areas of higher data density.

The water table in Dane County is highest (over 1000 ft above sea level) in the western part of the county near Mt Horeb and Blue Mounds, and is lowest (less than 840 ft) along the Yahara River in the southeast. In general the water table is a subdued reflection of the county's topography. Local perched groundwater conditions occur along several of the higher topographic ridges west of Madison. In some shallow water wells in these areas water levels stand up to 100 ft above the regional water table. Local aquitards in the upper Paleozoic aquifer probably cause these perched conditions, but the available data are too sparse to delineate areas where the perched conditions occur.

Groundwater divides

Several groundwater divides cross Dane County and separate shallow groundwater into basins analogous to surface-water basins (plate 1). Shallow groundwater moves radially away from groundwater divides. The groundwater divide between the Upper Black Earth Creek/Wisconsin River Basin and the Yahara Lakes Basin was primarily determined from shallow piezometer data obtained from DNR monitoring records (HydroSearch, 1991) and two additional piezometers installed by WGNHS. The remaining groundwater divides separating the Black Earth Creek Basin from the Sugar River Basin, and the Koshkonong River Basin from the Yahara Lakes, were determined using water levels in domestic wells.

Groundwater and surface water divides in Dane County are not wholly coincident. Figure 8 superimposes the two types of divides, and shows that the divides differ significantly in several areas, notably between Madison and Verona and just west of Middleton. In these areas, groundwater passes beneath surface topographic divides. For example, just east of Verona surface water drains to the southwest toward the Sugar River while groundwater moves southeast, toward the Yahara River. West of Middleton, surface water drains south toward the Sugar River, but groundwater moves north toward Black Earth Creek. Cline (1965) also noticed these non-coincident divides.

Shallow groundwater movement

Shallow groundwater in Dane County moves generally perpendicular to the lines of equal water table elevation (plate 1). Shallow groundwater movement occurs within the major groundwater basins described above, and groundwater does not cross the groundwater divides. Near major lakes, streams, and wetlands shallow groundwater flows toward the surface water bodies.

Deep groundwater flow

Configuration of the potentiometric surface

The potentiometric surface of the Mount Simon aquifer (fig.9) is based on water-level measurements in deep wells cased through, or nearly through, the shaley facies of the Eau Claire Formation. This map reflects the composite hydraulic head, averaged over the thickness of the aquifer, as measured between 1992 and 1994. The majority of available data (points indicated on map) are from wells near the Madison metropolitan area. Few deep wells exist in rural areas of the county, and deep hydraulic heads over much of the county are therefore poorly known.

The elevation of the potentiometric surface ranges from about 800 feet above sea level in central Madison to over 900 ft near Verona and in western Dane County near Blue Mounds. A significant low in the potentiometric surface beneath Madison results from long-term pumping of municipal wells. In this area the potentiometric surface has been lowered until it is below the level of the Yahara lakes.

Three significant potentiometric divides in Dane County roughly reflect surface topography but are only generally mapped due to the scarcity of deep data points. The positions of these divides are similar to positions delineated by Cline (1965), but are not directly comparable because Cline used a different set of wells and did not distinguish wells open to the Mount Simon Fm from wells open to shallower formations. A divide west of Madison separates the Yahara basin from the western Wisconsin River basin, while a divide extending west near Verona separates the Wisconsin River basin from the Pecatonica and Sugar River basins. A third regional divide east of Madison separates the Yahara basin from the Koshkonong/Rock River basin to the east.

The subdued reflection of surface topography in the deep potentiometric surface is evidence of good hydraulic connection through all aquifer units in Dane County. The configuration of the potentiometric surface is a reflection of shallow groundwater recharge and discharge relationships combined with the effects of deep pumping.

Deep groundwater movement

Groundwater in the Mount Simon aquifer moves horizontally in directions approximately perpendicular to the equipotential lines in figure 9. For example, groundwater originating in the potentiometric high west of Middleton can move west from the divide toward the Wisconsin River, while groundwater originating just east of the divide can move east to discharge to the Yahara lakes or be captured by pumping wells. Groundwater does not cross the potentiometric divides. In the Madison area a significant amount of groundwater flows into the central cone of depression where it is captured by pumping wells. South of Madison groundwater moves to the southeast along the trend of the Yahara River valley.

Vertical groundwater movement

Hydrogeologic cross sections

Shallow and deep groundwater systems are well connected in Dane County. Figure 10 shows hydrogeologic cross sections from west to east and from north to south across the county through the central isthmus in the center of Madison. The cross sections show scaled profiles of the land surface, major aquifer units, and the water table and potentiometric surface. Equipotential lines on the sections are based on the calibrated regional groundwater flow model (Krohelski and others, 1999). These sections do not follow single groundwater flow lines and so they do not represent quantitative flow nets because groundwater flow can occur into or out of the plane of the sections. Instead, vector arrows on the sections show the general vertical and horizontal components of groundwater movement.

The relative positions of the water table and potentiometric surface on the cross sections illustrate the presence of upward or downward hydraulic gradients across Dane County. Where the water table is higher than the potentiometric surface groundwater moves downward from the upper aquifers to the lower Mount Simon aquifer. This situation occurs near Pine Bluff , toward the west side of figure 10A. In this area the total hydraulic head indicated by the equipotential lines decreases downward from about 930 ft at the water table to about 920 ft in the Mount Simon aquifer. Groundwater in this area moves downward and both east and west from the potentiometric high. Just to the east of Pine Bluff the section shows the vertical expression of the groundwater divide between the Yahara and Wisconsin River basins.

The potentiometric surface is also below the water table in the central portion of both cross sections in figure 10. A major cone of depression exists in the Madison area as a result of groundwater pumping. As a result, groundwater moves downward in the isthmus area near the state capitol and lakes Mendota and Monona. Much of the downward-moving water in this area is eventually discharged to wells.

Groundwater discharge occurs in areas where the potentiometric surface is above the water table and hydraulic gradients are upward. Figure 10A shows a strong upward gradient near Elvers Creek, toward the west side of the section. Here, the potentiometric surface is significantly higher than the water table, and hydraulic heads decrease from about 880 ft in the Mount Simon aquifer to less than 860 ft near the water table.

While the upward and downward components of groundwater flow in Dane County are very important, most groundwater flow in the county is near horizontal and perpendicular to the equipotential lines shown on figure 10. The 33:1 vertical exaggeration on these sections makes the vertical component of flow appear to be more pronounced than it is in the field. Most equipotential lines are nearly vertical, with the major horizontal inflection occurring where they cross the Eau Claire aquitard. Note that where the aquitard is thin or absent, as it is on the eastern side of Dane County near Deerfield, the equipotential lines are almost vertical.

Areas of recharge and discharge for the Mount Simon aquifer

Superposition of the elevation of the water table (plate 1) with the configuration of the potentiometric surface of the Mount Simon aquifer (fig. 9) provides a general map of areas of recharge and discharge to the Mount Simon aquifer. Where the water table is higher than the potentiometric surface the vertical hydraulic gradient is downward, and groundwater moves downward to recharge the Mount Simon. Where the potentiometric surface is above the water table the vertical gradient is upward, and groundwater moves upward from the Mount Simon into overlying units. The presence or absence of the Eau Claire aquitard and the hydraulic properties of the shallow Paleozoic rocks largely control the rate of vertical movement.

Figure 11 shows approximate areas of recharge to and discharge from the Mount Simon aquifer based on the available field data. Figure 11A shows areas of recharge to the Mount Simon. Recharge potentially occurs over broad topographically higher areas of Dane County. An exception is the Madison area, recharge is currently occurring beneath large portions of Lakes Mendota, Monona and the downtown isthmus. This is a reversal of the natural flow direction, which was historically upward prior to drawdown due to pumping.

Areas of discharge from the Mount Simon aquifer (fig.11B) are not as extensive as recharge areas and tend to be concentrated along lowlands, lakes and wetlands. The flow of springs, stream baseflow, and wetland seepage in these areas originates in part from deep regional groundwater flow.

Springs

Numerous springs occur in Dane County and serve as natural points of groundwater discharge. A spring survey completed in the 1950's (Wisconsin Conservation District, 1959) identified 229 springs in the county (fig.12). The discharges of these springs measured in the 1950's ranged from negligible to over 2000 gallons per minute (gpm), with an average flow of 50 gpm and total flow from all mapped springs of over 9000 gpm. The largest springs occur at low topographic elevations near major surface water bodies and probably discharge groundwater from regional groundwater flow systems. Many small springs occur at higher elevations, particularly in the driftless part of Dane County, and probably receive local flow from various units in the upper Paleozoic aquifer. Certainly many more springs occur in the county than have been mapped in spring surveys or shown on figure 12.

Recently, additional studies on springs in the county have emphasized their importance to surface-water resources and their connection to groundwater flow systems. Potter and others (1995) and Amann (1993) investigated springs in the Garfoot Creek basin west of Cross Plains and located six springs in the basin. They concluded that the major source of perennial flow in Garfoot Creek is spring discharge, and that a single spring in the basin contributes over 20 percent of all the surface water flow in Garfoot Creek measured at the foot of the basin (Potter and others, 1995). Isotopic data and discharge data from this spring suggest that it captures flow from an area larger than the topographic basin of Garfoot Creek, and imply a good connection between shallow and deep groundwater movement. Springs in the Token Creek basin, northwest of Madison, discharge over 3400 gpm and sustain flow in Token Creek (WRM, 1997).

Groundwater pumping has adversely affected some springs in Dane County. As part of this study, several springs in the Madison area were investigated in order to document relationships between pumping of deep municipal wells and reductions in spring flows and water levels. The pumping of Madison well 14 (715 ft deep; cased to 117 ft) influences the level of Merrill spring, located on the southwest shore of Lake Mendota. In addition, there is a direct correlation between the pumping of Madison City well 1 (since abandoned) and shallow groundwater levels near Council Ring springs, located on the western shore of the UW-Madison Arboretum.

Groundwater-Surface Water Interactions

Measurements of stream bed leakance

There is generally a good hydraulic connection between surface water features in Dane County are the groundwater system. We conducted field measurements of stream bed leakance (vertical hydraulic conductivity of stream bed materials divided by their thickness) at 12 sites on major streams in Dane County (fig.13). Leakance was calculated along stream reaches ranging from 600 to 1300 ft in length. We measured surface water discharge at the upstream and downstream ends of each reach using a current meter, and measured vertical hydraulic gradients using minipiezometers.

Estimated values of streambed leakance ranged from 1.1 to 25.5 ft/d/ft, with an average of 8.5 ft/day/ft (table 5). At six of the twelve sites the measurement error in streamflow was judged to be too large to allow leakance estimates. Based on minipiezometer measurements, four of the twelve reaches are losing water to the groundwater system while the remainder are gaining from groundwater.

Table **5**. Results of stream bed leakance survey.

Stream	Station	Map symbol	General sediment characterization	vertical flux direction	Estimated Leakance* (ft/d/ft)
Black Earth Creek	1	BEC1	sand and gravel	gaining	3.5
Black Earth Creek	2	BEC2	sand w/some gravel	losing	1.1
Pheasant Branch	1	PB1	silty sand	gaining	--
Pheasant Branch	2	PB2	silty sand	gaining	--
Koshkonong Creek	1	KC1	fine sand	losing	25.5
Koshkonong Creek	2	KC2	sandy silt	gaining	--
Upper Yahara R.	1	UY1	silt w/organics	gaining	--
Upper Yahara R.	2	UY2	silt	losing	8.3
Sixmile Creek	1	SC1	sandy silt	gaining	--
Sixmile Creek	2	SC2	silt	gaining	6.8
Garfoot Creek	1	GC1	sandy silt w/organics	losing	5.6
Sugar River	1	SR	silt w/organics	gaining	--
* – indicates measurement error too large to provide meaningful estimates					
				Mnimum	1.1
				Maximum	25.5
				Mean	8.5

Lake gradient survey

Downward leakage of surface water to groundwater occurs along much of the shoreline of Lakes Mendota and Monona. Temporary piezometers were installed several feet into lake sediment at 17 locations around the perimeter of these lakes during the summer of 1995 to measure the vertical hydraulic gradient through the shallow sediments beneath the lake (table 6; fig.13). At 11 of the 17 sites the gradients were downward, indicating that the lakes were losing water to the groundwater system. The six sites with upward gradients are on the north and northwest shore of Lake Mendota, and on the south shore of Lake Monona, while all piezometers near the Madison isthmus showed downward flow.

Results of the regional groundwater model (Krohelski and others, 1999) are consistent with the lake gradient survey. Figure 13 includes model-determined groundwater/surface water flux directions at major surface water features simulated in the model. Solid triangles indicate that the model predicts upward flow, from groundwater to surface water. Open triangles indicate downward flow, from surface water to groundwater. Over most of Dane County, the model predicts that surface water features should gain water from the groundwater system. However, the model predicts downward flow over much of lakes Mendota, Monona, and the Madison isthmus. The model and the field measurements are also generally consistent with the mapped areas of recharge and discharge to the Mount Simon aquifer shown in figure 11.

Table 6. Gradient measurements along the shore of Lakes Mendota and Monona, measured in July, 1995.

Location	Avg gradient*	direction	Sediment Type
Lake Mendota			
Lake Shore Beach	0.14	down	sand
Spring Harbor	0.21	down	silt w/organics
Marshall Park	0.05	down	sand
Mendota County Park	0.31	up	sandy silt
Governor Nelson State Park	0.08	up	sandy silt
Warner Park	0.08	up	sand
Maple Bluff Park	0.02	down	silty sand
Tenney Park	0.01	down	sand
Kappa Sigma Fraternity (off Langdon)	0.12	down	silt
Lake Monona			
Olin Park	0.02	down	sand
Law Park (Williamson St)	0.18	down	silt
Clarke Park	0.10	down	silty sand
Yahara Place Park	0.06	down	sandy silt
Olbrich Park	0.02	down	sand
Tonyawatha boat ramp	0.03	up	sandy silt
Oneida Park	0.07	up	sandy silt
Esther Beach Park	0.03	up	silty sand

*each gradient represents an average of two measurement at the site

Source differentiation using environmental isotopes

The isotopic composition of groundwater and surface water in Dane County helps distinguish sources of water to wells and springs. Within a relatively small geographic area, such as Dane County, the ^{18}O:^{2}H ratio can help distinguish groundwater from surface water. Groundwater originating as recharge on the land surface should have an isotopic composition similar to the composition of modern precipitation. This precipitation, in turn, should have a composition close to that predicted by the meteoric water line, a worldwide statistical relationship between ^{18}O and ^{2}H (Freeze and Cherry, 1979).

Isotopic composition of groundwater in Dane County should fall on or close to the meteoric water line. In contrast, the isotopic composition of surface water should fall to the right of the meteoric water line, because evaporation from lakes and wetlands fractionates the water by removing the lighter isotopes. Therefore, examining the isotopic composition of water produced by a well can help indicate whether the well is capturing a significant amount of surface water.

Figure 14 is a plot of the ^{18}O:^{2}H relationship for various wells, springs, and surface water bodies sampled in Dane County (see table 7). The figure also shows the worldwide meteoric water line. Notice that, as expected, all water in Dane County is isotopically lighter than ocean water, and that the majority of samples from wells and springs plot on or near the meteoric water line.

Samples of surface water deviate, as expected, from the meteoric water line. Samples from lakes Mendota, Wingra, and Monona plot to the right of the line. A sample from the Yahara River just north of Lake Mendota plots almost exactly on the meteoric water line, suggesting that the baseflow of the Yahara River is composed almost entirely of groundwater. Fractionation of isotopes occurs in order of lakes down the Yahara chain. Lake Mendota is the least fractionated, followed by Lake Wingra and Lake Monona.

The isotopic relationships suggest that at least one of the public supply wells sampled is producing water partially derived from surface water. The isotopic composition of a sample from Madison Unit well #3 (DN-50) plots to the right of the meteoric water line, on a line with the composition of Lake Mendota. This suggests that well 3 produces water derived in part from leakage out of the lake. Unit well 3 is located on the northeast side of the Madison isthmus, about 2000 feet from Lake Mendota. Based on the regional groundwater model (Krohelski and others, 1999) the zone of contribution for this well intersects that lake, and the well has one of shortest travel times of all wells studied in Dane County, ranging from 4 to about 150 years. Other wells sampled do not show this relationship, but the technique has promise for documenting the production of surface water by other wells located near lakes in Dane County.

Age of groundwater produced by wells and springs

Groundwater produced by wells in Dane County ranges in age from less than five years to over 3,000 years, where age refers to the length of time the water remains in the groundwater flow system. Both numerical particle tracking and tritium isotopes provide estimates of groundwater age. Tritium has long been used to estimate the relative age of groundwater (Bradbury, 1991; Henry, 1988).

Water samples from 29 sites in Dane County were tested for tritium content (table 7). Tritium contents ranged from 0.8 TU to 25.2 TU. Based on these results, samples from four sites contained groundwater older than about 35 years. These sites include a bedrock test well located in the headwaters of Garfoot Creek, municipal wells Middleton #4 and Madison #23, and a shallow monitoring well located in clayey sediments near the Truax landfill. Most other sites, including the Yahara lakes and three springs, contained water interpreted to be of recent age, here defined as less than ten years old. However, these sites probably produce water that is a mixture of old (long flow path) and younger (shorter flow path) water, and the tritium results are therefore indeterminate.

Model estimates of groundwater age are based on the time required for a hypothetical particle of water to travel from a recharge area to the top or bottom of the open interval of a well. In general, groundwater flow paths, and thus ages, are shorter for the upper end of the open interval than for the lower end of the interval. Table 7 shows these model-predicted ages. Individual wells can collect water of vastly different ages depending on the depth of the open interval. For example, Madison well #7 collects water having modeled ages of 70 years at the top of the open interval and 3700 years at the bottom of the open interval.

Table **7**. Isotopic data from groundwater and surface water in Dane Co. Shading indicates tritium contents consistent with water older than about 35 years. Empty boxes represent no sample or no estimate possible.

sample location	*sample ID*	*Sample date*	*open interval, ft below land surface*	*O18, permil SMOW*	*deuterium, permil SMOW*	*tritium, T.U.*	*tritium error, +/- T.U.*	*estimated tritium age (yrs)*	*model - predicted age (yrs)*
DEEP WELLS									
Garfoot Creek test well (deep)		*12/14/93*	*--*	*-8.58*	*--*	*0.8*	*0.5*	*>35*	
Garfoot Creek test well		*12/14/93*	*--*	*-9.22*	*--*	*12.9*	*1*	*recent*	
Madison Unit #3	*MD-3*	*07/12/95*	*148-753*	*-7.76*	*-54.25*	*14.4*	*1.1*	*recent*	*5-150*
Madison Unit #7	*MD-7*	*06/27/95*	*237-737*	*-8.35*	*-54.63*	*19.6*	*1.5*	*recent*	*70-3700*
Middleton Unit #4	*MT-4*	*06/26/95*		*-8.81*	*-57.63*	*0.8*	*0.5*	*>35*	*54-2900*
Middleton Unit #5	*MT-5*	*06/26/95*	*240-809*	*-8.85*	*-57.99*	*29.8*	*2.1*	*>10*	*135-3500*
Madison Unit #14	*MD-14*	*06/27/95*	*117-715*	*-9.04*	*-58.36*	*21.1*	*1.7*	*>10*	*40-2100*
Madison Unit #15	*MD-15*	*06/27/95*	*172-753*	*-8.58*	*-57.27*	*12.5*	*1.1*	*recent*	*36-2000*
Madison Unit #16	*MD-16*	*11/08/93*		*-8.77*	*--*	*5.2*	*0.6*	*>10*	*87-2699*
Madison Unit #17	*MD-17*	*01/15/94*		*--*	*--*	*12.2*	*0.9*	*recent*	*3-2230*
Madison Unit #23	*MD-23*	*06/28/95*	*104-500*	*-8.51*	*-57.06*	*1.5*	*0.6*	*>35*	*11-1400*
Springfield Corners test well		*10/19/93*	*258-342*	*-8.64*	*--*	*6.6*	*0.6*	*>10*	
Springfield Corners test well		*10/19/93*	*376-end*	*--*	*--*	*17.2*	*1.2*	*recent*	
Springfield Corners test well		*10/19/93*	*0-251*	*-8.39*	*--*	*18.1*	*1.2*	*recent*	
SunPrairie Well #5	*SP-5*	*06/27/95*	*645-884*	*-8.54*	*-57.70*	*3.8*	*0.7*	*>10*	*50-2000*
SHALLOW WELLS									
Truax Landfill - MW-5B	*MW-5B*	*07/13/95*		*-8.68*	*-56.62*	*20.8*	*1.5*	*>5*	*470-600*
Nevin Fish Hatchery - deep	*FH-well*	*06/27/95*		*-9.11*	*-59.44*	*13.6*	*1.2*	*recent*	*50-130*
Truax Landfill - MW-13	*MW-13*	*07/11/95*	*56-67*	*-8.97*	*-57.90*	*17.1*	*1.3*	*recent*	*4-8*
Truax Landfill - MW-13A	*MW-13A*	*07/11/95*	*144-149*	*-8.73*	*-57.50*	*20.0*	*1.5*	*recent*	*39-41*
Truax Landfill - MW-5	*MW-5*	*07/11/95*	*88-18*	*-11.28*	*-79.15*	*12.9*	*1.1*	*recent*	*3-10*
Truax Landfill - MW-5A	*MW-5A*	*07/11/95*	*171-176*	*-8.72*	*-56.53*	*1.1*	*0.5*	*>35*	*150-200*
First St Garage	*MW-6B*		*6-16*	*-8.74*	*-58.19*	*12.1*	*1*	*recent*	
First St Garage	*MW-6B*		*41-36*	*-8.51*	*-56.59*	*25.2*	*1.9*	*>10*	
SPRINGS									
Nevin Fish Hatchery-spring	*FH-spring*	*06/27/95*	*--*	*-9.36*	*-59.60*	*22.2*	*1.7*	*>10*	*1-8*
Wingra Spring	*Wingra Spring*	*07/11/95*	*--*	*-9.06*	*-56.42*	*25.0*	*1.8*	*>10*	*30-80*
Badger Mill Creek Spring	*BMC spring*	*07/02/95*	*--*	*-8.93*	*-59.31*	*13.0*	*1*	*recent*	*1-7*
SURFACE WATER									
Clark Beach, Fall	*Lake Monona,Fall*	*11/21/95*	*--*	*-5.58*	*-44.43*				
Warner Park, Fall	*Lake Mendota,*	*11/21/95*	*--*	*-5.99*	*-45.02*				
Yahara River	*Yahara River*	*11/21/95*	*--*	*-9.39*	*-60.67*				
Lake Mendota	*Lake Mendota*	*06/26/95*	*--*	*-6.29*	*-47.05*	*11.4*	*0.9*	*recent*	
Lake Monona	*Lake Monona*	*06/26/95*	*--*	*-5.52*	*-44.18*	*15.1*	*1.3*	*recent*	
Lake Wingra	*Lake Wingra*	*06/26/95*	*--*	*-5.77*	*-43.52*	*13.7*	*1.1*	*recent*	

Groundwater Use

Distribution of pumping

Groundwater is the source for all drinking water supplies and most industrial and agricultural water supplies in Dane County, with public water supplies accounting for about 73 percent of the total. In 1992, total groundwater use by public supply wells was about 51 million gallons per day (MGD), and the City of Madison was the largest single consumer (DCRPC, 1999). Historically, groundwater use increased rapidly from the 1940s to about 1970. Since 1970, increases in groundwater use have been less dramatic, probably as a result of increased conservation efforts. Under current projections, municipal and industrial groundwater use will increase to about 55 MGD by 2020 (DCRPC, 1999). These withdrawals are from high-capacity wells completed primarily in the Mount Simon aquifer. Such wells are generally clustered near the Madison metropolitan area, with additional wells in outlying communities. Additional groundwater is used by the approximately 21,000 rural domestic supply wells serving over 55,000 people outside of the urban service areas. These rural domestic wells are generally only a few hundred feet deep and are finished in the upper Paleozoic aquifer.

Effects of groundwater use

Groundwater withdrawals from municipal wells have significantly affected groundwater levels in the Madison metropolitan area. Using the regional groundwater flow model, Krohelski and others (1999) showed that the water table and potentiometric surfaces in the vicinity of Madison have declined more than 60 ft from pre-development conditions, and that a significant cone of depression exists beneath much of Madison. The lakes and wetlands within the cones of depression were largely groundwater discharge areas under pre-development conditions, but are now areas of groundwater recharge. These lakes and wetlands receive less water under current pumping conditions than they did in pre-development times. The model also suggests that deep aquifer pumping has reduced baseflows in streams near Madison.

Municipal well zones of contribution

Delineation of areal zones of contribution for municipal wells in Dane County illustrates horizontal groundwater movement to these wells. Bradbury and others (1997) used the regional groundwater flow model to delineate zones of contribution for high-capacity wells in Dane County. The zone of contribution (ZOC) of a well is the land surface area where recharging precipitation enters a groundwater system and eventually flows to the well (fig.15). Delineating the zones of contribution for municipal wells is a critical step in establishing wellhead protection areas for the wells.

The particle tracking code PATH3D (Zheng, 1991) was used to model the ZOC for each pumping well by tracking imaginary particles backwards from the well location up-gradient to points where they enter the groundwater flow system. The possible points of entry represented in the regional groundwater flow model are the water table (i.e. recharge from the ground surface through the unsaturated zone) and surface water bodies, such as rivers and lakes. The velocity of the particles depends on the gradient in head, the hydraulic conductivity, and the porosity of the aquifer materials. PATH3D uses the head distribution, grid spacing and porosity values to calculate particle velocity vectors (velocity and direction of movement).

The composite map of particle traces for all municipal wells in Dane County (fig 16) illustrates the complexity of the groundwater flow systems in the county. Each trace line represents the three-dimensional path of a single hypothetical "particle" of water from the water table to a particular well. The collection of particle pathlines for each well outlines the steady-state zone of contribution for that well. In figure 16, these three-dimensional traces are projected onto a two-dimensional map, resulting in some apparent angular refractions of the particle tracks where the particles are moving vertically from one model layer to the next. All traces on figure 16 are *steady-state* particle paths, meaning that these are the paths that groundwater would take assuming that the groundwater system is steady (i.e. recharge is constant, pumping rates and water levels are unchanging) for an infinitely long period of time. Therefore, the length of a particular pathline is not necessarily related to the velocity of the particle, although in general the longer paths are associated with longer travel times. Steady-state travel times for many wells from recharge to entry into the well are on the order of several thousand years.

The collection of particle paths illustrates that the source for groundwater produced by municipal wells in Dane County is local, and for almost every well the steady-state zone of contribution lies entirely within the county itself. It also shows that much of the recharge for the City of Madison wells (the largest municipality in Dane County) originates within or very near the Madison city limits.

Wells located near the Yahara Lakes may be deriving significant quantities of water from downward leakage from the lakes themselves. Based on the regional groundwater model, City of Madison wells located near the Yahara lakes could draw roughly 25 percent of their water from downward leakage out of the lakes. Any particle path on figure 16 which terminates in a lake or wetland indicates that lake is supplying some water to the well.

The particle paths also illustrate significant hydraulic interference between wells, particularly in the Madison metropolitan area, that results in complex zones of contribution. There are frequently differences in groundwater flow direction between the shallow Paleozoic aquifer and the deeper Mount Simon aquifer, as illustrated by wells having particle paths radiating in two different directions. These wells are usually open to both the shallow Paleozoic dolomite and sandstones (model layer 2) and deeper Mount Simon Sandstone (model layer 3), and produce water from both units.

Groundwater Protection

Aquifer Susceptibility

As part of the Dane County Regional Hydrologic Study, Fritz (1996) constructed and tested an aquifer contamination susceptibility map for Dane County (Plate 2). This map rates the relative susceptibility (extreme, high, moderate, low) of shallow aquifers to contamination from surface sources. The map illustrates the combined effects of soil properties, the hydrogeologic setting, and the distribution of groundwater recharge and discharge areas in limiting the downward movement of contaminants from the land surface.

Fritz (1996) used the soil contaminant attenuation method (SCAM3) (Bridson and others, 1994) for evaluating soil properties The method is a simple rating system that evaluates the soil properties considered to be the most important in attenuation and degradation of contaminants. These properties include texture of the surface and subsurface horizons, pH, depth of solum, soil drainage, subsoil permeability, and organic matter content. Based on these properties, Fritz assigned each soil type in Dane County to one of three attenuation categories- good, fair, or poor.

Fritz's (1996) hydrogeologic setting classification is a combination of depth to bedrock, depth to the water table, and presence of an unlithified aquifer (Unlithified aquifer types are shown on Plate 1). The hydrogeologic setting categories are based on the thickness of the unsaturated zone and presence of an unlithified aquifer and range from 1 (most susceptible) to 4 (least susceptible).

The final data layer included in the susceptibility map is the distribution of recharge and discharge areas based on the work of Swanson (1996). Areas of groundwater recharge are more susceptible to contamination than areas of groundwater discharge.

The susceptibility map (plate 2) shows a wide range of groundwater contamination susceptibility across the county. In general, areas of shallow bedrock or shallow groundwater are most susceptible, including large parts of the driftless area of western Dane County. Moraine areas just west of Madison consist of relatively thick till and deep water table; these areas are less susceptible to contamination. In other areas of the county the contamination susceptibility varies spatially over small distances as local conditions vary. The final map is used best as an educational and regional planning tool to show the relative risk of groundwater contamination throughout the county.

Wellhead protection

Delineating the zones of contribution for municipal wells is a critical step in establishing wellhead protection areas for the wells. A wellhead protection area (WHPA) is defined by the federal Safe Drinking Water Act as the "surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water or well field ." In practical terms, the ZOC is a technically-defined area based on groundwater hydraulics, while the WHPA is a legally-defined area including all or part of the ZOC and within which zoning practices or other land-use controls can be implemented to help protect groundwater from contamination.

The Wisconsin Department of Natural Resources (WDNR) has the responsibility and authority to delineate wellhead protection areas for all public water supplies in Wisconsin (WDNR, 1992). In 1992, the WDNR prepared the Wisconsin Wellhead Protection Program Plan (WDNR, 1992), which required the DNR to perform initial ZOC delineations for all existing municipal wells in the State. At the same time, the Wisconsin Administrative Code, Chapter NR811, was revised to require that a wellhead protection program plan be submitted for each new municipal well constructed in Wisconsin after April 1, 1992.

Time-constrained ZOC boundaries are more useful for wellhead protection planning than the steady-state zones of contribution shown on figure 16. Figure 17 shows 5-, 50-, and 100-year zones of contribution for five municipal wells near Middleton. These zones of contribution result from truncating the pathlines shown on Plate 2 at the three different travel times. Such boundaries should be more useful for WHPA delineation in real human terms. For each of these wells, the ZOC is best viewed in a three-dimensional sense as an ellipse with a cross-section represented by the shaded area of the ZOC and extending from the water table to the bottom of the deep sandstone aquifer. It is interesting to note that many of the time-constrained ZOCs are rather small, and that even the travel paths for the 100-year flow boundaries are only on the order of one or two miles long.

Summary

Suggestions for future work

This study has identified several areas in which additional data collection or analyses would benefit water-resources management in Dane County. The most important suggestions for future work are as follows.

The current understanding of the hydrogeology of rock units making up the upper Paleozoic aquifer is inadequate for future groundwater protection and management and needs to be improved. These rock units, which often lie near the land surface, are a major control on groundwater recharge and contaminant movement, yet the hydrogeology of these units has not been evaluated across the county in any systematic way.

There is a need for improved measurements and monitoring of hydraulic head in the Mount Simon aquifer and the upper Paleozoic aquifer. Current measurements of hydraulic head in the deep bedrock aquifers are mostly limited to deeply-cased wells in the Madison area; few measurements are available in rural areas of the county. Accurate potentiometric maps, which can be used for wellhead protection studies and evaluation of regional and local groundwater movement, require better data than are currently available. More accurate delineation of potentiometric divides would be possible with such measurements.

Springs are an important but poorly-understood resource in Dane County. A renewed inventory of the locations and condition of major springs, and delineation of the zones of contribution for these springs are necessary to aid management decisions as development and water use impinge on spring areas.

Regional groundwater management requires a better understanding of the horizontal extent, thickness, and vertical hydraulic properties of the shaley facies of the Eau Claire Formation than currently exists. This aquitard is a major control on the movement of groundwater between shallow and deep bedrock aquifers.

Lakes Mendota and Monona contribute significant water to nearby supply wells through vertical leakage through the lake beds, yet the water quality implications of this leakage are poorly understood. A better understanding of the hydraulic connections between the Yahara lakes and the groundwater system is needed in order to aid groundwater and surface water management decisions in the Madison area.

Groundwater and surface water in Dane County are intimately connected, yet are usually managed independently. Improved models of groundwater/surface water interaction, coupled with more-extensive measurements of base flow in surface streams would contribute to improved management of both resources.

Conclusions

This report summarizes the hydrogeology of Dane County and leads to the following conclusions:

A conceptual model consisting of four hydrogeologic units provides a useful description of the hydrogeology of Dane County at a regional or county-wide scale. These hydrogeologic units consist of groups of stratigraphic units. From top to bottom, they include (1) unlithified aquifers, consisting of sand, gravel, till, lacustrine material, and loess of Quaternary age; (2) an upper Paleozoic aquifer, consisting of sandstones and dolomites of Ordovician and Cambrian age; (3) the shaley facies of the Eau Claire Formation, consisting of shale and siltstone of Cambrian age; and (4) the Mount Simon aquifer, consisting of sandstone of the Eau Claire and Mount Simon Formations, of Cambrian age.

The shaley facies of the Eau Claire Formation forms an important aquitard over much of Dane County, limiting the movement of groundwater between the lower Cambrian sandstones and the upper Paleozoic sandstones and dolomites. This shaley facies is up to 40 ft thick in western Dane County, but thins to the east, and is probably absent in the northeastern parts of the county. Where it occurs, the shaley facies helps limit the movement of water between the upper and lower bedrock units.

A shallow unlithified aquifer, which can yield economically useful quantities of groundwater, occurs near the land surface over parts of central Dane County. The most permeable parts of this aquifer occur in river valleys, such as lower Black Earth Creek, and along the Wisconsin and Yahara Rivers. This aquifer is unconfined in some places and in others is confined by clayey lake sediment.

The shallow water table in Dane County forms several naturally-occurring basins, analogous to but not entirely coincident with surface water basins. There are many places in the county where shallow groundwater can move horizontally beneath topographic divides. The deeper potentiometric surface, representing hydraulic head in the sandstone aquifer, also forms basins roughly, but not exactly, coincident to surface topography.

Surface water, shallow groundwater, and deep groundwater are intimately connected in Dane County. Almost all groundwater in Dane County originates as recharge occurring within the county. Most lakes and streams in the county are discharge points for groundwater.

Groundwater withdrawals by pumping from high-capacity wells in the Madison metropolitan area since the turn of the century have lowered hydraulic heads in the deep sandstone aquifer. These head declines have propagated upward to the surface, resulting in reduced groundwater discharge to lakes, streams, and wetlands in the Madison area. In fact, in the isthmus area of central Madison the historic direction of groundwater flow, from the aquifers to the lakes, has been completely reversed, so that now parts of Lakes Mendota and Monona are losing water to the groundwater system. Wells located near the Yahara lakes draw significant quantities of water from downward leakage out of the lakes.

The two main controls on groundwater recharge in Dane County are topography and soil properties. Recharge is non-uniform across the county, and varies spatially from about 0.2 to 13 in/yr, averaging about 5 in/yr. Recharge usually occurs in the higher parts of the landscape, along the crests and flanks of broad ridges, and along steep wooded slopes. Lower areas of the landscape are more often areas of groundwater discharge.

A three-dimensional numerical groundwater flow model (Krohelski and others, 1999) simulates regional groundwater flow in Dane County with acceptable precision for regional water-resources planning. The model is a powerful tool that can be used to assess groundwater flow patterns, groundwater/surface-water relationships, effects of pumping wells, and zones of contribution for pumping wells.

Almost all groundwater used in Dane County originates within the political boundaries of the county. Steady-state zones of contribution show that some wells produce water originating as recharge up to 10 or 15 miles away, while others produce water originating very near the well. Advective travel times from the water table to the wells range from less than 10 years to several thousand years. Many wells in the Madison area capture water from the Yahara Lakes.

Bounding the steady-state zones of contribution by specific time-of-travel criteria produces time-related zones of contribution which should be useful for wellhead protection planning. For most Dane County wells the 5-year zone of contribution is probably too small - typically less than 1000 ft across- to serve as a useful wellhead protection area. The 50- and 100-year zones of contribution are generally several thousand feet to a mile in length and probably represent more appropriate areas for groundwater protection measures.

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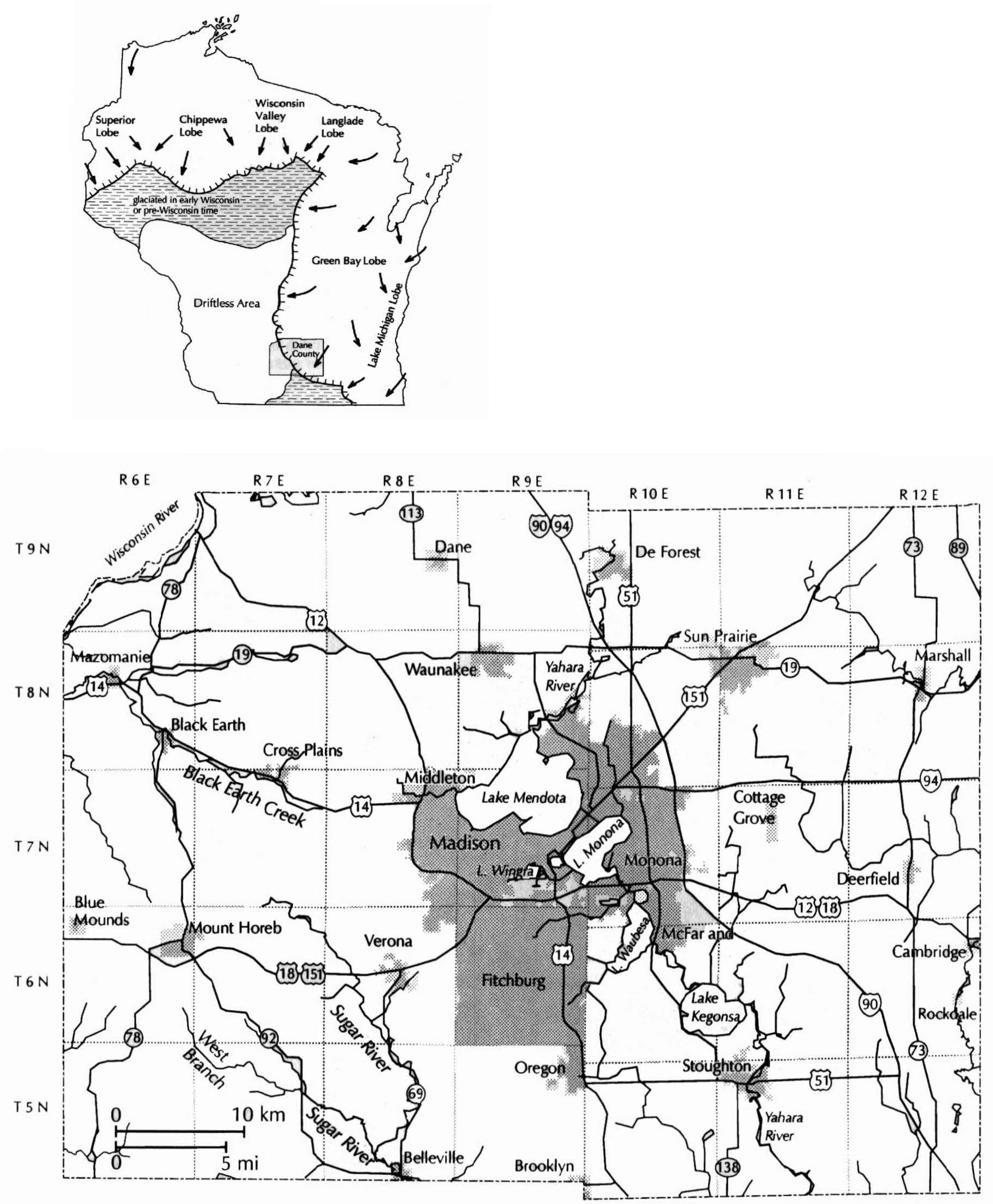


Figure 1. Location of Dane County, Wisconsin.

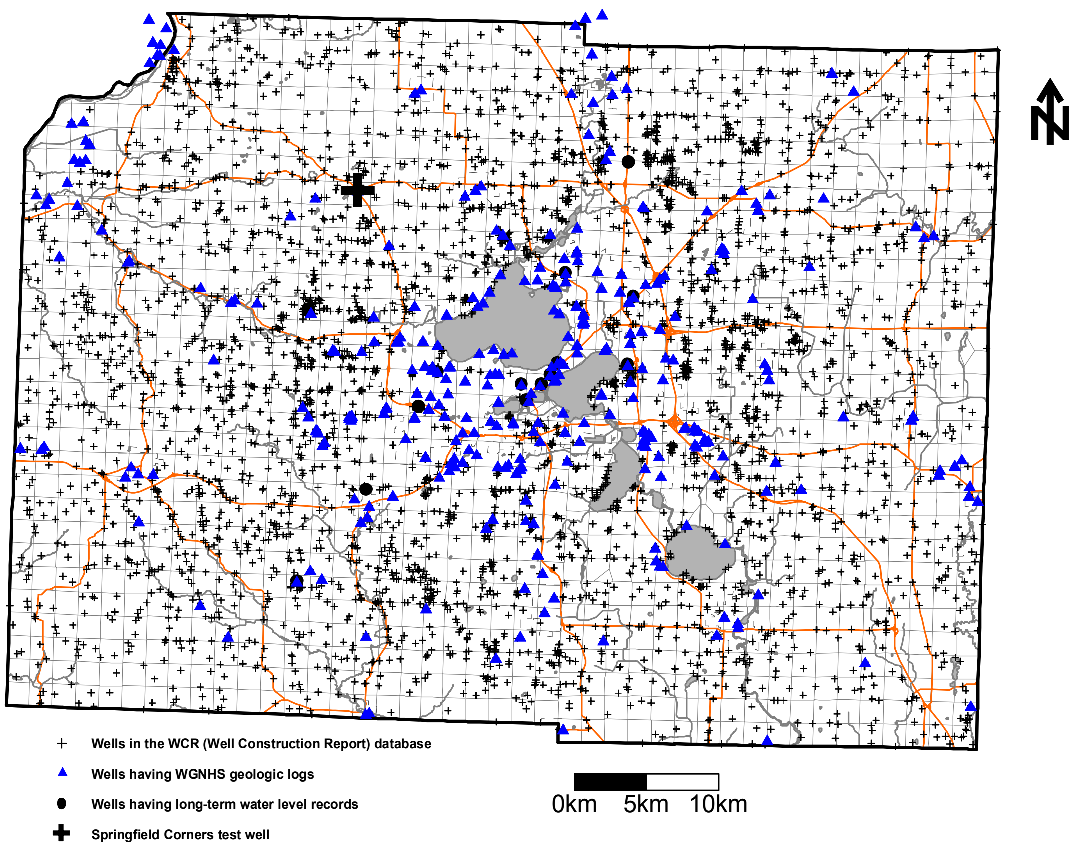


Figure 2. Distribution of well construction reports, geologic logs, and long-term water-level records in Dane County.

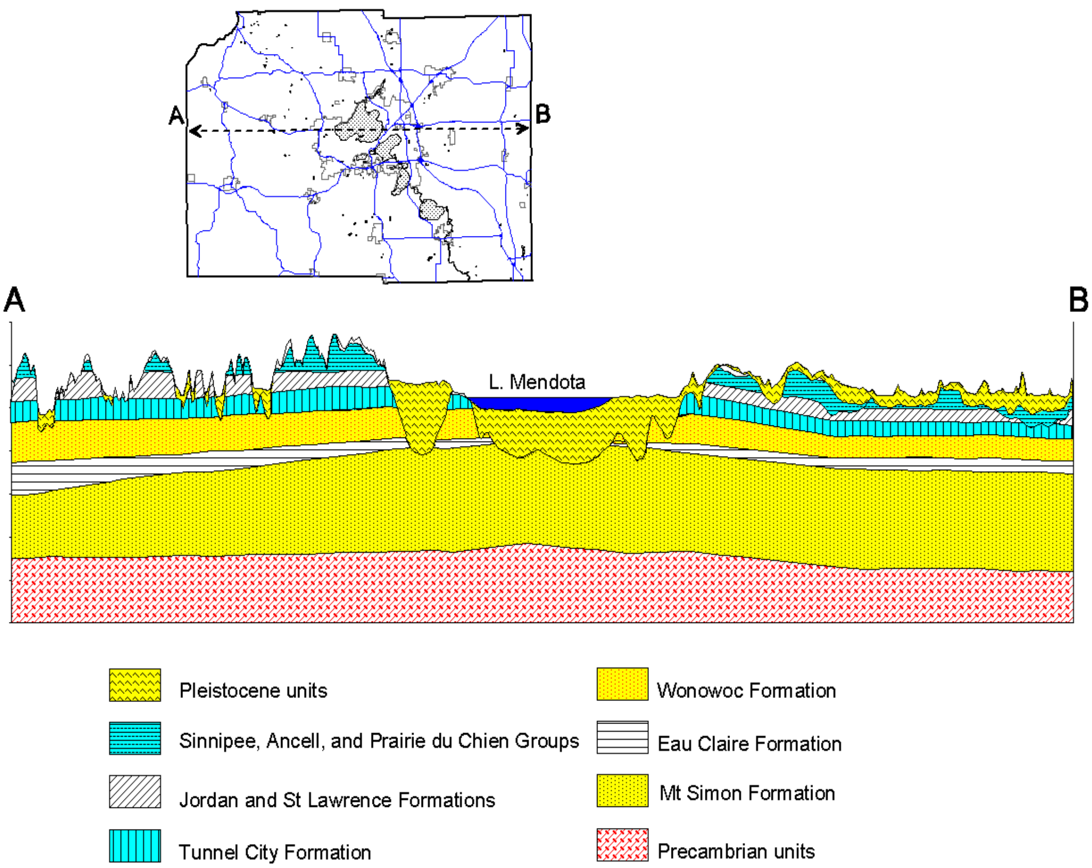


Figure 3. Stratigraphic cross-section across Dane County, showing subsurface stratigraphy (from Massie-Ferch and others, 1997).

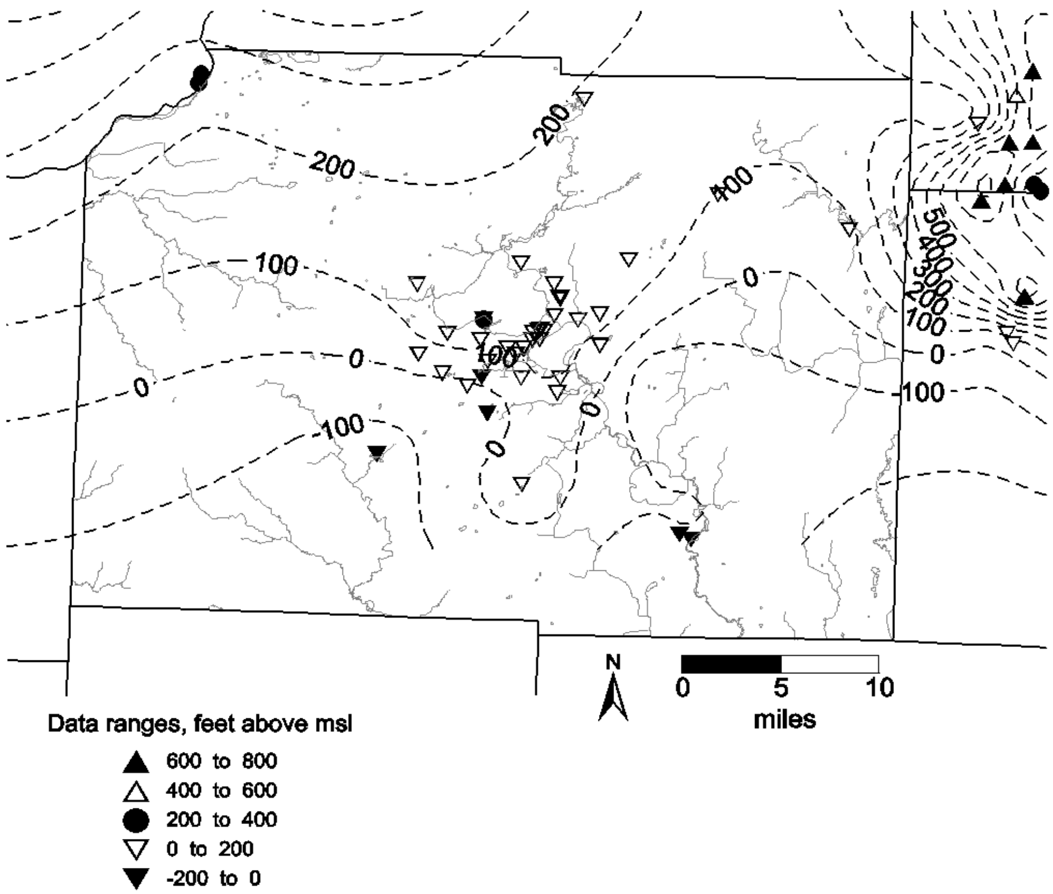


Figure 4. Approximate elevation of the PreCambrian surface.

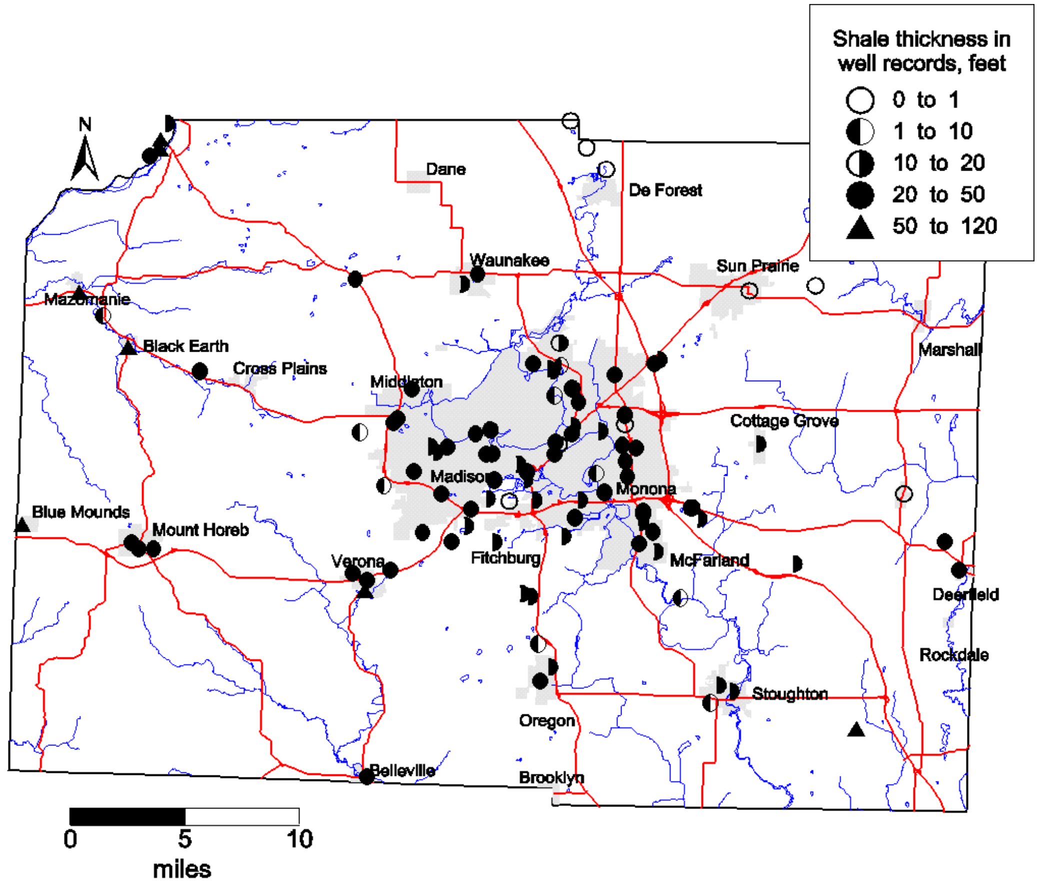


Figure 5. Thickness of the Eau Claire aquitard.

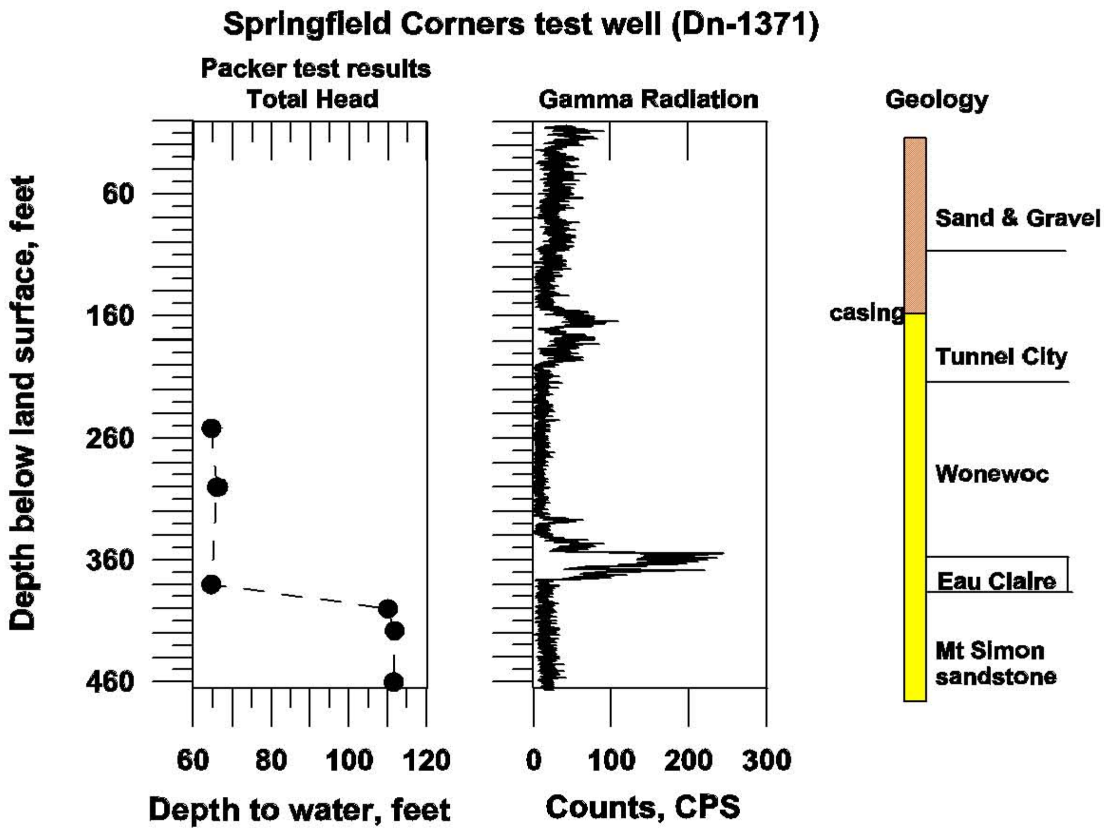


Figure 6. Geologic and geophysical data from well Dn-1371, near Springfield Corners.

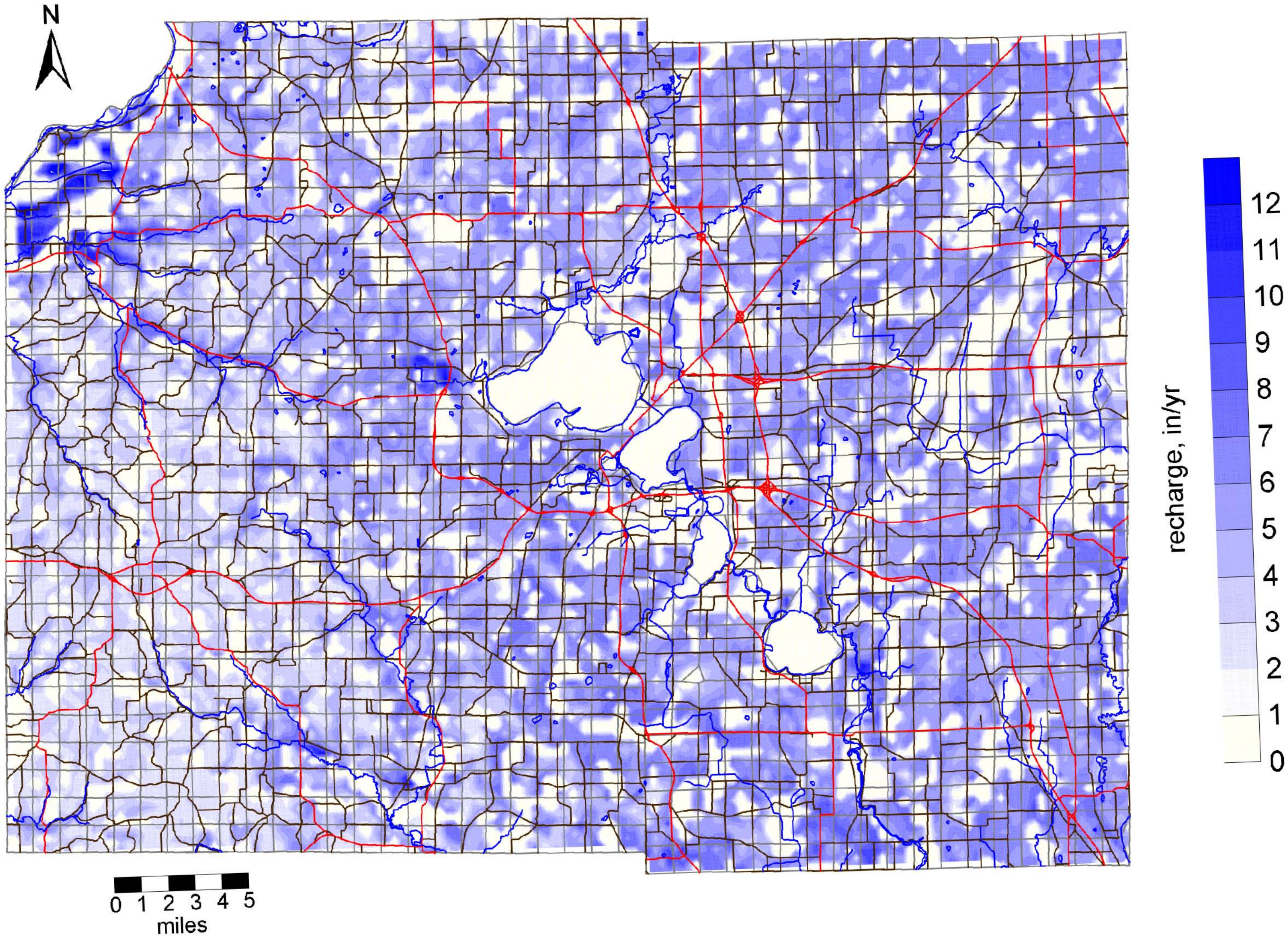


Figure 7. Estimated recharge rates based on the regional groundwater model.

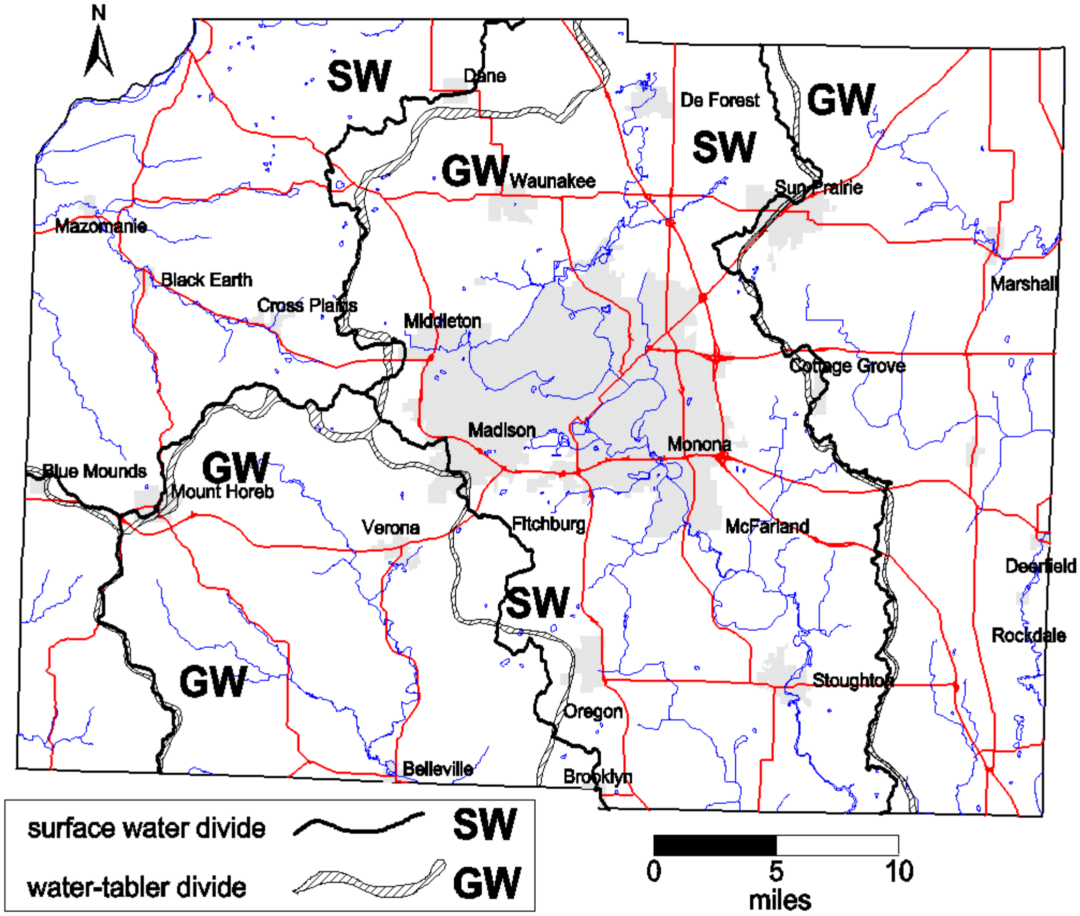


Figure 8. Locations of major groundwater divides (at the water table) and major surface water divides.

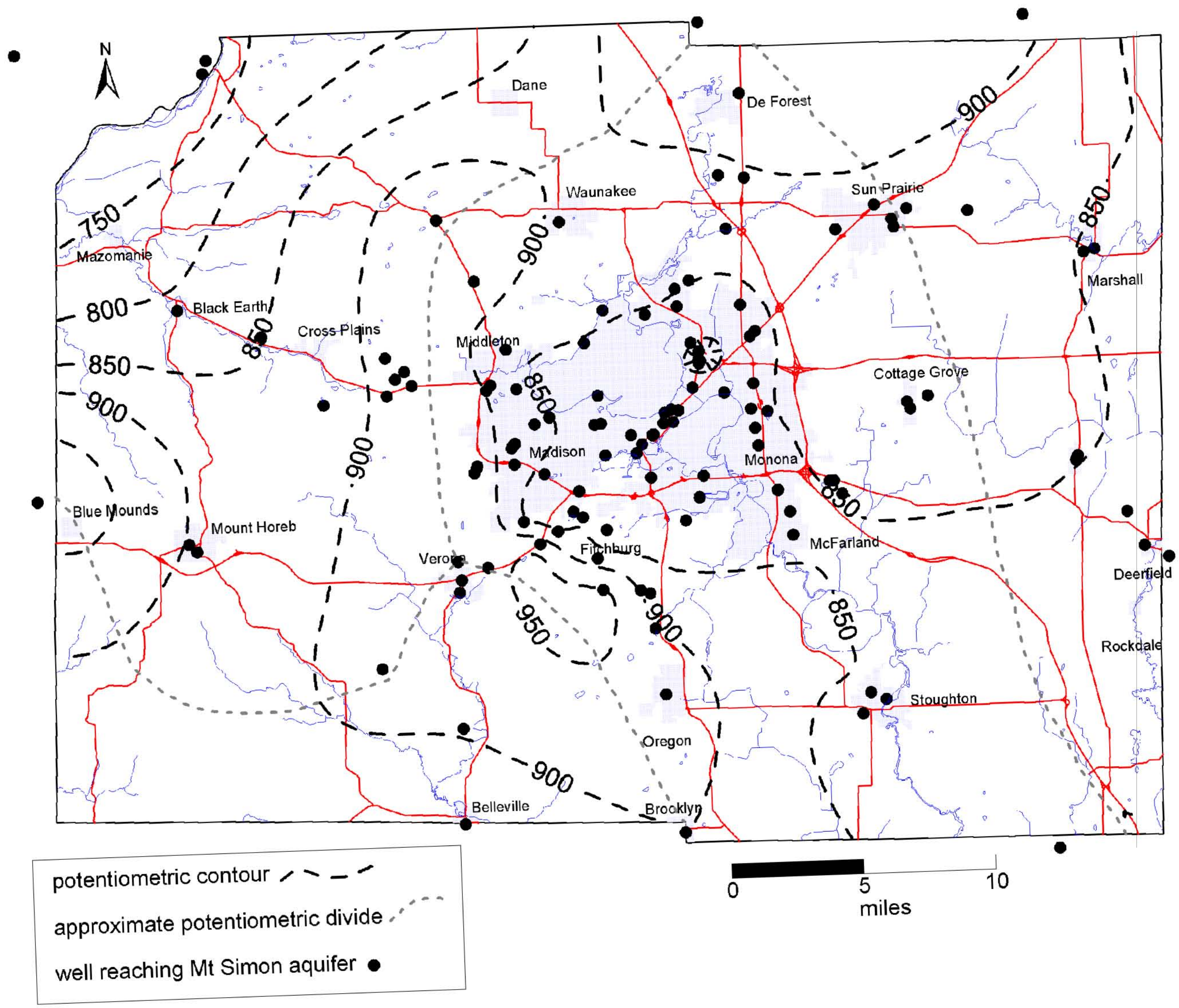


Figure 9. Potentiometric surface of the Mt Simon aquifer, 1995.

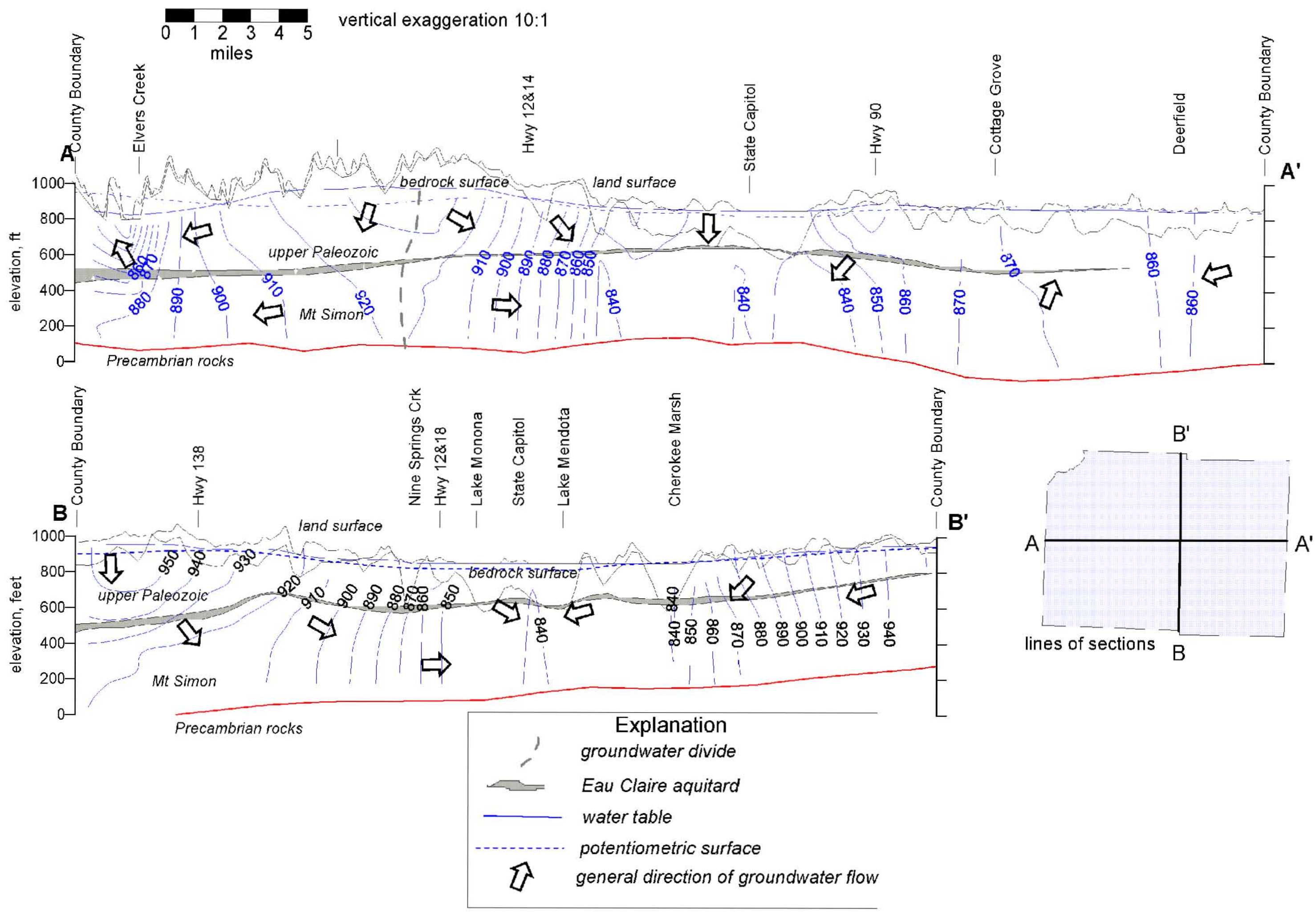
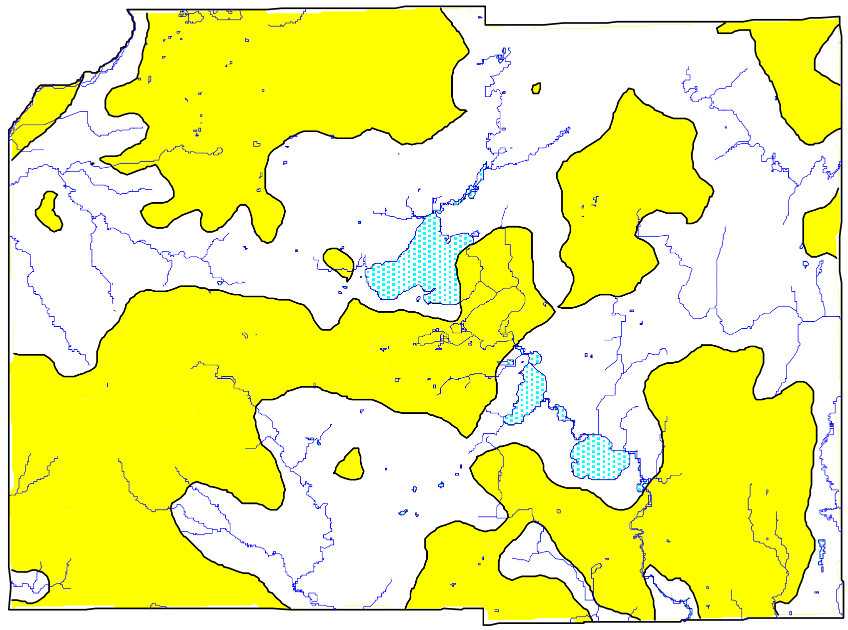


Figure 10. Hydrogeologic cross sections across Dane County, showing equipotential lines and the vertical direction of groundwater movement. A: west to east; B: south to north.

A.



B.

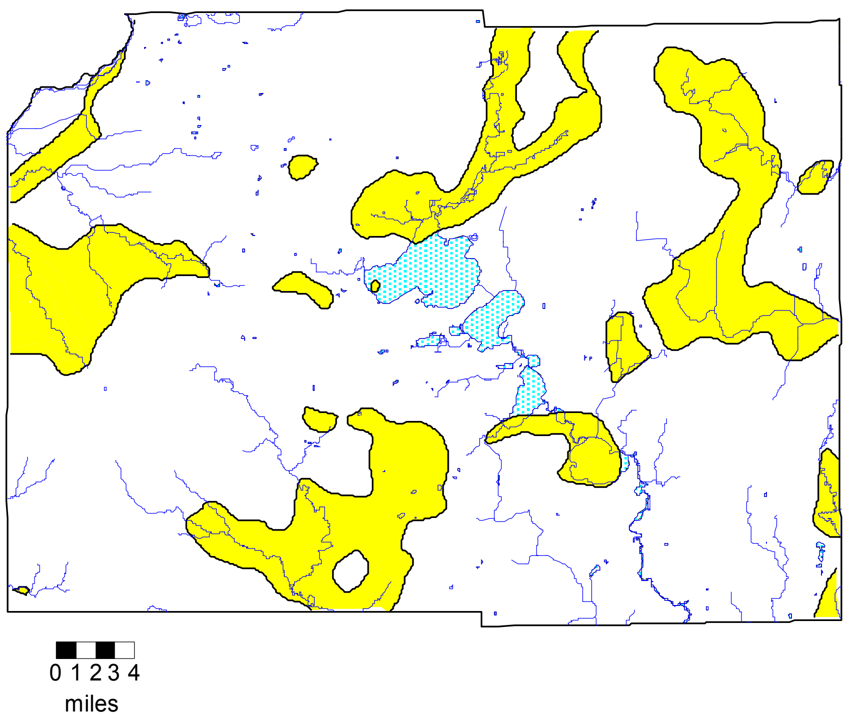


Figure 11. Areas of recharge to and discharge from the Mount Simon aquifer, based on water level measurements. A: areas of recharge; B: areas of discharge.

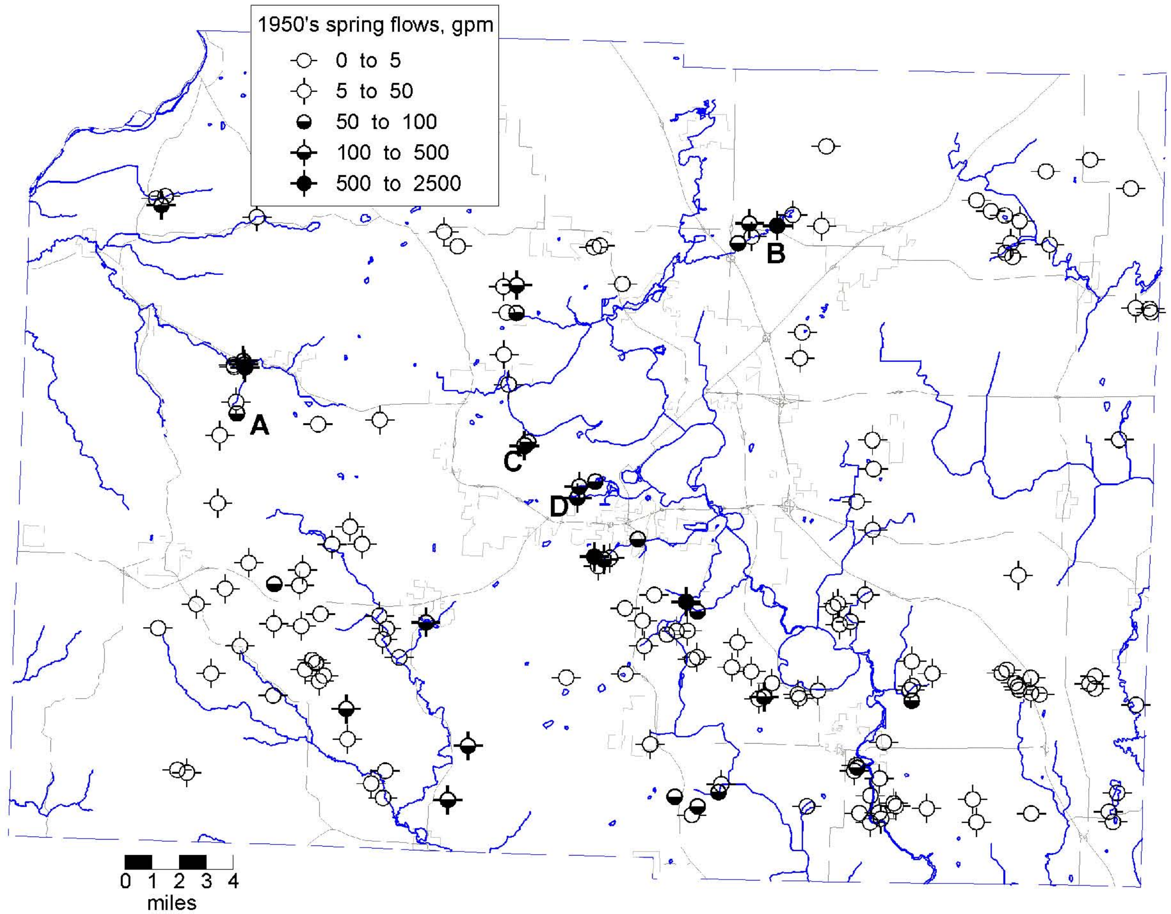


Figure 12. Mapped springs in Dane County, with range of flow indicated. Letters indicate springs referred to in text: A. Garfoot Creek; B. Token Creek; C. Merrill spring; D. Council Ring spring.

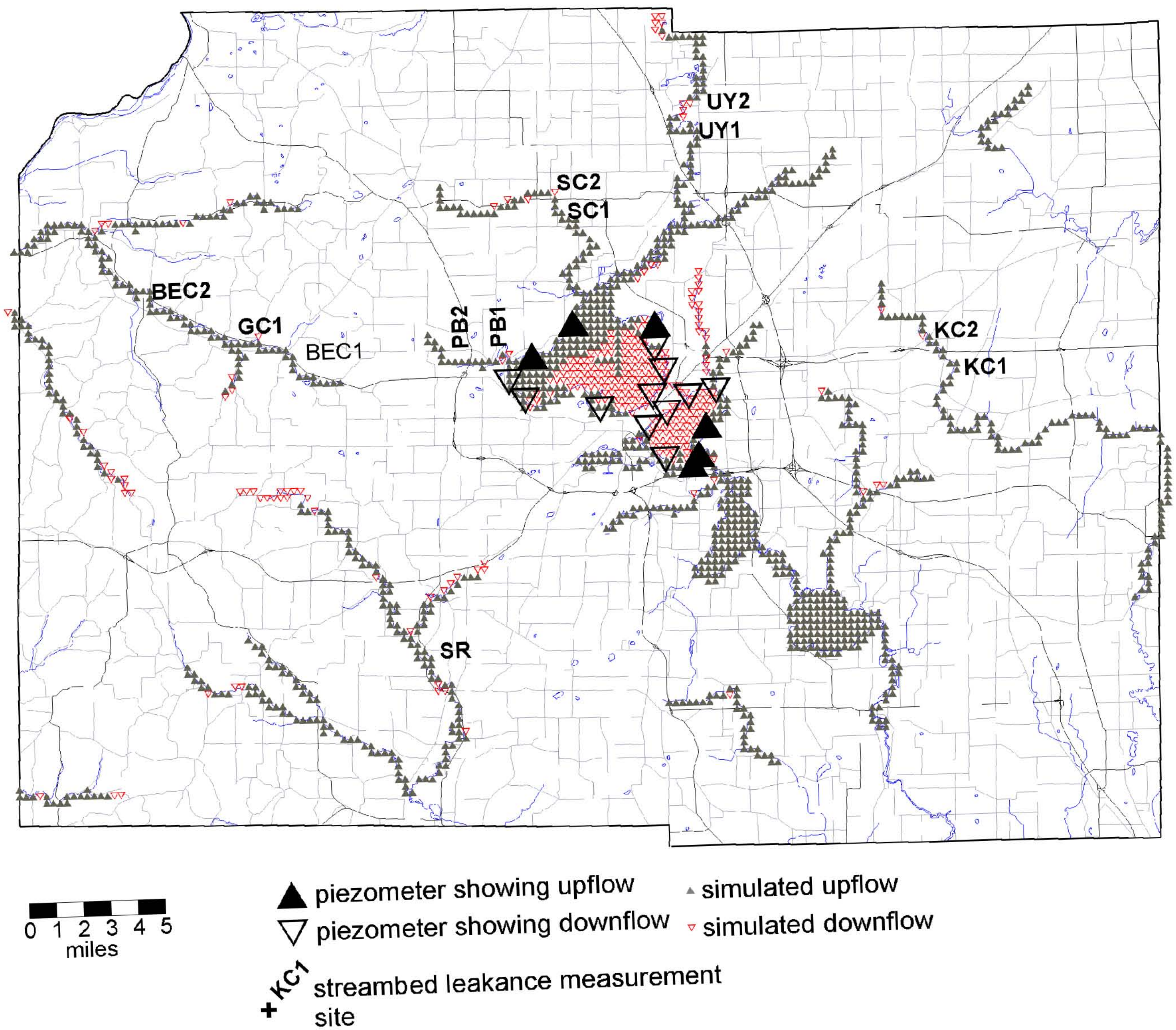


Figure 13. Groundwater-surface-water relationships.Small triangles indicate gaining (solid) of losing (open) areas of surface water based on the regional model. Large triangles indicate field measurements of upward (solid) or downward (open) hydraulic gradients along the shores of lakes Mendota and Monona. Crosses indice measurement sites for streambed leakance.

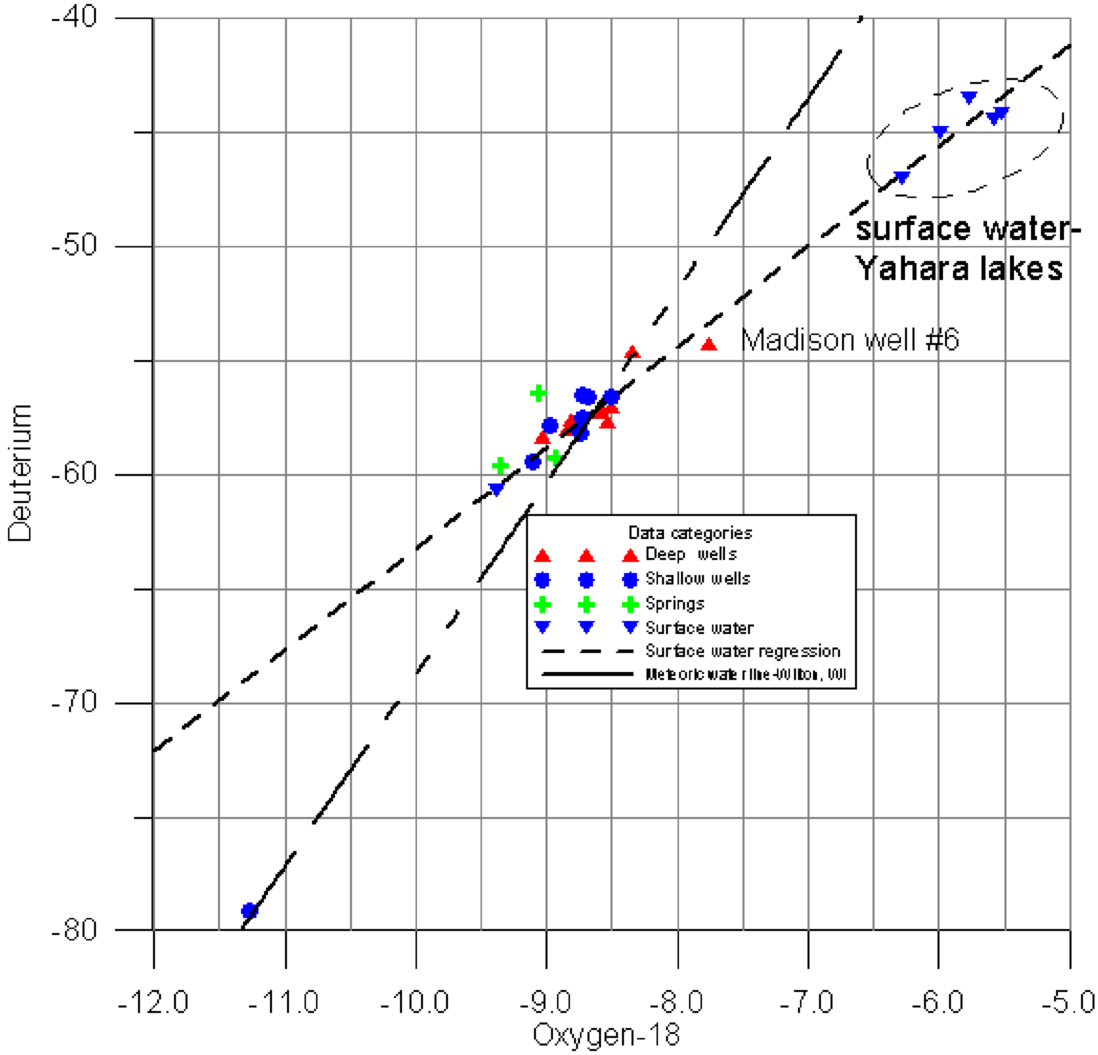


Figure 14. Results of oxygen-18/deuterium sampling of groundwater and surface water in Dane County.

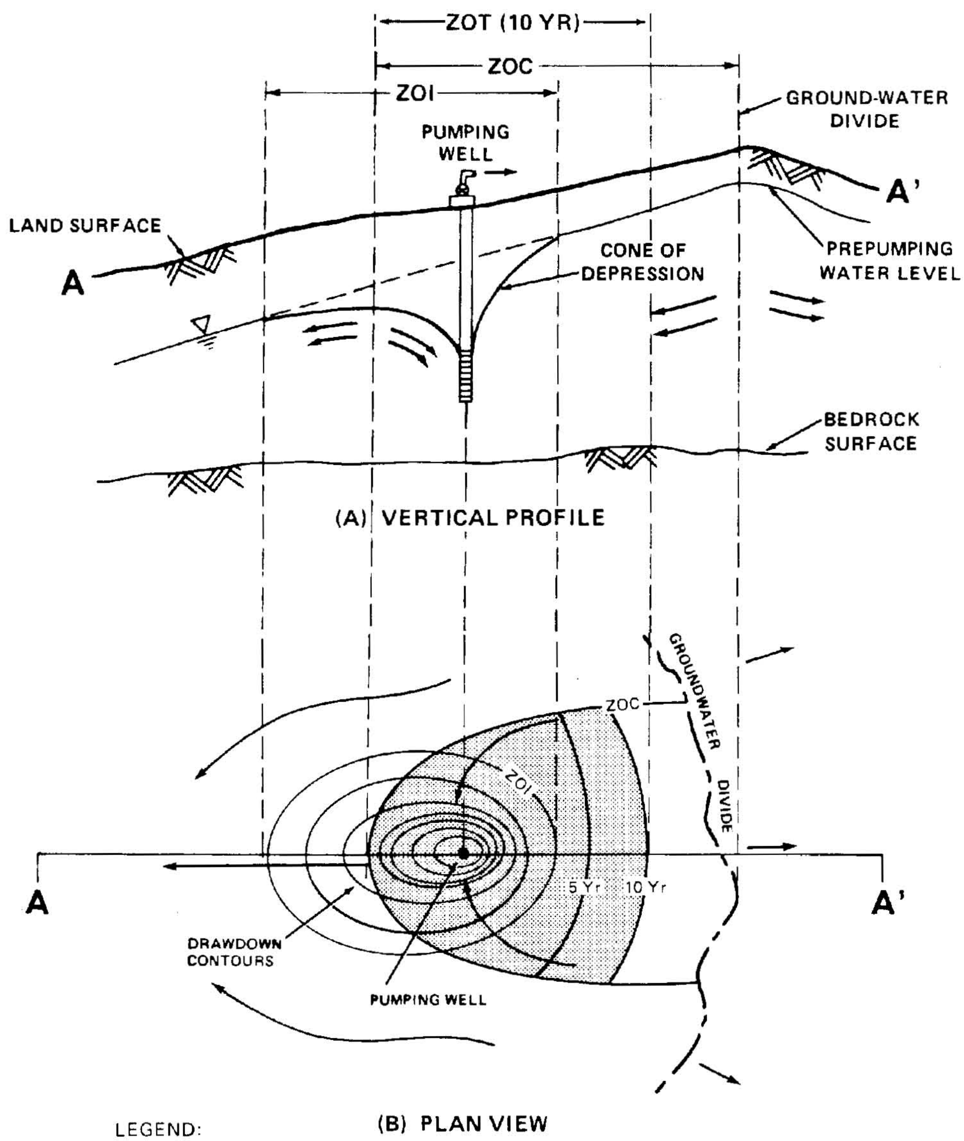


Figure 15. Idealized concept of a zone of contribution in a uniform flow field (from USEPA, 1987).

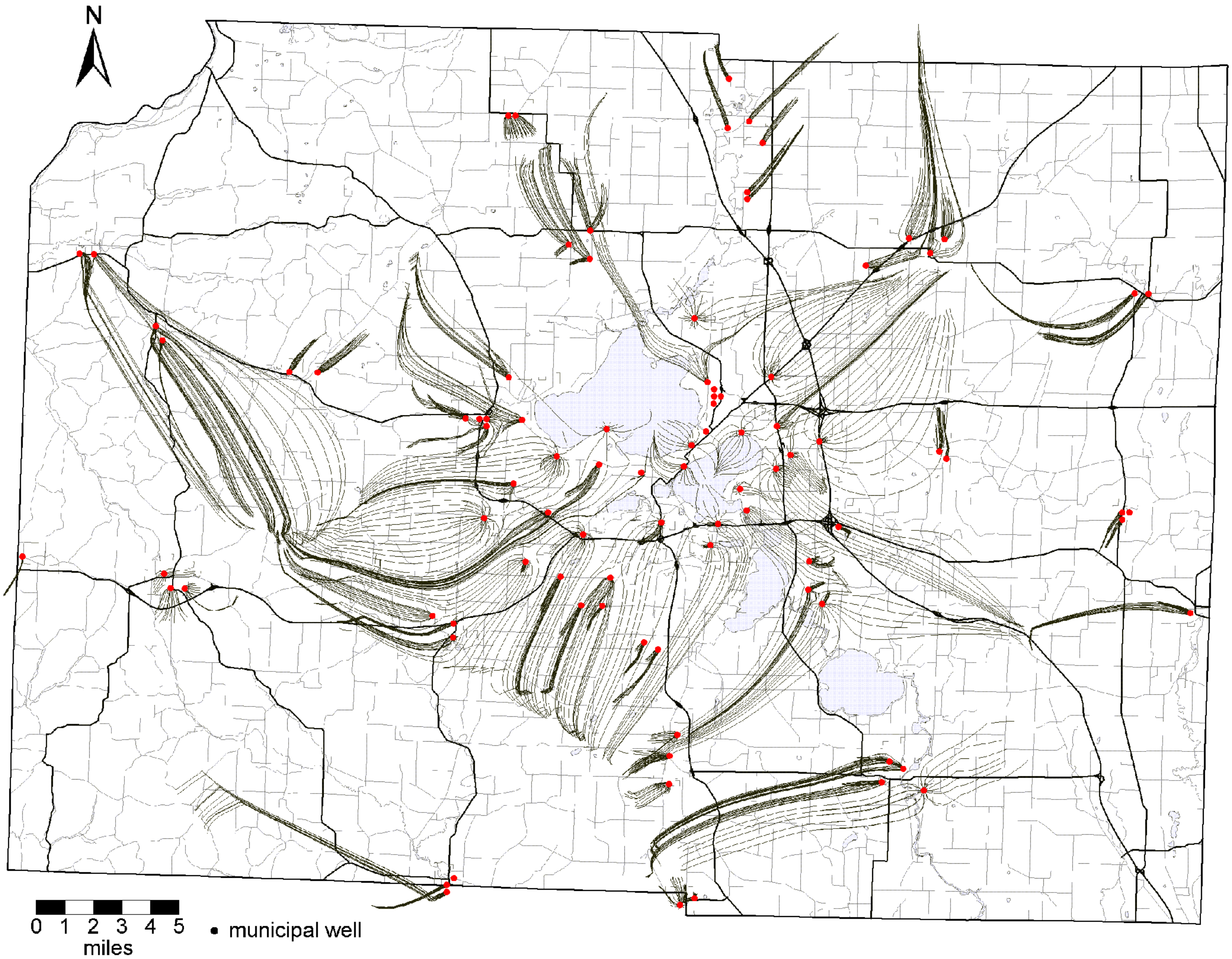


Figure 16.. Pathlines outlining zones of contribution for municipal wells in Dane County.

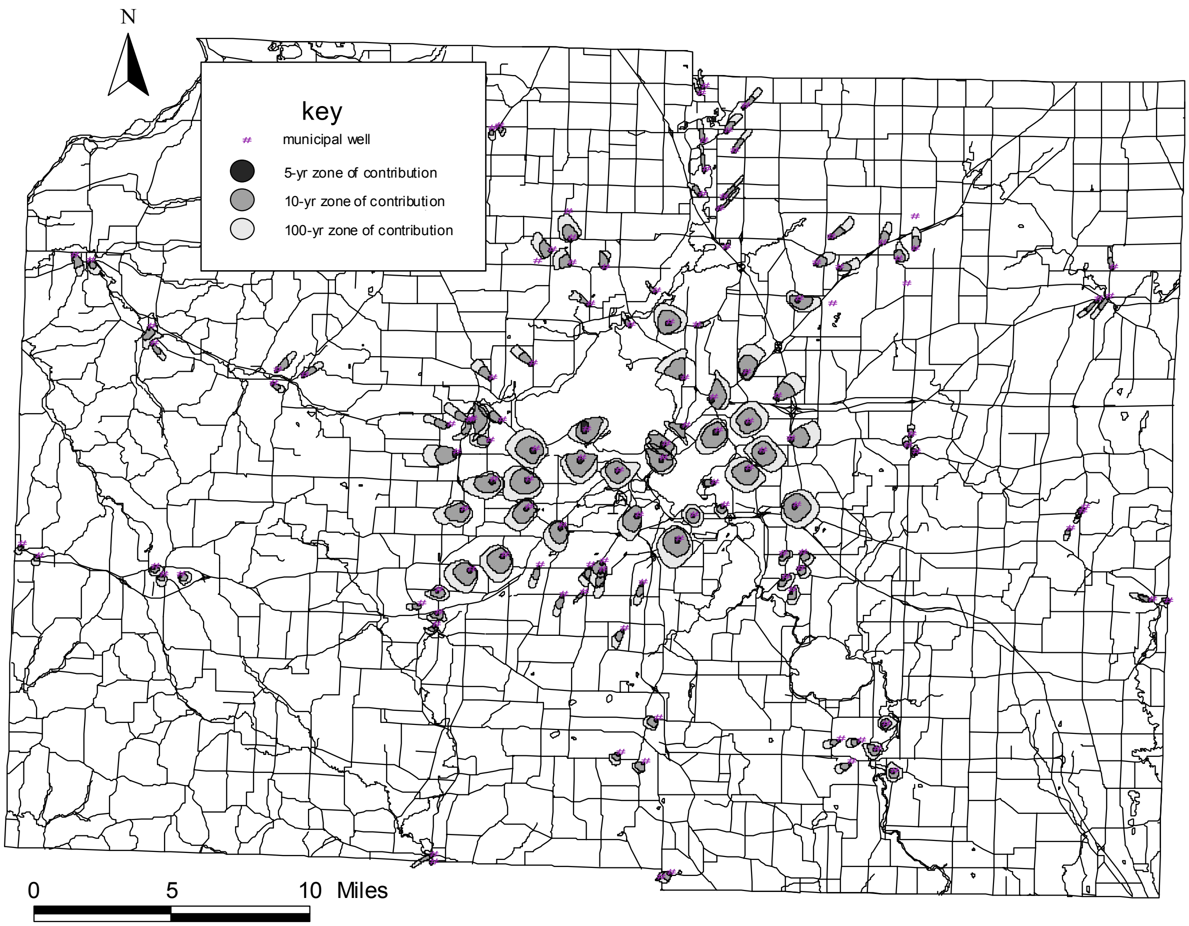


Figure 17. Time-delimited zones of contribution for municipal wells in Dane County.