The Effects of Large-Scale Pumping and Diversion on the Water Resources of Dane County, Wisconsin

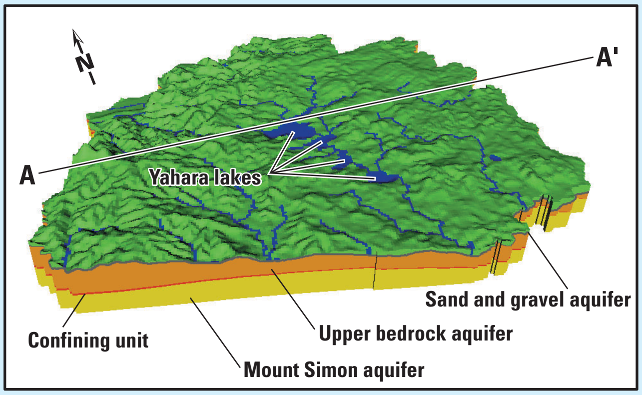
Introduction

Throughout many parts of the U.S., there is growing concern over the effects of rapid urban growth and development on water resources. Ground-water and surface-water systems (which comprise the hydrologic system) are linked in much of Wisconsin, and ground water can be utilized both for drinking water and as a source of water for sustaining lakes, streams, springs, and wetlands. Ground water is important for surface-water systems because it commonly has greater dissolved solids and more acid-neutralizing capacity than surface water or precipitation. The supplies of ground water are finite, however, and, in many cases ground water used for one purpose cannot be used for another. Moreover, ground-water use and withdrawal patterns may not be easy to alter once established. Thus, urban and rural planners are faced with decisions that balance the need for ground-water withdrawals while maintaining the quantity and quality of ground water for sustaining surface-water resources. Science-based information on the ground-water system and the connections to surface-water systems provides valuable insight for such decisions.

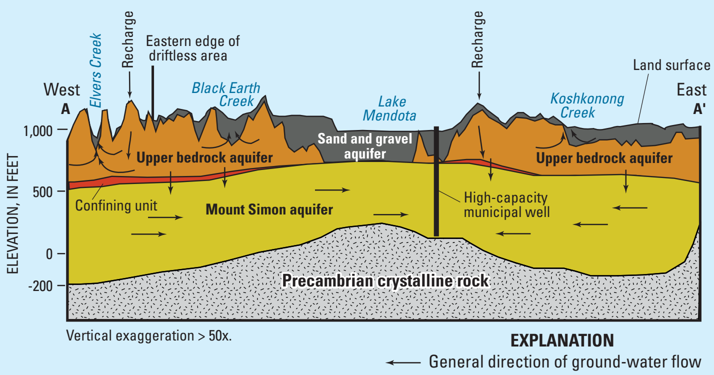
The regional hydrologic system in Dane County, Wisconsin, illustrates the effects of pumping and diversion on ground- and surface-water resources. Ground-water withdrawals from pumping average around 50 million gallons per day in the county, and ground water is the sole drinking-water supply for county residents. Large-scale pumping (large quantities pumped from wells distributed over a large area) is concentrated around the Madison metropolitan area and the Yahara lakes. Away from these pumping centers, ground water sustains lakes, streams, and wetlands, including important trout streams such as Black Earth Creek located in western Dane County. In an effort to improve the water quality of the Yahara lakes, the wastewater associated with the pumping is not returned to the areas where it was pumped but is diverted 9 miles south of the city of Madison. The pumping captures ground water that would normally discharge to the lakes; the diversion reintroduces the water far enough downstream that it does not re-enter the hydrologic system near the lakes. Dane County recently has had tremendous growth, and there is concern that the additional ground-water withdrawals needed to supply the larger population will adversely affect water-dependent ecosystems that are important for the local quality of life.

Dane County hydrologic setting

Bradbury and others (1999) describe the geologic and hydrogeologic setting for Dane County; a brief overview of this work is described here. Three aquifers and one confining unit underlie the Dane County area as shown in the block diagram (below). A shallow sand and gravel aquifer is made up of glacial and alluvial materials overlying the bedrock. Except in narrow alluvial valleys, the sand and gravel aquifer is thin or absent in western Dane County (called the "driftless area"). The upper bedrock aquifer underlies the unlithified deposits and overlies the Eau Claire Formation. The upper bedrock aquifer is made up of Cambrian sandstone and dolomite. A shale, which is part of the Eau Claire Formation, forms a confining unit at the base of the upper bedrock aquifer. This confining unit largely is absent in the pre-glacially eroded valleys of the Yahara lakes area and northeastern Dane County. Beneath the confining unit, a lower bedrock aquifer (the Mount Simon aquifer) overlies Precambrian crystalline basement rock. The Precambrian crystalline basement rock is assumed to be impermeable and forms the lower boundary of the ground-water-flow system.



Block diagram showing the model domain and hydrostratigraphy used in the Dane County Regional Model. Much of the geologic detail is consolidated into three major aquifers and one confining unit.



West-East cross section showing the upper aquifers and the lower (Mount Simon) aquifer. Schematic flow-lines also are included to illustrate the local and regional ground-water flow that occurs in the county.

Precipitation-derived water enters the ground-water system as recharge to the water table. This recharge takes place primarily in upland areas throughout Dane County. Rates of recharge are variable because of differing soil percolation rates, slope, and relative position in the landscape. As shown in the cross section, local ground-water systems with short flow paths are common in the sand and gravel and upper bedrock aquifers; regional flow with longer flow paths are present in the Mount Simon aquifer. Some of the recharging water may move downward to the sand and gravel or upper bedrock aquifers, travel a short horizontal distance, and then move upward to discharge in surface waters and wetlands. A relatively small portion of this recharge moves downward through the confining unit and into the Mount Simon aquifer. Because of the conductive nature of the Mount Simon aquifer and the presence of the nearly impermeable Precambrian rock, flow paths in the aquifer primarily are horizontal. Pumping wells extract water from both the Mount Simon and the overlying bedrock aquifer; this pumping captures a portion of the ground water that discharged to area lakes, streams, springs, and wetlands under pre-development conditions. In places where large withdrawals of ground water occur, streams and lakes may recharge the ground-water system.

In order to improve the understanding of the hydrologic system and the effects of increased ground-water use, a Dane County Regional Hydrologic Study was initiated. The study was a cooperative effort among the Dane County Regional Planning Commission, the Wisconsin Geological and National History Survey, and the U.S. Geological Survey. The study included the development of a regional ground-water flow model, which helps managers make informed water-resources decisions on an ongoing basis. The model helped identify major areas of ground-water recharge and discharge, estimate the amount of ground water discharging to surface-water bodies, and simulate ground-water flow direction and rates. Once the model was developed, it was used for assessing effects of future ground-water withdrawals and the effects of proposed water-management programs. The initial model was completed in 1995 and has been updated annually to incorporate current conditions and updated modeling codes and procedures. The purpose of this Fact Sheet is to describe how the model was developed and used.

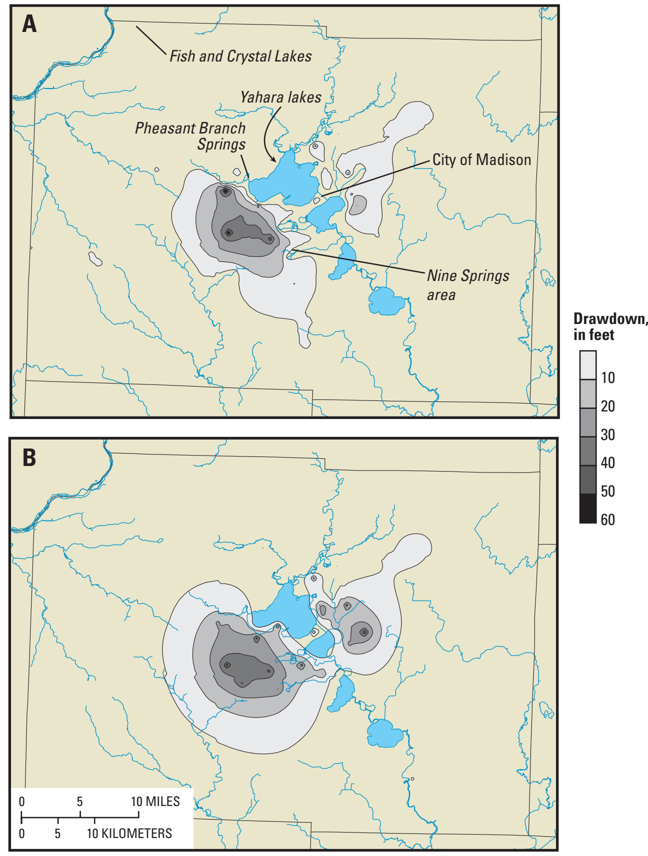
How ground-water flow models work

Understanding the ground-water-flow system can be difficult, so investigators commonly use mathematical models to simulate a simplified version of the system using computers. The computer code relies on two basic principles to perform simulations. The first is that water flows "downhill," or more exactly, from high potential to low potential. The second principle is that water cannot be created or destroyed; thus, what flows into the ground-water system must either flow out or be stored. Changes in storage are identified by changes in water levels within the system. Using these principles, as well as site geology and locations of streams and lakes in the area being studied, the hydrologic system is simplified and represented in a mathematical model. It should be noted that, whereas seemingly simple in principle and operation, ground-water modeling can be complex because of uncertainty in important model inputs such as properties of the material in the subsurface and timing of water additions and subtractions.

Model calibration

The ground-water flow model for the Dane County area was developed using the computer program MODFLOW (McDonald and Harbaugh, 1988). The model inputs included such variables as the amount of rain and snow that enters the ground-water system (that is, the amount of precipitation minus the amount of runoff to streams and the amount removed by evaporation and plant uptake). In addition, the locations of large wells, streams, and lakes in Dane County were entered into the model. The model was calibrated using 1992 pumping rates, and simulated ground-water levels and flows to or from the streams were compared to the ground-water levels and flows measured in the study area. Using a trial-and-error approach, the various model inputs were varied until model-simulated levels and flow approximated measured values. Measured-to-simulated ground-water levels from over 3,000 wells and measured-to-simulated flows in 13 streams were compared during the model calibration process.

Important surface-water features can be affected by ground-water pumping. One such feature is the Pheasant Branch spring shown above.



Figures 1a and 1b. Simulated drawdown from pre-development conditions in the upper bedrock (fig. 1a) and Mount Simon (fig. 1b) aquifers resulting from high-capacity pumping at typical 1992 discharge rates. The Yahara lakes supply water to the wells, which splits the drawdown into two distinct cones of depression. Contour interval is 10 feet.

Model results: comparison of pre-development conditions to current conditions

Pre-development conditions were simulated by removing the pumping wells from the calibrated base model. This resulted in a representation of the hydrologic system before development that can be compared to current conditions to assess the effects of pumping on water resources.

As shown by contouring the simulated drawdown (the amount of water-level decline from predevelopment conditions caused by the pumping), the greatest effect of pumping on water levels results in the Madison metropolitan area. Shallow and deep ground-water levels in the vicinity of Madison declined more than 60 feet (fig. 1a and 1b). The largest declines are at the centers of two cones of depression that are split by the Madison lakes. Directly adjacent to and beneath these lakes there is no simulated drawdown of the water table and only about 10 feet of drawdown simulated in the Mt. Simon aquifer. Two distinct cones of depression indicate that these lakes are important sources of water to the pumping wells. This result is expected because the confining unit is absent or thin in this area and the aquifers are in good hydraulic connection with the lakes.

It is interesting to note that prior to the large-scale pumping and diversion associated with development, the lakes and wetlands within the Madison area primarily received ground water. These lakes and wetlands primarily lose water to the ground-water system as a result of present-day pumping and diversion (fig. 2). Moreover, the largest area where ground

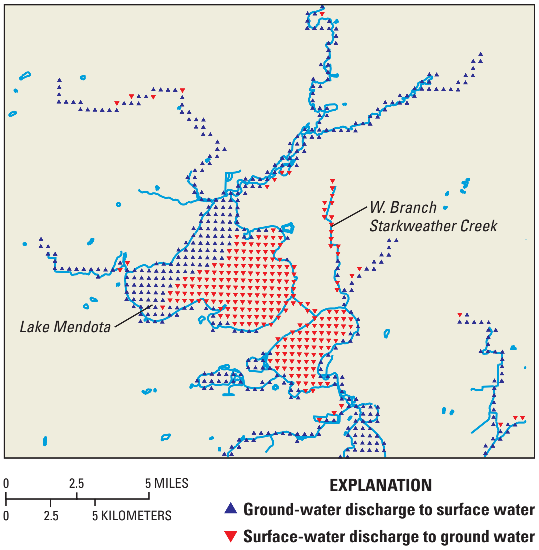


Figure 2. Model results showing the effects that pumping and diversion have had on the ground-water/surface-water interaction. During pre-development conditions, ground water would have flowed to the lakes, streams, and wetlands in the modeled area. Under 1992 conditions shown here, the lakes and streams lose water to the ground-water system (red triangles) in areas where development (and associated pumping and diversion) are concentrated.

water currently is discharging to a lake (the northwestern side of Lake Mendota) is relatively undeveloped. Because ground water is the sole source of drinking water for the county, additional pumping and diversion associated with future development in this undeveloped area could create a condition where Lake Mendota is losing water to the ground-water system on all sides. Such a change in the sources of water to the lake could affect the lake-water quality, food-web dynamics, and fish community.

The model also can be used to compare simulated pre-development baseflows to simulated current baseflows. It is apparent that pumping has reduced baseflow in streams (see table 1). That is, the current pumping and diversion near the city of Madison captures ground water that would contribute flow to these streams under pre-development conditions. The amount of baseflow decrease depends on how close to the pumping centers

Table 1. Comparison of pre-development and current conditions simulated baseflows in selected Dane County, Wisconsin streams

Gaging station name	Simulated baseflow[1], in cubic feet per second	
	Pre-development	Current
Black Earth Creek at USGS gage above Black Earth	14.5	13.1
Badger Mill Creek at STH 69 south of Verona	2.0	0.6
E. Branch Starkweather Creek at Milwaukee St.	2.2	0.9
Koshkonong Creek at Bailey Rd. near Sun Prairie	0.6	0.1
Koshkonong Creek at Hoopen Rd. near Rockdale	36.4	33.8
Maunesha River south of USH 151	12.3	11.9
Mt. Vernon Creek at USGS Gage	2.4	2.1
Murphy (Wingra) Creek at Beld St.	3.4	1.3
Nine Springs at Hwy. 14	4.9	2.2
Pheasant Branch Creek at USH 12 at Middleton	2.7	1.2
Six Mile Creek at Mill Rd. near Waunakee	5.0	4.3
Token Creek at USH 51	13.0	10.6
W. Branch Starkweather Creek at Milwaukee St.	2.8	0.0
W. Branch Sugar River at STH 92 near Mt. Vernon	5.6	5.3
Yahara River at Golf Course near Windsor	8.8	8.0

[1] Baseflow is the part of streamflow because of ground water discharging to the stream.

the stream is located. In one extreme case (W. Branch Starkweather Creek —see table 1), the stream is simulated as being dry for much of its length because of pumping and diversion. In reality, the stream flows during storm events but typically is dry during non-storm periods.

Finding the contributing areas for drinking-water wells

Once the model is completed it can be used to trace mathematical water particles to determine where the ground water goes (if we track forward in time) or where it came from (if we track backward in time). This approach was used to simulate the area that supplies ground water to wells (called contributing areas). Model simulations indicate that, for the longest flowpaths, it can take many thousands of years for ground water to move from the area where it enters the ground to where it discharges to a well, stream, or lake. Particles were tracked backwards from each municipal well located in Dane County. The resulting contributing areas (fig. 3) illustrate that the source for ground water withdrawn by municipal wells in Dane County lies entirely within the county boundaries for almost every well.

Evaluating pumping scenarios

The model also can be used to evaluate the effects of different pumping scenarios on ground-water availability and their effect on water resources. The model developed for Dane County demonstrated that an adequate drinking-water supply is available for Dane County if no other uses for the ground-water resources are included. Model results also demonstrated that, depending on the distribution and rate of withdrawal of proposed and existing wells, water quality may be affected, wetlands may be lost, and baseflow in streams may be reduced substantially.

Two scenarios were simulated with the model based on water-use projections for the year 2020 (DCRPC, 1997). The scenarios are: 1) the central 50 percent of Madison municipal wells (inner ring of red dots in fig. 4) provide 75 percent of the daily water demand and the outer 50 percent of wells (outer ring of yellow dots in fig. 4) provide 25 percent, and 2) the central 50 percent of Madison wells provide 25 percent of the daily water demand and the outer 50 percent provide 75 percent. By providing the majority of water from the central wells (scenario 1), the major sources of water for the wells are lakes and wetlands near Madison; baseflows in rural

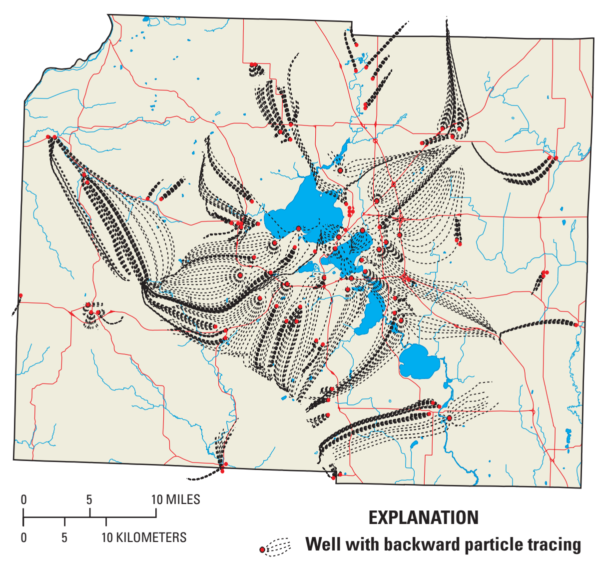
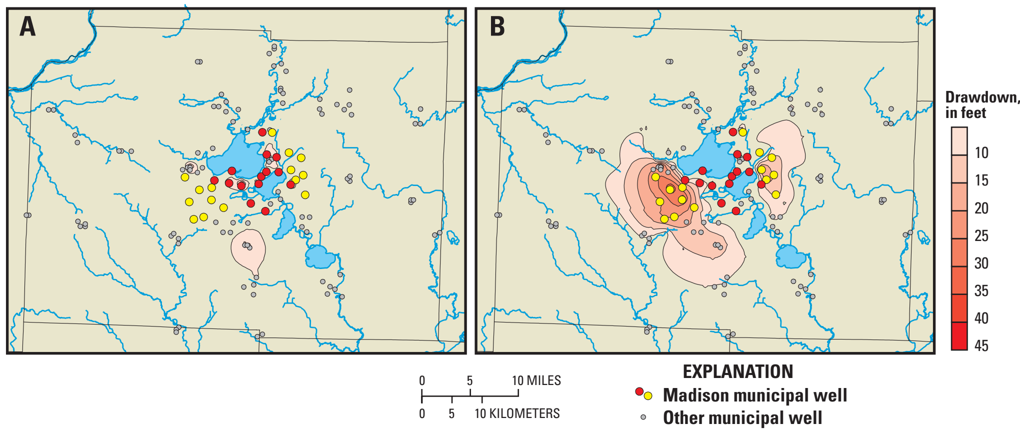


Figure 3. The areas that contribute water to the each municipal well in the county are simulated using backward particle-tracking (from the well to the recharge area) within the modeled system. The long particle paths represent a time of travel from the recharge area to the well on the order of thousands of years.

county streams are only slightly affected. Scenario 2 indicates that the wells would capture water that normally would flow to area wetlands and streams rather than removing water from the lakes. This result is demonstrated by the increased drawdown from 1992 conditions for scenario 2 (fig. 4b). The additional drawdown in the water table for scenario 2 is much greater than scenario 1, indicating that scenario 2 would have the greatest adverse effect on wetlands and streams in the county. These scenarios are for illustrative purposes only and do not account for the feasibility (economic, political, or other considerations) of implementing any particular pumping strategy. Such considerations would have to also be taken into account to fully assess the practicability of different strategies.



Figures 4a and 4b. The model can be used to simulate changes in the hydrologic system for a selected management scenario. In this example, the Madison municipal wells are divided into an inner ring (red dots) and outer ring (yellow dots). In 4a (scenario 1) the inner ring pumps 75 percent of the total water pumped and the outer ring pumps the remaining 25 percent; in 4b (scenario 2) the outer ring pumps 75 percent of the total water pumped and the inner ring pumps the remaining 25 percent. As shown, if the outer rings are required to supply 75 percent of the total water, there will be increased drawdown in the areas near the wells. There is much less drawdown from pumping the inner ring of wells because the water primarily is derived from the Yahara lakes (a relatively large source of water).

How this regional model has been applied to smaller site investigations

The Dane County ground-water-flow model is suitable for use as a tool for regional water management, but because of its regional focus, the model should not be used for site-specific simulation. However, the model provides a valuable framework within which site-specific studies can be carried out. The following are examples of ongoing site-specific studies that have made use of the Dane County model.

Pheasant Branch Watershed – The Dane County model was used for a smaller-scale ground-water/surface-water modeling study done by the U.S. Geological Survey, in cooperation with the City of Middleton and the Wisconsin Department of Natural Resources. The study focused on the effects of urbanization on streamflows and spring flows (Hunt and Steuer, 2000; Hunt and others, 2001; Steuer and Hunt, 2001), and the models are now part of a large watershed-scale project conducted by the Wisconsin Department of Natural Resources, University of Wisconsin – Madison, Wisconsin Geological and Natural History Survey, and U.S. Geological Survey.

Nine Springs Watershed – The Nine Springs watershed, located just south of the City of Madison (fig. 1a), contains an unusually large concentration of cold-water springs and associated wetlands. The Dane County model was used as a starting point for the construction of a detailed inset model to investigate these springs and to determine the effects nearby land-use changes may have on the springs and wetlands (Swanson, 2001). Model simulations helped quantify anticipated reductions in spring discharge resulting from nearby ground-water withdrawals and simulated the land-surface area contributing recharge to the springs. This information is critical for making land-use decisions to protect the quality and quantity of spring discharge.

Fish and Crystal Lakes – Elevation of the stage of Fish and Crystal Lakes, located in northwestern Dane County (fig. 1a), has increased 9 feet since 1966 and caused flooding of some near-shore residences. By using the Dane County model as a starting point, a new U.S. Geological Survey computer program that simulates lakes was coupled to a model of the ground-water system and was used to determine that increasing ground-water recharge was responsible for the lake-stage increase. The model was then used to simulate how pumping from Fish Lake would lower the stage of both lakes and how the lake stages would recover when pumping was stopped (Krohelski and others, 2001).

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Information

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