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Simulation of regional groundwater flow in southeastern Wisconsin

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Regional Aquifer Model for Southeastern Wisconsin

Report 1:
Data Collection, Conceptual Model Development, Numerical Model Construction, and Model Calibration

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Administrative Report to the Southeastern Wisconsin Regional Planning Commission

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1. Abstract

We developed a three-dimensional groundwater flow model to simulate and assess the effects of historical and current groundwater withdrawals on groundwater conditions in the seven-county region of southeastern Wisconsin administered by the Southeastern Wisconsin Regional Planning Commission (SEWRPC). A steady-state simulation reproduced predevelopment conditions before the onset of large-scale pumping. A transient simulation reproduced the response of water levels and fluxes to gradually increasing withdrawals between 1864 and 2000. The project was initiated in 1999 under the leadership of SEWRPC with the participation of stakeholders from the major municipalities using groundwater in southeastern Wisconsin. The model was constructed cooperatively by the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS).

This report documents data collection, conceptual model development, numerical model construction, and model calibration. A second report (Feinstein and others, 2003) presents results for the seven-county study area.

The seven counties in the study area are Kenosha, Milwaukee, Ozaukee, Racine, Walworth, Washington, and Waukesha. Two shallow aquifers underlie this area. The first consists of unlithified sand-and-gravel deposits contained in generally fine-grained till. The second, the fractured Silurian dolomite aquifer, is located below the unlithified deposits aquifer in the eastern part of the study area. The deep aquifer system consists of a series of Cambrian and Ordovician sandstone units as well as some dolomite and shale. Over the eastern two-thirds of the seven-county region, the shallow and deep parts of the flow system are separated by the low-permeability Maquoketa Formation. Precambrian basement rocks form the nearly impermeable base of the groundwater flow system.

We used the U.S. Geological Survey groundwater flow model code, MODFLOW (McDonald and Harbaugh 1988), to construct the southeastern Wisconsin groundwater flow model. The detailed region of the model is called the nearfield and encompasses the seven-county region as well as Dodge and Jefferson Counties and the eastern half of

Rock County. The rest of the model, called the farfield, is used only to set the appropriate fluxes and heads at the edge of the nearfield.

Newly developed sources of data for the nearfield were used to define the geometry of hydrostratigraphic units, the spatial distribution of hydraulic conductivity in each unit, the geometry and elevation of surface-water bodies, the spatial distribution of recharge rates, and the historical record of well withdrawals. Special attention was paid to the thickening and thinning of dolomite and sandstone units, and to mapping fine-grained and coarse-grained sections of rock as a guide to hydraulic conductivity distribution. We also constructed a surface-water network dense enough to provide discharge points for recharge circulating as shallow groundwater flow, and assembled a comprehensive history of high-capacity well withdrawals from both shallow and deep systems at approximately 10-year intervals from 1864 to 2000.

Model calibration included a comparison of modeled and observed water levels and gaged stream flows to simulated stream gains and losses. Water levels calculated by the calibrated model compared favorably to estimates of predevelopment conditions and to water level changes through time. Simulated stream gains fell within the expected interval (80 to 50 percent of flow duration) for most of the sites in the seven-county region where flow duration was estimated.

The quality of the steady-state and transient calibrations was most sensitive to the horizontal hydraulic conductivities of the unlithified material and the deep sandstone aquifer, to recharge rates, to the vertical hydraulic conductivity of the Maquoketa shale, and to the estimated pumping rates.

2. Introduction

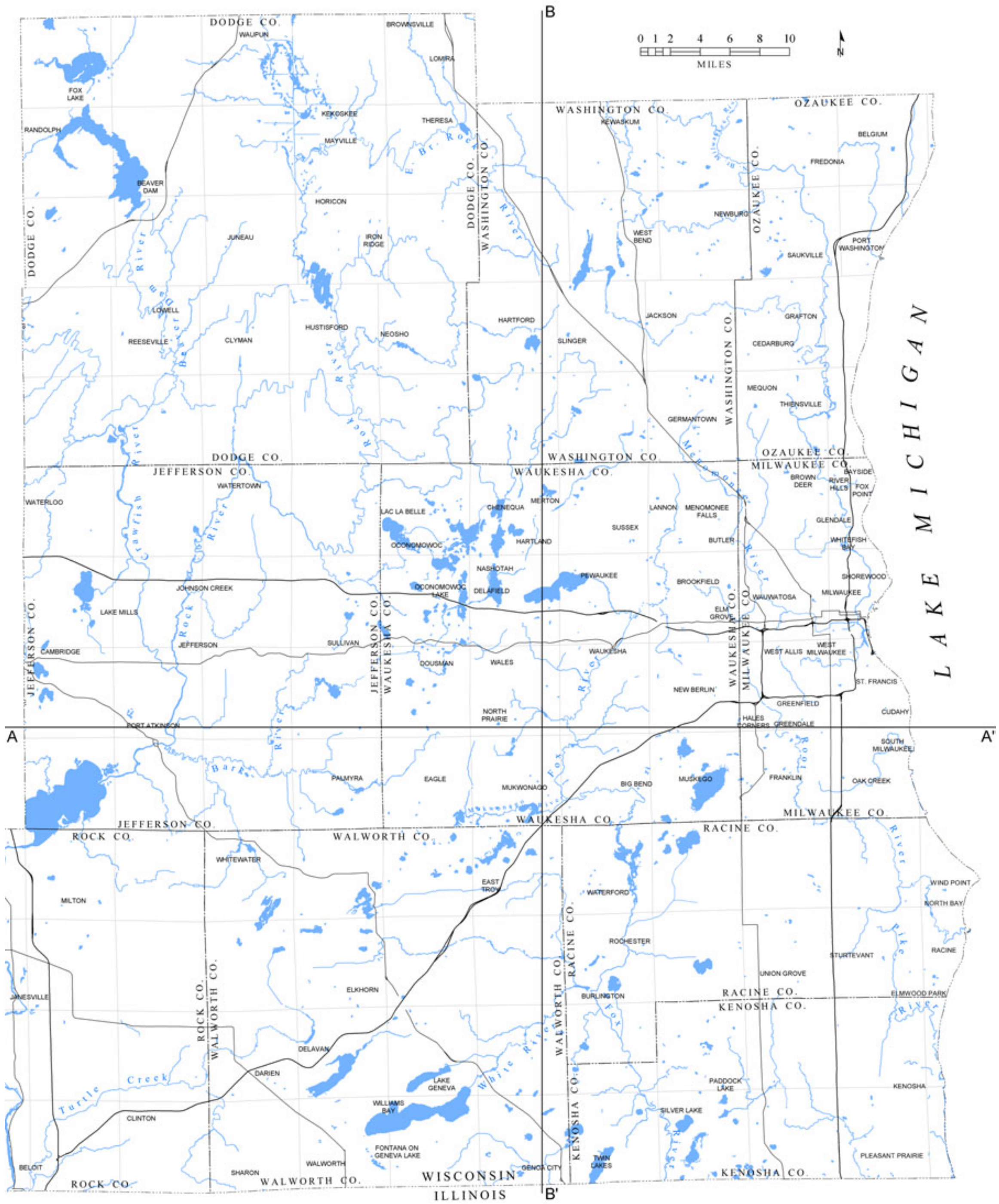
Southeastern Wisconsin (Washington, Ozaukee, Waukesha, Milwaukee, Walworth, Racine, and Kenosha Counties) is one of the most rapidly developing regions of the state, and in 1996 contained about 37 percent of the state's population. The economic growth and suburban expansion in this area have been due, in part, to the abundant water supplies available for public, domestic, and industrial uses. Lake Michigan is the source for about 70 percent of all water used in the region, mainly in the lakeshore counties (Ozaukee, Milwaukee, Racine, and Kenosha), which lie mostly within the Great Lakes drainage basin. Farther inland, Washington, Waukesha, and Walworth Counties are principally in the Mississippi River basin, and, because of international limitations on diversion of water out of the Great Lakes basin, rely on groundwater for over 99% of their needs (SEWRPC/WGNHS, 2002). In 1995, about 93 million gallons per day (mgd) of groundwater was withdrawn for public, domestic, industrial, commercial, and agricultural uses (Ellefson and others, 1997; SEWRPC/WGNHS, 2002).

Groundwater in the region is withdrawn from three major aquifer systems (SEWRPC/WGNHS, 2002). The shallowest system is composed of unlithified glacial and fluvial sediments of Pleistocene age, hereafter called the unlithified sand-and-gravel aquifer. These sediments range in lithology from coarse gravel to fine silt, and in thickness from only a few feet to several hundred feet in preglacial bedrock valleys. The unlithified sand-and-gravel aquifer is discontinuous in nature because it is interspersed with thick fine-grained till deposits. This aquifer supplies water to domestic wells in many parts of the region and to municipal and industrial wells where it thickens in the preglacial valleys. Below the sand and gravel, fractured dolomite of Silurian and Devonian age is an important source of water over the eastern two thirds of the region. This system, hereafter called the Silurian dolomite aquifer, is absent west of its subcrop in western Waukesha County. To the east, it supplies many domestic and some municipal and industrial wells. The unlithified sand-and-gravel and Silurian dolomite aquifers constitute the water-producing layers in the shallow part of the flow system.

Below the shallow Silurian dolomite aquifer, shales and dolomites of the Ordovician Maquoketa Formation and dolomites of the Sinnipee Group form an important aquitard that restricts vertical flow between the shallow and deep parts of the flow system. West of the Maquoketa subcrop, the Sinnipee Group is a minor aquifer due to weathering at the bedrock surface and is considered to be part of a third, deep aquifer system. This system, used mainly for large municipal and industrial supplies, is dominated by up to hundreds of feet of Ordovician and Cambrian-age sandstones interbedded with lower-conductivity shales and dolomites. Hereafter called the deep sandstone aquifer, it constitutes the deep part of the flow system.

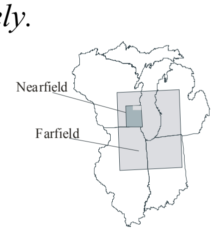
Since the turn of the century, groundwater use has caused significant changes in the shallow and deep parts of the flow system. Concentrated pumping and well interference have drawn down the potentiometric surfaces in the Silurian dolomite and deep sandstone aquifers. Water-level declines, measured in deep monitoring wells over the last 50 years, average between 6 and 10 feet per year. Cones of depression centered on Waukesha County and suburban Chicago have intersected so that pumping in one area can affect water levels in the other area. At the same time, groundwater quality has decreased, with significant increases in total dissolved solids and radioactivity in some wells (e.g., Aquifer Science and Technology, 1999).

Future management of groundwater resources in southeastern Wisconsin requires a comprehensive understanding of regional hydrogeology and groundwater flow. In 1998, the Southeastern Wisconsin Regional Planning Commission (SEWRPC) recommended the development and construction of a regional groundwater flow simulation model for use as a tool in regional groundwater management (SEWRPC, 1998). Beginning in 1999, SEWRPC and the Wisconsin Department of Natural Resources (WDNR) organized funding of the work through support from local water utilities. The WGNHS and the U.S. Geological Survey (USGS), have worked cooperatively to construct this model focused on the entire seven-county SEWRPC region (Figure 1). This groundwater flow simulation is intended to be a regional framework model that can lead to more detailed studies of smaller areas within the region.



A-A' and B-B' show trace of cross sections in Figures 6 and 7, respectively.

Figure 1. Southeastern Wisconsin model nearfield area.



Purpose and Scope of this Report

The groundwater modeling program in southeastern Wisconsin has the following objectives (SEWRPC, 1998):

1. To determine essential hydrogeologic parameters of the regional aquifers by the compilation and analysis of all relevant existing data.
2. To provide a better understanding of groundwater flow systems in both the shallow and deep aquifers in southeastern Wisconsin.
3. To investigate groundwater flow paths under different use scenarios for purposes of determining wellhead protection areas, understanding well interference, and examining interconnections among different aquifers and between groundwater and surface water.
4. To investigate impacts of groundwater withdrawals from different aquifers and determine major recharge areas for long-term aquifer protection.
5. To permit optimization of the distribution of new wells and pumping schedules to minimize drawdown and well interference, and better manage aquifer resources.
6. To permit determining the interactions between surface water and groundwater for purposes of groundwater resource management; and,
7. To permit the study and future evaluation of groundwater quality changes.

The groundwater modeling program consists of four phases:

(1) Data collection, compilation and conceptual model development;
(2) Construction and calibration of a three-dimensional regional groundwater flow model;
(3) Compilation of steady-state and transient model results at the regional scale;
(4) Targeted hydrogeologic analyses and scenario testing.

This report summarizes work carried out in phases 1 and 2. A companion report (Feinstein and others, 2003), which provides an overview of model results for the period 1864 to 2000, corresponds to phase 3 of the project. Subsequent reports corresponding to phase 4 will apply the model to optimize future use of the groundwater resource. The WGNHS and USGS have already begun a demonstration study in Waukesha County that converts a subset of the regional model into a refined inset model capable of addressing local water-supply issues.

Previous Studies

Southeastern Wisconsin has been included in several previous groundwater modeling studies. Regional investigations covering a broad multi-state area include work of the Illinois State Water Survey (Burch 1991) and the U.S. Geological Survey. The USGS studied groundwater flow in the Chicago-Milwaukee area (Young and others 1988) and conducted the Northern Midwest Regional Aquifer-System (RASA) Analysis (Mandle and Kontis 1992, Young 1992a,b). Studies limited to southeastern Wisconsin include work conducted by the USGS (Young, 1976) to investigate pumping drawdown in the deep sandstone aquifer. A more recent model over the same area was constructed by Jansen and Rao (1998). These Wisconsin efforts focused on the deep sandstone aquifer as a single aquifer represented by one model layer. This approach simplifies the interaction between the shallow and deep flow systems and neglects the three-dimensional circulation within the Cambrian-Ordovician units of the deep sandstone aquifer.

Recently, the shallow groundwater resources and geology of the region were studied in a cooperative effort between the WGNHS and SEWRPC (SEWRPC/WGNHS, 2002). As a followup to that baseline study, and in preparation for the model described in this report, a more detailed investigation of the hydrostratigraphy of the deep sandstone aquifer was undertaken by the WGNHS (Eaton and others, 1999) and the USGS (Carlson and Feinstein, 1998). This work built on earlier studies by using the extensive subsurface deep-well database at the WGNHS and available hydraulic testing information to define the geometry (thickness) and hydraulic properties of individual units within the deep sandstone aquifer.

Model Improvements

The groundwater model described in this report represents a significant advance over previous models, and is designed both to evaluate regional hydrogeology, including the effects of water use, and to provide a framework for more detailed site-specific studies in the future. This model incorporates the following improvements:

- The horizontal grid discretization is much finer than in previous models, allowing more geologic detail;
- The model includes many more vertical layers than previous models, allowing a more realistic depiction of regional hydrostratigraphy and groundwater circulation;
- All aquifer systems are included in a single model, allowing improved simulation of the interaction between shallow and deep aquifer systems;
- Groundwater flow into and out of major surface water features (lakes, streams, and wetlands) is simulated explicitly;
- The model incorporates new interpretations of the hydraulic properties of aquifers and aquitards;
- A graphical user interface provides rapid data entry and better visualization of model results such as groundwater pathlines.

3. Approach

The project to simulate shallow and deep groundwater flow in southeastern Wisconsin is based on extensive data compilation and some new data collection, combined with numerical model development.

Data Collection and Compilation

The scope of the regional project included the compilation, synthesis, and re-interpretation of existing geologic and hydrogeologic data from numerous sources. Basic data for the project were obtained from geologic logs and well construction reports on file at the WGNHS, and from long-term records of groundwater levels maintained by the USGS. In addition, the project team undertook an extensive review of previous hydrogeologic studies in southeastern Wisconsin and in neighboring states.

Several recent and concurrent studies in southeastern Wisconsin made important contributions to this regional synthesis:

- an assessment of shallow hydrogeology, groundwater flow and the configuration of the water table (SEWRPC/WGNHS, 2002);

- a characterization of the hydrostratigraphy of the deep sandstone aquifer in southeastern Wisconsin (Eaton and others, 1999);
- a detailed analysis of hydraulic characteristics of the Maquoketa Formation, an important regional aquitard (Eaton, 2002);
- an evaluation of groundwater recharge based on hydrograph separation and basin characteristics (Cherkauer, 1999, 2001); and,
- Pleistocene geologic mapping for Waukesha County (Clayton, 2001) and other southeastern Wisconsin counties.

Data collection for the groundwater flow model also included the acquisition of new geophysical logs from eleven deep municipal wells in the area. Geophysical logging is the measurement of physical and chemical properties of the rock formations and borehole fluids using wireline tools in open wells. A typical suite of logs obtained for this project includes natural gamma radiation, single-point resistance, borehole diameter, spontaneous potential, fluid temperature and conductivity, and borehole flow. In three wells, we also conducted dynamic flowmeter tests (Paillet, 2000) to estimate aquifer parameters (Jansen, 2001). Analysis of these geophysical logs also provided new measurements of hydraulic head in deep wells. Table 1 lists the wells logged during this project and describes the data collected.

After compiling available data, the project team developed a new conceptual hydrostratigraphic framework for the study area. This conceptual understanding is based on the synthesis of data sets from WGNHS deep well log records, geographic information system (GIS) coverages, and surface water records for southeastern Wisconsin.
The data sets include:

- top and bottom surfaces of shallow and deep hydrostratigraphic units;
- maps of location and depth of bedrock valley networks;
- estimates of horizontal and vertical hydraulic conductivity in hydrostratigraphic units based on well pumping data, segregation of coarse-grained and fine-grained well log intervals and observation of regional bedrock weathering;
- digital records of surface water stages along major streams in the seven-county SEWRPC region as well as parts of three counties immediately to the west.

Table 1. Geophysical logs for municipal wells in Waukesha County obtained for this project

WGNHS ID[1]	WUWN[2]	Owner[3]	Well #[4]	date logged	depth logged[5] (ft)	lithology samples[6]	natural gamma	caliper	resistance	normal resistivity	fluid temp	fluid cond	impeller flowmeter	heatpulse flowmeter	video	dynamic flow[7]	discrete H2O samples[8]
WK0855	BH413	New Berlin	5	6/12/2000	1667	x	x		x						x		
WK1501U	BH415	New Berlin	7	6/14/1999	1919	x	x		x		x	x			x		
WK1511	BH416	New Berlin	8	5/14/2001	1940	x	x		x	x	x	x	x	x	x	x	x
WK1382	MK401	New Berlin	10	11/9/1998	320	x	x		x								
WK0137	BH443	Pewaukee	2	3/15/2000	949	x	x		x		x	x					
WK1389	LK033	Pewaukee	9	8/16/1999	1390		x	x	x		x	x		x	x		
WK1352	-	Sussex	5	3/29/2000	1240	x	x	x	x		x	x	x	x	x	x	x
WK0007	BH429	Waukesha	3	5/7/2001	1550	x	x	x	x		x	x		x	x		
WK0125	BH431	Waukesha	5	12/16/1999	1890	x	x		x		x	x		x	x		
WK0168	BH432	Waukesha	6	5/3/1999	2050	x	x	x	x		x	x					
WK0887	BH435	Waukesha	9	3/12/2001	2100	x	x	x	x	x	x	x	x	x	x	x	x

[1] ID assigned by WGNHS
[2] Wisconsin Unique Well Number
[3] Water utility
[4] Water utility designation for well
[5] Maximum depth logged (often less than total depth due to obstructions)
[6] Rock cuttings available from WGNHS
[7] Flowmeter logging while well was pumped
[8] Water samples collected using thief sampler from discrete depth intervals

Numerical Model Construction

The regional groundwater flow model of southeastern Wisconsin uses the MODFLOW96 code, originally developed by the USGS (McDonald and Harbaugh, 1988). This finite-difference code can simulate groundwater flow through aquifers and aquitards interacting with surface water in three dimensions under both steady and transient conditions. The code simulates three-dimensional hydraulic head and flux distributions over the entire model domain based on inputs in the form of boundary conditions, aquifer and aquitard geometry, hydraulic properties, pumping rates, and recharge. The model simulates all major current and historic municipal wells in southeastern Wisconsin (using the MODFLOW Well package). The model also simulates flow into and out of major surface-water features in the area (using the MODFLOW River, Drain and General Head Boundary packages). Use of the graphical user interfaces Groundwater Vistas (Environmental Simulations Inc., 1998), and GMS (Groundwater Modeling System, Environmental Modeling Systems, Inc., 2000), facilitated model construction, data entry, and visualization of results. The Groundwater Vistas interface also includes graphical representation of stream flux and water levels measured at particular locations in the model that were used in model calibration.

Nearfield and Farfield

The model domain consists of a *nearfield* portion coincident with the seven-county SEWRPC region and parts of three adjoining counties (Dodge, Jefferson, and Rock), and a *farfield* portion extending well into the state of Michigan to the east, into Illinois to the south, into the middle of Wisconsin to the west, and as far as Green Bay to the north (Figure 1). The nearfield is the focus of the model results and is the area of greatest detail in the model. The nearfield extends beyond the seven-county area into Dodge, Jefferson and Rock Counties in order to include the full extent of recharge areas for wells pumping within the SEWRPC region. The hydrogeologic conditions assigned to the farfield ensure that the correct amount of water enters or exits the study area at different depths at different times in response to stresses such as pumping. The database for the tops and bottoms of hydrostratigraphic units in the nearfield was extended to the farfield based on regional studies for Michigan, Illinois, and Wisconsin (Eaton and others, in preparation). The distribution of hydraulic conductivity for the farfield is based on previous modeling work conducted by the U.S. Geological Survey for the Chicago-Milwaukee model (Young and others, 1988, Young, 1992a). Recharge and surface-water/groundwater interactions are not explicitly modeled in the farfield except in areas immediately adjacent to the nearfield.

The location, stages, and routing of water bodies in the nearfield portion of the model were derived by combining digital hydrography and digital elevation model (DEM) data using a geographic information system (GIS). The 1:100,000-scale hydrography data (USGS, 2001a) contain very detailed location information for streams, lakes and wetlands. The DEM data (USGS, 2001b) have a grid resolution of 30 meters (98.4 ft) and represent land elevations and surface-water elevations. Using the GIS, the hydrography data were subdivided into unique line segments representing the surface-water features in model cells. These line segments were ordered in a downstream direction using a GIS routine, and their elevations within model cells were taken from the DEM, which yielded the stream, lake and wetland stages used in the nearfield portion of the model.

Model Calibration

Model development and calibration took place in two stages. First, an initial steady-state model represented predevelopment conditions in the absence of pumping. Second, a transient model corresponding to changing conditions between 1864 and 2000 simulated the effect of pumping on regional water levels. The steady-state and transient models of past conditions are the basis for simulations of future conditions that incorporate expected pumpage. They are also the basis for more detailed inset models (refined models for areas within the existing regional model) that are aimed at helping communities meet projected water demand by optimizing well configurations. A modeling study that targets the effect of proposed shallow pumping on surface-water bodies near the village of Eagle in Waukesha County is already underway to demonstrate the inset approach.

Model calibration consisted of repeated comparisons of model outputs (heads and fluxes) to targets of measured or estimated field conditions (water levels and stream flows) followed by adjustment of model parameters in order to improve the model fit. Repeated perturbations of parameter values generated statistical measures of model sensitivity that guided the calibration process. More detail on model calibration is provided in Section 7 of this report.

Water Use

Groundwater has been a valuable resource in southeastern Wisconsin for more than 100 years. Groundwater usage was quantified by compiling pumping rates for individual high capacity wells that serve as input or "stress" for the transient groundwater flow model. The compilation covers the time-period from 1864 to 2000. It includes pumping rates for 794 high-capacity industrial, agricultural and municipal wells for the entire nearfield model area (the seven SEWRPC counties plus Dodge, Jefferson, and the eastern half of Rock County), and 508 high capacity wells representing pumping centers for the farfield area (northern Illinois, northeast Wisconsin, western Rock County and Dane County).

Pumping data used in the model were compiled from a number of published sources (Chamberlin, 1877; Wiedman and Schultz, 1915; Young, 1976; Lawrence and Ellefson, 1982; Lawrence et al, 1984; Young et al, 1988; Jansen and Rao, 1998) as well as from Wisconsin Department of Natural Resource (WDNR) records and from Illinois State Water Survey publications (Visocky, 1997). The pumping history for the seven-county SEWRPC region has been compiled for the 15 periods shown in Table 2.

Although pumping rates for municipal wells were generally available, there are few records of actual pumping rates for industrial and other non-municipal wells. Major industrial pumpage in the greater Milwaukee area was compiled in earlier modeling efforts and those rates were used when and where available. The number of industrial and non-municipal wells for which there were no records of pumping rates is about 10% of the total number of wells in the model. Pumping rates for those wells were estimated using pumping-test and pump-capacity data from individual well construction reports on file with the WDNR and WGNHS.

Estimated total pumping in the seven-county region is currently 93 million gallons per day (mgd) (Ellefson and others, 1997). The flow model withdraws about 64 mgd from municipal and non-municipal wells in this area for the 1990-2000 period (Table 2). The difference between estimated pumping and simulated pumping occurs because most domestic wells were not simulated. In unsewered areas, private residential pumpage returns as recharge to shallow groundwater via septic systems, and does not represent a net loss to the groundwater system. For 1979, private residential pumpage was estimated to be 23% of total withdrawals (Lawrence and Ellefson, 1982). Assuming that 77% of the pumping is from wells that do not return flow to the groundwater, then the model should account for about 72 mgd in 2000 rather than only 64 mgd. The apparent shortfall is probably due to industrial pumping for which records are unavailable, particularly in Milwaukee County. However, the actual shortfall might not be as large as 8 mgd if the ratio of private residential pumping to total pumping has grown over time with the increased pace of residential development, especially in Waukesha, Washington and Walworth counties.

Table 2. Pumping periods and withdrawals from the 7-county SEWRPC area[1].

Period	Span	Withdrawals[2] (million gallons per day) Shallow[3]	Deep[4]	Total
1	1864-1880	0.00	0.00	0.00
2	1880-1900	0.01	0.07	0.08
3	1900-1910	0.04	0.64	0.68
4	1910-1920	0.62	3.30	3.92
5	1920-1930	0.89	5.96	6.85
6	1930-1940	1.66	11.07	12.73
7	1940-1945	3.25	15.85	19.10
8	1945-1950	4.18	16.93	21.11
9	1950-1961	5.11	18.02	23.13
10	1961-1965	6.86	18.99	25.85
11	1965-1970	9.79	23.48	33.27
12	1970-1980	12.67	25.38	38.05
13	1980-1985	20.44	30.62	51.06
14	1985-1990	22.84	31.13	53.97
15	1990-2000	30.34	33.52	63.86

[1] Kenosha, Milwaukee, Ozaukee, Racine, Walworth, Washington and Waukesha Counties.
[2] High-capacity municipal and industrial wells excluding private residential wells.
[3] Unlithified deposits and Silurian aquifers.
[4] Sinnipee dolomite and Deep Sandstone aquifer.

For 623 out of 794 nearfield wells, complete data (pumping rates, open interval elevations, and locations) were available through the USGS and WGNHS databases. The remaining 171 wells from the USGS regional groundwater flow model of the Chicago-Milwaukee area (Young and others, 1988) had pumping records up to 1985 and known locations but no information on their open or screened elevations. Pumping from these wells was assumed to be in the upper sandstone aquifer, which is consistent with well construction patterns for the time period 1864 to 1980.

Also included in the model pumping database are the withdrawals from the Milwaukee Metropolitan Sewerage District (MMSD) Deep Tunnel that, since its construction in the early 1990s, intercepts groundwater in the Silurian dolomite underneath Milwaukee County. The withdrawal rate of 2.8 mgd (Rust/Harza, 2002) is applied in the appropriate locations for the 1990-2000 model pumping period.

The pattern of groundwater pumping in the seven-county SEWRPC region has changed over time (Figure 2). Although the deep groundwater system still supplies a majority of the groundwater pumped, use of the shallow system is increasing at a similar rate (Figure 2a). A correlation between population increase and groundwater use over time (Figure 2b) will be used to implement pumping scenarios in the model based on predicted population growth.

Milwaukee County was the largest consumer of groundwater in the mid-20th century (Figure 3), but it has since been surpassed by all but Kenosha County, and today uses relatively little groundwater. Groundwater water use from high-capacity wells peaked in Milwaukee County in the 1940s at 12 millions of gallons per day (mgd) and then steadily decreased due to increased reliance on water from Lake Michigan. This change was driven by head decreases in the deep groundwater system, as well as lack of capacity and increased susceptibility to contamination in the shallow system.

Waukesha County became the largest consumer of groundwater in the 1960s (Figure 3), and now accounts for more than one-half (36 mgd) of all groundwater withdrawn from the aquifers by high capacity wells in the SEWRPC region. In Waukesha, use of shallow aquifers (Figure 3) was negligible up to the 1960s, but it has since increased so that today approximately one third of total pumpage is from the shallow aquifers. Washington and Ozaukee counties are still mostly dependent on the shallow aquifers. Racine County is more dependent on the deep sandstone aquifer, and Walworth County relies equally on shallow and deep wells. Washington, Ozaukee, Racine, and Walworth counties all use similar amounts of water (5-10 mgd). The amount of groundwater withdrawn by

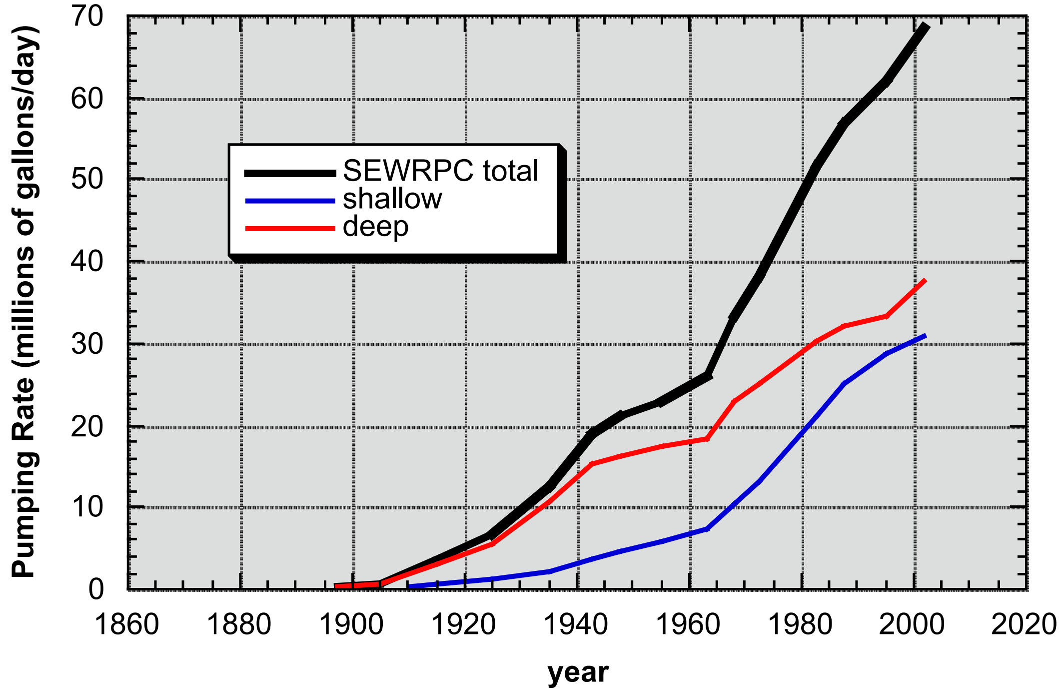


Figure 2a. Pumping rates for the entire 7-county SEWRPC region. Shallow and deep rates.

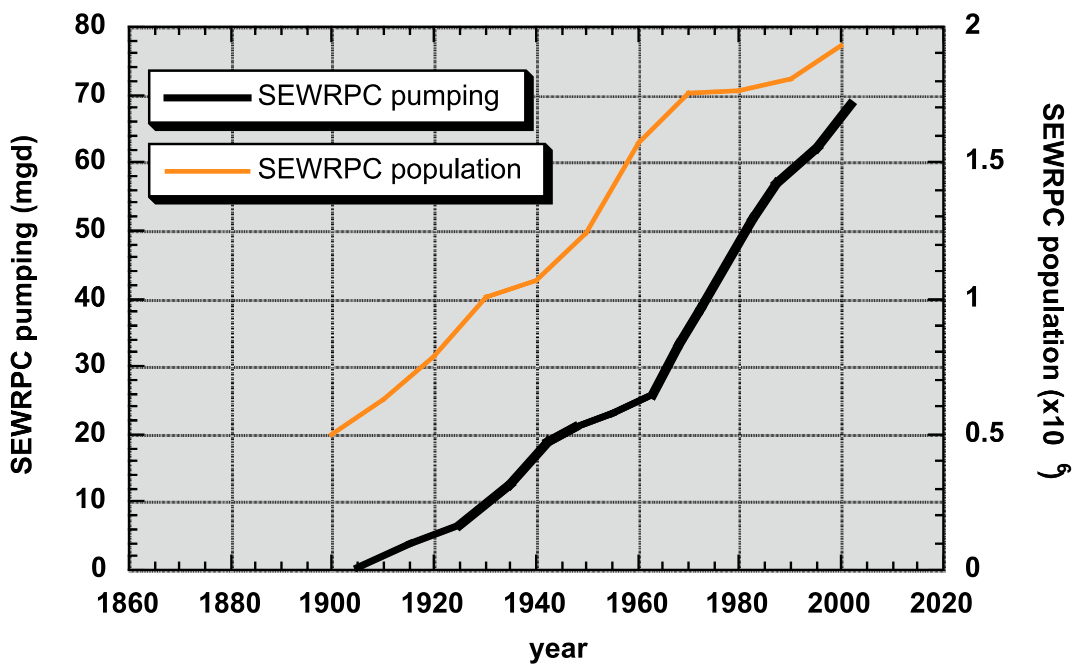


Figure 2b. Pumping rates for the entire 7-county SEWRPC region. Comparison of pumping and population trends.

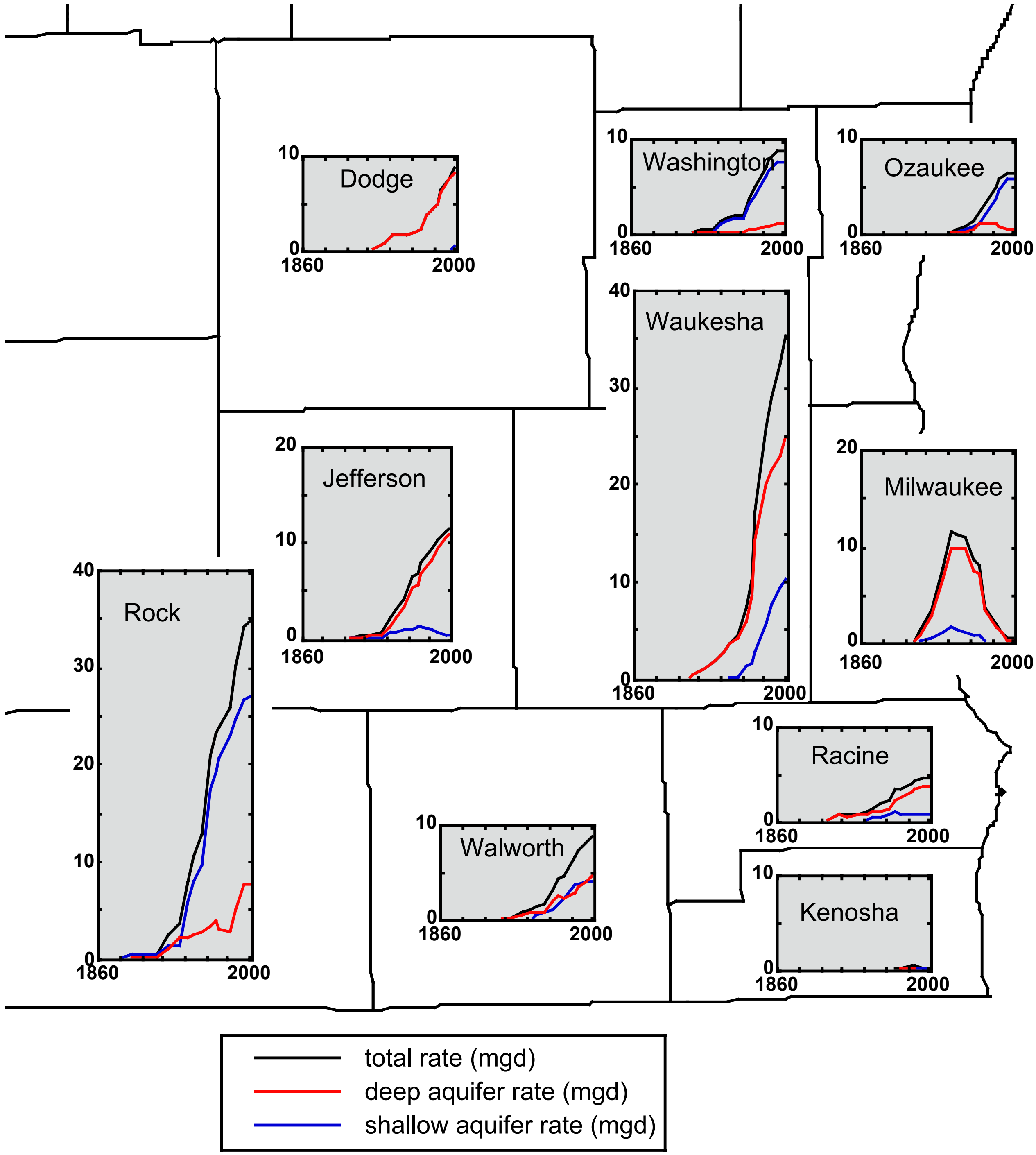


Figure 3. Shallow and deep pumping rates by county for the model nearfield.

The vertical and horizontal scales are the same for all inset graphs but the limits of the vertical scales have been extended for Waukesha, Milwaukee, Jefferson, and Rock counties.

Milwaukee and Kenosha Counties is negligible (<1 mgd) when compared to the five other SEWRPC counties.

Water use in the three counties to the west of the SEWRPC region is also shown in Figure 3. The total groundwater usage rate in Rock County is nearly as large as that used in Waukesha County except that most groundwater in Rock County is withdrawn from thick sand bodies in the unlithified sand-and-gravel aquifer near the Rock River. Both Dodge and Jefferson Counties use the deep sandstone aquifer to supply most of their groundwater needs.

4. Conceptualization of the Groundwater System

For simulation of groundwater flow, a conceptual model of the system is essential because it forms the basis for model development. The conceptualization is a necessary simplification of the natural system because inclusion of all the complexities of the natural system into a computer model is not feasible. Steps in the development of the conceptual model are:

1) definition of aquifers and aquitards,
2) identification of shallow and deep parts of the flow system,
3) identification of sources and sinks, and
4) identification and delineation of hydrologic boundaries encompassing the area of interest.

Aquifers and Aquitards

The bedrock hydrostratigraphy of southeastern Wisconsin (Eaton and others, 1999) consists of Paleozoic sedimentary units generally thickening to the east. In most places, Pleistocene deposits of till, sand and gravel, or lake sediment cover the bedrock units, and bedrock outcrops are rare. The basic framework of the hydrostratigraphy is presented in Figures 4a and 4b. The deep sandstone aquifer, corresponding to Cambrian-Ordovician

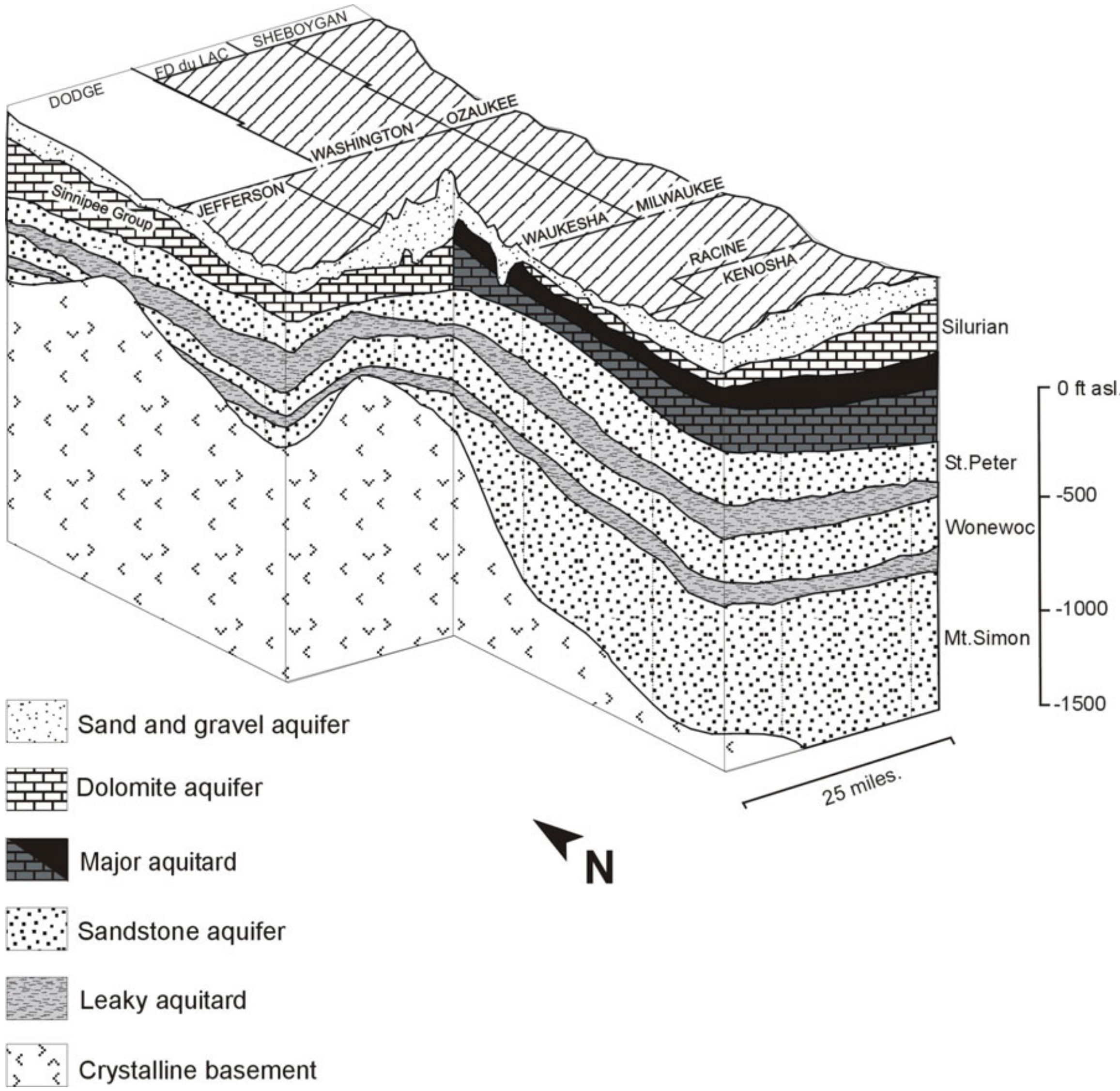
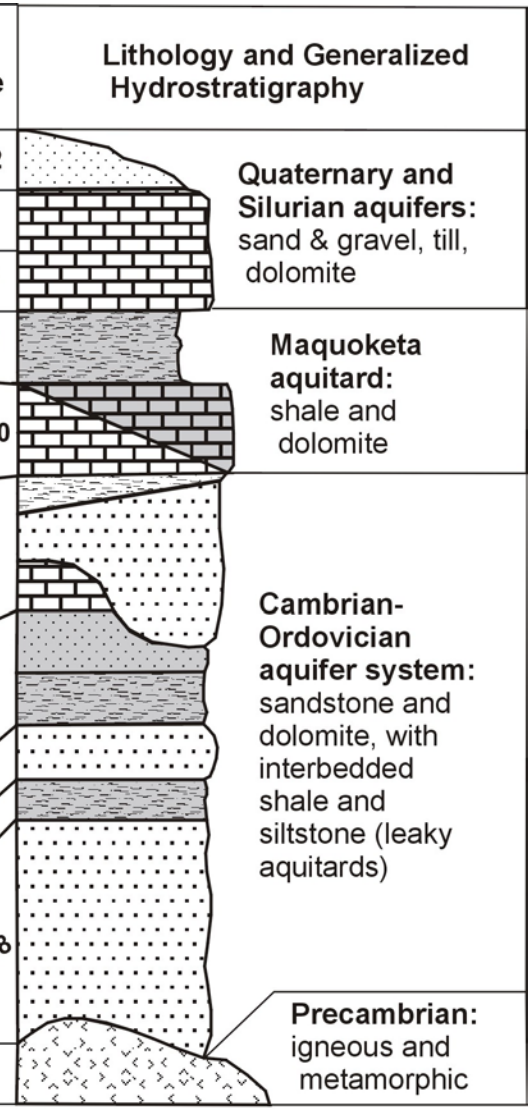


Figure 4a. Schematic diagram showing regional hydrostratigraphic framework in southeastern Wisconsin (SEWRPC/WGNHS, 2002). Vertical exaggeration ~100x

Stratigraphic Nomenclature		Initial hydraulic values		Calibrated hydraulic values		Model Structure
Group	Formation	Kh (ft/d)	Kv (ft/d)	Kh (ft/d)	Kv (ft/d)	
Quaternary	(undiff.)	0.003-7	0.001-0.1	0.2-100	0.005-1	Layers 1-2
Devonian	(undiff.)	30	0.03-0.1	30	0.03-0.1	Layer 4*
Silurian	(undiff.)	1-4	0.001-0.1	1-4	0.001-0.1	Layers 5-6
	Maquoketa	0.0003-0.3	0.0001-0.001	0.0003-0.3	0.000005-0.001	Layers 7-8
Sinnipee**	Galena	0.003-0.3	0.0001-0.01	0.04-0.3	0.0005-0.01	Layers 9-10
	Platteville					
Ancell	Glenwood	1-5	0.001-0.1	1.2-6	0.0004-0.04	Layer 11
	St. Peter					
Prairie du Chien	(undiff.)					
Trempealeau	Jordan	0.5-2	0.0001-0.01	0.24-2.4	0.00004-0.004-	Layer 12
	St. Lawrence					Layer 13
Tunnel City	(undiff.)					
Elk Mound	Wonewoc	3-7	0.001-0.1	2.4-8.4	0.0004-0.04	Layer 14
	Eau Claire	0.5-2	0.0001-0.03	0.6-3.6	0.00004-0.004	Layers 15-18
	Mt. Simon	1-5	0.0003-0.1	1.2-6	0.00012-0.04	
Precambrian		not simulated				



*Layer 3 not shown because it represents Mesozoic rock that is absent in southeastern Wisconsin

**The Sinnipee is an aquitard below the Maquoketa and an aquifer to the west. Where the Maquoketa is present, the upper layer of the Sinnipee Kh=0.04 and Kv=0.0005 ft/day. Where the Maquoketa is absent, the Sinnipee Kh=0.3 and Kv=0.01 ft/day. For the lower layer of the Sinnipee, Kh and Kv values depend on proximity to the unit's western subcrop.

Figure 4b. Simplified stratigraphic nomenclature and hydrostratigraphic column in southeastern Wisconsin (from Ostrom, 1967). Multiple hydraulic conductivity values were used for parameter zonation in the nearfield. Units shaded gray represent aquitards.

units, rests on the Precambrian crystalline basement rocks, which transmit little water and form the bottom boundary to the aquifer system. In ascending order, the major water-producing units of the deep aquifer are sandstones of the Mt. Simon Formation, the Wonewoc Formation and the St. Peter Formation.

Between the Mt. Simon Formation and the Wonewoc Formation lies the Eau Claire Formation, composed of shale and sandstone. A laterally extensive shaly zone within the Eau Claire Formation forms an important aquitard, the Eau Claire aquitard, over much of southern Wisconsin. Rocks of the Trempealeau and Tunnel City Groups, between the Wonewoc and St. Peter Formations, also form a leaky aquitard made up of interbedded sandstone, shale, siltstone and dolomite. Overlying the St. Peter Formation, dolomite of the Sinnipee Group and shale of the Maquoketa Formation together make up a major aquitard between deep and shallow aquifers. The Sinnipee Group dolomite was of particular interest in our hydrostratigraphic conceptualization because its hydraulic properties depend on whether it is overlain by the Maquoketa shale. Where it is not, and forms the uppermost bedrock unit, it is highly weathered, relatively permeable, and is considered part of the deep sandstone aquifer (Figures 4a, 4b). Deep wells are generally cased through the Maquoketa shale and open from the Sinnipee to the St. Peter sandstone or lower in the deep part of the flow system. The Silurian aquifer, predominately dolomite, and the unlithified Pleistocene materials (till, sand and gravel, and lake sediment) constitute important shallow sources of public and domestic water supply.

The Mt. Simon Formation, which is absent to very thin in parts of Washington County and thickens to over 1500 ft in northeastern Illinois, dominates the three-dimensional geometry of the deep sandstone aquifer in the study area. Much of this thickening occurs abruptly along a southwest-northeast fault zone across Waukesha County. This feature is commonly called the Waukesha Fault zone, but its geometry and characteristics are poorly understood. In the thickened section of the Mt. Simon, geophysical logs suggest the presence of a fine-grained interval that extends from about 500 ft to 800 ft below the top of the unit over much of southeastern Wisconsin. The overlying Eau Claire Formation, the Wonewoc Formation and the Trempealeau-Tunnel City Groups are thin (less than 200 ft thick), relatively planar and not continuous throughout the study area. In contrast, the St. Peter Formation varies in thickness but is generally continuous. Eaton and others (1999) mapped contact surfaces between the individual formations in southeastern Wisconsin using the subsurface well database at WGNHS. Some of the minor formations in the stratigraphic column (Figure 4b) are thin and discontinuous across the study area. Relatively few well logs show the Devonian or Prairie du Chien Groups, or individual formations of the Trempealeau Group. For the purposes of this SEWRPC model, these units are lumped into larger packages together with the Silurian dolomite, the St. Peter Formation and the Trempealeau-Tunnel City Groups, respectively.

All southeastern Wisconsin sedimentary rocks dip gently to the east and south, and erosion at the bedrock surface has truncated the uppermost units so that the Maquoketa Formation and overlying rocks are only present in the eastern part of the study area. Unlithified Pleistocene materials blanket these rocks at thicknesses of less than 25 ft to over 400 ft in areas where the bedrock surface is incised. Well logs were used to map areas where the glacial material is greater than 200 ft thick (Figure 5). These buried valleys cut down through the shallowest bedrock: the Silurian-Devonian dolomite, the Maquoketa shale and the Sinnipee Group dolomite. Where the Sinnipee Group dolomite is the uppermost bedrock unit in the west, it forms a minor part of the deep aquifer system. Unlithified Pleistocene materials can form aquifers in areas where they are sufficiently thick and dominated by sand and gravel, but are aquitards near Lake Michigan where they are primarily clays and silts.

The buried bedrock valleys are potential sources of recharge to the deeper bedrock aquifers because they form flowpaths for shallow groundwater to move to the top of the deep sandstone aquifer with little or no resistance from intervening bedrock units. West-east (Figure 6) and south-north (Figure 7) cross sections near the city of Waukesha show hydrostratigraphy and intersect bedrock valleys. The deep sandstone units (especially the Mt. Simon) thicken east of the Waukesha fault (Figure 6). The sandstone sequence also thickens toward the Illinois Basin (Figure 7).

The Waukesha fault zone is not explicitly included in the model. Exploratory simulations indicated that inserting either a high or low permeability band across the vertical extent of the

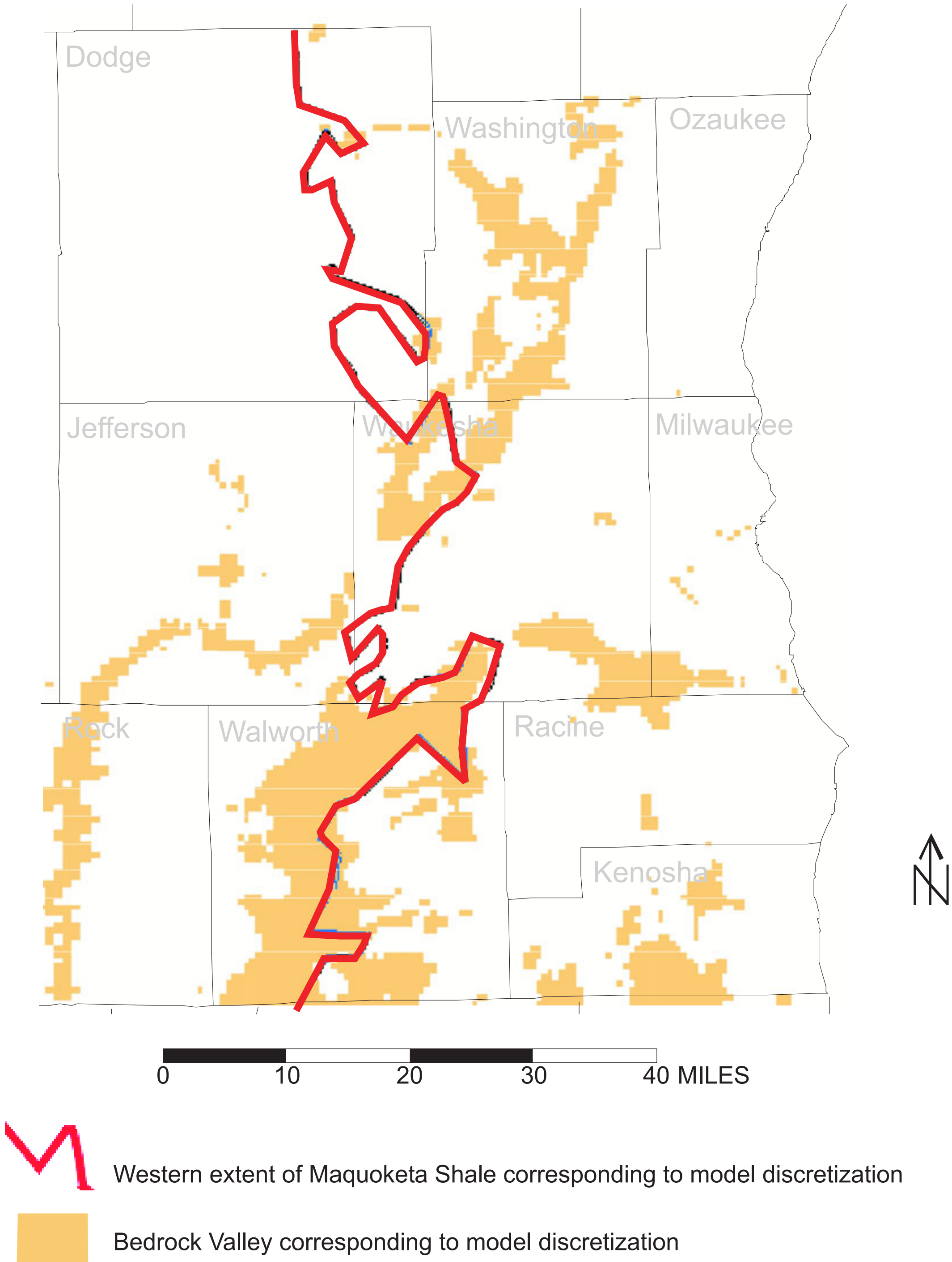


Figure 5. Bedrock valleys in the nearfield.

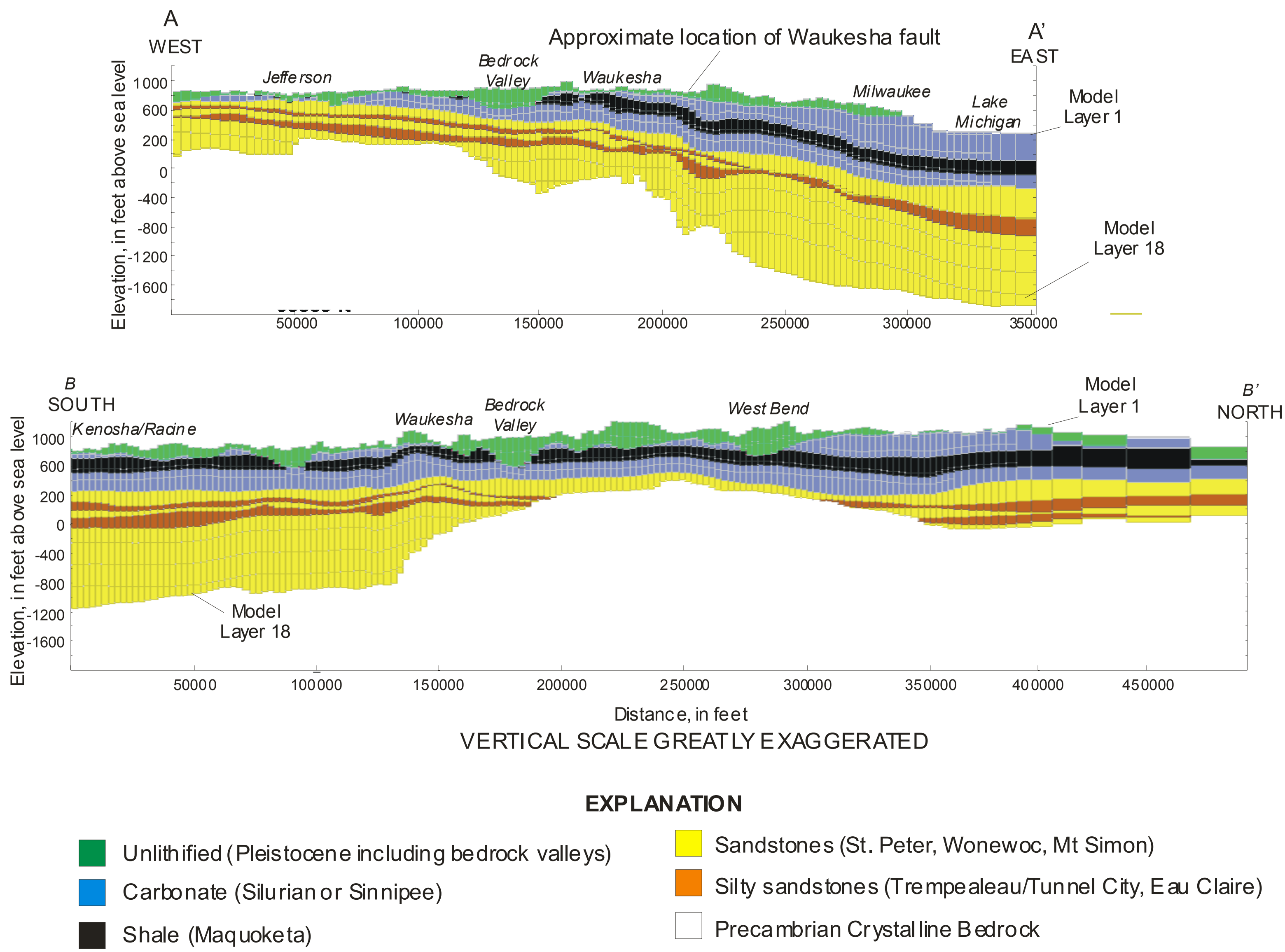


Figure 6. Hydrostratigraphy by model layer along model row 120. Trace of section A-A' is shown on Figure 1.
Figure 7. Hydrostratigraphy by model layer along model column 87. Trace of section B-B' is shown on Figure 1.

fault zone trace had a very small influence on model results at the regional scale, and, therefore, the fault was not represented by a distinct hydraulic conductivity zone in the model. However, the fault is implicitly present to the degree that it marks a boundary across which significant thickening of units (especially the Mt. Simon sandstone) occurs on the downthrown, or eastern, side.

Shallow and Deep Parts of the Groundwater Flow System

Groundwater can move anywhere in the flow system bounded at the top by the water table and the bottom by the Precambrian crystalline bedrock basement. However, pumping wells are often restricted to one part of the system. The deep part extends from the Precambrian basement to the bottom of the Maquoketa shale and incorporates the deep sandstone aquifer and the Sinnipee Group dolomites. The shallow part extends from the top of the Maquoketa shale to the water table and incorporates the Silurian dolomite and unlithified deposits. Deep wells are open to units located below the Maquoketa shale, while shallow wells are open to units above the shale. Downward flow between the shallow and deep parts of the system, called leakage, is enhanced where the Maquoketa shale is absent, but it also occurs where the Maquoketa is present under both natural and pumping conditions.

Sources and Sinks

Recharge at the water table is the most important source of water for the groundwater system in southeastern Wisconsin. Surface water bodies such as streams, lakes and wetlands are a second potential source for groundwater, especially when they are in the vicinity of pumping wells. More often, however, surface water is a sink where local or regional flow systems terminate. The recharge rate at the land surface varies spatially and depends on factors such as the soil type, the depth to water table, the land slope, and the land cover. Most of the recharge that enters the water table circulates as groundwater along shallow flow paths back to the land surface where it discharges to streams, lakes, seeps, springs and wetlands. Shallow wells capture some groundwater that would have otherwise discharged to surface water bodies. Another portion descends to the deep part of the flow system where it follows relatively long flow paths that commonly terminate at regional discharge points beyond the Lake Michigan shoreline or at deep pumping wells. In general, Lake Michigan serves as a regional sink for shallow and deep groundwater, but it can serve as a source for wells or other features such as the MMSD Deep Tunnel underlying Milwaukee.

Boundary Conditions

Boundary conditions represent hydraulic heads or groundwater fluxes at the edges of the model domain or at the intersection of the ground-water system with other systems. The edge of the farfield, equivalent to the edge of the entire model domain (Figure 8), is treated everywhere as a no-flow boundary. Within most of the farfield, the water-table heads at the top of the groundwater system are fixed (Figure 8). These constant head boundary nodes provide a source of water to the farfield region of the model. Previous groundwater studies (Mandle and Kontis, 1992) provide adequate information to define these farfield boundary heads. The inner portion of the farfield defines a region where water-table heads are fixed in the model only along major rivers (Figure 8). This transition zone allows the model to more realistically simulate water level changes with time at the edge of the nearfield.

In the nearfield, the water table is free to fluctuate in response to the interaction of local recharge, water bodies, subsurface properties, and pumping. Internal nearfield boundaries for the groundwater system include lakes, streams, and wetlands (Figure 9). Lake Michigan represents a regional head-dependent boundary (occupying “General Head” cells) set at the long-term lake-level average of 577 feet above mean sea level. Important surface-water features such as the Milwaukee, Menomonee, Root, Rock, and Fox Rivers, their major tributaries, and major lakes are represented by a boundary type that can receive water from or supply water to the subsurface (“River” cells), while minor features such as headwaters of streams, wetlands, ponds, seeps, and agricultural drains are represented by a boundary type that can only receive water (“Drain” cells). More detail on the role of surface water bodies in the model is provided in a separate Open-File report (Eaton and others, in preparation). High-capacity pumping wells constitute a final internal boundary type in both the model nearfield and model farfield.

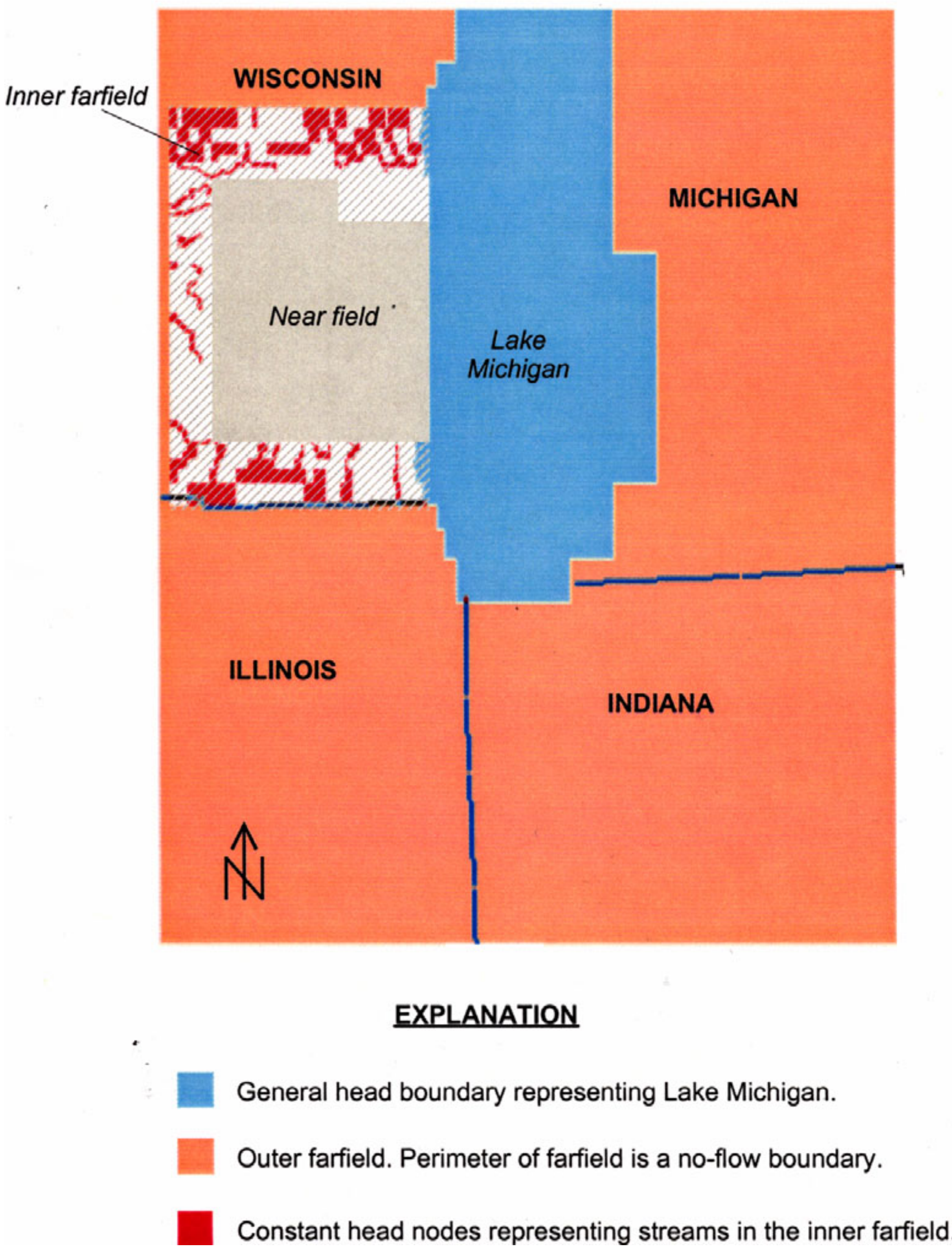


Figure 8. Boundary conditions in model farfield. Model boundary conditions conform to grid discretization, which is coarse on the eastern side of Lake Michigan.

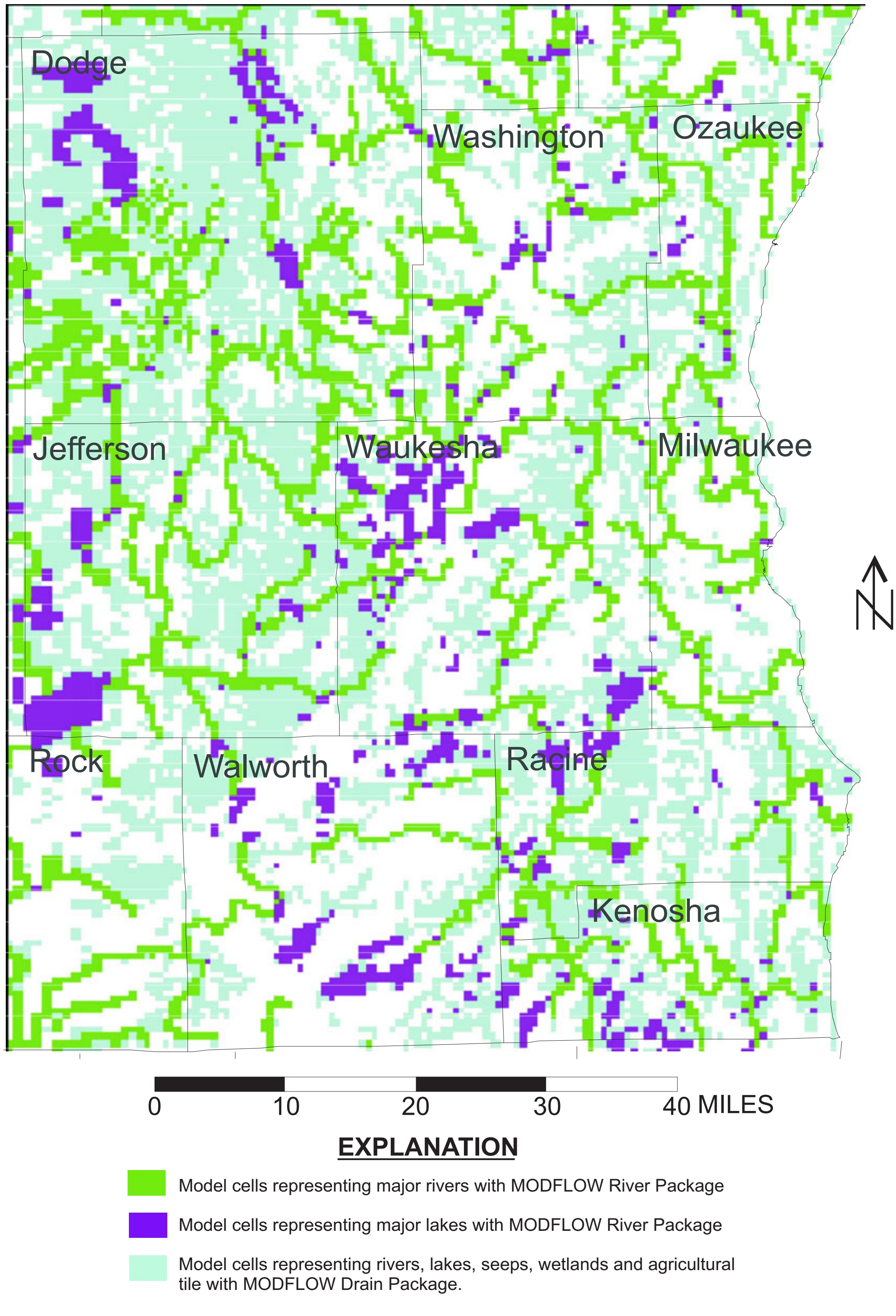


Figure 9. Representation of surface water in model nearfield.
Model River cells are 19.5 percent of the nearfield.
Model Drain cells are 30.2 percent of the nearfield.
White areas have no surface-water boundary conditions.

5. Hydraulic Properties of the Groundwater Flow System

Recharge

The most important source for groundwater in southeastern Wisconsin is recharge at the water table. The regional model uses recharge rates estimated from stream baseflow for watersheds in southeastern Wisconsin (Cherkauer, 2001). Combining baseflow separation techniques in small watersheds with a regression technique, Cherkauer (2001) estimated lumped recharge rates for hydrologic basins throughout the seven-county SEWRPC region. This derived pattern of recharge was used in the study area (Figure 10). For the western part of the nearfield that is not covered by the recharge studies, recharge is assigned a single value equal to the average Southeastern Wisconsin rate of 4.5 in/yr.

Hydraulic Conductivity

Development of a regional model requires information on the three-dimensional distribution of hydraulic conductivity across the study area and outlying areas. A summary of initial estimates and calibrated hydraulic conductivity values for all model hydrostratigraphic units is presented in the table in Figure 4b. The following discussion describes the process for estimating hydraulic conductivity for three general categories of materials: unlithified materials (sand, silt, and clay); clastic bedrock units (sandstone and siltstone); and carbonate bedrock (dolomite, shale, and limestone).

<u>Unlithified Units</u>

The hydrogeologic properties of unlithified materials are extremely variable and are related to the origin and environment of deposition of the materials. In coordination with a regional shallow groundwater and geologic study (SEWRPC/WGNHS, 2002), new maps were constructed showing the distribution of Pleistocene materials for all counties in southeastern Wisconsin (e.g., Clayton, 2001). These maps illustrate the distribution of shallow Pleistocene

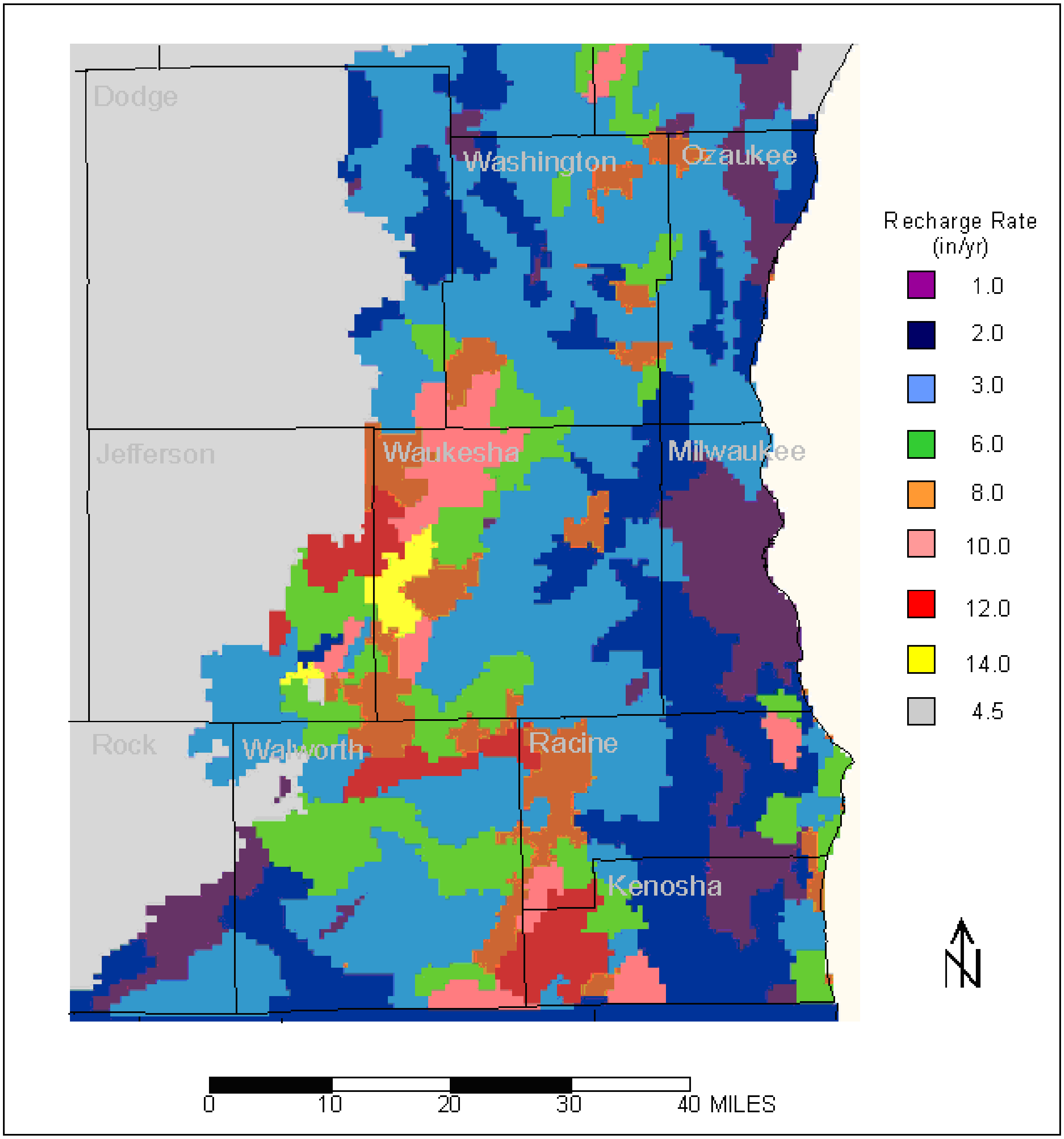


Figure 10. Recharge rate zonation in model nearfield.

materials resulting from different glacial advances and retreats, which deposited coarse sand and gravel (e.g., Kettle Moraine) as well as finer-grained sandy and clay-silt tills. We used data compiled from hydrogeologic testing (Rayne and others 1996, Simpkins 1989, Rodenbeck 1988) to estimate hydraulic conductivity of these sediments, and classified them into three categories: high, moderate and low hydraulic conductivity (SEWRPC/WGNHS, 2002). This mapped distribution of estimated horizontal hydraulic conductivity of Pleistocene materials (Figure 11a), developed initially to map groundwater vulnerability (SEWRPC/WGNHS, 2002), was used as input for the uppermost layer representing unlithified materials in the regional flow model.

Hydraulic conductivity of unlithified materials in the deeper parts of buried bedrock valleys is also quite variable (Batten and Conlon, 1993) and was estimated by quantifying the percent of fine-grained material in available well log samples. We estimated vertical hydraulic conductivity (Figure 11b) using a thickness-weighted, harmonic-mean averaging method based on the proportion of fine and coarse material in the Pleistocene section. This method is described in more detail in a separate Open-File report (Eaton and others, in preparation).

We used several different types of analyses to estimate representative values of hydraulic conductivity for each aquifer or aquitard identified in the regional hydrostratigraphy, and to assess the spatial variation of hydraulic conductivity within each unit across southeastern Wisconsin. Many different hydrogeologic investigations have been completed in the bedrock units in southeastern Wisconsin, and data from these studies were compiled into a series of tables and charts (Carlson and Feinstein, 1998).

Deep Sandstone Units

Sandstone-dominated units in southeastern Wisconsin are only found in the deep part of the flow system and the deep part of the flow system consists only of these units. They include relatively pure sandstones (the St. Peter and Wonewoc Formations) and sandstones mixed with siltstone, shale, and dolomite (Trempealeau-Tunnel City Groups, Eau Claire and Mt. Simon Formations). The model incorporates values for multiple horizontal and vertical hydraulic conductivity zones for each of these sandstone units. Several types of analyses were used to estimate their hydraulic conductivity values (Eaton and others, in preparation). First, we calculated an overall estimate of the transmissivity of the deep sandstone aquifer by averaging results of a suite of aquifer tests conducted in southeastern Wisconsin in the early 1950s (Foley and others, 1953). Dividing the average transmissivity by the average thickness of the deep sandstone aquifer (indicated by structure contour maps) yielded an average hydraulic conductivity between 2 and 3 ft/day, which compares favorably to the values from later pumping tests and packer tests conducted in southeastern Wisconsin (Nicholas and others, 1987, Young 1992b, Carlson and Feinstein 1998). We then refined the estimate of mean values and ranges of horizontal hydraulic conductivity for each unit in the Cambrian-Ordovician aquifer system from deep well specific-capacity data, using a spreadsheet-based optimization method (Eaton and others, 1999).

These expected values are a good indicator of average hydraulic conductivity for units, but they do not provide information on the spatial heterogeneity within a unit, which is likely a function of the proportion of fine-grained material. The hydraulic conductivity of each sandstone formation varies laterally in relation to the percentage of fine-grained material present in the formation. To help quantify the spatial variation, we assembled a fine-material database using hundreds of geologic logs available for the nearfield area. The database includes the elevation of intervals of fine-grained material (silty sandstone, siltstone, shale) in each stratigraphic unit. By plotting the spatial distribution of fine-grained material in each unit, we defined spatial zones where the percentages of fine-grained material were less than, about equal to, or greater than the average for each unit (Eaton and others, in preparation).

Using this zonation, we varied hydraulic conductivity in inverse proportion to the percentage of fines in each unit. The range of values for each zone preserves both the expected hydraulic conductivity for each unit and the expected transmissivity for the entire deep sandstone aquifer. The horizontal hydraulic conductivity zonation is shown in Figure 12a for a predominately coarse-grained unit, the Wonewoc Formation. The zonation is shown in Figure 13a for a more fine-grained unit, the Eau Claire Formation. The values assigned to the zones in each figure have been adjusted by the results of the calibration process described in later sections, which indicated that all the values suggested by the above analysis should be increased by a factor equal to 1.2.

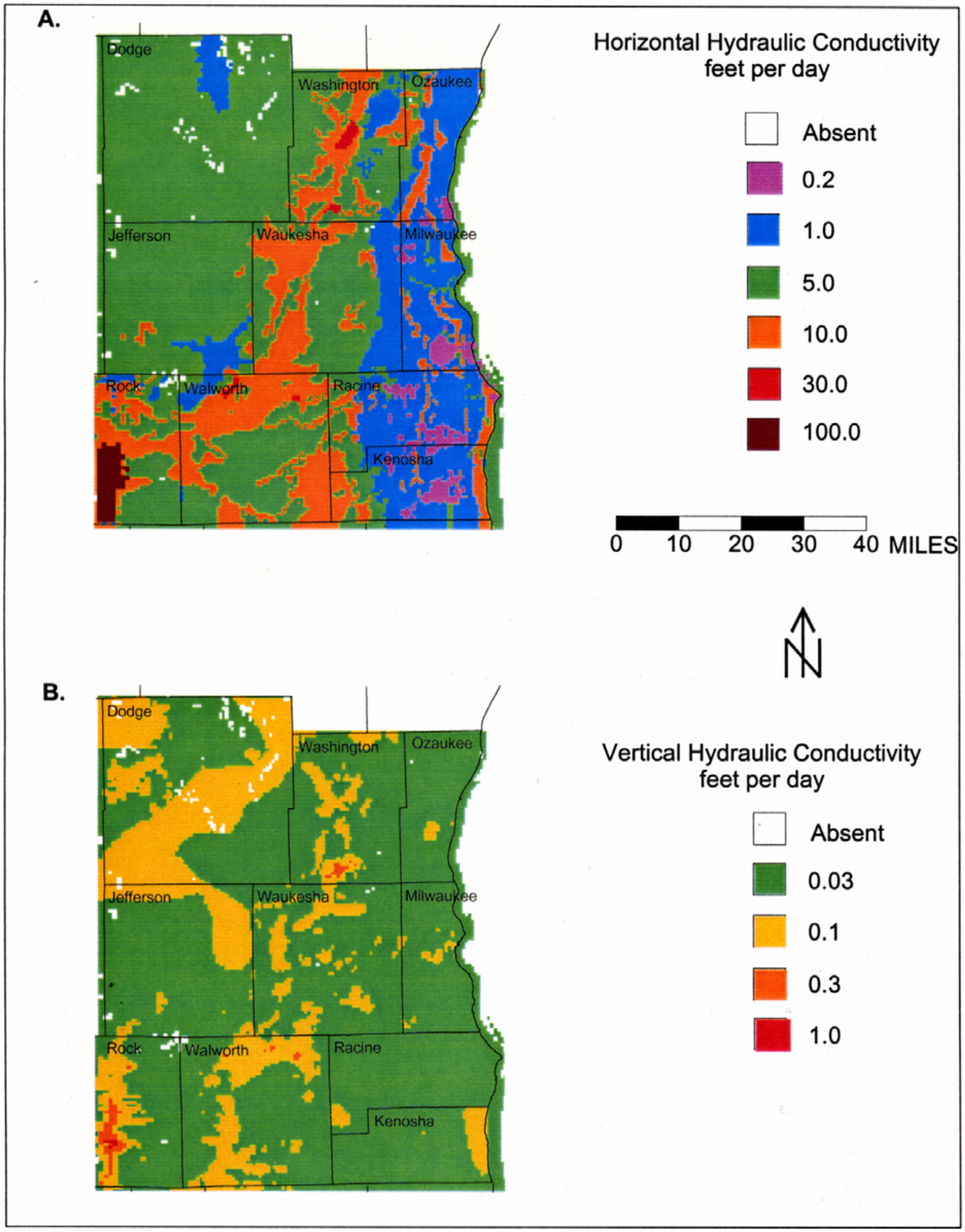


Figure 11. Hydraulic conductivity of unlithified deposits in the nearfield.
a) Horizontal hydraulic conductivity. b) Vertical hydraulic conductivity.

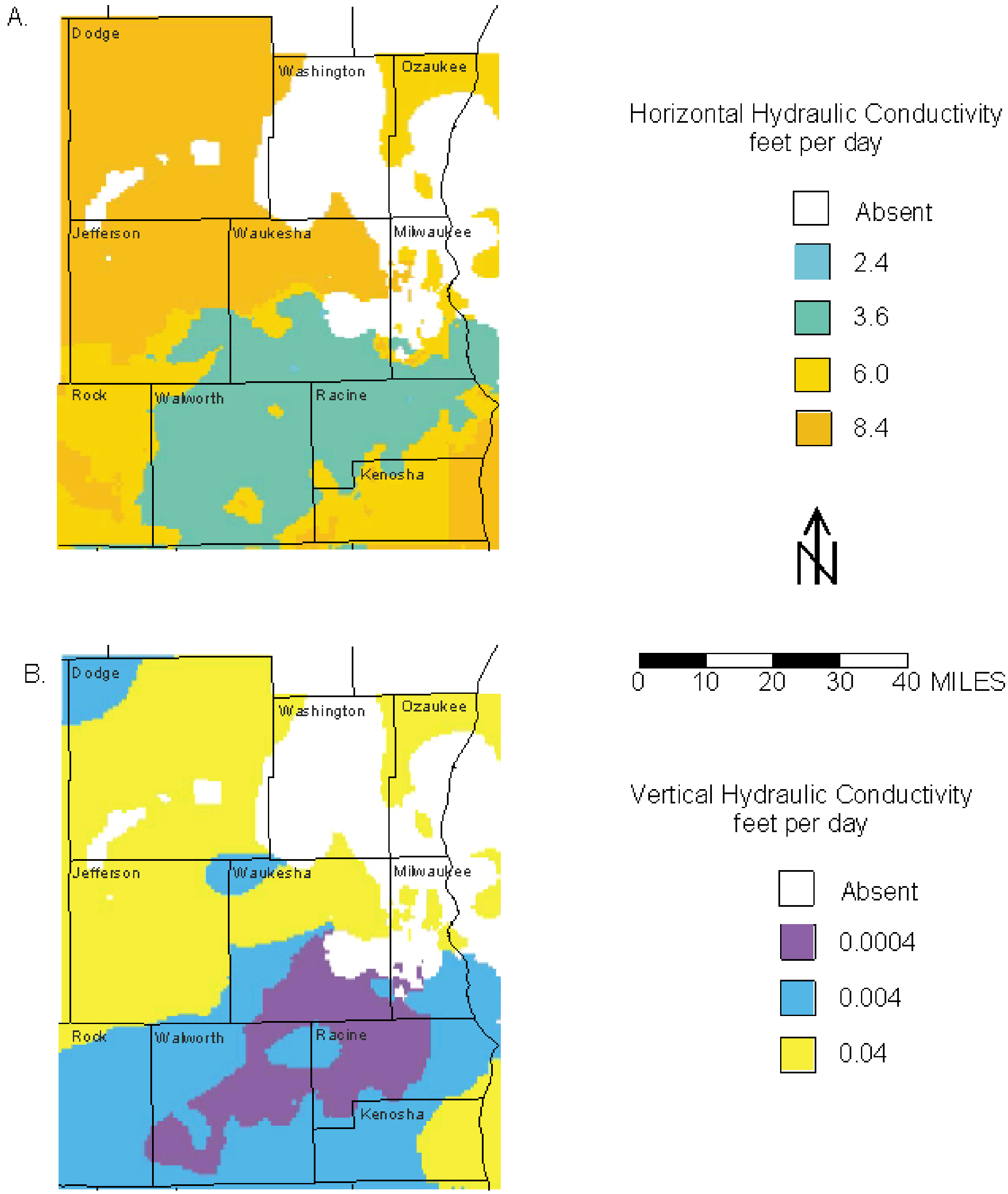


Figure 12. Hydraulic conductivity of Wonewoc Formation in the nearfield.
a) Horizontal hydraulic conductivity. b) Vertical hydraulic conductivity.

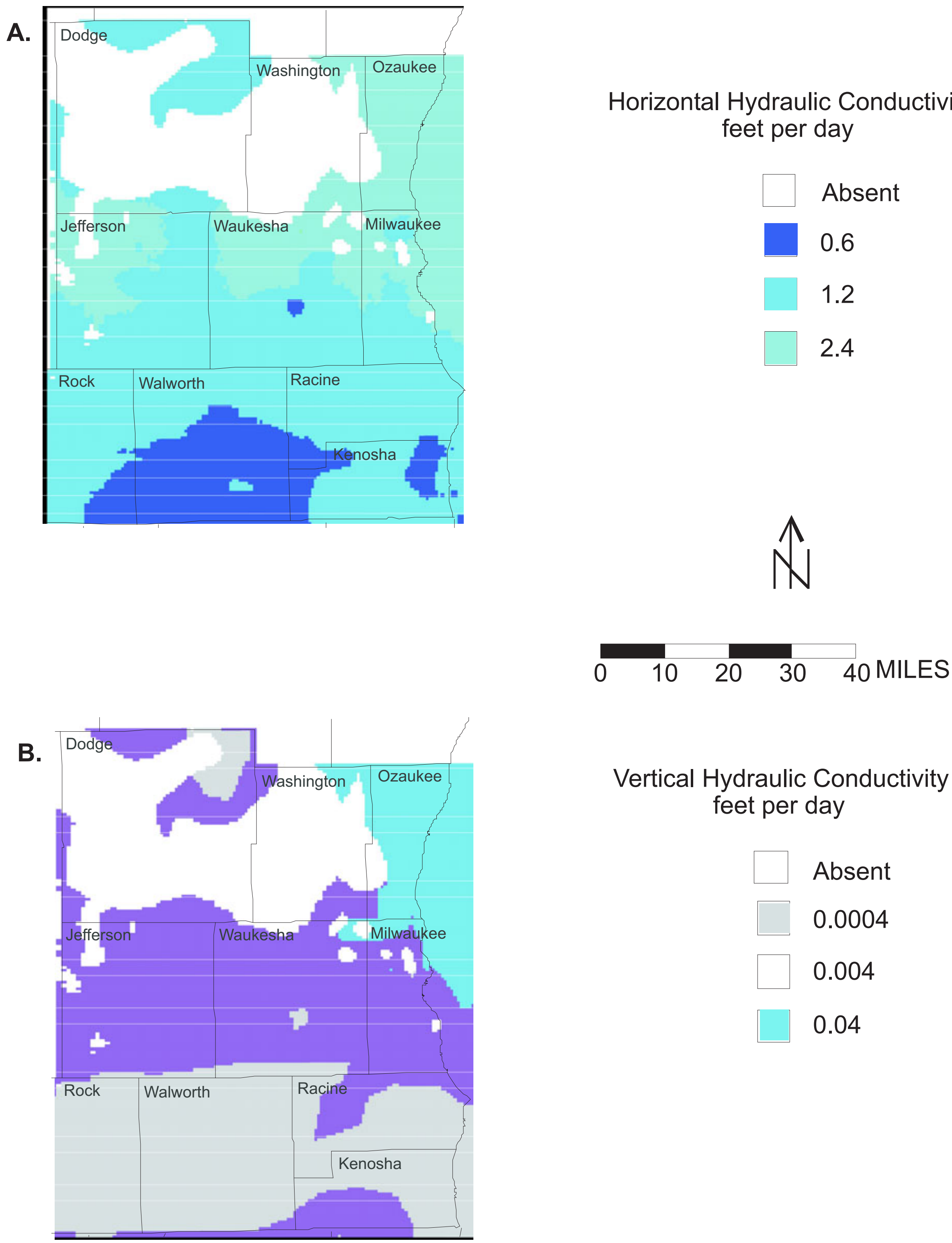


Figure 13. Hydraulic conductivity of Eau Claire Formation in the nearfield.
a) Horizontal hydraulic conductivity. b) Vertical hydraulic conductivity.

No overall estimates of vertical hydraulic conductivity are available for the distinct sandstone units. Using well data on the distribution of fine grained lithologies, we estimated vertical hydraulic conductivity in a similar way as horizontal hydraulic conductivity, except that we calculated a thickness-weighted harmonic mean across coarse and fine-grained intervals (Eaton and others, in preparation). The spatial distribution of values allowed us to define zones that grouped areas of similar vertical hydraulic conductivity for each unit. The zonation of vertical hydraulic conductivity is shown in Figure 12b for a predominately coarse-grained unit, the Wonewoc Formation. The zonation is shown in Figure 13b for a more fine-grained unit, the Eau Claire Formation.

Where the top of the St Peter sandstone is less than 200 ft from the land surface, the hydraulic conductivity of the deep sandstone aquifer units was assigned a higher value due to weathering, as has been found elsewhere (Runkel and others, 2003). This zone is restricted to the western portions of Jefferson and Dodge counties.

Figures 12 and 13 represent final hydraulic conductivity values after adjustments made as part of the model calibration process. The horizontal hydraulic conductivity values shown in the figures are 1.2 times the initial values derived from the database analysis; the vertical hydraulic conductivity values shown are 0.4 times the initial values.

<u>Carbonate Bedrock Units</u>

For carbonate-dominated formations such as dolomite of the Sinnipee Group, the Maquoketa shale and the Silurian-Devonian dolomite, the distribution of hydraulic conductivity is related to both the distribution of fine-grained lithologies and to weathering and the development of fractures. For instance, numerous investigators have reported considerably higher hydraulic conductivity values in a weathered zone near the bedrock surface (e.g., Carlson 2000, Stocks 1998) or in zones of bedding-plane (Eaton 2002, Muldoon and others 2001) and vertical fractures (Jansen 1995). A recent re-evaluation of the hydrogeologic attributes of similar Paleozoic strata based on more extensive field data in Minnesota (Runkel and others, 2003) emphasizes the importance of fracture porosity in regional hydrostratigraphy.

The spatial distribution of hydraulic properties in carbonate rocks (Figure 14) in southeastern Wisconsin assumes that fractures and dissolution enhance the hydraulic conductivity wherever these units constitute the uppermost bedrock formations. The upper 20 ft of the Silurian dolomite is considered to have a relatively higher hydraulic conductivity due to weathering (Rovey 1990). A similar weathered high-conductivity zone was mapped in the Sinnipee Group dolomite where it subcrops below unlithified material. In addition, research at field sites in Waukesha County and northern Illinois suggest that the hydraulic conductivity of carbonates is enhanced in proximity to glacial bedrock valleys even at depths greater than 20 ft because of weathering (Eaton 2002, Mills and others, 1998). The estimated extent of such a zone of high vertical hydraulic conductivity within the upper parts of the Maquoketa shale and Sinnipee Group dolomite is shown in Figure 14.

Streambed and Lakebed Leakance

The combination of hydraulic conductivity and thickness of streambeds and lakebeds controls water movement between groundwater and surface-water features. The combination of vertical hydraulic conductivity with lake- or stream-bed thickness (vertical hydraulic conductivity divided by thickness) is called leakance. Field estimates of leakance for the water bodies in southeastern Wisconsin are not available. However, if typical riverbeds are assumed to be several feet thick, riverbed leakances cluster around values of 0.1 to 10 ft/day/ft (Calver, 2001).

In Dane County, Wisconsin, measured riverbed leakances ranged between 1.6 ft/day/ft and 37 ft/day/ft, averaging 8 ft/day/ft (Krohelski and others, 2000). The value selected for streambed leakance in the southeastern Wisconsin model was 5 ft/day/ft, a value sufficiently high to allow easy communication between groundwater and surface water. Field studies generally show that water bodies such as lakes and wetlands support smaller leakances than streambeds, and fine sediment transport causes lower hydraulic conductivity in the center portion of lakebeds compared to the perimeter (McBride and Pfannkuch, 1975). For this reason the initial leakance value assigned to the outer nodes representing the perimeter of a lake or wetland was set to 0.5 ft/day/ft and the value assigned to inner nodes was 0.05 ft/day/ft.

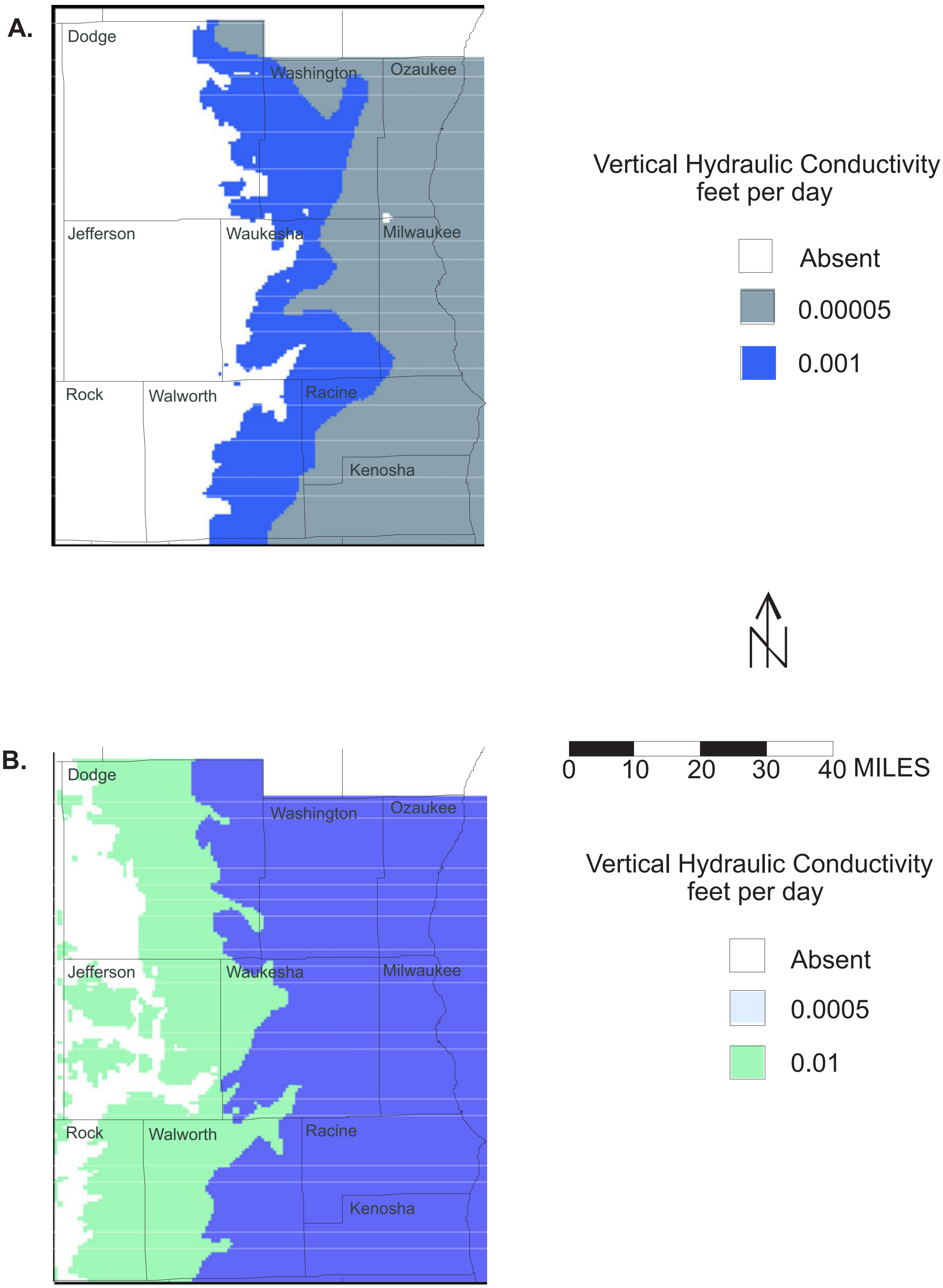


Figure 14. Vertical hydraulic conductivity in the nearfield.
a) upper layer of Maquoketa shale. b) upper layer of Sinnipee dolomite.

Exchange between groundwater and surface water is also proportional to the width and length of the surface water body. For each model cell, the area of each stream in contact with the groundwater was estimated on the basis of length information available through the GIS database. Stream widths were estimated from a series of reports on surface water resources (Ball and others, 1970, Kernen and others, 1965, Poff and others, 1964 and 1968, Poff and Threinen, 1961a, 1961b, 1961c, 1962, 1963, and 1964, Weber and others 1968, 1969).

Storage Parameters

Among the sources of water to pumping wells is storage volume released from compression of units and expansion of the water in confined aquifers (elastic storage), and drainage of pores in water-table aquifers (unconfined storage). These mechanisms are both important in southeastern Wisconsin.

A series of aquifer tests performed in the 1950s on the deep sandstone aquifer in Milwaukee and Waukesha Counties yielded storage coefficients averaging 0.00039 with a small spread among tests (Foley and others, 1953). The deep aquifer system, including all sandstone, shale, and dolomite layers, has an average thickness of 1500 ft in the areas where the tests were performed, and the specific storage corresponding to the average storage coefficient is 2.6e-7 ft^{-1}. This value was applied to all model units to represent the capacity to release water by elastic storage in the presence of drawdown from pumping.

Whenever pumping produces a decline in the water table, water is released from the subsurface material by drainage of pores. To account for this source of water, a specific yield equal to 0.15 was assigned to all the unlithified deposits in the model. This value is an estimated average specific yield for the sand, silt, and clay deposits that constitute the glacial and alluvial deposits (Anderson and Woessner, 1992). To account for the case where dewatering and unconfined conditions could occur in the Silurian, Maquoketa, or Sinnipee units, a specific yield equal to 0.01 was assigned to these carbonate units. This value reflects the predominance of fracture flow in the carbonates. Unconfined conditions can occur in the Silurian dolomite where overlying unlithified material is almost or completely absent. It is possible that it can also occur in the deeper Maquoketa or Sinnipee units near the center of the pumping cone of depression where drawdown is greatest. Finally, a specific yield equal to 0.05 was assigned to the units in the Cambrian-Ordovician system below the Sinnipee dolomite. This relatively low value for sedimentary aquifers reflects the combination of fracture and porous-medium flow in these units. Dewatering of the sandstone units is only likely to occur in the western portion of the nearfield where the St. Peter sandstone is near the surface and potentially under unconfined conditions.

6. Model Development

The steps involved in developing the three-dimensional model were:

1. construction of the finite-difference grid with model layers corresponding to the regional hydrostratigraphic units;
2. input of horizontal and vertical hydraulic conductivities based on data analysis;
3. input of boundary conditions that control surface-water/groundwater interactions;
4. initial calibration of the predevelopment steady-state model to predevelopment water levels and fluxes;
5. input of storage parameters for the transient model;
6. input of pumping wells with their locations and pumping rates into the transient model;
7 . calibration of the transient model by matching measured water levels over time to simulated values, then iterating between the predevelopment and transient models to arrive at a common parameter set.

We developed the steady state model first. This model simulates flow in the shallow and deep parts of the groundwater systems before the system was stressed by pumping wells, circa 1864. Prior to developing the more complicated transient model, the steady-state model gave us a preliminary understanding of the predevelopment flow system, and allowed us to eliminate numerical instabilities that arise when modeling large complex systems. The heads calculated by the steady-state model represent the estimated head distribution in 1864 and so are used for the initial heads of the transient model. The transient model simulates groundwater flow from the end of the predevelopment time in 1864 until the year 2000. We assume that the physical system represented by the transient model is identical to that represented by the steady state model with the exception of pumping wells. To model transient flow, specific storage and specific yield estimates were added to the steady state input parameters. The pumping rates discussed in Section 3 were discretized into 15 stress periods (Table 2) ranging in length from 5 years to 20 years for a total length of 136 years.

Grid and Layering

The entire model domain is shown in Figure 8. The model consists of 205 rows, 166 columns and 18 layers, totaling 34,030 cells per layer and about 600,000 cells in the entire model. The grid is aligned with the north-south and east-west Wisconsin Transverse Mercator (WTM) coordinate axes in feet. The X- and Y-grid spacing within most of the seven-county SEWRPC region is set to a constant value of 2500 ft. This spacing rapidly increases using an expanding mesh outside the nearfield to a maximum of almost 20 miles at the outer edges of the model domain.

In contrast to previous flow models for this region, this model is fully three-dimensional. The model simulates individual hydrostratigraphic units, both aquifers and aquitards, by either a single model layer or a series of model layers for each significant hydrostratigraphic unit. Due to erosion at the bedrock surface, and non-deposition of formations in some areas, some of the hydrostratigraphic units are not continuous across the model domain. However, the numerical code used to simulate the flow system, MODFLOW, requires that all layers be present over the entire model domain. Therefore, special provision was made for the model layers where the corresponding hydrostratigraphic units are in fact not present. Using a layer thickness of 1 foot, a high vertical hydraulic conductivity and a low horizontal hydraulic conductivity, these thin model layers are effectively transparent to regional groundwater flow. While they maintain the horizontal head distribution and prevent horizontal flow, thin layers do not obstruct vertical flow. These property distributions in thin layers enable the finite-difference grid structure to accommodate regional flow despite the discontinuous hydrostratigraphy.

Several hydrostratigraphic units are represented by multiple layers in the groundwater model. Because MODFLOW calculates a single value of hydraulic head for each node in a model layer, individual model cells in a layer have no vertical variation in head. However, due to pumping, there are significant vertical head gradients within some hydrostratigraphic units. Representing a hydrostratigraphic unit with several layers allows us to model the vertical head distribution within a single hydrostratigraphic unit. For example, we use four model layers to represent the complex head distribution in the Mt. Simon Formation.

Multiple layers are also used to represent variation in hydraulic properties within a hydrostratigraphic unit. For example, the weathered and fractured upper portions of the carbonate units in the Sinnipee Group and Silurian dolomite aquifer constitute a layer above the unweathered and more competent portions of these units.

Parameter Zonation

The hydraulic conductivity analyses discussed in Section 5 were used to create the input files for the model distribution of horizontal and vertical hydraulic conductivities for the nearfield. The farfield vertical and horizontal hydraulic conductivities were adapted from the previous regional model (Young and others 1988). To represent the hydrostratigraphic units and the variation found in these units, there are a total of 62 individual horizontal hydraulic conductivity zones and 66 vertical hydraulic conductivity zones. The aquifer storage properties were also zoned but more coarsely. Fewer data were available and the variation of specific storage is much less than that of hydraulic conductivity.

Each hydrostratigraphic unit has several conductivity zones within it to represent variation of hydraulic conductivity within each unit. That variation might be due to weathering as is the case for the change in vertical hydraulic conductivity in the Sinnipee dolomite from 0.01 ft/day in the weathered portion to 0.0005 ft/day in the unweathered portion of this unit (Figure 14b). Hydraulic conductivity zonation changes due to relatively minor lithologic variation in the unit are also included. The horizontal hydraulic conductivity of the Eau Claire Formation increases from 0.6 ft/day in the southern nearfield to 2.4 ft/day in the northern nearfield (Figure 13a). This change represents a slight variation in this unit caused by a higher percentage of fines in the south grading to a lower percentage in the north.

The distribution of storage and specific yield values in the model is less complex than the distribution of hydraulic conductivity. As discussed above, the specific storage is set constant for all the units at a value of 2.6×10^{-7} ft^{-1}; it is multiplied by layer thickness in each cell to yield the cell storage coefficient that is input to MODFLOW. The specific yield, the value of storage used in case a model layer becomes unconfined, varies from 0.15 in the unlithified deposits (both sand and till) to 0.05 in the sandstone units to 0.01 in the carbonate units.

A very low specific yield, equal to the specific storage (2.6×10^{-7}), was assigned to the upper layer of the Sinnipee, model layer 9. This zone was inserted to keep the model from exaggerating the extent of deep unsaturated conditions in the presence of strong vertical gradients. This change is discussed in more detail in a companion report dedicated to model results (Feinstein and others, 2003).

Representation of Surface Water

Surface waters interact with and are connected to groundwater. Multiple MODFLOW packages have been developed to represent the interaction between groundwater and distinct types of water bodies. This model of southeastern Wisconsin uses the General Head Boundary Package, the River Package, and the Drain Package to model various surface water bodies within the nearfield. Packages are modules within the MODFLOW groundwater flow program that control input and output for various aspects of the model such as internal boundary conditions. The nearfield surface water boundary conditions are shown in Figure 9.

The larger streams and lakes in the nearfield are simulated using the River Package. The streams are routed: that is, the stage elevations of the river cells decrease in all cases as one moves downstream. The interaction between the water bodies and groundwater is controlled by 1) the gradient between the stream or lake stage elevation and the groundwater elevation, 2) the area of the streambed or lakebed in the model cell, and 3) the streambed or lakebed leakance term (equal to the hydraulic conductivity of the bed divided by its thickness). In this model, the streambed conductance is set large but in agreement with previous estimates of streambed conductance (Krohelski and others, 2000), so that the stream elevations are very nearly equal to the groundwater elevations. This condition is to be expected for the major surface water bodies. The lakebed leakances are assigned so that most of the exchange with groundwater occurs along the lake perimeter. The river cells representing major streams and lakes constitute 19.5% of the nearfield water-table cells (Figure 9). In areas immediately adjacent to the model nearfield, simulated water bodies correspond to the major streams identified on USGS 7.5 minute quadrangle maps. This portion of the model is called the inner farfield and is identified in Figure 8. In the remainder of the model, called the outer farfield, water bodies are not explicitly simulated.

Lake Michigan is simulated as a general head boundary. The General Head Boundary Package uses an algorithm similar to the River Package to simulate the connection between surface water and the groundwater. The elevation of Lake Michigan was set to a uniform stage of 577 feet (close to long-term average as well as 2003 conditions). The conductance term was set very high so that there is negligible resistance across its bed and the adjacent simulated groundwater elevation is nearly equal to the stage of Lake Michigan. The use of a separate package for Lake Michigan facilitates the analysis of Lake Michigan's influence on the model mass balance.

Initial calibration of the steady state model showed that unreasonably high hydraulic conductivities of unlithified materials were required for model mass balance. Small surface water features could not be represented in the model using the River Package, and aquifers in the model were forced to carry water that would, in reality, discharge to surface water. To correct this deficiency, we used the Drain Package to simulate discharge to the smaller hydrologic features, amounting to 30.2% of nearfield water-table cells (Figure 9). For more detail on the addition of drains to accommodate shallow groundwater flow, see the associated Open-File Report (Eaton and others, in preparation). Discharge to these drains together with discharge to surface water bodies in river cells were compared to observed discharge at selected locations to aid model calibration.

Representation of Pumping History

The pumping rates in high-capacity wells are the only time-varying boundary conditions in the model. Groundwater withdrawal from pumping wells represents the largest change in stresses to the actual groundwater flow system over the time period of the transient model from 1864 to 2000. The other boundary conditions are assumed to be constant over time. The pattern of recharge and the surface water stages are assumed to have not changed from the time of the predevelopment model in 1864 to the last stress period of the transient model in 2000. However, the model automatically updates the flows into and out of the nearfield as a function of the nearfield and farfield pumping through time.

The 794 nearfield and 508 farfield pumping wells were simulated by the MODFLOW Well Package. For wells that cross multiple model layers, the total discharge in the well is distributed across the layers as a function of their individual transmissivities.

Model Assumptions and Limitations

Construction of a regional flow model on the scale described here requires the adoption of some important simplifying assumptions and limitations, as follows:

- The minimum resolution of the regional model is the area of the smallest grid cell. The minimum grid cell size is 2500 ft (~0.5 miles) on a side in the nearfield area. Aquifer and aquitard properties are assumed to be homogeneous within grid cells even though, in reality, much smaller-scale heterogeneity is present. This regional-scale flow model provides a framework for more detailed inset models that will be better able to simulate smaller scale flow.

- The focus of this regional scale groundwater flow model is the seven-county area of southeastern Wisconsin. The actual boundaries of the flow model extend far into Michigan and Illinois, but model data outside the area of southeastern Wisconsin is intended solely to provide appropriate flow boundary conditions to the nearfield area of focus. Therefore, no results are presented and no hydrologic data should be inferred from areas of the model domain outside southeastern Wisconsin.

- The model assumes steady-state flow in the late 1800s prior to the beginning of extensive pumping in the deep sandstone aquifer. An initial steady-state flow field is required for simulating the transient effects of pumping in the 20th century, and this assumption controls the minimum allowable hydraulic conductivity of the Maquoketa aquitard. Field measurements (Eaton, 2002) suggest that vertical hydraulic conductivity of the Maquoketa aquitard may be lower than values used in this model. Further work is needed to investigate possible transient flow in the deep aquifer system induced by the ice retreat following Pleistocene glaciation in southeastern Wisconsin.

- The model ignores pumping from shallow domestic wells. We have neglected all domestic pumping, representing on the order of 25% of the total pumping in the region, because most domestic wells are installed in unsewered areas where the water discharged is first extracted from the shallow system and then returned to the shallow system via septic systems. There are, however, some sewered areas with significant domestic pumping, notably Mequon and Thiensville in southern Ozaukee County, where there is a net loss of water to the shallow groundwater system. In these areas, the model underestimates well withdrawals and, therefore, is likely to underestimate water-level declines in the shallow part of the flow system.

- The eastern boundary of the model domain is a no-flow condition that runs from north to south across the middle of the state of Michigan. However, the exact location of a boundary separating regional groundwater flow systems is unknown. It is possible that under both natural and pumping conditions there is a deep groundwater divide under the state which separates groundwater flow moving west toward Lake Michigan from groundwater flow moving east toward the Michigan Basin. We tested the effect of this boundary by performing a trial simulation in which the no-flow condition was changed from the middle of the state to the eastern coastline of Lake Michigan. The influence on simulated water levels was very small. Therefore, it appears that our uncertainty about the true location of the eastern flow boundary is not an important limitation on the reliability of the model.

- The many active and abandoned deep wells open to both the shallow Silurian dolomite aquifer and the deep sandstone aquifer represent significant vertical conduits for flow (Foley and others, 1953). We have not attempted to insert these pathways into the model. The calibrated vertical conductivity values of aquitards such as the Maquoketa Shale probably incorporate the regional distribution of these pathways just as the bulk horizontal hydraulic conductivity reflects the presence of bedding planes and fractures.

- The model uses constant recharge rates for the entire period between 1864 and 2000. While it is likely that rates have changed over that time, it is impossible to unravel the competing effects of urbanization and climate change in such a way to determine if rates have decreased or increased in any given area.

7. Model Calibration

Groundwater flow models are calibrated by varying input parameters over physically reasonable ranges until the model output approximates observed target values to an acceptable degree. We conducted sensitivity analyses to determine which parameters or groups of parameters had the greatest control on the flows and heads and thus on the target values. The results of the sensitivity analysis guided the choice of parameter values within the framework of our conceptual model until the best match was found between the model values and observations.

The steady state model was calibrated first. The transient model was then developed from that initially calibrated version. Both the steady state and transient models were calibrated by iterating between them until a common parameter set gave model results that matched the target heads and fluxes for the predevelopment and transient times. During these calibration runs, a total mass balance with less than 1% error was maintained.

Steady-state Predevelopment Calibration

The steady-state model was matched against water-level targets distributed over both the shallow and deep parts of the flow system. The match was evaluated graphically and statistically.

Water-Level Targets

Target values for calibration of the model to predevelopment conditions were derived from several sources. Forty-eight target heads for the water table in the SEWRPC counties were taken from the water table map (SEWRPC/WGNHS, 2002), and were chosen to correspond to upland areas between surface water bodies. This location in upland areas maximizes the sensitivity of the targets to the hydraulic conductivity and recharge values. If the targets were located adjacent to a surface water body, their usefulness would be limited because the head in that cell would be constrained principally by the elevation of the surface water. An additional 25 head targets were taken from water table maps for Dodge and Jefferson Counties and water table well measurements in Rock County. We assumed that the water table elevation has not changed significantly since predevelopment. Twenty-eight target values for head in the deep sandstone aquifer system were chosen from a contour plot of predevelopment heads presented in Young and others (1988). An additional 19 deep head targets were taken from well data compiled by Weidman and Schultz (1915).

Evaluation of Goodness of Fit

One way to evaluate the quality of the match between simulated and observed water levels is to plot them together on a graph. Figure 15 is a cross plot that compares the observed to simulated water levels at each target location in the steady-state predevelopment model. The closer a symbol is to the diagonal line, the better the fit. The open symbols show the shallow heads while the shaded symbols show the deep sandstone aquifer heads. Overall, the plot indicates good agreement between target values and simulated values.

Another way to evaluate the calibration is through statistics. Table 3 summarizes the goodness of fit by applying statistical measures to the residuals, the differences between the target and simulated water levels. The residual mean, equal to the sum of all the residuals divided by the number of targets, is a measure of whether the model tends to underestimate (positive residual mean) or overestimate (negative residual mean) observed water levels. The small value of -0.12 feet for all targets shows that the model has little overall bias. However, when the deep sandstone aquifer residuals are separated from residuals corresponding to more shallow units, some bias is present in the subsets. The shallow residual mean is –5.7 feet and the deep sandstone residual mean is 9.1 feet, showing the model overestimates the shallow heads and underestimates the deep heads.

The absolute residual mean is a measure of how much the model varies on average from the targets in either a negative or positive direction. For all targets this average error is 20.2 feet while that of the shallow and deep residuals is 20.5 and 19.8 feet, respectively. To achieve a standard measure of fit that is not dependent on the range of water levels in the target set, the absolute mean of the residuals can be divided by the total range of water levels observed, and expressed as a percentage. Resulting values can be used to assess the goodness of fit (Table 3). For the predevelopment steady-state model, there is a good fit overall: shallow targets by themselves have a good fit (less than 5%) and deep targets have an adequate fit (less than 10%).

Table 3. Calibration statistics for steady-state predevelopment model: Water Levels.

Statistical Measure	All Targets (ft)	Shallow Targets* (ft)	Deep Targets (ft)
Number Water Levels Observed	120	73	47
Residual mean	-0.12	-5.7	9.1
Absolute residual mean	20.2	20.5	19.8
Minimum Residual	-75.9	-75.9	-70.5
Maximum Residual	96.3	81.0	96.3
Range of Target Values	467.4	467.4	240.0
Absolute residual mean/Range	4.3%	4.4%	8.2%

* *Because shallow calibration targets correspond to current rather than predevelopment conditions, calibration statistics for shallow wells were also computed for heads generated by the transient model for the period 1990-2000. This second set of statistics is virtually identical to those reported here since there is little drawdown at the regional scale in the shallow system, especially in the unlithified deposits.*

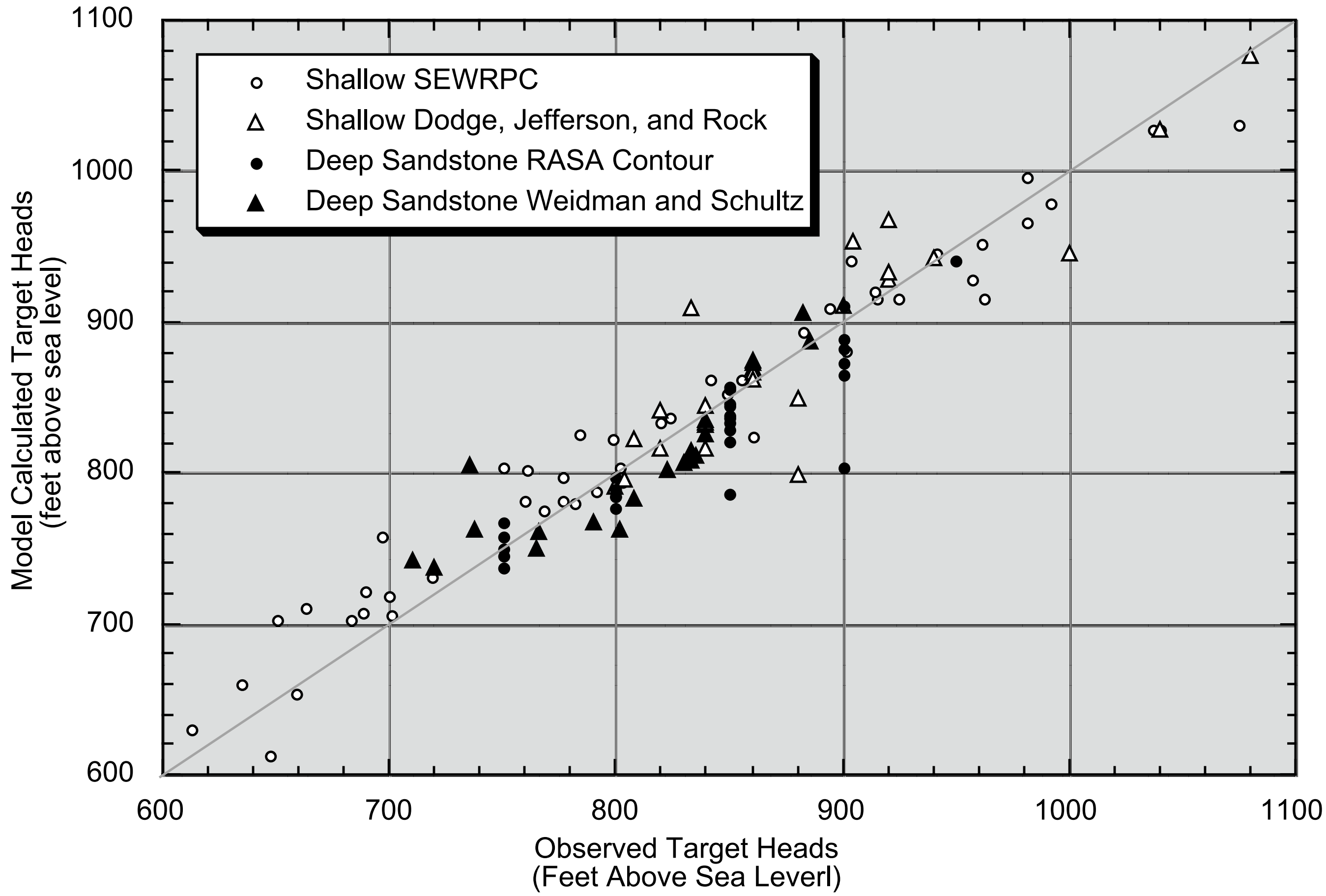


Figure 15. Cross plot showing the goodness of the fit between the target heads (X-axis) and model calculated heads (Y-axis) for steady-state predevelopment model.

Transient Calibration

The transient model was evaluated using multiple target sets. Simulated results were compared not only to observed water levels, but also to observed water-level trends in response to pumping, to vertical gradients within the deep sandstone aquifer, and to stream fluxes.

<u>Water-level Targets</u>

Historical water levels are available from 56 wells in the Wisconsin Groundwater Network (website: wi.water.usgs.gov). Data collected at 10 intervals between 1940 and 2000 provide calibration statistics for the transient calibration. The head in each model layer penetrated by a well was weighted by the transmissivity of the layer to arrive at a single composite water level for the well. The calibration statistics are grouped in Table 4. The absolute residual mean averages 22 ft for all wells over the period of record and 23 ft for deep wells. Given the large range of water levels induced by pumping (on the order of 500 ft for most of the period), this average error is relatively small.

<u>Trend Targets</u>

Of the 56 wells in the Wisconsin Groundwater Network, long records exist for 10 wells that are open to the deep groundwater system. The simulated water levels for these deep targets were calculated for the top and bottom model layers intersecting the open interval of the target well and then compared to the measured water levels (Figure 16). In general, the measured trends are close to the top and bottom lines shown on Figure 16. The entire nearfield portion of the deep system shows significant decreases in heads over time due to pumping. The model reflects the rate and magnitude of these decreases.

Table 4. Calibration statistics through time for transient model.

Date	All Wells			Deep Wells		
	Number Water Levels Observed	Residual Mean (ft)	Absolute Residual Mean (ft)	Number Water Levels Observed	Residual Mean (ft)	Absolute Residual Mean (ft)
1940	5	-11.3	13.4	4	-5.2	8.8
1945	10	-8.8	22.0	7	+2.7	19.3
1950	31	-1.2	25.5	19	+4.9	27.8
1965	32	-1.0	21.9	20	+6.3	24.8
1970	35	+0.8	22.7	21	+5.6	25.1
1980	34	-4.6	21.2	22	-0.6	20.2
1985	29	+7.4	23.0	18	+13.4	28.2
1990	29	+4.1	20.1	18	+6.9	22.5
2000	16	+3.9	21.5	9	-0.9	22.8

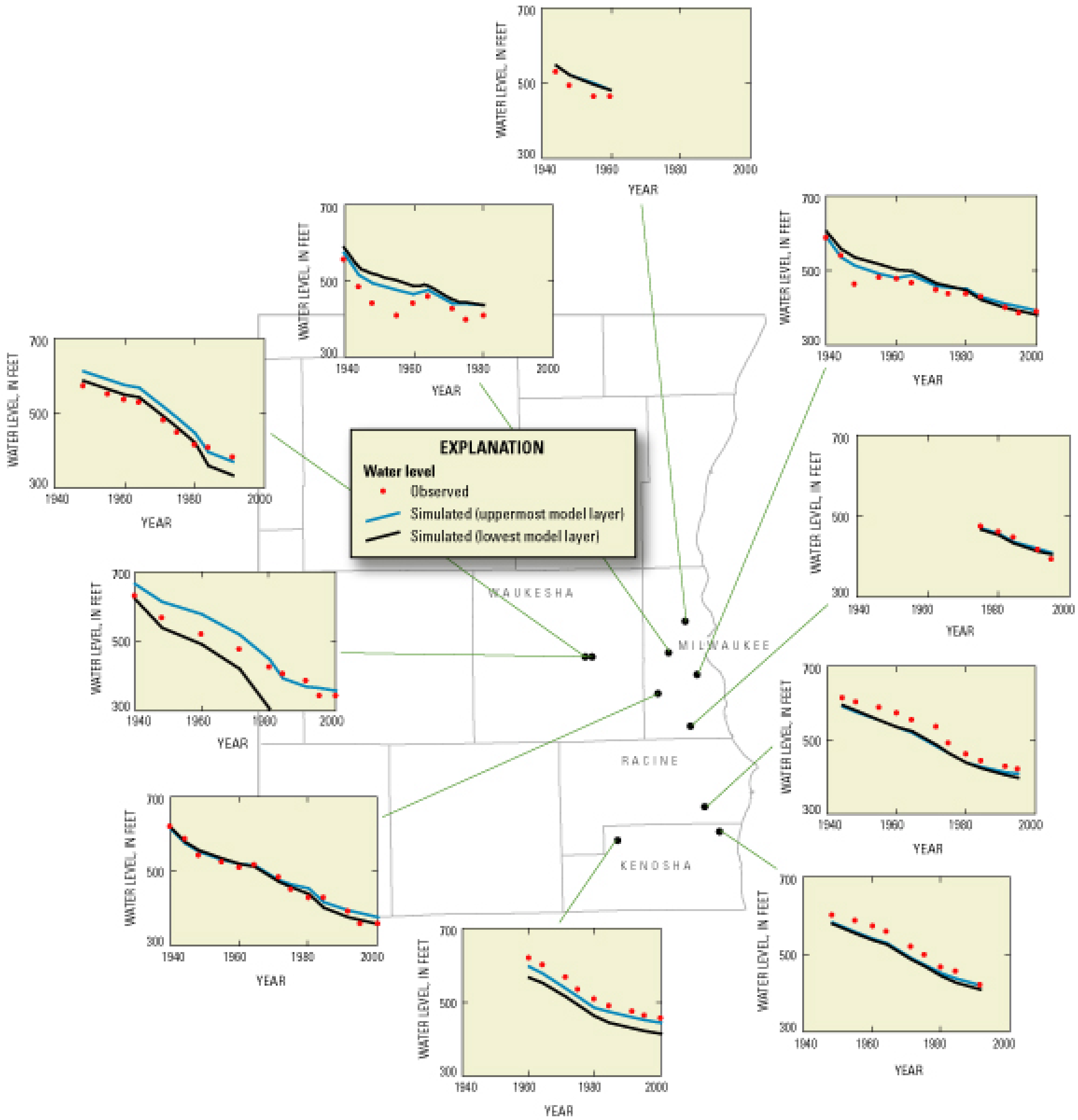


Figure 16. Observed and simulated water levels in deep observation wells that show appreciable drawdown since 1940.

The red points are the observed water levels over time; the blue lines are the simulated water levels in the uppermost model layer open to the well; the black lines are simulated water levels in the lowest layer open to the well.

Packer Tests

The target set of 56 wells used for the transient calibration was supplemented by packer test data (Figure 17). In these tests, portions of the wells are isolated from the rest of the open interval using packers so that water levels corresponding to particular formations and intervals can be recorded. The water-level data shown in Figure 18 are the result of packer testing conducted in 7 deep wells in the early 1980s. Most of the wells are boreholes open from the Sinnipee into the Mt. Simon sandstone, while each packed intervals corresponds to a single unit in the deep sandstone aquifer. The heads in the isolated interval were allowed to come to equilibrium and recorded. The depth of the packers was then changed and the heads from another interval recorded to construct a vertical head profile for the well.

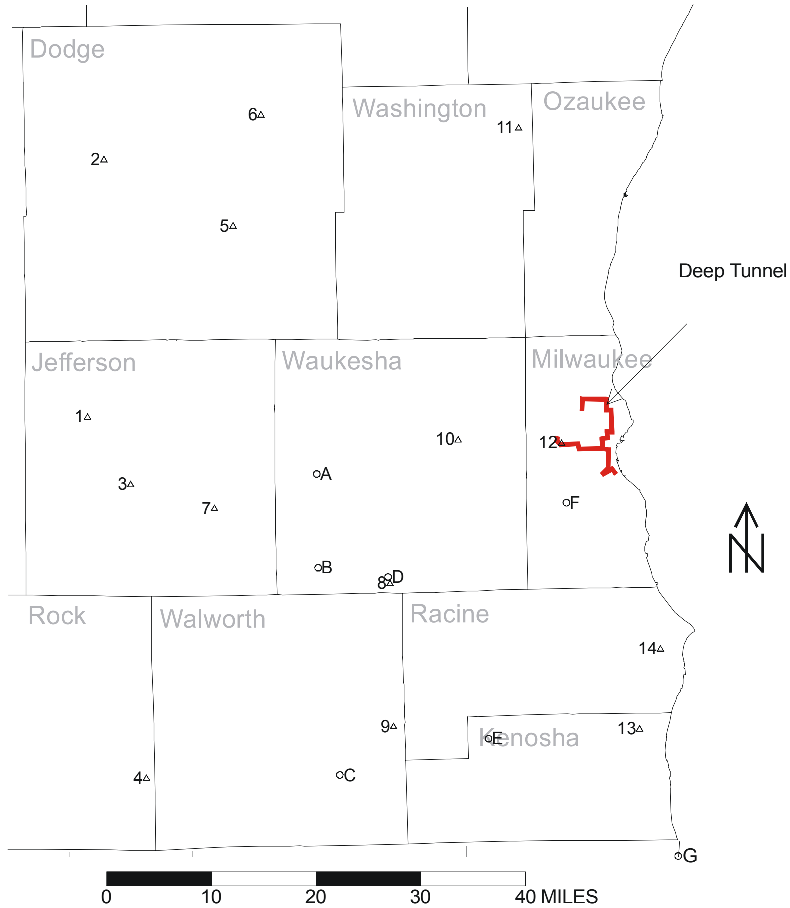
In Figure 18, the observed and modeled 1980 head profiles for the seven wells are compared. In A vertical line indicates no head difference or gradient with depth, and therefore, no vertical flow. A near-horizontal line indicates a strong vertical gradient. The first four wells to the west (left) are all located in areas where the Maquoketa Formation is thin or absent. The similar slopes of the observed and simulated profiles imply significant downward leakage across the Sinnipee to replenish groundwater flow at the bottom of the deep system. Farther to the east (right) where the Maquoketa Formation is an effective aquitard, the circulation within the deep system is largely horizontal except near pumping wells. The model reflects the absence of vertical gradients observed at the three eastern-most well locations.

Flux Targets

In addition to head targets, 14 stream flows, eight in the SEWRPC counties and six in Dodge, Jefferson, and Rock Counties, were used for model calibration. Flux targets are very useful during calibration because they provide a way to determine if the assumed quantity of recharge flux over a given basin area and the routing of groundwater from the water table to water bodies in that basin is simulated correctly.

The measurements of stream flow that serve as flux targets for the regional model were derived from the USGS stream-gaging network (Figure 17). They were selected because their records were long enough that a statistical analysis could be conducted to estimate baseflow, the amount of stream flow due to groundwater discharge. For this model, baseflow was expected to lie between the Q_{80} (streamflow exceeded 80 percent of the time) and the Q_{50} (streamflow exceeded 50 percent of the time) flow durations. Stream flow records were adjusted to account for surface water discharge from sewage treatment plants and other sources. In areas dominated by permeable surficial deposits, baseflow commonly tends to approach the Q_{50} streamflow. In more fine-grained areas, baseflow tends to approach the Q_{80} streamflow.

The model-calculated flux is bounded by Q_{80} and Q_{50} values for five of the eight flux targets in the seven-county SEWRPC region (Figure 19) and is close to the Q_{80} in the remaining three cases. Only two of the six flux targets in Dodge, Jefferson, and Rock Counties fall between the Q_{50} and Q_{80} fluxes. Good agreement to flux targets is not expected in these outlying counties because information was not available to provide more than a single average recharge value for this large area. Since the recharge rate determines the amount of baseflow to streams in each basin, the use of a single recharge value results in too much shallow groundwater flow in some of these outlying areas and not enough in others. However, the sum of all the model-calculated fluxes is 810 cubic feet per second (cfs). This simulated overall value meets the calibration criterion because it is bounded by the summed Q_{80} and Q_{50} fluxes for the target streams, equal to 593 and 1526 cfs, respectively.



EXPLANATION

○	Packer tested well	▵	USGS stream-gaging station
A	Dousman Well #2	1	Crawfish River at Milford
B	Eagle Well #2	2	Beaverdam River at Beaverdam
C	Lake Geneva Well #1	3	Rock River at Jefferson
D	Mukwonago Well #2	4	Turtle Creek at Carvers Rock near Clinton
E	Bong Recreational Area Well	5	Rock River at Hustiford
F	Greenfield High School Well	6	East Branch of the Rock River near Mayville
G	Zion USGS Well	7	Bark River near Rome
		8	Mukwonago River at Mukwonago
		9	White River near Burlington
		10	Fox River at Watertown Road near Waukesha
		11	North Branch Milwaukee River near Filmore
		12	Menomonee River at Wauwatosa
		13	Pike River near Racine
		14	Root River at Racine

Figure 17. Location of packer-tested wells, USGS stream-gaging stations and the Milwaukee Deep Tunnel.

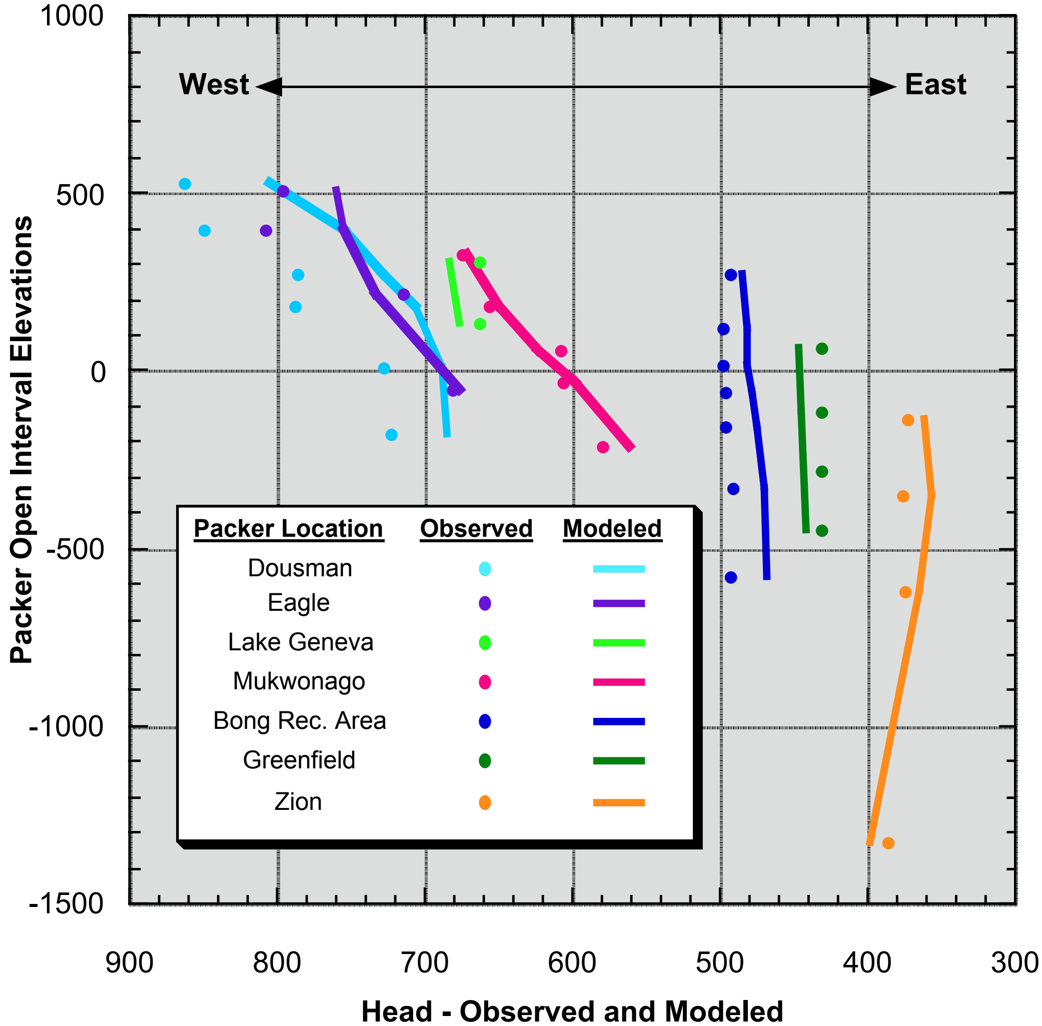


Figure 18. Comparison of vertical head profiles between observed and modeled heads for packed wells.

The X-axis corresponds to the measured and modeled heads. The Y-axis corresponds to the elevation (feet above sea level) of the measurement in the packer. All packer and head elevations reported in feet above sea level.

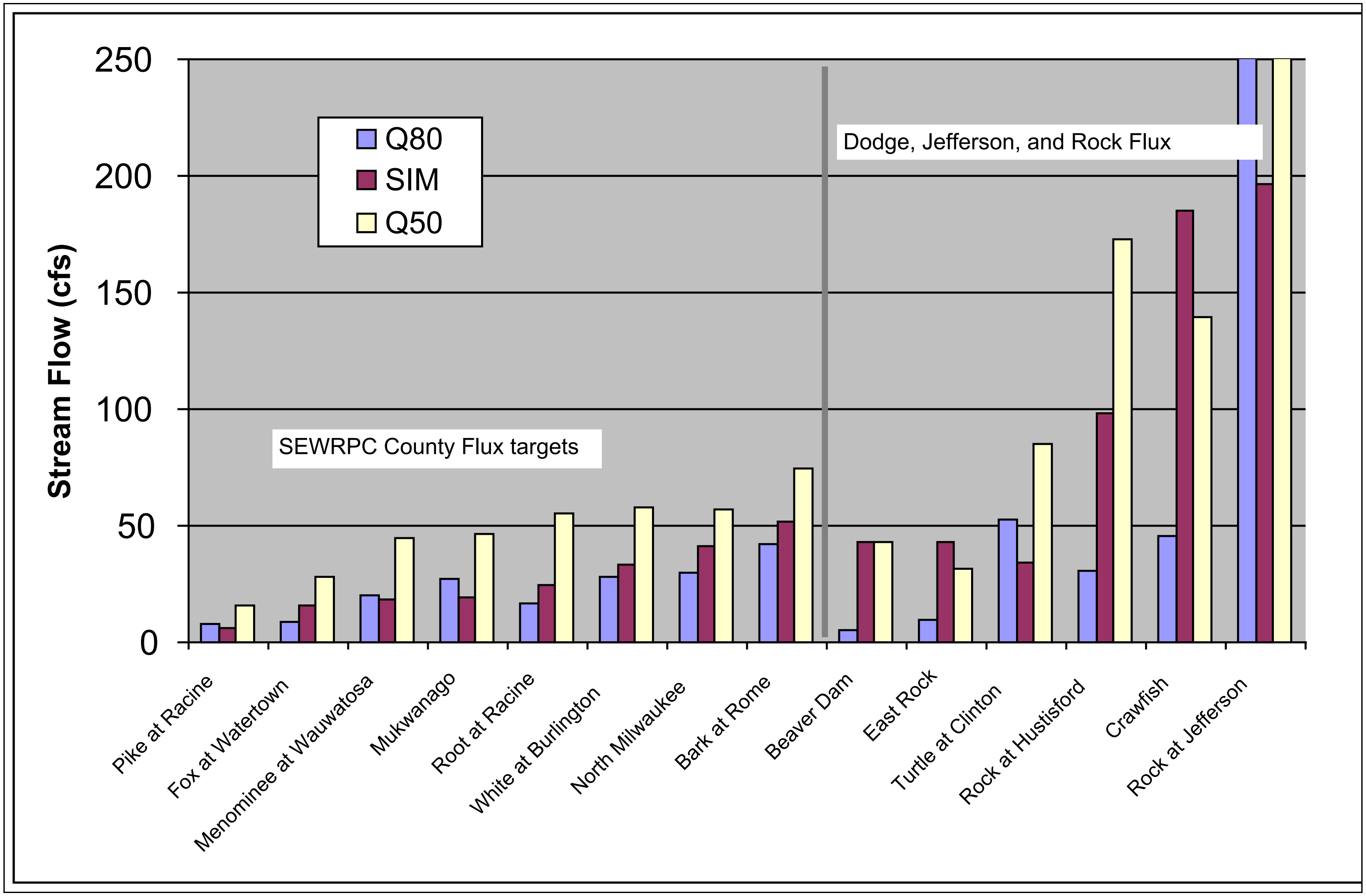


Figure 19. Comparison of simulated baseflow to Q80 and Q50 measurements of streamflow.

Sensitivity Analyses

Sensitivity analyses were conducted for both the steady state predevelopment and transient models, first, to determine the crucial inputs to the model, and, second, to aid in calibration. Sensitivities are calculated by varying parameters or groups of parameters and recording the model response in terms of changes in water levels at target locations. In our analyses, the parameters were all varied by 5 percent. The changes in the heads at the target locations due to the parameter change were then recorded and averaged for comparison to other head changes from a different parameter or group of parameters. If a relatively small change in the parameters creates a large head change, that parameter or group of parameters is constrained by the targets and is important for calibration of the model.

Steady-State Analysis

A study was performed to show which parameters most influence the steady-state simulation. Figure 20 shows the relative sensitivities across multiple parameter sets for the predevelopment model. The vertical and horizontal hydraulic conductivities are grouped by hydrostratigraphic unit. The recharge zones are grouped and included as a parameter set to show the importance of recharge to model calibration. In addition to the parameter sensitivities, the contributions to the sensitivities from the shallow and deep aquifers are shown. For example, the horizontal and vertical hydraulic conductivity of the Maquoketa shale has negligible influence on the heads in the shallow aquifers but significant influence on those in the deep sandstone aquifer.

Inspection of Figure 20 indicates that the most influential parameters for the steady-state calibration are recharge, the permeability of the Pleistocene (unlithified) deposits, and the permeability of the deep sandstone aquifer units. Calibration of the steady-state model was achieved in large measure for the shallow system by varying the unlithified and Silurian dolomite conductivities, and for the deep system by varying the horizontal sandstone hydraulic conductivities and the vertical Maquoketa and Sinnipee hydraulic conductivities.

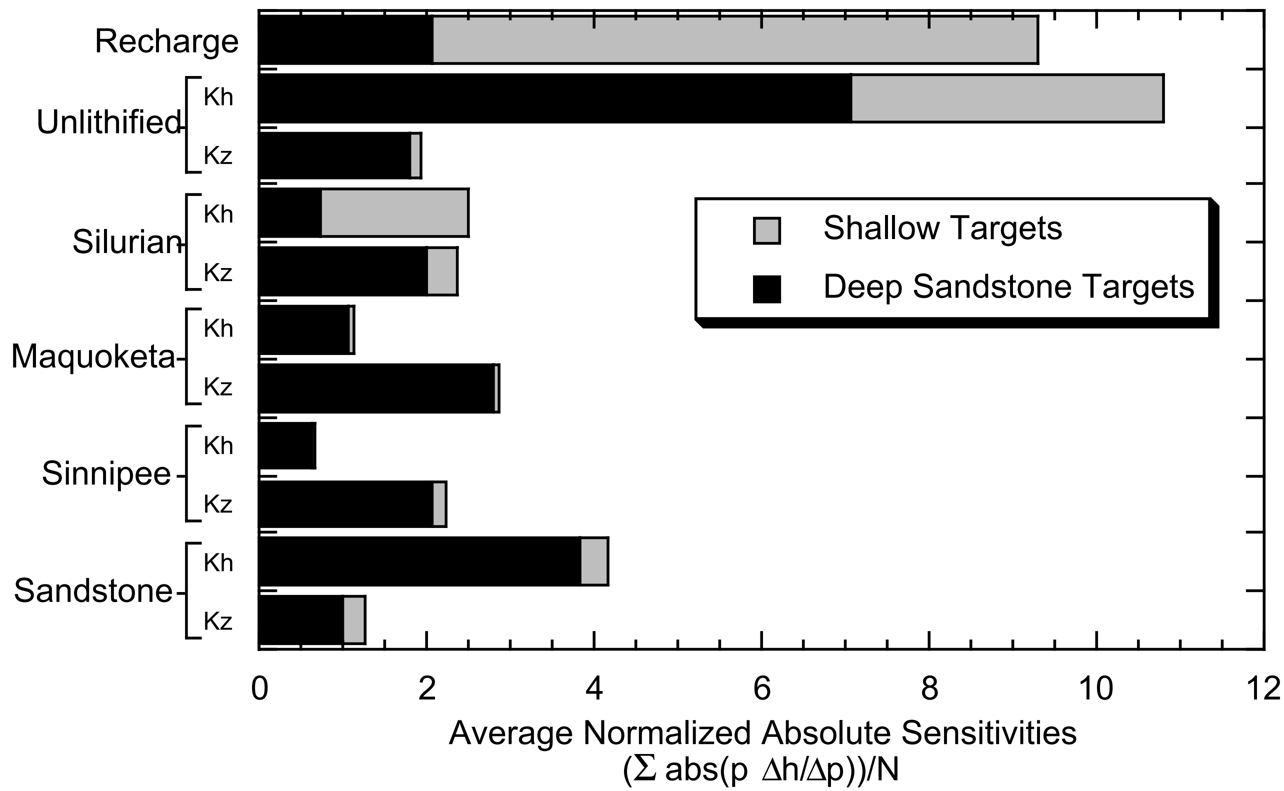


Figure 20. Parameter sensitivities for the steady-state predevelopment model.

Sensitivities are computed as the ratio of ***Δh****=change in water level at a shallow or deep target to* ***Δp****=change in parameter value, normalized by multiplying the ratio times* ***p****=the original parameter value, then averaged by summing and dividing by the number of targets* ***N****. The absolute value of the sensitivities is in units of feet. The bar lengths correspond to the average absolute sensitivity across parameter sets.*

A separate analysis (not shown) was conducted on the sensitivity of the results to the 5 ft/day hydraulic conductivity assigned to streambed material, a parameter that in part controls the ease with which baseflow can enter streams. The analysis showed that the model solution has little sensitivity unless the hydraulic conductivity is reduced to unrealistically low levels.

Transient Analysis

A sensitivity analysis was also conducted to reveal model structure and guide calibration in the case of the transient model simulation that incorporates pumping conditions from 1864 to 2000. In addition to the parameter groups in the steady state sensitivity, three additional parameter groups, pumping rates, specific storage, and specific yield were studied in the transient sensitivity analysis (Figure 21).

The most striking result of this analysis is the great importance of pumping rates and specific storage to calibration of the model. In particular, a small change in pumping rates has a very large effect on the model heads, nearly twice that of the next most sensitive parameter group, the horizontal sandstone hydraulic conductivities. This result stresses the importance of good records of pumping rates for creation of regional scale models. Neither the pumping rates nor the specific storage was varied during calibration because the estimates are based on good data sources (well records and aquifer tests, respectively). However, the large sensitivities of the model to the horizontal hydraulic conductivity of shallow and deep units and to the vertical hydraulic conductivity of the Maquoketa Formation meant that these parameters could be adjusted within reasonable ranges to bring simulated water levels closer to observed levels.

Coupling of the steady-state calibration and transient calibration yielded the final parameter inputs for the groundwater model. The average and range of horizontal and vertical hydraulic conductivity for hydrostratigraphic units over the nearfield are shown in Figures 22a and 22b. The bar lengths are proportional to the average hydraulic conductivity values over all zones within a unit. The average is calculated as the geometric mean over the seven-county region. Note that the vertical conductivities of distinct units are compared on a logarithmic scale.

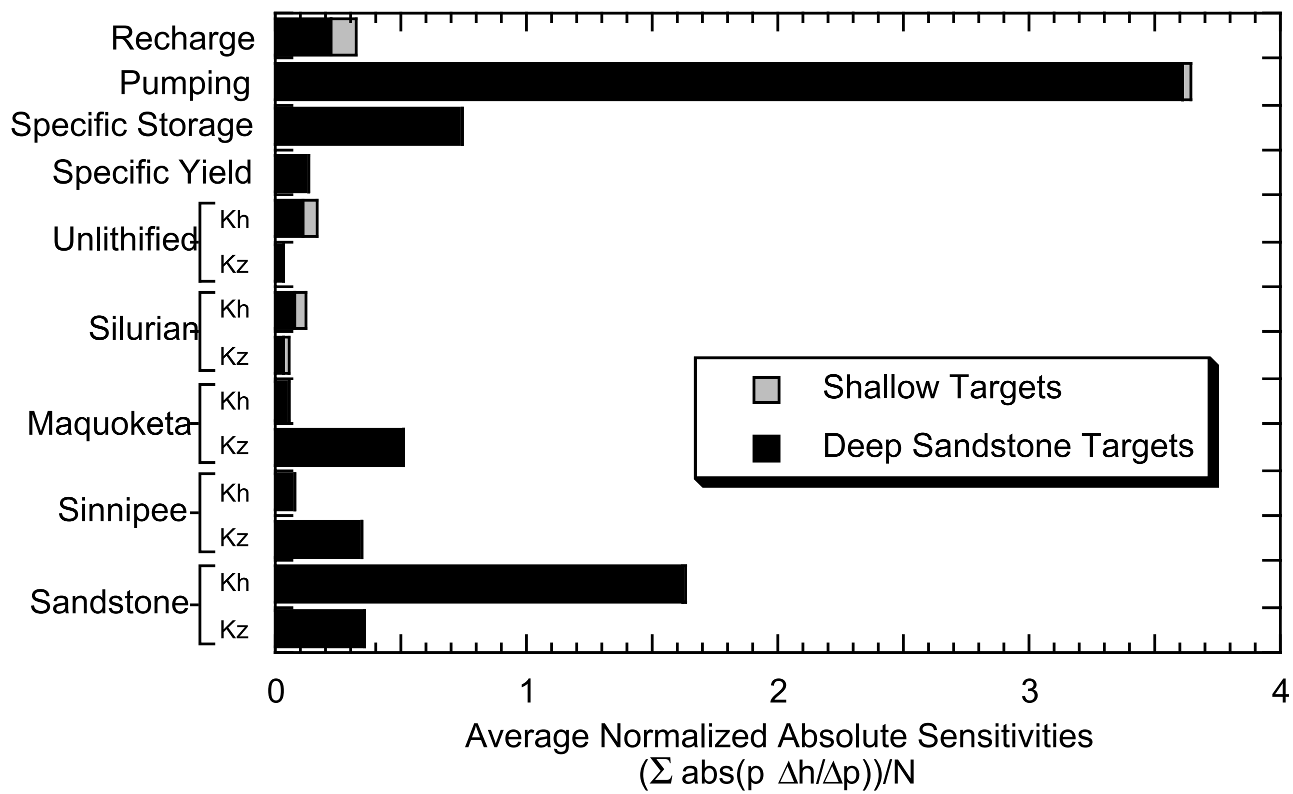


Figure 21. Parameter sensitivities for the transient model.

Sensitivities are computed as the ratio of ***Δh****=change in water level at a shallow or deep target to* ***Δp****=change in parameter value, normalized by multiplying the ratio times* ***p****=the original parameter value, then averaged by summing and dividing by the number of targets* ***N****. The absolute value of the sensitivities is in units of feet. The bar lengths correspond to the average absolute sensitivity across parameter sets.*

The average values reflect the lithology of each unit, in the sense that relatively pure sandstone units (the St. Peter and Wonewoc) have high hydraulic conductivities while carbonates and shales have lower values. Acceptable calibration required that relatively high hydraulic conductivity values be assigned to the unlithified deposits. This outcome probably reflects the large area and thickness of cells in the model. While local near-surface measurements in areas dominated by till would typically yield horizontal hydraulic conductivity values less than 1 or even 0.1 ft/day, the model calibration suggests there is enough heterogeneous coarse-grained material at different depths within the unlithified section (model layers 1 and 2) to raise the overall average to approximately 3 ft/day. Similar relations between the scale of consideration and the appropriate magnitude of hydraulic conductivity have been observed in many hydrogeologic settings (Bradbury and Muldoon, 1990, Schulze-Makuch and Cherkauer, 1998).

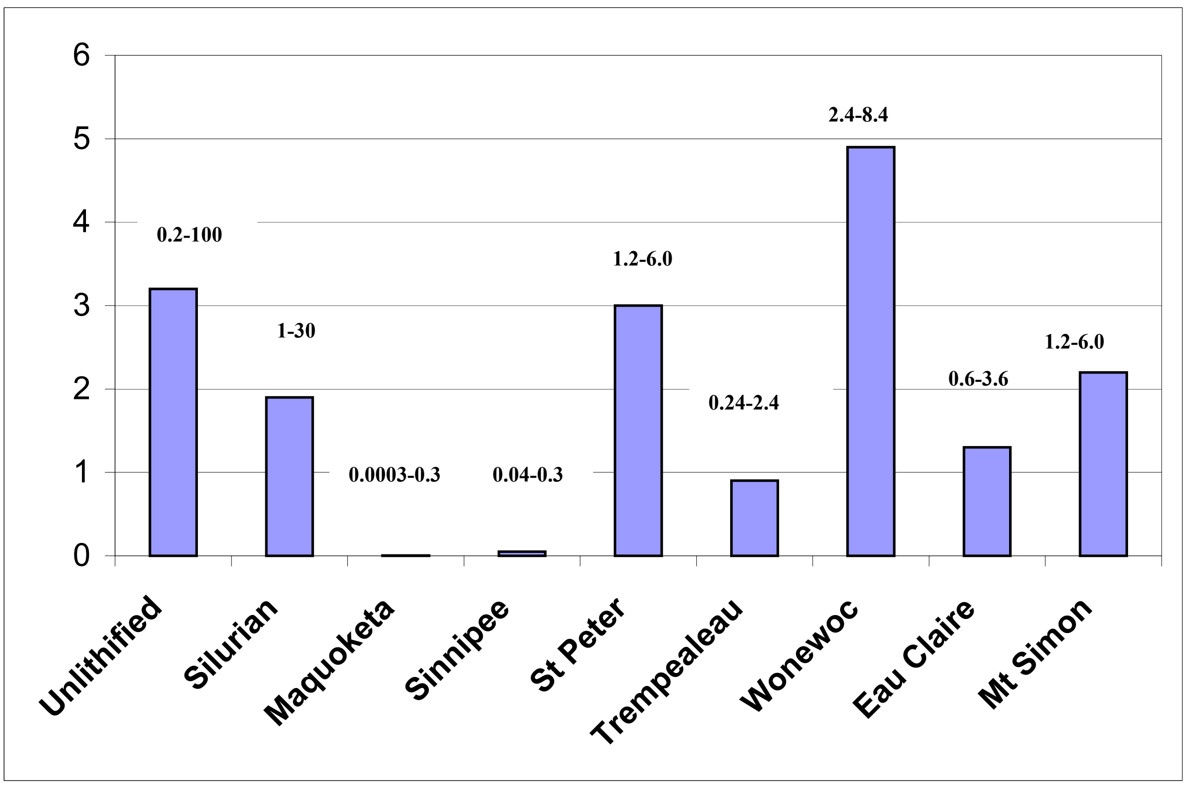


Figure 22a. Central tendency and range of horizontal hydraulic conductivity (ft/day) in 7-county SEWRPC region.

Central tendency, corresponding to bar height, defined by geometric mean of cell values weighted by cell area.

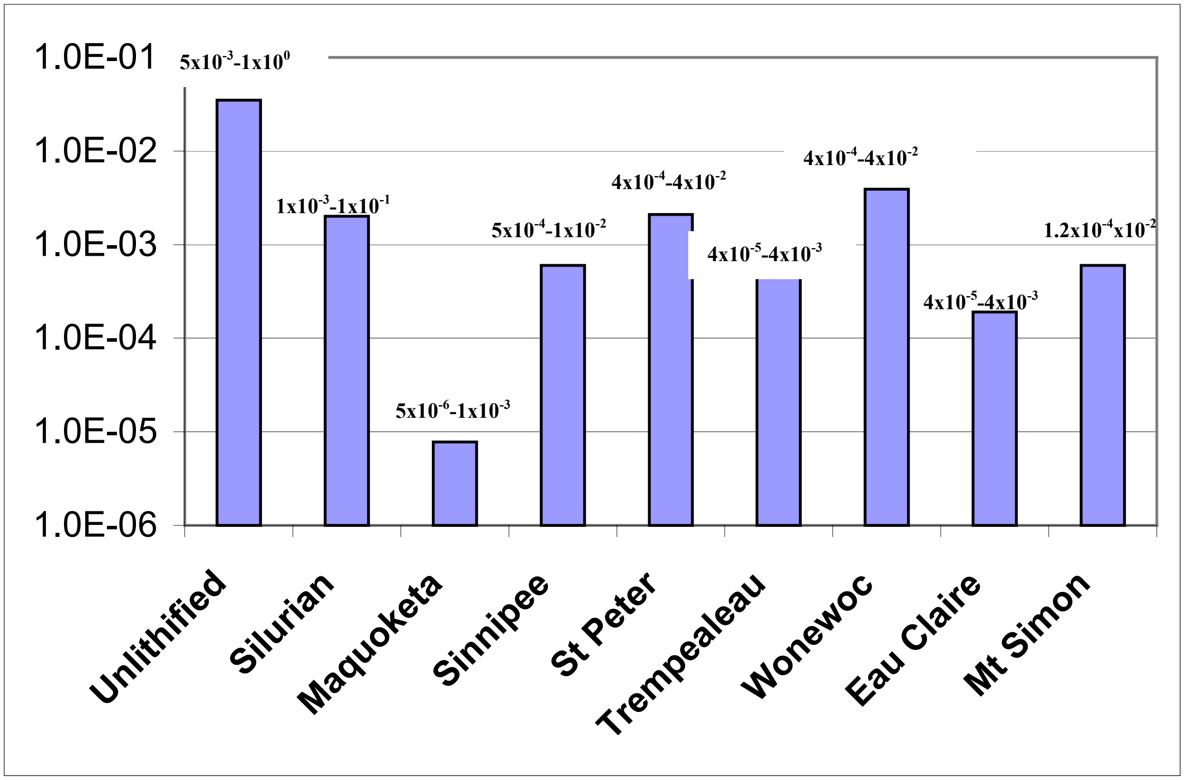


Figure 22b. Central tendency and range of vertical hydraulic conductivity (ft/day) in 7-county SEWRPC region.

Central tendency, corresponding to bar height, defined by geometric mean of cell values weighted by cell area. Note that vertical hydraulic conductivity is plotted on a logarithmic scale.

8. Summary

Through a joint project, the U.S. Geological Survey, the Wisconsin Geological and Natural History Survey, and the Southeastern Wisconsin Regional Planning Commission have developed and calibrated a numerical groundwater flow model for the seven-county SEWRPC region of southeastern Wisconsin. This report describes model development; a second report describes model results. The new model represents a significant advance over previously-constructed groundwater flow models for the region in several respects:

- The model is three-dimensional and fully transient; it simulates groundwater levels from the late 1800s through the present day;
- The model completely links all major groundwater units present in southeastern Wisconsin, and simulates both shallow and deep aquifers
- The model simulates groundwater flow into or out of the major surface water features present in southeastern Wisconsin
- The model contains an accurate history of groundwater withdrawals in southeastern Wisconsin

The model was developed and calibrated in both steady-state and transient modes. The predevelopment steady-state model provides a good match to the pattern of water levels based on historical measurements from before the onset of the pumping. The transient model calibration closely reproduces observed patterns of drawdown through time across the study area. The models also agree with estimates of baseflow to streams.

Since the model performance is so sensitive to pumping rates, the fit achieved in model calibration is due in part to the detailed analysis used to apportion pumping through time from shallow and deep aquifers across 10 counties in southeastern Wisconsin. The quality of the fit suggests that the recharge and hydraulic conductivity patterns used in the model are reasonable. It also suggests that the model properly routes groundwater from recharge at the water table to surface-water bodies and wells, and it properly partitions groundwater flow between that which circulates within the shallow part of the flow system and that which replenishes the deep sandstone aquifer.

The model provides a tool for simulating regional groundwater flow and regional groundwater withdrawals in southeastern Wisconsin. A companion report (Feinstein and others, 2003) summarizes the results of model simulations from predevelopment to the present day and presents interpretations of the groundwater flow system based on these simulations. The model also provides a framework for more detailed investigations of specific geographic areas and for the construction of smaller, more refined inset models.

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Regional Aquifer Model for Southeastern Wisconsin

Report 2:
Model Results and Interpretation

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Administrative Report to the Southeastern Wisconsin Regional Planning Commission

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1. Abstract

A new groundwater flow model of southeastern Wisconsin demonstrates and helps quantify the effects of long-term pumping on the natural circulation of groundwater. The model focuses on the seven-county SEWRPC region and simulates the evolution of groundwater levels and flows between 1864 and 2000 for the entire flow system extending from shallow unlithified and dolomite deposits at the top of the system to sandstone units at depth. Intensive groundwater use has influenced the flow system throughout the SEWRPC area and beyond its borders. Along with increased drawdown, pumping over time has reduced flow to surface water from groundwater, shifted groundwater divides, increased leakage from the shallow to the deep parts of the flow system, and redirected groundwater pathlines. The modeling study yields the following conclusions:

- The major pumping center in southeastern Wisconsin has shifted from the city of Milwaukee to eastern Waukesha County. In response, the center of the cone of depression in the deep part of the flow system has shifted westward about eight miles from Milwaukee to the vicinity of the Village of Elm Grove where deep water levels have dropped about 500 ft since the onset of pumping.

- If historic trends continue, pumping will increase by as much as 40% between 2000 and 2020, and will produce over 100 ft of additional drawdown at the center of the regional cone of depression in the deep part of the flow system.

- The most important source of water to pumping wells is water transferred from the surface-water system to the groundwater system from within the seven-county SEWRPC region: according to the model it currently accounts for 79% of combined shallow and deep pumping. Most of the transfer is groundwater that would discharge to surface water under natural conditions but now discharges to wells, while a smaller part is water induced directly from streams and lakes.

- The remaining sources of water for shallow and deep wells are release of groundwater from storage below the seven-county region and below Lake Michigan (11%) and net groundwater flow into the region mostly from the west (10%). Flow into the region is mostly water moving toward deep wells that would otherwise discharge to surface water located west of the counties under study.

- Pumping from the sandstone aquifer has reversed the direction of flow in the deep part of the flow system below the Lake Michigan coastline.

- Between 1864 and 2000, pumping caused a 7% reduction of direct and indirect discharge of shallow groundwater to Lake Michigan. This analysis does not account for the effect of other possible controls on discharge such as climate change or urbanization.

- Downward leakage from the shallow to the deep parts of the flow system occurs everywhere in the study area, but it is most pronounced in the western areas within the seven-county region where the Maquoketa shale is absent. Under current conditions about 4% of recharge leaks to the deep part of the flow system for the seven-county region, but in areas where the Maquoketa shale is absent the proportion climbs to 13%.

- The area contributing water to deep wells has expanded appreciably over time. Recharge to this area, bounded by the groundwater divide, is a key source for deep wells. Between 1864 and 2000, the groundwater divide moved about 9 miles west from Waukesha County into Jefferson County. Long travel paths passing below multiple counties demonstrate the degree to which groundwater is a regional resource.

2. Introduction

This publication is the second of two reports devoted to modeling the groundwater flow system in southeastern Wisconsin. The first entitled "Regional Aquifer Model for Southeastern Wisconsin, Report #1: Data Collection, Conceptual Model Development, Numerical Model Construction, and Model Calibration" describes the construction and calibration of a regional model for southeastern Wisconsin using the MODFLOW code for groundwater flow (McDonald and Harbaugh, 1988). Further information on data analysis and construction of the regional flow model is available in a Wisconsin Geological and Natural History Survey Open-File Report (Eaton and others, in preparation). The model has two versions. The first, a steady-state simulation, reproduces natural or predevelopment conditions. The second, a transient simulation, reproduces the response of the system to pumping. By comparing the results of the predevelopment to the transient versions of the model, it is possible to trace the changes to the regional groundwater system through time. In this report, these changes are presented in a variety of ways to better understand the workings of the regional flow system.

Under natural conditions, all groundwater originates as recharge, and all groundwater discharges to surface water bodies such as rivers and lakes. Most groundwater travels along shallow flow paths and discharges to nearby streams, but some penetrates deeper into the groundwater system and travels long distances before discharging upward to large features such as Lake Michigan.

Pumping from wells alters the natural system. With development, groundwater discharges not only to surface-water bodies, but also to wells. As wells are pumped, water levels[1] drop, flow is redirected, and less groundwater discharges to surface water. The degree of change depends on the evolution of pumping over time, the proximity of

[1] The term "water levels" in this report always refers to groundwater levels, also known as hydraulic heads. Groundwater levels are specific to locations and depths in the groundwater system; they correspond to the level that water would attain in a hypothetical well open to a specific location and depth. Thus, a groundwater level for the St. Peter Formation refers to the water level that would occur in a well that is open only to the St. Peter. A set of water levels distributed spatially over a single unit corresponds to the unit's "potentiometric surface".

wells to surface water, and the depth at which pumping occurs. In particular, deep pumping tends to draw water away from shallow, local flow systems and into longer travel paths that are part of the regional system.

Purpose and Scope of this Report

The southeastern Wisconsin regional groundwater model provides a tool to understand the long-term effect of pumping on the natural groundwater flow system over the seven counties administered by the Southeastern Wisconsin Regional Planning Commission (SEWRPC). These counties are Kenosha, Milwaukee, Ozaukee, Racine, Walworth, Washington and Waukesha (Figure 1). The results of the modeling effort described in this report form the basis for subsequent studies aimed at anticipating effects of future water use and better managing the linked groundwater/surface-water resource.

Hydrogeologists and hydrologists at the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS) have performed the work described in this report. The model simulates groundwater conditions over the 7-county SEWRPC region as well as under Lake Michigan to the east of the region and in Dodge, Jefferson, and eastern Rock Counties to the west of the region. The modeling results fall into the following categories:

- Water levels and drawdown through time
- Sources of water to wells
- Shallow groundwater interactions with Lake Michigan before and since pumping began
- The evolution of flow directions and groundwater divides
- Movement of water from the shallow to deep parts of the flow system before and after pumping
- Simulation and visualization of groundwater pathlines.

Model output is presented in figures and tables that demonstrate the regional effects of pumping on the natural system. The results cover a very large area and are not intended to simulate groundwater conditions immediately around an individual well or stream. However, the model incorporates sufficient spatial and temporal detail with respect to

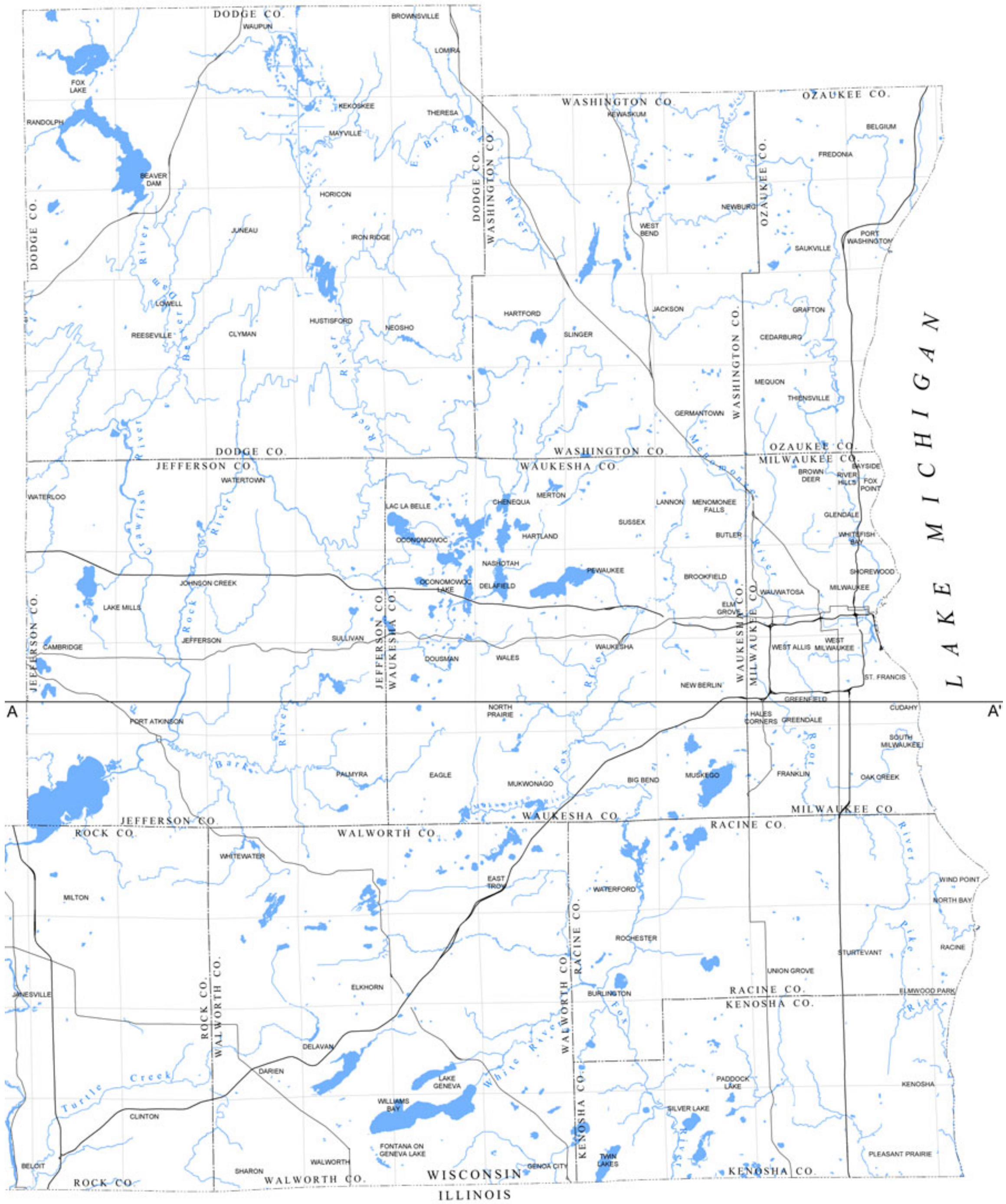


Figure 1. **Area of southeastern Wisconsin simulated in model.**

Explanation: A-A' shows trace of cross section in Figure 2.

geology, hydrology and well placement to examine a wide range of effects in different parts of the study area at different times.

Key Concepts

Interpretation of the modeling study depends on several key hydrogeologic concepts summarized here.

<u>SEWRPC Region and Model Nearfield:</u> The SEWRPC region is composed of seven counties in southeastern Wisconsin. However, the groundwater flow system does not respect administrative boundaries. In particular, there is significant exchange of groundwater between the seven-county region and areas to the west in Dodge and Jefferson Counties and the east side of Rock County. For this reason, close attention was paid in development of the model not only in the SEWRPC region, but also in the adjacent western counties. Together they constitute the model nearfield shown in Figure 1. In this report, results are sometimes reported for the SEWRPC region alone and sometimes for the entire model nearfield.

<u>Aquifers and Hydrostratigraphic Units:</u> Aquifers are unlithified or lithified deposits that readily transmit water to wells. Hydrostratigraphic units are unlithified or lithified deposits that form a mappable layer that can be represented in a groundwater flow model. The two terms are not used interchangeably. For example, the unlithified deposits in southeastern Wisconsin, mostly glacial in origin, form a continuous hydrostratigraphic unit that lies on top of bedrock. Most of the unlithified deposits in the region are fine-grained till, not suitable as aquifers. However, alluvial sediments and outwash bodies within the unlithified deposits form local aquifers (collectively called the "unlithified sand-and-gravel aquifer") that sustain even large-scale municipal pumping. Silurian dolomite and local Devonian deposits form the top of the bedrock in the eastern two-thirds of the seven-county region. Known as the "Silurian dolomite aquifer", these rocks are both a hydrostratigraphic unit and an aquifer because fracturing in the unit is sufficiently widespread to support high-capacity wells in many areas. The underlying Maquoketa shale is a unit but not an aquifer and the same condition holds for the dolomites that form the Sinnipee Group below the shale. However, in places where the

Sinnipee Group is not overlain by the Maquoketa shale (in the western part of the 7-county region where they subcrop below the unlithified deposits), these units are sufficiently weathered to count as the top of an aquifer system. This system, composed of Cambrian-Ordovician rocks, is referred to as the “deep sandstone aquifer”. The major hydrostratigraphic units that contribute to the deep sandstone aquifer are clean sandstone formations (the St. Peter, the Wonewoc, and parts of the Mt. Simon) and mixed formations consisting of sandstone, siltstone, shale and dolomite (the Trempealeau-Tunnel City Groups, the Eau Claire, and parts of the Mt. Simon).

Shallow and Deep Parts of Groundwater Flow Systems: A major aquitard formed by the Maquoketa shale marks the boundary between the shallow part of the flow system, where groundwater circulates through unlithified deposits and underlying Silurian dolomite, and the deep part of the flow system, where groundwater moves mainly through sandstone and silty sandstone units, and to a certain extent through the overlying Sinnipee dolomite. Figure 2 shows this configuration for a representative west to east vertical cross section. Where the Maquoketa shale is present, little flow occurs between the shallow and deep parts of the groundwater system and only the shallow part is in good connection with surface water bodies. Where the Maquoketa shale is absent, circulation between the shallow and deep parts is enhanced. The same rate of pumping causes more drawdown in deep wells confined by the Maquoketa shale in the eastern part of the study area than in unconfined deep wells further to the west.

Resolution of the Model: The dimensions of cells in the finite-difference grid limit the spatial resolution of the groundwater flow model. Although spatial variations in the groundwater system can occur at any scale, from feet to miles, the model does not compute water levels and flows everywhere. For the model nearfield, most cells extend 2500 ft from north to south and 2500 ft from east to west. Therefore, model results correspond to average conditions over an approximate half-mile by half-mile area. For example, simulated drawdown at a particular time due to pumping a specific group of wells represents an average decline in water levels over the area of the cell containing the

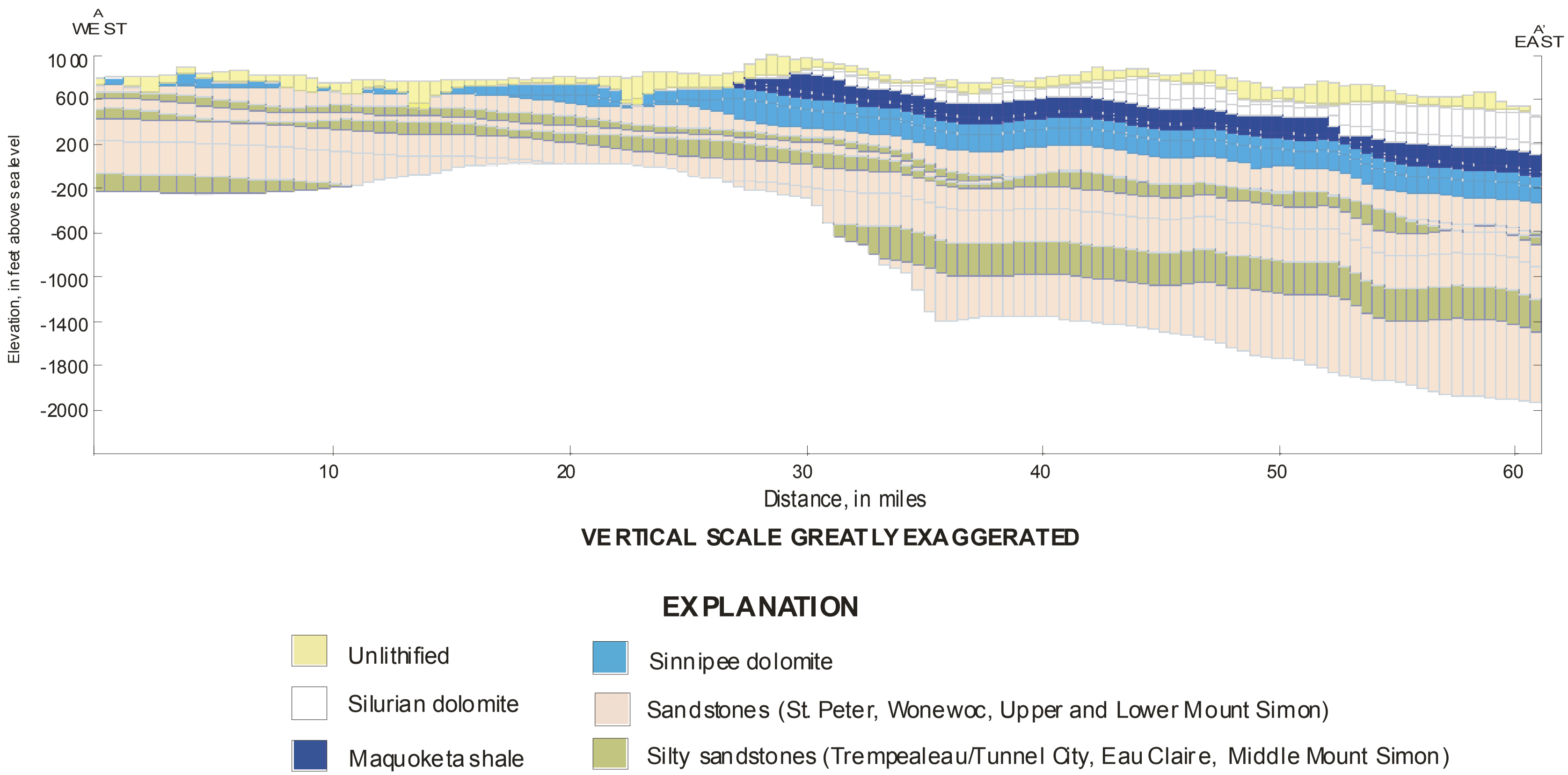


Figure 2. **Hydrostratigraphic units in model.**

Explanation: Trace corresponds to A-A' in Figure 1.

wells. It does not reflect the presence of a small cone of depression, for example, that might develop around a single well located somewhere within the cell. The vertical resolution of the model is also limited. In general, water levels, drawdowns, and fluxes correspond to single hydrostratigraphic units or subdivision of units within the flow system.

Transient model simulations require time to be divided into discrete steps, and the length of these steps affects the temporal resolution of the model. The model simulates changes in pumping in steps over periods that average about 10 years long. Pumping rates at all wells are constant during each period and generally represent the rates at the middle of the period. The model contains 15 such pumping periods between 1864 and 2000. Model output is reported at selected times during and at the end of each period.

<u>Discharge Locations</u>: There are two categories of discharge locations (or "sinks") for groundwater in the model. The first includes surface water bodies, such as Lake Michigan, rivers and streams, inland lakes and ponds, wetlands, springs and seeps, agricultural tiles, and the water table itself. The second consists of pumped wells. Some wells extract groundwater from shallow aquifers, some from deep aquifers, and some from both parts of the flow system.

<u>Local and Regional Flow Systems</u>: When groundwater circulates from the water table to the nearest discharge location, for example a stream, it is part of a local groundwater flow system. When groundwater circulates more deeply so that it flows under discharge locations before arriving at a more distant sink, such as a major river or Lake Michigan, then it is part of a regional groundwater flow system. It is important to note that some groundwater circulating strictly in the shallow system can still follow a regional flow path, while groundwater entering the deep system can follow local flow paths, especially in areas where the shallow and deep systems are in good communication. In southeastern Wisconsin, deep local flow is only likely to occur where the Maquoketa shale is absent.

Sources of Water to Wells: Precipitation that recharges to the water table is the ultimate source of groundwater. The groundwater eventually discharges to surface water and wells. To isolate the specific sources of water to wells, it is necessary to account for groundwater that would flow elsewhere if it were not for wells. The discharge to wells is drawn from four classes of available groundwater (Winter et al., 1998). The first source, and usually the most important, is groundwater "captured" from surface water, defined as groundwater that would discharge to surface water under natural conditions, but that is diverted to wells by pumping. One example is captured baseflow to streams. The second source is groundwater flow "induced" from surface water, defined as water that is directly removed from surface water and enters the groundwater system due to pumping. Induced flow from streams and other water bodies usually requires a reversal of hydraulic gradients caused by wells near surface-water bodies, so that the groundwater system gains water instead of yielding it to streams. The third source is "storage release", defined as the water released from the groundwater reservoir in response to declining water levels resulting from pumping. This source derives either from drainage of pores at the water table or from compression of the aquifer matrix (and expansion of the water) at depth. It is most important at the onset of pumping or after an increase in pumping. The fourth source is "cross-boundary flow". This flow actually originates as one or more of the other three sources acting outside the study area. For this investigation, cross-boundary flow corresponds to groundwater flow from surrounding counties that flows into the seven-county SEWRPC region because of pumping within the region. Part of the cross-boundary flow is "captured" (that is, groundwater that in the absence of pumping would leave the study area) and part is "induced" (that is, groundwater that enters the study area only because pumping is active). For this report, the "cross-boundary flow" does not include flows from the Lake Michigan side of the study area because they are counted either as part of induced flow from surface water (when water moves directly from the lake to wells) or captured flow from surface water (when water that would otherwise discharge to the lake is captured by wells).

Groundwater and Surface-Water Divides: Groundwater or surface-water divides are imaginary surfaces that separate water that flows toward one discharge location from water that flows to another. In plan view, a divide appears as a line separating two areas of a map. Groundwater divides mark the boundaries of groundwater systems. It is possible to map local divides that segregate recharge areas by their discharge location. It is also possible to map regional divides, such as the boundary that separates all groundwater flow in the deep system that follows long travel paths to Lake Michigan from groundwater discharging in other areas. Surface-water divides define watersheds in which all overland runoff contributes to a single surface-water body. Land-surface topography controls the boundary of the watershed. While groundwater flow is influenced by topography, groundwater divides do not necessarily coincide with surface-water divides. This study demonstrates cases where groundwater originating in one surface watershed discharges to a surface-water body (or well) in another surface watershed.

Recharge and Leakage: Recharge is infiltration at the land surface that percolates to the water table and becomes groundwater flow. The amount of recharge in a period of time that becomes groundwater in an area is its recharge flux. Most groundwater flow ultimately originates as recharge (a smaller amount can originate as percolation from surface-water bodies, especially under the influence of pumping). Most groundwater flow circulates from the water table through shallow flow systems and returns to the water table where it discharges to surface-water bodies. However, a part of the recharge flux flows to the deep part of the flow system, where it exits from the study area as cross-boundary flow, circulates back upward to the shallow system, or discharges to deep wells. In this report, the portion of the recharge flux entering the deep part of the flow system by downward movement is called “leakage”. Deep pumping increases the amount of leakage both where the Maquoketa shale is present and absent.

Travel Times and Effective Porosity: A model solution simulates the water level for each model cell as well as the volume of groundwater that flows across the cell in a unit of time such as a day. However, although a set of model inputs uniquely determines the water levels and volumetric rates of flow simulated by the model for a given pumping period, it does not uniquely determine the velocity of a groundwater particle moving through the cell for that period. The velocity is undetermined because groundwater does not flow uniformly through the entire volume represented by a model cell. Instead, the same total flow is distributed preferentially through variable conductivity pathways too small to measure or represent in the model. These pathways result from small variations in rock type, the geometry of pore space between sand grains, joints and bedding plane fracture openings, and the degree to which the openings are interconnected. An extra parameter, called the effective porosity, is needed to address the importance of preferential flow in different portions of the model. The values assigned to the effective porosity do not affect the model solutions of heads or flows. They only affect the use of the model output to determine the travel times between points of interest, such as the travel time between the water table and deep wells.

In settings where preferential flow zones do not exercise much influence on groundwater velocities, the effective porosity is close in value to the total porosity of the rock. If zones of preferential flow are more important, the rates of groundwater velocity are greater, and the values that must be assigned to the effective porosity to reproduce high velocities are smaller. In cases where virtually all the flow occurs through discrete fractures in the volume represented by the cell, then the effective porosity needed is close to the small secondary porosity associated with only the fractured part of the rock.

In the study area of the model, model cells are 2500 ft on a side and average about 100 ft in thickness. For some hydrogeologic units, such as unlithified sands and silts, the small-scale variation in conductivity pathways over the volume represented by model cells is generally small. Effective porosity values equal to 10% or more are appropriate. For other geologic units, such as fractured dolomite and shale, the influence of small preferential flow zones on groundwater velocity is great, and it is appropriate to set effective porosities to 1% or less (Domenico and Schwartz, 1990). For the deep sandstone units in southeastern Wisconsin, there is uncertainty about appropriate values for effective porosity. It is often assumed that flow occurs uniformly through the porous sandstone matrix such that relatively low velocities correspond to relatively high values of effective porosity. However, there is increasing recognition that even in sandstone aquifers, porosity due to fractures can be important and that flow occurs preferentially as well as through the matrix. A recent comprehensive analysis of the hydrogeology of sandstone and other bedrock units in Minnesota (Runkel et al. 2003) emphasizes the importance of relatively rapid flow through secondary or fracture porosity. In southeastern Wisconsin, the influence of fractures on flow through deep sandstone units is unknown. In the face of this uncertainty, a range of low to high effective porosities is used to represent deep aquifer systems. On the basis of this range of values, range of travel times to wells is reported.

3. Effect of Pumping on Water Levels

The groundwater flow model for southeastern Wisconsin simulates groundwater levels before large-scale pumping began, and then the gradual decline in water levels as pumping increased. It accounts for changes in pumping both in the nearfield of the model and in surrounding regions such as northern Illinois.

Predevelopment Water Levels

Pumping in southeastern Wisconsin began around 1864. Predevelopment water levels represent average conditions up to 1864. The water table configuration in Figure 3a shows predevelopment conditions in the shallow part of the flow system. The contours simulated by the flow model reflect the strong influence of topography and the surface-water network on the variations in the water table.

The water levels in the St. Peter Formation shown in Figure 3b represent predevelopment conditions in the deep part of the flow system. The contours simulated by the flow model are influenced by topography and surface water where the Maquoketa shale is absent west of its subcrop located in Dodge and western Waukesha and Walworth Counties. Over this area the shallow and deep parts of the system are in good communication. East of the Maquoketa subcrop, the potentiometric surface in the deep part of the flow system is more regular and slopes uniformly to the east. In this area the two parts of the flow system are not well connected, so that the deep groundwater discharges over long flow paths to Lake Michigan, rather than to shallow, nearby discharge locations associated with streams and other water bodies.

Drawdown in Shallow and Deep Parts of Flow System

The onset of withdrawals from shallow and deep wells gradually changed the groundwater flow system between 1864 and 2000. In 1950, deep pumping centered on Milwaukee with significant shallow pumping along the Rock River around Janesville (Figure 4a). By 2000, the deep pumping center had moved to central and eastern Waukesha County with significant shallow pumping in Rock County, Washington and Ozaukee Counties (Figure 4b). The total high-capacity pumping in the model nearfield (the SEWRPC counties plus Dodge and Jefferson County and eastern Rock County) increased from negligible pumping in 1864, to 37 million gallons per day (mgd) in 1950, to 113 mgd in 2000. Section 3 of Report 1 of this study provides more detail on the distribution of pumping through time and space.

The decline in water levels caused by pumping is different for the shallow and deep parts of the flow system. Shallow wells in the unlithified sand-and-gravel and Silurian dolomite aquifers generally cause little regional drawdown because local surface-water features (streams, lakes, and wetlands) help to maintain the water table. Often the major effect of these shallow wells is to reduce the amount of groundwater discharge to such local surface-water features. At the resolution of the model, simulated drawdown in the Silurian dolomite aquifer occurs mainly in Ozaukee County and parts of western Washington, northeastern Waukesha, and northern Milwaukee Counties (Figure 5). Simulated drawdown in the Silurian dolomite between 1864 and 2000 approaches 200 ft in the vicinity of pumping centers in southern Ozaukee County.

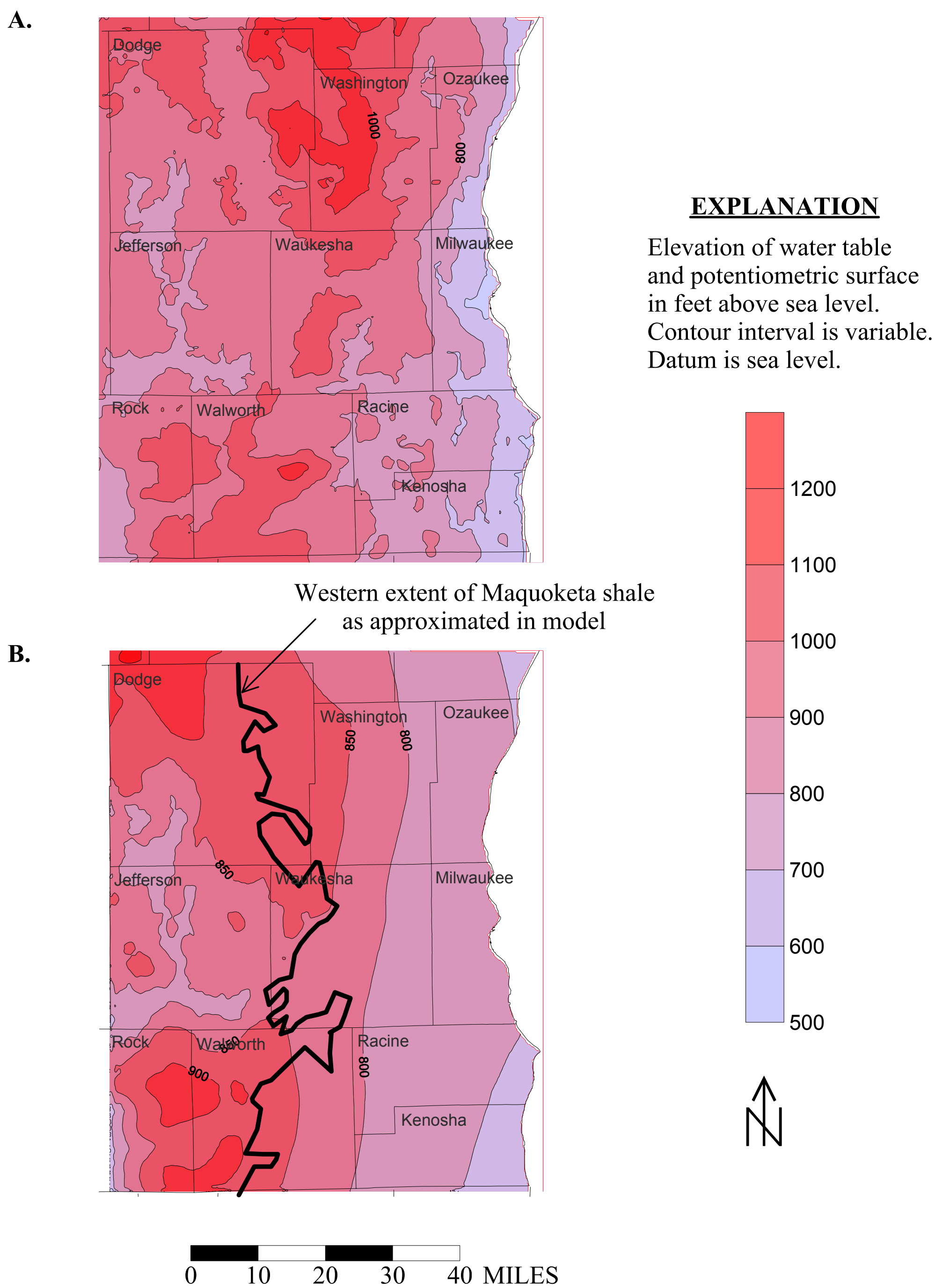
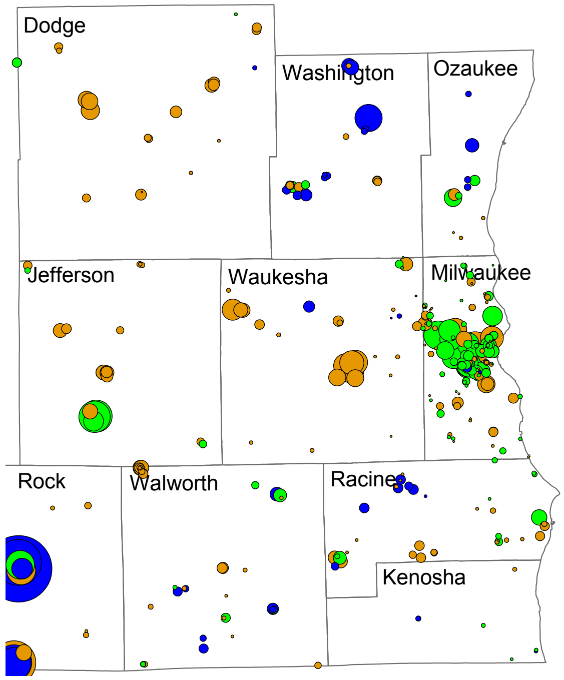


Figure 3. **Simulated Predevelopment Water Levels.**
A. Water table. **B. St. Peter Formation.**

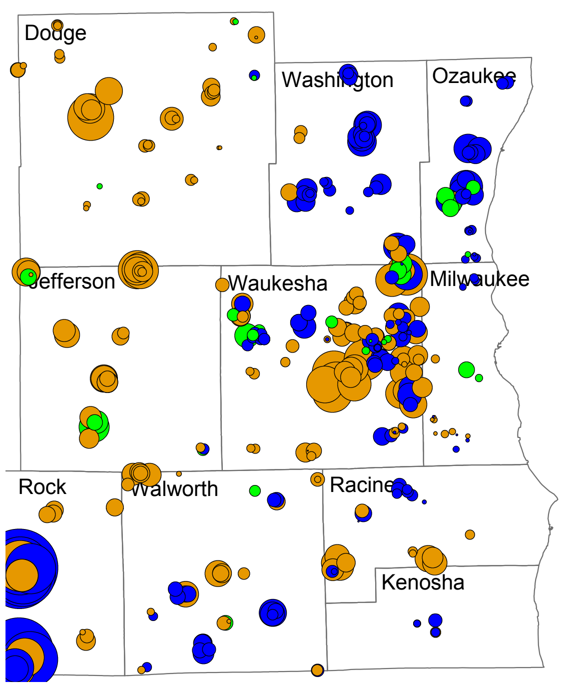
A



Blue = Pumping from Shallow System
Green = Pumping from both Shallow and Deep System
Orange = Pumping from Deep System

Circle diameter corresponds to magnitude of pumping.
Total pumping from shallow wells = 10.2 mgd
Total pumping from wells open to both shallow and deep aquifers = 12.0 mgd
Total pumping from deep wells = 14.4 mgd

B



Blue = Pumping from Shallow System
Green = Pumping from both Shallow and Deep System
Orange = Pumping from Deep System

Circle diameter corresponds to magnitude of pumping.
Total pumping from shallow wells = 53.5 mgd
Total pumping from wells open to both shallow and deep aquifers = 5.2 mgd
Total pumping from deep wells = 54.1 mgd

Figure 4. Distribution of shallow and deep pumping.
A. 1950. B. 2000.

Increased drawdown over time is more dramatic in the deeper parts of the flow system. The conditions in the St. Peter Formation are representative of the entire deep sandstone aquifer. In 1950, pumping centered in Milwaukee produced a regional cone of depression centered below Milwaukee with maximum drawdown in the St. Peter potentiometric surface exceeding 300 ft (Figure 6a). By 2000, increased pumping especially in Waukesha County moved the center of the regional cone of depression approximately 9 miles west with maximum drawdown in the St. Peter approaching 500 ft (Figure 6b). A single regional drawdown cone is evident for both 1950 and 2000 (the model resolution is not sufficient to capture local deviations from the regional pattern associated with individual wells). The cone of depression extends not only to the west below Dodge, Jefferson, and Rock Counties, but also under Lake Michigan to the east. The drawdown patterns are affected not only by pumping in southeastern Wisconsin, but also by pumping outside the model nearfield. The effect of pumping in northeastern Illinois is especially evident in the drawdown contours shown for Racine and Kenosha Counties.

Hydrographs of simulated water levels through time also show the evolution of drawdown at selected locations. Figure 7 shows water levels in the St. Peter at 5 locations along a line from Watertown to Milwaukee, following the approximate regional southeastward dip of the geologic units. Watertown and Oconomowoc are located far from pumping centers and beyond the most westward extent of the Maquoketa shale. At these locations the St. Peter potentiometric surface shows little drawdown in 2000. Pewaukee, Elm Grove and Milwaukee are close to pumping centers in areas where the deep sandstone aquifer is confined by the Maquoketa shale. The decline in Milwaukee water levels was sharp from 1864 until about 1950 and then slowed. Simulation results indicate that the rate of decline in Pewaukee and Elm Grove water levels has also slowed, but only slightly. There is still an appreciable downward trend in these areas.

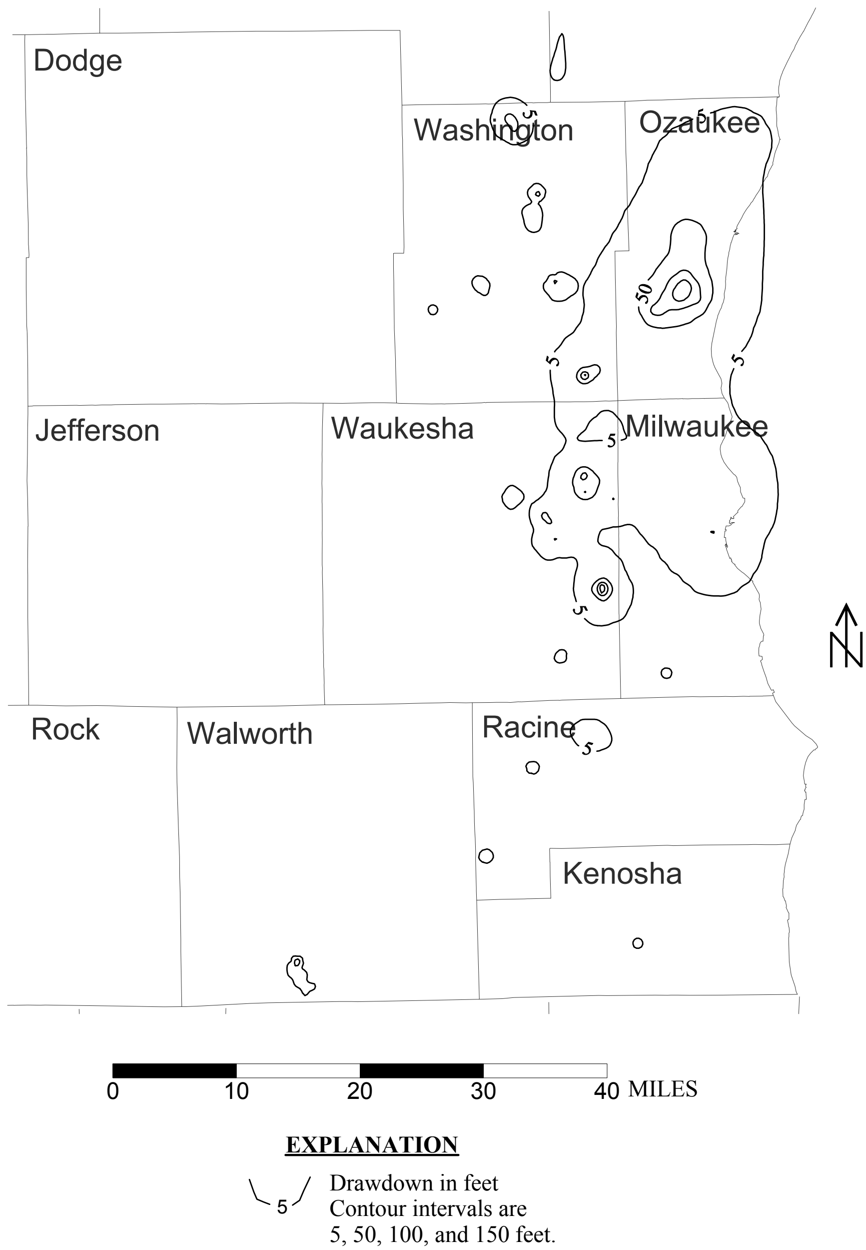


Figure 5. **Simulated shallow drawdown relative to predevelopment conditions: Silurian Aquifer in 2000**

Note: The model underestimates drawdown in parts of Ozaukee County where household wells are active but pumping rates are not well known. Shallow household wells can produce significant regional drawdown in sewered areas of Ozaukee County because their discharge water is not returned to the groundwater through septic systems.

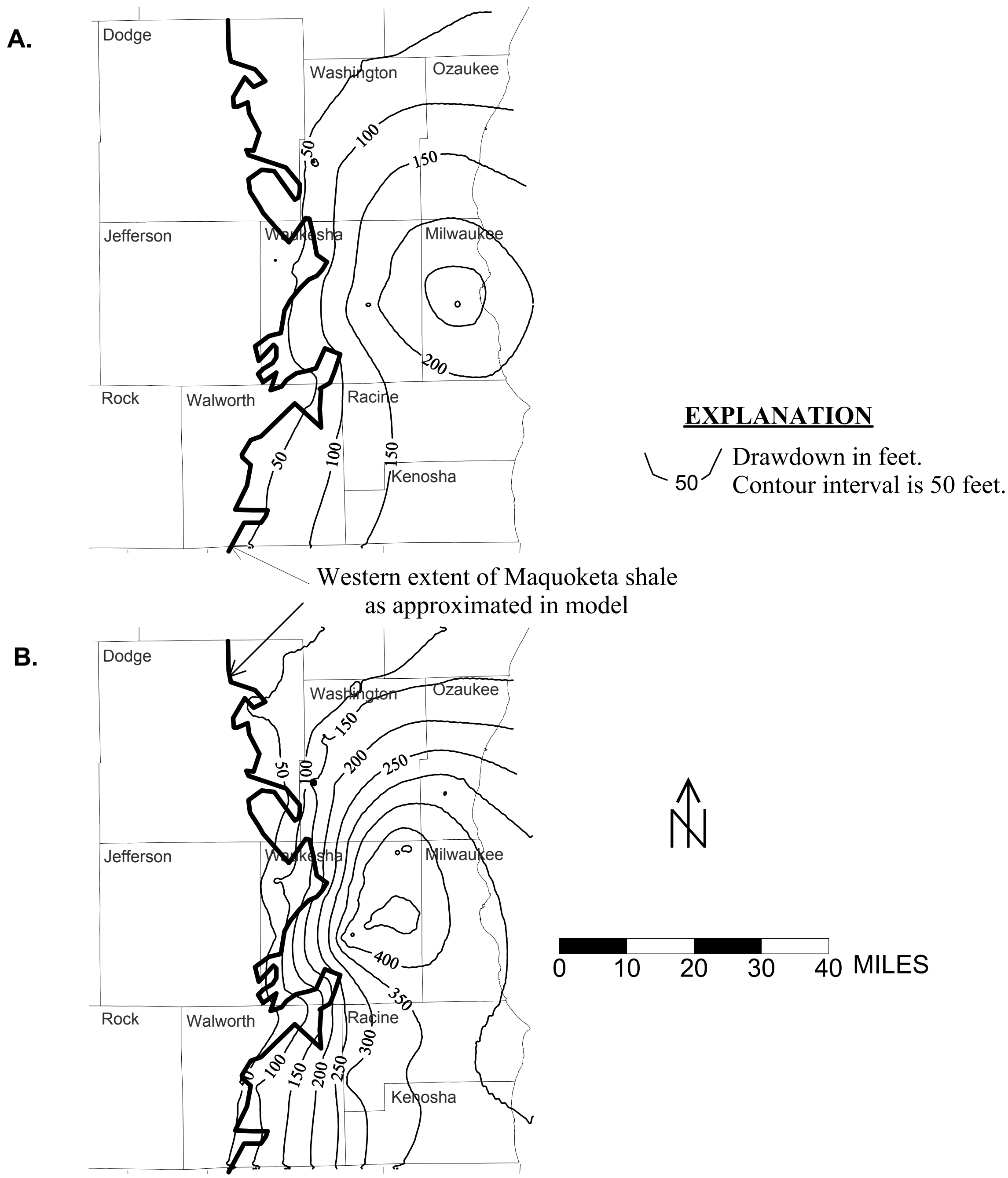


Figure 6. **Simulated deep drawdown relative to predevelopment conditions: St. Peter Formation.**
A. 1950. B. 2000.

Unsaturated Conditions at Depth

It is possible for deep pumping below an aquitard to cause locally unsaturated conditions below the aquitard. Under these circumstances, the model simulates a transition to unconfined conditions, producing a second water table in the deep part of the flow system and allowing for release of water from storage by draining of rock pores. Model results suggest that in recent years, the top of the Sinnipee dolomite below the Maquoketa shale has become unsaturated directly under the city of Waukesha pumping center (Figure 8). An unsaturated condition at this depth, depending on how it spreads, could influence the well yields and groundwater geochemistry around deep wells open to the Sinnipee, the St. Peter Formation, and below. However, the simulated results are uncertain because of the limited resolution of the model layering and because the MODFLOW code does not explicitly simulate unsaturated flow. To confirm the extent of deep unsaturated conditions, it would be necessary to use more specialized flow models constructed at a finer scale and calibrated to water levels collected directly from this area. Appropriate deep wells for such data collection are currently unavailable.

Future Drawdowns

The groundwater model is a useful tool for simulating future drawdowns. Future drawdowns depend on future pumping. To arrive at a low-end estimate of future pumping, no change from year 2000 pumping rates was assumed. As a more reasonable approximation of future pumping, the overall trend in nearfield pumping rates was extrapolated beyond 2000 to 2020. If present trends continue, pumping in 2010 will be 10-20% greater than 2000 rates, and pumping in 2020 will be 30-40% greater than 2000 rates. Multipliers in those ranges were applied to all pumping, shallow and deep, in the model nearfield for the 2000 to 2010 and 2010 to 2020 periods. Pumping outside the nearfield was fixed at 2000 levels.

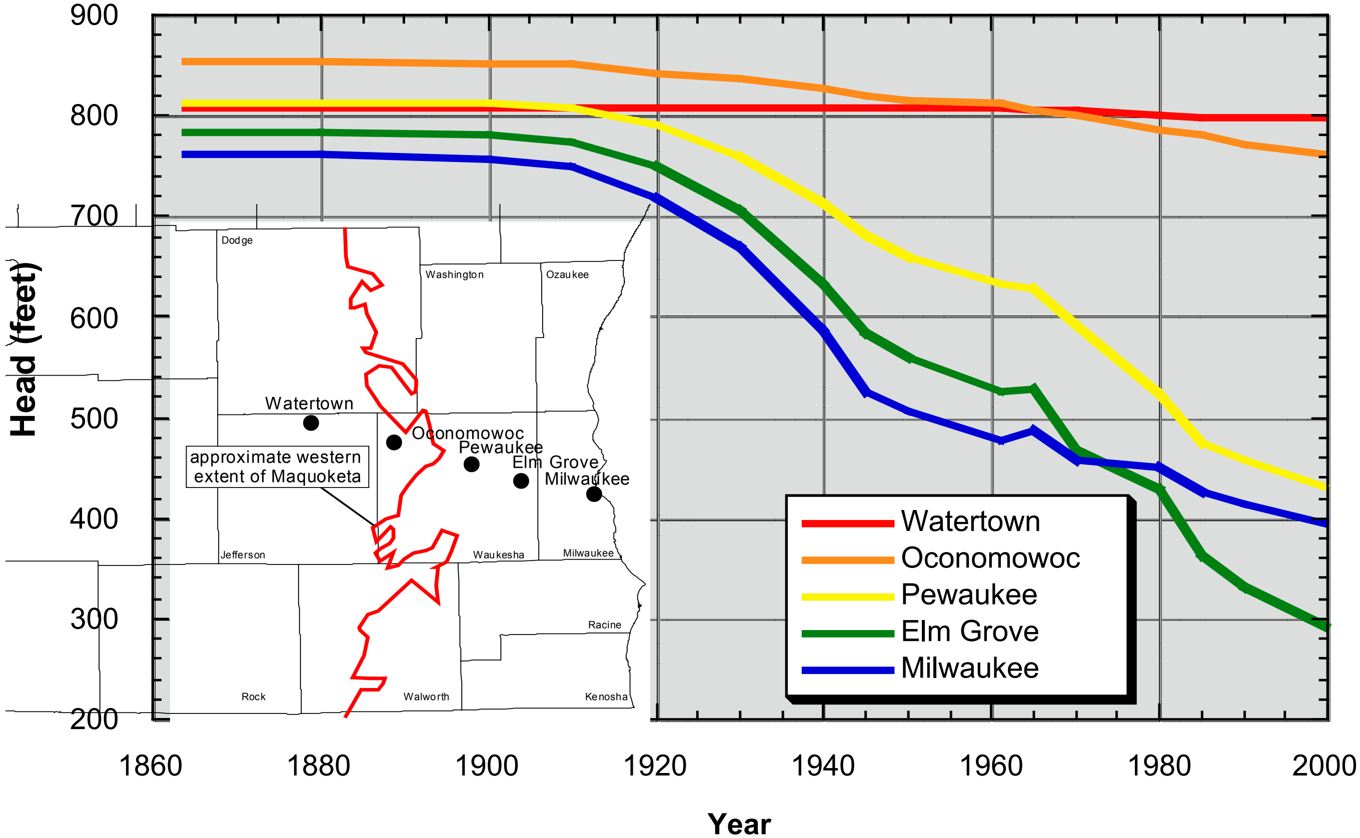


Figure 7. Decline in deep water levels at selected locations.

Explanation: Curves represent simulated hydraulic heads at the top of the deep system (St. Peter Formation).

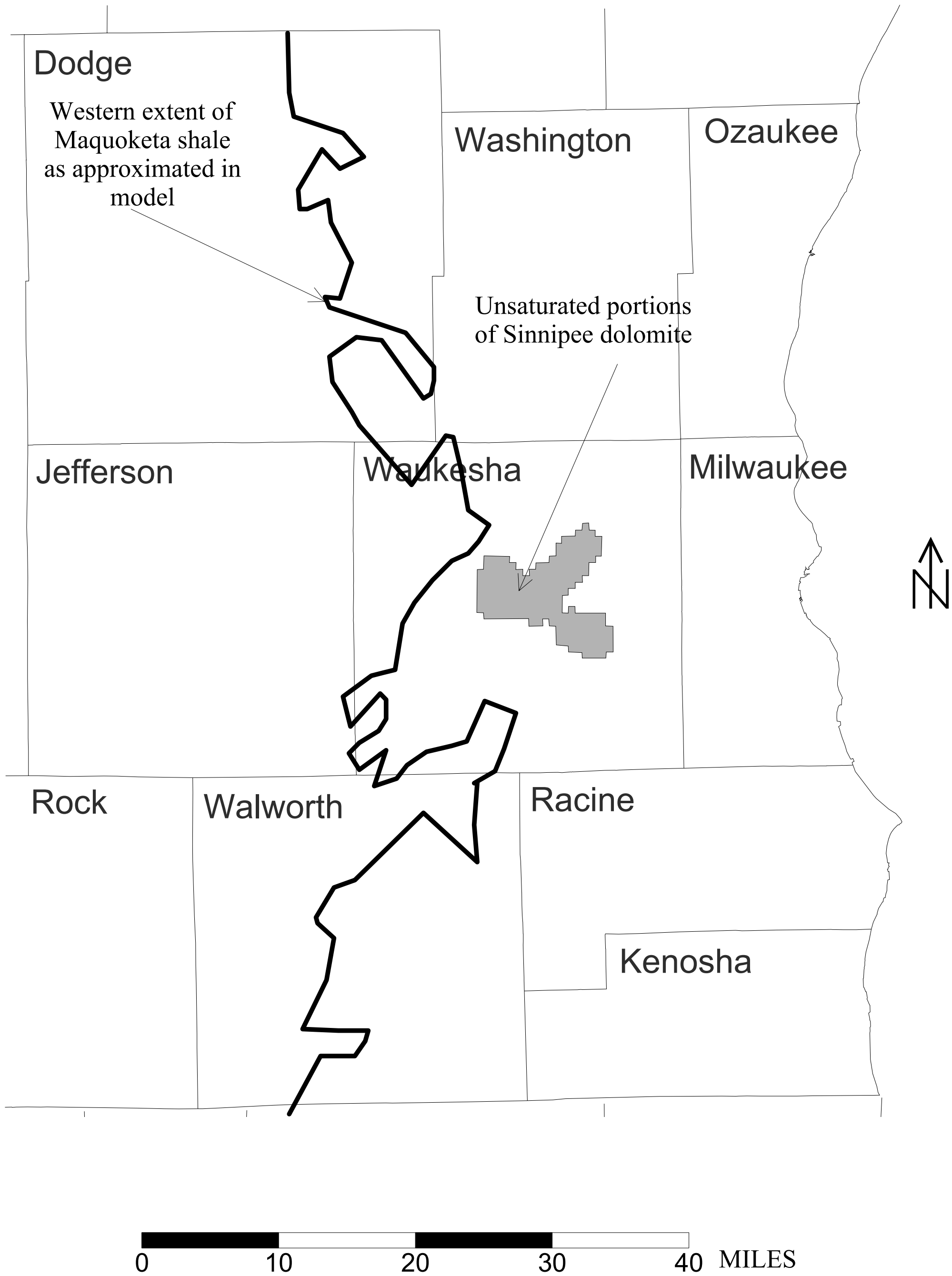


Figure 8. **Simulated unsaturated conditions in deep part of flow system: Sinnipee dolomite in year 2000.**

Model results show the relation between future pumping rates and future drawdowns. Predictive simulations (Table 1) indicate that if overall pumping remains constant at year 2000 rates, little additional drawdown will occur in the deeper part of the flow system over the subsequent 20 years although the cone of depression will continue to spread laterally. As water levels stabilize, less water will be released from storage below the seven-county region. In contrast, if pumping rates continue to rise according to historical trends, then additional drawdown will be significant. For example, the model simulates 125 ft of additional drawdown by 2020 in the St. Peter Formation below the Village of Elm Grove. West of the Waukesha County pumping centers, the model simulates 26 ft of additional drawdown at Oconomowoc and 5.5 ft of additional drawdown at Watertown. Under these circumstances the deepening and spread of the cone of depression in the deep sandstone will involve significant transfers of groundwater from storage to wells. Model results for historical and future shallow and deep drawdown are available for municipalities throughout the seven-county SEWRPC region. However, it is important to emphasize that the simulated future drawdowns depend on uncertain estimates of future pumping that do not take account of the installation of new wells and changing proportions of withdrawals between wells.

Table 1. Additional drawdown in St. Peter Formation between 2000 and 2020 at selected locations.

Note:

Additional drawdown is calculated for two pumping scenarios.
St. Peter drawdown is representative of conditions in the deep sandstone aquifer.

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Pumping rates for 2020 sustained at 2000 rates over entire model.

Town[*]	Simulated 2000 Drawdown Relative to Predevelopment (ft)	Additional 2020 Drawdown Relative to 2000 (ft)
Watertown	12.1	0.1
Oconomowoc	93.9	2.0
Pewaukee	385.7	14.9
Elm Grove	495.6	15.1
Milwaukee	368.5	16.1

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Pumping rates for 2020 extrapolated from 2000 rates according to trend over model nearfield; elsewhere, pumping sustained at 2000 rates.

Town[*]	Simulated 2000 Drawdown Relative to Predevelopment (ft)	Additional 2020 Drawdown Relative to 2000 (ft)
Watertown	12.1	5.5
Oconomowoc	93.9	26.3
Pewaukee	385.7	90.7
Elm Grove	495.6	125.0
Milwaukee	368.5	76.6

[*] Town locations shown on Figure 7.

4. Sources of Water to Wells

To arrive at a better understanding of the effect of pumping on the groundwater flow system, it is useful to determine the sources of water that contribute to well discharge. There are four sources in the SEWRPC area: “captured” flow from surface water, “induced” flow from surface water, storage release, and cross-boundary flow. The model distinguishes between these sources for different regions and aquifer systems and shows how pumping diverts water from the natural groundwater and surface-water systems in the seven-county SEWRPC region.

Sources to Shallow Wells in 2000

In year 2000, groundwater discharge to shallow high-capacity wells amounted to nearly 30 mgd in the seven-county region (compared to about 530 mgd in the region that discharged to surface water as base flow). Shallow pumping occurs in the unlithified sand-and-gravel deposits and the Silurian dolomite aquifer. According to the model, about 61% of the water extracted from these shallow units was derived from groundwater flow that in the absence of pumping would have discharged to streams and Lake Michigan (Table 2). About 27% was derived directly from water bodies due to reversed hydraulic gradients at the groundwater-surface-water interface. Storage release, making up the balance (about 12%), is also an important source because even small declines in water-table elevation release significant water from storage by drainage of pores. The amount of groundwater contributed to shallow wells from increased cross-boundary flow into the seven-county area is negligible because the direction of shallow flow is controlled more by natural discharge locations than by pumping.

Sources to Deep Wells in 2000

In year 2000, high-capacity deep pumping amounted to about 33 mgd in the seven-county region. Deep pumping occurs primarily in the deep sandstones aquifer, but many wells are also open to the Sinnipee dolomite. Simulation results indicate that about 68% of the groundwater extracted from these deep units would have discharged to streams and Lake Michigan but instead, because of pumping, leaks downward from the shallow to the deep

Table 2. Sources of Water to Shallow Wells in 2000. SEWRPC 7-county region only.

	Flux (mgd)	Percent Source
Shallow Pumping in Year 2000	29.58	--------
Groundwater Flow "Captured" from Surface Water		
Captured Baseflow to Streams, Lakes, Wetlands	16.82	56.9%
Captured Shallow Discharge to Lake Michigan	1.14	3.9%
Groundwater Flow "Induced" from Surface Water		
Induced Flow from Streams, Lakes, Wetlands	7.81	26.4%
Induced Flow from Lake Michigan	0.25	0.8%
Shallow Groundwater Storage Release (below 7-County region)	3.43	11.6%
Cross-Boundary Shallow Groundwater Flow		
"Captured" Lateral Flow Across Inland Boundaries	0.13	0.4%
Total sources	29.58	100.0%

Explanation: Shallow pumping includes all discharge from the Shallow Aquifer System (composed of Unlithified Deposits and the Silurian dolomite).

Recharge is assumed constant between Predevelopment and Year 2000. It is the ultimate source of groundwater under both predevelopment and pumping conditions, but because it is does not change in response to pumping, it is not proper to consider it as a source of water to wells.

Cross boundary flow originates chiefly as base flow capture and storage release outside the 7-county SEWRPC area.

part of the flow system (Table 3). The contribution by induced flow from surface water bodies is small, 4%: it is limited to water derived directly from Lake Michigan because of reversed hydraulic gradients along the coastline. Storage release from below the seven-county region is also a small source of water, 3%, but storage release in the part of the deep aquifer below Lake Michigan is more important, contributing 8% of deep withdrawals. In contrast to the shallow part of the system, flow across the boundaries of the deep part of the system is a very important source of water to wells. About 18% of the water withdrawn from deep wells originates outside the 7-county region from the north and west. Most of this deep lateral flow occurs below the western boundaries of Washington, Waukesha and Walworth Counties.

Water Balance for Deep Part of Flow System

Model results illustrate the significant effect of pumping on the water balance in the SEWRPC region. Figure 9 shows in detail the various fluxes that provide groundwater to the deep part of the flow system under the seven-county region and contrasts the sources of water before and after pumping. Under predevelopment conditions, the net flow of groundwater was out of the deep units along its three inland boundaries as well as along its Lake Michigan boundary (Figure 9a). The flow escaping the deep part of the flow system by lateral flow was balanced by downward leakage into the system, equal to about 5 mgd. Most of this downward flow occurred where the Maquoketa shale is absent. These shallow to deep transfers in the western portions of Waukesha and Walworth counties accounted for about three quarters of all the deep flow. According to model results, about one-quarter of the deep flow originated as leakage through the Maquoketa shale.

By year 2000, pumping from deep wells had reversed the groundwater flow across three of the four lateral boundaries of the deep part of the flow system (Figure 9b). Along the southern boundary, net groundwater flow out of the study area increased relative to predevelopment conditions because of large-scale pumping in Illinois. But along its western and northern boundaries, the seven-county region became a net importer of

Table 3. Sources of Water to Deep Wells in 2000. SEWRPC 7-county region only.

	Flux (mgd)	Percent Source
Deep Pumping in Year 2000	33.33	-------
Groundwater Flow "Captured" from Surface Water		
Baseflow leaked downward from Shallow System	19.69	59.1%
Deep Discharge to Lake Michigan	2.84	8.5%
Groundwater Flow "Induced" downward from shallow rocks below Lake Michigan	1.30	3.9%
Deep Groundwater Storage Release		
Release below Lake Michigan	2.63	7.9%
Release below 7-County region	1.00	3.0%
Cross-Boundary Deep Groundwater Flow		
"Captured" Lateral Flow Across 7-County Inland Boundaries	2.39	7.2%
"Induced" Lateral Flow Across 7-County Inland Boundaries	3.48	10.4%
Total sources	33.33	100.0%

Explanation: Deep pumping includes all discharge from the Deep Aquifer System (composed of the Sinnipee Dolomite and the deep sandstone units).

Recharge is assumed constant between Predevelopment and Year 2000. It is the ultimate source of groundwater under both predevelopment and pumping conditions, but because it is does not change in response to pumping, it is not proper to consider it as a source of water to wells.

Captured and induced cross-boundary flow originates chiefly as downward leakage and storage release outside the 7-county SEWRPC area.

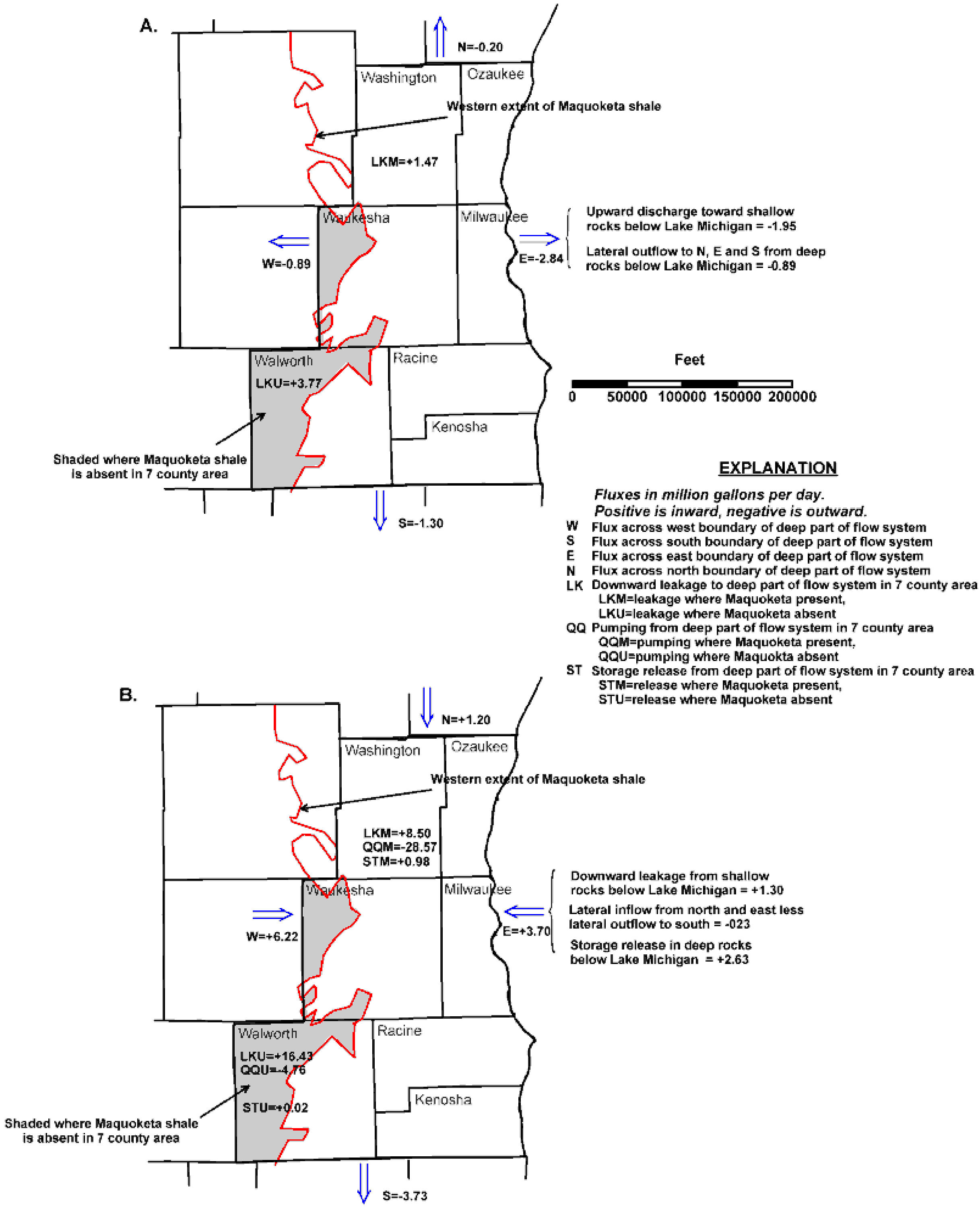

Figure 9. **Water balance (mgd) for deep system below seven-county region. A. Predevelopment. B. 2000.**

Explanation: Positive fluxes are into deep part of flow system below seven-county region. Negative fluxes are out of deep part of flow system below seven-county region.

groundwater. Wells have also had a profound effect on the exchange of water between Lake Michigan and the flow system under the SEWRPC region. Model simulations show that before pumping, the deep part of the flow system lost almost 3 mgd to the groundwater system under the lake, but it now receives almost 4 mgd from that same area, representing a net reversal of about 6.5 mgd as a source of water for the approximately 33 mgd extracted from deep wells. Two thirds of the water derived from the deep aquifer extending under the lake originates as storage release. The amount is large because the cone of depression caused by pumping initiated in 1864 continued to spread farther to the east through 2000, causing the deep sandstone aquifer units under even the eastern part of the Lake to compress and release water from storage.

As pumping increased over time, the leakage between the shallow and deep parts of the flow system grew in strength. By the year 2000, simulation results indicate that leakage had increased from about 5 to 25 mgd. The amount of downward flow was far greater in the areas where the Maquoketa shale is absent even though most of the pumping occurred (and continues to occur) below where it is present. This contrast implies a large transfer of shallow groundwater from the western portions of the study area into the deep part of the flow system and then movement east to pumping centers underlying areas such as the city of Waukesha.

The 25 mgd of shallow groundwater that leaked to the deep part of the flow system in 2000 over the seven-county region is the most important source of water to deep wells, but still amounts to only 4% of the 583 mgd of recharge flux to the region. Under natural conditions leakage was equal to 5 mgd, whereas under year 2000 conditions, the leakage caused by pumping amounts to an additional 20 mgd. The fraction of the recharge flux at the water table that replenishes the top of the sandstone aquifer is greatest where the Maquoketa is absent. Under predevelopment conditions the model indicates that 3.0% of recharge leaks to the deep part of the flow system where the Maquoketa is absent, but only 0.3% where it is present. Under 2000 conditions the corresponding values for where the Maquoketa is absent and present increase to 12.8% and 1.9% respectively, showing the strong influence of deep pumping on vertical flow patterns throughout the seven-county region.

Storage Release over Time from Deep Part of Flow System

Future water-level trends depend not only on the amount of future pumping, but also on the time necessary for any part of the flow system to adjust to increased pumping. The groundwater system around discharging wells adjusts initially by releasing water from storage as water levels drop. As more water is captured and/or induced from surface-water bodies, water levels tend to stabilize around pumping centers. It is possible to use the model to calculate the overall response time to stabilize drawdown in southeastern Wisconsin for the shallow and deep parts of the regional flow system. To perform this calculation, year 2000 pumping rates were applied for the entire flow model to background predevelopment conditions, and maintained constant for 200 years. The model indicates that 50% of the long-term drawdown in the shallow system over the seven SEWRPC counties occurs within 3 years and 90% within 30 years. The response time of the deep system in the study area is even shorter. In the deep system, 50% of the long-term drawdown occurs within 2 years and 90% within 15 years. These results imply that in response to a single step increase of pumping across the region, drawdown continues for about 15 to 30 years, after which additional drawdown is small and wells receive relatively little water from storage derived from below the seven-county region.

The flow model integrates the response of drawdown and storage release to the accumulated changes in pumping that have occurred between 1864 and 2000. The changes in pumping are simulated as a series of steps of five or ten years duration. The model simulation shows that in response to the historical pattern of pumping, the absolute amount of water released from storage in the deep part of the flow system over the model nearfield did not vary greatly from one period to another because the system continuously adjusted to the successive increases in discharge (Table 4). However, as total deep pumping increased from about 4 mgd to over 56 mgd between 1920 and 2000, the proportion of discharge to deep wells derived from storage decreased exponentially, from about 60% in 1920 to 6% in 2000, (Table 4). The important sources of water to deep wells shifted from storage release (due to declining water levels in the vicinity of the wells) to vertical leakage from the shallow system (some through the Maquoketa shale but most from downward flow west of its subcrop), as well as cross-boundary flow and inflow from under Lake Michigan. As the regional cone of depression has expanded in size, some of the groundwater now moving to deep wells originates as storage release under Lake Michigan at locations far to the east of regional pumping centers. Most, however, originates as shallow groundwater to the west of pumping centers that would have discharged to surface water bodies under natural conditions but is diverted to longer and deeper flow paths in response to deep pumping.

Table 4. Storage Release over Time in Deep Part of Flow System. Entire model nearfield.

Year	Deep Nearfield Pumping	Storage Release Below Nearfield Area	Storage Release Below Lake Michigan	Total
1920				
Flux (mgd)	3.83	0.78	1.51	2.29
Pct. of Deep Pumping	-------	20.4%	39.4%	**59.8%**
1950				
Flux (mgd)	22.30	1.58	3.70	5.28
Pct. of Deep Pumping	-------	7.1%	16.6%	**23.7%**
1980				
Flux (mgd)	37.60	1.50	3.51	5.01
Pct. of Deep Pumping	-------	4.0%	9.3%	**13.3%**
2000				
Flux (mgd)	56.66	1.05	2.64	3.69
Pct. of Deep Pumping	-------	1.8%	4.7%	**6.5%**

In the future, deepening cones of depression and accompanying storage release could play a more important role as a source of water to deep wells. If well discharge in southeastern Wisconsin were to be significantly increased, for example on the order of

40% by 2020, then the accelerated drawdown would cause the contribution of storage to increase and account for more than 10% of all groundwater withdrawn by deep wells.

5. Shallow Groundwater Interactions with Lake Michigan

Regional pumping has reduced the amount of groundwater discharged to Lake Michigan from unlithified and Silurian/Devonian deposits in the shallow part of the flow system. Under both predevelopment and pumping conditions, simulation results show that groundwater movement across the shallow part of the flow system along the Lake Michigan coastline is almost exclusively toward the lake. However, pumping has decreased the total amount of groundwater discharge to the lake. The decrease appears in two ways. First, pumping reduces the direct discharge of groundwater beneath the coastline to deposits under the lake and ultimately up through the lakebed into the lake itself. Second, pumping reduces indirect groundwater discharge to Lake Michigan. Indirect discharge consists of baseflow to streams that flow into the lake. All streams east of the subcontinental surface-water divide (approximate location shown on Figure 10) flow into Lake Michigan.

Predevelopment Conditions

Under predevelopment conditions, a portion of the water that recharged the shallow groundwater system along the coastline circulated directly to Lake Michigan. This zone corresponds to most of Ozaukee County and the eastern fringes of Milwaukee, Racine and Kenosha Counties, and is indicated by the combined solid and stippled portions shown on Figure 10. Within the zone, the model indicates that areas where the recharge flux circulated to streams (80% of the area) existed alongside areas where the recharge flux circulated directly to the Lake (20% of the area). The flow from the latter areas contributed 13.3 mgd of direct groundwater discharge to Lake Michigan (Table 5). West of this zone, no groundwater discharged directly to the lake, but instead it flowed to local surface-water locations or leaked downward to the deeper parts of the flow system.

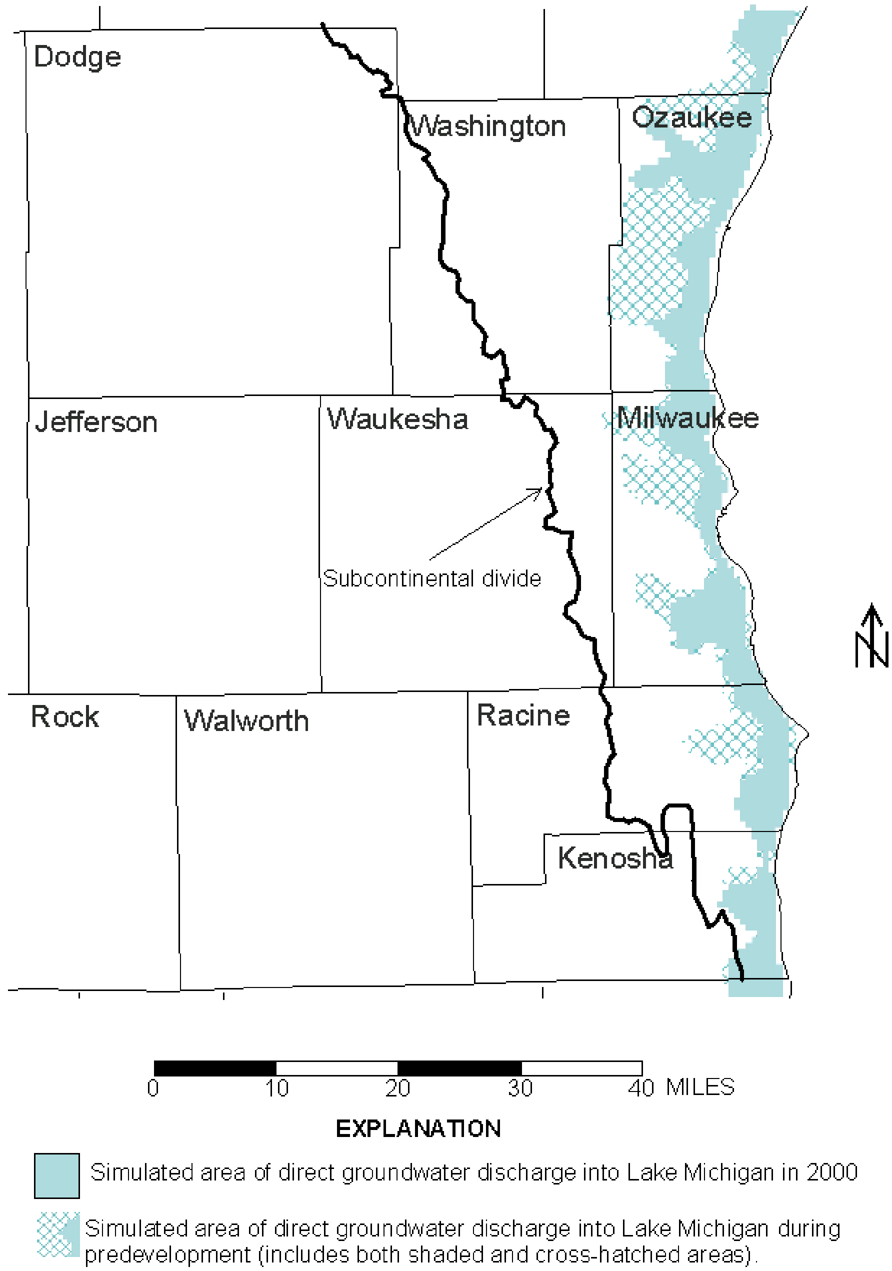

Figure 10. **Areas containing sources of direct groundwater flow to Lake Michigan: Predevelopment and year 2000.**

Explanation: The two zones encompass areas from which recharge to the water table discharges directly to Lake Michigan.

The combined hatched and solid zones correspond to predevelopment conditions. The solid zone alone corresponds to 2000 pumping conditions.

Some of the groundwater recharged within each zone contributes baseflow to streams rather than direct discharge to the lake. However, no groundwater recharged outside these zones flows directly to the lake.

Table 5. Effect of Pumping on Groundwater Interactions with Lake Michigan. Ozaukee, Milwaukee, Racine and Kenosha counties.

Year	Pumping East of Subcontinental Divide	Direct Discharge to Lake Michigan	Indirect Discharge to Lake Michigan	Total Discharge to Lake Michigan
1864	0.00 mgd	13.27 mgd	144.79 mgd	158.06 mgd
1950	2.57 mgd	12.86 mgd	142.95 mgd	155.81 mgd
Percent Change from 1864		*-3.1%*	*-1.3%*	*-1.4%*
2000	17.20 mgd	12.15 mgd	134.05 mgd	146.20 mgd
Percent Change from 1864		*-8.4%*	*-7.4%*	*-7.5%*

Explanation: Pumping and discharge fluxes refer to shallow part of flow system only.

Direct discharge refers to shallow groundwater flow into Lake Michigan.

Indirect discharge refers to shallow groundwater flow into surface water bodies east of the subcontinental divide that empty to Lake Michigan.

The model simulation accounts for effect of pumping on groundwater discharge to Lake Michigan, but it does not account for effects of urbanization and climate change. It also does not account for any flow of pumped water that is discharged to the sewer and deep tunnel system east of the subcontinental divide and is returned to Lake Michigan as storm flow or treated sanitary flow.

In the area between the subcontinental divide and Lake Michigan (Figure 10), the model indicates that groundwater contributed 145 mgd to streams as baseflow. This predevelopment flux eventually was routed to Lake Michigan as stream discharge and, therefore, constituted indirect groundwater discharge to the lake.

Effect of Pumping

For year 2000 conditions, the model indicates that pumping from wells reduced the coastline area where there was direct groundwater discharge to Lake Michigan to the zone indicated by the solid pattern in Figure 10. The largest loss of area where groundwater discharged directly to the lake occurred in Ozaukee and northern Milwaukee

Counties where pumping from the Silurian aquifer is most active. According to the model, the amount of direct discharge dropped from 13.3 mgd before pumping, to 12.9 mgd in 1950, to 12.2 mgd in 2000 (Table 5). The indirect discharge followed a similar pattern, dropping from 145 mgd before pumping, to 143 mgd in 1950, to 134 mgd in 2000 (Table 5). Overall, the model indicates that combined direct and indirect discharge to Lake Michigan diminished by 7.5% between 1864 and 2000.

The model results provide an estimate of how pumping alone affects groundwater discharge to Lake Michigan. In simulating the effects of pumping on groundwater exchange with the lake, the model ignores any changes in recharge rates over the period between 1864 and 2000. Although the model assumes constant recharge rates throughout this period, there are at least two factors that might have caused long-term changes in recharge: urbanization and climate change. These mechanisms could have decreased recharge flux in some areas (due to less infiltration through paved areas) and increased the flux in others (due to shorter periods of frozen soil in winter). It is possible, for example, that the simulated decrease in groundwater discharge to Lake Michigan caused by pumping has been offset by increased recharge over at least part of the coastal area.

Another factor neglected by the model is return flow to Lake Michigan from storm and sanitary sewers and from the Deep Tunnel that underlies Milwaukee. Part of the water pumped from the shallow and deep parts of the flow system east of the subcontinental divide is discharged to sewers and routed back to the Lake. While this return flow offsets part of the decline in groundwater discharge to the Lake that occurs because of pumping, it also changes the timing, location, and quality of the discharged water relative to natural conditions.

6. Groundwater Flow Directions and Groundwater Divides

The regional flow model is an important tool for illustrating groundwater flow directions and groundwater divides. Groundwater divides often do not coincide with surface-water divides. In particular, for southeastern Wisconsin, there is no correspondence between groundwater divides in the deep part of the flow system and the subcontinental surface-water divide shown in Figure 10. Note that the surface-water divide is entirely within the seven county SEWRPC region. In this report, groundwater divides are illustrated using simulated flow arrows that indicate the direction of groundwater flow through the model nearfield.

Predevelopment Conditions

Prior to development, local topography controlled shallow groundwater flow. The variations in lateral direction of flow and the alteration between upward and downward flow formed many relatively small-scale flow systems that discharged locally. Figure 11a shows flow directions in the unlithified deposits for predevelopment conditions.

Flow directions in the St. Peter Formation are representative of flow in most of the deeper sandstone units. Prior to development, small-scale flow systems formed in the St. Peter west of the Maquoketa shale, but regional flow was dominant east of the Maquoketa subcrop. Figure 11b shows flow directions in the St. Peter Formation at the top of the deep sandstone aquifer for predevelopment conditions. A deep groundwater divide separates the area to the west where local flow systems were active (indicated by the variety of arrow directions) with the area to the east where a single regional flow system dominated (indicated by uniform arrow directions). This deep groundwater divide is closely related to the Maquoketa shale subcrop, but it is distant from the subcontinental surface-water divide marking the edge of the Lake Michigan basin. For example the deep groundwater divide is 18 miles west of the subcontinental divide in central Waukesha County. West of the divide, St. Peter groundwater interacted with the shallow part of the flow system, while groundwater east of the divide flowed over long distances toward Lake Michigan.

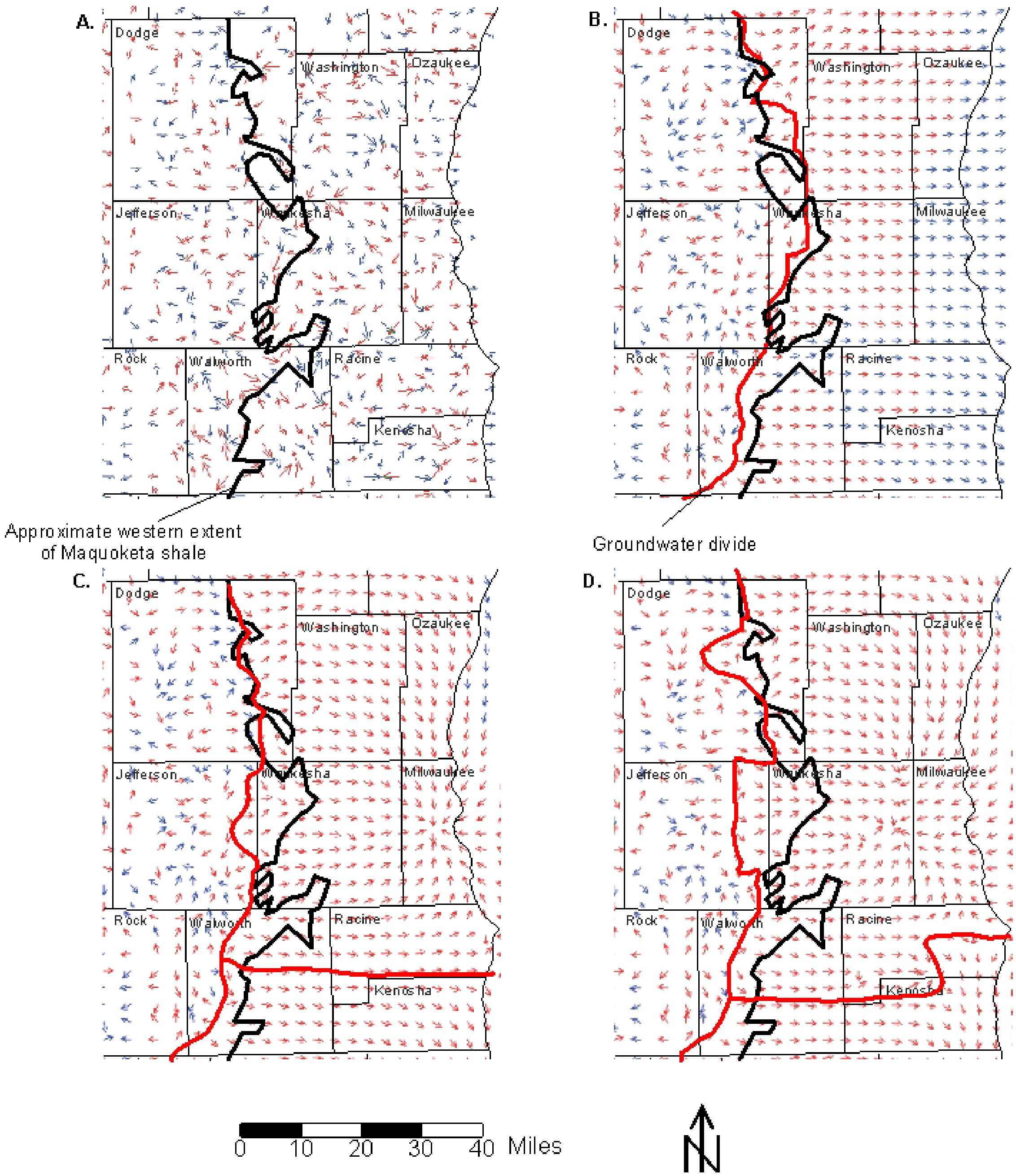

Figure 11. **Flow Directions and Groundwater Divides**
A. Unlithified deposits, Predevelopment
B. St. Peter Formation, Predevelopment
C. St. Peter Formation, 1950.
D. St. Peter Formation, 2000.

Explanation. Red arrows indicate downward flow.
Blue arrows indicate upward flow.

Effect of Pumping

Pumping has had very little effect on simulated directions of flow in the shallow part of the flow system. However, it has moved the location of the regional groundwater divide in the deep part of the system westward almost entirely outside the seven-county region. Figures 11c and 11d show the positions of the divide in 1950 and 2000 relative to its predevelopment position. In 1950, the regional flow in the deep sandstone aquifer converged on the pumping center under Milwaukee. By 2000, flow paths converge under eastern Waukesha County.[1] The regional groundwater divide has moved from Waukesha County westward about 10 miles into Jefferson County, far removed from the edge of the Maquoketa shale and approximately 27 miles from the western edge of the Lake Michigan surface-water basin. This displacement of the divide in response to pumping is directly related to the increase in leakage to the deep part of the flow system in areas where the shale is absent.

The flow-direction plots for the St. Peter Formation (Figures 11b, 11c, 11d) also show the changing location of the groundwater divide between a regional groundwater system centered in southeastern Wisconsin and another centered in northern Illinois. The model shows that in 1950 (Figure 11c) the divide was located along the Kenosha/Racine County boundary. Increases in northern Illinois pumping after 1950 moved the boundary north into eastern Racine County, but the development of local cones of depression around Union Grove moved the divide south in western Racine and in Walworth Counties. While northern Illinois pumping decreased overall in the 1990s, the 2000 divide is still north of the 1950 boundary in some places (Figure 11d).

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[1] The geographical center for the deep part of the flow system is below the Village of Elm Grove in Waukesha County. The location is shown in Figure 7.

7. Vertical Movement between Shallow and Deep Parts of Flow System

Under predevelopment conditions flow between the shallow and deep systems was downward over only part of southeastern Wisconsin. In the absence of pumping, the model simulates a regional system in which groundwater first leaked to the deep part of the flow system under areas encompassed by Washington, Waukesha and Walworth Counties and then moved upward toward the shallow part of the system over most of Milwaukee, Racine and Kenosha Counties (note the pattern of red and blue arrows in Figure 11b). In time, however, increases in pumping caused flow to be downward over the entire seven-county region (Figures 11c and 11d). In this section of the report, the vertical movement of groundwater between the two parts of the flow system is examined in more detail.

Leakage to Deep Sandstone Aquifer

The rates of downward groundwater movement simulated by the model vary considerably over different areas of the model nearfield for both predevelopment and pumping conditions. Figure 12 shows the rate of downward flow at different times to the top of the St. Peter Formation as a color flood map. The rates correspond to the downward flux in cubic feet per day over a square foot of area. A value greater than 1.000e-004 for an area indicates substantial downward flow. A value of 1.000e-006 or less indicates very little downward flow. Where the figures show no color, there is either upward flow or no vertical flow.

Under predevelopment conditions, local flow systems extended down to the deep part of the sandstone aquifer in the area west of a line that approximately follows the boundary marking the westernmost edge of the Maquoketa shale. The intermingling of colored and white areas west of this boundary in Figure 12a indicates the presence of many local flow systems in which groundwater moved downward from recharge areas and then upward to adjacent discharge areas. The amount of downward flow decreased eastward across the SEWRPC region across a transition zone straddling the Maquoketa subcrop. In the eastern part of the SEWRPC region, water in the deep part of the flow system moved

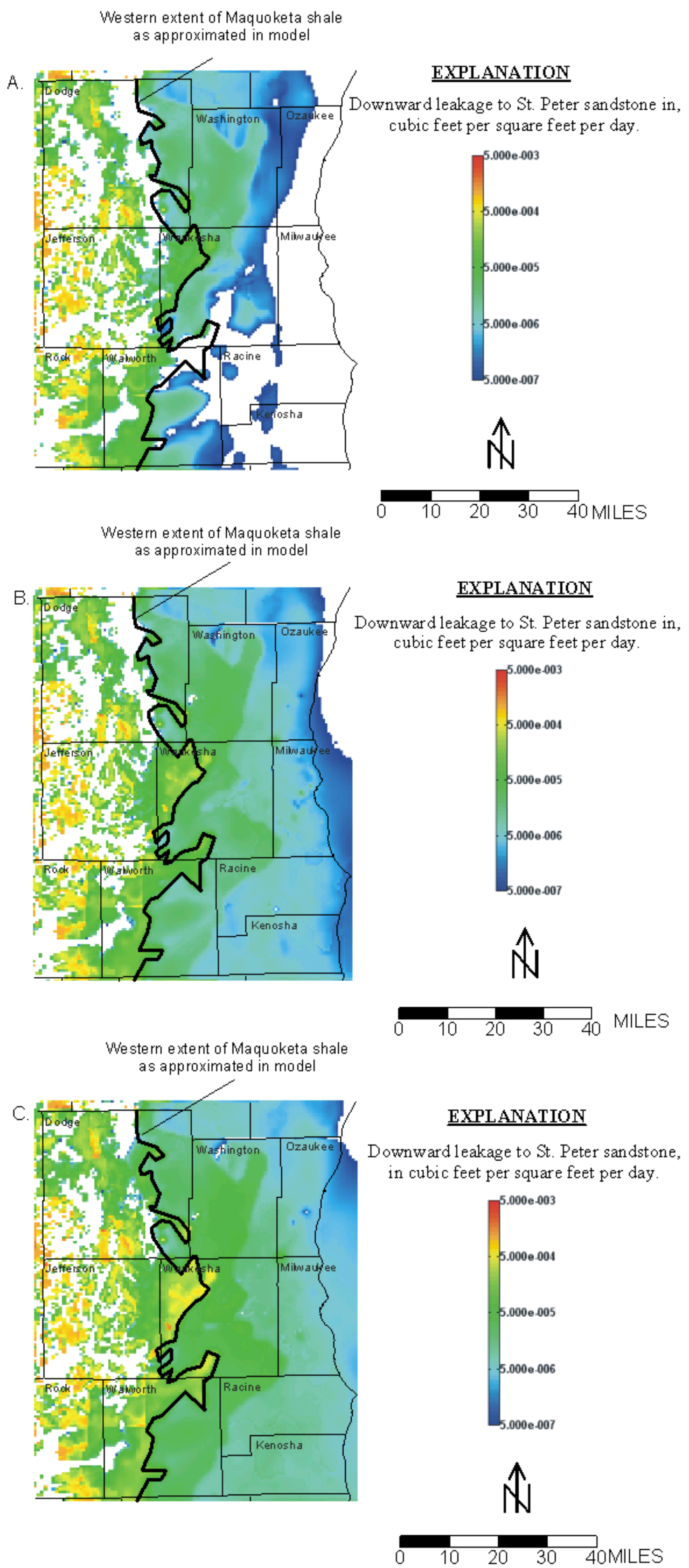


Figure 12. Downward leakage to top of St. Peter Formation. A. Predevelopment. B. 1950. C. 2000.

laterally through the sandstone aquifer and eventually traveled upward toward the regional discharge location, Lake Michigan.

By 1950, model simulations show that the area of downward leakage extended over all of southeastern Wisconsin with locations of significant vertical flow occurring just west of the edge of the Maquoketa shale (Figure 12b). The simulated leakage rates in these areas are 100 to 1000 times greater than the leakage rates below the city of Milwaukee even though the major pumping center was located below the city.

In 2000, two areas of downward leakage were prominent within the seven-county region. The first occupied much of northwestern Waukesha County. The second extended from south-central Waukesha County into north-central and northwestern Walworth County. Simulation results also suggest a third area of enhanced leakage in north-central Jefferson to south-central Dodge Counties (Figure 12c).

Zones of Relatively Rapid Circulation to Deep Wells

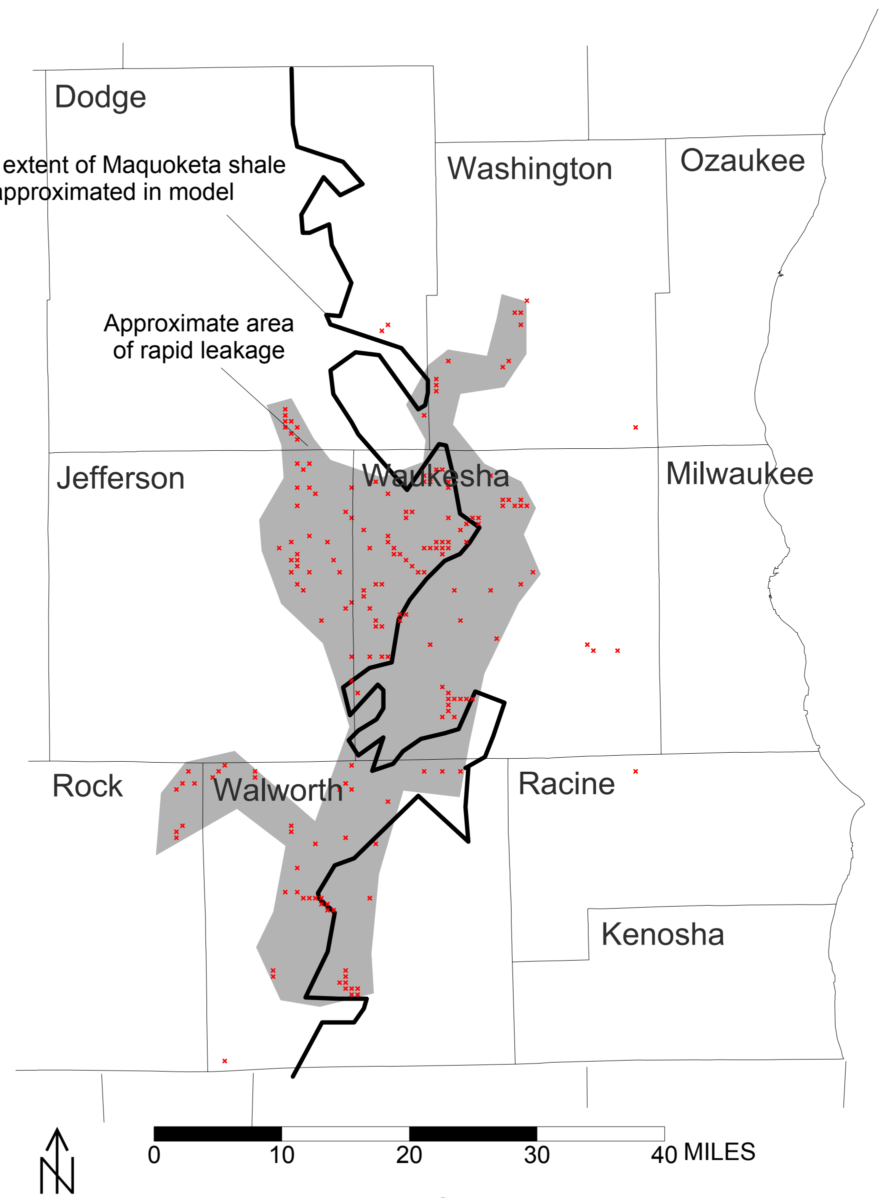
Numerical particle tracking was used to explore the connection between areas of vertical movement between the shallow and deep parts of the flow system on the one hand, and groundwater flow to deep wells on the other. Particle tracking simulates the movement of imaginary mathematical particles through the groundwater system. This method assumes advective flow only, so that the particles move at the same rates and directions as the groundwater. Given the geometry, aquifer, properties, and flow output of the model, it is possible to use mathematical particles to track and visualize groundwater flow from the water table to any shallow or deep destination in the flow system. The method combines the input and output to the MODFLOW model with an associated particle-tracking code called MODPATH (Pollack, 1994). In this study, a release of particles was simulated at the water table every 2500 feet across the nearfield to determine which ones moved to the deep part of the flow system and then traveled to deep wells. The particle tracking generates both pathlines and times of travel. However, because the time of travel depends on assumed and uncertain values of effective porosity, it is not possible to report a single expected time of travel to deep wells from different locations. Instead, a range of times was reported that correspond to the low-end and high-end effective porosity values listed in Table 6. In general, the high-end values result in travel times that are 10 times longer than the low-end values for particles that circulate into the deep part of the flow system.

Table 6. Assumed Effective Porosity Values for Calculating Travel Times.

Unit	Assumed Low-End Values	Assumed High-End Values
Unlithified	0.05	0.20
Silurian, Maquoketa, Sinnipee	0.005	0.01
Sandstone Aquifer	0.005	0.10

Explanation: Low-End values yield relatively high velocities and shorter travel times.
High-End values yield relatively low velocities and longer travel times.

Of particular interest are areas where groundwater flow from the water table to deep wells is relatively rapid. To identify these areas, particle-tracking analyses were performed using a specified set of pumping conditions. For this purpose, pumping in southeastern Wisconsin and the surrounding region is sustained indefinitely into the future at year 2000 rates. For the flow system that results, Figure 13 shows the zone that encompasses all particles that move relatively rapidly from the water table to deep wells. “Relatively rapidly” implies less than 200 years of travel time assuming low-end porosity values and less than 2000 years of travel time assuming high-end values. The median time of travel for these particles is about 100 years for low-end porosity assumptions and about 1000 years for high-end assumptions. The most important sources of water for deep wells occur beyond the western-most extent of the Maquoketa shale. The areas shaded in Figure 13 are those where land-use changes that might reduce recharge to the water table could, in the long run, have an effect on the groundwater available to deep wells. Given that the largest pumping centers are in central and eastern Waukesha County, it is striking how distant some of the source areas are from the deep wells.



EXPLANATION

× Starting particle location at water table where travel time to deep wells is less than 200 years for assumed low effective porosity values.

Figure 13. Areas of relatively rapid circulation from water table to deep wells.

The source areas are most clearly identified with the absence of the Maquoketa shale, but the exact configuration is also influenced by zones where recharge rates are high (see Figure 10 in Report 1 of the modeling study) and areas where the pattern of bedrock valleys place unlithified deposits in close communication with the deep sandstone aquifer (see Figure 5, Report 1).

Groundwater Pathlines

Plotting simulated pathlines projected on vertical sections in different parts of the model helps illustrate the workings of the groundwater system in the presence of pumping. Figure 14 shows particle starting locations spaced 2500 ft apart along four west-to-east sections. The particle placement is intended to focus on areas west and east of the edge of the Maquoketa shale from north to south across southeastern Wisconsin. The model simulated particle movement for 500 years assuming sustained year 2000 pumping conditions and low-end effective porosity values. Figure 15 shows particle paths along each of the section lines in Figure 14. The figure only shows pathlines for particles that move more than 2500 ft to either shallow or deep discharge locations.

The particle-tracking results clearly illustrate how groundwater moves from recharge west of the Maquoketa subcrop to wells east of the subcrop. The plots in Figure 15 show the presence of long pathlines (most prominent in the southern-most sections) that begin in the western portion of the model nearfield. Some of the plots also show movement through the Maquoketa shale. These paths are representative of the leakage between the shallow and deep parts of the flow system that, under the influence of pumping, occurs even where the deep sandstone aquifer is confined by the aquitard. The travel times over these near-vertical pathlines that begin close to pumping centers are longer than the travel times for groundwater that originates in distant source areas and move laterally through the deep sandstone aquifer to deep wells. From the point of view of time of travel and source-water protection, the distant source areas for deep wells in southeastern Wisconsin are probably more important than source areas that are nearby but underlain by the Maquoketa shale.

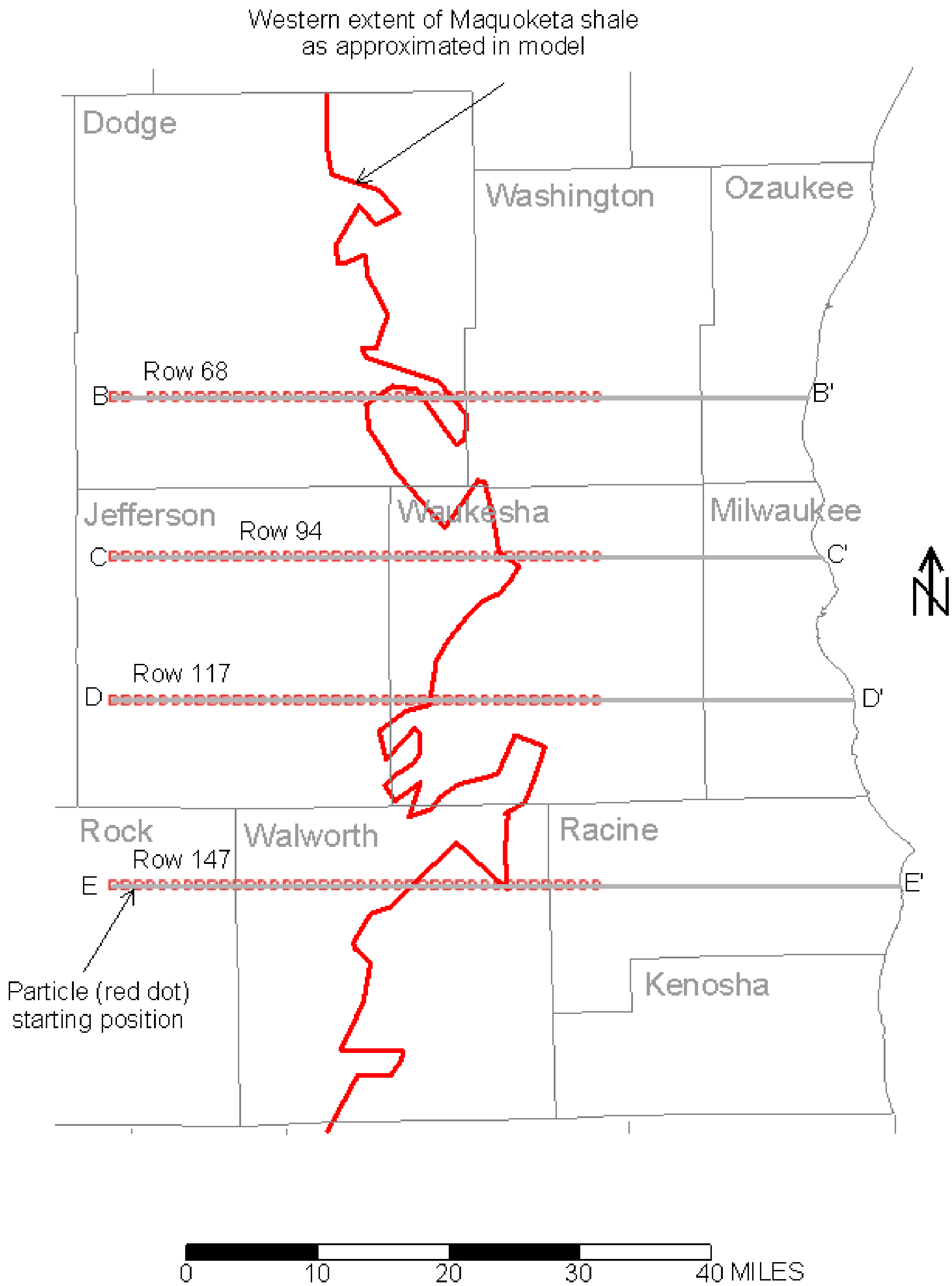


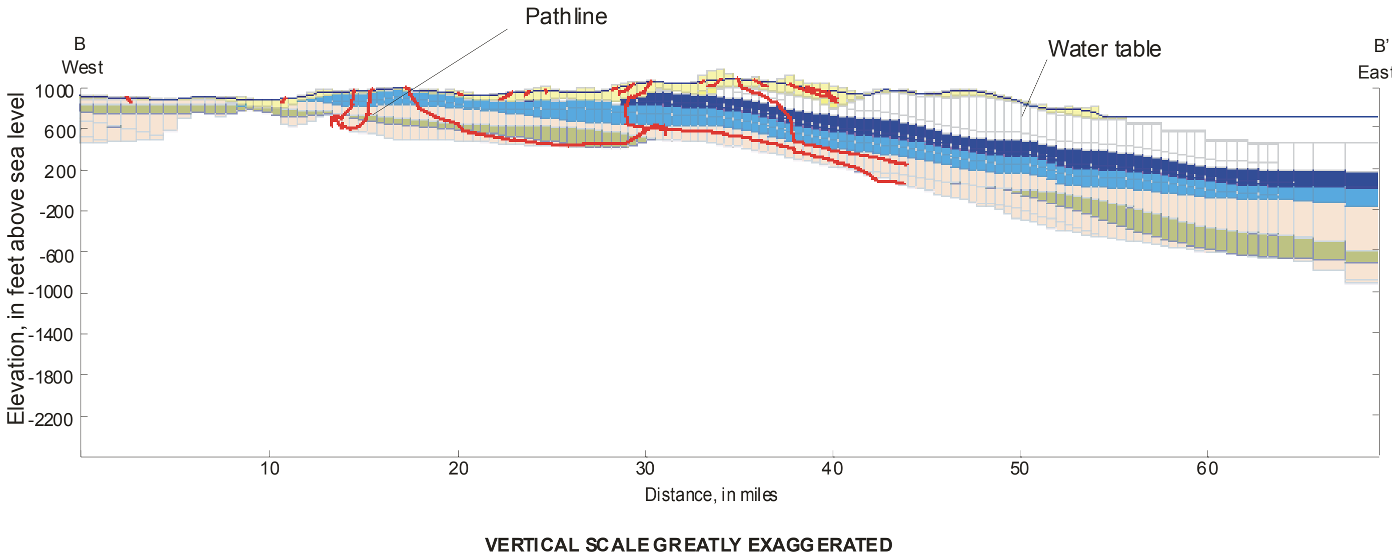
Figure 14. **Particle release locations for pathlines originating west and east of Maquoketa Shale subcrop.**

Explanation: Particles are released at water table and then pathlines traced from water table to discharge point (surface water body, well, or water table).

The groundwater flow system corresponds to 2000 pumping conditions sustained 500 years into the future.

Row numbers correspond to the MODFLOW model grid.

A.



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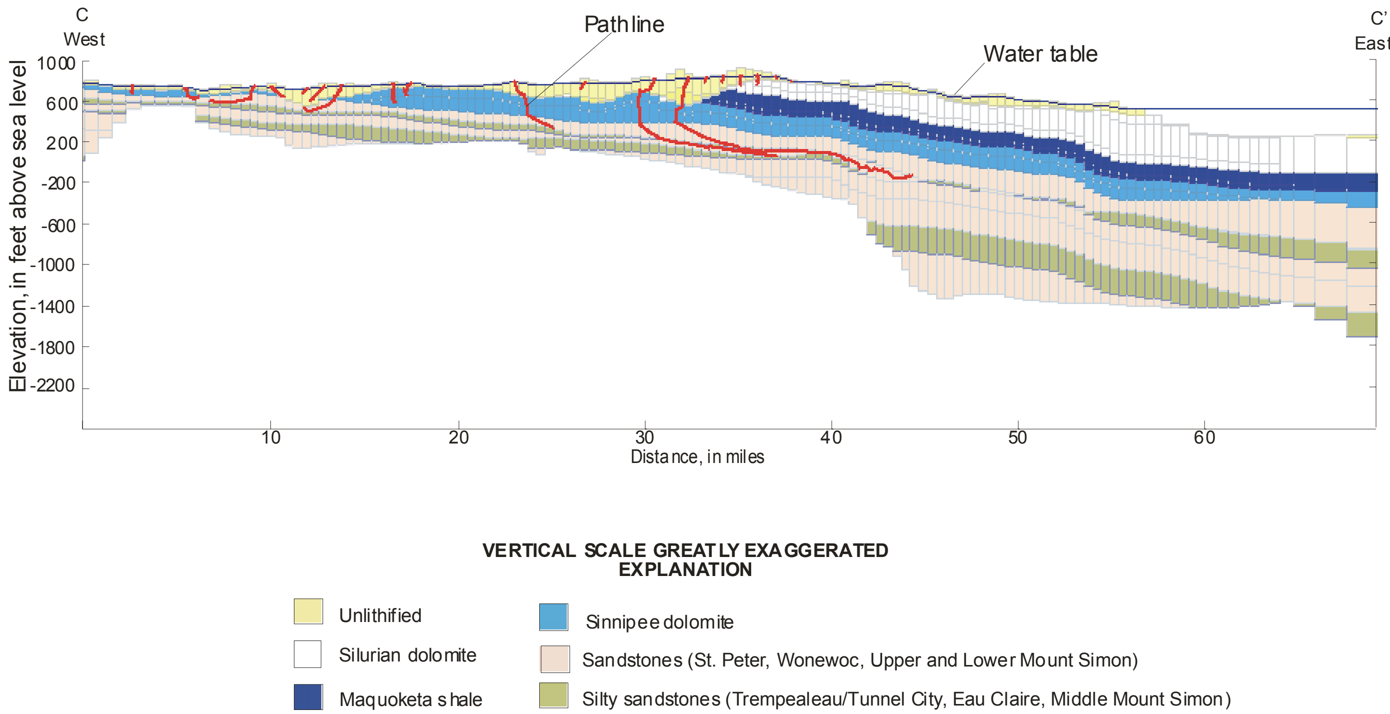
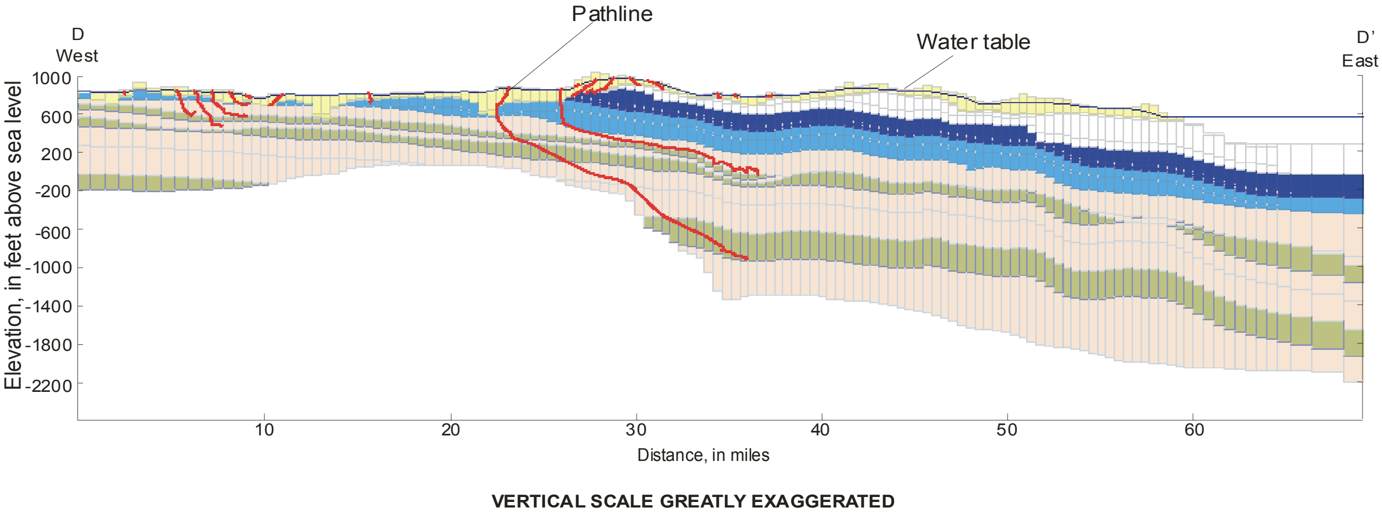


Figure 15. Traces of selected deep pathlines projected on vertical sections
A. southern Dodge/Washington Counties (model row 68 in Figure 14).
B. northern Jefferson/Waukesha Counties (model row 94 in Figure 14).

C.



D.

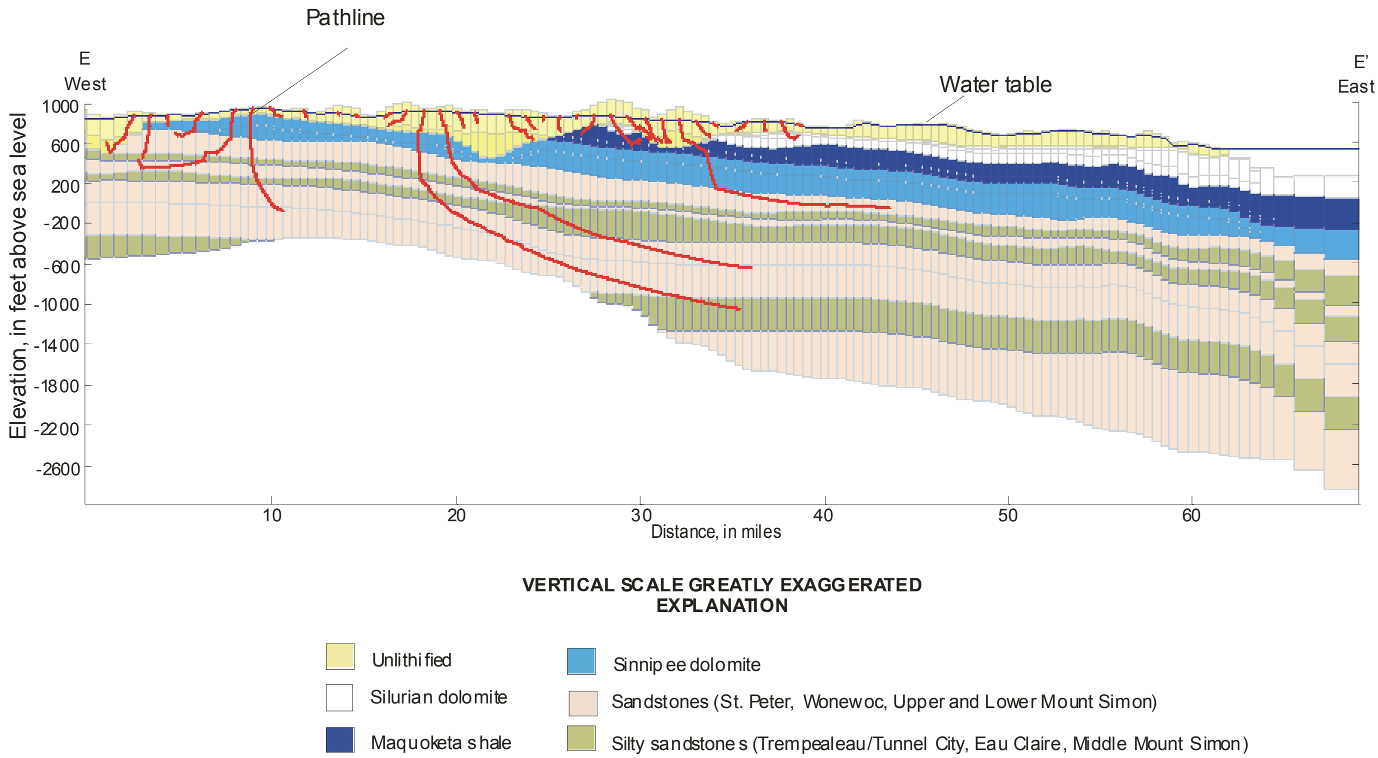


Figure 15. Traces of selected deep pathlines projected on vertical sections
C. south-central Jefferson/Waukesha Counties (model row 117 in Figure 14).
D. northern Rock/Walworth Counties (model row 147 in Figure 14).

8. Conclusions

The groundwater flow model for southeastern Wisconsin simulates regional groundwater flow and documents the changes that pumping has caused on the natural circulation of groundwater and surface water at the regional scale. The major findings fall into six categories.

Predevelopment conditions:

- Under natural conditions before pumping, topography and geology were the main control on groundwater movement. In the shallow part of the flow system, local groundwater circulation to surface-water bodies occurred over the entire seven-county region, while the deep part was separated into a zone of local circulation in the west and a zone of regional circulation in the east which discharged toward Lake Michigan.

Consequences of regional pumping:

- Regional groundwater pumping has affected flow patterns less in the shallow than in the deep part of the flow system. The center of the shallow regional cone of depression is in Ozaukee County where drawdown in excess of 200 ft corresponds to concentrated pumping from the Silurian aquifer.

- The major pumping center in southeastern Wisconsin has shifted from the city of Milwaukee to the city of Waukesha. In response to this shift, the center of the cone of depression in the deep part of the flow system has shifted westward about eight miles from Milwaukee to near the Village of Elm Grove, where water levels in the deep sandstone units have dropped about 500 ft since the onset of pumping.

- It is possible that unsaturated conditions exist at depth in the Sinnipee dolomite below the city of Waukesha. If unsaturated conditions do exist at depth and are spreading with continued pumping, it could have implications for well yields and well-water quality.

- If high-capacity pumping is extrapolated according to historic trends it will increase by as much as 40% between 2000 and 2020, producing over 100 ft of additional drawdown at the center of the regional cone of depression for the deep part of the flow system.

Sources of water to wells:

- The most important source of water to both shallow and deep high-capacity wells is groundwater that would otherwise discharge as baseflow to streams and inland lakes; it currently (i.e., in year 2000) accounts for about 58% of combined shallow and deep pumping. An additional 12% is water induced directly from streams and lakes. Captured and induced flow from Lake Michigan or shallow rocks below the Lake accounts for 9% of pumping.

- Pumping from the sandstone aquifer has reversed the direction of flow in the deep part of the flow system below the Lake Michigan coastline and now causes a major transfer of water from the part of the aquifer under the lake to deep wells. Most of this water originates as storage release in the deep part of the flow system at the edge of the cone of depression below the Lake (about 4% of total current withdrawals).

- Pumping has also reversed gradients and drawn water into the 7-county region from surrounding counties. This captured and induced cross-boundary flow, chiefly from the west, currently amounts to 10% of total pumping.

- Under current conditions release of groundwater from storage below the seven-county region contributes about 7% of combined deep and shallow pumping.

Interaction of shallow groundwater with Lake Michigan:

- Between 1864 and 2000, pumping caused a 7.5% reduction of direct and indirect discharge of groundwater through the shallow part of the flow system to Lake Michigan; this reduction is separate from effects of unknown magnitude attributable to urbanization and climate and is partly offset by return flow from sewers.

Location of deep groundwater divide:

- Before pumping, the groundwater divide between the zones of local and regional circulation in the deep part of the flow system was already west of the subcontinental divide for surface water (about 18 miles distant in Waukesha County). Pumping has shifted the deep groundwater divide even farther from the lake over time; for example, between 1864 and 2000 the groundwater divide moved about 10 additional miles west from Waukesha County into Jefferson County.

Leakage to the deep part of the groundwater system:

- Downward leakage between the shallow and deep parts of the flow system occurs everywhere in the study area, but it is most pronounced in the western areas within the seven-county region where the Maquoketa shale is absent.

- Under current conditions about 4% of groundwater recharged at the water table eventually leaks to the deep part of the flow system over the seven-county region, but in areas where the Maquoketa shale is absent the proportion climbs to 13%.

- Model output in combination with particle tracking reveals the areas where groundwater recharged to the water table circulates most readily to deep wells. The most rapid movement from the water table to deep wells occurs in northwestern Waukesha County and along a band from southern Waukesha County through northern Walworth County.

- The long travel paths from the water table to deep wells passing below multiple counties demonstrate the degree to which groundwater is a regional resource.

9. Future Work

Applications

The regional flow model described in this report will be used to simulate future conditions based on scenarios tied to different development and water-use strategies. It will also contribute to a series of studies aimed at optimizing future management of the groundwater resource at both a regional and local scale. Delineation of wellhead protection zones is an important need for regional groundwater protection in southeastern Wisconsin that can be addressed using more detailed, inset versions of the model. These more detailed studies will help determine how best to minimize drawdown by locating wells more efficiently, and how best to balance withdrawals from shallow and deep wells to minimize adverse effects on surface-water bodies. Inset versions of the model targeted to local problems will in many ways duplicate the regional model, but will require a finer resolution for input and a more advanced treatment of interactions between groundwater and surface water.

Research

Important areas of possible research grow out of the findings and limitations of the modeling project. They include:

- Investigations (specialized saturated/unsaturated flow modeling, geochemical modeling, installation of sealed deep test holes) to determine the degree to which deep unsaturated conditions exist in the Sinnipee dolomite and what effect, if any, such conditions have on groundwater chemistry.

- Re-evaluation of hypotheses regarding the cause of geochemical patterns in the deep part of the flow system in light of the changing flow patterns simulated by the model.

- Performance of quantitative studies using data from ongoing aquifer storage and recovery (ASR) projects in eastern Wisconsin to calculate effective porosity values from tracer recovery times, the results of which would help constrain the travel times output by the model particle tracking.

- Close examination of historical streamflow data in southeastern Wisconsin to determine the degree to which climate change has altered recharge rates and affected groundwater interactions with Lake Michigan independently of pumping.

- Investigations of paleohydrogeology related to the advance and retreat of the Wisconsin continental ice-sheet, to evaluate the possibility that lingering hydraulic effects from the ice sheet caused transient flow conditions to occur at depth before the onset of pumping.

- Study of the predevelopment steady-state assumption, possible inhomogeneities and scale-dependent effects that might explain the discrepancy between the value for the vertical hydraulic conductivity of the Maquoketa shale that was needed to calibrate the regional model and lower hydraulic conductivity values measured or inferred in local studies of the shale.

- Use of the model to evaluate the role that the Waukesha fault system and wells open to multiple aquifers have on vertical movement between the shallow and deep parts of the flow system.

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