Regional Groundwater-Flow Model of the Lake Michigan Basin in Support of Great Lakes Basin Water Availability and Use Studies

By D.T. Feinstein, R.J. Hunt, and H.W. Reeves

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Because of its size and complexity, the Lake Michigan Basin model depended on contributions from a large team of geologists and hydrologists for its development. The authors were fortunate to collaborate with many other USGS scientists:

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NAVD 29), except for Great Lake levels, which are referenced to the International Great Lakes Datum of 1985 (IGLD 85).

Altitude and elevation, as used in this report, refer to distance above the respective vertical datum.

Horizontal spatial reference for the model grid is in Universal Transverse Mercator projection Zone 16, North American Datum of 1983 (NAD 83).The grid coordinates are in units of feet.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Regional Groundwater-Flow Model of the Lake Michigan Basin in Support of Great Lakes Water Availability and Use Studies

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Abstract

A regional groundwater-flow model of the Lake Michigan Basin and surrounding areas has been developed in support of the Great Lakes Basin Pilot project under the U.S. Geological Survey's National Water Availability and Use Program. The transient 2-million-cell model incorporates multiple aquifers and pumping centers that create water-level drawdown that extends into deep saline waters. The 20-layer model simulates the exchange between a dense surface-water network and heterogeneous glacial deposits overlying stratified bedrock of the Wisconsin/Kankakee Arches and Michigan Basin in the Lower and Upper Peninsulas of Michigan; eastern Wisconsin; northern Indiana; and northeastern Illinois. The model is used to quantify changes in the groundwater system in response to pumping and variations in recharge from 1864 to 2005. Model results quantify the sources of water to major pumping centers, illustrate the dynamics of the groundwater system, and yield measures of water availability useful for water-resources management in the region.

This report is a complete description of the methods and datasets used to develop the regional model, the underlying conceptual model, and model inputs, including specified values of material properties and the assignment of external and internal boundary conditions. The report also documents the application of the SEAWAT-2000 program for variable-density flow; it details the approach, advanced methods, and results associated with calibration through nonlinear regression using the PEST program; presents the water-level, drawdown, and groundwater flows for various geographic subregions and aquifer systems; and provides analyses of the effects of pumping from shallow and deep wells on sources of water to wells, the migration of groundwater divides, and direct and indirect groundwater discharge to Lake Michigan. The report considers the role of unconfined conditions at the regional scale as well as the influence of salinity on groundwater flow. Lastly, it describes several categories of limitations and discusses ways of extending the regional model to address issues at the local scale.

Results of the simulations portray a regional groundwater-flow system that, over time, has largely maintained its natural predevelopment configuration but that locally has been strongly affected by well withdrawals. The quantity of rainfall in the Lake Michigan Basin and adjacent areas supports a dense surface-water network and recharge rates consistent with generally shallow water tables and predominantly shallow groundwater flow. At the regional scale, pumping has not caused major modifications of the shallow flow system, but it has resulted in decreases in base flow to streams and in direct discharge to Lake Michigan (about 2 percent of the groundwater discharged and about 0.5 cubic foot per second per mile of shoreline).

On the other hand, well withdrawals have caused major reversals in regional flow patterns around pumping centers in deep, confined aquifers—most noticeably in the Cambrian-Ordovician aquifer system on the west side of Lake Michigan near the cities of Green Bay and Milwaukee in eastern Wisconsin, and around Chicago in northeastern Illinois, as well as in some shallow bedrock aquifers (for example, in the Marshall aquifer near Lansing, Mich.). The reversals in flow have been accompanied by large drawdowns with consequent local decrease in storage. On the west side of Lake Michigan, groundwater withdrawals have caused appreciable migration of the deep groundwater divides. Before the advent of pumping, the deep Lake Michigan groundwater-basin boundaries extended west of the Lake Michigan surface-water basin boundary, in some places by tens of miles. Over time, the pumping centers have replaced Lake Michigan as the regional sink for the deep flow system.

The regional model is intended to support the framework pilot study of water availability and use for the Great Lakes Basin (Reeves, in press). To that end, the model is designed as a platform to

- allow evaluation of broad sustainability indicators for the overall groundwater regime;
- address the effects of future changes in water use and in climate on water availability; and

- host embedded refined models needed to address water-supply and ecologic issues at the local scale.

The regional model is commensurate in size and scope with other groundwater-availability models recently or currently under development by the USGS in different parts of the country, and contributes to a national perspective on groundwater availability by providing information required for regional comparison and analysis.

1. Introduction

In 2005, at the request of Congress, the U.S. Geological Survey (USGS) began a national program called the National Assessment of Water Availability and Use (Grannemann and Reeves, 2005) to provide citizens, communities, and natural-resource managers with

- clearer knowledge of the current status of the Nation's water resources,
- documentation of trends in water availability and use over recent decades, and
- improved ability to forecast the availability of water for future economic and ecological uses.

Groundwater is an important component of water use nationally, and groundwater-flow models are a powerful method of integrating a wide variety of hydrogeologic data and analyzing the varied responses of a groundwater system to changes in pumping and climate. A groundwater-flow model was developed of the Lake Michigan Basin as part of the National Assessment of Water Availability and Use to assess water availability in the western part of the Great Lakes Basin. The groundwater model is part of a larger set of studies integrated under the Great Lakes Basin Pilot project (fig. 1); collectively, the studies are designed to evaluate water availability and use in the Great Lakes Basin as a whole from the standpoint of both groundwater and surface water. Water availability is assessed in terms of fluxes and storage of water in water bodies and aquifers and in terms of rates of withdrawal, consumption, and return of water to surface and subsurface natural systems. The analyses support summary indicators reflecting the degree to which human activities have modified the natural system; they also allow for further examination of how future pumping and climate conditions might affect water supply and ecological requirements. The Lake Michigan Basin groundwater-flow model—referred to hereafter as the "LMB model"—contributes to each of these objectives in the context of groundwater availability. The comprehensive framework and findings for groundwater and surface water based on all the Great Lakes Pilot project studies are summarized in USGS Professional Paper 1778 (Reeves, in press, which serves as an overview of the status and sustainability of surface and subsurface fresh-water resources in the Great Lakes region.

1.1 Purpose and Scope

This report documents the development of a regional groundwater-flow model (the LMB model) used to evaluate the past and current (2010) availability of groundwater for an 83,000-mi^2 study area in and surrounding the Lake Michigan Basin. The status and trends of water availability across all or parts of Michigan, Wisconsin, Indiana, and Illinois are quantified by means of model simulations of historical water levels from 1864 to 2005, past and current drawdown around pumping centers, sources of water to shallow and deep wells, and interactions of groundwater with surface water, particularly with Lake Michigan. The report

1. defines sources and sinks of groundwater (including recharge—the primary source of water; and pumping and discharge of groundwater to surface-water features—the primary sinks for groundwater; each is an element of the groundwater budget that varies with time);
2. presents maps showing the direction and magnitude of flow in several aquifer systems (including the location of groundwater divides and their movement in response to pumping); and
3. describes the ways in which the flows and storage of the natural groundwater system in the western half of the Great Lakes Basin are largely unchanged since the advent of pumping in the late 19th century, and the ways in which pumping produced appreciable changes by the beginning of the 21st century.

The LMB model is designed to provide

- a forecasting tool to assess the regional effects of future changes in water use and climate in the western part of the Great Lakes Basin;
- a platform for development of embedded, higher-resolution models used to address water-management issues at smaller (local) scales;
- a means of documenting and archiving information from a wide variety of sources on the hydrogeology and water use in the region; and
- a basis for developing indicators of sustainability of water resources.

The application of the model to each of these aspects of water-availability is presented in the USGS Professional Paper that summarizes the findings of the Great Lakes Basin pilot studies (Reeves, in press).

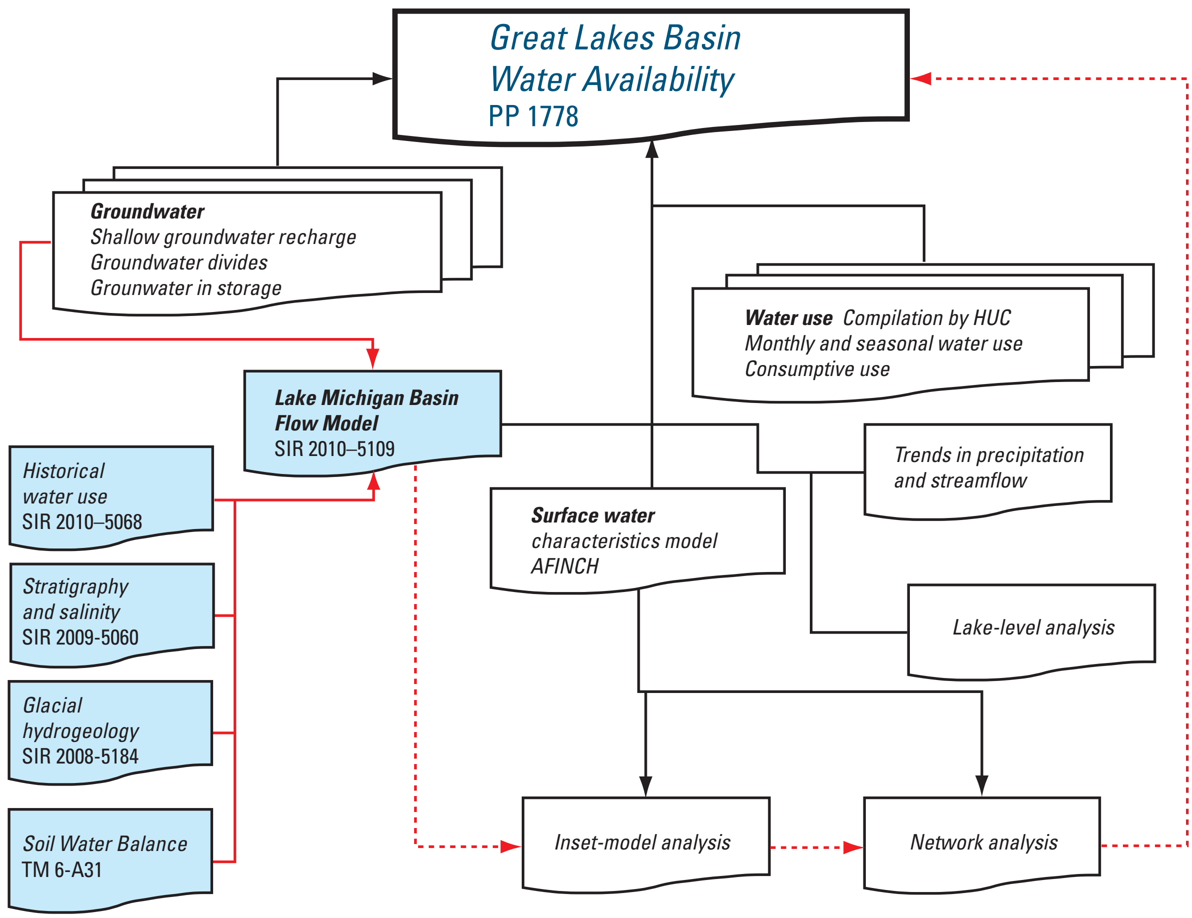


Figure 1. Great Lake Basin pilot investigations and reports structure. (Shaded boxes are reports that discuss aspects of model construction. Red lines indicate investigations contributing to or partly based on the flow model.)

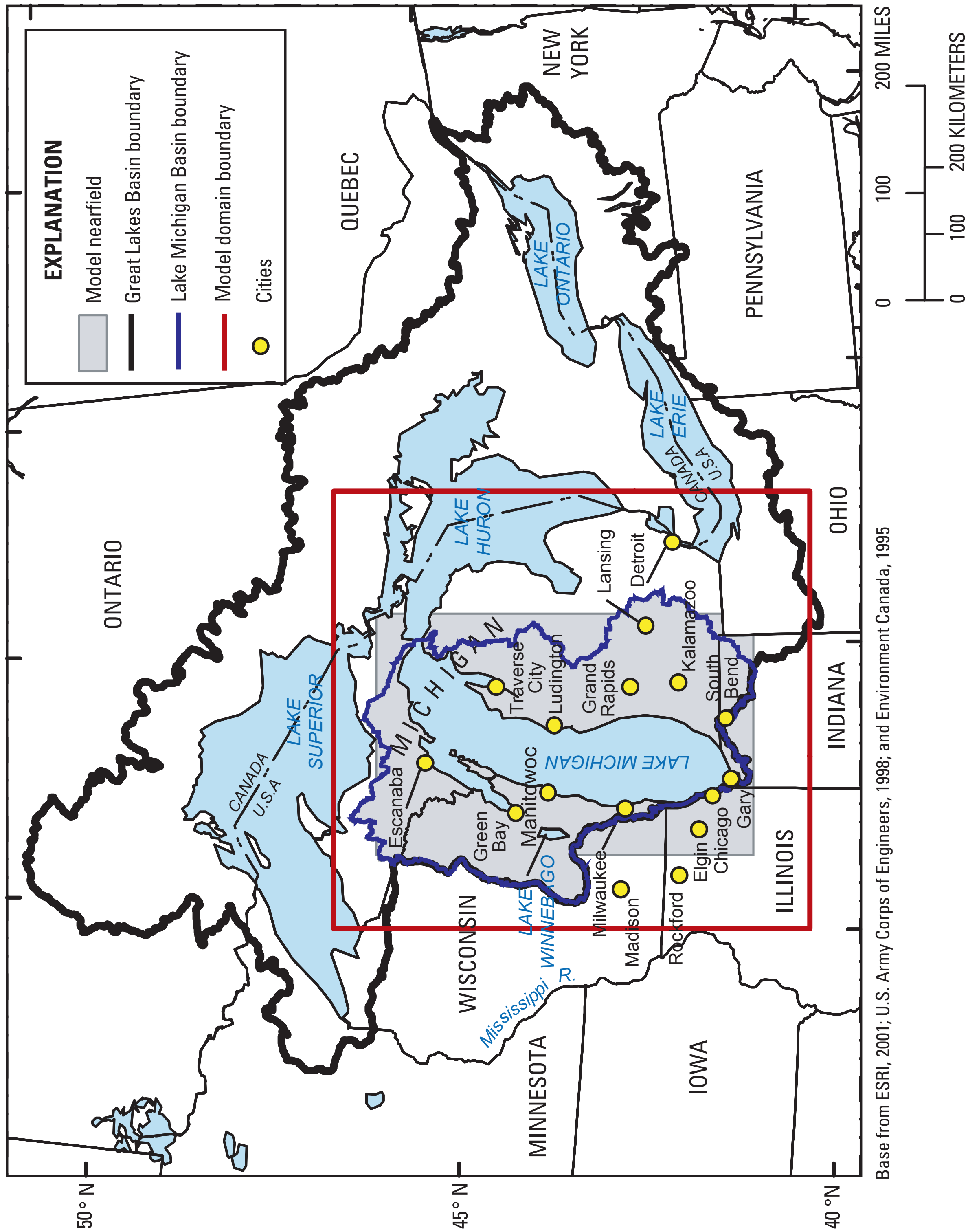
1.2 Description of Study Area

The study area (model domain) includes the western part of the Great Lakes Basin in the Upper Midwestern United States (fig. 2). It is centered on Lake Michigan and extends to parts of Lake Superior, Lake Huron, Lake St. Clair, and Lake Erie. It encompasses eastern Wisconsin, northern Indiana, northern Illinois, northwestern Ohio, and nearly all of Michigan. The model domain is divided into the *nearfield*, which corresponds to the principal area of interest in which the hydrogeology is well defined, and the *farfield*, which incorporates less detail and functions as a boundary for the nearfield area (fig. 3). The nearfield is divided into seven subregions (fig. 3) that facilitate model calibration and discussion of model results. The subregions (with abbreviations) are as follows:

1. Southern Lower Peninsula, Michigan (SLP_MI)
2. Northern Lower Peninsula, Michigan (NLP_MI)
3. Upper Peninsula, Michigan (UP_MI)
4. Northeastern Wisconsin (NE_WI)
5. Southeastern Wisconsin (SE_WI)
6. Northern Indiana (N_IND)
7. Northeastern Illinois (NE_ILL)

All abbreviations used in this report are listed in table 1.

Most of the nearfield area lies within the Lake Michigan Basin (the combined area of the lake and its surface drainage). However, certain areas outside the Lake Michigan Basin, particularly on the west side of the lake, are important to include in the model nearfield because they host pumping centers that have an appreciable effect on groundwater flow within and near the basin boundaries. It is also important to include these areas because of their relation to groundwater and surface-water divides: water-level records from the early 20th century, plus results of models in southeastern Wisconsin and northeastern Illinois, indicate that, before and shortly after groundwater-resource development, groundwater divides in the deep part of the flow system did not coincide with surface-water divides defining the Lake Michigan drainage but extended west of the Lake Michigan Basin into Wisconsin and Illinois (Feinstein and others, 2005; Sheets and Simonson, 2006).



Base from ESRI, 2001; U.S. Army Corps of Engineers, 1998; and Environment Canada, 1995

Figure 2. Location of study area.

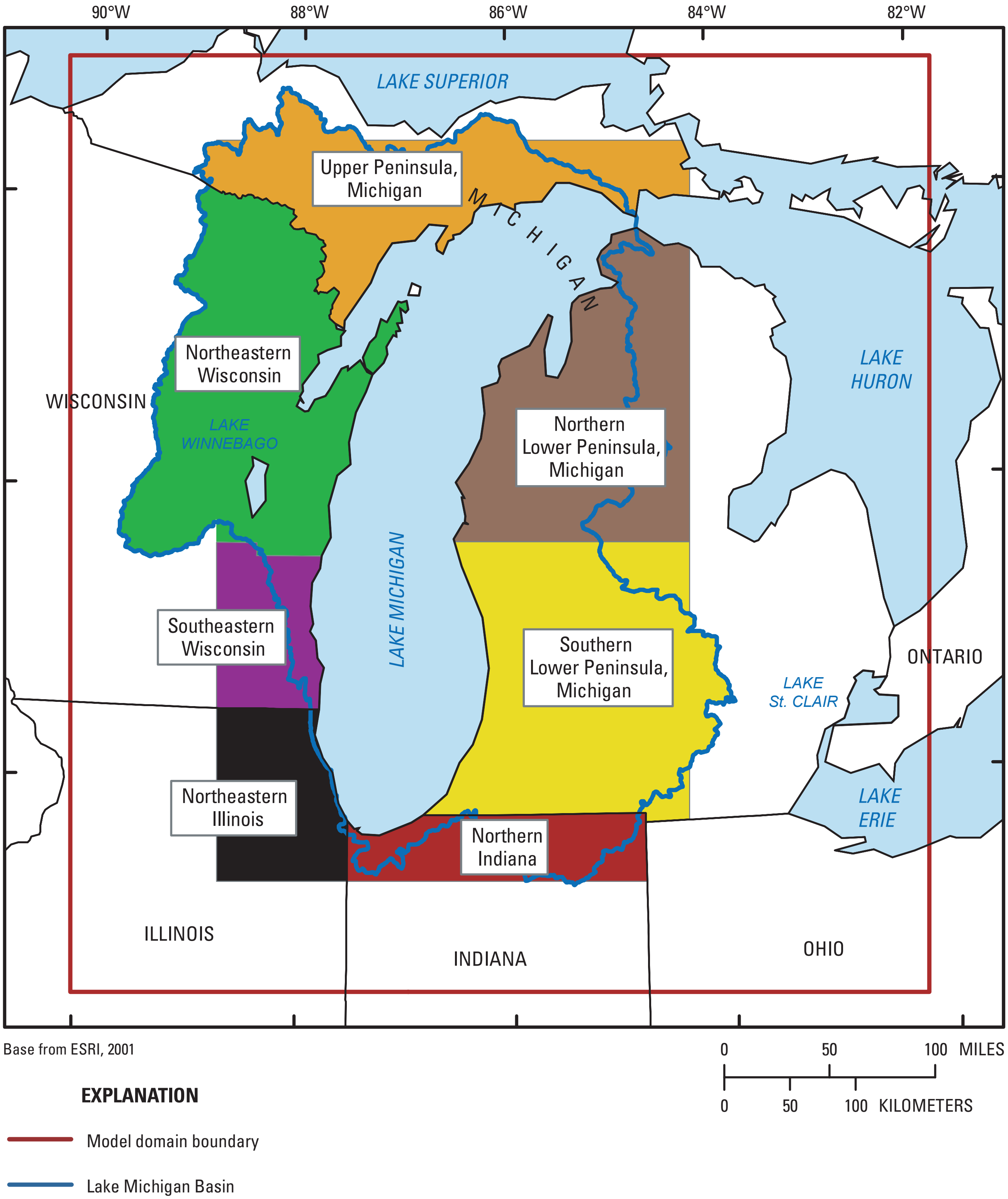


Figure 3. Model nearfield and subregions. (The combined area of the colored blocks representing model subregions constitues the model nearfield.)

Table 1. Abbreviations used in this report.

Lake Michigan Basin and Subregions		
LMB	Lake Michigan Basin	
SLP_MI	Southern Lower Peninsula, Michigan	
NLP_MI	Northern Lower Peninsula, Michigan	
UP_MI	Upper Peninsula, Michigan	
NE_WI	Northeastern Wisconsin	
SE_WI	Southeastern Wisconsin	
N_IND	Northern Indiana	
NE_ILL	Northeastern Illinois	
Hydrogeologic units and aquifer systems		
QRNR	Quaternary hydrogeologic unit	Quaternary aquifer system
JURA	Jurassic hydrogeologic unit	
PEN1	Upper Pennsylvanian hydrogeologic unit	
PEN2	Lower Pennsylvanian hydrogeologic unit	
PENN	--	Pennsylvanian aquifer system
MICH	Michigan hydrogeologic unit	
MSHL	Marshall hydrogeologic unit	Marshall aquifer system
DVMS	Devonian-Mississippian hydrogeologic unit	
SLDV	Silurian-Devonian hydrogeologic unit	Silurian-Devonian aquifer system
MAQU	Maquoketa hydrogeologic unit	
SNNP	Sinnipee hydrogeologic unit	
STPT	St. Peter hydrogeologic unit	
PCFR	Prairie du Chien/Franconia hydrogeologic unit	
IRGA	Ironton-Galesville hydrogeologic unit	
EACL	Eau Claire hydrogeologic unit	
MTSM	Mount Simon hydrogeologic unit	
C-O	--	Cambrian-Ordovician aquifer system
Parameters		
K	Hydraulic conductivity (foot per day (ft/d))	
K_h	Horizontal hydraulic conductivity (foot per day (ft/d))	
K_v	Vertical hydraulic conductivity (foot per day (ft/d))	
S_s	Specific storage (1/foot (1/ft))	
S_y	Specific yield (dimensionless)	
S	Storage coefficient (dimensionless)	
MODFLOW boundary-condition cells		
CHD	Constant head	
GHB	General head boundary	
RIV	River	
RCH	Recharge	
WEL	Well	
MNW	Multinode well	

The area of the entire LMB model domain is 180,963 mi^2. Less than half of this area falls within the Lake Michigan Basin, which covers 66,843 mi^2, of which 44,922 mi^2 is land and 21,921 mi^2 is waters of Lake Michigan (National Geophysical Data Center, 1998). As discussed above, the model nearfield includes all the Lake Michigan Basin and some neighboring areas. The inland part of the model nearfield not covered by Lake Michigan is 60,785 mi^2.

The climate of the Lake Michigan Basin and adjacent areas is controlled by movement of air masses from the Arctic and from the Gulf of Mexico and also is moderated by the size and position of the Great Lakes within a large continental land mass (Sheets and Simonson, 2006). In winter, cold, arctic air moves across the basin and absorbs moisture from the comparatively warmer Great Lakes; condensation as the air masses reach land creates heavy snowfalls on the leeward sides of the Great Lakes, including along the western shore of Michigan. In summer, most of the Great Lakes Basin is dominated by warm, humid air from the Gulf of Mexico, and only the most northern part of the basin receives cooler and drier air from the Canadian northwest (Government of Canada and U.S. Environmental Protection Agency, 1995). These conditions create a range of climatic conditions for the part of the Great Lakes Basin occupied by the model nearfield, as reflected in 30-year average data for that area from 1971 to 2000 (PRISM Group, 2008). The average winter temperature ranges from 3.1 °F (16.0 °C) in the northern part of the model nearfield to 21.1 °F (−6.1 °C) in the southern part of the model nearfield, with an overall mean of −10.4 °C (13.2 °F). The corresponding range in summer is from 71.2 °F (21.8 °C) to 84.0 °F (28.9 °C), with an overall mean for the model nearfield of 79.0 °F (26.1 °C). The 30-year averages for precipitation in the model nearfield range from 27.4 in/yr (695 mm/yr) to 40.5 in/yr (1,029 mm/yr), with an overall mean of 33.5 in/yr (851.2 mm/yr). The precipitation pattern, in conjunction with the intensity of evapotranspiration—itself partly a function of temperature—influences distribution of recharge to the groundwater system, which is an important input to the LMB model. The variation of precipitation and temperature with time causes variation in the rate of recharge.

Land-use/land-cover patterns also influence recharge; for example, rates of infiltration across the land surface, all other factors being equal, are generally greater in forested areas than in cropped areas (Seybold and others, 2003). In the model nearfield, the dominant land-use/land-cover types are forest, agriculture, and urban (fig. 4), which correlate with the distribution of population density (fig. 5). Groundwater use historically is greatest in urban areas served by public-supply and industrial pumping, but it has long been important in rural areas for public and domestic supply and for irrigation.

The physiography of the Great Lakes Basin is the result of a series of continental glaciers that scoured the area, the latest of which was the Laurentide Ice Sheet of the Wisconsin-stage glaciation during the Pleistocene Epoch (Sheets and Simonson, 2006). Most of the Great Lakes Basin is covered by glacial landforms such as moraines and till plains (Fenneman and Johnson, 1946). The surface topography of the model nearfield includes the higher elevations at the drainage boundaries of the Lake Michigan Basin and the lower elevations near the shoreline of the lake itself (fig. 6). The nearfield subregions of the LMB model differ in degree of topographic relief (table 2); relief is greatest in the Northern Lower Peninsula of Michigan and least in Northern Indiana. The water-table surface at the top of the groundwater system, which is the driving force for groundwater flow, generally is a subdued reflection of the land-surface topography.

Table 2. Altitude and relief in model nearfield.

[All altitudes relative to prevailing vertical datum. (See explanation in "Conversion Factors and Abbreviations" section at front of report.) Sources: National Geophysical Data Center, 1998, GEODAS Gridded data format, accessed April 2008 at *http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html?dbase=grdglb*. U.S. Bureau of the Census, 2006, County boundaries, accessed April 2008 at *http://gis.glin.net/ogc/services.php#mi_county_boundaries_2000*]

Nearfield subregions	Area (square miles)	Minimum altitude (feet)	Maximum altitude (feet)	Range of relief (feet)	Mean altitude (feet)
Southern Lower Peninsula, Michigan	14,159	479	1,280	801	836
Northern Lower Peninsula, Michigan	11,689	376	1,732	1,356	972
Upper Peninsula, Michigan	9,400	482	1,975	1,493	978
Northeastern Wisconsin	13,242	433	2,014	1,581	976
Southeastern Wisconsin	3,497	440	1,345	906	865
Northern Indiana	4,209	377	1,201	824	730
Northeastern Illinois	4,589	520	1,214	694	819
Total nearfield	**60,785**	**376**	**2,014**	**1,638**	**907**
Lake Michigan bed (excluding islands)	21,921	−327.4	577.4	905.5	294.3

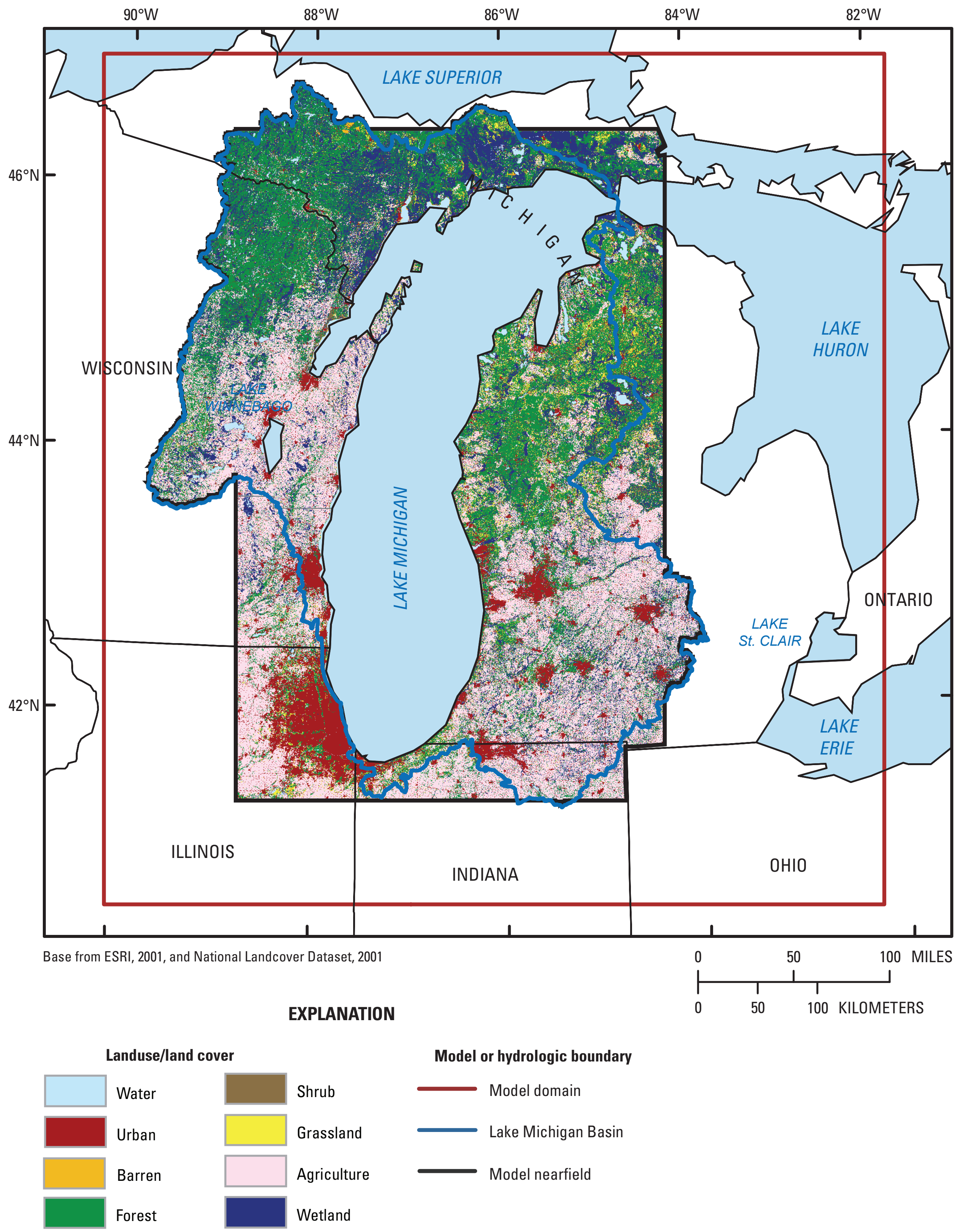


Figure 4. Land use/land cover in model nearfield.

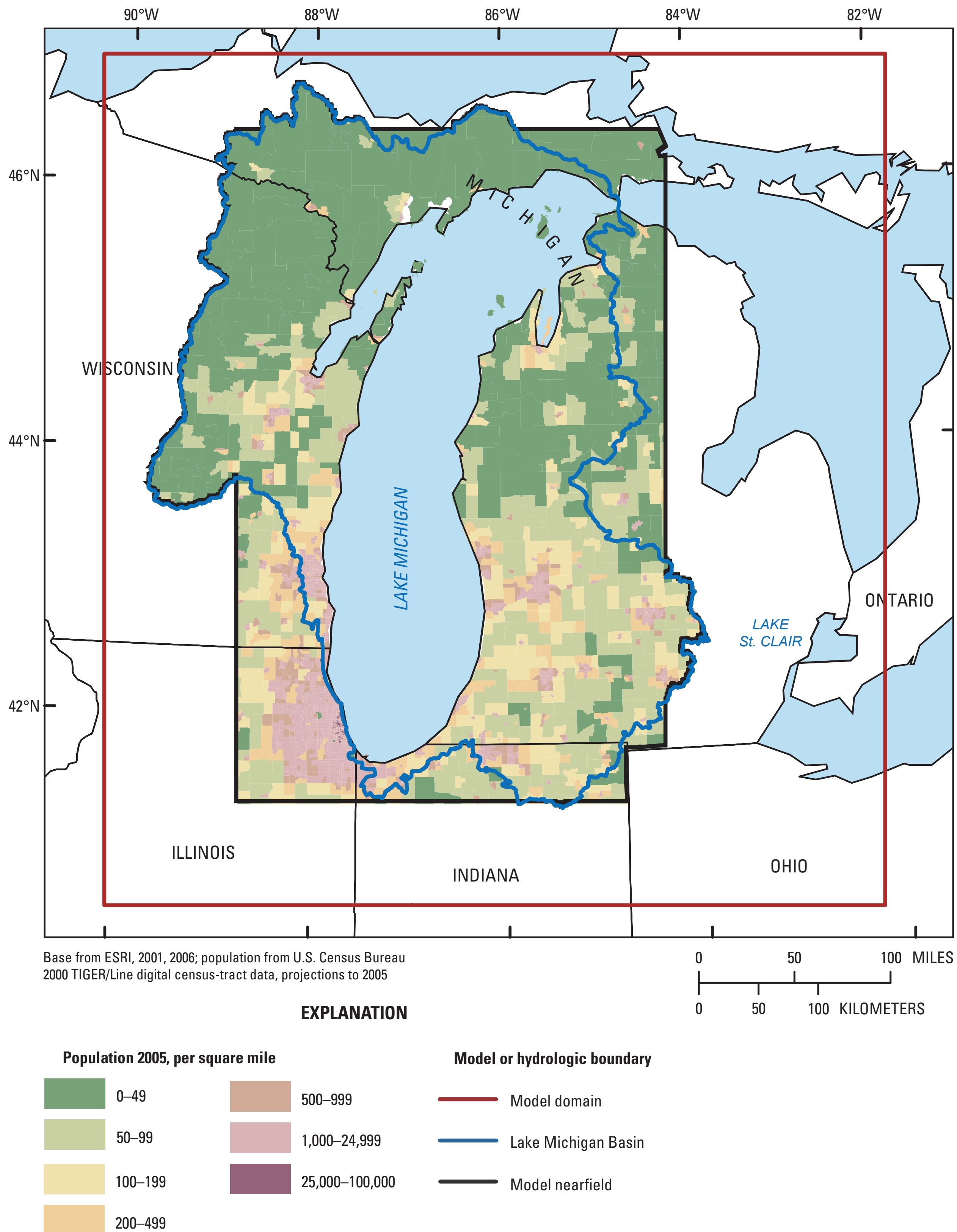


Figure 5. Population distribution in model nearfield.

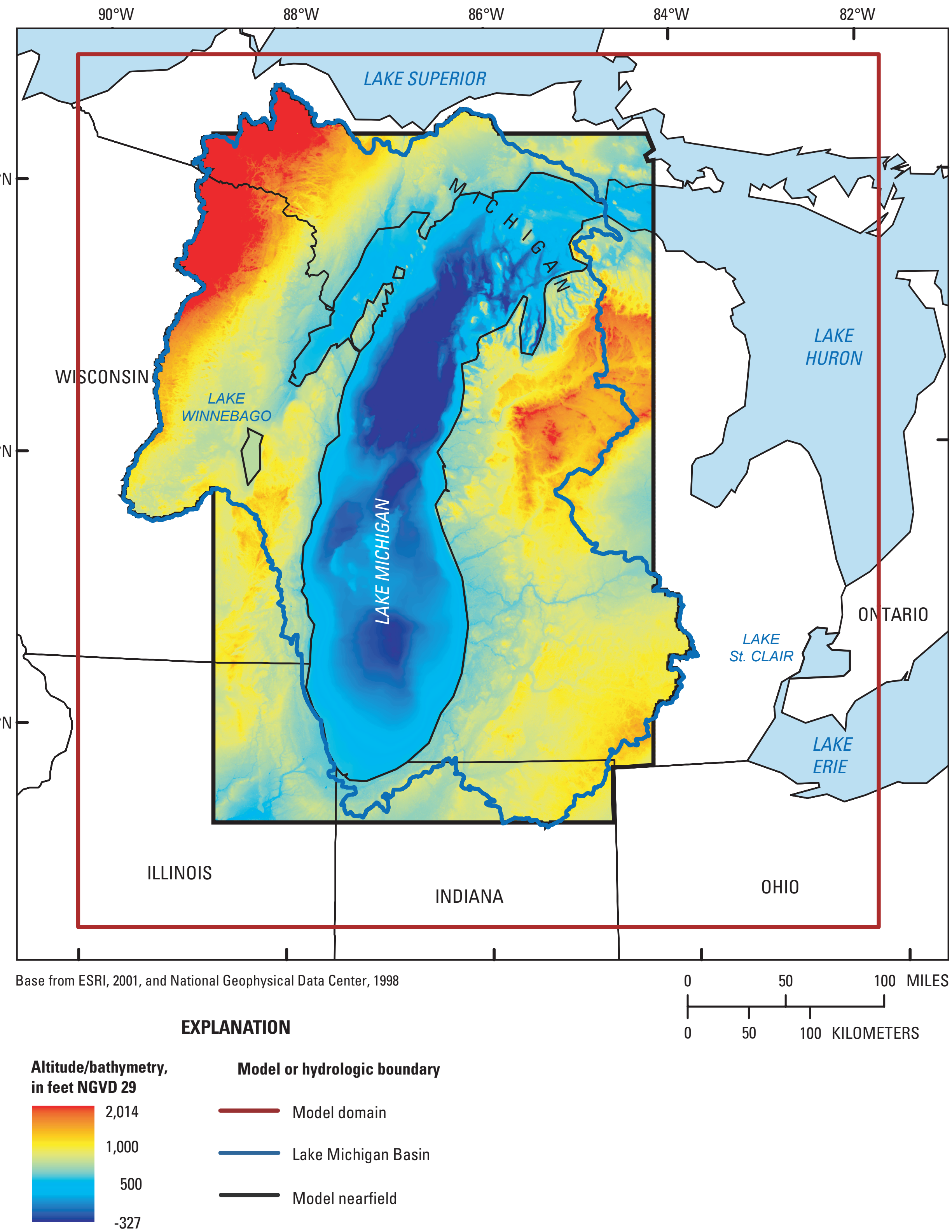


Figure 6. Land-surface and lakebed altitude in model nearfield.

The surface-water network also affects groundwater flow; under natural conditions, streams and lakes often serve as discharge areas for groundwater. The surface-water basin draining to Lake Michigan is surrounded by other major drainage basins inside the model domain associated with the Mississippi River, Lake Superior, Lake Huron, Lake St. Clair, and Lake Erie (fig. 7*A*). The surface-water features within these basins, in particular the major rivers (fig. 7*B*), constitute an important input to the groundwater-flow model. The boundaries of the hydrologic basins around major surface-water features (fig. 7*C*) tend to correspond to the major shallow groundwater divides.

The bedrock surface that underlies the glacial and alluvial deposits has a generally subdued topography because of glacial scouring. Bedrock units in the model nearfield range from Precambrian to Jurassic in age (fig. 8*A*). Precambrian units consist of crystalline rocks and metamorphosed sedimentary rocks. Precambrian bedrock of the Canadian Shield, approximately 3.5 billion years old, crops out on the northern boundary of the model domain. The overlying Paleozoic and Mesozoic rocks are sedimentary in origin. These bedrock units dip away from the crests of the Wisconsin, Kankakee, Findlay, and Algonquin Arches into the Michigan Basin, a structural basin consisting of an ovate-shaped accumulation of sedimentary rocks (fig. 8*B*). This series of large-scale structural basins and arches control the position and extent of bedrock units in the northern Midwest in general and in the model domain in particular (fig. 8*B*). The Wisconsin Arch, Kankakee Arch, Findlay Arch, and Algonquin Arch all dip radially into the Michigan Basin; the rocks are relatively thin along the arches and thicken dramatically toward the center of the Michigan Basin. The Michigan Basin is centered in the Lower Peninsula of Michigan and reaches a maximum thickness of about 15,000 ft.[1] An overview of the Paleozoic and Mesozoic units that constitute the bedrock follows in section 3.1; more detailed discussion by subregon is in appendix 1.

1.3 Water Use In and Around the Lake Michigan Basin

Although water demand in the Great Lakes Basin is predominantly met through surface-water withdrawals, the population in the Lake Michigan Basin uses appreciable amounts of groundwater at an estimated rate of 1,500 million gallons per day (Sheets and Simonson, 2006). There are several areas of concentrated withdrawals (fig. 9). The areas of largest groundwater withdrawals in the Great Lakes Basin are on the west side of Lake Michigan around Chicago in the Northeastern Illinois subregion (NE_ILL) and around Waukesha andMilwaukee in the Southeastern Wisconsin subregion (SE_WI).

Other major pumping centers in the model nearfield include the Green Bay and Lake Winnebago area in the Northeastern Wisconsin subregion (NE_WI), the cities of Lansing, Grand Rapids (now mostly supplied by surface water), Jackson, and Kalamazoo in the Southern Lower Peninsula, Michigan subregion (SLP_MI), as well as communities in southern Michigan and in the Northern Indiana (N_IND) subregion such as Michigan City, Elkhart, and South Bend. Changes in pumping through time are a major stress on the groundwater system that cause water levels to fluctuate and groundwater divides to migrate. As a result, historical pumping from high-capacity public-supply, irrigation, and industrial wells is an important input to the LMB groundwater-flow model. High-capacity wells are defined for this study as those that extract on average more than 70 gal/min (100,000 gal/d). Domestic wells commonly extract less than this rate.

1.4 Saline Groundwater in the Lake Michigan Basin

A hydrogeologically important characteristic of the the Lake Michigan Basin area is the presence of saline water[2] in several of the water-bearing formations. In the Lower Peninsula of Michigan, saline water is present near land surface in lowland areas, particularly on the east side of the Lower Peninsula (Wahrer and others, 1996; Hoaglund, 2004). Shallow bedrock units in some areas are rendered nonpotable by salinity (Meissner and others, 1996; Ging and others, 1996; Westjohn and Weaver, 1996c). Deeper bedrock units in the Michigan Basin host water with specific gravity greater than 1.20, corresponding to dissolved solids (DS) concentrations in excess of 300,000 mg/L (Gupta and Bair, 1997). The high salinity in the Paleozoic bedrock extends into northern Indiana where water in shallow Silurian and Devonian rocks commonly have DS concentrations greater than 10,000 mg/L (Schnoebelen and others, 1998). Under northeastern Illinois, saline water in Cambrian-Ordovician units is commonly present at DS concentrations exceeding 10,000 mg/L at 2,000 ft below sea level (Bond, 1972; Visocky and others, 1985; Nicholas and others, 1987), and upconing of deep saline water toward wells in originally freshwater areas can be a problem around pumping centers withdrawing from the deep sandstone aquifers. In Wisconsin, saline water in bedrock aquifers is more isolated, attaining DS concentrations greater than 1,000 mg/L in pockets between Milwaukee and Green Bay near Lake Michigan (Ryling, 1961).

[1] Note that “Lake Michigan Basin” refers to the lake plus its drainage area, whereas “Michigan Basin” refers to the geologic feature.

[2] Definitions of “salinity” and “saline water” are varied in hydrological literature. For purposes of this report, “saline water” is used to mean water having a dissolved solids concentration greater than 10,000 mg/L, regardless of composition, or a density that can be interpreted as representing a dissolved solids concentration greater than 10,000 mg/L.

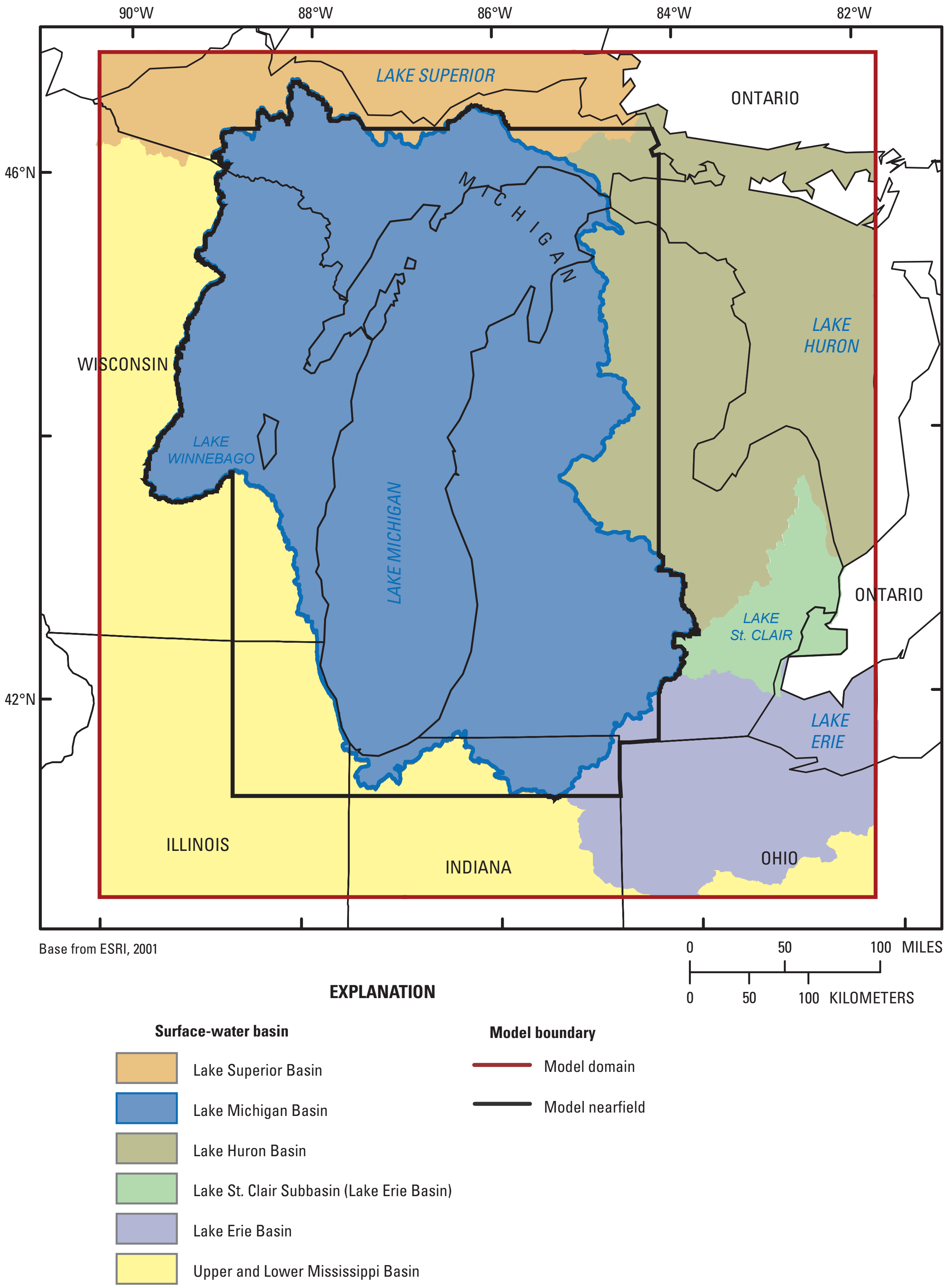


Figure 7A. Major surface-water basins in model domain.

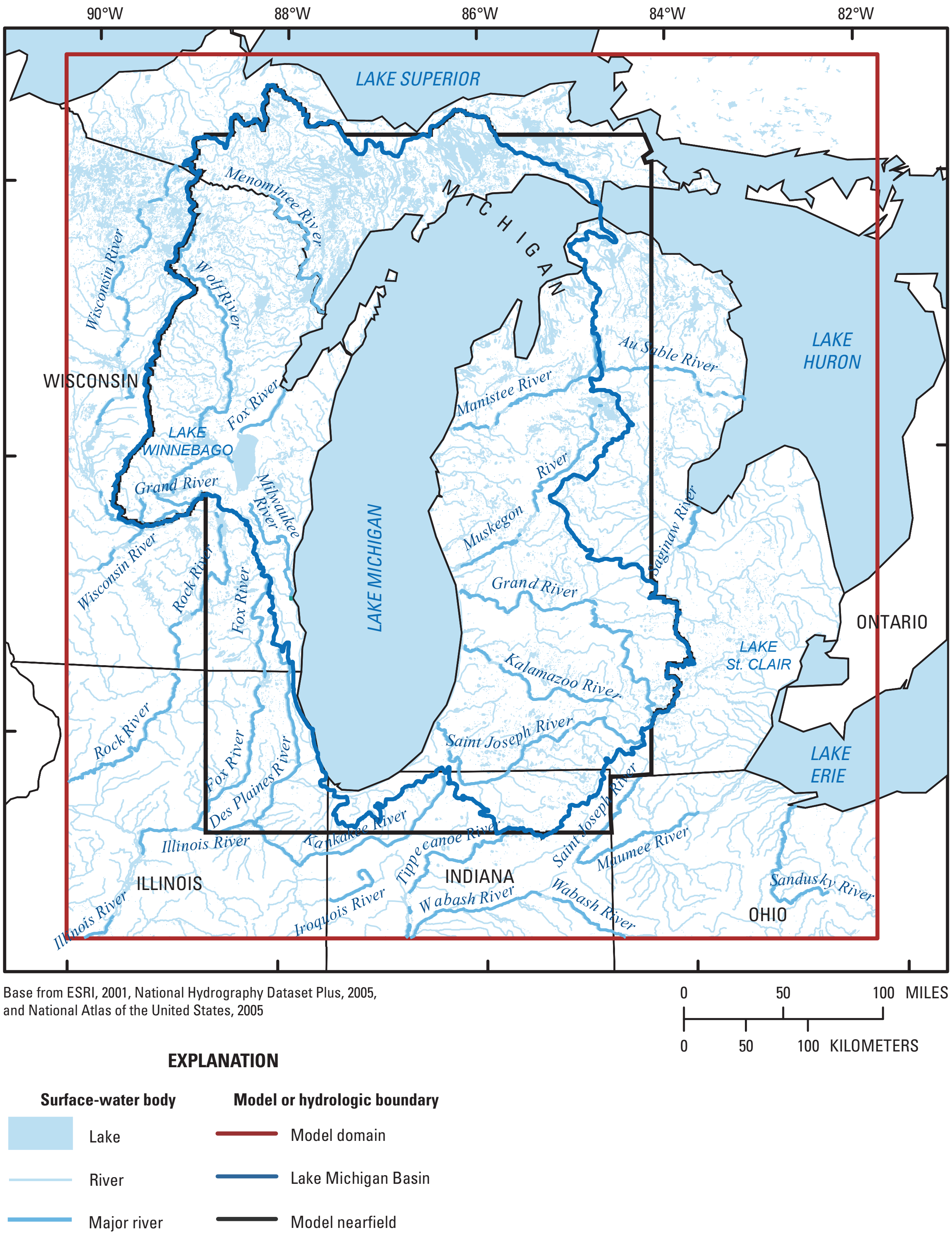


Figure 7*B*. Major rivers in model domain.

Figure 7*C*. Major level 3 and 4 hydrologic units in model domain.

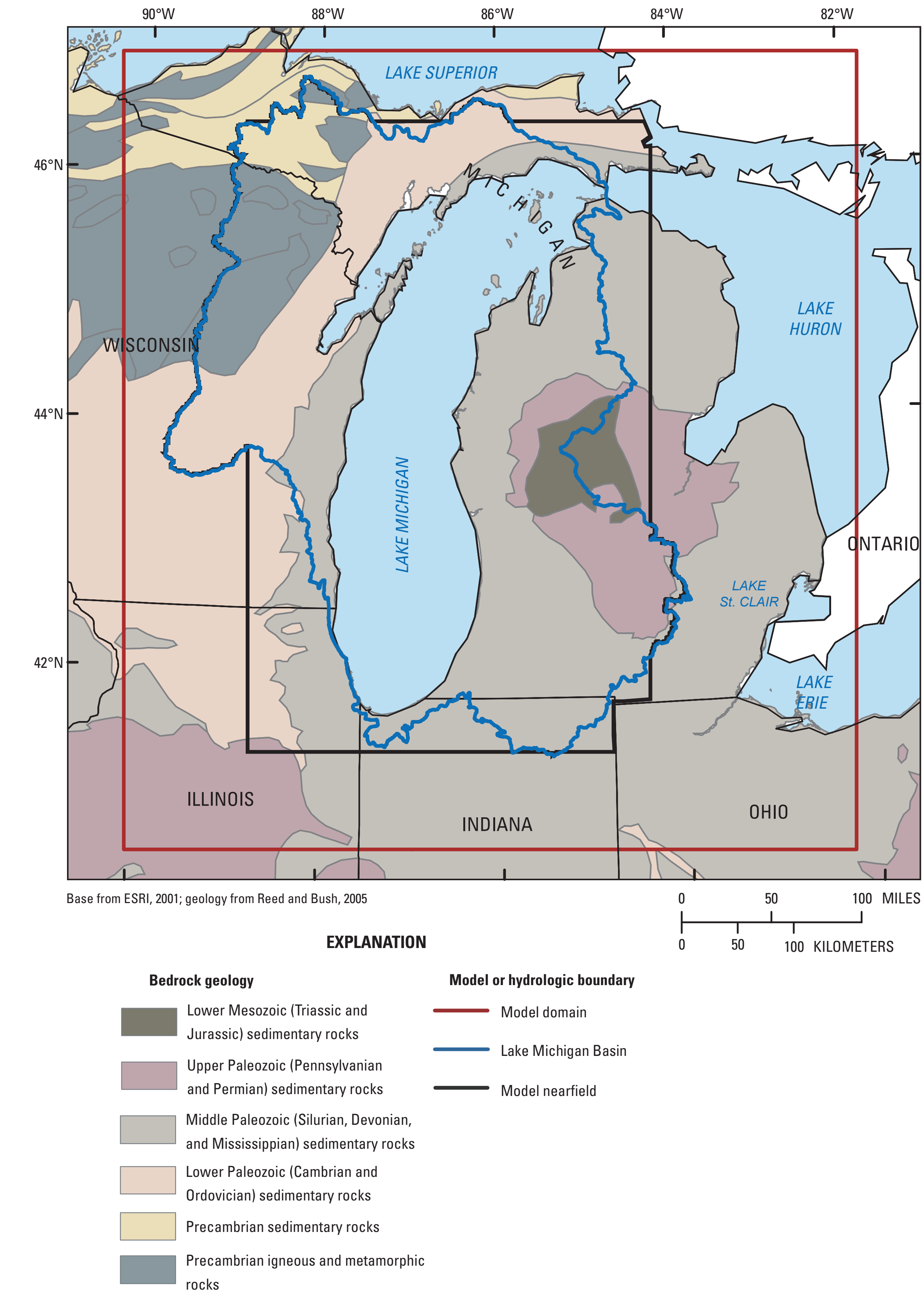


Figure 8*A*. Uppermost bedrock units in the study area.

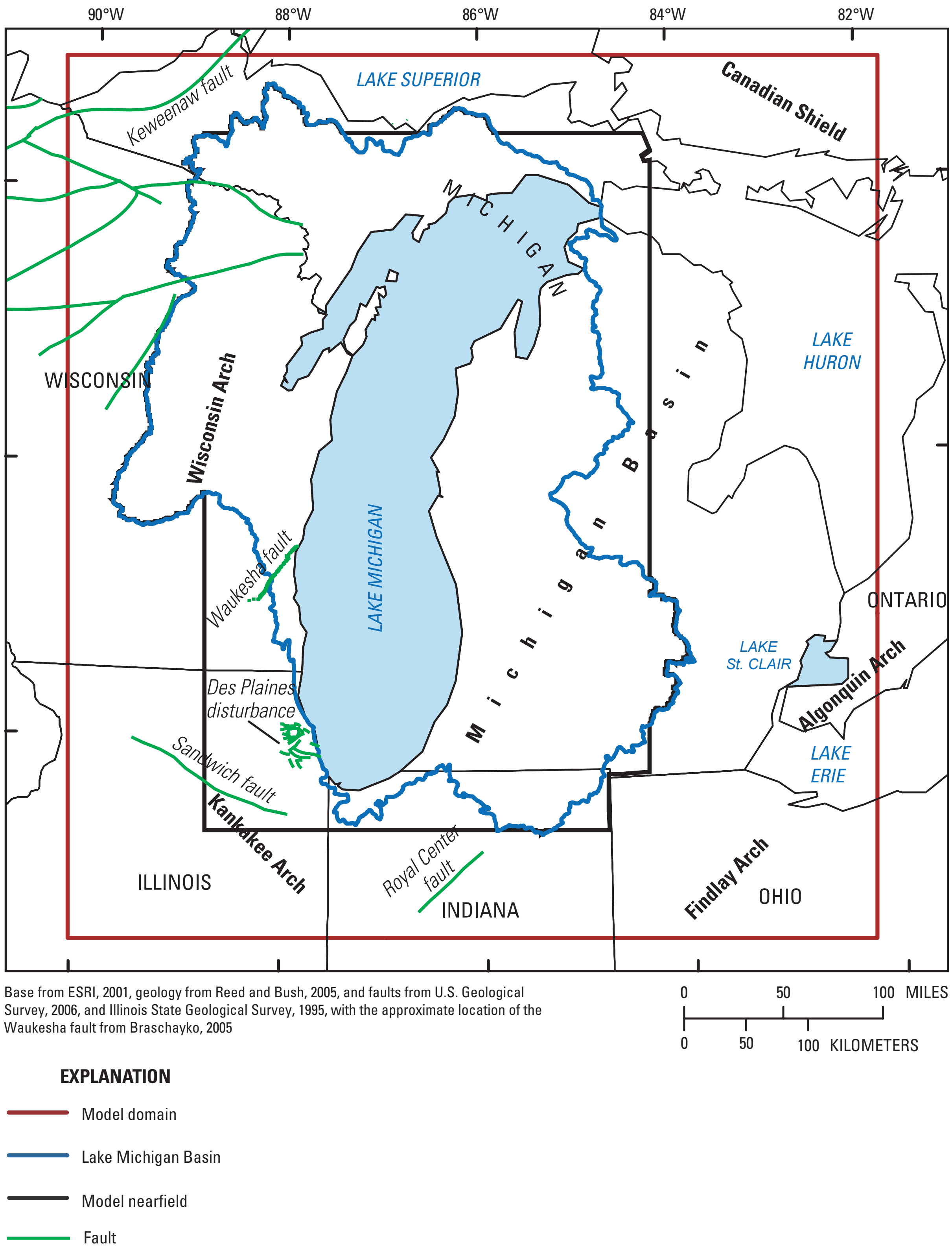


Figure 8*B*. Uppermost bedrock structural features in the study area.

Figure 9. Estimated 1995 groundwater-withdrawal rates for major metropolitan areas in the U.S. part of the Great Lakes Basin.

Characterization of flow patterns of saline aquifer can be complicated by the effects of the density of the water. Standard methods for hydrogeologic analysis are based on a standard water density of about 1 g/cm^3. Freshwater with a standard density flows in response to hydraulic pressures. Water with an appreciably higher density due to high DS concentrations (for example, 100,000 mg/L or greater) will flow in response to hydraulic pressures but will also have a tendency to flow downward because it is heavier, complicating analysis and simulation of water movement. The density of the water also influences the ease with which it can flow horizontally or vertically through subsurface material. The density of saline water, thus, influences the movement of groundwater flow by changing both hydraulic gradients and hydraulic conductivity relative to freshwater conditions. By changing the dynamics of flow, saline conditons also potentially influence the response of aquifers to pumping. Accordingly, one of the chief sets of inputs to the LMB groundwater-flow model is the subsurface distribution of salinity.

1.5 Previous Hydrogeologic Investigations and Modeling Studies

Published studies of groundwater in the Lake Michigan Basin area include surveys of the region's hydrogeology and large-scale modeling efforts by the USGS and state geological agencies.

Within the hydrogeologic literature are comprehensive treatments of the stratigraphic framework for the Great Lakes region, focusing on the occurrence of groundwater and the properties of aquifers and confining units (Allen and Waller, 1975; Weist, 1978; Olcott, 1992). Recent studies of the Great Lakes Basin have also emphasized the connection between geology and water resources (Government of Canada and the U.S. Environmental Protection Agency, 1995; Grannemann and others, 2000; Coon and Sheets, 2006). Most of the work dedicated to regional hydrostratigraphy has been done at the state level.

In Michigan, fundamental investigations targeted the distribution of glacial deposits (Leverett and Taylor, 1915) and the incidence of artesian wells (Allen, 1977), whereas subsequent studies contributed to a better understanding of the hydrogeology (Passero and others, 1981; Westjohn and others, 1994; Westjohn and Weaver, 1996a,b; Westjohn and Weaver, 1998).

In Wisconsin, pioneers in hydrogeology published seminal works (Chamberlin, 1877; Weidman and Schultz, 1915), which were followed by regional studies describing groundwater conditions in areas such as southeastern Wisconsin (for example, Foley and others, 1953) and northeastern Wisconsin (for example, Knowles, 1964). In more recent years, the Wisconsin Geological and Natural History Survey and the USGS published several framework hydrogeologic studies for Wisconsin (Young, 1992; Batten and Bradbury, 1996; Kammerer and others, 1998; Southeastern Wisconsin Regional Planning Commission and Wisconsin Geological and Natural History Survey, 2002).

Hydrologic basin studies published by Indiana state agencies cover a range of hydrogeologic information for the southern part of the Lake Michigan Basin area (Indiana Department of Natural Resources, 1987, 1990, 1994, and 1996). These basin studies are complemented by a series of USGS publications that define the hydrostratigraphy for the northern part of Indiana (Fenelon, Bobay, and others, 1994; Casey, 1997; Fowler and Arihood, 1998; Bugliosi, 1999).

In Illinois, previous hydrologic investigations focused not only on data collection and stratigraphic interpretation (for example, Nicholas and others, 1987) but also on issues arising from the large areas of water-level decline around Chicago, on the source of water to wells, and on the presence of saline conditions in the deep part of the flow system (Suter and others, 1959; Walton, 1960; Walton and Csallany, 1962; Walton, 1965; Visocky and others, 1985).

Some of the earliest groundwater-flow models were developed in the upper Midwest, where electric-analog and analytical techniques were used to forecast drawdown and evaluate sources of water to wells in the Chicago area (Walton, 1964; Prickett, 1967). Applications of numerical groundwater-flow modeling were undertaken in the 1970s and 1980s to test hydrogeologic interpretations and to develop management tools in Illinois (Prickett and Lonnquist, 1971), in southeastern Wisconsin (Young, 1976), in Michigan (Fleck and McDonald, 1978), and in northern Indiana (Bailey and others, 1985; Lindgren and others, 1985).

The USGS Regional Aquifer-System Analysis (RASA) program, which spanned 1978–95, enhanced understanding of large-scale groundwater- flow systems in the United States. The RASA studies generated data that increased knowledge of the bedrock and surficial aquifers in the Great Lakes Basin and helped to strengthen interpretations of the subsurface hydrostratigraphy. The program also supported a series of groundwater-flow models that provided a quantitative understanding of subsurface flow at the regional scale. Study areas for three sets of RASA modeling studies overlap the Lake Michigan Basin model domain.

Mandle and Kontis (1992) constructed a regional model of the aquifers underlying the northern Midwest. The model area extended from central Missouri to the southern shore of Lake Superior and from central Michigan to the South Dakota-Minnesota border, covering 378,880 mi^2. The computer code used in their study was based on finite-difference programs documented in Trescott (1975) and Trescott and Larson (1976). The application incorporated a uniform grid resolution of 16 mi and used multiple layers to represent major aquifers. Confining units were not included explicitly, but their effect on vertical flow was included by means of a resistance term. The Trescott and Larson code was modified to correct the freshwater heads for the density effects of salinity (without modeling the movement of salinity). The upper boundary of the model was fixed to represent the observed water-table surface, under the assumption that drawdown in the uppermost aquifers was negligible at this scale. Major rivers also were represented with fixed stages. Model simulations showed that groundwater withdrawals had created extensive drawdown in all bedrock aquifer formations under the pumping conditions in 1980, decreasing discharge to rivers and reversing flow across confining units near major pumping centers. Mandle and Kontis (1992) also noted that the grid resolution of the model was too coarse to examine small-scale features of the flow system. A second phase of modeling for the northern Midwest RASA (Young and others, 1989) produced a more detailed transient model of the Chicago-Milwaukee area. It used a version of the computer code MODFLOW developed and documented by McDonald and Harbaugh (1983). The code was modified to include a method developed by Bennett and others (1982) to calculate the approximate withdrawal rates from each aquifer penetrated by a multiaquifer well (Kontis and Mandle, 1988). The Chicago-Milwaukee model featured grid cells as small as 2 mi on a side, allowing for a more refined simulation of the development of the two, large coalescing areas of water-level decline in southeastern Wisconsin and northeastern Illinois.

The separate series of RASA studies devoted to the Lower Peninsula of Michigan included an initial model constructed by Mandle and Westjohn (1989) that simulated the effects of a steady-state water table and salinity on the bedrock hydrology. This model had a horizontal grid spacing on the order of 3 mi over an area of about 22,000 mi^2. A subsequent model of the same area by Hoagland and others (2002a,b) used estimates of groundwater recharge (Holtschlag, 1997) to more accurately simulate the shallow and deep parts of the flow system and to estimate direct (riparian) and indirect (base-flow) discharges to the three Great Lakes bounding the Lower Peninsula. The later model used a grid spacing of 3,281 ft (1 km) and individual layers for glaciofluvial sediments, till and red-bed confining units, Pennsylvanian aquifers, Pennsylvanian confining units, and the Marshall aquifer. The underlying Mississippian shale beds were represented by a no-flow boundary. The modelers assumed steady-state conditions without pumping and did not consider the influence of variable density due to salinity. However, they subjected the model to a rigorous calibration process to improve the reliability of estimates of groundwater discharge to surface-water features in Michigan's Lower Peninsula.

A third series of RASA studies focused on quantifying regional flow in an area just south of the LMB model in northern Indiana, as well as in parts of Ohio and Illinois. The model of the Midwestern Basins and Arches aquifer system by Eberts and George (2000) simulated flow in the water-table aquifer and the underlying areally extensive Silurian-Devonian carbonate-rock aquifer. The model simulated only regional groundwater flow, estimated to be about 10 percent of the total groundwater flow. The model grid consisted of square cells 4 mi on a side and two layers, one for unconsolidated deposits and one for bedrock. The regional flow pattern at the time was not influenced by historical changes in regional pumping, which justified the use of a steady-state model. The simulated flow system showed long flow paths (as much as 50 mi in length) in some areas of the model and indicated that very old water was associated not only with these long flow paths but also with short flow paths where small hydraulic gradients resulted in sluggish flow rates.

Subsequent to the RASA studies, a new generation of regional models was applied to evaluate groundwater flow systems and water budgets in Michigan (for example, Holtschlag and others, 1996; Hoaglund and others, 2002a; Reeves and others, 2004), in eastern Wisconsin (for example, Krohelski, 1986; Conlon, 1998; Krohelski and others, 2000), in northern Indiana (for example, Fenelon and Watson, 1992; Arihood and Basch, 1994; Bayless and Arihood, 1996; Arihood and Cohen, 1998), and in northeastern Illinois (for example, Burch, 1991). Although most of these models were used to develop input datasets and calibration targets for different parts of the LMB model, two additional models were of particular importance in furnishing a variety inputs for the present study.

Feinstein and others developed a model centered on southeastern Wisconsin (Feinstein, Eaton, and others, 2005; Feinstein, Hart, and others, 2005). The model represented all rock units, including confining beds, from land surface to the top of the Precambrian sequence, by means of 18 layers. Minimum grid resolution was 2,500 ft in the model nearfield of southeastern Wisconsin. The model was calibrated for both predevelopment and pumping conditions by using heads and stream base-flow observations for the period 1864 to 2000. Feinstein, Hart, and others (2005) concluded that nearly 80 percent of water pumped from wells in southeastern Wisconsin is diverted from groundwater that was previously discharged as base flow to streams and lakes. The model indicates that, under 2000 conditions, only a small amount of water replenishing the regional cone of drawdown for the deep part of the flow system was induced from Lake Michigan. In addition, the modeling showed that, between 1864 and 2000, withdrawals from shallow wells open to glacial material and the upper bedrock had reduced shallow groundwater discharge to Lake Michigan by 8.5 percent. Most of this water is probably returned to the lake through the sewage and water-treatment system, however. Finally, the modeling indicated that, between 1864 and 2000, the western limit of the contributing area for deep wells in pumping centers in southeastern Wisconsin shifted about 10 mi west of the original western boundary of the deep part of the regional groundwater flow system, which discharged toward Lake Michigan under natural conditions.

Meyer and others (2009) constructed and calibrated a regional groundwater- flow model centered in northeastern Illinois. The layering and grid spacing are similar to those in the model centered on southeastern Wisconsin by Feinstein and others (Feinstein, Eaton, and others 2005; Feinstein, Hart, and others, 2005). The model simulates groundwater withdrawals in northeastern Illinois and the surrounding area from 1864 to 2002. As part of the study, the regional model is used to set conditions at the edge of a refined inset model centering on Kane County, an area of special interest because of increasing groundwater withdrawals.

Although many models intersect the LMB model domain, there were several motives for developing a new model as part of the Great Lakes Basin pilot study, which is a part of the National Assessment of Water Availability and Use. The LMB model is based on multiple databases that have been assembled from a variety of sources to represent water use, glacial stratigraphy, bedrock stratigraphy, salinity, recharge, and the surface-water network. Recent advances in groundwater-modeling techniques, particularly in the areas of variable-density modeling and calibration methods, allow some past modeling limitations to be overcome. Faster computers mean that smaller grid sizes for the groundwater model can be used than in the RASA-generation models, allowing for more realistic simulations over the Lake Michigan Basin and adjacent areas. Finally, the sustainability issues that accompany the debate over the Great Lakes Compact[3] may best be addressed with a tool that not only incorporates a large regional area corresponding to the western half of the Great Lakes Basin but also is capable of supporting embedded models that can address local management and diversion issues.

[3] A major water-availability issue in the Great Lakes Basin for the past decade has been management of Great Lakes water; in particular, control and regulation of diversions of water outside the basin. Decisions regarding regional water management by representatives of the Great Lakes States and Provinces are embodied in the Great Lakes-St. Lawrence River Basin Water Resources Compact (Council of Great Lakes Governors, 2005b) and the Great Lakes-St. Lawrence River Basin Sustainable Water Resources Agreement (Council of Great Lakes Governors, 2005a). In 2008, this interstate compact between the eight Great Lakes States received consent and approval by Congress and was signed into law (U.S. Congress, 2008). The compact is a good-faith agreement by the eight Great Lakes U.S. States and two Great Lakes Canadian Provinces. This compact and agreement build upon the Great Lakes Charter Annex of 2001 (Council of Great Lakes Governors, 2001) and seek to "protect, conserve, restore, improve and effectively manage the Waters and Water Dependent Natural Resources of the Basin." Key features, which have gained significant attention in the region, are regulation of diversions of water outside of the basin and development of water-management goals and policies for the states and provinces within the basin.

2. Data and Methods

Data from many sources contribute to a series of databases that support numerical codes used either to calculate inputs to the LMB model or to run simulations. The data, databases, and numerical codes are summarized in this section.

2.1 Data Sources

2.1.1 Hydrostratigraphic Units and Model Layering

The USGS National Elevation Dataset furnished land surface for the model domain. The initial definition of the sequence of hydrostratigraphic units extending from land surface to the top of Precambrian rocks was derived in part from RASA data (Kontis and Mandle, 1980), supplemented by framework studies in each state. For Michigan, several interpretive compilations target the bedrock stratigraphy (Bricker and others, 1983; Michigan Department of Environmental Quality, 1987; Nadon and others, 2000; Swezey, 2008), whereas others include data for both unconsolidated (mostly glacial) deposits and for Michigan Basin bedrock (Western Michigan University Department of Geology, 1981; Michigan Department of Environmental Quality, 2003). In eastern Wisconsin, county and regional studies were tapped to delineate the model layering (Foley and others, 1953; LeRoux, 1957; Newport, 1962; Knowles, 1964; Knowles and others, 1964; Olcott, 1966; Hutchinson, 1970; Green and Hutchinson, 1965; Krohelski, 1986; Batten, 1987; Conlon, 1998; Batten 2004; Feinstein, Eaton, and others, 2005). Stratigraphic interpretations are based on well data contained in databases compiled by state agencies (Wisconsin Department of Natural Resources, 2006; Wisconsin Geological and Natural History Survey, 2004). Data sources for stratigraphy in northern Indiana include framework studies of bedrock topography and structure (Becker and others, 1978; Bassett and Hasenmueller, 1980; Shaver and others, 1986; Rupp, 1991; Casey, 1992; Bunner, 1993; Casey, 1994; Gray, 2003) and bedrock representations in model studies (for example, Eberts and George, 2000). Local studies focus on the glacial stratigraphy (for example, Bayless and others, 1995). The bedrock stratigraphy and structure of northeastern Illinois are described by many studies (for example, Emrich and Bergstrom, 1962; Buschbach, 1964; Emrich, 1966; Kolata and others, 1978; Kolata and Graese, 1983; Mikulic and others, 1985; Nichols and others, 1987; Brown and others, 2000; Kay and others, 2004). The recent modeling study by the Illinois State Water Survey (Meyer and others, 2009) produced a hydrogeologic model underlying the groundwater flow model for northeastern Illinois based on many previous studies. It represents the full sequence of stratigraphic units overlying the Precambrian rocks and includes vertical offsets in layer surfaces owing to major faulting. The Illinois State Water Survey generously supplied the USGS with their stratigraphic and structural interpretation, which is directly adapted to the LMB model layering. Finally, the stratigraphy in northwestern Ohio, limited to the model farfield, is available through comprehensive geologic studies (Wickstrom and others, 1992; Ohio Division of Geologic Survey, 2005).

2.1.2 Hydrogeologic Properties of Aquifers and Confining Units

In order to establish initial values for model inputs such as horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and specific yield, data were compiled for both unconsolidated and bedrock deposits. Glacial mapping covering the model domain allowed correlation of hydrogeologic properties with types of glacial deposits (Soller and Packard, 1998; Fullerton and others, 2003). Recent surveys in Michigan yielded estimates of hydrogeologic properties for both glacial and bedrock sediments (Michigan Department of Environmental Quality, 2005, 2006; Apple and Reeves, 2007). For eastern Wisconsin, estimates from many individual studies were compiled, with special attention to results of aquifer tests in bedrock units (Drescher, 1953; Foley and others, 1953; LeRoux, 1957; Newport, 1962; Knowles, 1964; Olcott, 1966; Feinstein and Anderson, 1987; Rovey, 1990; Batten and Conlon, 1993; Jansen, 1995; Stocks, 1998; Muldoon and others, 2001). Existing compilations of subsurface properties were especially helpful (Eaton and others, 1999; Carlson, 2000). Several studies provided information on glacial sediments (Simpkins, 1989; Bradbury and Muldoon, 1990; Rodenback, 1988; Rayne and others, 1996; Clayton, 2001) and on the regional confining unit, the Maquoketa (Eaton, 2002). Overviews of hydrogeologic properties are available for northern Indiana (Indiana Department of Natural Resources, 1987, 1990, 1994, 1996; Fenelon, Bobay, and others, 1994) and are supplemented by estimates contained in studies of particular locations (for example, Lapham, 1981; Fenelon and Watson, 1992; Bayless and Arihood, 1996; Arihood, 1998; Fowler and Arihood, 1998) and by RASA modeling that extends into Ohio (Eberts and George, 2000). The Illinois sources for hydrogeologic-property estimates in the northeast part of the State include hydrogeologic investigations and modeling reports (for example, Walton, 1960; Zeizel and others, 1962; Nicholas and others, 1987; Batten and others, 1999; Walker and others, 2003; Kay and others, 2006).

2.1.3 Recharge

Several studies that combined data collection and some method of estimation linked to the data were used to represent the spatial distribution of recharge in the LMB model for Michigan (Holtschlag, 1996; Neff, Piggott, and Sheets, 2005), for eastern Wisconsin (Cherkauer, 1999; Cherkauer, 2001; Dripps and others, 2001; Cherkauer, 2004; Dripps and Bradbury, 2007; Hart and others, 2008a), for northern Indiana (Rosenshein, 1963; Fowler and Arihood, 1998), and for northeastern Illinois (Hensel, 1992; Arnold and Friedel, 2000). These studies used topography, climate variables, land use, and soil variables to estimate recharge (for example, U.S. Geological Survey, 2000a,b; U.S. Department of Agriculture, 2006). These data were incorporated in a recently developed soil-water-balance (SMB) model used to provide recharge estimates for the LMB model (Westenbroek and others, 2010).

2.1.4 Surface-Water Network

The surficial extent and stages of streams and water bodies (lakes and wetlands)[4] in the entire LMB model domain were derived from two compilations of data: the National Hydrography Dataset for the United States (U.S. Geological Survey, 2001a, 2005a) and the Great Lakes Aquatic Gap Project (Brenden and others, 2006). These data were used to impose boundary conditions as part of model construction (see section 4) and to define base-flow targets as part of model calibration (see section 5).

2.1.5 Groundwater Withdrawals

Producing a historical database of groundwater withdrawals between 1864 and 2005 for the LMB model required data from many studies, including compilations at the regional scale (Mandle and Kontis, 1992; Solley and others, 1998; Kay, 2002). For Michigan, several reports and databases from comprehensive studies include local information (Michigan Department of Public Health, 1943; Bedell, 1982; Baltusis and others, 1992; Michigan Department of Environmental Quality, Water Bureau, 2006a–e). In Eastern Wisconsin, data from county studies are complemented by compilations in larger surveys that serve as snapshots of water use in time (DeVaul, 1975a,b,c; Lawrence and Ellefson, 1982; Lawrence and others, 1984; Krohelski and others, 1987; Ellefson and others, 1993, 1997; Wisconsin Department of Natural Resources, 1997; Ellefson and others, 2002; Buchwald, 2009). For southeastern Wisconsin, a historical database for withdrawals was incorporated in the most recent model of the area (Feinstein, Eaton, and others, 2005; Feinstein, Hart, and others, 2005). The water-use record in northern Indiana is available for much of the historical period through various statewide studies (Indiana Department of Natural Resources, Water Division, 1980; Arvin and Spaeth, 1996), regional studies (Indiana Department of Natural Resources, 1987, 1990, 1994, 1996), and local studies (for example, Stallman and Klaer, 1950). Major compilations are available for groundwater withdrawals in northeastern Illinois for past periods (for example, Suter and others, 1959; Sasman, 1965; Schicht and others, 1976; Avery, 1995; Visocky, 1997), but the main data source is the ongoing Illinois Water Inventory Program of the Illinois State Water Survey begun in 1979 to collect annual pumping rates for high-capacity wells—that is, wells that can produce greater than 70 gal/min. Historical pumping in Ohio, whose area is restricted to the farfield of the model domain, was not examined in this study.

[4] Streams are, of course, flowing bodies of water. However, the simplified distinction between “streams” and “water bodies” used in the remainder of this report is similar to and consistent with USGS usage elsewhere—specifically, in the “Streams and Waterbodies” map layer of the National Atlas of the United States (*http://www-atlas.usgs.gov/mld/hydrogm.html*).

2.1.6 Salinity

Salinity levels within the LMB model domain range from freshwater concentrations (DS less than 1,000 mg/L to saline water (typically defined as DS greater than 10,000 mg/L) to brine (DS greater than 100,000 mg/L). Salinity is highest in the Michigan Basin, where shallow and deep aquifers both contain saline water. The distribution of DS was defined by using data from studies in Michigan (Gupta, 1993; Ging and others, 1996; Meissner and others, 1996; Wahrer and others, 1996; Westjohn and Weaver, 1996; Gupta and Bair, 1997) and in northern Indiana and northwestern Ohio (Gupta, 1993; Schnoebelen and others, 1995; Schnoebelen and others, 1998). On the west side of Lake Michigan, DS concentrations greater than 10,000 mg/L are recorded in deep bedrock aquifers in northeastern Illinois (Bond, 1972; Visocky and others, 1985; Nicholas and others, 1987; Balding, 1991) and more sporadically for rocks underneath parts of Wisconsin near Lake Michigan (Ryling, 1961; Kammerer and others, 1998).

2.1.7 Water Levels

The LMB model was calibrated to reproduce historical groundwater levels throughout the model domain at various depths. The U.S. Geological Survey maintains a historical database from a long-term network of wells that record water levels in various aquifer units (see the U.S. Geological Survey National Water Information System Web site at *http://waterdata.usgs.gov/nwis/gw*). In addition to this national resource, compilations are available for various periods in each of the states within the LMB model domain. For Michigan, they include predevelopment records (Barton and others, 1996), long-term hydrographs of network wells (Cornett and others, 2006), and databases of logs submitted by well drillers that include water levels (Michigan Department of Environmental Quality, 2003).

For eastern Wisconsin, available water-level data include observations and mapped contours derived from observations for the deep bedrock from the early 1900s (Weidman and Schultz, 1915), water levels collected in the early 1980 as part of the RASA studies from intervals in test wells isolated by packers and corresponding to individual hydrostratigraphic units (Young, 1992), contoured representations of the water table at the regional scale (Kammerer, 1995), and a historical compilation of driller-log records (Wisconsin Geological and Natural History Survey, 2004). In addition to the available U.S. Geological Survey network records in northern Indiana, there are early collections of water levels (Capps, 1910) and more recent collections (Crompton and others, 1986; Kay and others, 1996; Eberts, 2000), as well as driller-log databases (Indiana Department of Natural Resources, Division of Water, 2002). Historical compilations in northeastern Illinois record not only the recovery of water levels in deep aquifers after heavy pumping around Chicago diminished in the 1980s when the city converted to Lake Michigan public supply (Visocky and others, 1985; Nicholas and others, 1987; Visocky, 1993), but also the renewed drawdown due to development in areas around Chicago (Visocky, 1997; Burch, 2002).

2.1.8 Groundwater Discharge to Streams and Lake Michigan

The LMB model was also calibrated to reproduce observed groundwater discharge to streams, as base flow. Base flow is sustained or fair-weather streamflow and is composed largely of groundwater discharge. The network of U.S. Geological Survey streamgages provides the data for calculating base flow from streamflow records at the outlet of hydrologic basins (Mason and Yorke, 1997; Rutledge, 1998). Several studies have estimated base-flow characteristics of streams within the LMB model domain (Holmstrom, 1978; Singh and Ramamurthy, 1993; Fowler and Wilson, 1996; Arnold and others, 2000; Neff, Day, and others, 2005). Other studies estimated direct groundwater discharge to Lake Michigan, as well as indirect groundwater discharge to the lake via base flow of streams within the basin (Sellinger, 1995; Grannemann and Weaver, 1999; Holtschlag and Nicholas, 1998). Several geophysical and modeling studies estimated direct groundwater discharge to the west side of Lake Michigan (Bradbury, 1982; Cherkauer and Hensel, 1986; Cherkauer and others, 1987; Nauta, 1987; Craig, 1989; Webb, 1989; Cherkauer and others, 1990; Mueller, 1992).

2.1.9 Lakebed of Lake Michigan

The hydraulic conductivity and thickness of the lakebed of Lake Michigan determines the rate of groundwater discharge to the lake. The bathymetry of the lakebed has been mapped (National Oceanic and Atmospheric Administration, 2005), and geophysical methods have been used to determine the geologic and hydraulic properties of shallow lakebed sediments (Wold and Hutchinson, 1979; Cherkauer and others, 1987). The Illinois State Geological Survey conducted 400 mi of continuous seismic profiling combined with gravity coring of bottom sediments in southern Lake Michigan (Lineback and others, 1971), the data from which were interpreted as geologic cross sections (Lineback and others, 1972). A second effort under the auspices of the Sea Grant program in Wisconsin used electrical surveys to attempt to evaluate the ease of vertical flow by estimating the vertical hydraulic conductivity of the shoreline lakebed (for example, Cherkauer and others, 1987).

2.2 Databases and Algorithms

The resources of the Great Lakes Basin Pilot program allowed construction of four databases that were used for hydrostratigraphic, water-use, and salinity inputs to the LMB model. Each database is documented in a separate U.S. Geological Survey Scientific Investigations Report. The database work was supplemented by two contracts to state agencies in support of the LMB model databases, one for water-use information and one for mapping of glacial categories. In addition to customized databases, the model relies on particular computer codes to calculate historical recharge, to account for variable-density groundwater flow, and to perform nonlinear regression as part of the calibration process.

2.2.1 Hydrostratigraphic Units

Surface elevations of hydrostratigraphic units were constructed by Lampe (2009) in support of the development of the LMB model. The hydrostratigraphic units were delineated by grouping the bedrock geology within the model domain into aquifers and (or) confining units (fig. 10). In the Lampe study, top and bottom surfaces for 14 hydrostratigraphic bedrock units were constructed over the model domain. The mapped units, in downward order, are as follows:

- Jurassic red beds, under parts of central Michigan (*confining unit*).
- Pennsylvanian sandstones of the Grand River and Saginaw Formations, under parts of the Lower Peninsula of Michigan (*aquifer*).
- Pennsylvanian Saginaw shales and the Parma Sandstone, combined with the Mississippian Bayport Limestone, under parts of the Lower Peninsula of Michigan (*either aquifer or confining unit depending on location*).
- Mississippian shales of the Michigan Formation, under parts of the Lower Peninsula of Michigan (*confining unit*).
- Mississippian Marshall Sandstone, under parts of the Lower Peninsula of Michigan (*aquifer*).

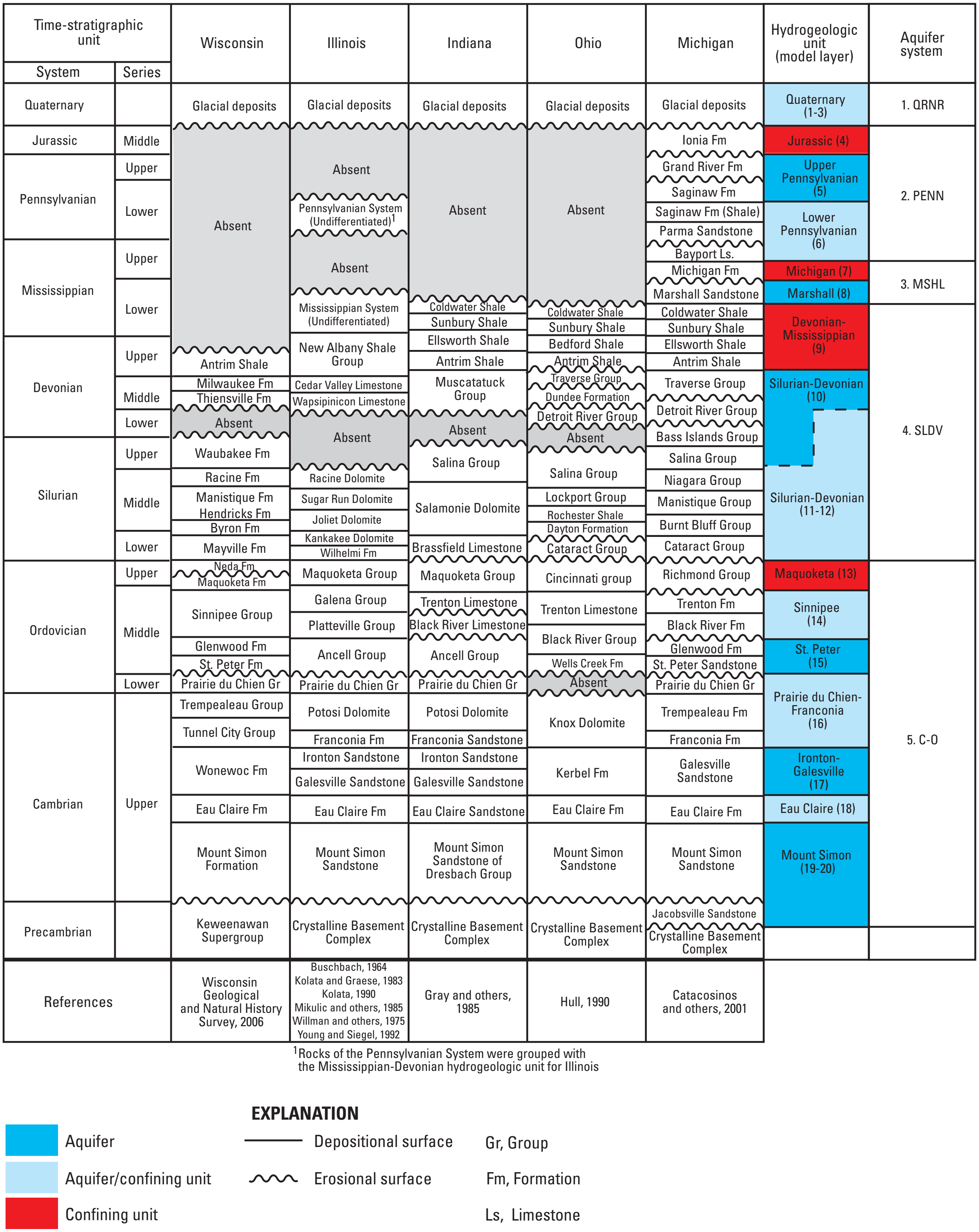


Figure 10. Composite section showing time- and rock-stratigraphic framework and nomenclature for the Lake Michigan Basin region correlated with the hydrogeologic units and aquifer systems in the groundwater model. (Aquifer-system abbreviations are defined in table 1.)

- Coldwater Shale and other Mississippian shales, combined with Devonian shales, under the Lower Peninsula of Michigan and extending under parts of northern Indiana and part of Lake Michigan (*confining unit*).
- Silurian and Devonian dolomites, under parts of eastern Wisconsin, northeastern Illinois, and the Upper Peninsula of Michigan and all of the Lower Peninsula of Michigan and northern Indiana (*either aquifer or confining unit depending on location and interval*).
- Ordovician shales of the Maquoketa Group and related groups, under parts of eastern Wisconsin, northeastern Illinois, and the Upper Peninsula of Michigan and all of the Lower Peninsula of Michigan and northern Indiana (*confining unit).*
- Ordovician dolomites of the Sinnipee Group and related formations/groups, under parts of eastern Wisconsin, northeastern Illinois, and the Upper Peninsula of Michigan and all of the Lower Peninsula of Michigan and northern Indiana (*either aquifer or confining unit depending on location*).
- Ordovician sandstones of the St. Peter Formation and related formations/groups, under most of eastern Wisconsin, northeastern Illinois, and the Upper Peninsula of Michigan and all of the Lower Peninsula of Michigan and northern Indiana (*aquifer*).
- Ordovician dolomites of the Prairie du Chien Group and upper Cambrian sandstone units including the Franconia Formation and related formations/groups, under parts of eastern Wisconsin, northeastern Illinois, and the Upper Peninsula of Michigan and all of the Lower Peninsula of Michigan and northern Indiana (*either aquifer or confining unit depending on location*).
- Cambrian Ironton and Galesville Sandstones and related formations, under most of eastern Wisconsin, northeastern Illinois, and the Upper Peninsula of Michigan and all of the Lower Peninsula of Michigan and northern Indiana (*aquifer*).
- Cambrian siltstone and sandstone of the Eau Claire Formation, under most of eastern Wisconsin, northeastern Illinois, and the Upper Peninsula of Michigan and all of the Lower Peninsula of Michigan and northern Indiana (*either aquifer or confining unit depending on location*).
- Cambrian Mount Simon Formation, under most of eastern Wisconsin, northeastern Illinois, and the Upper Peninsula of Michigan and all of the Lower Peninsula of Michigan and northern Indiana (*aquifer*). In parts of the Upper Peninsula of Michigan the Mount Simon Formation is underlain by a Precambrian unit—the Jacobsville Sandstone—which acts as an aquifer and is tapped by pumping wells. It is lumped with the Mount Simon Formation to form a single mappable unit in the LMB model framework.

This sequence of units represents the entire bedrock thickness within the model domain. The database report contains isopach (thickness) maps for each hydrostratigrahic unit. Details on the incorporation of the hydrogeologic model into the groundwater-flow model are presented in section 4 of this report ("Model Construction").

2.2.2 Thickness and Properties of Quaternary Deposits

Unconsolidated sediments overlying the bedrock in the LMB model are largely glacial in origin and Quaternary in age. The thickness and texture of the unconsolidated sediments are described for an area incorporating most of the model domain by Arihood (2009). More than 450,000 water-well driller logs in Michigan, eastern Wisconsin and northern Indiana were used to glean information for mapping the thickness and texture of the unconsolidated material over nearly the entire model domain, as well as to construct a database of water levels for use in model calibration. The hydraulic conductivites representing glacial deposits in the model were computed by using the areal and vertical distribution of the coarse fraction of glacial sediments (silty sand, sand, and gravel) as recorded in driller logs. The method used to convert the coarse-fraction mapping into hydraulic conductivity is presented in section 4 of this report ("Model Construction"). The use of the water levels derived from the water-well driller logs is discussed in section 5 ("Model Calibration").[5]

The depth of the bedrock surface in parts of the lower peninsula of Michigan, in places exceeding 1,000 ft, required additional analysis to properly map the thickness of the Quaternary deposits. A cooperative study by Michigan State University, the USGS, and the Michigan Department of Environmental Quality (David Lusch, Michigan State University, Department of Geography, RS & GIS Research and Outreach Services, written commun., April 2009; Remote Sensing and Geographic Information Science, 2006) supplemented the information from driller-log data compiled by Arihood (2009).

[5] Northeastern Illinois was excluded from Arihood's analysis, so results from other studies, notably Feinstein, Eaton, and others (2005) and Meyer and others (2009), were used to map the thickness, texture, and hydraulic conductivity of the QRNR deposits.

2.2.3 Distribution of Glacial Categories in Wisconsin and Michigan

The calculation of hydraulic conductivity for glacial (Quaternary) deposits in the model domain is a function of not only material texture at a location but also the glacial category mapped for that location. In this study the glacial categories were characterized as

- clayey till,
- loamy till,
- sandy till,
- fine stratified deposits,
- medium and coarse stratified deposits, and
- organic deposits.

The extent of each category corresponds to the distribution of sets of glacial units mapped for USGS regional compilations (Soller and Packard, 1998; Fullerton and others, 2003). Details on the procedure for converting mapped units into glacial categories are given in section 4 of this report ("Model Construction"). One aspect of the procedure required further data collection and interpretation. Because the regional geologic mapping of Quaternary deposits focuses on surficial deposits, the validity of the mapping of glacial categories is increasingly uncertain with depth and is especially uncertain for thick glacial deposits (considered to be sequences greater than 100 ft). In order to extend the mapping in eastern Wisconsin to areas with thicker glacial deposits and also to check the assignments of glacial categories derived from Fullerton and others (2003) for the shallow deposits, a contract was arranged with the Wisconsin Geological and Natural History Survey and with David Mickelson, Professor Emeritus, University of Wisconsin-Madison. The results of these contracts were reinterpreations of the glacial categories for eastern Wisconsin, both for the upper 100 ft of Quaternary-deposit thickness and for areas where the Quaternary-deposit thickness is greater than 100 ft (T. Hooyer, WGNHS, written commun., December 6, 2006).

As part of his contract, Professor Mickelson also studied the assignment of glacial categories in the Lower Peninsula of Michigan and northern Indiana. He indicated areas where the surficial glacial categories derived from Fullerton might not be representative of the upper 100 ft of Quaternary sediment (D. Mickelson, University of Wisconsin, written commun., April 30, 2007).

2.2.4 Groundwater Withdrawals

The historical database for groundwater withdrawals from high-capacity wells within the model domain for the period extending from 1864 to 2005 is described Buchwald and others (2010). The database details changes in pumping with time and assigns pumping by aquifer and type of end use: public supply, industry, or irrigation. The database contains average pumping rates for more than 13,000 glacial and bedrock high-capacity wells assigned to 12 time intervals (typically 10 years in length). Details on the input of the withdrawal records into the LMB model are presented in section 4 of this report ("Model Construction").

2.2.5 Illinois Water-Use Information

Part of the groundwater withdrawals record was assembled from databases maintained by the Illinois State Water Survey. It has been collecting water use data for Illinois since at least the early 1940s, primarily in regions where water resources were being extensively developed, such as in the northeastern Illinois area. Documentation of annual groundwater withdrawals for individual high-capacity wells began in 1978 and is available through 2005 through the Illinois Water Inventory Program. Because of the high quality of this historical database for not only municipal but also private industrial and irrigation pumping, the USGS, as part of the Great Lakes Pilot project, contracted with the Illinois State Water Survey to extract information from the database for northeastern Illinois and put it in a form convenient for input to the LMB model. The pumping history that resulted is presented in section 4 of this report ("Model Construction").

2.2.6 Distribution of Salinity

Maps showing the distribution of DS concentrations were constructed by Lampe (2009). The maps correspond to the Quaternary sediments, the upper Pennsylvanian units, the Marshall aquifer, an interval within the Silurian dolomites containing evaporites (the Salina Group), the Sinnipee Group, the Prairie-du-Chien/Franconia layers, and the Mount Simon Formation. Salinity in areas with no data was assumed equal to that in adjacent units or was interpolated vertically by using DS concentrations from units above and below. The maximum DS concentration in the database, approximately 400,000 mg/L, is within the Silurian Salina Group in the Michigan Basin.

The mapped distribution of DS was used to compute the initial density-distribution condition for the LMB model, as discussed in section 4 of this report ("Model Construction").

2.2.7 Numerical Codes

Several major numerical codes were used to (a) calculate inputs, (b) simulate variable-density groundwater flow, and (c) estimate values of model parameters.

2.2.7.1 Calculation of Historical Recharge

In the Lake Michigan Basin and adjacent areas, recharge is the chief source of water to the groundwater system. Recharge varies spatially as a function of local precipitation patterns, slope of the land surface, and soil conditions. Recharge varies temporally as a function of climatic variation and land-use changes. A soil-water balance model (SWB) that incorporates these spatial and temporal factors was developed for the LMB model as part of the Great Lakes Basin study. The code and method, based on previous work by Thornthwaite and Mather (1957) and Dripps (2003), was developed by Westenbroek and others (2010). The SWB model calculates recharge by using commonly available geographical information system (GIS) data layers (for example, land use, hydrologic soils group, soil available water content, and surface slope as an indication of overland flow direction) in combination with climatological data. The SWB model computes precipitation, evapotranspiration, runoff, infiltration across the land surface, percolation through the unsaturated zone, and recharge to the water table on a daily basis. The daily recharge estimates are then summed to correspond to the time intervals required by the model input. Details on the application of this code to the model nearfield are given in section 4 of this report ("Model Construction").

2.2.7.2 Simulation of Variable-Density Groundwater Flow

The proximity of saline water to pumping centers both east and west of Lake Michigan requires the use of a variable-density groundwater flow model. The U.S. Geological Survey SEAWAT-2000 code (Langevin and others, 2003) combines the features of MODFLOW-2000 (Harbaugh and others, 2000) developed for groundwater-flow problems under freshwater conditions and the features of the MT3DMS transport code (Zheng and Wang, 1999) developed for simulating the advection, dispersion, retardation, and decay of dissolved constituents in groundwater. The SEAWAT-2000 code solves the variable-density flow equation by formulating the matrix equations in terms of fluid mass and assuming that the fluid density is a linear function of solute concentrations. The application of SEAWAT to the LMB model is described in sections 3 and 4 of this report ("Model conceptualization" and "Model Construction").

2.2.7.3 Parameter Estimation by Nonlinear Regression

Calibration of the groundwater-flow model requires adjustment of parameter values in order to minimize the difference between observed and simulated heads and flows. The calibration of the LMB model is conditioned by the large number of parameter types and zones, the presence of areas where cell-by-cell variation of parameters is crucial to the solution, the large number and variety of calibration targets, the distinct sensitivity of parameter updates to different target groups, and the need to reconcile parameters that control the predevelopment steady-state solution (for conditions which existed before large-scale pumping) with parameters that strongly influence the transient historical solution (for the period from 1864 to 2005).

The LMB model was calibrated by using a combination of manual adjustment of parameter values and application of PEST (Doherty, 2008a), a parameter estimation code that uses nonlinear regression. PEST automatically adjusted selected parameters (hydraulic conductivity, recharge, riverbed conductance) through a series of model runs. After each run, simulated groundwater levels, vertical gradients, and base flows were compared to observed values. The runs continued until the differences (residuals) between simulated and observed values were minimized. The calibration processes, as in all studies, depended on subjective choices, such as parameter zonation and target weighting. However, the calibration approach used for the LMB model extends traditional nonlinear regression parameter estimation by employing three advanced tools: (1) *pilot points* (Doherty, 2003; Doherty and others, in press); (2) *Tikhonov regularization* (Tikhonov, 1963a,b; Doherty, 2003; Fienen and others, 2009); and (3) *hybrid singular value decomposition* (Tonkin and Doherty, 2005; Hunt and others, 2007), also referred to as SVD-Assist (SVDA) by Doherty (2008a). An overview on the use of these tools for parameter estimation is provided by Hunt and others (2007) and by Doherty and Hunt (in press); additional information is in section 5 of this report.

3. Conceptual Model of Regional Groundwater System

Developing a conceptual model for the groundwater-flow system in the Lake Michigan Basin requires the definition of the *hydrogeologic framework*: that is, the identification of hydrogeologic units within the glacial and bedrock geology that can be characterized as aquifers or as confining units and grouped into aquifer systems. The second element of the conceptual model consists of the hydrologic behavior of the *regional flow system* in terms of shallow and deep flow, and regional divides. The flow system is also characterized by sources of water (recharge, movement of water from surface water to groundwater, release of water from storage) and sinks (discharge to surface waters, pumping centers, addition of water to storage). The varying strength of sources and sinks (most notably in the case of Lake Michigan itself) has a large influence on water levels and water movement. The third conceptual element is the *interaction between groundwater and surface water*. Discharge of groundwater to surface water affects the location of groundwater divides, whereas the pumping of groundwater can appreciably alter the natural pattern of local and regional discharge. An additional element in this conceptual model is *salinity of water*. High concentrations of dissolved solids, especially in the sedimentary rocks of the Michigan Basin affect the rate and direction of groundwater flow. Finally, attention is paid to the implications of simulating the flow system as *confined* or *unconfined*.

3.1 Hydrogeologic Framework [6]

The study area for the LMB model encompasses most of the Michigan structural basin, which is centered in the Lower Peninsula of Michigan and extends into parts of Illinois, Wisconsin, Indiana, Ohio, and Ontario, Canada. The Michigan Basin is bounded to the north by the Canadian Shield, to the west by the Wisconsin Arch, to the southwest by the Kankakee Arch, to the southeast by the Findlay Arch, and to the east by the Algonquin Arch (Olcott, 1992; Lloyd and Lyke, 1995) (fig. 8). The Kankakee Arch separates the Michigan Basin from the Illinois Basin—part of which is included in the southwest section of the study area. The Findlay Arch separates the Michigan Basin from structural basins to the southeast outside the model domain. Cambrian rocks of the Wisconsin Arch make up the western boundary of the model.

The subsurface stratigraphy varies across the LMB model domain, so a series of stratigraphic columns representing Wisconsin, Illinois, Indiana, Ohio, and Michigan are shown on figure 10. Shallow units along the Wisconsin Arch are correlated stratigraphically with deeper units in areas to the north in the Upper Peninsula of Michigan and to the south in northeastern Illinois, Indiana, and Ohio. Differing depositional environments are reflected by facies changes that result in variations of rock types within a unit. The sedimentary sequence of Cambrian, Ordovician, and Silurian units consists of sandstones, carbonates, and shales that overlie Precambrian basement rock. The sequence ranges in thickness from hundreds to thousands of feet along the Wisconsin/Kankakee Arches to greater than 10,000 ft in the center of the Michigan Basin (Sonnenfeld and Al-Aasm, 1991). The complete rock sequence is not present everywhere within the model domain. On the west, north, and south side of Lake Michigan, the youngest bedrock units are Silurian (except some Devonian rocks near Milwaukee and in northern Indiana); but on the east side, in the Lower Peninsula of Michigan, younger rocks of Mississippian, Pennsylvanian, and Jurassic age exceed 1,000 ft in thickness. Throughout the model domain (except for scattered locations in the northwest corner), the upper bedrock surface is mantled by Quaternary deposits that are mostly glacial in origin but can contain some alluvial deposits.

Bedrock aquifers (fig. 11) can contain a variety of conduits subject to preferential flow and associated with fractures, joints, faults, and karst features. For example, carbonate (mostly dolomite) rocks in the model domain commonly contain dissolution and bedding planes that route flow preferentially and, possibly, in a particular direction (see, for example, Bradbury and Muldoon, 1994). However, it is not possible to include these local features in a regional model where the cell size is on the order of a mile in lateral extent and whose layers can be on the order of 1,000 ft thick. Instead, the entire bedrock sequence within the model domain is treated as an equivalent porous medium whose individual unit hydraulic conductivities are assumed to be bulk properties reflecting the integrated effect of conduits on flow. This approach is common to modeling at the regional scale (Anderson and Woessner, 1992); the omission of relatively small-scale preferential and anisotropic features is expected to have little effect on the results sought from a regional model, such as drawdown patterns around large pumping centers or the pattern of groundwater exchange with Lake Michigan.

Appendix 1 contains brief descriptions of the geologic framework for the Quaternary deposits at the regional scale and for bedrock units in each subregion of the model. The characteristics of the lithologic units described in the appendix allow the units to be identified as aquifers (defined as geologic formations that contain sufficient saturated permeable material to yield significant quantities of water to springs and wells) or as confining units (defined as bodies of distinctly less permeable material stratigraphically adjacent to one or more aquifers that restrict the movement of water into and out of the aquifers). Some lithologic units are aquifers in some locations and confining units elsewhere. The series of aquifers, confining units, and mixed units define a *hydrogeologic sequence*. The complete order from land surface to crystalline basement for the LMB model is

1. aquifer/confining unit: Quaternary (QRNR)
2. confining unit: Jurassic red beds (JURA)
3. aquifer: Upper Pennsylvanian Grand River and Saginaw Formations (PEN1)
4. aquifer/confining unit: Lower Pennsylvanian Saginaw Formation and Parma Sandstone and Mississippian Bayport Limestone (PEN2)
5. confining unit: Mississippian Michigan Formation (MICH)
6. aquifer: Mississippian Marshall Sandstone (MSHL)
7. confining unit: Devonian/Mississippian shales (DVMS)
8. aquifer/confining unit: Silurian/Devonian carbonates and evaporites (SLDV)
9. confining unit: Ordovician Maquoketa Group/Formation and related units (MAQU)
10. aquifer/confining unit: Ordovician Sinnipee Group and related units (SNNP)
11. aquifer: Ordovician St. Peter Formation/Sandstone and related units (STPT)
12. aquifer/confining unit: Ordovician Prairie du Chien Group and Cambrian Franconia Formation/Sandstone (PCFR), considered part of the Knox Megagroup in some locations (Visocky and others, 1985)
13. aquifer: Cambrian Ironton and Galesville Sandstones and related units (IRGA)
14. aquifer/confining unit: Cambrian Eau Claire Sandstone/Formation (EACL)
15. aquifer: Cambrian Mount Simon Sandstone (MTSM) and, locally, the Precambrian Jacobsville Sandstone.

[6] For ease of presentation abbreviations are used in this section and in subsequent sections to refer to hydrogeologic units and aquifer systems. They are listed in table 1.

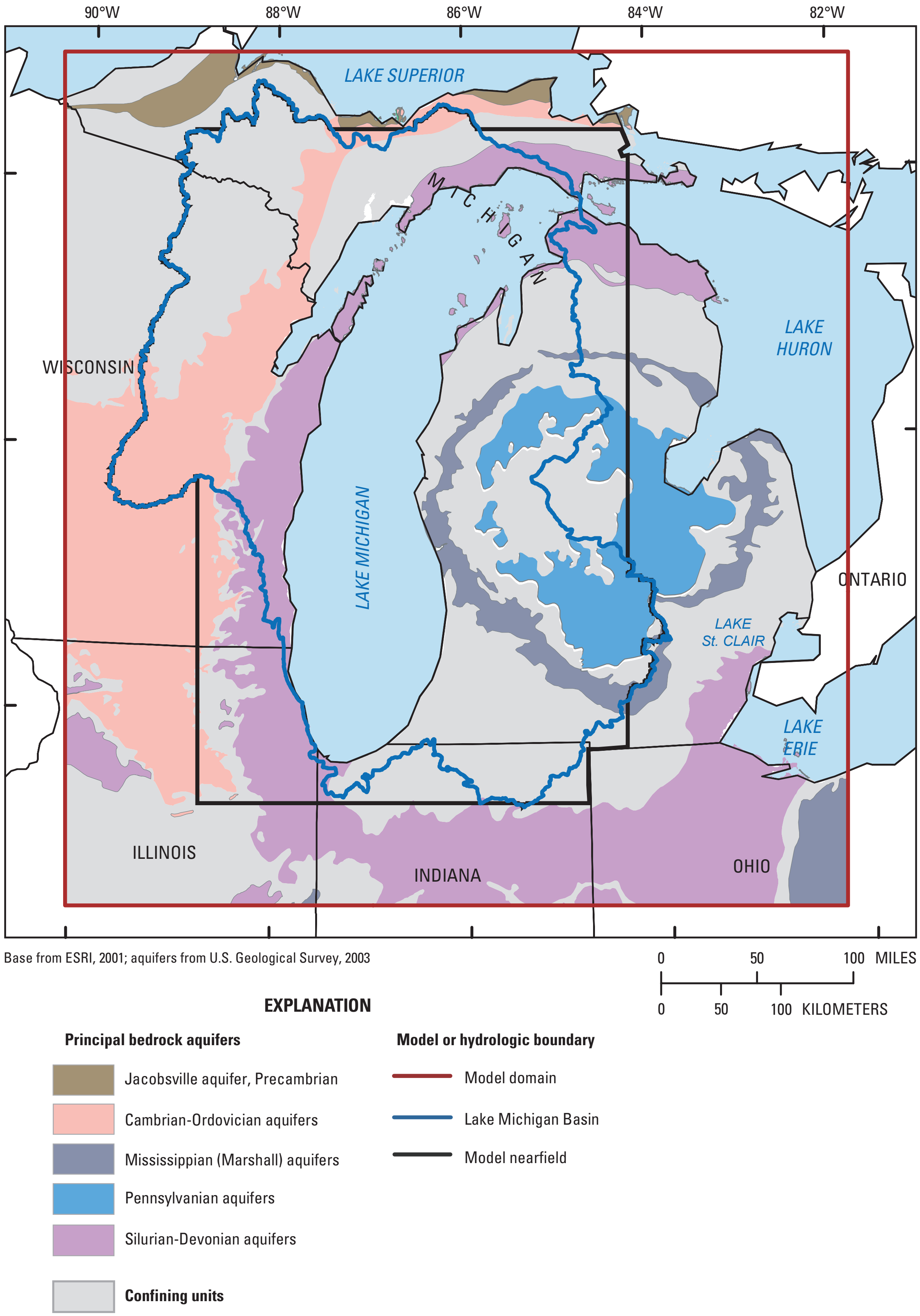


Figure 11. Principal bedrock aquifers.

In all, the LMB model incorporates five hydrogeologic units defined as aquifers (PEN1, MSHL, STPT, IRGA, and MTSM), six hydrogeologic units defined as mixed aquifer/confining units (QRNR, PEN2, SLDV, SNNP, PCFR, and EACL), and four hydrogeologic units identified as confining units (JURA, MICH, DVMS, and MAQU). The MTSM is described as an aquifer unit even though it commonly contains fine-grained beds several hundred feet below its surface. These beds are incorporated into the bottommost layer of the model, which, in turn, overlies the Precambrian crystalline basement. The crystalline rocks are assumed to be highly resistant to vertical flow, so the interface between sedimentary rocks and the crystalline, Precambrian basement was made the bottom boundary of the flow model.

The sequence of 15 hydrogeologic units is not continuous throughout the model domain. The JURA, PEN1, PEN2, MICH, MSHL, and DVMS units are commonly absent north, west, and south of the Michigan Basin, and other units are absent near the crest of the Wisconsin Arch and toward the western edge of the model. These units, including the SLDV, MAQU and older Paleozoic rocks, were progressively eroded, leaving only thin QRNR deposits and the Mount Simon Sandstone over Precambrian crystalline rock. Bedrock highs can also produce relatively small areas where the QRNR is absent, especially in the northwestern part of the model domain.

Groundwater flows primarily through aquifers and aquifer/confining units, whereas confining units stratify the groundwater-flow system and separate aquifers or aquifer systems. *Aquifer systems* contain one or more aquifers and aquifer/confining units and are typically capped by a confining unit. The hydrogeologic framework of the LMB model consists of five aquifer systems (see also color coding at right side of fig. 10):

1. The Quaternary (QRNR) aquifer system, consisting of one hydrogeologic unit: QRNR
2. The Pennsylvanian (PENN) aquifer system, consisting of three hydrologic units: JURA, PEN1, and PEN2
3. The Marshall (MSHL) aquifer system, consisting of two hydrologic units: MICH and MSHL
4. The Silurian-Devonian (SLDV) aquifer system, consisting of two hydrogeologic units: DVMS and SLDV
5. The Cambrian-Ordovician (C-O) aquifer system, consisting of seven hydrogeologic units: MAQU, SNNP, STPT, PCFR, IRGA, EACL, and MTSM.

(The vertical extent of the five aquifer systems is shown schematically in fig. 16, discussed in the next section of the report.)

The distribution of groundwater withdrawals is correlated with the aquifer systems. West of Lake Michigan and in the Upper Peninsula of Michigan (where the units composing the PENN and MSHL aquifer systems are almost entirely missing), the major pumping centers withdraw water from the QRNR, SLDV, and C-O aquifer systems. East of Lake Michigan in the Lower Peninsula of Michigan (where the SLDV and C-O systems are typically too deep and too saline to be exploited), the major pumping centers are in the QRNR, PENN, and MSHL aquifer systems. South of Lake Michigan in northern Indiana and northeastern Ohio (where the PENN and MSHL systems are missing and the C-O system is too deep and saline), the major pumping centers withdraw from the QRNR and, to a much lesser extent, the SLDV aquifer systems. The distribution of wells in the QRNR deposits depends chiefly on the type of glacial material (for example, on the abundance and thickness of outwash deposits), whereas the distribution of wells in bedrock units depends largely on the presence of sandstone or fractured carbonates and their relative thickness.

Another way to characterize the distribution of hydrogeologic units and aquifer systems is by the subregions of the model nearfield. Three of the subregions share a similar geologic framework: NE_WI, SE_WI, and NE_ILL. The sequence of hydrogeologic units and aquifer systems for these subregions is shown in figure 12; it comprises the QRNR, SLDV, and C-O aquifer systems. The entire stack of bedrock slopes gently (on the order of 1° of dip) from the Wisconsin/Kankakee Arches toward the Michigan Basin. Figure 13 shows a similar sequence for the UP_MI, which slopes gently to the south. The Jacobsville Sandstone, which lies between the MTSM and Precambrian sandstone, is an aquifer in this area. The SLDV is present only in the UP_MI in a rim near the Lake Michigan shoreline. To the south of Lake Michigan, in the N_IND subregion, the relatively thin, north-sloping QRNR and SLDV aquifer systems (fig. 14) yield water to wells. The sedimentary sequence for the SLP_MI and NLP_MI subregions (fig. 15) is quite distinct from that of other subregions and includes the PENN and MSHL aquifer systems. The shape of the structural bowl defining the Michigan Basin is distinctive in the section, as are the large number of hydrogeologic units available for water production. Water use from bedrock aquifers, especially in the Michigan Basin, diminishes with depth because the cost of pumping increases and water quality degrades as DS concentrations increase.

Hydraulic gradients and groundwater- flow directions in bedrock on the west and south sides of Lake Michigan tend to align with the dip of bedrock units. On the east side of the lake, however, the hydraulic gradient is west towards the lake and opposite the dip of the bedrock units. Faults generally are not thought to affect the groundwater- flow system in the vicinity of the Lake Michigan basin, with these major exceptions: the Waukesha fault in southeastern Wisconsin, which bounds relatively thin Paleozoic deposits to the west and relatively thick deposits to the east (Feinstein and others, 2005), and the Sandwich fault zone and the probable impact structure known as the Des Plaines Disturbance (Meyer and others, 2009), features which control the thickness of Paleozoic aquifers and confining units in northeastern Illinois.

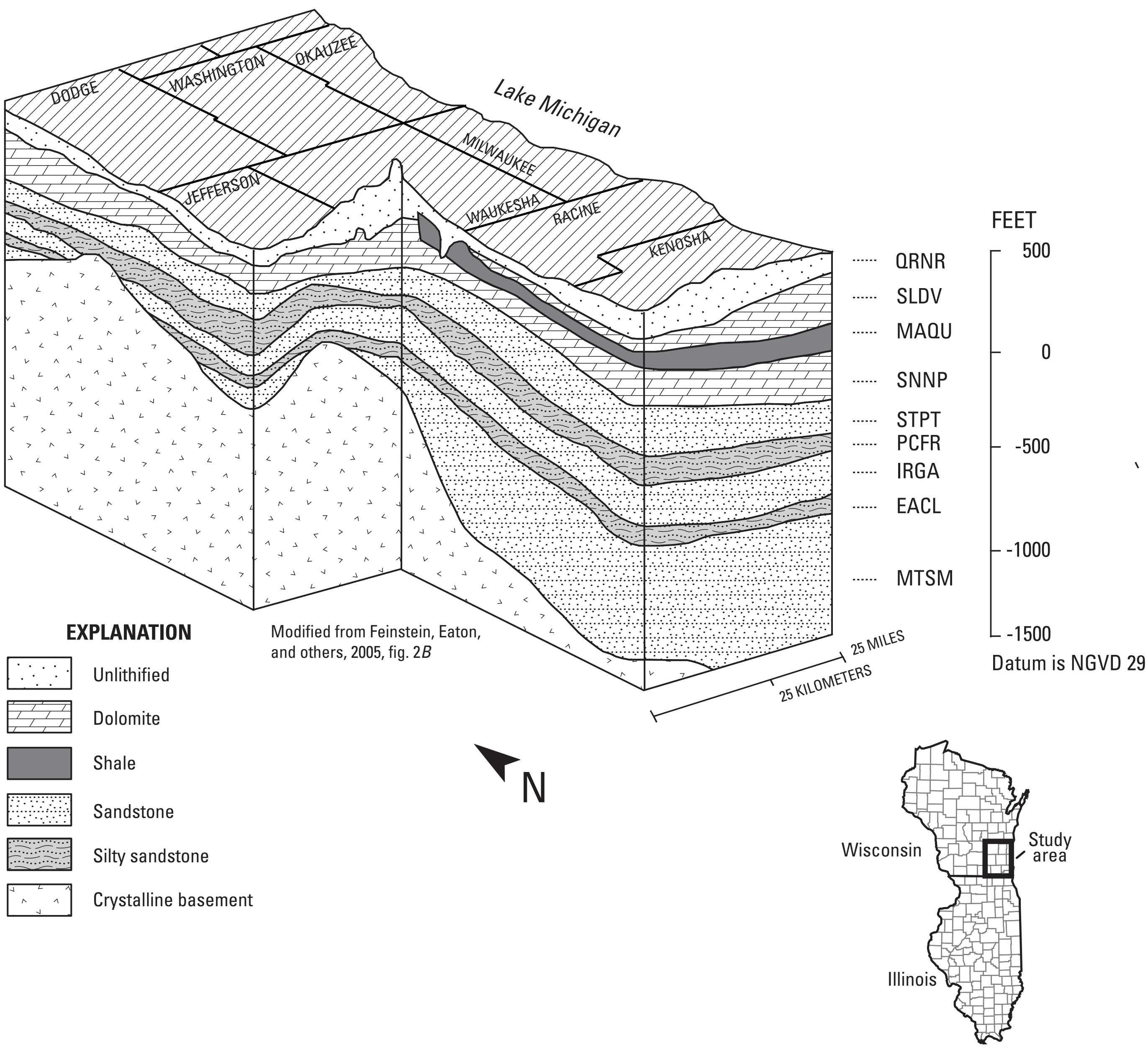


Figure 12. Schematic of hydrostratigraphy in southeastern Wisconsin, northeastern Wisconsin, and northeastern Illinois.

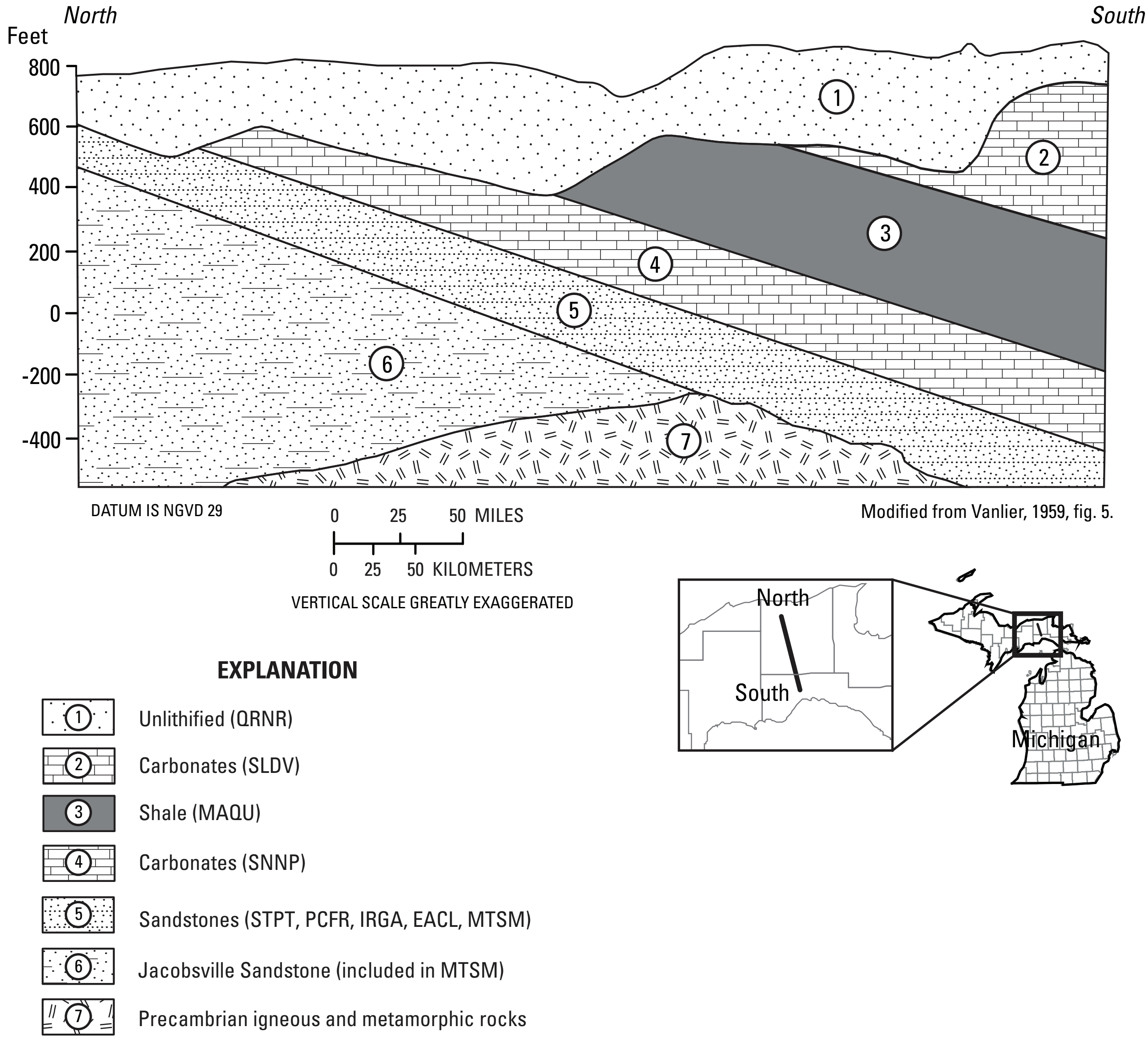


Figure 13. Schematic of hydrostratigraphy in the Upper Peninsula, Michigan.

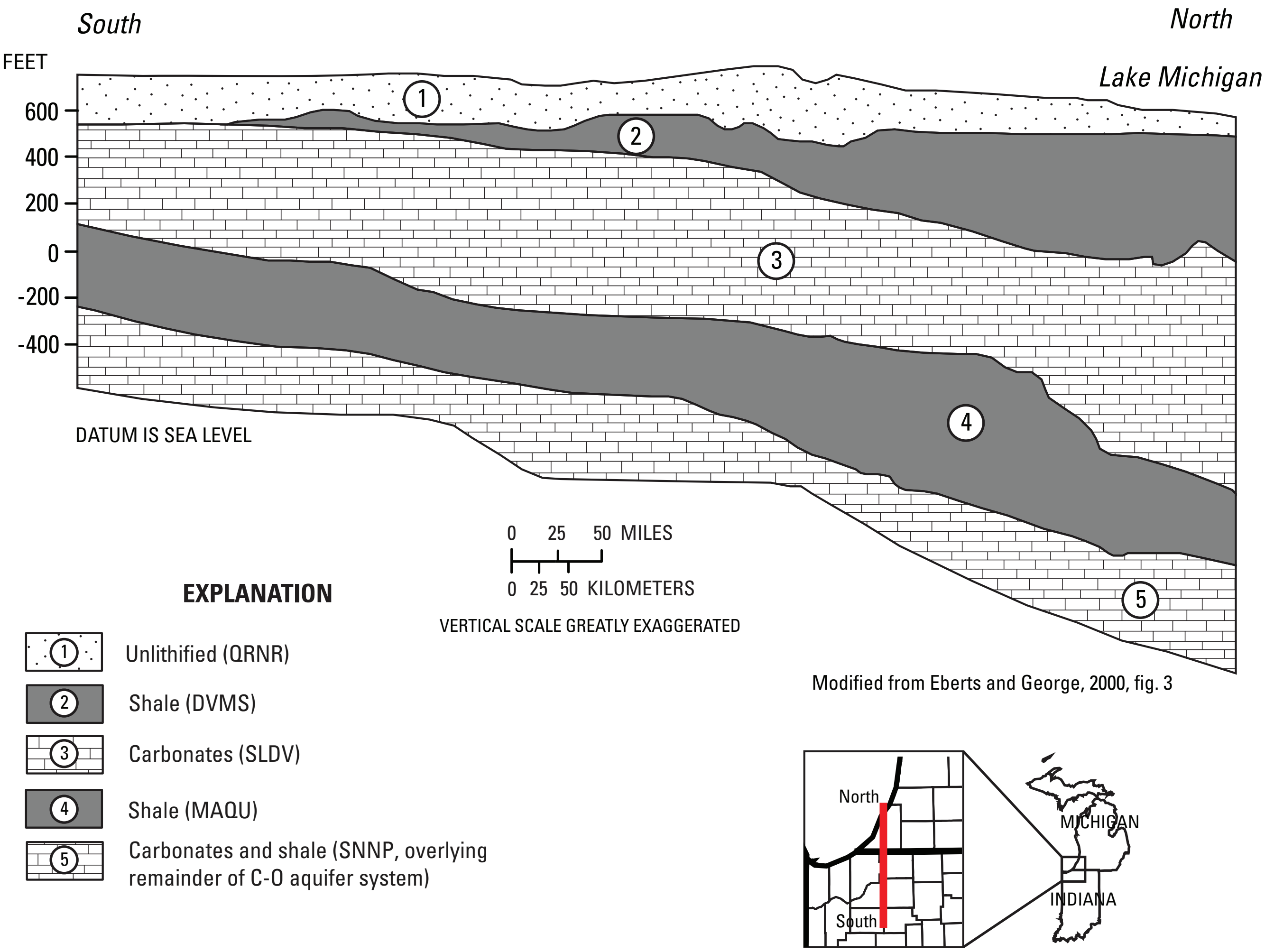


Figure 14. Schematic of hydrostratigraphy in northern Indiana.

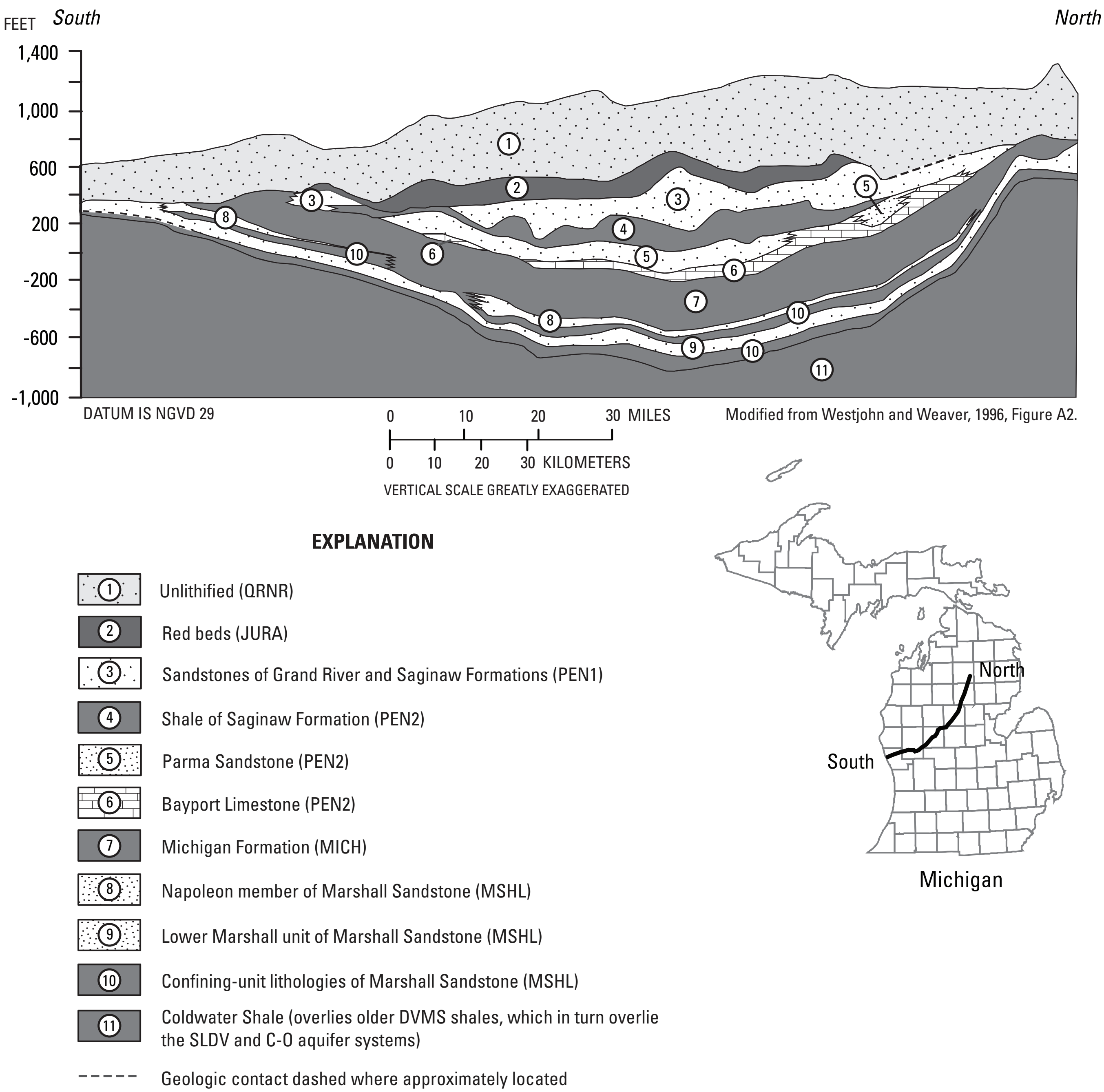


Figure 15. Schematic of hydrostratigrapy in the northern and southern Lower Peninsula, Michigan.

3.2 Regional Flow System

The regional flow system for the LMB model is largely controlled by Lake Michigan in its role as the central discharge location for both surface water and groundwater; it is secondarily controlled by the regional divides that bound the peripheral extent of the Lake Michigan groundwater basin (fig. 16). The regional groundwater divides do not necessarily coincide with the extent of the Lake Michigan drainage basin (that is, the boundaries of the topographic basin that encloses the surface water that ultimately discharges to Lake Michigan). The groundwater regional divides enclose the three-dimensional system of groundwater that discharges (1) directly to Lake Michigan, (2) indirectly to Lake Michigan via discharge to surface-water features tributary to the lake, or (3) to pumping wells inside the Lake Michigan drainage basin. The regional groundwater divides that defined the natural regional groundwater- flow system (that is, the divides that existed before the installation of pumping wells) have shifted over time as a result of pumping (Sheets and Simonson, 2006). For example, a large pumping center near a groundwater divide can move it from its original predevelopment location, enlarging the size of one groundwater basin at the expense of another, particularly if the wells are in confined aquifer systems (Sheets and others, 2005). The locations of groundwater divides vary with depth and do not, in general, correspond to vertical planes (fig. 16). The location of a divide between two groundwater basins near the water table can be very different from the location of the same divide at depth (Feinstein, Eaton, and others, 2005; Feinstein, Hart, and others, 2005; Sheets and Simonson, 2006; Bradbury and others, 2007).

One of the primary applications of the LMB model is to determine how regional divides at different depths within the Lake Michigan groundwater basin have moved through time. The Lake Michigan groundwater basin is surrounded by adjacent regional groundwater basins that are associated with surface-water drainage basins (shown in fig. 7*A*). They are

- the Mississippi River Basin to the west and south,
- the Lake Superior Basin to the north,
- the Lake Huron Basin to the northeast and east, and
- the Lake St. Clair and Lake Erie Basins to the east.

Regional groundwater divides separate the Lake Michigan groundwater basin from each of the neighboring lake systems to the west, north, and east (figs. 2 and 16). South of Lake Michigan, shallow and deep divides separate subsurface flow that discharges northward to surface-water features tributary to Lake Michigan from subsurface flow that discharges to the south toward the Illinois River Basin.

It is useful to distinguish *shallow* and *deep* groundwater flow within different parts of the Lake Michigan Basin. For this report, the shallow part of the subsurface flow system refers to the circulation of groundwater above the first major and relatively continuous bedrock confining unit, whereas the deep part of the flow system refers to everything below. Shallow groundwater flow is either unconfined (for example, where flow occurs in coarse-grained QRNR deposits or in bedrock overlain by coarse-grained QRNR deposits) or semiconfined (for example, flow in areas where fine-grained glacial deposits overlie a bedrock aquifer without an intervening bedrock confining unit). Deep groundwater flow is always within bedrock and always confined. Pumping wells and withdrawals can be described as shallow or deep depending on the open interval of the well and its relation to the uppermost bedrock confining unit.

The relative depth referred to by *shallow* and *deep* depends on the continuity of confining units over the area under consideration. West of Lake Michigan, the shallow flow system generally refers to the QRNR and SLDV aquifer systems overlying the Maquoketa confining unit. West of the subcrop of the Maquoketa confining unit, however, the shallow flow system extends deeper and includes the C-O aquifer system. This change in regime is illustrated in figure 17*A*, where shallow flow in the westernmost part of the Lake Michigan groundwater basin and in the Mississippi River groundwater basin farther to the west extends to deeper units than it does east of the Maquoketa confining unit subcrop. On the east side of the lake, shallow groundwater flow can refer to flow in the QRNR aquifer system only when it is underlain, for example, by Mississippi-Devonian shales; or it can refer, for example, to the combined thickness of the QRNR and PENN aquifer systems overlying the Michigan Formation. Under predevelopment prepumping conditions, the exchange of groundwater between the shallow and deep parts of the flow system is typically small (as illustrated in fig. 17*A*), but pumping from either shallow or deep wells can induce upward or downward leakage (as illustrated in fig. 17*B*). These vertical connections between the shallow and deep flow systems have important implications for water availability from the standpoints of quantity and of quality because they control the source areas that contribute water to deep wells. The LMB model was designed to compute estimates of the locations and rates of leakage between the shallow and deep parts of the flow system under both predevelopment and stressed conditions.

3.3 Sources and Sinks

The regional groundwater flow pattern is influenced by the location and strength of sources and sinks of water. Recharge to the water table is the most important source of water for the groundwater system in the Lake Michigan Basin and adjacent areas. The recharge rate varies spatially and depends on factors such as soil type, depth to water table, land slope, and vegetation. Surface-water features such as streams, lakes, and wetlands also can be sources for groundwater, especially in the vicinity of pumping wells. Finally, return by well injection or through leakage from surface impoundments is a potential source of water to the subsurface.

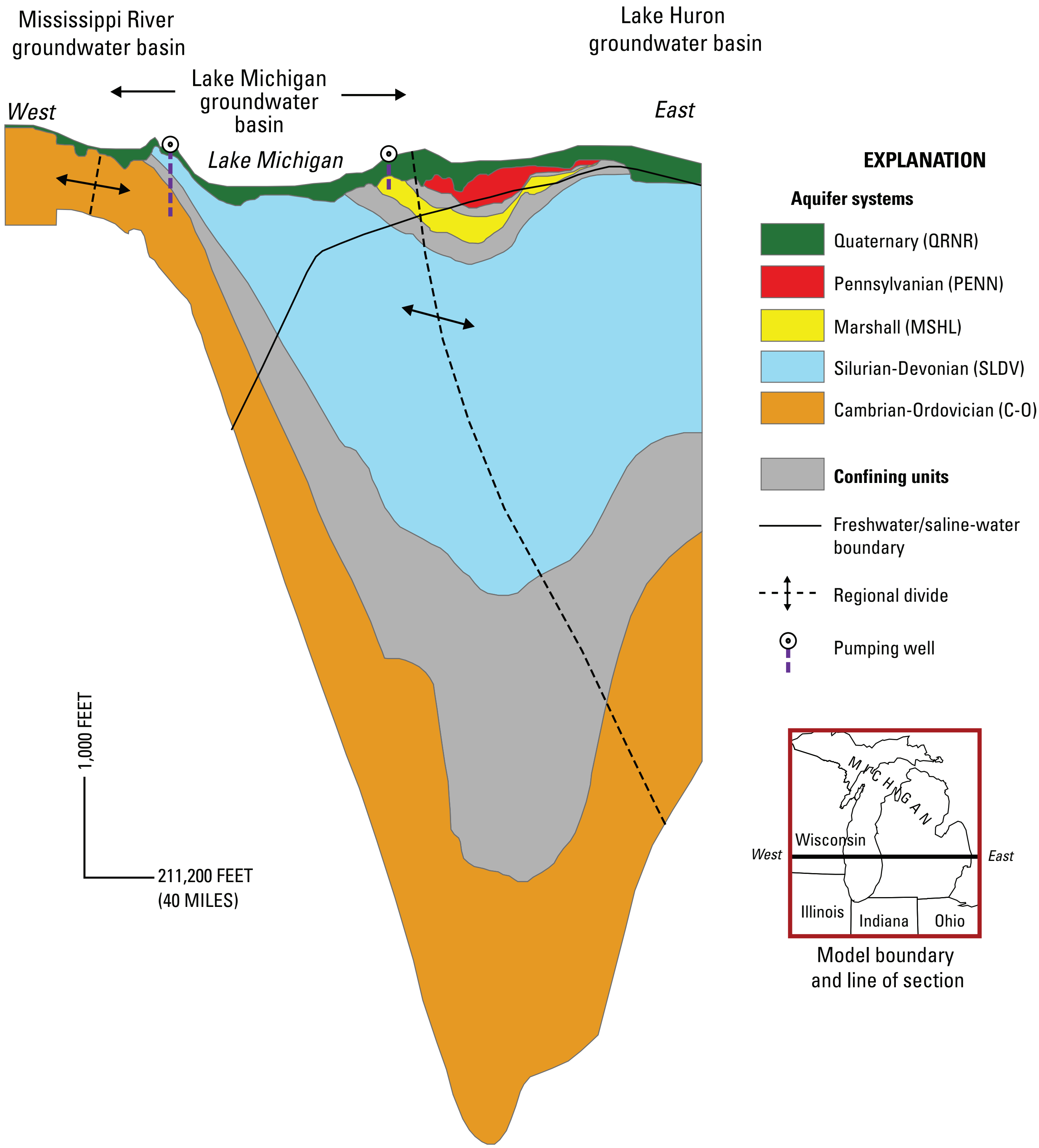


Figure 16. Schematic of flow system and aquifer systems. (Large vertical exaggeration is applied to the schematic section; the true geologic boundaries—without vertical exaggeration—are much more flat-lying than shown, and the aquifer-system thicknesses are small relative to their lateral dimensions.)

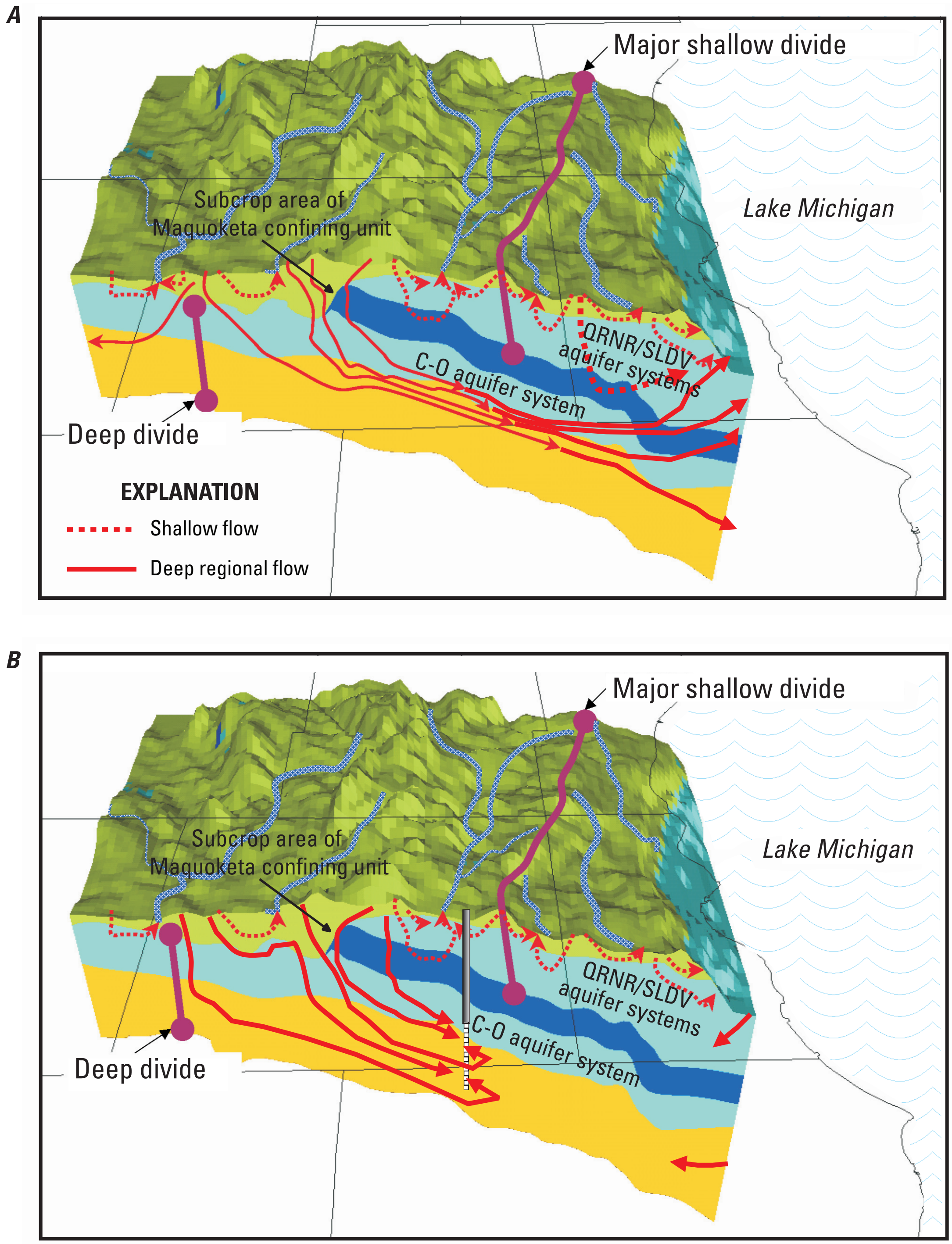


Figure 17. Block schematic of shallow and deep parts of flow system: *A*, Predevelopment. *B*, Postdevelopment. (Pumping wells in postdevelopment capture and reverse deep flow that discharged toward Lake Michigan under predevelopment conditions.)

Surface-water bodies and pumping wells usually act as sinks in areas where local or regional groundwater flow systems discharge. Most of the recharge that crosses the water table circulates as groundwater along shallow flow paths back to the surface, where it discharges as *base flow* to streams, lakes, seeps, springs, and wetlands. Shallow wells capture some groundwater that would otherwise discharge to surface-water bodies. Another portion of recharge moves as *leakage* to the deep part of the flow system, following relatively long flow paths that commonly end at regional discharge areas such as Lake Michigan or deep pumping wells. Although Lake Michigan generally serves as a regional sink for both shallow and deep groundwater, it can serve as a source of water for wells, especially near the shoreline.

Besides recharge, exchange with inland surface water and with Lake Michigan, discharge to pumping wells, and infiltration by injection or from impoundments, there are two other source/sink terms that contribute to a groundwater budget analysis for any study area within the model—underflow and storage. *Underflow* refers to the quantity of water that laterally enters or exits the area under consideration at a given time. For example, there is lateral flow into and out of the nearfield area of the LMB model, so the farfield acts as a source or sink with respect to the nearfield. Under pumping conditions, the direction and amount of underflow can change with time. Under both predevelopment and postdevelopment conditions, underflow can cross the vertical projection of topographic boundaries defining a drainage area like the Lake Michigan Basin. The resulting incongruity between groundwater and surface-water divides can be an important issue when estimating and assigning the availability of water resources to distinct geographic regions (be they drainage basins or political jurisdictions).

Changes in pumping from wells can cause regional changes in water levels related to release of water from *storage* (following drawdown) or increase in storage (following recovery). The change in storage reflects the amount of water-level change the drainage and elastic properties of the aquifer material and the unconfined or confined nature of the aquifer. One aim of the LMB model is to simulate the dynamics of groundwater storage in response to changes in recharge and pumping for distinct geographic areas, historical intervals, and aquifer systems.

The LMB model is designed to quantify the water budget associated with the groundwater sources and sinks described above. In some cases the budget components are inputs to the model (for example, spatially and temporally varying recharge rates, time-varying pumping rates); in other cases they are model results (for example, exchange with surface water, storage changes, underflow between basins). The spatial and temporal discretization of the model design can affect the rates of sources and sinks estimated by the model. For example, the simulated amount of storage release around pumping wells is conditioned by the time resolution over which well-withdrawal rates are held stepwise constant (see section 4 of this report, “Model Construction,” and section 8, “Model Limitations and Uncertainty”).

3.4 Groundwater/Surface-Water Interactions

Three types of surface-water features are represented in the LMB model—streams, inland water bodies, and the Great Lakes. Streams input to the model commonly include some first-order, most second-order, and all higher order reaches. (First-order reaches are equivalent to headwaters of streams without tributaries. Second-order reaches begin at the confluence of first-order tributaries. If two second-order reaches flow into each other, they form a third-order reach, and so on.) Inland water bodies include lakes and wetlands more than 20 acres in area (including the largest inland surface-water feature in the model domain, Lake Winnebago, shown in location map in fig. 2). All of Lake Michigan and parts of three other Great Lakes—Lake Superior, Lake Huron and Lake Erie (including Lake St. Clair, which connects the latter two)—are represented in the LMB model. Each set of surface-water features is simulated in the model by a distinct boundary condition (see section 4 of this report, “Model Construction”).

In the LMB model, groundwater discharge to Lake Michigan is estimated as

1. direct discharge through the lakebed, or
2. indirect discharge to streams and water bodies tributary to the lake.

Indirect discharge is computed by summing base flow from the model to inland water bodies and streams within the Lake Michigan drainage basin.

The spatial resolution of the model affects the simulated rate of leakage between groundwater and surface-water features. Cell areas in the LMB model are nearly 1 mi^2, so multiple surface-water features can be represented by a single cell. The greater the number of surface-water features represented in the model, the more the water-table solution is constrained by these boundary conditions (Feinstein and others, 2006). If all bodies are included in temperate and humid zones like the Lake Michigan Basin, then the water-table surface in many areas is effectively prescribed by boundary-condition inputs, which limits the model’s usefulness; for example, in simulating the response of the shallow groundwater system to pumping. If smaller bodies are omitted to reduce the constraints imposed by boundary conditions, then the model’s nonrepresentation of existing discharge zones can distort the value of other model inputs as the solution seeks to duplicate the observed water-table configuration without the proper distribution of actual sinks (see fig. 18). The tradeoff imposed on a regional model such as the LMB model must be explicitly defined and, where possible, evaluated in terms of the effect on model results (as discussed in section 8 of this report, “Model Limitations and Uncertainty”).

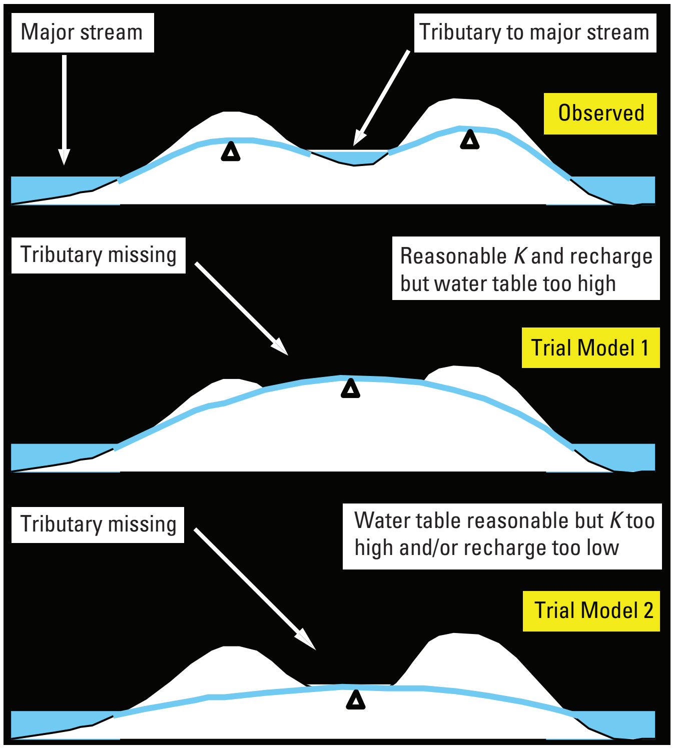


Figure 18. Effect of excluding low-order streams from model input.

3.5 Role of Salinity

A distinctive aspect of the Lake Michigan Basin hydrogeology is the presence of highly concentrated brines in most of the volume of sedimentary rocks dipping into Michigan Basin. Silurian evaporite deposits are the probable source for much of the saline water, although earlier deposits are present in Late Ordovician rocks. Substantial assemblages of halite, gypsum, anhydrite, sylvite, and other evaporite minerals are found in the Salina Group within the SLDV aquifer system, which was deposited during the greatest period of downwarping of the Michigan Basin. Intervals of rapid subsidence are marked by halite precipitation in the center of the basin and anhydrite precipitation toward the basin margins (Sonnenfeld and Al-Aasm, 1991). It is hypothesized that, during downwarping, the evaporite minerals originated from seawater that entered the Michigan Basin from the Kokomo Sea in what is now Indiana and from the Moose River Basin in what is now Lake Huron. The brines were formed in an area roughly circular in shape, and the deposited evaporite beds extend over a radial distance on the order of 100 mi beneath Indiana and Ohio, as well as Michigan.

Salinity associated with the evaporite beds yields DS concentrations greater than 500,000 mg/L in groundwater within the Salina Group (Sonnenfeld and Al-Aasm, 1991) and greater than 10,000 mg/L in several underlying and overlying units (Westjohn and Weaver, 1996a, b). Saline water extends into Cambrian-Ordovician rocks of northeastern Illinois (Visocky and others, 1985) and parts of the shoreline of Wisconsin (Ryling, 1961), suggesting that much of the groundwater in the Paleozoic rocks under Lake Michigan also is saline (see assumed freshwater/saline-water boundary in fig. 16).

Supply wells are completed in freshwater zones of the deep flow system, but the deep wells in Wisconsin and Illinois create drawdown that probably induces the westward flow of saline water under Lake Michigan toward the pumping centers (Young, 1992; Feinstein, Hart, and others, 2005). The extent to which salinity influences the propagation of water-level drawdown is unknown and the LMB model is used to investigate this issue. SEAWAT-2000 (Langevin and others, 2003), which incorporates the effects of density in the equation of groundwater flow, was used to simulate the effects of salinity on deep flow in the LMB model domain. Although not all the mechanisms associated with brine flow in a deep structural basin can be accommodated in this modeling effort (see section 8, "Model Limitations and Uncertainty"), an attempt was made to take account of the effect of variable density on hydraulic conductivity and gradients within and along the fringes of the Michigan Basin.

The central focus of the modeling effort is to simulate groundwater conditions in the freshwater areas that are important for considerations of water availability. Given this focus, it is appropriate to conceptualize the freshwater/saline-water interface as a kind of model boundary condition that can serve as either a source or a sink of saline water in response to pumping centers on both sides of Lake Michigan. The implementation of this boundary is discussed in report section 4; the effect of the boundary is evaluated in section 7, which compares results of variable-density and uniform-density flow simulations.

3.6 Confined and Unconfined Conditions

The transmissivity of a confined aquifer is independent of the water level (head), whereas that of an unconfined aquifer is a function of the *saturated thickness* of the aquifer, equal to the height of the water-table elevation above the bottom of the aquifer. Storage release in a confined aquifer due to a decline in water levels, which is associated with the elastic compression and expansion of the water and the rock matrix (proportional to the aquifer storage coefficient), is much less than storage release for an equivalent decline in an unconfined aquifer, which is associated with the drainable porosity of the aquifer material (proportional to the aquifer specific yield). Aquifers undergoing water-level decline caused by pumping can transition from confined to unconfined conditions. More than one water table can exist at a single location when unconfined conditions occur not only near the land surface but also in deep aquifers that are partly dewatered owing, for example, to the transient effects of deep pumping.

In general, the more accurate approach is to simulate a shallow flow system as an unconfined aquifer with transmissivity related to the saturated thickness and storage defined by the specific yield; however, treating the entire flow system as a confined aquifer in the LMB model produced a more stable numerical solution, especially during the calibration process. For this reason, multiple models were developed in this study to simulate cells in the flow system as (1) always confined (the "base" model) or (2) either confined or unconfined depending on the position of the water table (an "alternative" model). The properties of the confined-aquifer model were adjusted to account for the effect of saturated thickness on aquifer transmissivity and storage—see section 4 of this report. Model results are reported for the confined-aquifer model in section 6; the unconfined-aquifer model is described and its results compared to the confined-aquifer model in section 7.

4. Model Construction

The LMB model is discretized spatially by use of a finite-difference grid and temporally by use of time periods of constant pumping and recharge (stress). Boundary conditions (specified heads and flows) are specified in the model farfield and control the movement of water into and out of the model nearfield. Head-dependent boundary conditions representing inland surface water and Lake Michigan are specified within the model nearfield. A spatially and temporally variable top model boundary represents the rate of recharge. Finally, the location, depths and withdrawal rates of pumping wells from 1864 through 2005 are also represented as internal model boundaries.

Simulated water levels and flows between adjacent model cells are computed by using assumed subsurface properties of the QRNR and underlying bedrock aquifer systems; for example, the horizontal hydraulic conductivity (K_h) and vertical hydraulic conductivity (K_v) in the unconsolidated QRNR sediments and the bottom sediments of Lake Michigan, as well as by the zones of K_h and K_v assigned to the underlying bedrock sediments. Transmissivities of the aquifer systems represented in the LMB model are computed from the thicknesses and K_h values specified for each system. The response of the system to changing stresses is a function of not only the hydraulic conductivity (K) and thickness distribution but also the assumed storage properties of the sediments. Finally, the LMB model solution in particular depends on the treatment of the variable-density conditions associated with the brines emanating from ancient sediments in the Michigan Basin. All these model elements are discussed in this section.

4.1 Model Grid

The finite-difference grid is composed of rows and columns and a vertical stack of layers. The rows and columns define cells of rectangular or square lateral dimensions. The grid contains 391 rows oriented west to east and 261 columns oriented north to south. The dimensions of both rows and columns form rectangles in the nonuniform outer part of the grid (comprising the farfield and parts of the nearfield mostly outside of the Lake Michigan Basin) and from squares 5,000 ft on a side in the uniform inner part of the grid (comprising most of the model nearfield) (fig. 19). The uniform square cells cover a rectangular area centered on Lake Michigan that extends from row 10 to row 381 and from column 12 to column 248—equivalent to a rectangle 352.3 mi in the north-south directions along rows and 224.4 mi in the west-east direction along columns, summing to an area of about 79,060 mi^2, and incorporating 88,164 cells per layer out of the model total of 102,051 cells per layer. This inner-mesh area is completely inside the model nearfield, but the nearfield extends beyond it to include some rectangular cells that are inside the Lake Michigan drainage basin (fig. 19).

Outer-mesh rows and columns increase by a factor of 1.3 so that grid cells increase in size from 5,000 ft on a side at each edge of the inner mesh to a maximum size of about 10 mi at the northern edge of the mesh, about 13 mi at the southern edge, about 17 mi at the western edge, and about 22 mi on the eastern edge. The large lateral dimensions of the outer-mesh cells do not compromise the integrity of the finite-difference calculations because the 1.3 enlargement factor has little negative effect on the truncation of the Taylor expansions used in the numerical solution methods of the MODFLOW-2000 /SEAWAT-2000 codes (Anderson and Woessner, 1992). Because the outer-mesh cells are more than 10 mi on a side near the northwest, northeast, southwest and southeast corners of the model domain, simulated heads and flows are approximate in these areas. Simulated heads and flows are more accurate in the model nearfield, where cells sizes approach 1 mi^2.

The model nearfield (composed of all the uniform and some of the nonuniform cells) contains 88,687 cells per layer, including all the Lake Michigan cells. It incorporates an area of 83,263.5 mi^2 that amounts to 46 percent percent of the model domain. The Lake Michigan Basin (including all of Lake Michigan and its drainage area) covers about 37 percent of the total grid area but 80 percent of the nearfield. Lake Michigan itself covers 12 percent of the total grid area and sums to 27 percent of the nearfield.

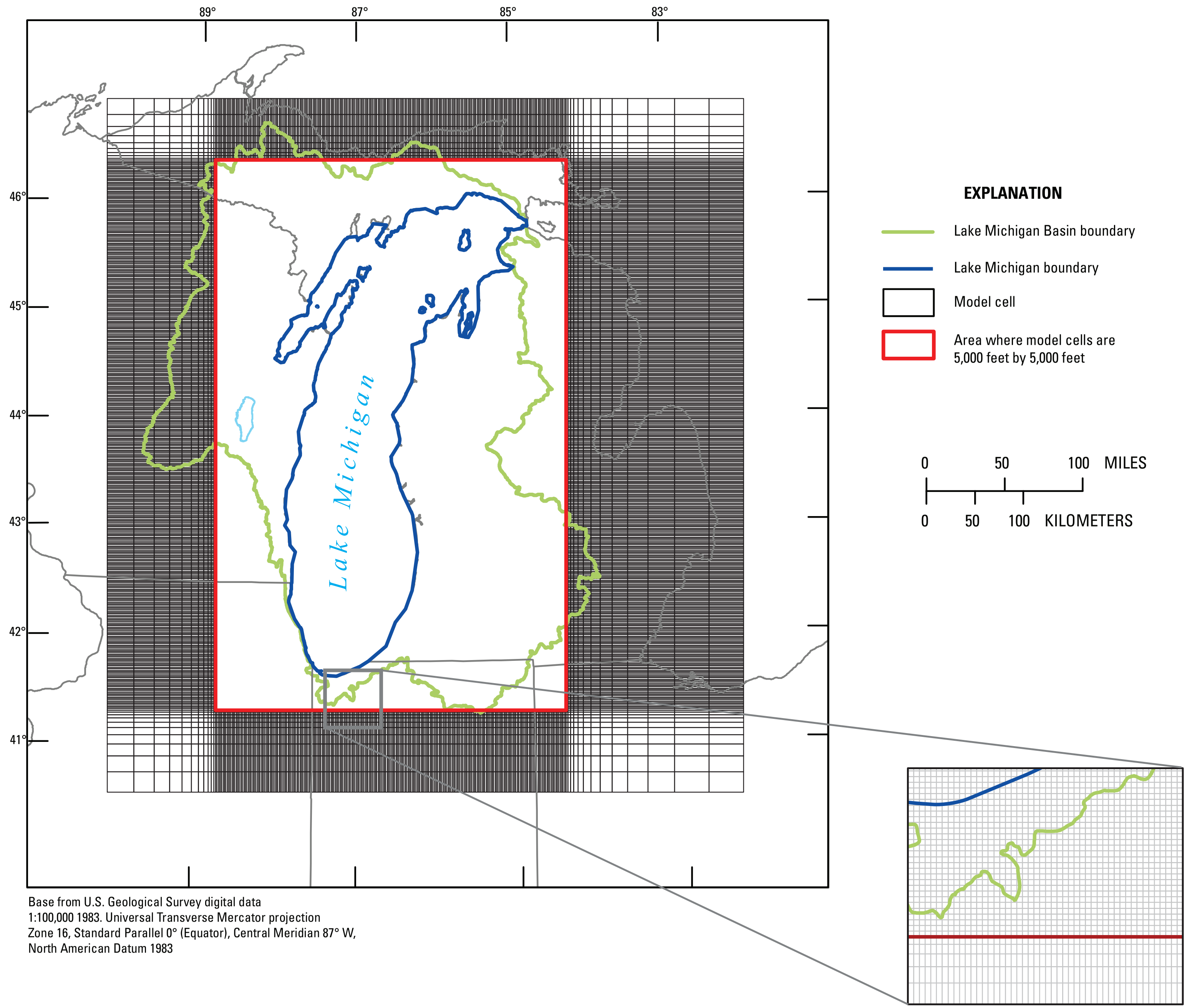


Figure 19. Model grid. (Inset shows example area of transition in northern Indiana from nonuniform grid cells (greater than 5,000 feet on a side) to uniform grid cells (equal to 5,000 feet on a side).)

4.2 Model Layering

The LMB model is a three-dimensional representation of the unconsolidated and sedimentary deposits extending from the water table to the Precambrian bedrock. The model is fully three-dimensional because the entire thickness is incorporated (there are no gaps) and that it includes not only aquifers but also confining units.

The 20 layers in the LMB model are defined in terms of hydrogeologic units. The numbering of layers is from top to bottom. Three hydrogeologic units—the Quaternary, the Silurian-Devonian, and the Mount Simon, are represented by multiple layers, whereas all remaining aquifers and all confining units are represented by a single layer (table 3). The thickness of each layer is variable and computed from elevation surfaces contained in the three-dimensional stratigraphic database prepared to support the LMB model (Lampe, 2009). Where a hydrogeologic unit is missing (that is, "pinched" between overlying and underlying units with thickness), then it is assigned a nominal thickness of 0.2 ft.[7] The top and bottom of each hydrogeologic unit at a particular row and column location is interpolated from well-log data and contour maps from each of the states covered by the model. The stratigraphic-database report (Lampe, 2009) contains isopach (thickness) maps for all 15 hydrogeologic units incorporated in the LMB model. Thicknesses of units under Lake Michigan were interpolated linearly from stratigraphic data available along the shoreline. However, recent mapping of units in the Michigan Basin was used to configure the thickness of the Devonian-Mississippian confining unit beneath the lake (Lampe, 2009). Unconsolidated material under the lake (lakebed) consists of glacial deposits mantled by recent (Holocene) deposits from the lake itself. Data compiled by Soller (1998) were used to estimate the thickness of unconsolidated sediments beneath the southern half of Lake Michigan (south of a line from Manitowoc, Wis., to Ludington, Mich.; see fig. 2) A shaded relief map (Colgan and Principato, 1998) and a discussion of the geomorphology of the lakebed (National Oceanic and Atmospheric Administration, 2005) were used to estimate the thickness of the unconsolidated sediments beneath the northern half of Lake Michigan. The median interpolated thickness of the lakebed is 55 ft; the thickness ranges from 8 to 278 ft under 90 percent of the lake; the maximum thickness is 456 ft along a ridge near the center of the water body.

A large proportion of groundwater flow circulates within the unconsolidated deposits, so three model layers are assigned to the QRNR system, rather than just one, to more accurately represent the geology and vertical flow field. Three layers are also assigned to the SLDV system to represent a 50-ft weathered zone at the top surface in thinner parts of the system along the Wisconsin and Kankakee Arches (Meyer and others, 2009) and to account for evaporite deposits in the middle part of the system in the Michigan Basin. The MTSM, which is more than 1,000 ft thick at certain pumping centers west of Lake Michigan, is divided into two layers to allow for a more accurate representation of the drawdown around C-O wells that penetrate as deep as the MTSM but extend only several hundred feet into the unit.

The QRNR, SLDV, and MTSM hydrogeologic units are each assigned multiple layers, but the total thickness of the unit at a given cell location is represented by only the top layer *unless* a threshold thickness value is reached, in which case the excess thickness is assigned to a second layer until (in the case of the QRNR and SLDV units) a second threshold is reached, in which case the additional thickness is assigned to a third layer. If the threshold thickness is not reached at a location, then the cell(s) in the "excess" layer(s) for the unit are assigned a nominal pinched thickness of 0.2 ft. The exact logic and thresholds for dividing the QRNR, SLDV, and MTSM units into multiple layers are presented in table 3. The vertical distribution of the lakebed thickness across model layers generally follows the same logic as the QRNR.

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[7] Pinched layers ordinarily participate in the model simulation; but because they are so thin and because they are assigned the same properties (hydraulic conductivity and storage parameters) as the first unpinched overlying layer, they have negligible effect on the model solution. Numerical experiments were conducted on larger to smaller pinched thicknesses to confirm that the high horizontal to vertical aspect ratios implied by a 0.2 ft pinched thickness in cells do not cause the solution to deteriorate. By using a very small pinched thickness, very little excess thickness is added to the model even in areas where layers are almost missing (for example, toward the northwest of the model domain where QRNR—layer 1—commonly overlies MTSM—layer 19). Infrequently, bedrock layers are at the surface of the model. In such cases, any overlying layers (QRNR plus any missing bedrock) are *inactive* as well as pinched; the layer properties are irrelevant because they do not participate in the model solution.

Table 3. Model layering.

3*A*. Correlation between model layers and hydrogeologic units and aquifer systems.

[For correlation between model layers, hydrogeologic units, aquifer systems, and lithostratigraphic units, see fig. 10]

Layer	Abbreviation	Hydrogeologic unit	Aquifer system	System abbreviation
Layer 1	QRNR-upper	Quaternary aquifer/confining unit	Quaternary	QRNR
Layer 2	QRNR-middle	Quaternary aquifer/confining unit	Quaternary	QRNR
Layer 3	QRNR-lower	Quaternary aquifer/confining unit	Quaternary	QRNR
Layer 4	JURA	Jurassic confining unit	Pennsylvanian	PENN
Layer 5	PEN1	Upper Pennsylvanian aquifer	Pennsylvanian	PENN
Layer 6	PEN2	Lower Pennsylvanian aquifer/confining unit	Pennsylvanian	PENN
Layer 7	MICH	Michigan Formation confining unit	Marshall	MSHL
Layer 8	MSHL	Marshall Sandstone aquifer	Marshall	MSHL
Layer 9	DVMS	Devonian-Mississippian confining unit	Silurian-Devonian	SLDV
Layer 10	SLDV-upper	Silurian-Devonian aquifer	Silurian-Devonian	SLDV
Layer 11	SLDV-middle	Silurian-Devonian aquifer/confining unit	Silurian-Devonian	SLDV
Layer 12	SLDV-lower	Silurian-Devonian aquifer/confining unit	Silurian-Devonian	SLDV
Layer 13	MAQU	Maquoketa confining unit	Cambrian-Ordovician	C-O
Layer 14	SNNP	Sinnipee aquifer/confining unit	Cambrian-Ordovician	C-O
Layer 15	STPT	St. Peter sandstone aquifer	Cambrian-Ordovician	C-O
Layer 16	PCFR	Prairie du Chien-Franconia aquifer/ confining unit	Cambrian-Ordovician	C-O
Layer 17	IRGA	Ironton-Galesville aquifer	Cambrian-Ordovician	C-O
Layer 18	EACL	Eau Claire aquifer/confining unit	Cambrian-Ordovician	C-O
Layer 19	MTSM-upper	Mount Simon aquifer	Cambrian-Ordovician	C-O
Layer 20	MTSM-lower	Mount Simon aquifer/confining unit	Cambrian-Ordovician	C-O

Table 3. Model layering.—Continued

3*B*. Layering logic for QRNR, SLDV, and MTSM layers.

QRNR
Layer 1 extends from land surface to maximum depth of 100 feet. *If* QRNR is greater than 100 feet thick, then layer 2 extends from 100 feet depth to maximum depth of 300 feet; otherwise, layer 2 is pinched. *If* QRNR is greater than 300 feet thick, then layer 3 extends from 300 feet depth to top of bedrock; otherwise, layer 3 is pinched.
SLDV
If the total thickness of the SLDV is less than or equal to 550 feet, then layer 10 extends from top of SLDV to 50 feet below top of SLDV. *If* SLDV is greater than 50 feet thick and less than 550 feet thick, then layer 11 extends from 50 feet below top of SLDV to bottom of SLDV; if SLDV is less than 50 feet thick, layers 11 and 12 are pinched. Layer 12 is pinched. *If* total thickness of SLDV is greater than 550 feet, then Layer 10 is upper part of SLDV; its thickness is equal to 50 feet plus total thickness of SLDV less 550 feet, the difference divided by 3. Layer 11 is middle part of SLDV; its thickness is equal to 250 feet plus total thickness of SLDV less 550 feet, the difference divided by 3. Layer 12 is lower part of SLDV; its thickness is equal to 250 feet plus total thickness of SLDV less 550 feet, the difference divided by 3. For example: Suppose the total thickness of the SLDV is equal to 300 feet; then Layer 10 is 50 feet thick. Layer 11 is 250 feet thick. Layer 12 is pinched. Suppose the total thickness of the SLDV is equal to 610 feet; then Layer 10 is 70 feet thick. Layer 11 is 270 feet thick. Layer 12 is 270 feet thick. Suppose the total thickness of the SLDV is equal to 1,450 feet; then Layer 10 is 350 feet thick. Layer 11 is 550 thick. Layer 12 is 550 thick.
MTSM
Layer 19 extends from top of Mount Simon to maximum depth of 300 feet below top of Mount Simon. *If* MTSM is greater than 300 feet thick, then layer 20 extends from 300 feet below top of Mount Simon to the model basement; otherwise, layer 20 is pinched.