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Simulation of the Regional Ground-Water-Flow System and Ground-Water/Surface-Water Interaction in the Rock River Basin, Wisconsin

Scientific Investigations Report 2009–5094

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph of the Rock River. (Photograph taken by Suzanne Wade, Rock River Coalition, Jefferson, Wisconsin.)

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KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

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Contents

Figures

Tables

Conversion Factors and Datums

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
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)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per year (Mgal/yr)	3,745	cubic meter per year (m^3/yr)
inch per hour (in/h)	25.4	millimeter per hour (mm/h)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity*	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity**	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Horizontal flux	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

*Hydraulic conductivity: The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area ($ft^3/d/ft^2$). In this report, the mathematically reduced form, foot per day (ft/d), is used for convenience.

**Transmissivity: 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.

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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Simulation of the Regional Ground-Water-Flow System and Ground-Water/Surface-Water Interaction in the Rock River Basin, Wisconsin

By Paul F. Juckem

Abstract

A regional, two-dimensional, areal ground-water-flow model was developed to simulate the ground-water-flow system and ground-water/surface-water interaction in the Rock River Basin. The model was developed by the U.S. Geological Survey (USGS), in cooperation with the Rock River Coalition. The objectives of the regional model were to improve understanding of the ground-water-flow system and to develop a tool suitable for evaluating the effects of potential regional water-management programs. The computer code GFLOW was used because of the ease with which the model can simulate ground-water/surface-water interactions, provide a framework for simulating regional ground-water-flow systems, and be refined in a stepwise fashion to incorporate new data and simulate ground-water-flow patterns at multiple scales.

The ground-water-flow model described in this report simulates the major hydrogeologic features of the modeled area, including bedrock and surficial aquifers, ground-water/surface-water interactions, and ground-water withdrawals from high-capacity wells. The steady-state model treats the ground-water-flow system as a single layer with hydraulic conductivity and base elevation zones that reflect the distribution of lithologic groups above the Precambrian bedrock and a regionally significant confining unit, the Maquoketa Formation. In the eastern part of the Basin where the shale-rich Maquoketa Formation is present, deep ground-water flow in the sandstone aquifer below the Maquoketa Formation was not simulated directly, but flow into this aquifer was incorporated into the GFLOW model from previous work in southeastern Wisconsin. Recharge was constrained primarily by stream base-flow estimates and was applied uniformly within zones guided by regional infiltration estimates for soils. The model includes average ground-water withdrawals from 1997 to 2006 for municipal wells and from 1997 to 2005 for high-capacity irrigation, industrial, and commercial wells. In addition, the model routes tributary base flow through the river network to the Rock River. The parameter-estimation code PEST was linked to the GFLOW model to select the combination of parameter values best able to match more than 8,000 water-level measurements and base-flow estimates at 9 streamgages.

Results from the calibrated GFLOW model show simulated (1) ground-water-flow directions, (2) ground-water/surface-water interactions, as depicted in a map of gaining and losing river and lake sections, (3) ground-water contributing areas for selected tributary rivers, and (4) areas of relatively local ground water captured by rivers. Ground-water flow patterns are controlled primarily by river geometries, with most river sections gaining water from the ground-water-flow system; losing sections are most common on the downgradient shore of lakes and reservoirs or near major pumping centers. Ground-water contributing areas to tributary rivers generally coincide with surface watersheds; however the locations of ground-water divides are controlled by the water table, whereas surface-water divides are controlled by surface topography. Finally, areas of relatively local ground water captured by rivers generally extend upgradient from rivers but are modified by the regional flow pattern, such that these areas tend to shift toward regional ground-water divides for relatively small rivers.

It is important to recognize the limitations of this regional-scale model. Heterogeneities in subsurface properties and in recharge rates are considered only at a very broad scale (miles to tens of miles). No account is taken of vertical variations in properties or pumping rates, and no provision is made to account for stacked ground-water-flow systems that have different flow patterns at different depths. Small-scale flow systems (hundreds to thousands of feet) associated with minor water bodies are not considered; as a result, the model is not currently designed for simulating site-specific problems. Despite its limitations, the model serves as a framework for understanding the regional pattern of ground-water flow and as a starting point for a generation of more targeted and detailed ground-water models that would be needed to address emerging water-supply and water-quality concerns in the Rock River Basin.

Introduction

The Rock River and its tributaries drain a geologically complex landscape containing numerous rivers, lakes, and wetlands (fig. 1) in a predominantly agricultural area of southeastern Wisconsin (fig. 2). Water quality of the Rock River is a concern for Federal, State, county, and local resource managers, particularly in regard to high concentrations of nutrients (nitrate and phosphate) in ground water and surface water. At least one study (Earth Tech, 2000) was done to explain phosphorous loading in surface waters in the Rock River Basin; however, the hydrologic model used for that study did not account for ground-water flow through aquifers, and therefore the model was not able to evaluate ground-water levels, ground-water-flow patterns or ground-water/surface-water interaction along stream reaches. Several countywide ground water investigations have been completed in the Rock River Basin, but a comprehensive ground-water-flow study of the basin has been lacking. Prior to the study described in this report, little was known about ground-water-flow patterns or ground-water/surface-water interactions in the basin.

The study described in this report was conducted by the U.S. Geological Survey (USGS), in cooperation with the Rock River Coalition. The primary objectives of the study were to improve understanding of the hydrogeology of the Rock River Basin, evaluate ground-water/surface-water interaction and base-flow contribution to the Rock River and its tributaries, and estimate patterns of ground-water flow. These objectives were achieved by developing a regional framework model, using the numerical computer code GFLOW, to simulate the ground-water-flow system of the basin. This framework model describes the regional characteristics of the ground-water-flow system without including the hydrogeologic detail or data density that would be necessary for answering site-specific questions. A calibrated framework model can be used with confidence to simulate a regional ground-water-flow system but with less confidence to simulate local-scale flow. A framework model is a tool that can be used to improve the overall understanding of the hydrology of a region by testing alternative conceptual models of the ground-water-flow system. Additionally, a framework model can be used to highlight areas where more hydrogeologic or water-quality data are needed. Finally, a framework model serves as a foundation from which local or site-specific models can be developed through refinement; having such as foundation benefits local-scale modeling efforts by reducing model construction time, reducing data-collection and interpretation efforts, and furnishing a simulated connection to the regional flow system.

A regional framework model integrates the most important components of the shallow and deep parts of the ground-water-flow system. In the Rock River Basin, the ground-water and surface-water systems are believed to be hydraulically well connected and, as a result, the ground-water-flow model is constructed to include many aspects of the surface-water network. The simulation of ground-water flow and its interaction with the surface-water network is a necessary foundation for understanding and protecting the basin's water resources. By improving the understanding of the hydrology of the Rock River Basin, this study provides a basis for interpreting previously collected water-quality data and managing water resources for the future. Another benefit of the study is that the sources and amount of base-flow contribution to the Rock River from its tributaries are more systematically described.

The hydrogeologic foundation that underlies the model of the Rock River Basin draws from previous geologic and hydrologic studies. The bedrock geology of the basin is described in a regional study by Young (1992) and is mapped by Mudrey and others (1982), with a digital representation by Cannon and others (1997). Other reports present descriptions of the soil and unconsolidated deposits of the area (Schwarz and Alexander, 1995; Soller and Packard, 1998) and of individual counties (Clayton and Attig, 1997; Mickelson and Syverson, 1997; Clayton, 2001). The general hydrology of the basin is described in a USGS Hydrologic Investigations Atlas (Cotter and others, 1969) and a Geologic Society of America field trip guide book (Holt and others, 1970). Additional hydrogeologic detail can be found in county geology and ground-water-resources reports and water-table maps for 9 of the 10 counties in the basin: Columbia County (Harr and others, 1978), Dane County (Cline, 1965; Bradbury and others, 1995; Bradbury and others, 1999), Dodge County (Devaul and others, 1983), Fond du Lac County (Newport, 1962; Batten, 2004), Jefferson County (Borman and Trotta, 1976), Rock County (LeRoux, 1963), Walworth County (Borman, 1976; Evans, 2004a), Washington County (Young and Batten, 1980; Evans, 2004c), and Waukesha County (Gonthier, 1975; Evans, 2004b). A few county- and regional-scale ground-water-flow models cover parts of the basin, including Dane County (Krohelski and others, 2000), Rock County (Gaffield and others, 2002), and the seven counties of the Southeastern Wisconsin Regional Planning Commission (Feinstein and others, 2005b).

Figure 1. Location of the Rock River Basin in Wisconsin.

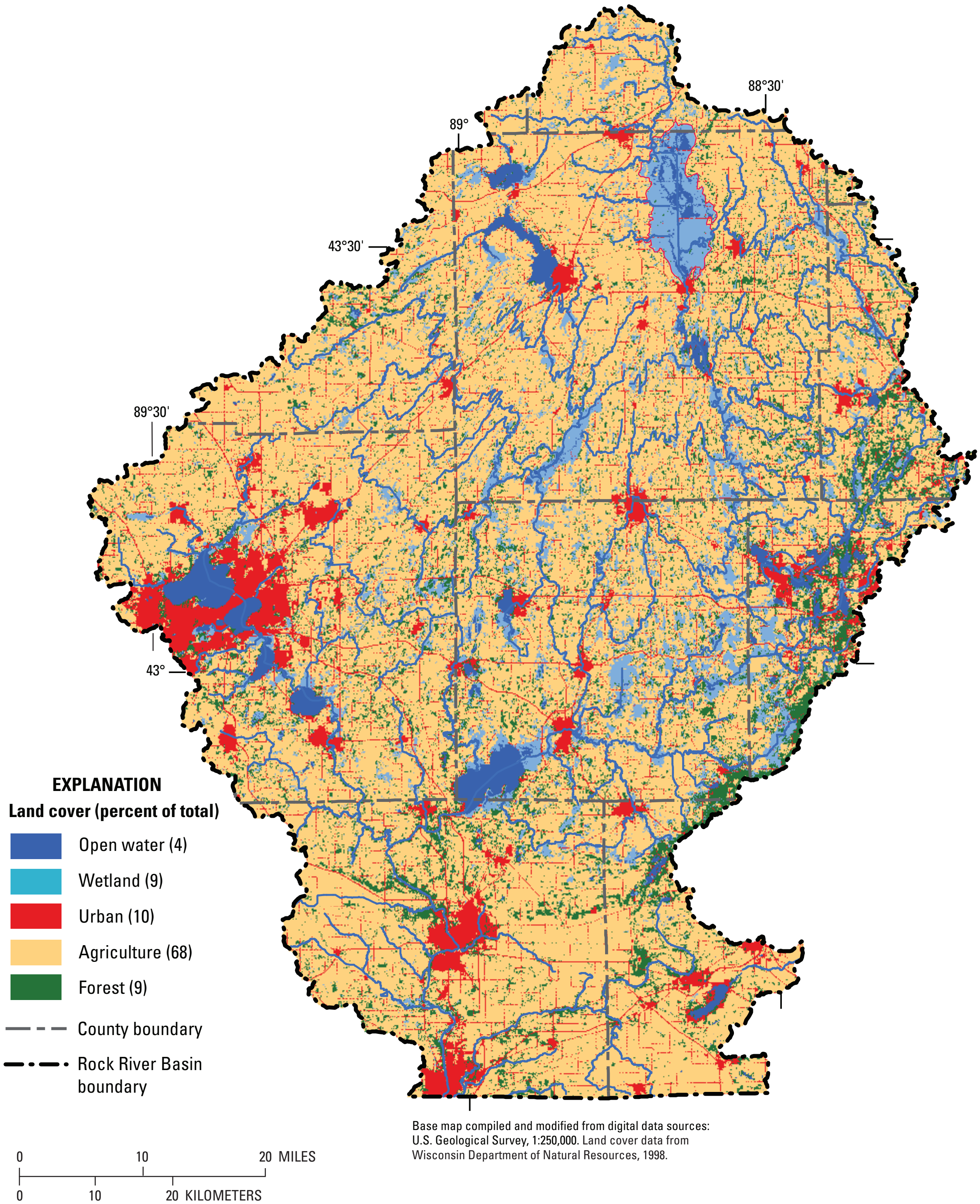

Figure 2. Land cover in the Rock River Basin.

Purpose and Scope

The purpose of this report is to describe the hydrogeology of the Rock River Basin and to describe the development and applications of a computer model that simulates regional ground-water flow in the basin. Geologic and hydrologic data used during this study consisted of interpretive maps, previously published reports, and historical streamflow and water-level measurements. The report includes a summary of selected hydrogeologic data, conceptualization of the hydrogeologic setting of the basin, and details on the construction and calibration of a one-layer, steady-state, analytic element model that simulates ground-water flow and its interaction with surface-water features at a coarse, regional scale. On the basis of model simulations, maps are presented that illustrate (1) ground-water-flow directions, (2) gaining and losing river reaches, (3) areas contributing ground-water recharge to selected tributaries, and (4) areas of relatively local ground water captured by rivers.

Physical Setting

The Rock River Basin covers approximately 3,700 mi^2 and includes major hydrologic features such as the Yahara, Crawfish, and Bark Rivers, as well as the Horicon Marsh. The Rock River (fig. 1) originates north of the Horicon Marsh near the town of Brandon in Fond du Lac County and flows south approximately 140 mi through Wisconsin to the Illinois border at Beloit, Wis. The river continues to flow south and west through Illinois before entering the Mississippi River near Moline, Ill. The basin north of Beloit, Wis., receives about 34 in. of precipitation annually, with temperatures that typically range from lows around 10ºF in the winter to highs around 85ºF in the summer (Natural Resources Conservation Service, 2002). Land cover in the basin is dominated by agriculture, but it also includes local areas of predominantly urban, wetland, forest, and open-water (fig. 2; Wisconsin Department of Natural Resources, 1998). Table 1 summarizes land cover and demographic information for the basin and selected tributary watersheds.

The Rock River Basin is part of the Eastern Ridges and Lowlands physiographic region of Wis. (Martin, 1965), and is covered by a mixture of glacial sediments that overlie layers of east-sloping sedimentary bedrock. Impermeable, Precambrian crystalline bedrock (for example, granite or quartzite) underlies the entire basin at depth. The surface of this crystalline bedrock is spatially variable and becomes deeper to the south toward the Illinois Basin and to the east toward the Michigan Basin. Above the crystalline rock are many layers of sedimentary bedrock (sandstone, shale and dolomite) of Cambrian age (Jordan, St. Lawrence, Lone Rock, Wonewoc, Eau Claire, and Mount Simon Formations), Ordovician age (Maquoketa, Galena, Platteville, Glenwood, St. Peter, Shakopee, and Oneota Formations), Silurian age, and Devonian age. Sediment carried by glacial ice and meltwater was deposited over the bedrock across most of the basin (fig. 3) during the Wisconsin Glaciation (10,000–25,000 years ago). Stratigraphic names used in this report are based on the nomenclature of Ostrom (1967) and Mickelson and others (1984), as presented in figure 4. A generalized geologic cross section for the Rock River Basin is shown in figure 5, with the uppermost bedrock formations shown in map view in figure 6.

Table 1. Physical and demographic characteristics for select tributary basins in the Rock River Basin (Wisconsin Department of Natural Resources, 1998).

[**Abbreviation**: mi^2, square mile]

Site number in figure 1	Tributary name	Surface-water-basin area (mi^2)	Population (2000)	Land cover, in percent			
				Forest	Urban	Agriculture	Wetland and open-water
1	Rock River upstream from Beloit (excludes Turtle Creek)	3,464	742,000	8	10	68	13
2	Turtle Creek at the Rock River	288	43,000	8	10	80	2
3	Yahara River near Fulton	518	292,000	6	20	63	11
4	Koshkonong Creek near Koshkonong Lake	161	31,000	9	9	71	11
5	Bark River at the Rock River	344	61,000	16	9	57	18
6	Crawfish River at Milford	762	63,000	5	6	76	12
7	Rock River at Robert Street at Fort Atkinson	2,237	280,000	8	8	69	15
8	Rock River near Horicon	456	31,000	5	6	71	17
9	West Branch Rock River at State Highway 49 near Waupun	113	13,000	3	7	82	9
10	East Branch Rock River near Mayville	183	18,000	8	8	75	9

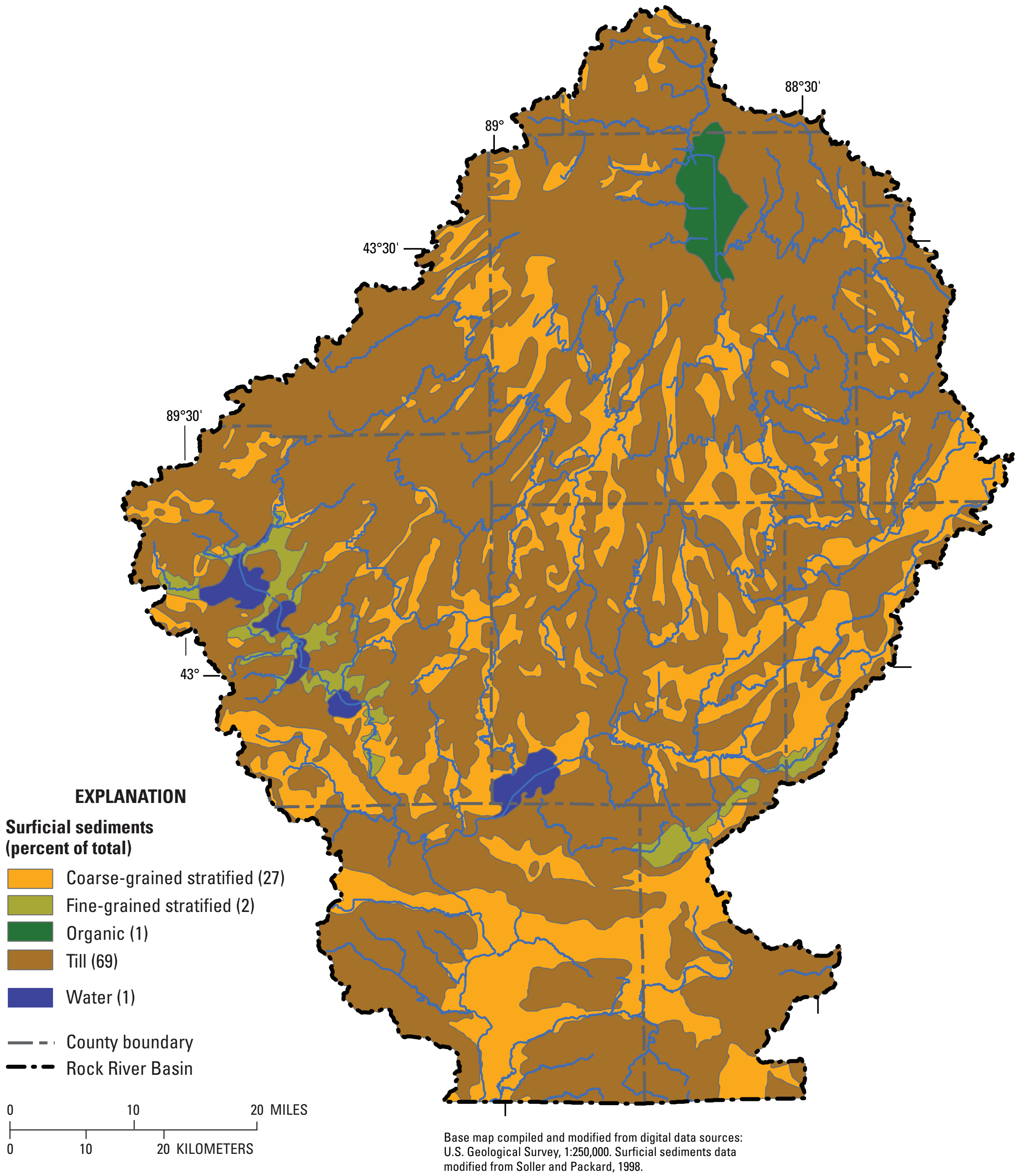

Figure 3. Surficial sediments in the Rock River Basin.

Study Methods

An analytic element ground-water-flow model, using the computer program GFLOW (Haitjema, 1995), was developed to simulate the regional ground-water-flow system and its interaction with surface-water features. This modeling program simulates ground-water flow on the basis of the Dupuit-Forchimer assumptions, which simplify a three-dimensional flow system into a two-dimensional, areal flow system. These assumptions are well suited for the large Rock River Basin where the ratio of horizontal to vertical dimensions is very large; that is, the total aquifer thickness does not exceed 2,000 ft, where as the Rock River Basin extends over 90 mi (475,000 ft). A complete description of analytic element modeling is beyond the scope of this report, but a brief description follows. Hunt (2006) gives a review of applications of the analytic element method, and Haitjema (1995) discusses the underlying concepts and mathematics of the method in detail.

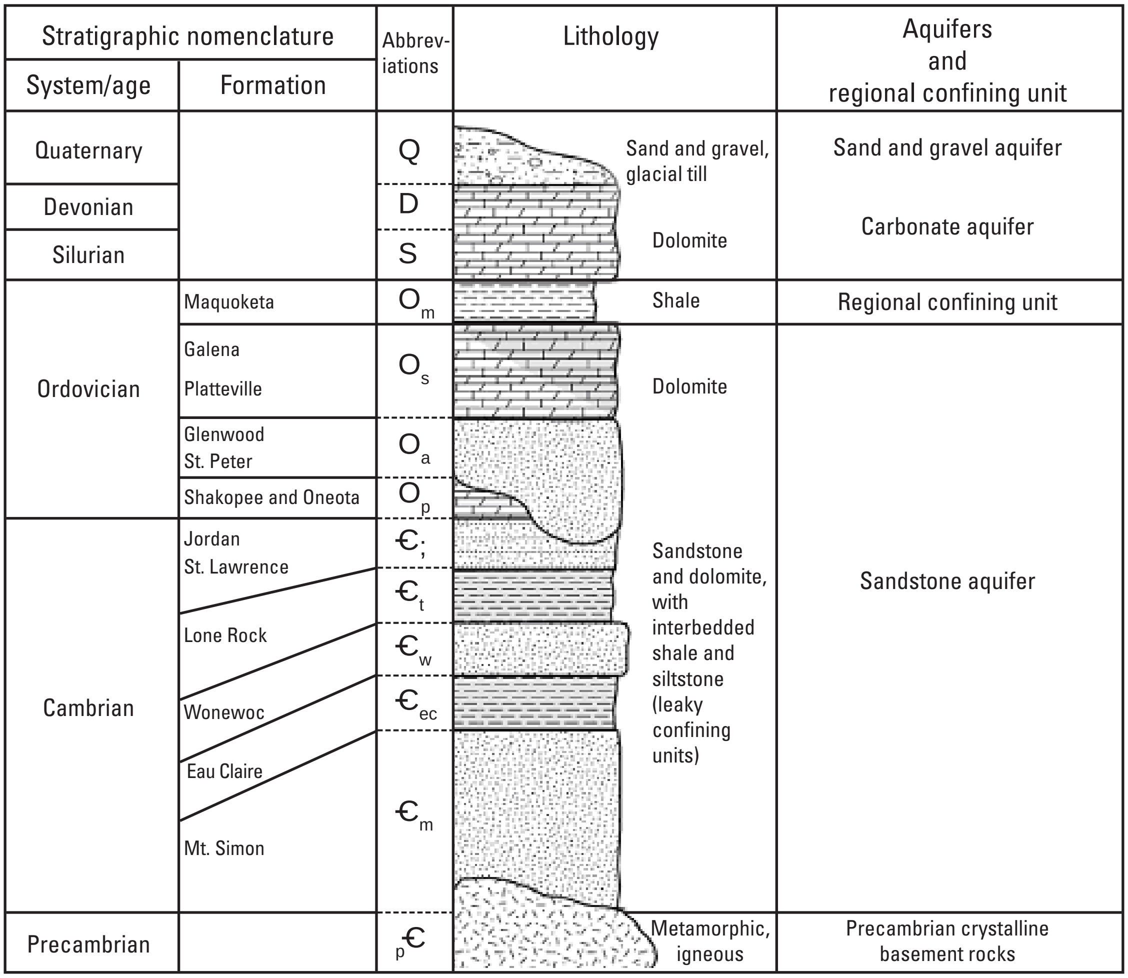

Figure 4. Stratigraphic units and corresponding lithologies in the Rock River Basin. (Modified from Feinstein and others, 2005b.)

An infinite aquifer is assumed in analytic element modeling. The problem domain (model area) does not require a grid or involve interpolation between cells (as are required for finite difference or finite element methods). To construct an analytic element model, the modeler enters features important for controlling ground-water flow (for example, wells and surface-water features) as mathematical elements or strings of elements. The amount of detail specified for the features depends on distance from the area of interest. Each element is represented by an analytic solution. The effects of these individual solutions are added together to form a solution for any location in the simulated ground-water-flow system. Because the solution is not confined to a grid, heads and flows can be computed anywhere in the model domain without interpolating between grid cells. In the GFLOW model used here, the analytic elements are two dimensional and are used only to simulate steady-state conditions (that is, water levels that do not vary with time). A primary value of large-scale analytic element modeling is to identify the main features controlling ground-water flow. These features can then be used to better define local conditions, test hypotheses, and answer site-specific questions as specific local data are incorporated into the model. The analytic element method and comparisons of analytic element to finite-difference numerical model techniques have been discussed by others (Haitjema, 1995; Hunt and others 1998; and Hunt and others, 2003).

The GFLOW model was calibrated by means of parameter-estimation techniques. Numerous publications detail the advantages of parameter estimation (for example, Poeter and Hill, 1997; Kelson and others, 2002). Briefly, the primary benefit of a properly prepared and executed parameter-estimation calibration over typical trial-and-error calibration is the ability to automatically calculate parameter values (for example, hydraulic conductivity and recharge) that are a quantified best fit between simulated model output and observed data (for example, ground-water levels and streamflows). In addition, parameter sensitivity can be quantified and assessed. In this study, the GFLOW model was coupled with the parameter estimation code PEST (Doherty, 2008).

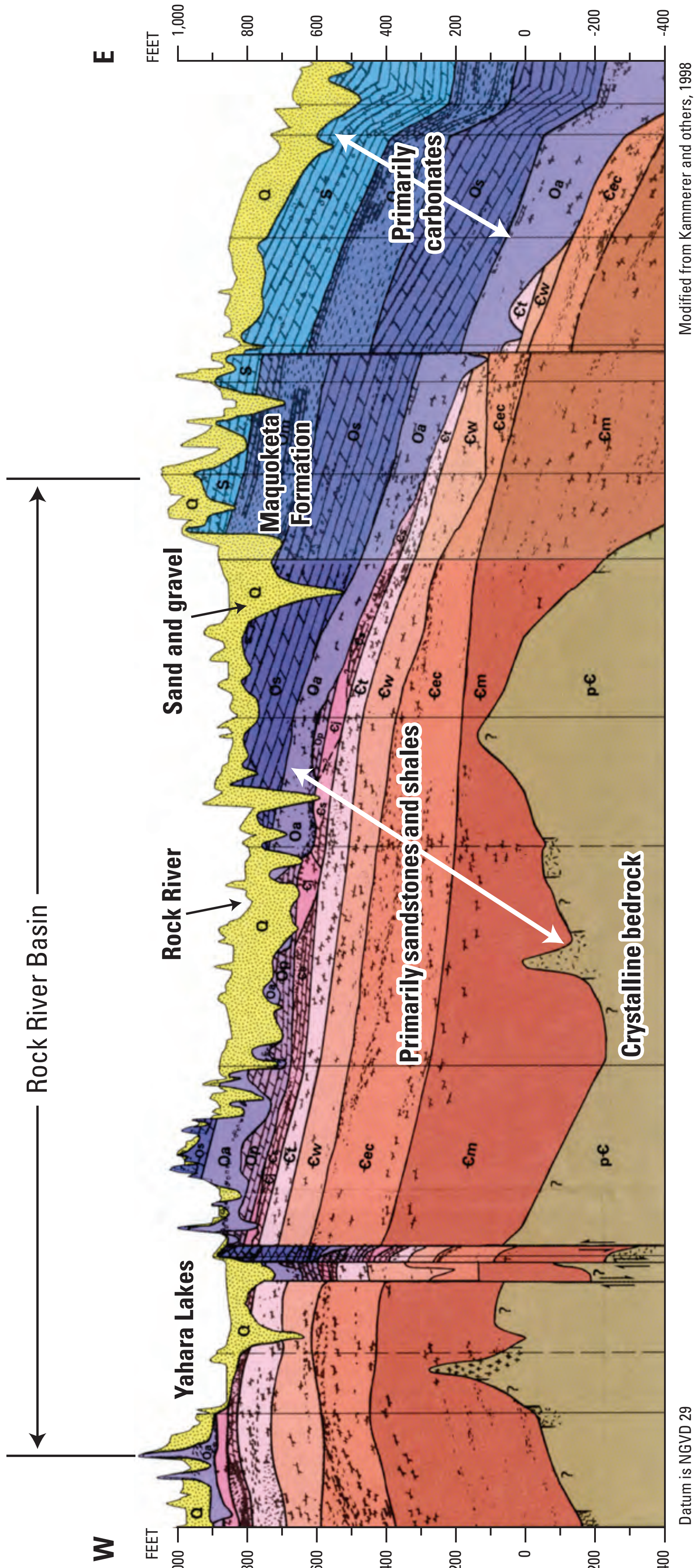

Figure 5. Generalized west-to-east geologic section for the Rock River Basin. Abbreviations for the geologic units are explained in figure 4.

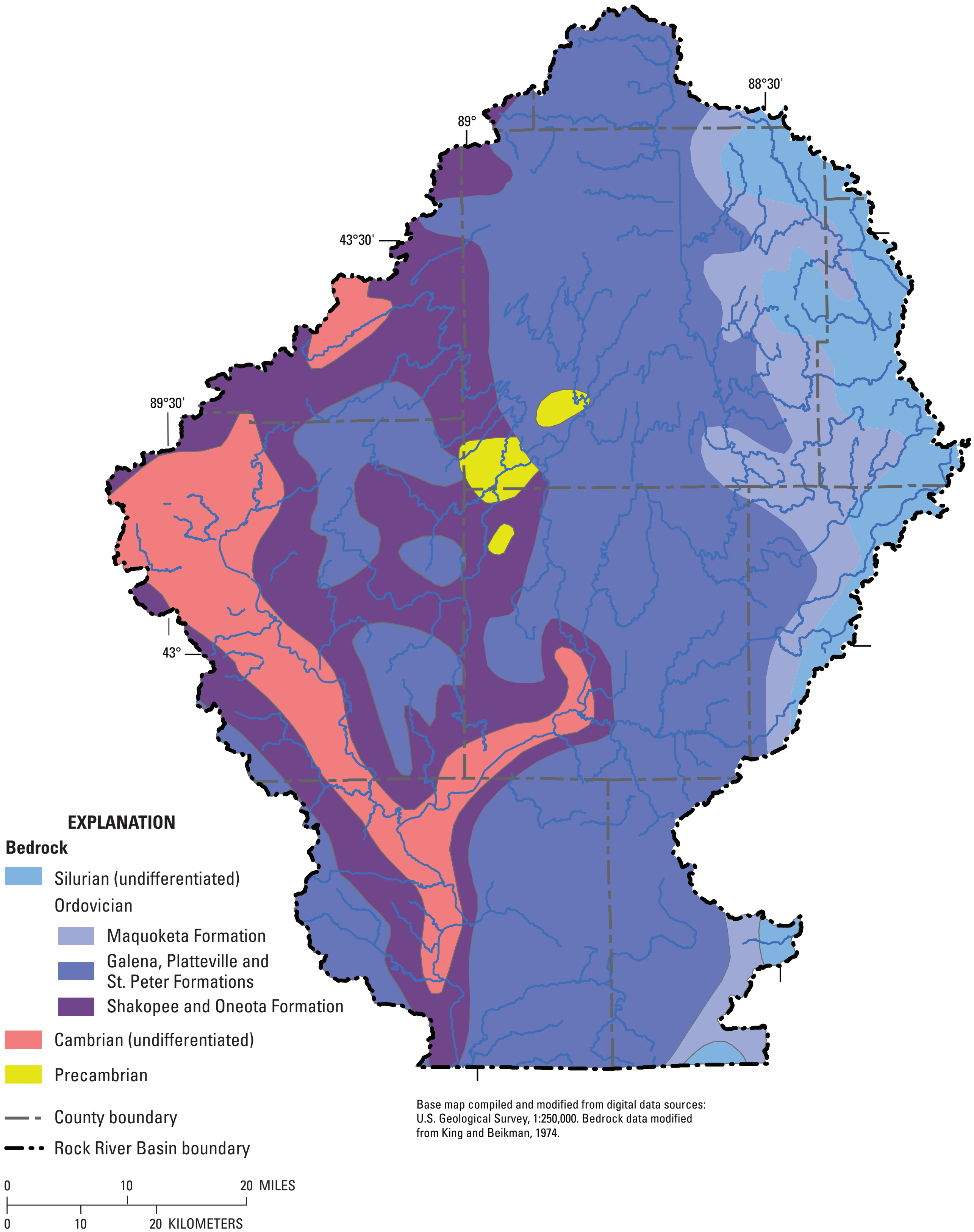

Figure 6. Generalized map showing the extent of the uppermost bedrock units in the Rock River Basin.

Conceptual Model of the Ground-Water-Flow System

Before simulating a ground-water system, a conceptualization of the system is essential because it forms the basis for model development. The conceptualization is a necessary simplification of the natural system because inclusion of all of the complexities of the natural system into a computer model is not feasible given the existing knowledge of the subsurface and current computer capabilities. Steps in the development of the conceptual model are (1) definition of aquifers and confining units, (2) identification of sources and sinks of water, and (3) identification and delineation of hydrologic boundaries encompassing the area of interest. The first two of these steps were accomplished by review and interpretation of available geologic and hydrogeologic data. The third step was accomplished through the model design. The conceptual model of the ground-water-flow system is shown in figure 7. The vertical scale of the conceptual model diagram has been greatly exaggerated to illustrate the geologic units; regional flow through the aquifers is primarily horizontal.

Aquifers and Confining Units

Three generalized regional aquifers and one regional confining unit are present in the Rock River Basin, based on the hydrogeologic units simulated for seven counties in southeastern Wisconsin (fig. 4; Feinstein and others, 2005b). Glacial sediments of varying thickness and permeability cover most of the basin and form a relatively thin sand and gravel aquifer above bedrock aquifers. In the eastern part of the basin, dolomite bedrock of Devonian and Silurian age forms a shallow carbonate bedrock aquifer above the Maquoketa Formation, which is a regional confining unit (figs. 5 and 7). (Dolomite is a carbonate rock similar to limestone.) The Maquoketa Formation is an approximately 200-ft-thick layer of shale that separates the carbonate aquifer from an underlying, predominantly sandstone, bedrock aquifer. The underlying aquifer is composed of layers of dolomite, sandstone, and shale consisting of the Galena, Platteville, Glenwood, St. Peter, Shakopee, Oneota, Jordan, St. Lawrence, Lone Rock, Wonewoc, Eau Claire, and Mount Simon Formations. The combined thickness of these bedrock formations is substantial, generally on the order of 600 ft to 1,200 ft except in the far eastern part of the basin, where the thickness begins to increase by thousands of feet. Impermeable Precambrian crystalline basement rock forms the lower boundary of the ground-water-flow system.

The Maquoketa Formation is absent in most of the western part of the basin (figs. 5 and 6). In map view, the western edge of the Maquoketa "subcrop" is a linear representation of where the base of the Maquoketa Formation directly underlies the glacial sediments; that is, the Maquoketa Formation is present to the east of the subcrop beneath Devonian and Silurian age rocks, but has been removed by erosion west of the subcrop. In the conceptual model for the Rock River Basin, the sand and gravel aquifer is combined with the carbonate aquifer east of the Maquoketa subcrop (fig. 7). West of the Maquoketa subcrop, the carbonate aquifer is absent, and the sand and gravel aquifer is combined with the sandstone aquifer. In the conceptual model and the one-layer GFLOW model, flow within the sandstone aquifer east and below the Maquoketa subcrop has been ignored. Specifically, horizontal and vertical flow into the deep sandstone aquifer east of the Maquoketa subcrop has been incorporated into the conceptual and GFLOW models as a specified rate of ground-water flow, but ground-water flow within the sandstone aquifer itself has not been simulated directly below the Maquoketa Formation (see the "Model Construction and Assumptions" section). This simplification was used because of the natural hydrogeologic setting (shallow and deep aquifers separated by a major regional confining unit); limitations of the one-layer, two-dimensional ground-water-flow model; and the purpose of the Rock River Basin model, which includes simulation of shallow ground-water flow and ground-water/surface-water interaction. Ground water in the deep sandstone aquifer below the Maquoketa Formation has limited interaction with local surface-water bodies, and flow directions do not correspond with those above the Maquoketa Formation (Feinstein and others, 2005b). This deep aquifer has been simulated by others (Feinstein and others, 2005b) east of the subcrop.

Sources and Sinks of Water

The primary source of water to the ground-water-flow system is recharge to the water table. Recharge takes place nearly everywhere in the Rock River Basin except in ground-water discharge areas associated with surface-water bodies. Recharge rates tend to be spatially varied because of factors such as soil infiltration rates, ground slope and relative topographic position, and vegetative cover. However, these local differences tend to average out over large areas, such as the area drained by the Rock River and its tributaries.

Ground-water sinks are areas or features where water discharges from the ground-water-flow system, including surface-water features such as rivers, lakes, and wetlands. Pumping wells are another type of sink, capturing ground water that would otherwise discharge to surface-water bodies. In areas of large ground-water withdrawals, especially in surficial aquifers, rivers that otherwise would capture ground water may instead locally recharge the ground-water system. Only a small amount of the total recharge to the water table within the Rock River Basin is captured by wells. Locally, however, areas with large annual withdrawals (for example, the city of Madison) can capture a substantial portion of the local recharge.

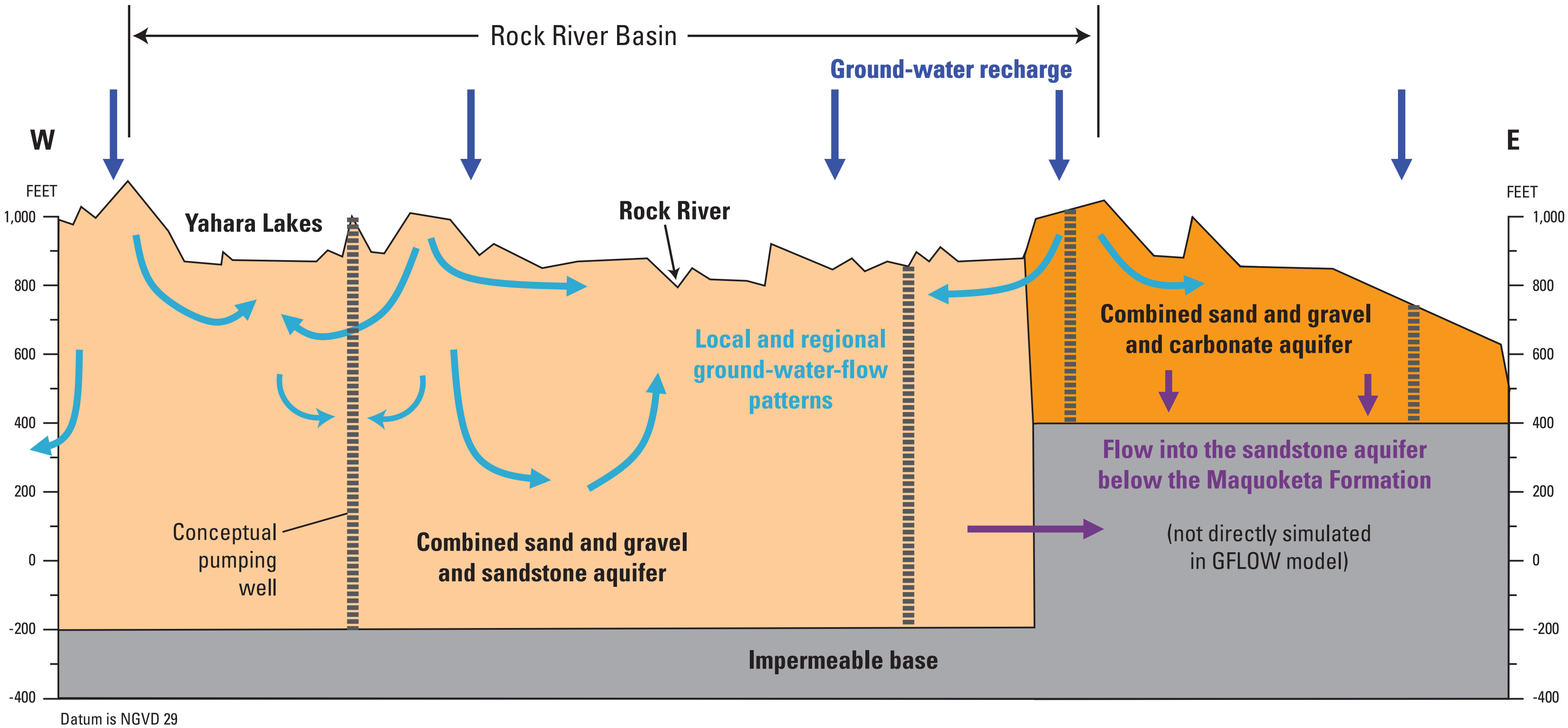

Figure 7. Generalized conceptual model of ground-water flow in the Rock River Basin. The Maquoketa Formation is implicity simulated as part of the combined sand and gravel and carbonate aquifer.

A secondary ground-water sink within the Rock River Basin is the subsurface movement of ground water across its boundaries into neighboring basins. This interbasin flow is generally not a substantial component of the water budget for the shallow part of the flow system (including the unconsolidated deposits and the upper bedrock) because the topographic boundary of a basin is generally a close approximation of the divide that separates shallow ground water flowing within the basin from shallow ground water flowing outside the basin. However, deeper flow in the sandstone aquifer can cross surface-water boundaries in response to gradients controlled by large sinks such as major pumping centers. For example, regional ground-water-flow simulations of southeastern Wisconsin (Feinstein and others, 2005b) show that the deep ground-water divide in the sandstone aquifer is several miles west of the shallow ground-water divide and that there is a net loss of ground water from the Rock River Basin through the deep sandstone aquifer below the Maquoketa Formation. The one-layer framework model has incorporated results from the SEWRPC model (Feinstein and others, 2005b) to account for this deep ground-water flow out of the basin (see the "Model Construction and Assumptions" section).

Water flows from areas of recharge (sources) to areas of discharge (sinks) through the ground-water-flow system. Of the recharge that enters the regional ground-water-flow system, part flows through local systems with short flow paths (usually less than about 2 mi). Local systems are common in the sand and gravel aquifer. Some of the water flows through a regional system with longer flow paths (on the order of tens of miles). The regional system generally consists of the sandstone and carbonate aquifers. Flow is largely horizontal in the local and regional systems except in regional discharge areas, where deep ground water flows upward to surface-water sinks. The presence of major vertical fractures can enhance local vertical flow.

Hydrogeologic Boundaries

The ground-water-flow model consists of two domains: the near field and the far field. The near field is the area of interest, which for this study is the entire Rock River Basin. The near-field rivers and lakes are represented by linesink[1] networks (Haitjema, 1995) that route base flow (the portion of total flow derived from ground water) downstream. The degree of ground-water/surface-water interaction in the near field depends on the riverbed sediment resistance (thickness divided by hydraulic conductivity) and the elevation difference between the river stage and the water table. The far field is the area surrounding the near field that contains hydrologic features that control the ground-water flow toward or away from the near field. These are rivers and lakes that border the Rock River Basin, and they are simulated with coarse linesink networks and little or no resistance between the surface-water features and the ground-water system. The function of the far field is to resolve the ground-water divides near the edge of the basin that determine, for the most part, what water is available for discharge to rivers and wells within the near field. The headwaters of the river systems surrounding the Rock River Basin were simulated as near-field linesinks in order to allow the river to "go dry" and be removed from the solution if the water table falls below the stream elevation - an important consideration near ground-water divides where ephemeral streams (streams with no base flow, only runoff from precipitation) tend to be prevalent.

Hydraulic Properties of the Ground-Water-Flow System

Initial estimates of hydraulic conductivity, recharge, and riverbed resistance for the regional ground-water-flow model were based on available geologic and hydrologic data. The following is a brief description of these estimates.

Hydraulic Conductivity

Hydraulic conductivities of the geologic units in the area have been estimated by others (table 2) through the use of specific-capacity tests, aquifer pumping tests, and hydrogeologic modeling. Horizontal hydraulic conductivities of the sand and gravel aquifer are reported to range from 0.2 to 100 ft/d. Measured horizontal hydraulic conductivities in the carbonate and sandstone aquifers range from 0.07 to 31 ft/d (Young, 1992). Vertical hydraulic conductivity in the sandstone and carbonate aquifers is generally ten to hundreds of times lower than the corresponding horizontal hydraulic conductivity estimates; vertical hydraulic conductivity of confining units, such as the Maquoketa Formation, is thousands of times lower than horizontal hydraulic conductivity of the aquifers (Feinstein and others, 2005b). In effect, the Maquoketa Formation forms a nearly impermeable boundary to vertical flow in the eastern part of the Rock River Basin. Although these ranges are useful for characterizing the system, the model requires specific values for the hydraulic conductivity across large regions, or zones, in the flow system. Thus, values associated with zones of locally uniform hydraulic conductivity were treated as calibration parameters. Values used in the modeling described here were initialized by using reasonable values, with the final values determined by use of PEST (Doherty, 2008) and constrained to a reasonable range based on available measurements and estimates (table 2).

[1]A linesink is a mathematical representation of a hydrologic sink, such as a stream (Haitjema, 1995).

Table 2. Previously reported horizontal hydraulic conductivities (feet per day) and calibrated values from the regional model.

[The sand and gravel aquifer is combined with the carbonate aquifer where it is above the Maquoketa Formation; it has been combined with the sandstone aquifer where the Maquoketa Formation and overlying carbonate aquifer are absent]

<table>
<tr><th colspan="2" rowspan="2">Hydrogeologic unit</th><th colspan="6">Horizontal hydraulic conductivity, in feet per day</th></tr>
<tr><th>Feinstein and others (2005b)</th><th>Krohelski and others (2000)</th><th>Gaffield and others (2002)</th><th>Young (1992)</th><th colspan="2">This report</th></tr>
<tr><td colspan="2">Sand and gravel aquifer</td><td>0.2–100</td><td>0.5–7</td><td rowspan="10">6.5</td><td></td><td rowspan="4">↑ 4.7 ↓</td><td>↑</td></tr>
<tr><td rowspan="3">Carbonate aquifer</td><td>Devonian</td><td>30</td><td>–</td><td>0.07–2</td><td rowspan="3">where absent</td></tr>
<tr><td>Silurian</td><td>1–4</td><td>–</td><td>–</td></tr>
<tr><td>Maquoketa</td><td>0.0003–0.3</td><td>–</td><td>–</td></tr>
<tr><td rowspan="6">Sandstone aquifer</td><td>Galena
Platteville</td><td>0.04–0.3</td><td rowspan="4">5</td><td>–</td><td colspan="2" rowspan="6">6.6</td></tr>
<tr><td>Glenwood
St. Peter
Shakopee
Oneota</td><td>1.2–6</td><td>0.9–6.8</td></tr>
<tr><td>Jordan
St. Lawrence
Lone Rock</td><td>0.24–2.4</td><td>0.34–5</td></tr>
<tr><td>Wonewoc</td><td>2.4–8.4</td><td>2.9–31</td></tr>
<tr><td>Eau Claire</td><td>0.6–3.6</td><td rowspan="2">10</td><td>0.7–3.9</td></tr>
<tr><td>Mount Simon</td><td>1.2–6</td><td>1.3–11</td></tr>
</table>

Recharge

Rates of recharge are varied because of differing precipitation rates and amounts, soil infiltration rates, slope of the land, relative topographic position, vegetative cover, and other factors. This spatial variability is difficult to estimate, but it often has minimal significance at regional scales. Thus, average recharge rates were applied uniformly across individual zones in the regional model and were loosely associated with patterns of soil infiltration properties (fig. 8; Schwarz and Alexander, 1995). For example, a zone of potentially high recharge was delineated around a contiguous area with relatively high soil infiltration rates in the east-central part of the basin. Average ground-water recharge rates were expected to be within the range reported for the Rock River Basin by Gebert and others (2007) and Cherkauer (2001, 2004). Recharge rates were treated as calibration parameters, with the values constrained to reasonable ranges and determined by use of the parameter estimation code PEST to match observed water levels and base flows.

Riverbed Resistance

Estimates of riverbed resistance are needed to simulate the interaction between surface water and ground water. Riverbed resistance is equal to the thickness of a riverbed or lakebed divided by its vertical hydraulic conductivity, and in this study was estimated as ranging from 0.5 day for rivers to 2 days for lakes[2]. These values correspond to a 1-ft sediment thickness and vertical hydraulic conductivities of 2 ft/d and 0.5 ft/d, respectively. This range of riverbed resistance is between values (0.3 to 2 days) simulated for rivers and lakes in Waukesha County (Hunt and others, 2000), Washington County (Dunning and others, 2003), and Rock County (Gaffield and others, 2002). Because of the relative insensitivity of the regional flow system to riverbed resistance (see “Sensitivity Analysis” section), this parameter was not adjusted during calibration.

[2]The unit “day” is a mathematical reduction resulting from thickness, in feet, being divided by hydraulic conductivity, in feet per day.

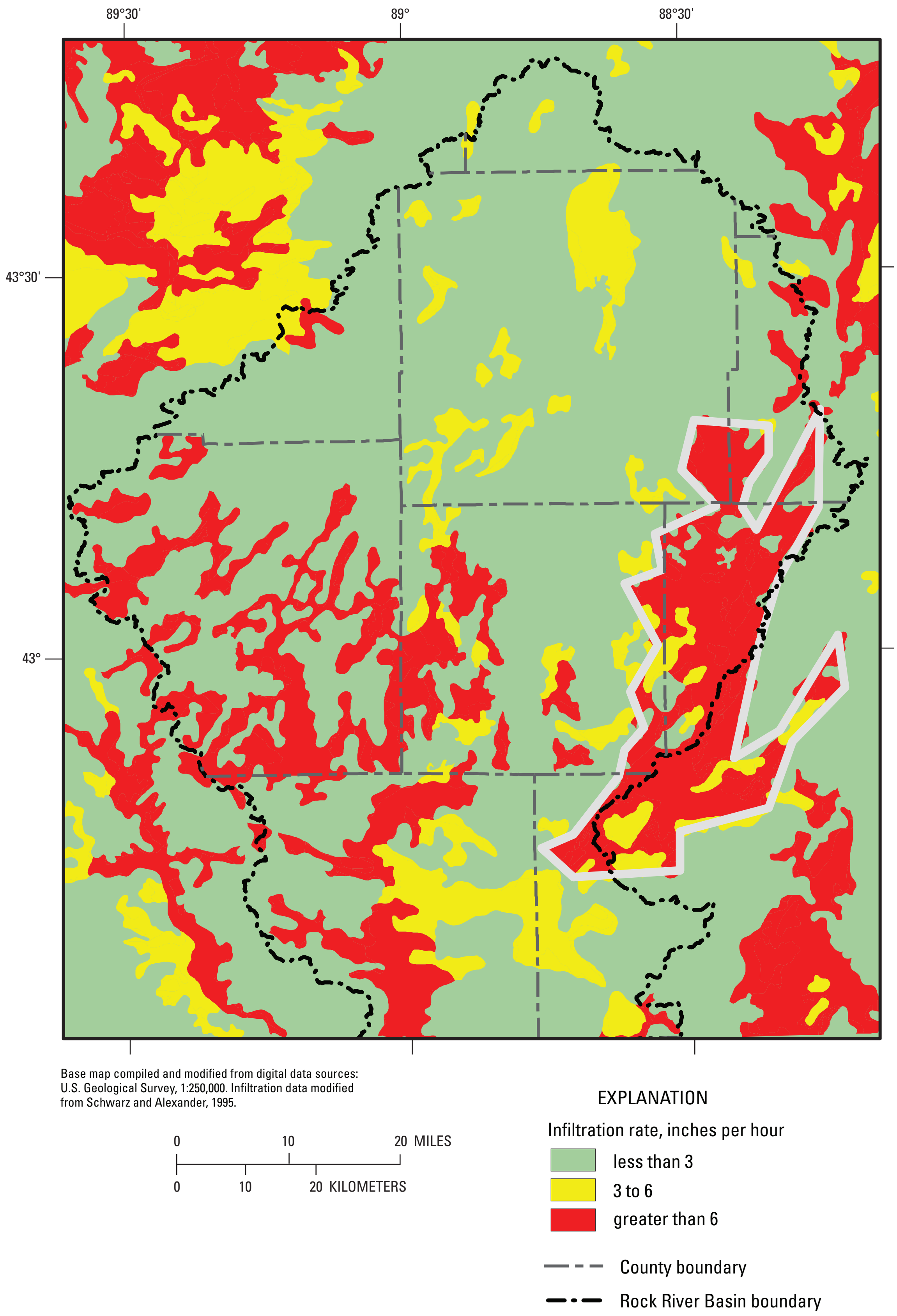

Figure 8. Estimated infiltration rates for soils in the Rock River Basin. Also shown is a zone of high recharge rate simulated in the GFLOW model.

Ground-Water Withdrawals

Ground-water withdrawals from all aquifers west of the Maquoketa subcrop and from aquifers above the Maquoketa Formation (where present) were incorporated into the GFLOW model, as per the conceptual model design (Appendixes 1, 2 and 3). Wells that withdraw ground water from aquifers below the Maquoketa Formation were excluded from the model. Pumping rates for individual public-supply wells in and around the Rock River Basin were computed as the annual average rate reported by each utility from 1997 to 2006 (fig. 9). Annual withdrawal rates were not available for industrial, commercial, and agricultural high-capacity wells during this period. Instead, estimated withdrawals from industrial, commercial, and irrigation wells in and around the Rock River Basin (fig. 10) for the period from 1997 to 2005 were based on either reported rates prior to 1990 or the type of water use (for example, crop irrigation, manufacturing) indicated on the well permit application. Pumping from small, individual private wells in the Rock River Basin is not included in the model because the discharge from these wells is widely distributed and relatively small (especially when including return flow from septic systems), so it has a negligible effect on the overall regional water table.

Total high-capacity-well withdrawal in the Rock River Basin (excluding withdrawal from below the Maquoketa Formation) is about 40,700 Mgal/yr. Municipal water supplies in the basin withdrew an average of about 30,800 Mgal/yr of ground water from 1997 to 2006, or roughly 75 percent of the total ground water withdrawn from all high-capacity wells. The largest municipal withdrawals in the model were in the five communities of Madison (11,850 Mgal/yr, of which about 15 percent is pumped from outside of the Rock River Basin) and Sun Prairie (870 Mgal/yr) in Dane County; Janesville (4,800 Mgal/yr) and Beloit (2,410 Mgal/yr) in Rock County; and Watertown (1,070 Mgal/yr) in Jefferson County. Ground-water withdrawal rates for irrigation (3,540 Mgal/yr) and industrial and commercial uses (6,350 Mgal/yr) in the basin totaled about 9,890 Mgal/yr from 1997 to 2005. Industrial withdrawals are substantial in Madison, Waterloo, Jefferson, and Beloit (fig. 10). Irrigation is used for agriculture throughout the basin and is particularly focused in an area north of Beloit and east of the Rock River (fig. 10). The ground-water-flow model of the Rock River Basin included withdrawal wells from outside of the basin (figs. 9 and 10), because ground-water withdrawal can influence the location of ground-water divides (Feinstein and others, 2005b). Total well withdrawal in the GFLOW model from outside of the surface-water basin was about 16,020 Mgal/yr.

Simulation of the Regional Ground-Water-Flow System

An analytic element ground-water-flow model of the Rock River Basin was developed by use of the computer program GFLOW (Haitjema, 1995). The model simulates the ground-water-flow system and its interaction with surface-water features. The model consists of one layer and simulates steady-state conditions (no change in water levels over time). Simulated rivers, zones of hydraulic conductivity, and zones of uniform areal recharge are shown in figure 11.

Model Construction and Assumptions

Initial model development included estimating the elevation of the base of the ground-water system, a recharge rate, and a horizontal hydraulic conductivity. The base of the model (200 ft below sea level, or NAVD 88,) roughly corresponds with the average crystalline bedrock elevation in the Rock River Basin. East of the Maquoketa subcrop, the base of the model (400 ft above NAVD 88) roughly corresponds with the average elevation of the base of the Maquoketa Formation. The sand and gravel aquifer was combined with (1) the underlying carbonate aquifer east of the Maquoketa subcrop, or (2) the sandstone aquifer west of the subcrop, which resulted in a single bulk hydraulic conductivity for each of these two zones. In two-dimensional areal models, where transmissivity (horizontal hydraulic conductivity multiplied by aquifer thickness) of a single layer represents the flow system, the base elevation is correlated with hydraulic conductivity. Therefore, parameter calibration focused on horizontal hydraulic conductivity in each zone rather than the aquifer base elevations.

As depicted in the conceptual model (fig. 7) and as mentioned previously, flow within the sandstone aquifer east of and below the Maquoketa subcrop has been ignored in the one-layer GFLOW model. However, vertical flow out of the carbonate aquifer and into the deep sandstone aquifer below the Maquoketa Formation has been incorporated into the GFLOW model as a uniform areal leakage rate based on results from a multilayer model of southeastern Wisconsin (Feinstein and others, 2005b). This vertical leakage out of the Rock River Basin model (about 0.1 in/yr; Daniel Feinstein, U.S. Geological Survey, written commun., 2008) was simulated as a reduction in recharge to the carbonate aquifer above the Maquoketa Formation (fig. 11). This implementation (reducing recharge at the water table rather than removing water at the base of the aquifer, because of model limitations) maintains the appropriate overall water budget, but it may induce minor biases in the simulated vertical flow path of ground water in the carbonate aquifer (see sections 3.2.6 and 3.5 of Haitjema, 1995). Such potential biases (slightly shallower flow paths) are expected to be minor considering the small leakage rate through the Maquoketa Formation (about 1 percent of recharge).

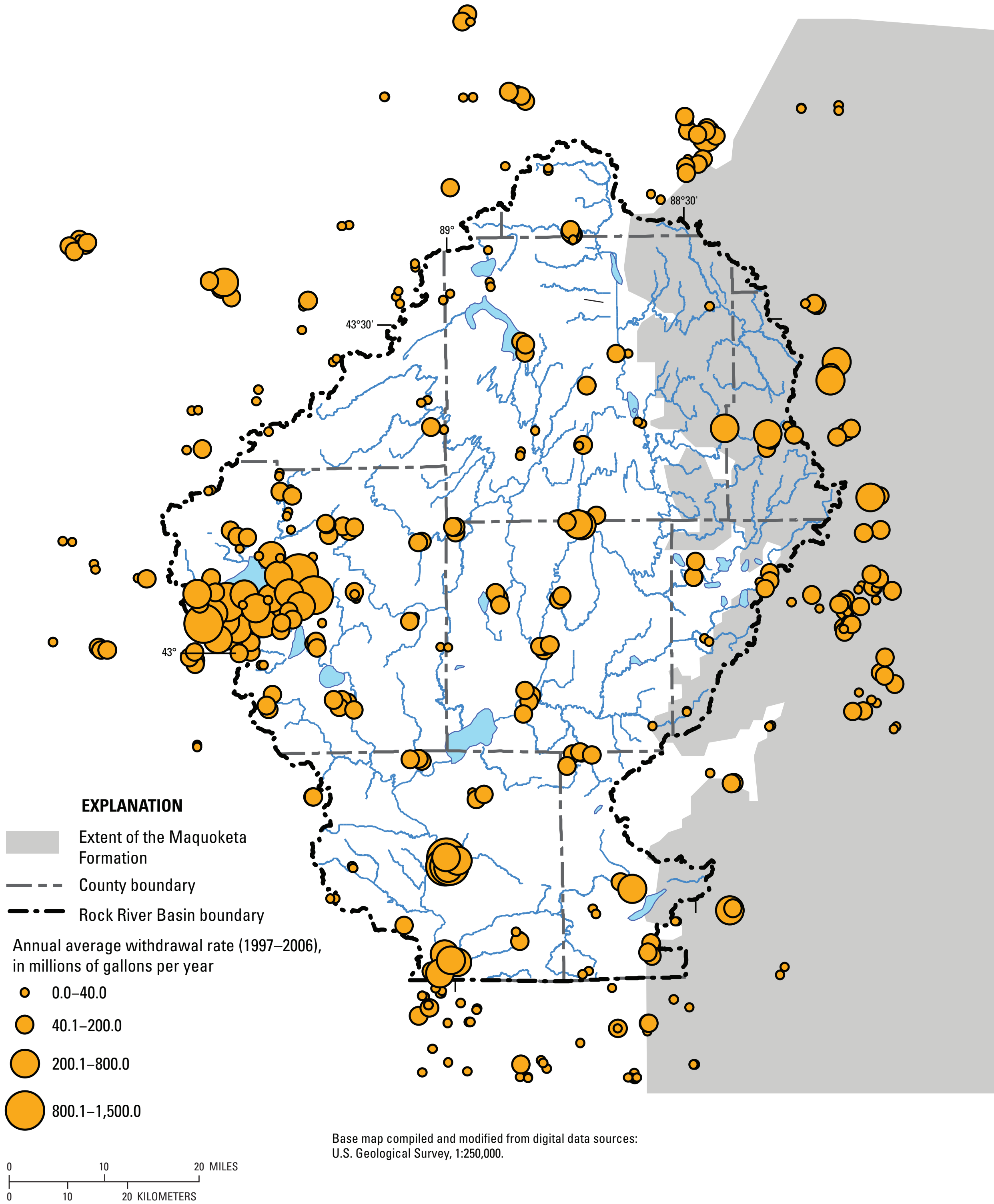

Figure 9. Ground-water withdrawal from public-supply wells in the GFLOW model of the Rock River Basin. Only wells that withdraw water from aquifers above the Maquoketa Formation are included in the GFLOW model where the Maquoketa Formation is present.

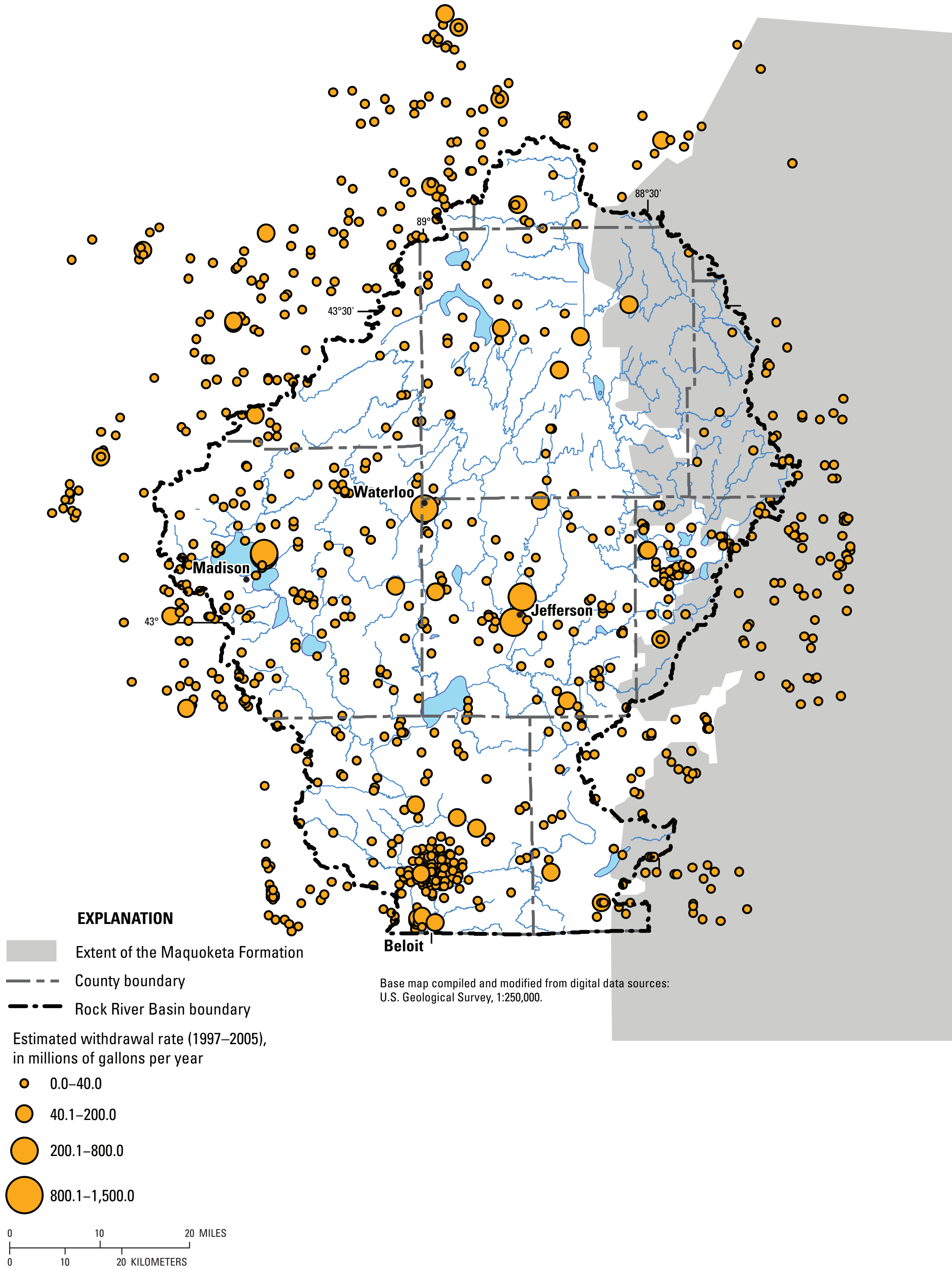

Figure 10. Ground-water withdrawal from agricultural, industrial, and commercial wells in the GFLOW model of the Rock River Basin. Only wells that withdraw water from aquifers above the Maquoketa Formation were included in the GFLOW model where the Maquoketa Formation is present. Estimated withdrawal rate based on historical rates or application (crop irrigation, manufacturing, etc.).

Horizontal flow into the deep sandstone aquifer below the Maquoketa Formation has been incorporated into the GFLOW model by means of discharge-specified linesinks along the trace of the Maquoketa subcrop as delineated in the multilayer model of southeastern Wisconsin (Feinstein and others, 2005b). Horizontal flux (in units of square feet per day) across the Maquoketa subcrop was multiplied by the layer thickness (feet) and totaled for all layers below the Maquoketa Formation on a cell-by-cell basis in the multilayer model (layers 9-18 described by Feinstein and others, 2005b). This volumetric discharge (cubic feet per day) was summed for a series of horizontally adjacent cells and was then divided by the length (feet) of a corresponding discharge-specified linesink in the GFLOW model to compute an equivalent flux across the Maquoketa subcrop for the GFLOW model. Because discharge-specified linesinks in GFLOW extend the full thickness of the model and can not be assigned to a specific aquifer (for example, to remove water solely from the sandstone aquifer west of the Maquoketa subcrop), the discharge-specified linesinks probably capture some water from the carbonate aquifer in the GFLOW model. The effect on simulated ground-water-flow patterns caused by this discrepancy between the multilayered SEWRPC model (Feinstein and others, 2005b) and the GFLOW model is expected to be slight because the total ground water withdrawn by the discharge-specified linesinks represents only about one-third of the total flow through the aquifers near the subcrop; and of this, about 75 percent is withdrawn from the sandstone aquifer because of the approximate 3-to-1 transmissivity ratio between the sandstone and carbonate aquifers. Moreover, the influence of the discharge-specified linesinks is expected to be relatively local. Nonetheless, simulated flow paths in the carbonate aquifer may show a small local deviation (horizontally refracted) due to the discharge-specified linesinks near the Maquoketa subcrop. Future refinements to the model that focus on ground-water flow in only near-surface aquifers may benefit from the removal of local discharge-specified linesinks (in addition to other potential aquifer refinements) for proper simulation of flow paths in the shallow aquifers.

The river network for the Rock River Basin (fig. 1) is represented in the GFLOW model as a series of linesinks (fig. 11). Multiple linesinks are joined into linesink strings representing individual reaches for each river. The river gradient (change in water-surface elevation over distance) assigned to a linesink is based on data from 7.5-minute topographic quadrangle maps. GFLOW solves for the exchange between ground water and surface water at the center of each linesink.

In the near field of the model–that is, within and immediately adjacent to the Rock River Basin–each linesink is assigned a width based on stream order and field observations; widths ranged from about 10 to 500 ft. Each near-field linesink is also assigned a resistance term that, once multiplied by the river width and the difference between the fixed river level and calculated water-table elevation adjacent to the river, accounts for the ground-water flow across the riverbed. As defined previously, the resistance is equal to the thickness of the riverbed divided by its hydraulic conductivity. In the regional model, a single value of resistance equal to 0.5 day was applied to all rivers. Initial parameter sensitivities demonstrated that the model results were not sensitive to changes in riverbed resistance when varied over reasonable ranges; therefore, the values for all rivers were fixed for all model runs.

Large lakes were simulated as linesinks with resistance along their shorelines and assigned widths based on the approximate distance from shoreline to shoreline (Haitjema, 2005) and a uniform resistance of 2 days; small lakes were ignored. Within the perimeter of each simulated lake, the recharge rate applied to the lake represents precipitation minus evaporation rather than ground-water recharge. Recharge to lakes in the model, as well as the Horicon Marsh, was set equal to 2.0 in/yr on the basis of estimates of precipitation minus evaporation in Wisconsin (Novitzki, 1982). The Horicon Marsh was further simulated as an area of high hydraulic conductivity (1,000 ft/d), through which internal ditches were simulated by use of linesinks.

Near-field linesinks are linked so that streamflow is routed from near the headwaters at higher elevations through tributaries to the main trunk of rivers at lower elevations. During the routing through the river network, the amount of water captured from and lost to the ground-water-flow system by the river is tabulated. This accounting allows the amount of water simulated in the river at any point to be compared to flows recorded at streamgages. In general, streamflow consists of (1) overland flow derived mostly from storms and (2) base flow derived from ground-water discharge. Only the base-flow component of streamflow is simulated with the GFLOW model.

Linesinks also represent water bodies in the model far field outside the Rock River Basin (fig. 11). However, these far-field elements are assigned no resistance or width. The assigned stage for each far-field linesink is equivalent to the water-table elevation along the linesink. The far-field linesinks, therefore, act as fixed water-level conditions that serve as major sinks for ground water that discharges outside the basin. In this manner, the far-field water bodies help to define the ground-water divide around the outer perimeter of the basin.

Other inputs to the GFLOW model include recharge zones and pumping wells. Recharge zones were evaluated on the basis of soil infiltration rates (fig. 8; Schwarz and Alexander, 1995), with the simulated recharge value estimated through model calibration. Recharge was simulated uniformly across the basin, except where stream base flows and hydrogeologic conditions indicated that recharge over a large area differed from that of the rest of the basin (fig. 8; Schwarz and Alexander, 1995). Wells are assumed to be fully penetrating (screened from the water table to the model base) and to have constant pumping rates, as described previously (see the "Ground-Water Withdrawals" section).

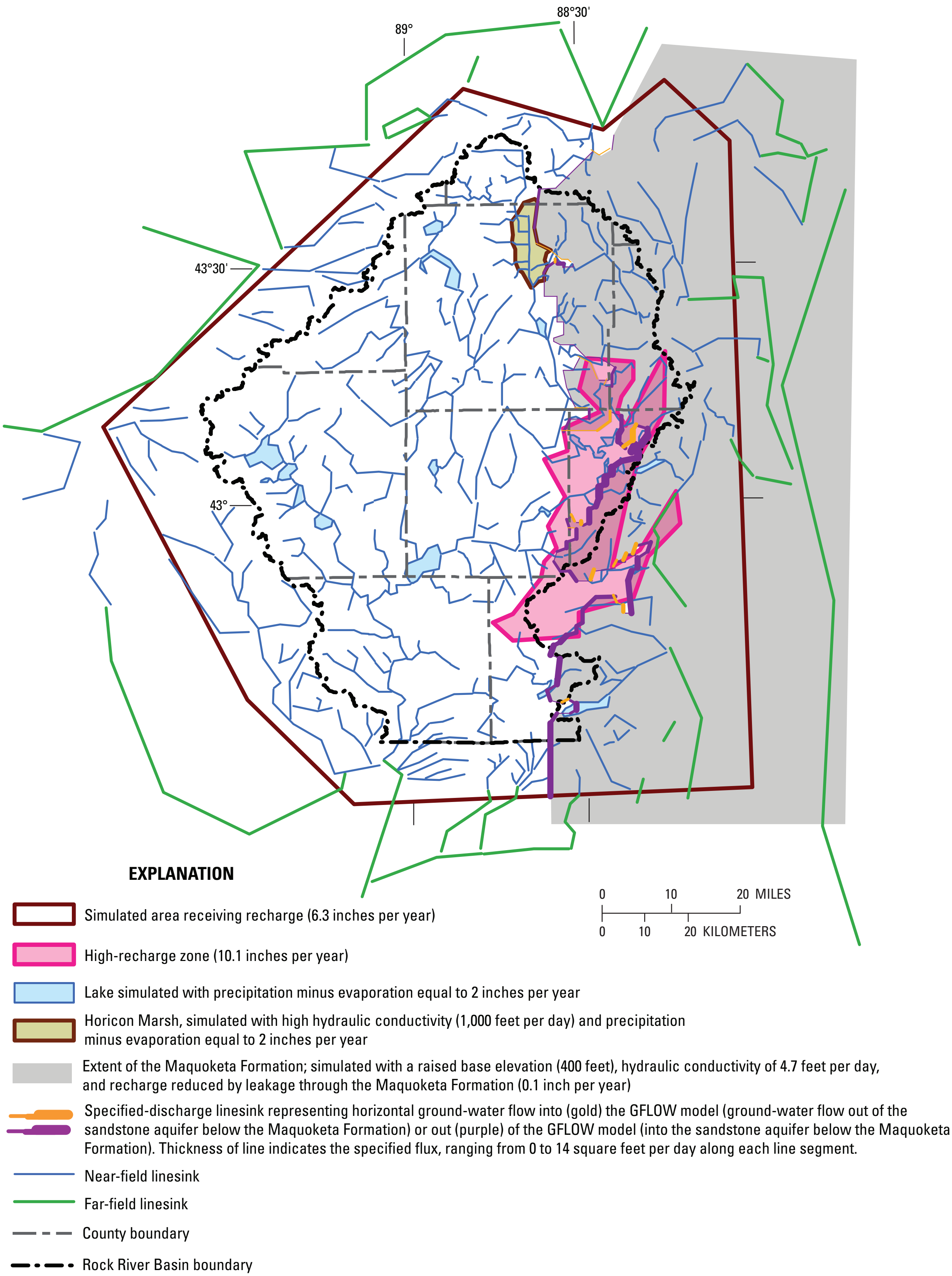

Figure 11. Features of the GFLOW model of the Rock River Basin. The area (white) west of the Maquoketa Formation was simulated as a sandstone aquifer with base elevation of -200 feet and hydraulic conductivity of 6.6 feet per day.

Model Calibration

Ground-water model calibration is a process whereby simulated values of ground-water levels and base flows are compared to observed values. The GFLOW model was calibrated with the aid of the parameter estimation program PEST (Doherty, 2008). The PEST program automatically adjusts parameter values within a reasonable range, and compares simulated ground-water levels and stream base flows to measured water levels and base flows after each run of the GFLOW model. Model calibration is considered complete when simulated and observed water levels and flows match reasonably well and values for parameters (in this model, hydraulic conductivity and recharge) are considered reasonable. The primary benefit of a properly constructed parameter-estimation routine is the capacity to automatically calculate parameter values that are a quantified best fit between simulated and observed data (for example, ground-water levels and stream base flow).

Although a steady-state model was used (in which ground-water levels do not change with time), measured water levels used for calibration spanned many years, and the location of many data points is somewhat uncertain (Appendixes 4 and 5). Simulated ground-water levels represent the average long-term water level, whereas measured water levels generally do not because water levels in wells can be influenced by (1) the depth and length of the well screen, (2) locally confined or perched conditions, and (3) seasonal variability in water levels. Water-level targets were arranged into two categories: (1) median values from 20 long-term observation wells in and around the Rock River Basin, and (2) water levels from 16,282 recently drilled wells (water years 1997–2006, or October 1996 to September 2006) with open intervals above the base of the Maquoketa Formation (where present). Well-construction information for these 16,282 wells was obtained from Well Construction Reports (WCRs; Wisconsin Department of Natural Resources, 2007), which contain limited information on the location and elevation of the well site. On the basis of WCR information, the well locations were estimated to the nearest quarter-quarter section. Target water levels were computed as the average water level for all wells in the same quarter-quarter section, which resulted in 8,220 WCR-derived water-level targets for calibration. An approximate evaluation of data quality is included in the calibration via the PEST weight assigned to each target (table 3). Higher weights were assigned to the 20 wells with long records and accurately measured reference-point elevations; lower weights were assigned to the 8,220 WCR-derived targets. The weighted residuals between measured and simulated values were used by PEST to determine the best fit.

In addition to water-level targets, base-flow measurements used for calibration were obtained from nine streamgages in the Rock River Basin that were used by Gebert and others (2007) to estimate recharge (table 3b). Gebert and others (2007) estimated base flow at these stations by means of the Base-Flow Index method (Wahl and Wahl, 1995; Institute of Hydrology, 1980a; 1980b) for daily streamflows from water year 1970 to water year 1999. Proration of weights assigned to the targets in PEST (table 3b) was based on the amount of flow so that the influence of both small and large streams on the parameter-estimation process was roughly similar to the influence of water level targets.

Only a subset of all possible parameters was estimated by PEST. Parameters were excluded if they were insufficiently sensitive for automated calibration (for example, riverbed resistance). In these cases, the parameter was fixed at a reasonable value. Hydraulic conductivities used in the calibrated model are listed in table 2 and shown on figure 11. Hydraulic conductivity representing the sand and gravel aquifer combined with the sandstone aquifer (west of the Maquoketa subcrop) was estimated to be about 6.6 ft/d. Hydraulic conductivity of the sand and gravel aquifer combined with the carbonate aquifer above the Maquoketa Formation was estimated to be about 4.7 ft/d. Recharge to most of the Rock River Basin was estimated at 6.3 in/yr. A higher recharge rate (10.1 in/yr) was calibrated for an area in the east-central part of the Basin where soil infiltration rates are relatively high (fig. 8; Schwarz and Alexander, 1995). The extent of this zone and the calibrated recharge rate match well with recharge rates in this area that were estimated with a watershed model (Cherkauer, 2001; 2004) and incorporated into a multilayer model of southeastern Wisconsin (Feinstein and others, 2005b).

Because of the uncertainties associated with some target data (location, elevation, seasonal variability, well construction, local conditions, etc.), along with simplifications inherent in constructing a regional model, perfect agreement between the simulated and measured values was not expected. Considering the wide range of measured water levels and simplifications necessary for the GFLOW model, the resulting match of simulated water levels and base flows to measured values was closer than expected (fig. 12). Summary statistics for the ground-water-level calibration (table 3a) are similar to those derived from other regional models in Wisconsin (for example: Krohelski and others, 2000, Feinstein and others, 2005a, Feinstein and others, 2005b). The mean error (a measure of the model bias) for the 20 long-term ground-water observation wells is -1.0 ft (a negative value indicates that measured values were less than simulated values); mean error for the 8,220 WCR wells is -8.6 ft. The root mean square difference (RMSD) and mean absolute difference (MAD), respectively, between measured and simulated water levels are 23.1 and 15.2 ft for the 20 long-term wells and 31.5 and 23.2 ft for the WCR wells. These RMSD and MAD values represent less than 7 percent of the total range of observed water levels across the model area. In addition to comparing measured and modeled water levels by means of summary statistics, spatial comparisons between the measured and simulated water levels were made (fig. 13). The agreement between simulated water levels and measured water levels in observation wells is generally close and shows little spatial bias. The match to WCR water levels shows some local banding but generally strikes a balance between oversimulated (simulated greater than measured value) and undersimulated (simulated less than measured value) water levels. Moreover, large differences (for example, greater than 60 ft) between simulated and observed water levels for WCR targets were not unexpected because these targets were not filtered to remove those potentially influenced by (1) very deep or very short well screens, (2) local confined or perched conditions, or (3) seasonally high or low water levels at the time of construction. Measured base flows were compared to simulated base flows at nine locations (fig. 14). Simulated base flows were within 10 percent of estimated base flows at four of the nine streamgages and within 40 percent of estimated base flows at seven of the nine streamgages (table 3b); this base-flow calibration is similar to other regional model calibrations in Wisconsin (for example: Krohelski and others, 2000, Feinstein and others, 2005a, Feinstein and others, 2005b).

Table 3a. Calibration results for ground-water level targets and associated weights used for calibration with the parameter estimation program PEST.

[ME, Mean error; MAD, Mean absolute difference; RMSD, Root mean square difference]

Well type	Number of targets	ME (feet)	MAD (feet)	RMSD (feet)	Weight
Median of time-series values at long-term observation wells	20	–1.0	15.2	23.1	10
Well-construction-report data	8,220	–8.6	23.2	31.5	0.8

Table 3b. Calibration results for stream base-flow targets and associated weights used for calibration with the parameter estimation program PEST.

[ft^3/s, cubic foot per second; in/yr, inch per year]

USGS station identifier	Station name	Target base flow (ft^3/s)	Simulated base flow (ft^3/s)	Difference (ft^3/s and percent)	Weight	Estimated recharge from Gebert and others, 2007 (in/yr)
05426000	Crawfish River at Milford	320	333	-13 (-4%)	2.0e-4	5.8
05431486	Turtle Creek at Carvers Rock Road near Clinton	97	77	20 (21%)	4.0e-4	6.6
05426250	Bark River near Rome	66	65	1 (2%)	4.0e-4	7.4
05427507	Koshkonong Creek near Rockdale	62	58	4 (6%)	4.0e-4	5.6
05424000	East Branch Rock River near Mayville	50	75	-25 (-51%)	4.0e-4	3.8
05423500	South Branch Rock River at Waupun	25	15	10 (39%)	8.0e-4	5.3
05423000	West Branch Rock River near Waupun	17	13	4 (25%)	8.0e-4	5.7
05427718	Yahara River at Windsor	15	14	1 (4%)	8.0e-4	2.7
05427900	Sixmile Creek near Waunakee	8.2	3.9	4.3 (53%)	8.0e-4	2.7

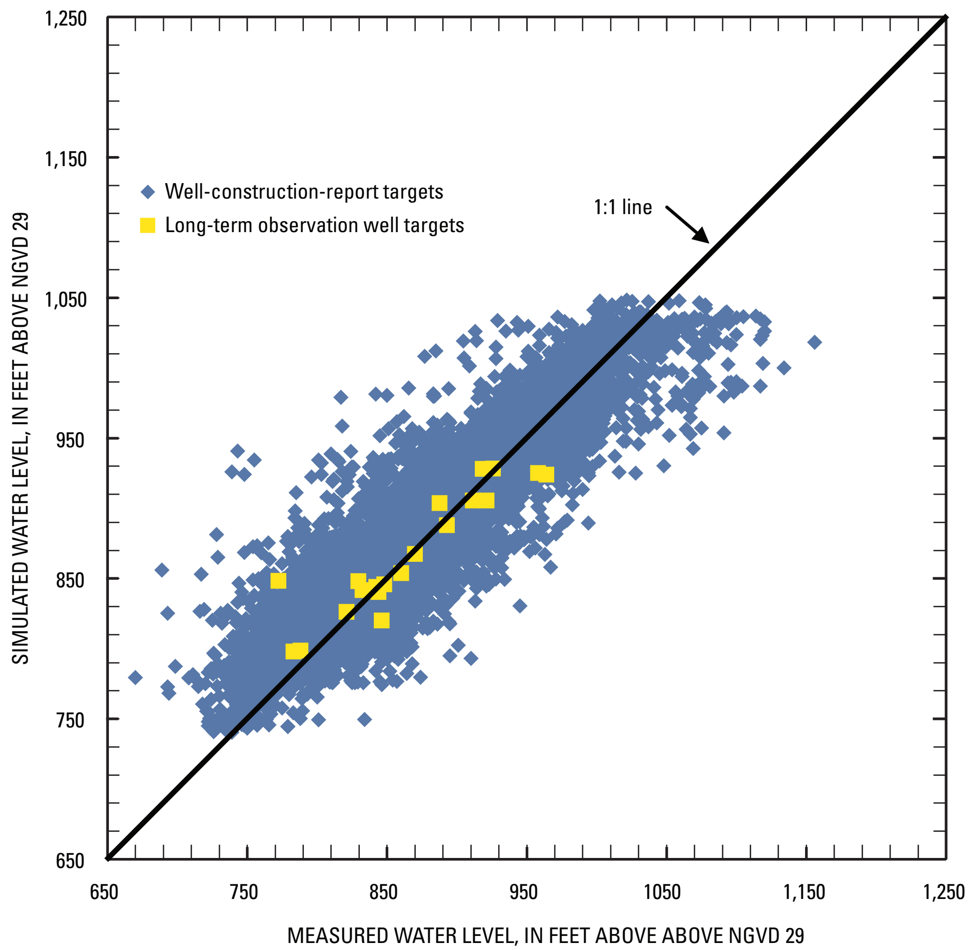

Figure 12. Comparison of measured and simulated water levels for the GFLOW model of the Rock River Basin.

Sensitivity Analysis

Some uncertainty about the accuracy of models is inevitable because the model parameter values are never exactly known. However, the importance of each input parameter and its effect on simulation results can be evaluated through sensitivity tests in which the value of a parameter, such as hydraulic conductivity, is adjusted above or below the calibrated value and the magnitude of changes in simulated ground-water levels and base flows are quantified. In this study, PEST was used to calculate the sensitivity of all water-level and streamflow observations to changes in each parameter value during the calibration process. For the final calibrated parameter values, sensitivities computed by PEST indicate that water levels and streamflows were most sensitive to the recharge rate applied to the basin and the hydraulic conductivity of the combined sand and gravel and sandstone aquifers west of the Maquoketa subcrop. Less sensitive parameters included hydraulic conductivity of the combined sand and gravel and shallow carbonate aquifers above the Maquoketa Formation, as well as the recharge rate applied to the area with high soil-infiltration rates. Insensitive parameters included sediment resistance for rivers and lakes and the base elevation of the model. Initial sensitivity analyses showed similar results and were used to guide selection of parameters for estimation.

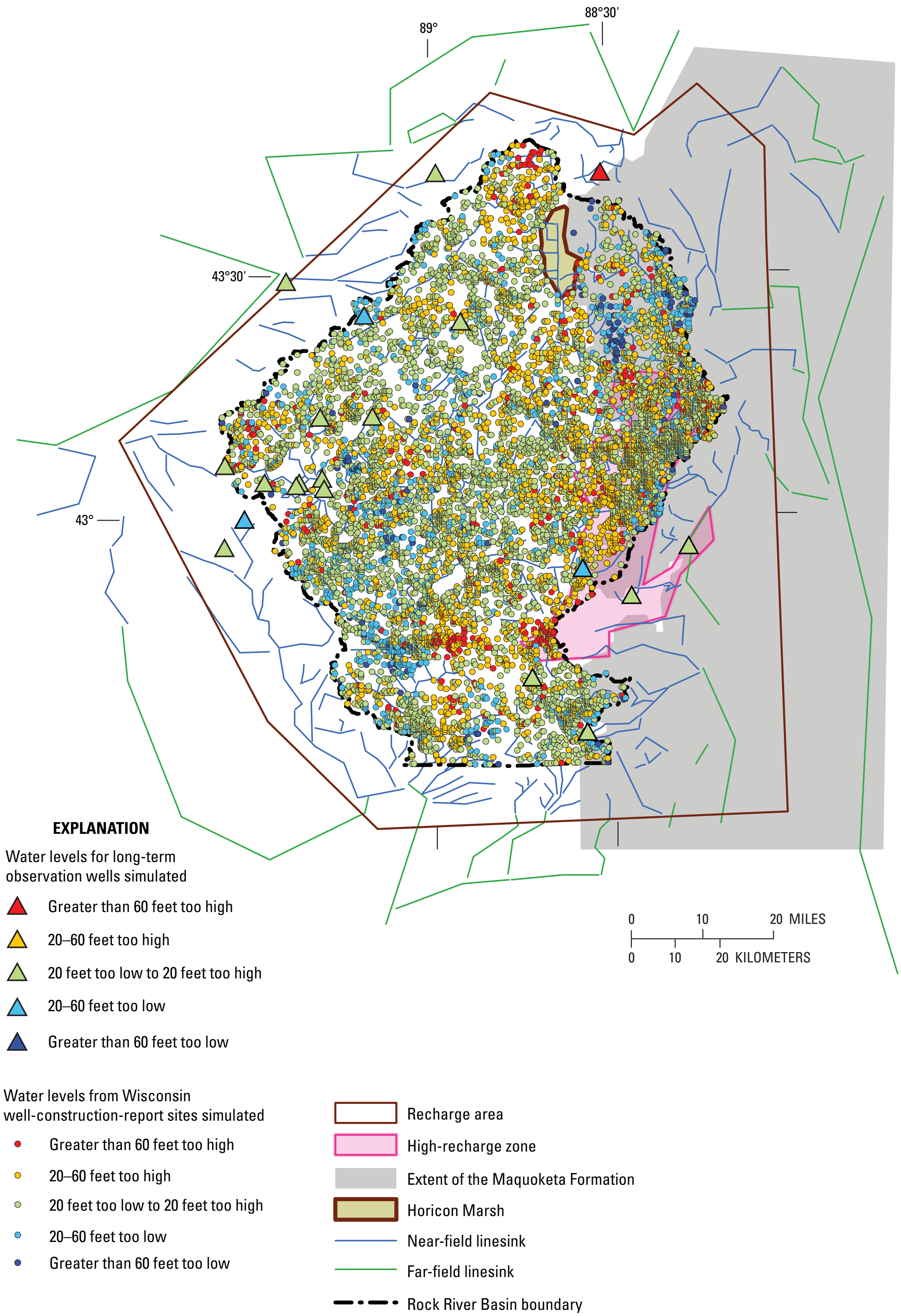

Figure 13. Water-level residuals for the GFLOW model of the Rock River Basin.

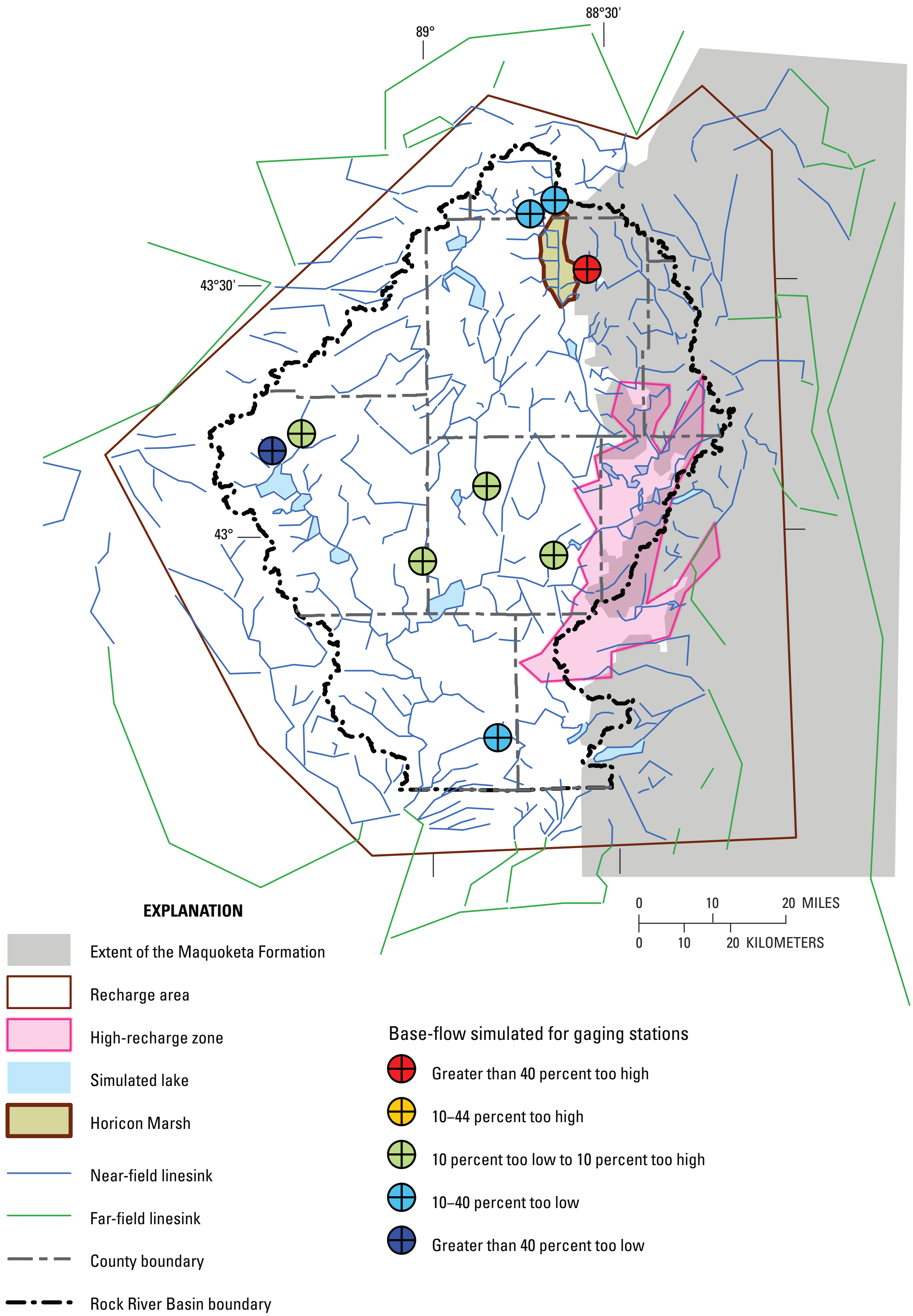

Figure 14. Base-flow residuals for the GFLOW model of the Rock River Basin.

Evaluation of Simulated Results of the Rock River Basin Model

Results from the regional GFLOW model include simulated water levels, flow directions, and ground-water interaction with surface-water features. Contours of simulated water levels are similar to water-table maps produced previously for several Rock River Basin counties. However, simulated water levels from the regional model are more constrained because the model must also account for all water that enters and exits the model, which is not a consideration for manually constructed water-table maps. Simulated particles of water can also be traced along flow paths in the model to illustrate flow directions. Figure 15 shows contours of the simulated water table and the path of several simulated particles of water flowing downgradient, starting at the water table and flowing to discharge locations such as wells and rivers. Much of the water that recharges at the water table discharges to nearby rivers.

The GFLOW model for the Rock River Basin integrates information over a large area, and direct application of the model is designed to address regional scale issues. Nonetheless, the model also forms a basis for possible future studies of specific parts of the basin, for which local refinement or extraction to a three-dimensional model would be necessary.

Following are three aspects of the ground-water-flow system to which the regional model has been directly applied in this report:

1. Identification of river reaches that are either gaining water from the ground-water-flow system or losing streamflow to the ground-water-flow system.
2. Determination of ground-water basins for major rivers.
3. Identification of relatively local ground-water-capture areas for rivers.

Simulated Gaining and Losing River Reaches

In humid climates such as that of Wisconsin, ground water typically discharges to surface-water features that are in direct connection with the ground-water system. However, surface-water discharge to ground water can occur, and it most commonly occurs where surface waters are naturally or artificially restricted or elevated, such as along the downgradient shoreline of a lake or a reservoir where the surface-water level has been elevated by a channel restriction or a dam. Surface water can also enter an aquifer where ground-water-withdrawal wells are near rivers and lakes or along river meanders where local hydraulic gradients can be complex.

Results of simulations illustrate regional patterns of ground-water/surface-water interaction along the shoreline of large lakes and reservoirs in the Rock River Basin (fig. 16). The upgradient (upstream) shorelines of the simulated lakes and reservoirs, like most river segments, are gaining (colored blue in fig. 16). However, some downgradient shorelines are losing (highlighted red in fig. 16), indicating that surface water is discharging into the ground-water-flow system along those segments. Additional losing segments are evident near ground-water pumping centers (for example, the Yahara Lakes near Madison). Although only large lakes and reservoirs that are well connected to the ground-water system were simulated in this model, similar ground-water/surface-water interaction patterns may occur near smaller lakes and reservoirs. Perched water bodies (those above the water table and not well connected to the ground-water system) may also lose water to the ground-water-flow system, with the amount largely dependent upon the permeability of the lakebed sediments. Likewise, the simulated results illustrate where headwater river segments are simulated as ephemeral (gray in fig. 16), indicating that these reaches do not receive ground water from the regional flow system. The GFLOW model automatically removed these ephemeral reaches from the ground-water-flow simulation during solution of the model. Where a more detailed understanding of ground-water/surface-water interaction is important, additional local refinement to the GFLOW model, or the extraction of a three-dimensional MODFLOW model (Harbaugh, 2005), may be necessary. Such local simulations would likely be improved by additional local data collection to compliment the new modeling objectives.

Simulated Ground-Water Basins

Areas that contribute ground water to major river segments can be evaluated by use of ground-water-level contours and simulated traces of water particles. Figure 17 shows simulated ground-water basins in relation to surface-water basins for major tributaries to the Rock River; additional information for each tributary basin is listed in table 4. Whereas ground-water and surface-water basins are commonly similar in size and shape, ground-water and surface-water divides can differ locally. This is particularly evident near some headwater areas, such as the northwestern edge of the Yahara and Crawfish River Basins where the surface-water basins extend beyond the ground-water basins. The location of ground-water divides is controlled by the configuration of the water table, whereas the location of surface-water divides is controlled by the land-surface topography. Moreover, river geometries, geologic factors, recharge, and in some cases pumping, all can influence the water table and therefore the location of ground-water divides. Further simulation of ground-water basins and contributing areas at local scales with refined river systems would result in a more accurate evaluation of how much surface-water and ground-water divides differ. Likewise, additional water level measurements would help to better identify the location and temporal movement of local ground-water divides.

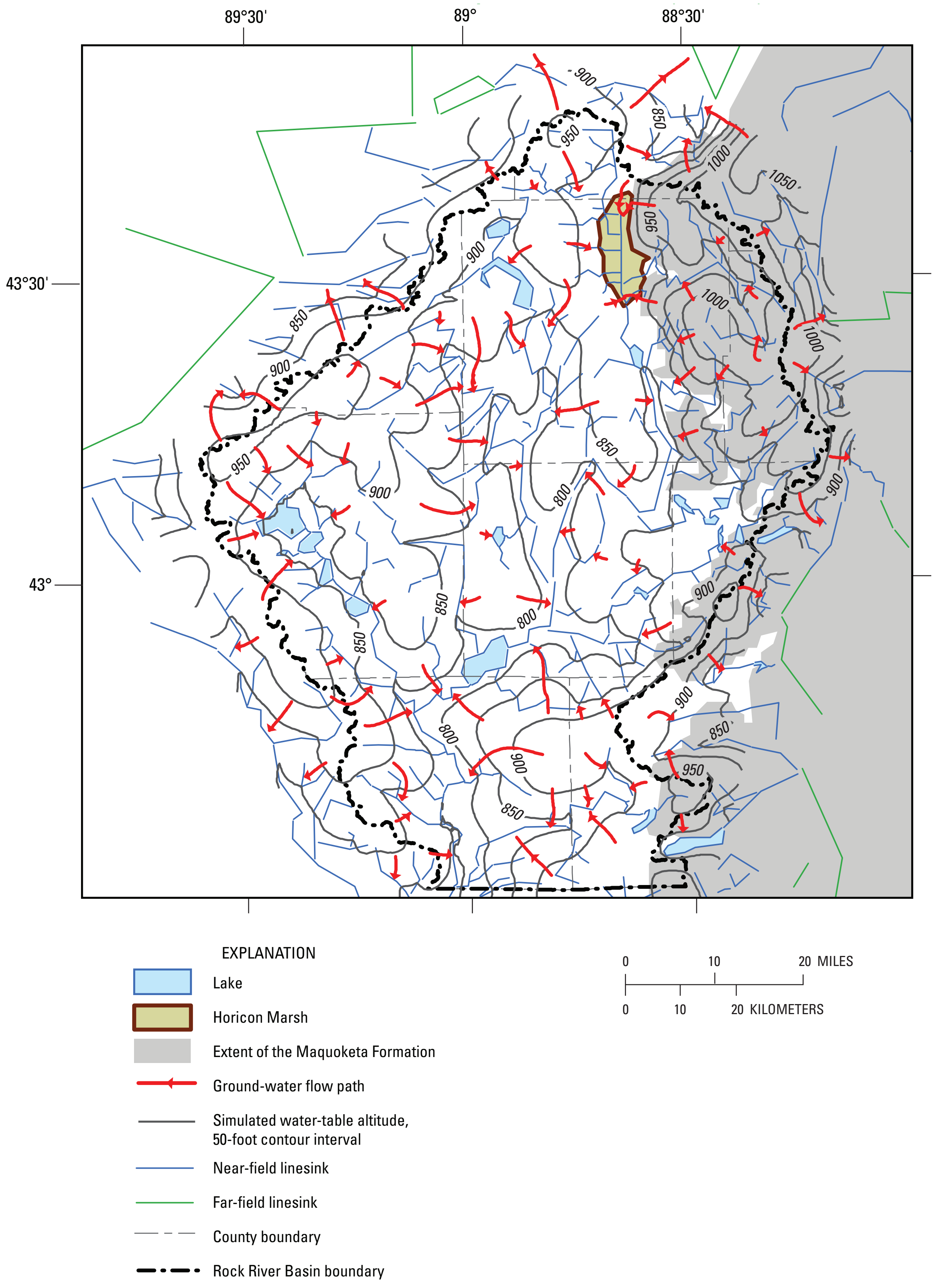

Figure 15. Simulated water-table altitude and ground-water flow directions from the GFLOW model in the Rock River Basin.

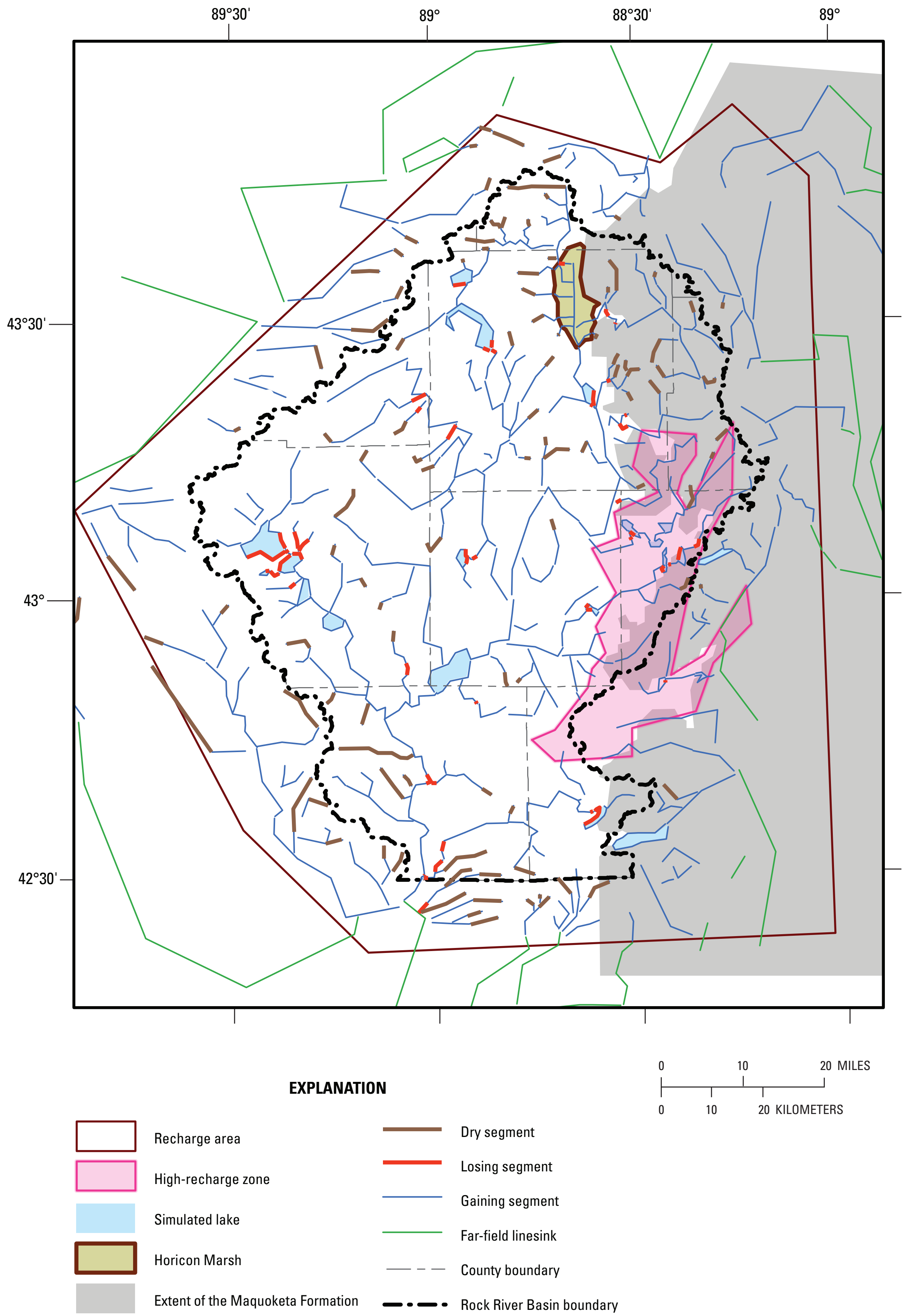

Figure 16. Simulated gaining (blue) and losing (red) river and lake shorelines in the Rock River Basin. Linesinks with zero simulated baseflow (dry) are also shown.

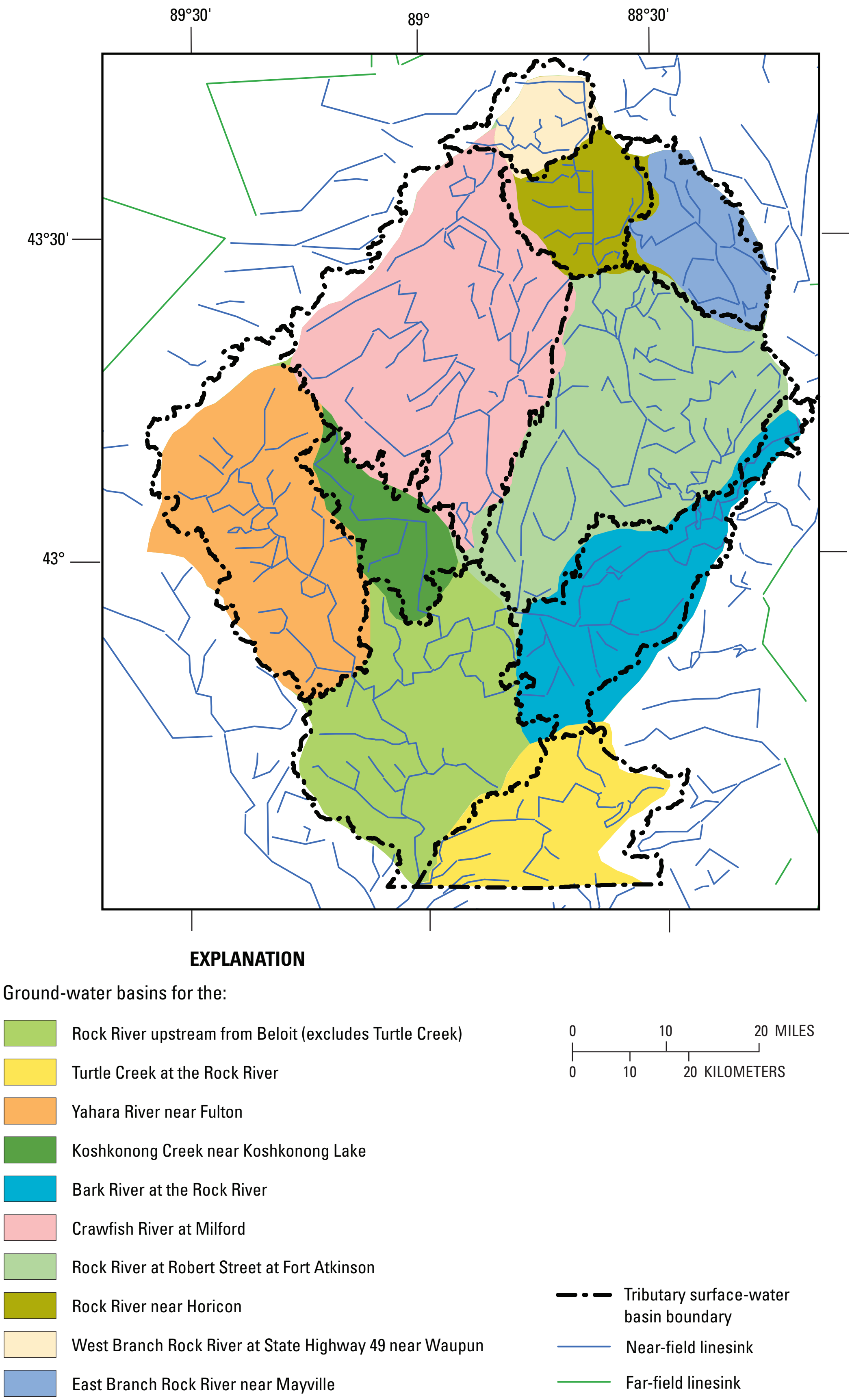

Figure 17. Simulated ground-water and mapped surface-water contributing areas for select tributaries to the Rock River.

Table 4. Hydrologic characteristics and simulated results for selected tributary river basins in the Rock River Basin.

[mi^2, square mile; ft^3/s, cubic foot per second]

Site number in figure 1	Station name	Surface-water-basin area (mi^2)	Ground-water-basin area (mi^2)	Simulated base flow (ft^3/s)	Area above Maquoketa subcrop (percent of surface-water-basin area)
1	Rock River upstream from Beloit (excludes Turtle Creek)	3,460	3,390	1,450	15
2	Turtle Creek at the Rock River	290	280	98	14
3	Yahara River near Fulton	520	520	164	0
4	Koshkonong Creek near Koshkonong Lake	160	160	67	0
5	Bark River at the Rock River	340	370	199	26
6	Crawfish River at Milford	760	750	333	0
7	Rock River at Robert Street at Fort Atkinson	2,240	2,220	1,020	24
8	Rock River near Horicon	460	420	173	48
9	West Branch Rock River at State Highway 49 near Waupun	110	90	16	0
10	East Branch Rock River near Mayville	180	170	75	99

Simulation of Relatively Local Ground-Water-Capture Areas for Rivers

In addition to delineating ground-water basins for select tributaries, the GFLOW model can be used to map areas of relatively local ground water that is captured along stream reaches. Such a map is useful for understanding the primary direction from which a stream reach gains water. For example, many head-water streams that are aligned perpendicular to regional ground-water-flow patterns gain the majority of their base flow along one shoreline, with the other shoreline gaining a smaller amount of ground water or potentially losing water to the ground-water-flow system. Such information may be useful for interpreting local sources of water for a stream and associated differences in the water chemistry among individual streams.

Traces of water particles were simulated with the GFLOW model to evaluate flow directions and delineate areas of relatively local ground water captured by streams. Particles were released in a series of densely spaced grids across the entire basin and tracked forward from the water table to a discharge point (river or well). The length of each path line was recorded and compared with the median flow path length (about 1.6 mi). For this report, relatively local ground-water-capture areas for rivers are defined as the areas in which all simulated particle paths flowing from recharge at the water table to discharge at a stream were less than 1.6 miles.

Relatively local ground-water-capture areas for rivers in the Rock River Basin generally extend a moderate distance upgradient from rivers and are modified by the regional flow pattern (fig. 18). For example, the area is centered on many rivers but is shifted toward regional ground-water divides for relatively small rivers such as Johnson Creek in Jefferson County and Badfish Creek in Dane County. The areas of relatively local ground-water capture are generalized and consider only major tributary rivers; some headwater tributaries were not simulated in the GFLOW model. Likewise, the area contributing to the Horicon Marsh likely extends farther around the marsh than was simulated because the marsh was simulated with a high-conductivity zone instead of a line sink. Conductivity zones do not stop the path of simulated particles because they are not ground-water sinks; line sinks can stop the path of simulated particles because ground water can discharge to these surface-water features, and thereby be removed from the aquifer. The analysis also excluded areas from which simulated particles ultimately discharged to withdrawal wells. Thus, white areas in figure 18 indicate areas in which simulated particles of water either discharged to a withdrawal well or discharged to a river but traveled more than 1.6 miles through the ground-water-flow system. Local or site-specific flow directions and particle path lengths would likely be improved through local refinement of the model. Likewise, measurements of local streambed and lakebed resistance would help to improve local simulations of particle paths.

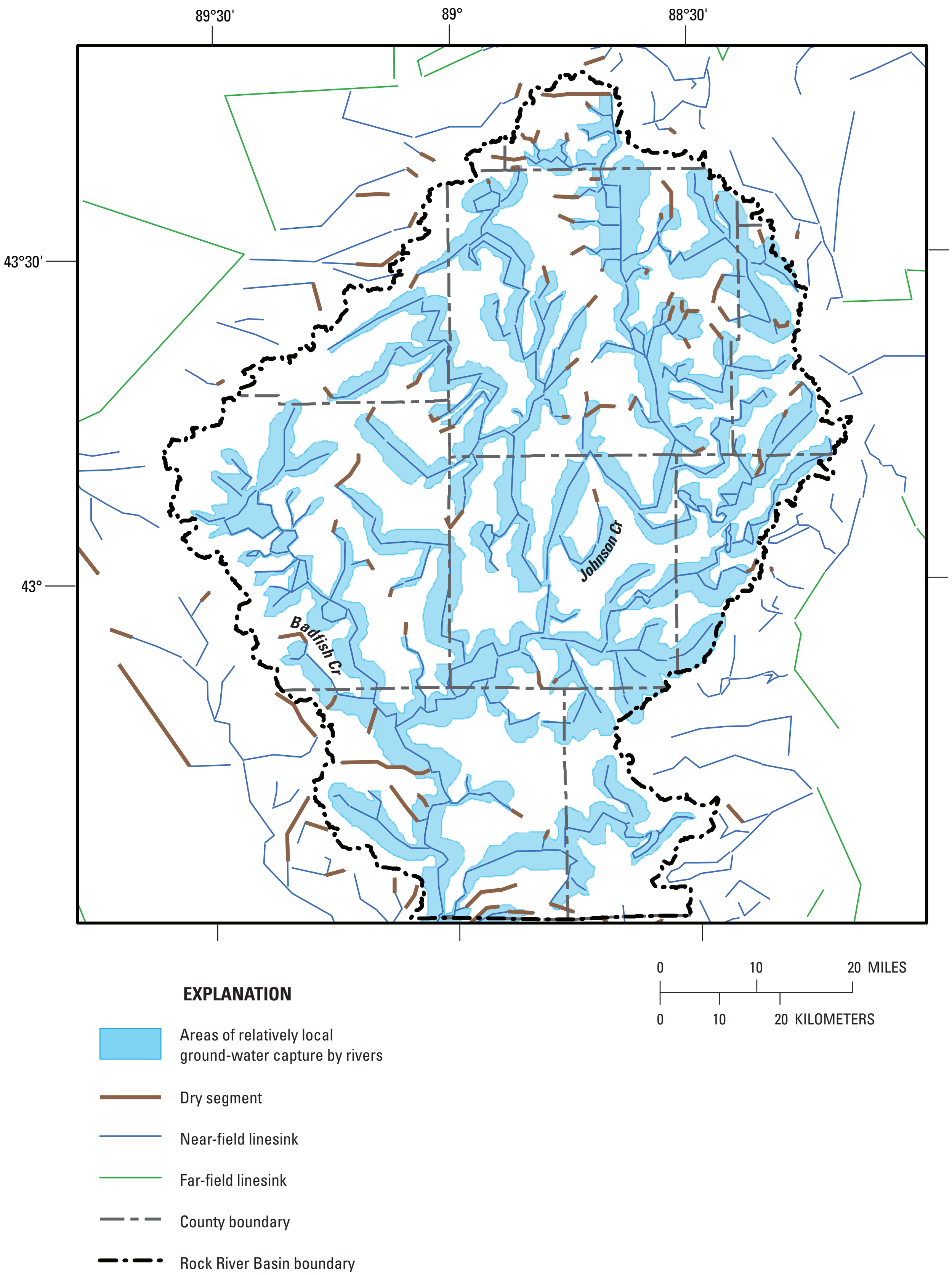

Figure 18. Simulated areas of relatively local (length of travel less than 1.6 miles) ground water captured by rivers in the Rock River Basin.

Model Limitations

As is the case with all ground-water-flow models, the GFLOW model of the Rock River Basin is a simplification of the physical system and has corresponding limitations in model precision and how the model can be used. For example, few first-order (headwater) streams were simulated, and larger streams were simulated with a coarse representation. Likewise, local complexities, such as wetlands, springs, perched water tables and karst aquifers, were not explicitly simulated in the regional model. This approach is well suited for a regional model, which is designed to evaluate effects of regional stressors (for example, estimated large-scale changes in recharge or pumping) on regional features such as large streams. However, use of the model to answer local-scale questions (for example, questions that focus on individual supply wells or a group of supply wells) would benefit from local refinement, including refinement and/or addition of linesinks and possibly local recalibration of the model to additional data for the area. Similarly, depending on the specific aquifer(s) targeted for a local refinement, local discharge-specified linesinks that represent flow below the Maquoketa Formation in the sandstone aquifer may need to be reevaluated and potentially removed. In addition, the regional model may not perform equally in all locations because local geologic complexities were not incorporated into the model. For example, the regional model has limited ability to delineate ground-water basins for headwater streams and supply wells, which are sensitive to local geologic conditions that were not simulated in the regional model.

The model-calibration process focused on long-term water-level and base-flow targets to estimate areally averaged properties of the bulk ground-water-flow system in the Rock River Basin. Short-term, transient phenomena (for example, seasonal water level fluctuations or periodic changes to pumping rates) were not simulated. Steady state models, such as the model described in this report, can be used to evaluate how the system responds to sustained, long-term changes. However, a transient simulation would improve understanding of how the system responds to temporary changes.

Moreover, the flow system contains several layered aquifers and confining units that were combined in this model. Ground-water flow directions within individual aquifers likely vary from that of the system as a whole and would need to be simulated with a three-dimensional model, such as MODFLOW (Harbaugh, 2005), if three-dimensional flow were important. For example, the GFLOW model should not be used to determine how deeper parts of the flow system respond to pumping from a cluster of wells below confining units where flow directions in the deep aquifer do not necessarily follow flow directions in the shallow aquifers. Instead, the GFLOW model provides a regional framework from which a local, three-dimensional model could be developed that would be integrated with the regional flow system. Simple hand calculations (Haitjema, 2006) can be used to evaluate whether a specific question warrants the additional resources of a three-dimensional simulation.

In addition, simulated particle paths that were used to map relatively local ground-water-capture areas (fig. 18) were generated at a regional scale. Local or site-specific flow directions and particle path lengths would likely be improved through local refinement. In particular, measurements of local streambed or lakebed resistance would improve simulations of both horizontal and approximate vertical flow paths near these surface-water features. Moreover, potential future applications of the model for which flow velocities are important (such as mapping a time-dependent contributing area to a well, such as a “10-year zone of capture”) would benefit from field measurements and analyses of porosity, ground-water age, and traveltimes. Water-level and base-flow targets alone do not provide sufficient information for calibrating ground-water velocities and travel times.

Summary

A regional, one-layer, analytic element ground-water-flow model was developed to simulate the ground-water-flow system in the Rock River Basin of southeastern Wisconsin. The model was developed by the U.S. Geological Survey (USGS), in cooperation with the Rock River Coalition, to contribute to the fundamental understanding of the region’s hydrogeology. The objectives of the regional model were to improve understanding of the ground-water-flow system, including ground-water/surface-water interaction, and to develop a tool suitable for evaluating the effects of potential water-management programs. Simulations made with the regional model reproduce ground-water levels and stream base flows representative of recent conditions (1997-2006) and illustrate ground-water-flow patterns with maps of (1) the simulated water table and ground-water-flow directions, (2) simulated gaining and losing river and lake sections, (3) simulated ground-water contributing areas to tributary rivers, and (4) simulated areas of relatively local ground water captured by rivers. In addition, the regional model was designed as a framework in which more detail could be added and from which three-dimensional inset models could be developed.

Three generalized regional aquifers and one regional confining unit are present in the Rock River Basin. The aquifers consist of (1) a sand and gravel aquifer that covers the entire basin, (2) a carbonate aquifer that is present below approximately the eastern one-quarter of the basin, and (3) a sandstone aquifer below the entire basin. The Maquoketa Formation, a regional confining unit, separates the carbonate aquifer above from the sandstone aquifer below. The

Maquoketa Formation and the carbonate aquifer above it have been eroded and are absent in approximately the western three-quarters of the basin. Simplifications were incorporated into the model to simulate the ground-water-flow system with a single layer of differing geologic properties. The sand and gravel aquifer is combined with the carbonate aquifer where it overlies the Maquoketa Formation; the sand and gravel aquifer is combined with the sandstone aquifer where the Maquoketa Formation and overlying carbonate aquifer are absent. Precambrian crystalline rock forms the base of the ground-water-flow system.

The analytic element ground-water-flow model code, GFLOW, was used to develop the regional ground-water-flow model. Model input was obtained from previously published geologic and hydrologic data. Pumping rates from municipal and private high-capacity wells also were simulated. Model calibration included a comparison between modeled and field-measured water levels and base flows in simulated rivers. After calibration, most measured water levels compared favorably to model-calculated water levels; the mean absolute difference and root mean squared difference between measured and simulated water levels were less than 7 percent of the total range in measured water levels. Simulated base flows generally matched measured base flows; simulated base flows were within 10 percent of the estimated base flow at four of nine stream-gage targets. As currently calibrated, the model can be used as a regional water-management tool. Because of the regional focus, however, the model may need to be refined for local-scale simulations.

Simulated water levels and particle tracking in the regional model illustrate ground-water-flow paths from recharge areas toward ground-water discharge areas, such as rivers and wells. Under current conditions, the Rock River, its tributaries, and most large lakes are primarily ground-water discharge locations (gaining reaches), but they include reaches and shorelines that lose surface-water to the ground-water-flow system. Losing river reaches and lake shorelines tend to be primarily along the downgradient side of lakes or reservoirs, near ground-water pumping centers, or along river meanders where local hydraulic gradients can be complex. Ground-water basins for selected tributary basins generally coincide with surface-water basins, but they can differ in headwater areas, such as along the north-western edge of the Yahara and Crawfish River Basins.

Simulated areas of relatively local ground water captured by rivers were estimated by simulating particles of water from the water table to discharge features, such as rivers and supply wells. For this report, relatively local ground water was defined as water that traveled less than 1.6 miles from recharge at the water table to discharge at a stream. These areas generally extend a moderate distance around the rivers and are modified by the regional flow pattern, whereby the areas are commonly shifted toward the upgradient ground-water-flow direction for relatively small rivers. For example, many head-water streams that flow perpendicular to regional ground-water-flow patterns gain the majority of their base flow only along one shoreline. Such information may be useful for interpreting local sources of water for a stream and associated differences in the water chemistry among individual streams.

For most efficient use, the regional model would require periodic updates and improvements as additional field data and estimates of future hydrologic stresses become available. Local refinements of the model could locally improve simulation of flow to rivers, lakes, and wells, especially when combined with additional data collection to improve characterization of local aquifer properties and recharge rates. The model also serves as a framework from which three-dimensional MODFLOW (Harbaugh, 2005) models could be developed. A combination of regional and local simulations would provide a suite of comprehensive tools that could be used by water-resources managers to address emerging water-supply and water-quality concerns in the Rock River Basin.

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Appendixes

Appendix data can be accessed by downloading files at http://pubs.usgs.gov/sir/2009/5094.

Appendix 1. Public-Supply Wells.

Appendix 2. Irrigation, Industrial, and Commercial Supply Wells.

Appendix 3. Public, Irrigation, Industrial, and Commercial Supply Wells in Illinois.

Appendix 4. Ground-Water Observation Network Water-Level Targets.

Appendix 5. Well Construction Report Water-Level Targets.

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