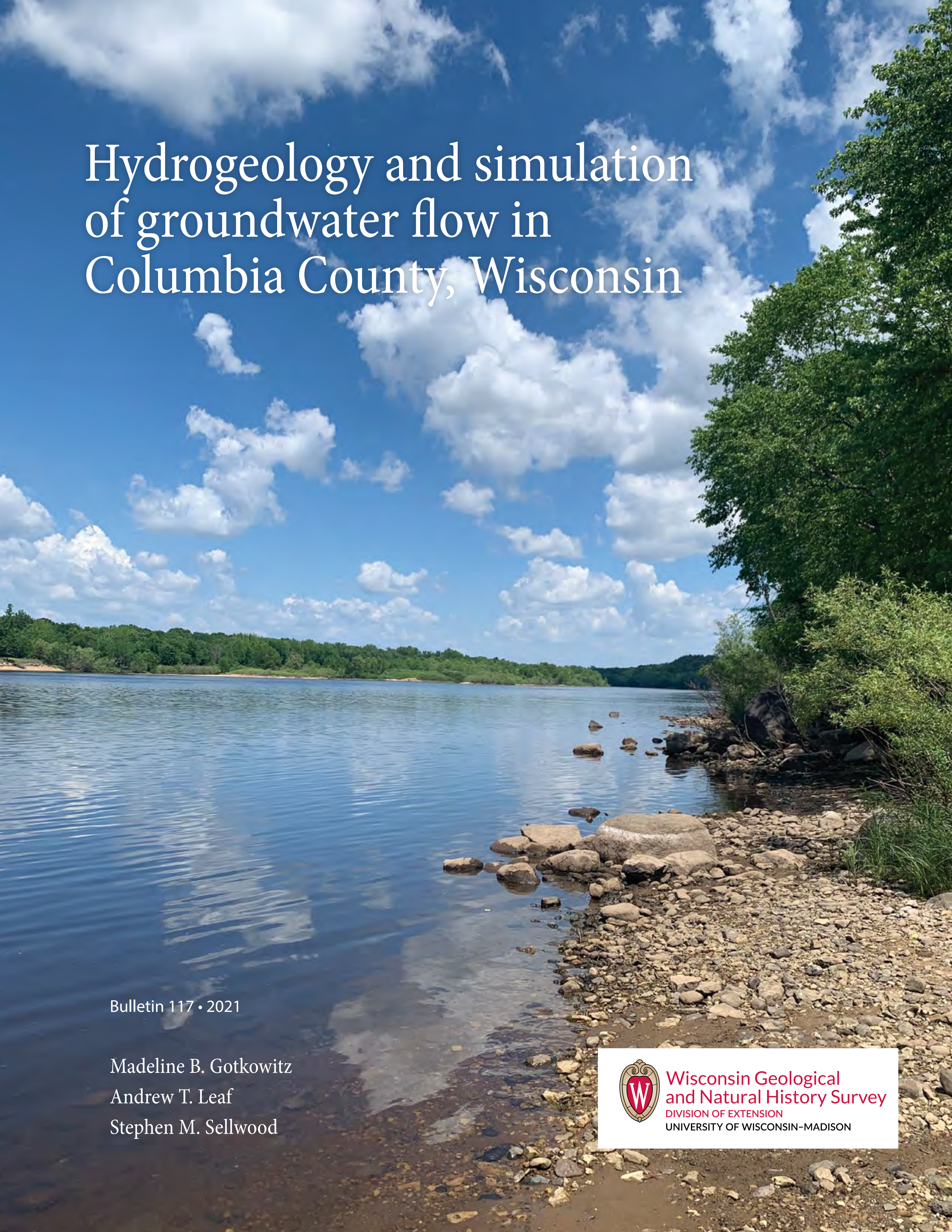

Hydrogeology and simulation of groundwater flow in Columbia County, Wisconsin

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Madeline B. Gotkowitz
Andrew T. Leaf
Stephen M. Sellwood

Wisconsin Geological and Natural History Survey
DIVISION OF EXTENSION
UNIVERSITY OF WISCONSIN–MADISON

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Author affiliations:

Madeline B. Gotkowitz—Wisconsin Geological and Natural History Survey
(current affiliation: Montana Bureau of Mines and Geology)
Andrew T. Leaf—U.S. Geological Survey, Upper Midwest Water Science Center
Stephen M. Sellwood—Wisconsin Geological and Natural History Survey
(current affiliation: TRC Companies, Inc.)

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Cover photos

Front: Wisconsin River, © Columbia County Land and Water Department

Back: Peter Chase, WGNHS geotechnician, preparing packers for well hydraulic tests in a quarry near Rio, Wisconsin, © Madeline Gotkowitz

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Appendices are provided in separate Excel files at https://wgnhs.wisc.edu/pubs/000985/.

Abstract

This report describes the regional hydrogeology and groundwater resources of Columbia County, Wisconsin, and documents a regional groundwater-flow model developed for the county. Regional hydrostratigraphic units include the unlithified aquifer, the upper bedrock aquifer, and the Elk Mound aquifer.

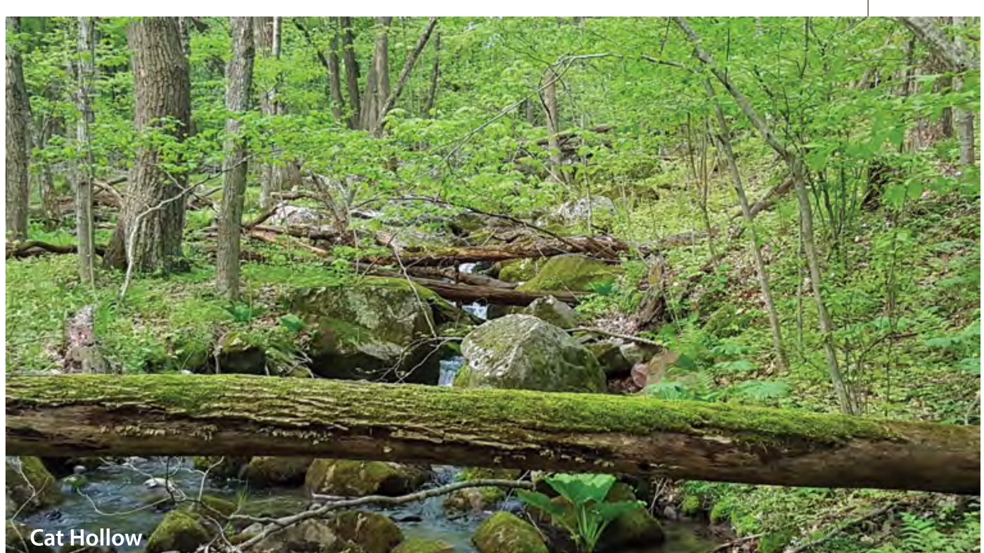
The unlithified aquifer consists of deposits that range in composition from sand and gravel outwash and stream deposits to silty, sandy till. This aquifer is less than 25 feet (ft) thick in much of eastern Columbia County, but it consists of permeable sand and gravel extending to over 250 ft thick in the Wisconsin River valley bottom.

The upper bedrock aquifer consists of Ordovician and Upper Cambrian sedimentary formations, including sandstone, siltstone, and dolomitic strata. The upper bedrock aquifer underlies the unlithified aquifer in eastern portions of the county, but it is absent to the west, where these formations are largely eroded. The contact between the Tunnel City Group and Wonewoc Formation (top of Elk Mound Group) forms the base of the upper bedrock aquifer. Bedding plane fractures are common to this aquifer, although only a portion of the observed fractures appear to be hydraulically active. The upper bedrock aquifer is a substantial source of groundwater at a regional scale. Measurements of hydraulic head showed a difference of several feet across the bottom of this aquifer to the underlying sandstone of the Wonewoc Formation, indicating that the basal facies of the Tunnel City Group functions as an aquitard separating the upper bedrock aquifer from the Elk Mound aquifer. Hydraulic characteristics vary considerably within the upper bedrock aquifer, depending on the local lithostratigraphy. For example, where present, the St. Lawrence Formation and fine-grained intervals of the Tunnel City Group may be locally extensive aquitards.

The Elk Mound aquifer consists of Cambrian sandstone of the Wonewoc, Eau Claire, and Mount Simon Formations. It is thin to absent in several locations but ranges up to 600 ft thick over much of southern Columbia County. The variation in thickness is due in large part to the irregular topography of the underlying Precambrian crystalline rock, which generally serves as the base of the groundwater system. In neighboring counties, a fine-grained facies within the Eau Claire Formation acts as a regionally extensive aquitard, referred to as the Eau Claire aquitard. Much of the data collected and compiled for this study suggest that shale or dolomite within the Eau Claire Formation, which is the equivalent of the Eau Claire aquitard, occurs only within southwestern Columbia County. There is little to no evidence of the Eau Claire aquitard over most of the county. Where the dolomite and shale are absent, the Elk Mound aquifer is relatively homogenous and does not include a mappable aquitard.

The second part of this study involved developing a three-dimensional steady-state groundwater-flow model. The model represents long-term average conditions in the regional groundwater system since about 1970. The six-layer model was constructed with the U.S. Geological Survey's MODFLOW-NWT code and has a uniform grid of 300 ft × 300 ft cells. The model extends beyond the boundaries of Columbia County to ensure that hydrologic conditions simulated within the county are consistent with regional conditions.

Recharge to the groundwater-flow model is based on results from a geographic information system- (GIS-) based soil-water-balance model. Recharge was simulated with the unsaturated zone flow (UZF) package in MODFLOW. This approach is



particularly useful for quantifying groundwater discharge to riparian wetlands because UZF tracks recharge that would lead to the simulated water table exceeding the land surface and reroutes it to nearby stream segments. The model includes pumping from 256 wells, and 178 of these are located within Columbia County. Pumping totaled about 28 million gallons per day on average since 1970, with 7.2 million gallons per day of the withdrawal from within the county. Model calibration was performed using PEST, a parameter estimation code.

Results from the calibrated model provide a groundwater balance for the region. About 83 percent of groundwater originates as recharge to the water table, 12 percent comes from leakage from streams, and about 5 percent of the groundwater flows into the model domain from surrounding areas. About 95 percent of the simulated groundwater discharges to streams and other surface water features, about 3 percent flows across model boundaries to surrounding areas of the groundwater system, and pumping accounts for 2 percent of discharge. Simulated flow paths are relatively local, from recharge in upland areas to discharge in nearby streams and wetlands.

The model has many potential applications, including simulating the effects of existing or proposed high-capacity wells, estimating the zone of contribution for these wells, and understanding relationships between surface water and groundwater. Future refinements to the model, such as incorporating new information about the extent and hydraulic characteristics of the Tunnel City Group, will improve the model's utility in simulating advective flow between the upper bedrock aquifer and the Elk Mound aquifer. If seasonal or annual variations in the groundwater system are of interest, this steady-state model could be brought into a transient mode.

Wisconsin River

Introduction

In 2008, personnel from the Columbia County Departments of Health, Land and Water Conservation, and Land Information formed a working group with the University of Wisconsin–Extension to develop the Columbia County Groundwater Project. Interest centered on concerns about groundwater quality: 21 percent of about 4,730 wells sampled in Columbia County (Center for Watershed Science and Education, 2019) exceeded the federal drinking water standard of 10 milligrams per liter for nitrate (U.S. Environmental Protection Agency, 2000). Issues related to groundwater quantity, such as the extent of drawdown related to pumping from high-capacity irrigation wells, also garnered attention from residents and local officials.

The purpose of the Columbia County Groundwater Project was to conduct a comprehensive inventory and assessment of the county's groundwater resources. Products of this project, including maps, reports, and models, provide technical and educational resources for managing the county's groundwater. The groundwater-resource data and analyses compiled in these products support planning and land-use management efforts by local officials, residents, and the business and agricultural communities. In addition to this report, project results were communicated through a series of public meetings held at several venues in the county. The meetings included presentations of the data, maps, and models developed for this investigation.

The Columbia County Groundwater Project was completed by the Wisconsin Geological and Natural History Survey (WGNHS), the U.S. Geological Survey (USGS), and Columbia County, with initial funding from the Columbia County Board of Supervisors. The Wisconsin Department of Natural Resources (WDNR) Bureau of Drinking Water and Groundwater provided additional funding in 2017 to reevaluate the model calibration and complete the documentation for the groundwater-flow model.

Scope

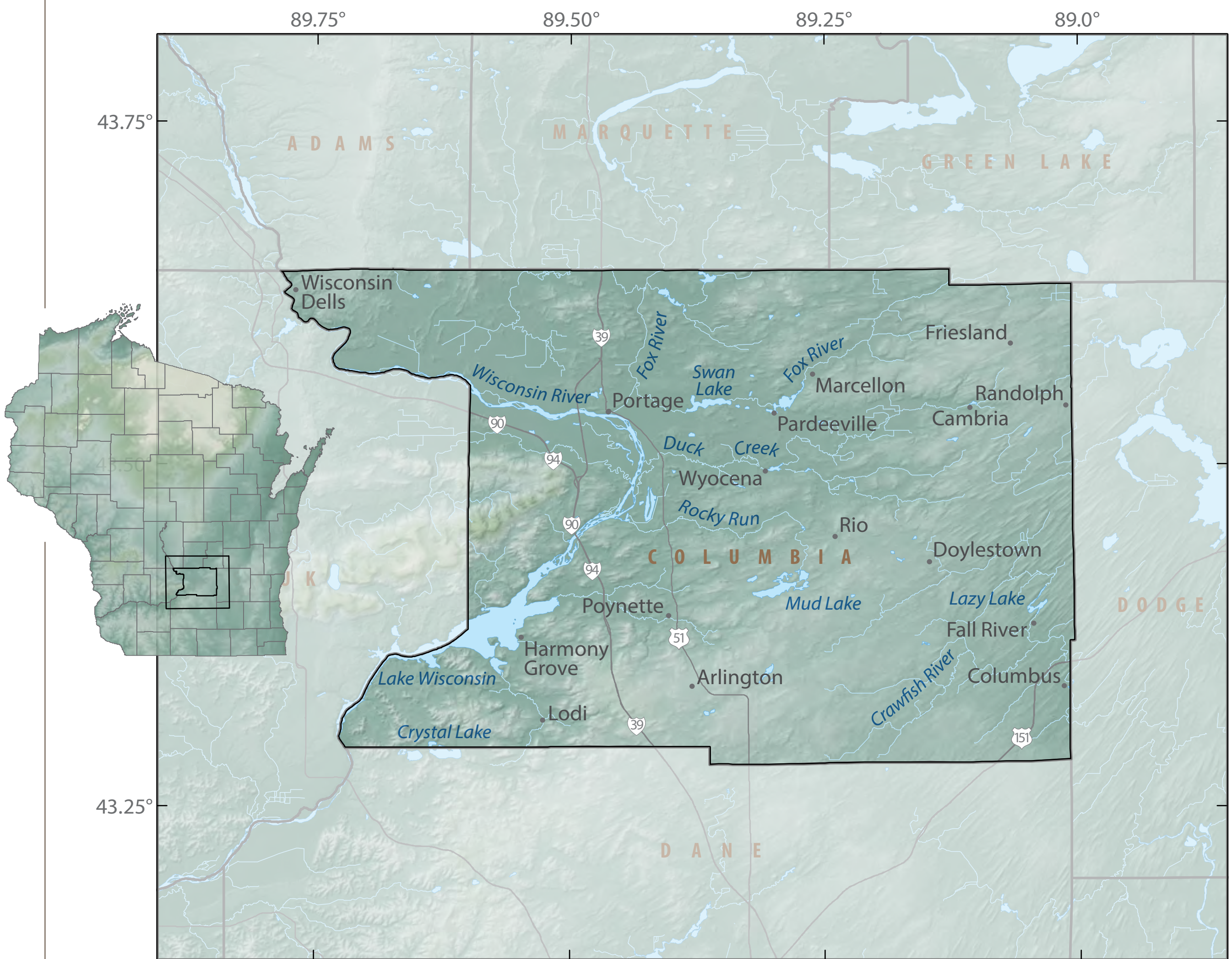
This report describes the regional groundwater-flow system in Columbia County as well as the local hydrologic regimes around population centers. It incorporates a framework for the regional hydrogeology and groundwater flow systems, including a summary of geologic features relevant to the hydrogeology. This report provides compilations of new data collected during field activities, including borehole geophysical logs, streamgage measurements, and hydraulic-head and hydraulic conductivity measurements in wells of opportunity. New and existing data were compiled to estimate the lateral extent and thickness of major aquifers and aquitards and to evaluate groundwater use in the county. Regional-scale maps of the water-table elevation (Sellwood, 2012a), groundwater-recharge estimates (Schoephoester and Gotkowitz, 2012), and groundwater vulnerability (Gotkowitz and Mauel, 2012b) were compiled for this project.

This report also documents the development and calibration of a three-dimensional computer model used to simulate regional groundwater flow. The model domain (fig. 1) is centered on Columbia County and extends into neighboring areas to encompass significant hydraulic boundaries. Regional groundwater-flow models such as this are useful to simulate capture zones, or zones of contribution, for wells. A zone of contribution is the part of the land surface over which recharging precipitation enters a groundwater system and eventually flows to a well. Model-simulated zones of contribution provide a scientific basis for identifying wellhead-protection areas and assessing potential contaminant sources. The model is also appropriate for quantitative analysis of the effects of current and proposed groundwater withdrawals and groundwater-flow patterns near land used for spreading industrial and agricultural waste, as well as for assessing connections between groundwater and surface-water features. This report includes a discussion of the limitations of the model for site-specific analyses, and applications of the model are presented by Gotkowitz (2021).

Physical setting

Columbia County encompasses 774 square miles in south-central Wisconsin, and as of 2019, it had a total population of about 57,500 (U.S. Census Bureau, 2020). Land use is dominated by agricultural row and forage crops, which extend over more than half of the landscape. Wetland areas cover about 15 percent of the county, grasslands cover 13 percent, and forests cover 20 percent. The county is home to three large surface-water basins.

Figure 1. Location of Columbia County, Wisconsin. The figure encompasses the model domain.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator.
Elevation: U.S. Geological Survey National Elevation Dataset, 2017.
Political boundaries: Wisconsin Department of Natural Resources, 2011.
Hydrography: National Hydrography Dataset, 2012.
Roads: U.S. Census Bureau, 2015.

The Fox River Basin lies to the north, within the Lake Michigan watershed. The Wisconsin River Basin extends across a large part of western and central Columbia County, and the Rock River Basin encompasses the southeastern region (fig. 2). Both the Rock and Wisconsin Rivers lie within the Upper Mississippi Basin.

Columbia County hosts four large lakes. The distinctive shape of Lazy Lake, just north of Fall River, conforms to the locations of the surrounding drumlins (fig. 1). Mud Lake, located between Poynette and Rio, is characterized as a marsh or wetland (Poff and Threinen, 1965). Swan Lake is a deep drainage lake on the Fox River. Lake Wisconsin, a large impoundment on the Wisconsin River, was created by the construction of a dam in 1914.

Several geologically distinct physiographic regions contain prominent topographic and geomorphic features (fig. 2). The Driftless Area extends from southwestern Wisconsin into the northwestern corner of Columbia County. This area includes the Wisconsin Dells, a series of deeply incised Cambrian sandstone canyons alongside the Wisconsin River. The Johnstown moraine marks the western edge of the glaciated region that covers most of eastern Wisconsin (fig. 2).

The Baraboo Hills form a steep topographic high to the west in Columbia County, ranging to just over 1,440 ft in elevation. The North and South Ranges consist of Precambrian quartzite and are the surface expression of an east-northeast-trending syncline that extends into neighboring Sauk County. Although quartzite outcrops are common, much of this landscape is covered by a thin layer of glacial deposits less than 25 feet (ft) thick.

About 4 miles (mi) south of the Baraboo Hills, Ordovician and Cambrian sandstone and dolomitic strata crop out in a series of ridges and bluffs ("sandstone ridges" in figure 2). One such ridge forms Gibraltar Rock, where the Ordovician St. Peter Sandstone rises to an elevation of 1,250 ft above sea level.

A large drumlin field cuts across much of eastern Columbia County, extending from Columbus north to Randolph. These elongate features trend northeast-southwest on the landscape, forming a series of 30- to 50-ft-high ridges that extend more than a mile in length. Wetlands are common to lowland areas between these drumlins.

Climate

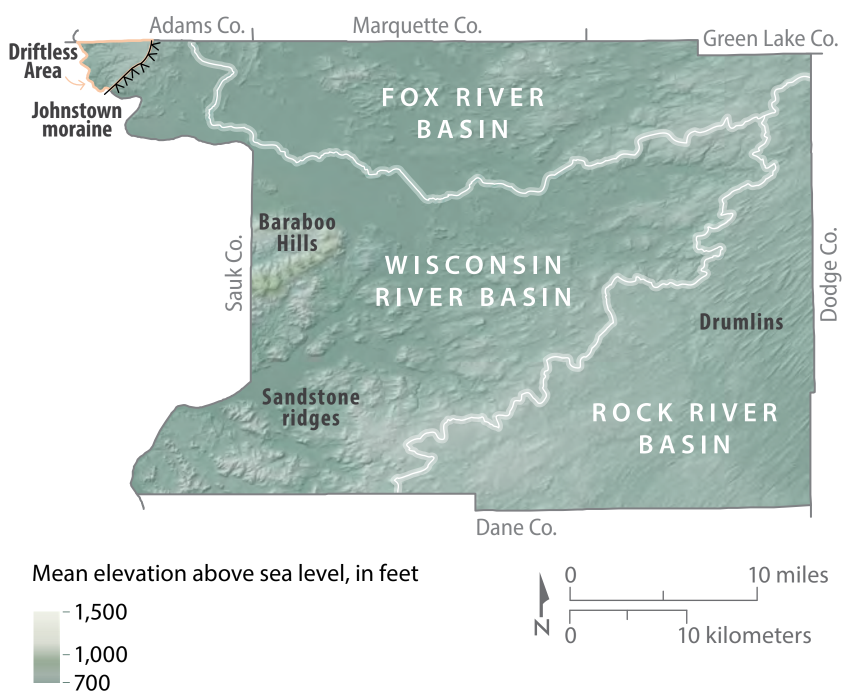
Precipitation records from Portage, Wisconsin (National Oceanic and Atmospheric Administration, 2017) indicate an average annual precipitation of 33.7 inches (in.) in Columbia County for the period 1941–2016 (fig. 3). Sixty-nine percent of this precipitation falls from April to September. Annual precipitation rates from 1941–1969 were compared to those from 1970–2016 (these periods were selected because much of the water-use data compiled for this project represent conditions since 1970, discussed below). Average annual precipitation increased by 4.4 in., from 31.0 in. per year (in./yr) during 1941–1969 to 35.4 in./yr from 1970 to 2016. This increase is generally consistent with trends in central and southern Wisconsin, where increases in average annual precipitation range from 2.0 to 3.9 in./yr (Kucharik and others, 2010).

The average annual air temperature from 1941 to 2016 was 46.5°F. The maximum average monthly temperature of 82.5°F occurs in July and the minimum average monthly temperature of 9.1°F occurs in January (National Oceanic and Atmospheric Administration, 2017).

Previous work

One early assessment of the geology and groundwater resources in Columbia County was provided by Harr and others (1978). Their work focused on estimating well yields in the sand and gravel and bedrock aquifers and it included a countywide bedrock geologic map. Additional mapping completed in Columbia County included a surficial geologic map by Hooyer and others (2015). They identified areas of till and undifferentiated glacial deposits, postglacial peat and stream sediment, and bedrock outcrops. Their map shows the locations and approximate lengths of drumlins within the county. Hooyer and others (2021) described the glacial history of the region.

Figure 2. Shaded-relief map of Columbia County showing major surface-water divides (white lines) and prominent topographic features. The Driftless Area, northwest of the Johnstown moraine, includes the Wisconsin Dells. Vs on moraine symbol point in direction of ice flow.



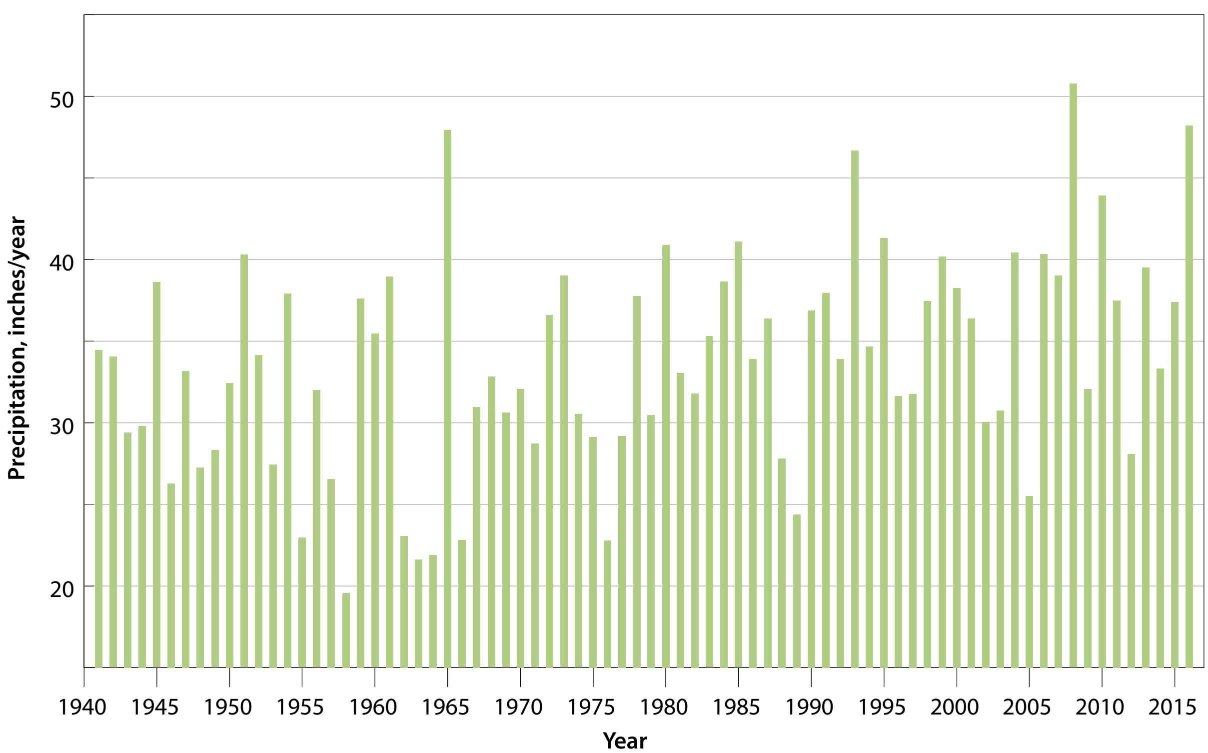
Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Elevation: U.S. Geological Survey National Elevation Dataset, 2017. Political boundaries: Wisconsin Department of Natural Resources, 2011.

Several hydrologic studies have addressed limited areas within Columbia County. Juckem (2009) developed a two-dimensional groundwater-flow model for the Rock River Basin to facilitate the evaluation of regional hydrologic management programs. Several reports addressed persistent elevated surface-water levels at Fish and Crystal Lakes (Krohelski and others, 2002; Johnson and Gotkowitz, 2012). These studies underscored the importance of local geomorphic and geologic features, such as meltwater-stream deposits and lake sediment, to the resulting interactions between groundwater and surface-water features.

Cotter (1969), Hindall and Borman (1974), and Olcott (1968) provided atlas-type summary maps of groundwater and surface-water resources for the Rock, Wisconsin, and Fox River Basins, respectively. Weidman and Schultz (1915) cataloged flowing wells and provided a historical perspective on groundwater conditions and water use in Columbia County. Regional-scale analyses of the hydrogeology and groundwater-flow systems completed by the USGS and the WGNHS in neighboring Dane (Parsen and others, 2016) and Sauk (Gotkowitz and others, 2005) Counties provided conceptual and numerical models representative of this region of the state.

Earlier publications stemming from the work reported here include a series of 1:100,000-scale maps and associated digital data that display the water-table elevation mapped from surface-water features and select wells in Columbia County (Sellwood, 2012a), groundwater susceptibility to contamination (Gotkowitz and Mauel, 2012b), and groundwater recharge (Schoephoester and Gotkowitz, 2012). These maps formed the basis for a series of educational fact sheets about groundwater resources in Columbia County (Gotkowitz, 2012; Gotkowitz and Mauel, 2012a; Sellwood, 2012b). The recharge analysis was used extensively in the work described in this report and is discussed further below.

Figure 3. Annual precipitation at Portage, Wisconsin, 1941–2016.



Methods and data sources

This study relied on a combination of existing and newly collected data. Subsurface records compiled from unpublished data at the WGNHS were organized as geographic information system (GIS) databases. These data are available in related publications (Gotkowitz and Mauel, 2012b; Schoephoester and Gotkowitz, 2012; Sellwood, 2012a). Data collected during this project are documented within this report.

Subsurface characterization

Well construction reports and geologic logs

Approximately 5,100 WDNR well construction reports (WCRs) from the study area were available for this project through databases maintained at WGNHS. The locations of about 2,900 of these WCRs were successfully identified using a GIS address-matching technique or by cross-checking with parcel ownership records, aerial photographs, and USGS 7.5-minute topographic maps. These records were suitable for compiling information about (1) the depth, thickness, and lithology of unlithified materials and bedrock units; and (2) the depth to groundwater. Measurements of the depth to groundwater, to the top of bedrock, and to various lithologic materials (for example, a change from sandstone to shale) were converted to elevations using an estimate of the land-surface elevation from the National Elevation Dataset (USGS, 2009) digital elevation model 10-meter (m) grid.

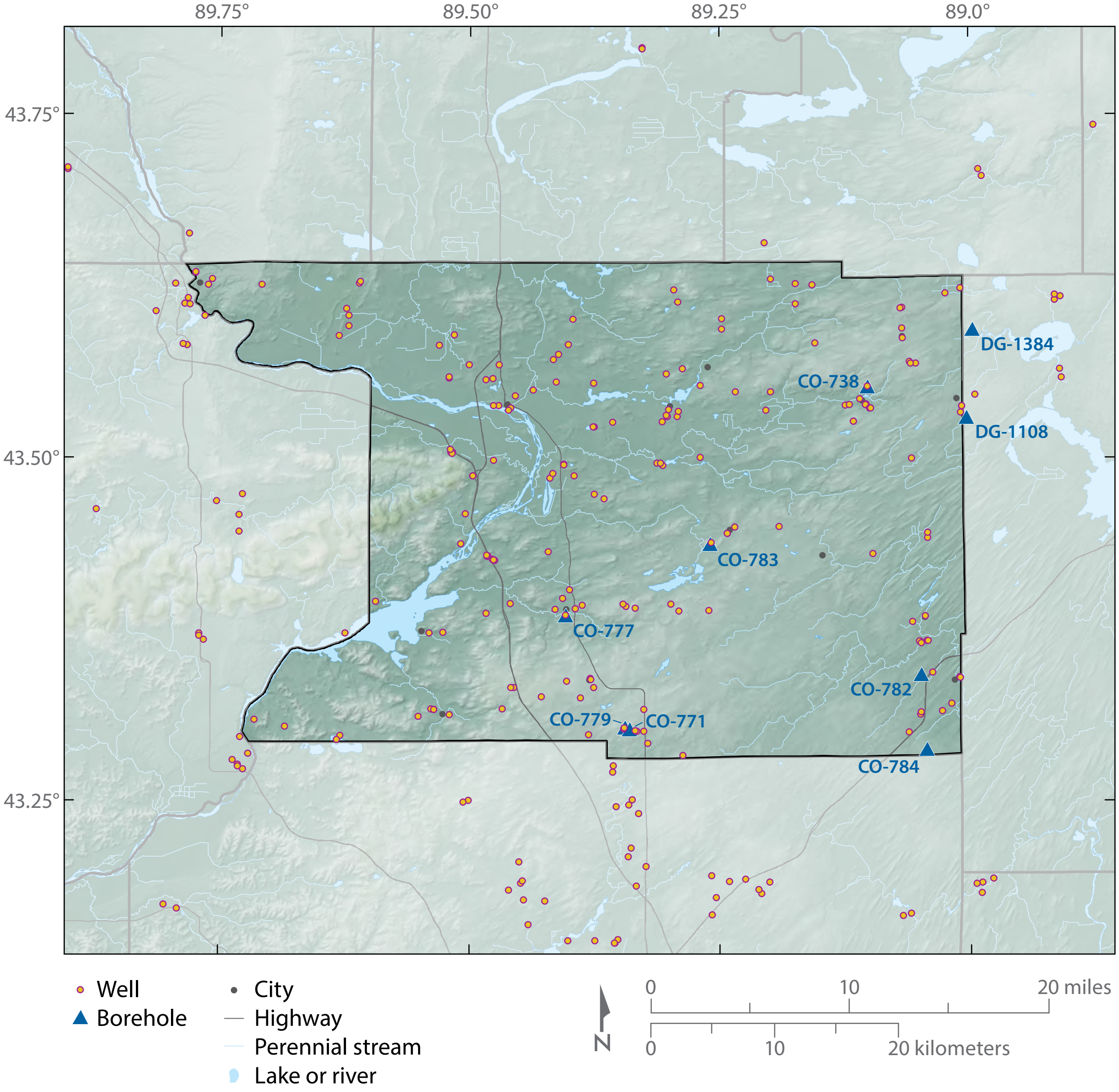
WGNHS geologic logs, which are largely based on interpretations of cuttings from high-capacity wells, contain descriptions of lithology and stratigraphy and are available through databases maintained at WGNHS. About 170 of these logs within Columbia County and an additional 540 logs within the entire model domain provided estimates of the top and bottom elevations of the hydrostratigraphic units. Geologic and hydrogeologic interpretations completed in Sauk (Clayton and Attig, 1990; Gotkowitz and others, 2005) and Dane (Parsen and others, 2016) Counties, and the regional-scale interpretation of the Eau Claire Formation compiled by Aswasereelert and others (2008), were important in developing these estimates of the thickness and extent of hydrostratigraphic units.

Subsurface investigations

Borehole geophysical logs collected by WGNHS in wells of opportunity (locations shown in figure 4) provided high-resolution subsurface information to inform the hydrostratigraphic characterization. The logs, which are maintained in databases at the WGNHS, include (1) vertical profiles of groundwater temperature and conductivity and (2) the resistivity and natural gamma radiation of unlithified and bedrock formations. Borehole caliper logs indicate changes in diameter along the length of the open (uncased) portion of each borehole and, along with optical borehole imaging logs, yield insights into the presence of solution openings and fractures. An impeller borehole flow meter was used to measure a vertical-flow profile under ambient (non-pumping) conditions at several wells. In wells with ambient groundwater flow, these logs were useful to identify flow into or out of discrete stratigraphic horizons and fractures within the uncased portions of the wells. In general, abrupt changes in the borehole flow rate indicate the presence of hydraulically active fractures. In contrast, a gradual increase or decrease in the flow profile indicates an area of porous media flow into or out of the borehole.

At well CO-784, WGNHS collected borehole flow logs under ambient and pumping conditions; these logs were used to estimate hydraulic conductivity variations with depth in the borehole. For a given depth interval in the borehole, the difference in borehole flow rate between the ambient and pumping flow logs is a function of: the drawdown observed in the well during pumping, the radius of the well, the radius of the cone of depression, and the transmissivity of the aquifer at the analyzed depth interval. Using an assumed distance for the radius of the cone of depression, the Thiem equation is used to solve for the transmissivity of each interval as described by Paillet (2001). The resulting transmissivity is fairly insensitive to the radius of the cone of depression so there is little error introduced by assuming this distance. The hydraulic conductivity of each tested interval is calculated by dividing the transmissivity of each analyzed depth interval by the length of the interval. Once the transmissivity of each interval is calculated, the Thiem equation can be used to calculate the hydraulic head difference that drives flow for each interval under non-pumping conditions, thus providing relative ambient heads with depth.

Figure 4. Location of boreholes used for packer tests and geophysical logging (triangles) and high-capacity wells (circles) in the model domain.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Elevation: U.S. Geological Survey National Elevation Dataset, 2017. Political boundaries: Wisconsin Department of Natural Resources, 2011. Hydrography: National Hydrography Dataset, 2012. Cities and roads: U.S. Census Bureau, 2015.

Straddle packer testing was completed at wells CO-783 and CO-779 (fig. 4) by WGNHS to evaluate vertical gradients within the groundwater system. The tests involved lowering a string of two inflatable packers to an interval of interest. The packer string included a screen set between the packers with associated piping to accommodate a submersible pump and pressure transducers. The packers were inflated at the desired depth, forming a seal against the borehole wall and creating an isolated zone of about 17 ft in length. Changes in the hydraulic head above, below, and within the packed zone were monitored before and after packer inflation to verify that the packers were seated and sealed against the borehole wall. Static water-level measurements indicate the vertical distribution of hydraulic head within the groundwater system and were used to calculate vertical gradients between isolated intervals. WGNHS performed specific capacity tests at these wells at constant discharge rates until drawdown stabilized. Pumping rates ranged from about 2 to 30 gallons per minute (gal/min), depending on pump performance in each packed zone. Groundwater samples for water-chemistry analysis were collected from the packed zones, with purge times of up to several hours before sample collection. However, laboratory results indicated that insufficient groundwater was purged to reach ambient water quality in the groundwater system, which was attributed to the long period (about 6 to 12 months) that these wells were open to ambient borehole flow before packer testing. Although the water-quality data are not presented in this report, it is useful to note that in this setting, intra-borehole flow in wells left under ambient (non-pumping) conditions may have altered the groundwater quality at the well over relatively long time periods (Lacombe and others, 1995).

Analysis of well-construction records

About 2,930 WCRs had sufficient information to permit estimation of hydraulic conductivity from specific capacity tests using the method of Bradbury and Rothschild (1985). Of these records, 177 wells were completed in unlithified aquifer sediments, and 2,754 wells were completed in bedrock formations. The hydraulic conductivity estimates obtained using specific capacity data were assigned to layers in the groundwater-flow model (see "Model parameter estimation," below) on the basis of the intersection of each well's open interval reported on the WCR with the model layer's elevations.

Well locations and pumping rates

The USGS identified records from 274 high-capacity wells (as of 2013) within the area shown in figure 4. In this report, the term "high-capacity well" describes those that are permitted to pump 70 gal/min or greater (approximately 100,000 gallons per day), and they typically include wells used for irrigation, industry, and public water supplies. Water-use records were compiled from various sources, including public water supply system reports (Public Service Commission of Wisconsin, 2011), data from the Dane County Groundwater Flow Model (Parsen and others, 2016), data from USGS reports (Maupin and others, 2014) and databases (U.S. Geological Survey, 2017).

Pumping rates at each well were averaged over the time periods each was operating (excluding years when wells were not in operation). Two sets of averages were compiled, post-1970 to 2010 and 2011 to 2012. The post-1970 rates were applied in the model calibration because this period coincided with much of the data compiled for calibration targets. Water-use data from 2011 and 2012 were compiled in anticipation of simulating capture zones for public supply system wells (Gotkowitz, 2021). Records were not available for all wells for all years, as documented in appendix 1. These records indicate that wells within Columbia County account for about 7.2 million gallons of the 28 million gallons per day of groundwater withdrawal from high-capacity wells in the model domain. The well locations and pumping rates applied in the model are included in appendix 1.

Several communities in Columbia County provided additional information about well locations and pumping rates at public water supply wells, including improved well locations and updates on new or reconstructed wells. These rates were cross-checked with records from the WDNR (R. Swale, personal commun., June 12, 2012). Several wells included in the well inventory completed for this project have subsequently been abandoned, taken offline, or reconstructed, as indicated in table 1 and appendix 1.

Table 1. Columbia County public water-supply systems and wells simulated in the model with their average pumping rate during 2011 and 2012.

Public water-supply system	Local well number	Wisconsin unique well number	Average pumping rate (gallons/minute)
Arlington	1	BF357	inactive
Arlington	2	FH500	32
Arlington	3	SO618	22
Arlington	—	BN475	abandoned
Cambria	3	BF358*/RG680**	79
Cambria	4	OU123*/YG115**	40
Cambria	—	BF359	abandoned
Columbus	1	BF360	57
Columbus	2	BF361	57
Columbus	4	EJ755	184
Fall River	1	BF362	73
Fall River	2	BF363	74
Friesland	1	BF364	1
Friesland	2	AW120	12
Harmony Grove	1	BF367	48
Harmony Grove	2	CC036	48
Lodi	2	BF365	61
Lodi	3	BF366*/NY856**	98
Lodi	4	OH446	76
Pardeeville	1	BF368	49
Pardeeville	2	BF369	inactive
Pardeeville	3	EP384	58
Portage	1	BF370	147
Portage	2	DG240	abandoned
Portage	3	BF371	152
Portage	6	BF372	86
Portage	7	BF373	265
Portage	8	EQ935	275
Portage	9	TQ310	444
Poynette	1	BF374	18
Poynette	3	BN481	128
Poynette	4	BF375*/YG586**	128
Randolph	1	BF627	abandoned
Randolph	2	BF628	abandoned
Randolph[1]	3	NY646	86
Randolph[1]	4	YI080	44
Rio	2	BF376	28
Rio	3	BF377*/WK859**	28
Wisconsin Dells	1	BF378	65
Wisconsin Dells	2	BF379	inactive
Wisconsin Dells	3	BF380	135
Wisconsin Dells[2]	4	BG952	69
Wisconsin Dells[2]	5	BG953	75
Wisconsin Dells	6	AC717	95
Wisconsin Dells	7	SO619	75
Wyocena	1	BF381	25
Wyocena	2	BF382	12

[1]Located in Dodge County.
[2]Located in Sauk County.
*/** IDs for original well (*) and reconstructed well (**)

[1]Located in Dodge County.
[2]Located in Sauk County.
*/** IDs for original well (*) and reconstructed well (**)

Streamflow measurements

Measurements of streamflow were used to aid in calibrating the groundwater-flow model. During this project, the WGNHS collected streamflow measurements at 42 locations within the study area, as documented in appendix 2. Measurements were made under low-flow conditions during dry periods of the year to provide insight into rates of baseflow from the groundwater system. Other measurements compiled for model calibration are discussed in "Model parameter estimation," below.

Recharge

Groundwater recharge is the primary source of water to a groundwater system, and estimating recharge rates generally is an important part of constructing and calibrating a groundwater-flow model. However, recharge is difficult to measure directly, in part because it varies spatially (with changes in soil type, vegetation, and topography) and temporally (with daily and seasonal differences in climate). Schoephoester and Gotkowitz (2012) used a Soil-Water-Balance code (SWB) model (Westenbroek and others, 2010) to estimate recharge for Columbia County. The SWB model estimates the deep infiltration of precipitation and snowmelt that passes through soil and the root zone. Schoephoester and Gotkowitz (2012) assumed that deep infiltration was the equivalent of groundwater recharge, which was a reasonable assumption for Columbia County, where climatic conditions are typical of the humid Upper Midwest and evaporation rates are relatively low. However, the SWB model does not account for the rejection of infiltrating water due to a shallow water table at or near the land surface (a process referred to as "Dunnian runoff" by Dunne and Black, 1970); therefore, the model may have overestimated recharge in wetlands and other low-lying wet areas. This limitation of the SWB model is discussed below (see "Boundary conditions," below).

The SWB model applies a mass-balance approach and accounts for all precipitation that reaches the land surface. The model is executed in a GIS environment wherein a grid of cells is overlain on digital maps of soil type, land use, and topography. The model calculates a value of deep infiltration at a daily time step in each model cell:

> **Deep infiltration** = precipitation + run-on – interception – runoff – evapotranspiration – change in soil-moisture storage

Precipitation that does not evaporate or is not (1) intercepted by the tree canopy, (2) transpired by plants, or (3) stored in soil pores is referred to in this report as "excess precipitation." Excess precipitation in a model cell with no available soil-moisture storage is routed to the adjacent downstream cell as runoff. The runoff may either infiltrate the soil or transpire in this cell, or it may continue as runoff to the next downstream cell. This determination is made on the basis of the available soil-moisture capacity in each cell. Precipitation and temperature are input to the model at daily time steps. The temperature is tracked over time to determine periods of snowfall and frozen ground, both of which decrease infiltration. The model uses the daily temperature record to calculate the rate of water use by plants. Westenbroek and others (2010) provided additional detail about calculations performed by the SWB model. Calibration of the groundwater-flow model relied on the SWB model results using the 1981 precipitation record from Portage. At about 33 in., precipitation in 1981 was close to average (fig. 3). Schoephoester and Gotkowitz (2012) summed the daily deep infiltration calculated at each SWB model cell over the year to produce a spatially variable estimate of annual recharge across the county. Recharge estimated for portions of the groundwater-flow model domain outside of Columbia County was based on several other sources (see "Boundary conditions," below).

Installing packer and pump into a well for hydraulic tests.

Groundwater-flow model

The groundwater-flow model was developed by USGS to conduct simulations of the hydrologic system of Columbia County. Details of model construction, underlying data sources, and calibration methods are given in "Simulation of the regional groundwater-flow system," below. Gotkowitz (2021) presents a variety of analyses completed with the model, including simulating zones of contribution to water supply wells for the purposes of wellhead protection and estimating the effects of pumping on water-table elevations and groundwater discharge to streams.

Hydrogeology

An understanding of the regional geology and the hydrogeologic setting underlies the analysis of the groundwater system. The data and methods described above were used to support the following interpretation of geologic deposits, aquifers, and confining units in Columbia County. The geometry of the aquifers and aquitards determined in this characterization provided the basis for the conceptual model and its translation to the numerical flow model, including model layers and geologic heterogeneity within and between layers.

Regional geology

The study area is underlain by Paleozoic (Cambrian and Ordovician) sedimentary bedrock (primarily sandstone and dolomite) overlying Precambrian crystalline bedrock. Although the Paleozoic bedrock is largely flat-lying, dipping regionally about 10 to 15 feet per mile, the Precambrian surface has an irregular, steeply rising topography where it crops out at the Baraboo Hills. Unlithified glacial deposits overlie the bedrock formations over most of the county; however, there are several areas where bedrock outcrops are common. These areas include the Wisconsin Dells to the west of the Johnstown moraine, throughout the Baraboo Hills, and in sandstone ridges south of the Baraboo Hills (fig. 2). Isolated outcrops of Precambrian and Ordovician bedrock are exposed north of Pardeeville, in the Town of Marcellon. The geologic units are summarized below from oldest to youngest, and a generalized stratigraphic column is provided in figure 5.

Precambrian bedrock in Columbia County consists primarily of quartzite and rhyolite. Thwaites (1957) developed a map of the surface elevation of Precambrian bedrock in Wisconsin that displays three datapoints within Columbia County. The map of the

Figure 5. Generalized stratigraphy, hydrostratigraphy, and model layers. Modified from Clayton and Attig (1990).

GENERAL BEDROCK STRATIGRAPHY				HYDROSTRATIGRAPHY AND FLOW MODEL	
Age		Stratigraphic name		Model layer	Name, lithology, type
Era	Period	Group	Formation		
Cenozoic	Quaternary—Holocene Epoch	Unnamed units		1,2	Unlithified aquifer
	Quaternary—Pleistocene Epoch		Holy Hill—Horicon Member		
Paleozoic	Ordovician	Sinnipee		3	Upper bedrock aquifer
		Ancell	St. Peter		
		Prairie du Chien			
	Cambrian	Trempealeau	Jordan		
			St. Lawrence		
		Tunnel City	Lone Rock, Mazomanie		
		Elk Mound	Wonewoc	4	Elk Mound aquifer—Wonewoc Formation
			Eau Claire	5	Elk Mound aquifer—Eau Claire Formation
					Eau Claire aquitard
			Mount Simon	6	Elk Mound aquifer—Mount Simon Formation
Precambrian		Unnamed units			Model base, no-flow boundary

elevation of the Precambrian surface compiled for this project (fig. 6) relied on Thwaites' interpretation and about 130 well records that reported the depth to quartzite or rhyolite.

Cambrian sedimentary rocks overlie the Precambrian bedrock over most of Columbia County, except for the Baraboo Hills. The oldest Cambrian strata, the Mount Simon Formation, is a fine- to medium-grained quartz sandstone bounded by the Precambrian surface at its base and overlain by the Eau Claire Formation. The Eau Claire Formation consists of fine-grained sandstone, siltstone, and mudstone, but varies substantially in composition across south-central Wisconsin (Aswasereelert and others, 2008). The Wonewoc Formation overlies the Eau Claire and consists of fine- to coarse-grained sandstone. Where the Eau Claire Formation has little to no siltstone or mudstone, the formation is difficult to distinguish from the Mount Simon and Wonewoc Formations. In these locations, the Eau Claire, Mount Simon, and Wonewoc Formations are often described as "undifferentiated sandstone of the Elk Mound Group."

Glauconitic sandstone and sandy dolomite of the Tunnel City Group overlie the Elk Mound Group in much of eastern Columbia County. In this region, the Tunnel City Group is likely dominated by very fine to medium-grained glauconitic and feldspathic sandstone of the Lone Rock Formation (Swanson and others, 2006). The Trempealeau Group overlies the Tunnel City Group and is composed of dolomite and siltstone of the St. Lawrence Formation and quartz sandstone of the overlying Jordan Formation (Ostrom, 1978). The Prairie du Chien Group dolomite overlies the Trempealeau Group. The youngest bedrock formations found in Columbia County include sandstone of the St. Peter Formation and dolomite of the Sinnipee Group; these formations are present in limited portions of the study area to the

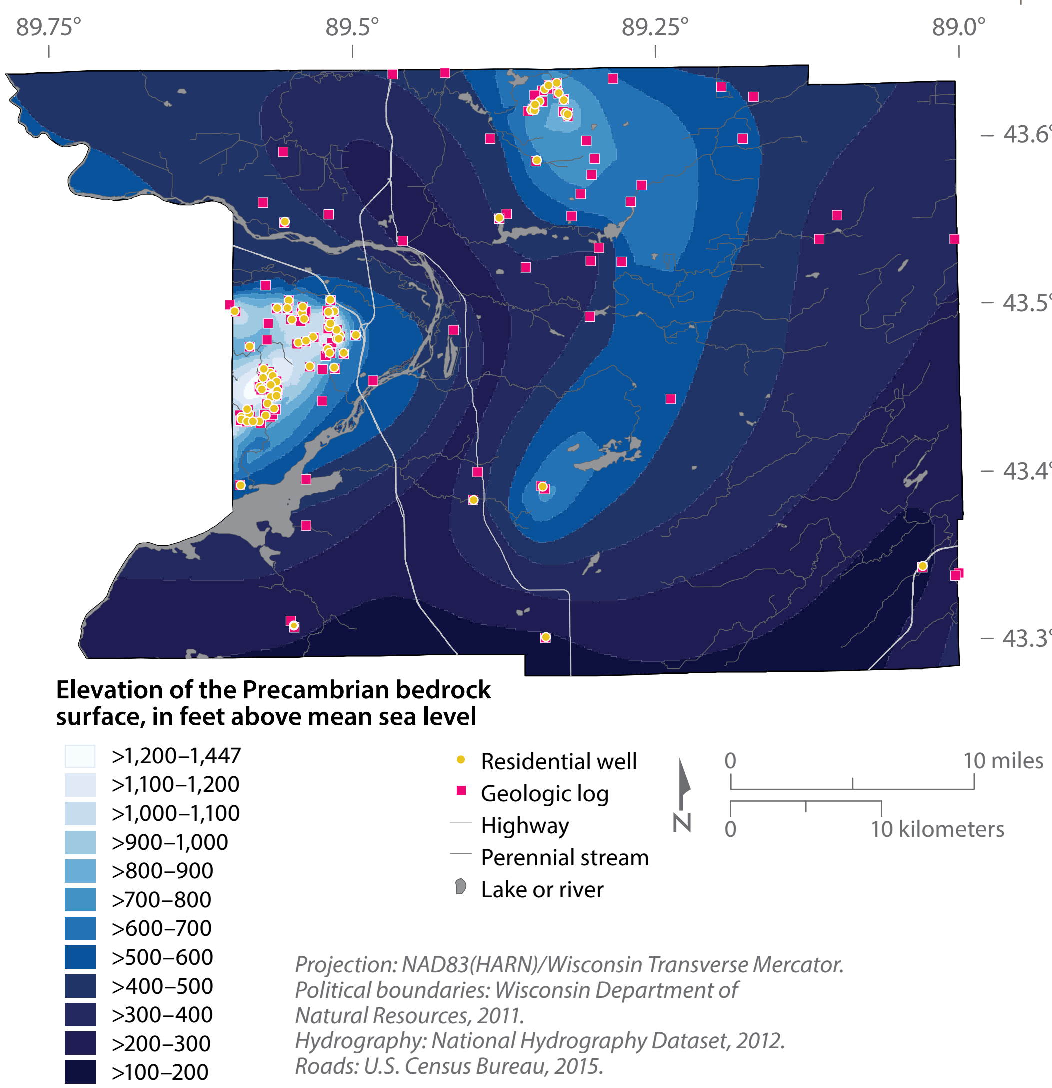


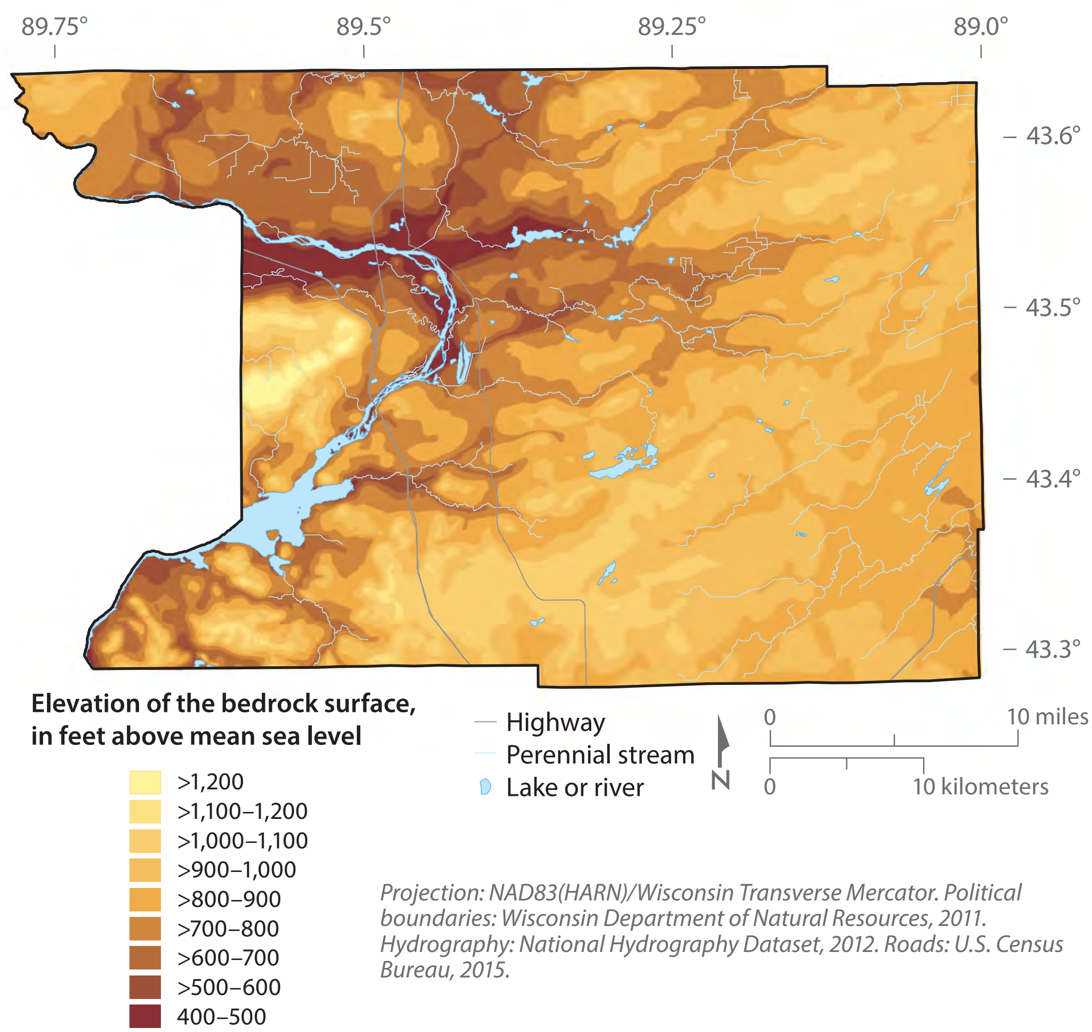
Figure 6. Elevation of the surface of the Precambrian crystalline bedrock, which also marks the bottom of model layer 6. Residential wells completed in crystalline rocks are shown as yellow circles. Pink squares mark locations where the elevation of the Precambrian surface is known from geologic logs.

southeast, near Columbus, and to the northeast, near Randolph (Harr and others, 1978).

The elevation of the uppermost bedrock surface varies dramatically across the county. West of the Wisconsin River, the surface of the Precambrian quartzite is exposed at elevations up to 1,440 ft. Valleys are incised into the Paleozoic strata beneath the Wisconsin and Fox Rivers, where elevations of the surface of the bedrock range from about 400 to 500 ft and 500 to 600 ft, respectively. The surface elevation map for the Paleozoic stratified bedrock developed for this project by WGNHS, shown in figure 7, is based on information from more than 2,780 WCRs.

The complex glacial history of Columbia County is reflected in the variety of surficial sediments that blanket this region. The Johnstown moraine (fig. 2) marks the maximum glacial extent of the Green Bay Lobe during the last part of the Wisconsin glaciation. Till of the Horicon Member of the Holy Hill Formation covers most of the county, except the area west of the moraine. The till consists primarily of gravelly, clayey, or silty sand (Hooyer and others, 2015). Sand and gravel deposited by meltwater streams of the Green Bay Lobe line broad, generally flat valleys occupied by Duck Creek and the Fox River (fig. 1). The Wisconsin River valley contains thick deposits of postglacial stream sediment that is similar in composition to the meltwater sediment. Peat deposits are common in the county and are widespread along Duck Creek and the Fox River and in low-lying areas formed between drumlins in eastern Columbia County. Hooyer and others (2015) identified an extensive peat deposit overlying glacial lake sediment 2 mi east of the Johnstown moraine and several similar deposits in isolated areas in the county. These glacial and postglacial deposits are referred to generally in this report as "unlithified materials."

Figure 7. Elevation of bedrock surface, which also marks the top of model layer 3.



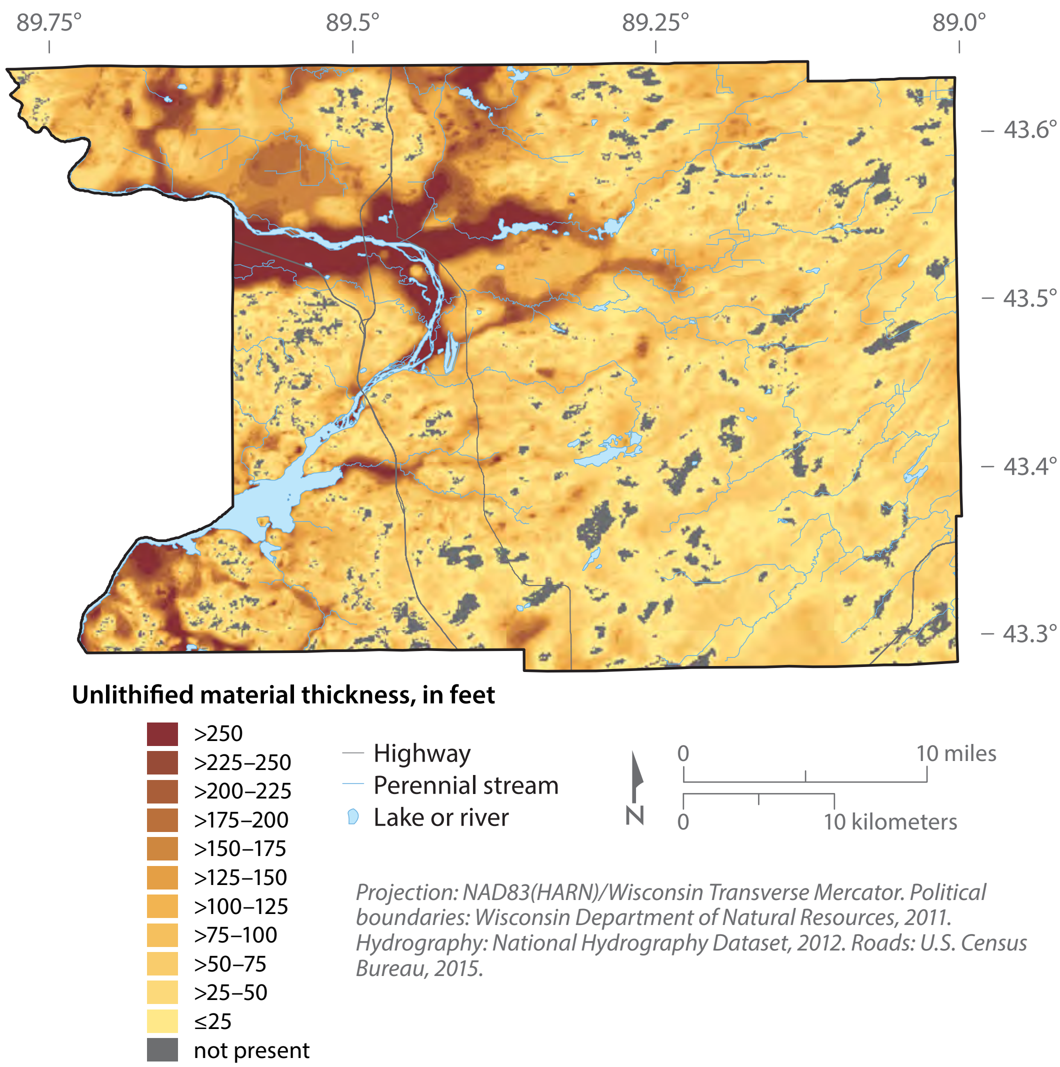
Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Political boundaries: Wisconsin Department of Natural Resources, 2011. Hydrography: National Hydrography Dataset, 2012. Roads: U.S. Census Bureau, 2015.

The thickness of unlithified materials overlying bedrock varies widely across the study area. The surface elevation map for the Paleozoic stratified bedrock (fig. 7) and the land-surface topographic data (USGS, 2009) were used by WGNHS to develop a map of the thickness of these sediments across the county, shown in figure 8. These materials are absent or thin in much of eastern Columbia County but exceed 250 ft thick where glacial and postglacial stream deposits fill deep bedrock valleys, such as those that underlie the Wisconsin and Fox Rivers.

Hydrostratigraphy

Hydrostratigraphic units can correspond to partial or entire geologic formations, or to several formations lumped together, that have similar hydraulic properties. Aquifers are hydrostratigraphic units that can store and transmit water at rates sufficient to supply groundwater to wells. Aquitards are units that are relatively impermeable and restrict the flow of groundwater. On the basis of data and analyses described below, we identified three hydrostratigraphic units that make up the groundwater-flow system in Columbia County. These include, from top (nearest the surface) to bottom (deepest): the unlithified aquifer, the upper bedrock aquifer, and the Elk Mound aquifer (fig. 5). Crystalline Precambrian rocks form the base of the Elk Mound aquifer and the groundwater-flow system. We further subdivided the hydrostratigraphic units into six layers during model development to improve the representation of geologic heterogeneity and hydraulic properties. A series of cross sections (fig. 9) illustrates the geometry of the groundwater flow-system, including the thickness, lateral extent, and complexity in contacts between these hydrostratigraphic units across the region.

Figure 8. Thickness of the unlithified materials, which constitute the unlithified aquifer and are represented by model layers 1 and 2.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Political boundaries: Wisconsin Department of Natural Resources, 2011. Hydrography: National Hydrography Dataset, 2012. Roads: U.S. Census Bureau, 2015.

Figure 9. Hydrostratigraphic cross sections *A–A'* through *E–E'*.

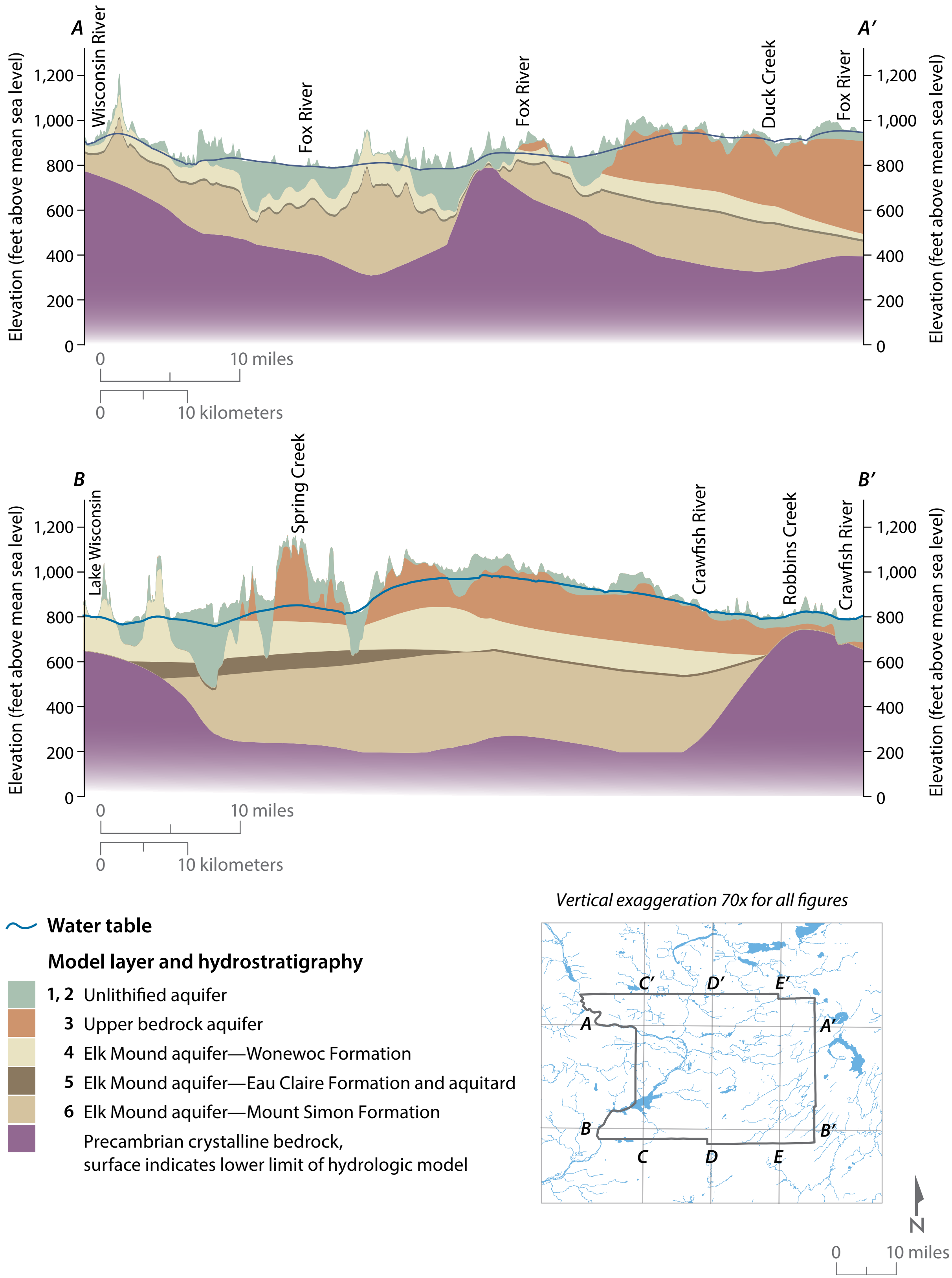
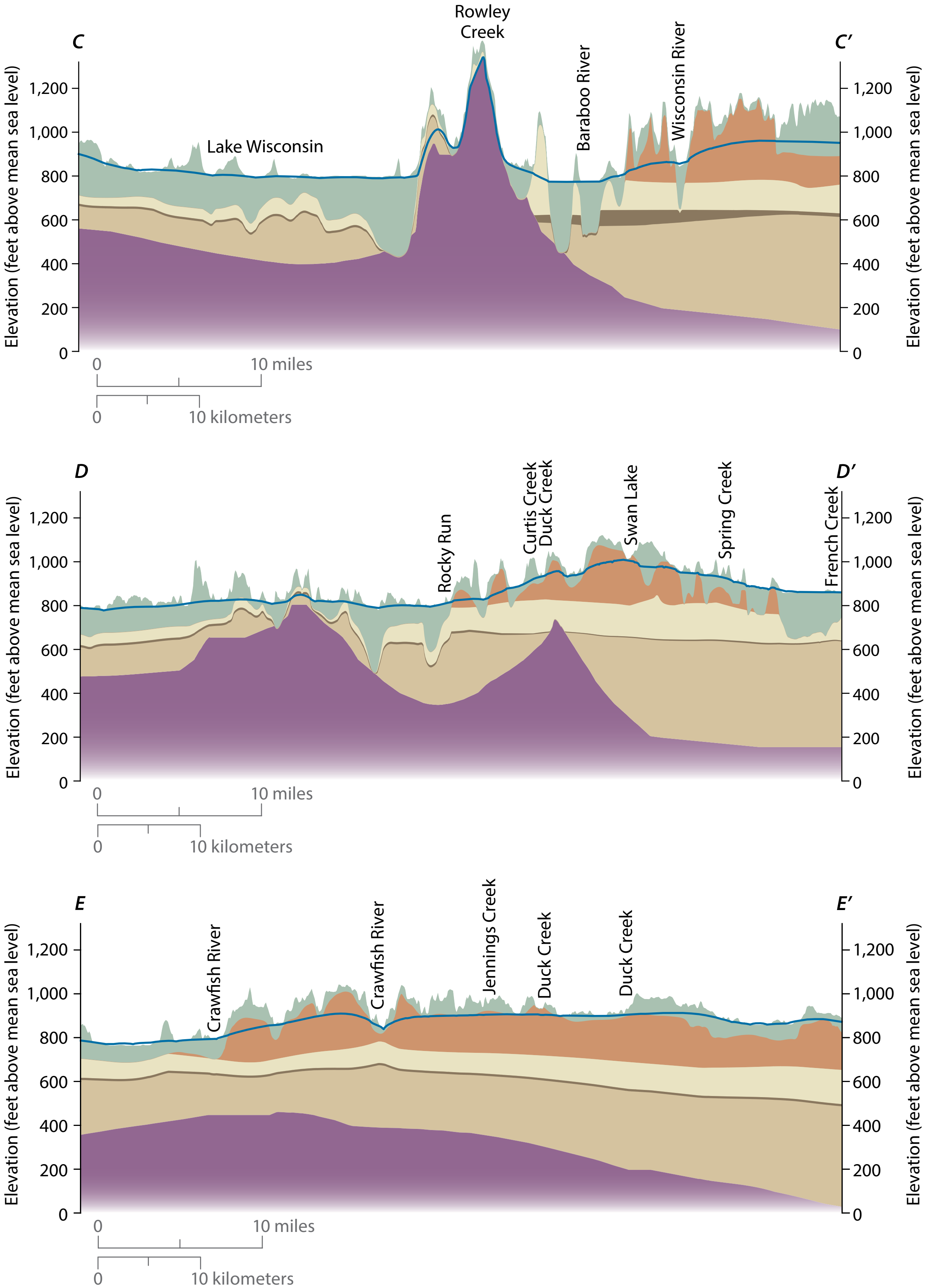


Figure 9. *(continued)*

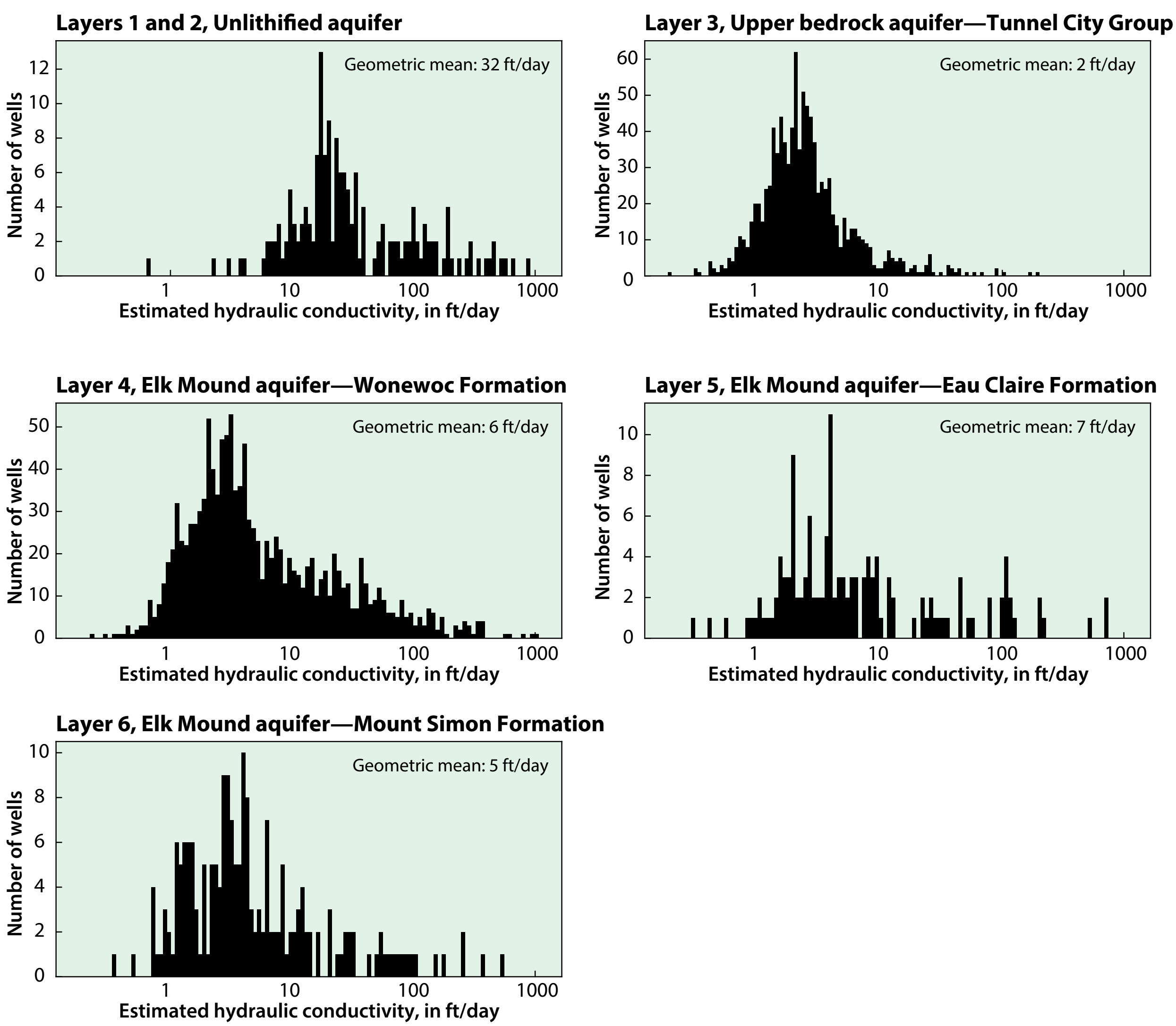


Unlithified aquifer

Unlithified materials of variable thickness cover most of Columbia County. These glacial and postglacial deposits range in composition from sand and gravel outwash and stream deposits to silty, sandy till. Where saturated and of sufficient thickness, these materials form the uppermost aquifer (figs. 8, 9). Specific capacity tests conducted by WGNHS at 177 wells completed in the unlithified aquifer yielded estimates of horizontal hydraulic conductivity ranging from less than 1 to 910 ft per day (ft/day) with a geometric mean of 31 ft/day (table 2). These data are positively skewed, with very few results less than 10 ft/day (fig. 10); estimates of hydraulic conductivity based on these data likely reflect areas where the unlithified aquifer is most productive because water supply wells are unlikely to be completed at locations and depths where the aquifer yield is low. This range of hydraulic conductivity values is reasonable given that some outwash deposits are composed of sand and gravel with little to no fine-grained material. This aquifer is subdivided into layers 1 and 2 in the groundwater-flow model to improve the simulation of vertical hydraulic gradients within these materials (see "Model domain and grid," below).

The unlithified aquifer yields large volumes of groundwater where the unlithified deposits are thick and dominated by high-conductivity sand and gravel sediment. Harr and others (1978) developed a map of the probable well yields in this aquifer, reporting well yields up to 1,000 gal/min. However, in areas where this aquifer consists of sand and gravel with no overlying fine-grained materi-

Figure 10. Histograms showing hydraulic conductivity estimated from specific capacity tests.



als, the unlithified aquifer is relatively unprotected from contamination at the land surface. For example, the Village of Poynette installed a public supply well in 1966 that was screened from a depth of 111 to 126 ft below the ground surface in the unlithified aquifer. According to well-construction records, elevated nitrate concentrations led to the replacement of this well in 2012 by a 440-ft-deep well completed in the underlying bedrock aquifer with a casing that extends to a depth of 250 ft.

Upper bedrock aquifer

The upper bedrock aquifer underlies the unlithified deposits and includes all saturated bedrock above the Wonewoc Formation and below the top of the bedrock surface, including the Tunnel City Group, St. Lawrence and Jordan Formations (undivided), Prairie du Chien Group, St. Peter Formation, and the Sinnipee Group. Where the water table is in bedrock, the water table defines the top of the aquifer. The upper bedrock aquifer consists of sedimentary formations, including sandstone, siltstone, and dolomite. However, erosional processes have limited the lateral extent of many of these layers. Although the hydraulic properties of these formations likely vary, there are relatively few hydraulic data associated with a single geologic layer because most wells are open to multiple formations, and many of the layers are present over limited areas. Additionally, one (or more) of these units is above the water table in many locations within the county. For this study, the lithostratigraphic layers encompassed in the upper bedrock aquifer are conceptualized as a single hydrostratigraphic unit that is represented by model layer 3.

The upper bedrock aquifer extends across the eastern portion of Columbia County (figs. 9 and 11). It is absent to the west, where erosion has removed all but isolated outcrops of Paleozoic formations above the Wonewoc Formation sandstone. The base of the upper bedrock aquifer is the contact between the Tunnel City Group and Wonewoc Formation. About 60 geologic logs describing wells and core holes within Columbia County identify this contact and were used by WGNHS to construct figure 11, a map of the combined thickness of the geologic strata that make up the upper bedrock aquifer. The combined thickness of these formations exceeds 300 ft in a few isolated locations; however, the saturated thickness of the aquifer is defined by the water-table elevation (further described in "Model results," below).

The range of hydraulic conductivity within the upper bedrock aquifer was assessed by analyzing borehole flow logs from well CO-784 (location shown in figure 4) and specific capacity data from WCRs for 985 wells that terminate in the upper bedrock aquifer. The specific capacity test data yielded estimates of horizontal hydraulic conductivity ranging from 0.2 to more than 200 ft/day with a geometric mean of 2.4 ft/day (table 2). The data generally follow a log-normal distribution, with few tests exceeding 10 ft/day (fig. 10). This distribution of hydraulic conductivity is consistent with values derived from analysis of flow logs under both pumping and ambient conditions at well CO-784 (table 3). During the analysis of the geophysical dataset, intervals of interest within the geophysical logs were assigned to fractured or unfractured intervals based on visual inspections of the optical borehole image and other geophysical logs. Intervals with discrete fractures yielded estimates of hydraulic conductivity ranging from 41 to 326 ft/day, and estimates from nonfractured intervals ranged from 3.0 to 15 ft/day (table 3).

Fracture flow in the upper bedrock aquifer

Fractures are commonly observed in geophysical logs of boreholes completed in the upper bedrock aquifer in Columbia County. The ability of a fracture to transmit groundwater is affected in part by the distance over which it persists in the aquifer and the degree to which it is connected to other fractures. Fractures that are suf-

Table 2. Hydraulic conductivity estimates from specific-capacity tests.

Model layer	Hydrostratigraphic unit	Number of tests	Hydraulic conductivity, feet/day		
			Minimum	Maximum	Geometric mean
1, 2	Unlithified aquifer	177	0.6	910	31
3	Upper bedrock aquifer	985	0.2	202	2.4
4	Elk Mound aquifer, Wonewoc Formation	1255	0.2	1072	5.7
5*	Elk Mound aquifer, Eau Claire Formation	136	0.3	749	6.7
6	Elk Mound aquifer, Mount Simon Formation	197	0.3	558	4.8

*Model layer 5 represents the Eau Claire aquitard in some portions of the domain.

Figure 11. Thickness and extent of the upper bedrock aquifer, model layer 3. The Tunnel City Group is present everywhere the upper bedrock aquifer is shown. Locations of geologic logs used to identify the contact of the Tunnel City Group with the Wonewoc Formation are shown as black circles.

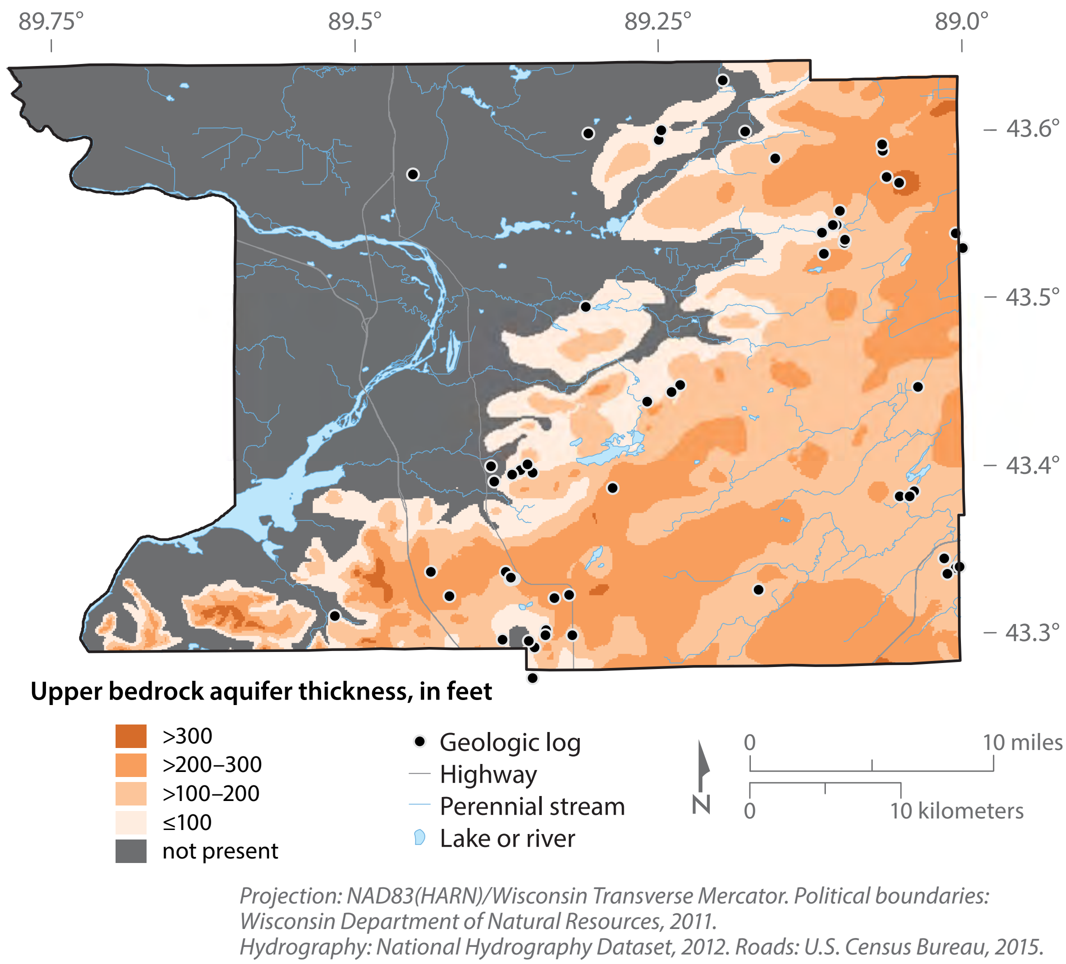


Table 3. Hydraulic conductivity estimates from flow logs and packer tests.

Well	Method	Hydrostratigraphic unit	Number of tests	Hydraulic conductivity, feet/day		
				Minimum	Maximum	Geometric mean
CO-784	Flow log	Upper bedrock aquifer				
		—Unfractured intervals	6	3.0	15	5
		—Fractured intervals	4	41	326	—
	Flow log	Elk Mound aquifer	4	1	10	—
CO-779	Flow log	Elk Mound aquifer	7	1.3	38	6.9
	Packer (specific capacity)	Elk Mound aquifer	13	0.4	68	7.6

ficiently extensive or well-connected to a network of fractures may transmit water more rapidly than the surrounding bedrock and are described as "hydraulically active." However, not all observed fractures appear to appreciably influence groundwater flow.

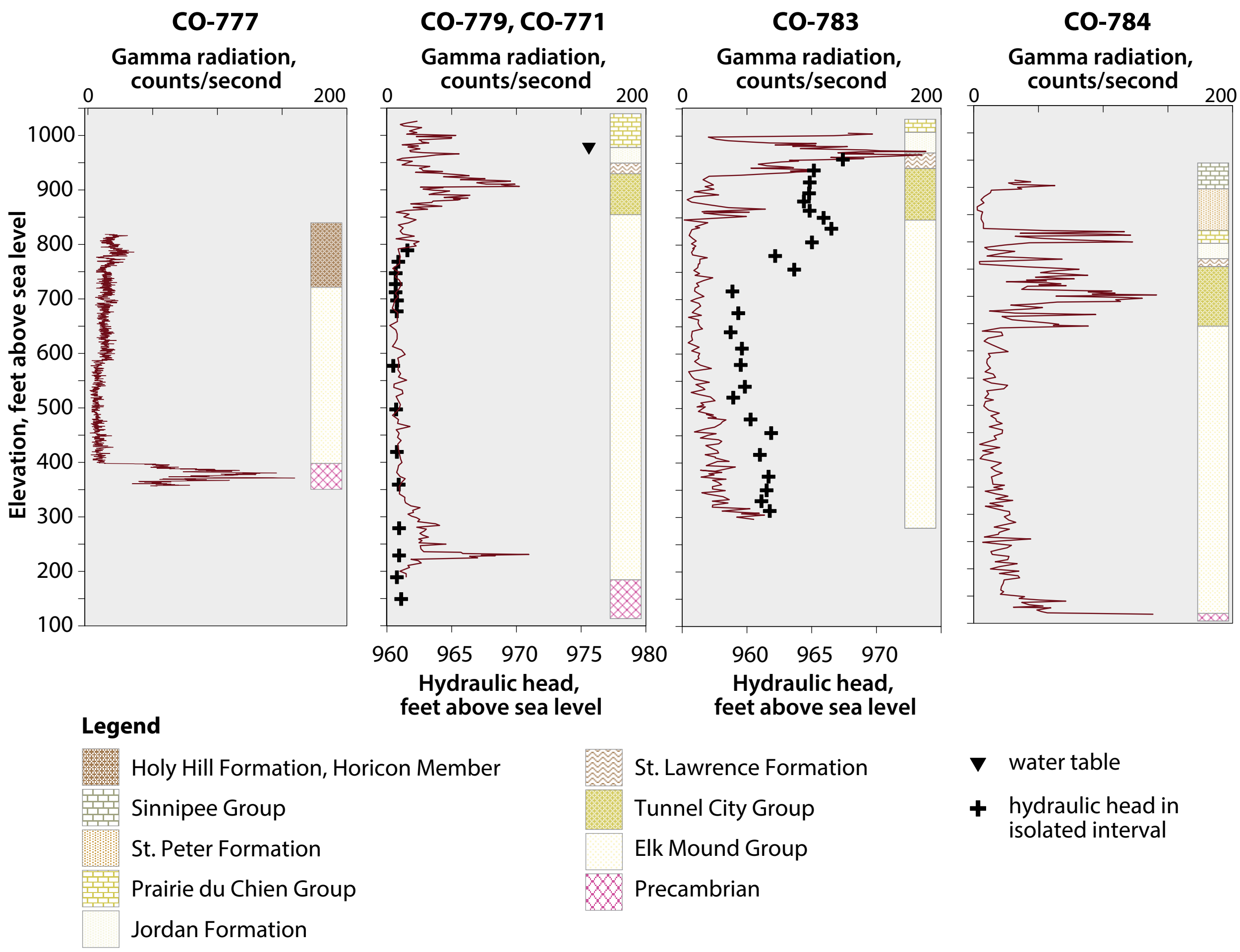
Flow logs collected at well CO-784 under ambient and pumping conditions allowed us to identify hydraulically active fractures in the upper bedrock aquifer and estimate hydraulic conductivity over aquifer thicknesses containing these fractures (table 3). In some cases, hydraulically active fractures can be identified based solely on borehole flow logged under ambient conditions. Sellwood (2015) identified active fracture flow in the sandstone of the Jordan Formation and Tunnel City Group in boreholes CO-782 and DG-1384 (locations shown in fig. 4). Fracture flow was also observed in the upper bedrock aquifer in boreholes DG-1108 and CO-783 (current study). Not all fractures in these formations are hydraulically active under ambient conditions. For example, in borehole CO-782, only a subset of the fractures visible with borehole imaging tools in the Tunnel City Group sandstone were hydraulically active (Sellwood and others, 2015). Other boreholes in the county, such as CO-738 (cased through the upper formations within the upper bedrock aquifer and open to the Tunnel City Group), showed no measurable borehole flow in the Tunnel City Group under ambient conditions. The results from these borehole investigations indicated that fracture flow within the upper bedrock aquifer is variable and dependent on specific fractures or fracture zones within the aquifer.

The observations described above, completed as a part of the current study, are based on locations in Columbia County and nearby in Dodge County. Several studies of the Tunnel City Group in Wisconsin and Minnesota noted the presence of bedding-plane-parallel fractures and their importance as preferential pathways for lateral groundwater flow. Field observations integrated with a numerical model demonstrated that fractures in the Tunnel City Group are likely continuous at scales on the order of several miles (Swanson and others, 2006). Although a single continuous fracture may be unlikely to extend over such distances, there is strong evidence for a higher-conductivity interval at a consistent stratigraphic horizon in the Tunnel City Group in Dane County (Parsen and others, 2016). Runkel and others (2006) suggested that heterogeneous and anisotropic preferential flow features in the Prairie du Chien Group of southeastern Minnesota are mappable at similar scales. Although our study did not evaluate the regional-scale continuity of discrete fractures, the data collected indicated that hydraulically active fractures are common in the upper bedrock aquifer. Rather than simulating flow through discrete fractures, the groundwater-flow model developed for this project simulated flow through porous media. Although it is a simplification of the natural system, this simulation was a practical approach to modeling the upper bedrock aquifer at a regional scale given the uncertainty in the lateral extent and connectivity of the fracture system.

Evidence for a laterally extensive aquitard at the base of the upper bedrock aquifer

The upper bedrock aquifer is an important source of groundwater at a regional scale, as demonstrated by the extensive use of these formations for water supply where it is present within Columbia County and by the relatively high horizontal hydraulic conductivity estimates for this hydrostratigraphic unit. However, several datasets support the conclusion that a facies change at the base of the Tunnel City Group restricts vertical groundwater flow and functions as an aquitard between the upper bedrock aquifer and the underlying Elk Mound aquifer. A hydraulic-head difference of about 5 ft was measured between the upper bedrock aquifer and the underlying Elk Mound aquifer at CO-783 (fig. 12), from about 965 ft to less than 960 ft at depth. Similarly, on the basis of a composite hydraulic-head profile from wells CO-779 and CO-771, a head difference of about 12 ft was measured between shallow monitoring well CO-771 (completed in the Jordan Sandstone) and well CO-779 (which is cased through the upper bedrock aquifer and open across the full thickness of the Elk Mound aquifer). The head difference measured between the upper bedrock and the Elk Mound aquifers served as a target for calibration of the groundwater-flow model. The observed restriction in vertical flow is represented by the hydraulic conductivity distributions in model layers 3 and 4 and reflects these conditions.

Figure 12. Stratigraphy, gamma signatures, and hydraulic heads measured in isolated intervals of study wells. Well locations shown in figure 4.



The confining properties of the basal portion of the Tunnel City Group observed in this study are consistent with other hydrogeologic characterizations of these formations. While working in Dane County, Meyer and others (2008) measured a decrease in head of about 10 ft from the upper bedrock aquifer across the Tunnel City Group to the top of the Elk Mound Group, indicating that the glauconite-rich Tunnel City Group may confine the Elk Mound aquifer. A detailed study in Minnesota (Runkel and others, 2006) characterized the upper portions of the Franconia Formation (the Tunnel City Group equivalent) as a relatively transmissive facies dominated by bedding-plane fractures and coarse clastic sediment in contrast to a confining interval consisting of fine clastic sediment in the lower Franconia Formation. Across the northern Midwest, the St. Lawrence Formation and underlying Tunnel City Group are generally considered to be an anisotropic confining unit that restricts vertical flow (Young, 1992).

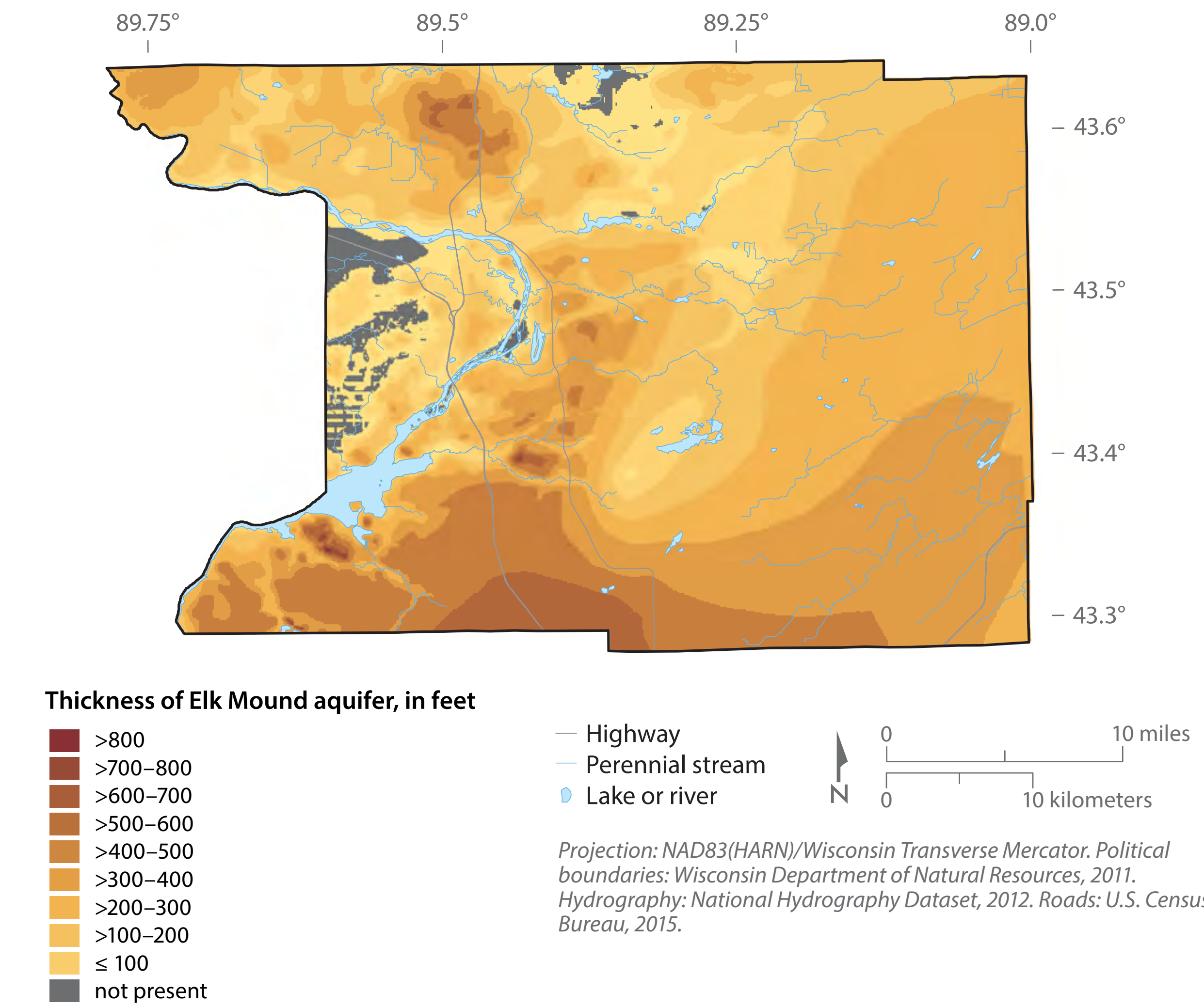
Elk Mound aquifer

The Elk Mound aquifer consists of saturated bedrock within the undifferentiated Elk Mound Group or within the Wonewoc, Eau Claire, and Mount Simon Formations where these strata are differentiated. As illustrated in figures 9 and 11, where the upper bedrock aquifer is present, the contact of the Wonewoc Formation with the overlying Tunnel City Group forms the top of the Elk Mound aquifer. In western regions of Columbia County, the upper bedrock aquifer is absent, and the top of the Elk Mound aquifer is the bedrock surface. Where the water table is within the bedrock, the water table forms the top of the aquifer. The Precambrian surface forms the base of the Elk Mound aquifer. As illustrated by cross sections *A–A′*, *C–C′*, and *D–D′* in figure 9, the Elk Mound aquifer is thin to absent in several locations, including in areas where crystalline rocks crop out and in portions of the Wisconsin River valley. Figure 13 shows the range in the Elk Mound aquifer's thickness from less than 200 ft over large portions of the county to more than 600 ft across much of southern Columbia County. The Wonewoc, Eau Claire, and Mount Simon Formations are represented by layers 4, 5, and 6, respectively, in the groundwater-flow model. These formations are largely indistinguishable from each other over much of Columbia County. However, the use of multiple layers to simulate this aquifer improves the representation of heterogeneity in lithology and hydraulic conductivity where they are present within the aquifer.

Heterogeneity within the Eau Claire Formation

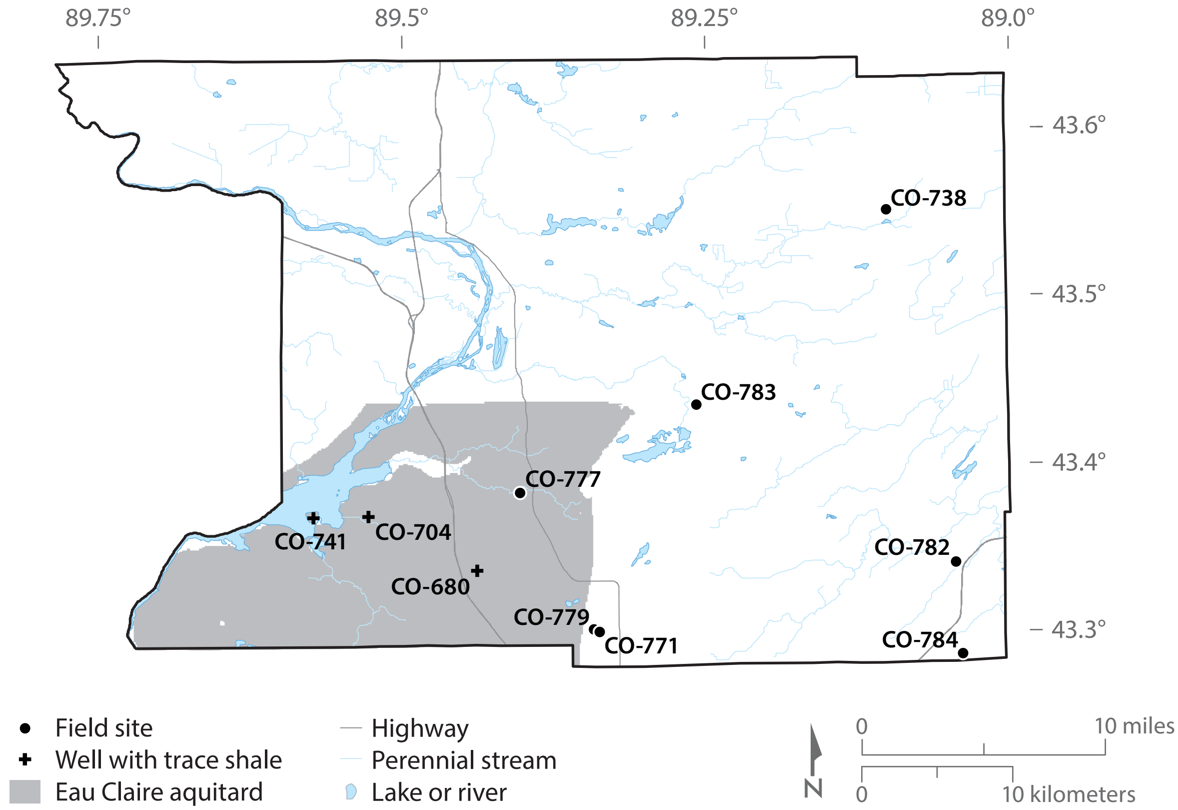
In Dane and Sauk Counties, the Eau Claire Formation contains substantial amounts of fine-grained lithologies, including laterally extensive interbedded horizons of shale, siltstone, dolomite, and shaly sandstone (Aswasereelert and others, 2008). Hydrogeologic studies of Dane (Parsen and others, 2016) and Sauk (Gotkowitz and others, 2005) Counties recognize the fine-grained portions of the Eau Claire Formation as the regionally significant Eau Claire aquitard, which exceeds 200 ft of thickness south of the Baraboo Hills and thins to the southeast. The subsurface data available to assess the extent of the Eau Claire aquitard in Columbia County include lithologic descriptions on geologic logs and drillers reports. A few geologic logs (CO-741, CO-704, and CO-680) in southwestern Columbia County report some shale or dolomite within undifferentiated Elk Mound Group sandstone, and these lithologies support the interpretation of the Eau Claire aquitard's extent shown in figure 14. Other lines of evidence do not indicate the presence of an aquitard within the Elk Mound aquifer. Fieldwork completed at locations farther east and descriptions of the lithology on geologic logs

Figure 13. Thickness of Elk Mound aquifer, model layers 4, 5, and 6.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Political boundaries: Wisconsin Department of Natural Resources, 2011. Hydrography: National Hydrography Dataset, 2012. Roads: U.S. Census Bureau, 2015.

Figure 14. Extent of Eau Claire aquitard (gray area) simulated in model layer 5. Locations of wells with geologic logs that report trace of shale are shown in addition to field sites with geophysical logs and head profiles.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Political boundaries: Wisconsin Department of Natural Resources, 2011. Hydrography: National Hydrography Dataset, 2012. Roads: U.S. Census Bureau, 2015.

in this region do not support differentiation between the Wonewoc, Eau Claire, and Mount Simon Formations. Hydraulic heads measured in isolated intervals within CO-779 (fig. 12) do not indicate vertical gradients within the Elk Mound aquifer, but instead indicate homogenous aquifer properties at this location. Head measurements from CO-783 display some variation within the Elk Mound aquifer. However, the magnitude of head change is low, which, along with the gamma radiation log and description of well cuttings from this location, indicates that there is no aquitard within the Eau Claire Formation or other portions of the Elk Mound Group at the location of CO-783. Gamma radiation logs collected at all other field sites in the eastern part of the county support the interpretation that the Elk Mound aquifer is vertically homogenous with no evidence of low-hydraulic-conductivity facies in the Eau Claire Formation.

The representation of the Eau Claire aquitard facies in the Dane County groundwater model developed by Parsen and others (2016) extends into the southwestern quadrant of Columbia County (fig. 14). Given their interpretation and a few data points that delineate the boundary of the fine-grained facies in Columbia County, we delineated a hydraulic conductivity zone within model layer 5, which corresponds to the Eau Claire Formation. Vertical and horizontal hydraulic conductivity values within this zone were allowed to vary during model calibration to best fit field observations of head and baseflow and a preferred condition of lateral homogeneity within the zone. Collection of additional subsurface data in the southwestern part of Columbia County could help refine the representation of the Eau Claire aquitard facies in future versions of the groundwater-flow model.

Specific-capacity-test data from 1,588 wells completed in the Elk Mound aquifer were analyzed after assigning each record to one of the three geologic formations in the aquifer on the basis of the total depth of the well. As shown in table 2 and figure 10, the three datasets have similar geometric means, from 4.8 to 6.7 ft/

day, and generally follow a log-normal distribution. These data are in good agreement with estimates based on the flow logs and packer tests completed for this study (table 3).

Hydraulically active fractures in the Wonewoc Formation were observed in nearby Dane County (Leaf and others, 2012; Sellwood and others, 2015). In Columbia County, Sellwood and others (2015) inferred the presence of a hydraulically active fracture at CO-782 at a depth of 46 ft below the top of the Elk Mound aquifer; however, this borehole was not deep enough to evaluate flow deeper in the aquifer. A visual inspection of the optical borehole imaging log from CO-784 and an analysis of the impeller flow meter logs (table 3) do not indicate the presence of hydraulically active fractures in the aquifer. A series of in-well heat tracer tests at this well reported by Sellwood and others (2015) similarly indicated the absence of fracture flow and the predominance of porous media flow within the Elk Mound aquifer at this location. Geophysical logs from CO-783, CO-779, and CO-738, and ambient flow meter logs collected at CO-783 and CO-779 (shown in fig. 12, except for well CO-738) do not indicate fracture flow in the aquifer.

Precambrian crystalline formations

At a regional scale, the Precambrian quartzite and rhyolite form the base of the groundwater system in Columbia County and are relatively impermeable to groundwater flow. The matrix permeability of these rocks is expected to be low in contrast to the overlying Cambrian sedimentary formations. However, in the Baraboo Hills region and the town of Marcellon, where the unlithified, upper bedrock, and Elk Mound aquifers are very thin or absent, some residential wells were drilled into the relatively impermeable crystalline quartzite, and the wells yield sufficient water for domestic supply (fig. 6). These wells were typically drilled several hundred feet deep into the quartzite and yield small amounts of water, with specific capacities commonly less than 0.1 gal/min per foot of drawdown. The groundwater flow to these wells was assumed to occur primarily through fractures.

Conceptual model of the groundwater-flow system

This conceptual model of the groundwater-flow system synthesizes the hydrogeologic data and interpretations presented above. The conceptual model includes significant features of the natural groundwater system but also imposes simplifications so that the natural system can be represented with a computer model. The flow model layers are also described here to illustrate the representation of the hydrostratigraphy and conceptual model in the numerical model.

The aquifers include the unlithified aquifer, the upper bedrock aquifer, and the Elk Mound aquifer. The unlithifed aquifer is thin or absent in much of eastern Columbia County but is thick and prolific in major river valleys. Dividing the unlithified aquifer into two model layers improves the simulation of vertical gradients where present.

The upper bedrock aquifer extends across the eastern and southern portions of the county. Fracture flow within the aquifer is variable and seems to depend on locally extensive fractures or fracture zones within it. A facies at the base of the Tunnel City Group is of sufficiently low hydraulic conductivity to form an aquitard between overlying sediments and the underlying Elk Mound aquifer. The upper bedrock aquifer is generally anisotropic, with greater lateral transmissivity compared to vertical groundwater flow. Although the flow through discrete fractures is not simulated by the modeling approach selected for this project, effects of anisotropy are captured by the variation in vertical hydraulic conductivity in layer 3, which represents the upper bedrock aquifer.

The Elk Mound aquifer extends across the study area, underlying the upper bedrock aquifer where it is present. The Eau Claire aquitard is present only in the southwestern corner of Columbia County, although it is well-defined outside the county to the south and west. Because there is no evidence of shale, siltstone, or dolomite facies within the mostly sandstone strata of the Eau Claire Formation beyond that area, the aquitard is not thought to be regionally extensive across the rest of the county. Furthermore, because sandstone dominates the composition of the Eau Claire Formation over much of the county, there is little to differentiate it from the overlying Wonewoc and underlying Mount Simon Formations. Precambrian crystalline rock forms the lower boundary of the groundwater system.

Sources of groundwater to the county include recharge from infiltration of precipitation and snowmelt, losing reaches of streams or lakes (areas where water infiltrates the subsurface instead of flowing downstream), and water flowing through the groundwater system from outside the county. Groundwater sinks or pathways of groundwater flow out of the county include discharge to lakes, streams, and wetlands; pumping from wells; and groundwater flow into neighboring counties.

Simulation of the regional groundwater-flow system

A regional-scale, three-dimensional groundwater-flowmodel was developed by USGS to simulate the hydrologic system in Columbia County. The model design reflects the hydrostratigraphic layers shown in figure 5 and the variations in their extent and thickness, as illustrated in figure 9. The numerical methods applied, model construction, calibration, results, and model limitations are described below. The model archive is available in Leaf and others (2021).

Methods

The computer code MODFLOW was used to construct a finite-difference model of the study area, applying the Newton Raphson solver (Niswonger and others, 2011). The model represents the groundwater system in a steady-state configuration; all stresses represented in the model, including recharge rates and simulated groundwater flow into the model, represent long-term average conditions since approximately 1970. Similarly, the model simulates groundwater levels and stream baseflows that represent long-term average conditions. A summary of the construction and calibration of the MODFLOW model, including the underlying data sources, is given below.

Model domain and grid

The model domain consists of an unrotated, uniform grid of 815 rows by 995 columns of 300-ft by 300-ft cells. The origin of the grid is located at 527,050 m easting and 296,350 m northing in Wisconsin Transverse Mercator coordinates; the extent of the domain is shown in figure 1.

The model has six layers corresponding to the hydrostratigraphy shown in figure 5. Layers 1 and 2 represent the unlithified aquifer (fig. 8), with the top of layer 1 defined by the land-surface elevation and the bottom of layer 2 set at the surface elevation of the Paleozoic stratified bedrock (fig. 7). This thickness was divided by two at each model cell to derive the thickness of layers 1 and 2. These two layers were dedicated to the unlithified aquifer to improve the simulation of vertical hydraulic gradients near surface-water features. Where the bedrock surface crops out, layers 1 and 2 were assigned arbitrary thicknesses of 1 ft each. The upper bedrock aquifer is represented by model layer 3, with a thickness and extent illustrated in figure 11. Layers 4, 5, and 6 represent the extent and thickness of the Elk Mound aquifer (fig. 13).

In areas where the hydrostratigraphic unit represented by a model layer is absent, the corresponding layer was assigned a thickness of 1 ft, and the hydraulic properties were assigned from the adjacent cell in the layer below. For example, in areas where the upper bedrock aquifer is absent, hydraulic properties in layer 3 were copied from the corresponding cells in layer 4. As discussed above, the Eau Claire aquitard extends across large areas in Dane and Sauk Counties, but pinches out toward the northeast and is not present at appreciable thicknesses over most of Columbia County. The hydraulic conductivity zone representative of the Eau Claire aquitard in layer 5 (fig. 14) was based on its extent in the Dane County Groundwater Model (Parsen and others, 2016) and lithologic descriptions in geologic logs, and it also was inferred from the geophysical logs discussed above. Outside of the inferred extent of the Eau Claire aquitard (fig. 14), layer 5 was assigned a thickness of 1 ft and the properties of the underlying cells in layer 6. The bottom of the model represents the Precambrian surface (fig. 6), which was assumed to constitute a no-flow boundary.

Elevations assigned to the top of layer 1 were sampled from a 10-m-resolution digital elevation model of the study area (USGS, 2013) by computing the mean value of the digital elevation model pixels within each model cell (as determined by the centroids; Perry, 2017). Elevations assigned to the bottom of layers 2, 3, and 6 were derived from raster surfaces shown in figures 7, 11, and 6, respectively. The bottom elevations of layers 4 and 5 were based on the relative position of the Eau Claire aquitard in the Dane County Groundwater Model (Parsen and others, 2016). For example, in the northern part of the Dane County Groundwater Model, the Eau Claire aquitard facies (where present) occurs at roughly 75 percent of the thickness of the lower aquifer (with 0 percent representing the Precambrian surface and 100 percent representing the bottom of the Tunnel City Group). Beyond the inferred extent of the aquitard facies (fig. 14), layer 5 was simply continued at this relative vertical position, as illustrated by cross sections *B–B′ and C–C′* in figure 9. Negative layer thicknesses in some areas, which resulted from interpolation between borehole data locations, were resolved by adjusting underlying layer elevations downward so that a 1-ft minimum layer thickness was maintained throughout each layer of the model.

Boundary conditions

Groundwater flow across the MODFLOW model perimeter was evaluated by insetting the MODFLOW model within a two-dimensional, steady-state, analytic-element model constructed using GFLOW (Haitjema, 1995). The GFLOW model was created by combining existing GFLOW models of Sauk County (Gotkowitz and others, 2005) and the Rock River Basin (Juckem, 2009). Analytic elements from the two models, including line features representing streams and lakes and polygons representing piece-wise constant zones of hydraulic conductivity and recharge, were combined. Additional elements, including pumping wells from the Dane County Groundwater Model (Parsen and others, 2016), were then added so that the composite model simulated regional groundwater flow across the MODFLOW model perimeter (fig. 15). The composite GFLOW model was then calibrated using PEST (parameter estimation software; Doherty, 2010) and the same observational dataset used to calibrate the MODFLOW model. The simulated groundwater flow along the boundary of the MODFLOW model was extracted from the calibrated GFLOW model and included in the MODFLOW simulation as a specified flow at each boundary cell using the Well package (Hunt and others, 1998). The flow at each vertical column of cells along the boundary was distributed among the six model layers on the basis of the fraction of total transmissivity (for the column of cells) in each layer.

Recharge to the groundwater system was simulated using the Unsaturated Zone Flow (UZF) package (Niswonger and others, 2006), which allows the position of the water table to be considered in determining recharge rates. In the UZF package, "deep infiltration" (water percolating past the root zone) is specified instead of recharge. Percolation through the unsaturated zone is simulated and becomes recharge to the groundwater-flow system when it reaches the water table. In a steady-state configuration, storage in the unsaturated zone is not simulated, meaning deep infiltration is applied directly to the water table. The applied deep infiltration becomes groundwater recharge if the water table is sufficiently below the land surface. In cells where the water table is close to the land surface (top of model layer 1), the applied deep infiltration is rejected and discharged from the groundwater flow solution as "surface leakage." In UZF, discharging surface leakage can be routed to surface-water boundary conditions or removed from the model.

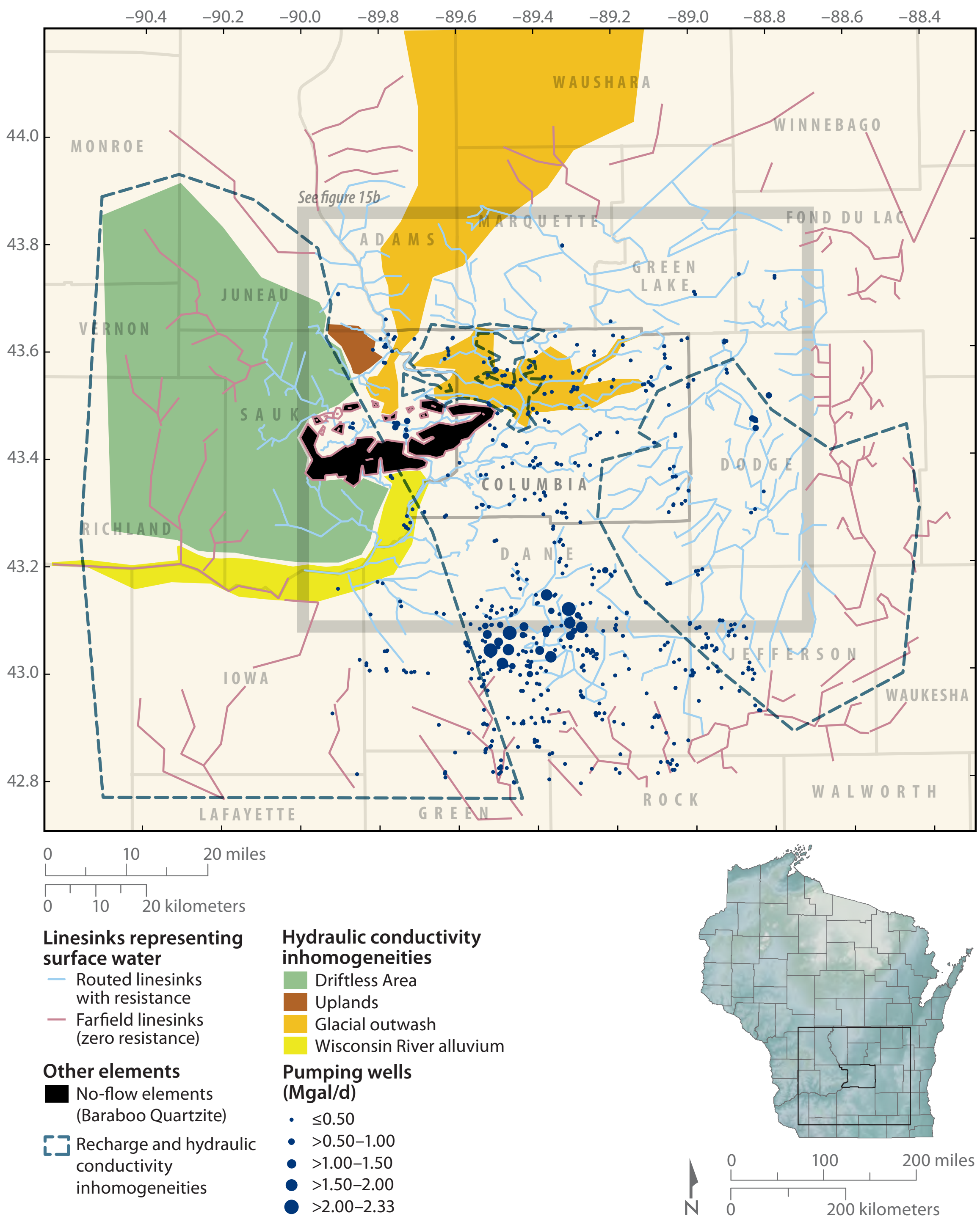
We used the UZF package because it precludes unrealistic simulation of the water table above land surface, which in turn yields a more realistic representation of groundwater discharge to lakes and riparian wetlands, improving the simulation of heads in those areas. When surface leakage from riparian areas is routed to the stream network, simulated baseflows are expected to be similar to those simulated without the UZF package (in which case the Recharge package would be used), as in reality, most riparian groundwater discharge ultimately reaches streams. The UZF package was applied in the Columbia County model to all cells that did not contain a stream boundary condition.

Deep infiltration to the UZF package was applied throughout Columbia County using estimates from the SWB model (Schoephoester and Gotkowitz, 2012; fig. 16). Outside of Columbia County, deep infiltration was applied on a zoned basis, using the Quaternary units mapped by D.M. Mickelson in Lineback and others (1983), except in the area coinciding with the Dane County Groundwater Flow Model (Parsen and others, 2016), where recharge values from that study were applied instead.

Surface leakage simulated by the UZF package is controlled by an additional parameter, SURFDEP, which can be conceptualized as representing the average variation in topography within a model cell. A value of 1 ft was used for SURFDEP on the basis of experimental model runs and evaluation of the surface leakage and stream discharge components of the model mass balance. SURFDEP dampens the amount of groundwater discharge to the land surface that is simulated when the water table is within SURFDEP distance of the model top, providing a smooth transition from the condition of no discharge to increasing discharge with higher simulated heads. In this way, SURFDEP also helps to stabilize the model solution by reducing the change in simulated flux between successive iterations.

Streams were simulated in the model using the Streamflow Routing (SFR2) package (Niswonger and Prudic, 2005); stream locations were based on the stream network described in the NHDPlus v2 database (McKay and others, 2012). In the SFR2 package, stream boundary conditions are simulated at reaches that occupy a single finite-difference cell. Reaches are in turn organized into segments that represent a stretch of stream, often between two confluences. Flowlines and attributes of streams from NHDPlus v2 were translated to SFR2 input using a procedure described by Leaf and others (2015). Streambed elevations were derived from a 10-m digital elevation model (USGS, 2013) using the minimum elevation within each model cell. The elevations were then smoothed to remove rises in the downstream direction. Because the digital elevation model typically represented the water surface instead of

Figure 15a. GFLOW model used to provide perimeter boundary flows for the MODFLOW model. (A) Analytic elements in the GFLOW model. The routed linesinks simulate groundwater/surface water interactions and baseflow in streams. The farfield linesinks define specified head boundary conditions along the perimeter of the model. Hydraulic conductivity and recharge inhomogeneities define areas where these parameters are different from the model's background values. The homogeneity shapes were based on physiographic areas and comparison of the model results to observed data during successive runs of the model.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Elevation: U.S. Geological Survey National Elevation Dataset, 2017.

Figure 15b. Boundary flow applied to the MODFLOW model. Red and blue circles indicate the direction and magnitude of flow computed in the GFLOW model results perpendicular to the MODFLOW model boundary. Blue circles indicate flows into the model, such as those to the northwest. Red circles indicate flows out of the model, such as those to the south, going toward the pumping wells and lakes near Madison. White circles indicate areas of no flow or very little flow. cfs, cubic feet per second; Mgal/d, million gallons per day.

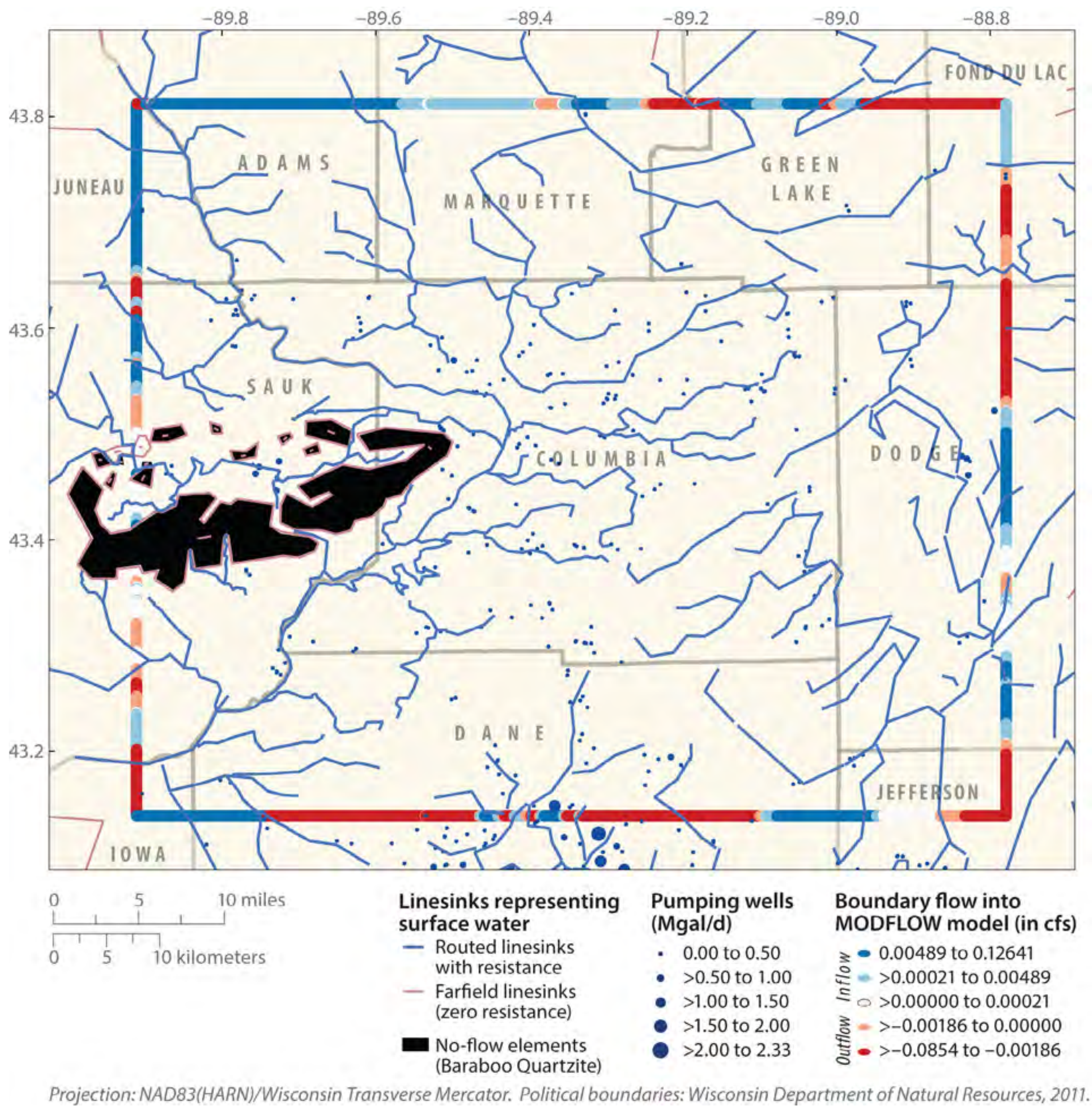
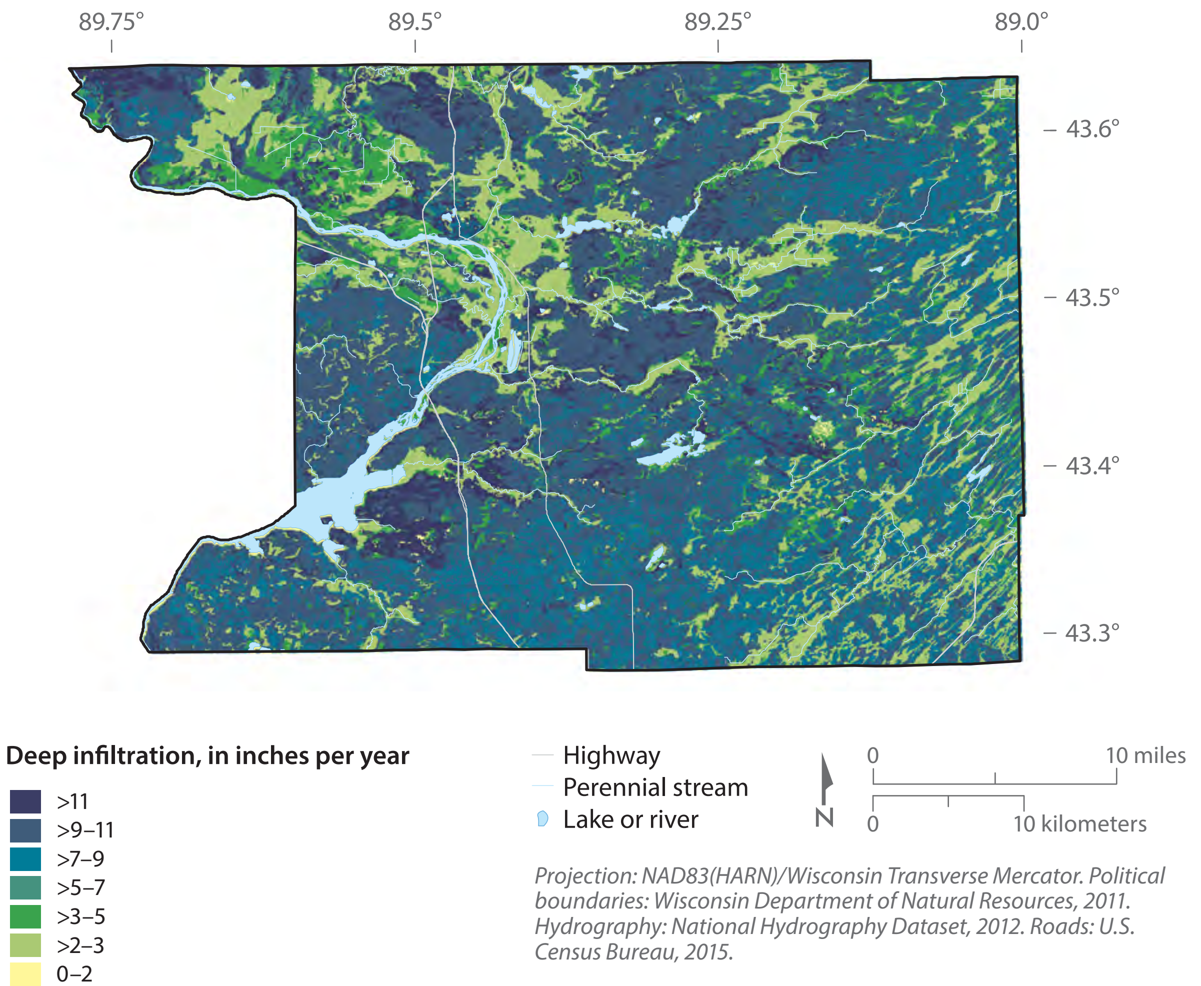


Figure 16. Estimates of deep infiltration across Columbia County from the Soil Water Balance model, based on the precipitation record from 1981. Adapted from Schoephoester and Gotkowitz (2012).



Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Political boundaries: Wisconsin Department of Natural Resources, 2011. Hydrography: National Hydrography Dataset, 2012. Roads: U.S. Census Bureau, 2015.

the streambed, the streambed elevations were further adjusted by subtracting the simulated stream depths from an initial model run and then re-smoothing the elevations.

The stream network was connected to the UZF package via the NHDPlus v2 Catchment dataset (McKay and others, 2012). Each segment in the SFR2 package was based on an NHDPlus Common Identifier (COMID) number, which identifies a section of stream between two confluences. The catchment polygons corresponding to each COMID were intersected with the model grid so that each grid cell was referenced to a COMID; the grid-cell COMIDs were then translated to the corresponding SFR2 segments. Surface leakage simulated by the UZF package was then applied evenly among the reaches in the corresponding SFR2 segment in the MODFLOW solution.

Upstream baseflow in the Wisconsin River was derived by performing baseflow separation on the streamflow record (using the modified baseflow index method; Wahl and Wahl, 1995) at the Wisconsin Dells streamgage (USGS streamgage 05404000; USGS, 2017) and subtracting the simulated net gain in baseflow between the model boundary and streamgage location. The derived baseflow was then added to the Wisconsin River as a specified inflow at the model boundary.

The SFR2 package was configured to estimate stream depth using Manning's equation (icalc=1; Niswonger and Prudic, 2005), which required the input of the stream-channel characteristics. Streambed slopes were computed on the basis of the smoothed streambed elevations, with a minimum slope of 0.0001 enforced. A rectangular channel geometry and uniform roughness (Manning's n) of 0.037—a reasonable value for natural channels with relatively low gradients (for example, Barnes, 1967)—were assumed.

Streambed conductance for each SFR2 reach was computed as the product of the channel length (obtained from NHDPlus), channel width (estimated from the NHDPlus arbolate sum attribute; for example, Feinstein and others, 2010, p. 266), and streambed vertical hydraulic conductivity divided by the streambed thickness. The vertical hydraulic conductivity of streambed sediments was assumed to be uniform and was included as a parameter in the model calibration process. Streambed thickness was fixed at a uniform value of 1 ft.

Pumping in the model was represented using the Multi-Node Well (MNW2) package (Konikow and others, 2009), which represents each well as a single element that can span multiple model cells. This method provides an independent solution of hydraulic head in the well bore, which allows for a more realistic simulation of pumping based on well capacity and hydraulic gradients. The discharge is apportioned among the layers intersected by the well on the basis of the transmissivity of each layer. Wells and pumping rates applied in the model are provided in table 1 and appendix 1.

Hydraulic properties

Hydraulic conductivity was applied as a constant value within 27 zones in model layers 1 and 2, with the zones corresponding to units mapped by Hooyer and others (2015) within Columbia County and by D.M. Mickelson in Lineback and others (1983) in areas outside of Columbia County; fig. 17). Hydraulic conductivity was also zoned in layers 3 through 6 but was allowed to vary within each zone using pilot point parameters (Doherty, 2003; see "Model calibration," below). Layer 3 contains a zone representing the upper bedrock aquifer. Outside of this zone, where the upper bedrock aquifer is absent, hydraulic properties from layer 4 were assigned to layer 3 on a cell-by-cell basis. Layers 4 and 6 each consist of a single zone representing the Elk Mound aquifer. Layer 5 contains a zone representing the aquitard within the Eau Claire Formation, which is similar to the aquitard found at the base of the Tunnel City Group in layer 3; outside of this zone, properties from layer 6 were assigned.

Although storage coefficients were not needed for steady-state model simulations, values of porosity were assigned to model cells for advective particle tracking simulations that are useful for wellhead-protection studies. In model layers 1 and 2, porosity was assigned to the hydraulic conductivity zones (fig. 17) on the basis of descriptions of Quaternary materials (Hooyer and others, 2015) and are provided in table 4. Where model layer 3 represents the upper bedrock aquifer, it was assigned a porosity of 0.05; layers 4, 5, and 6 (and layer 3 where the upper bedrock aquifer is not present) were assigned values of 0.15.

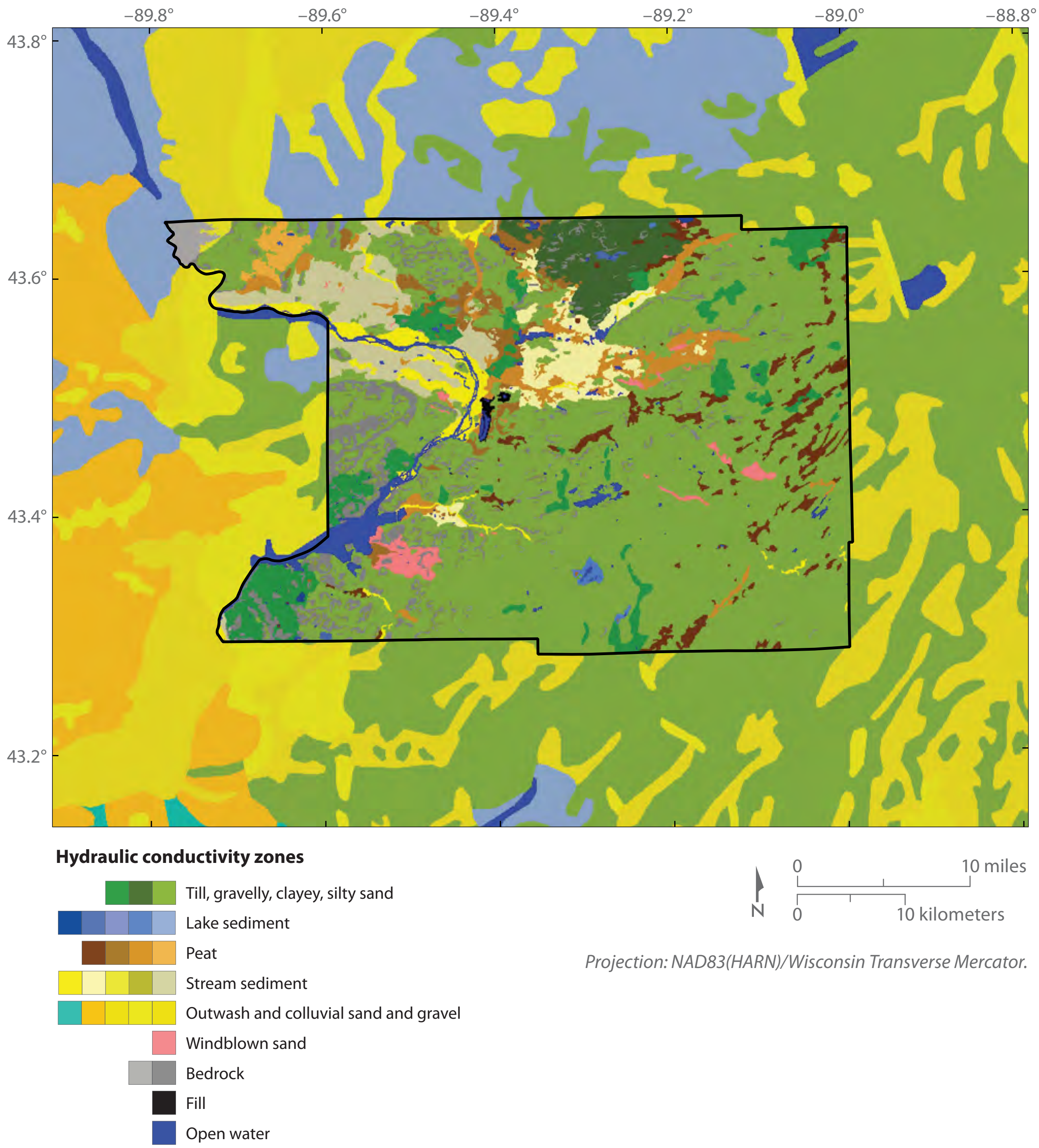
Model parameter estimation

Parameter estimation is the process of adjusting model parameters so that both model inputs and model outputs produce acceptable fits to "hard" knowledge (observations of water levels and flows) and "soft" knowledge (the conceptual understanding of the hydrogeologic system). Parameter estimation for the MODFLOW model was performed by "history matching," the process of systematically adjusting uncertain input parameters that control hydraulic conductivity and recharge so that the model results agree with equivalent observations (targets) such as groundwater levels and stream baseflows. This process is also referred to as model "calibration;" the two terms are used interchangeably in this section.

Table 4. Porosity assigned in layers 1 and 2 on the basis of a map by Hooyer and others (2015).

Sediment types in unlithified aquifer	Porosity
Fill	0.15
Hillslope sediment, primarily sand	0.20
Lake sediment with sand	0.10
Lake sediment with silt and clay	0.05
Peat overlying lake sediment	0.05
Peat overlying stream sediment	0.15
Stream sediment, sand and gravel	0.25
Stream sediment, silty sand	0.20
Till, clayey silt, sand	0.15
Windblown sand	0.30

Figure 17. Hydraulic conductivity zones in layers 1 and 2. Map-unit symbols are from Hooyer and others (2015; areas within Columbia County) and D.M. Mickelson in Lineback and others (1983; areas outside of Columbia County).



For model calibration, we used an overall approach that was similar to that of Leaf and others (2015), which followed the general guidelines of Doherty and Hunt (2010). We assembled an observational dataset of groundwater levels and stream baseflows from various sources (described in the next section) and weighted it to reflect observation uncertainty, information content, and importance to the modeling goals. The weighted observations formed the basis for an objective function consisting of the sum of squared, weighted residuals (differences between observations and equivalent model outputs) that provided a measure of model misfit.

Hydraulic parameters were defined so that hydraulic conductivity and recharge could be varied spatially across the model within estimated levels of uncertainty. Manual trial-and-error model runs were performed to refine the initial parameter values and identify issues with the conceptual model and (or) errors in model input or the observation dataset. Parameter estimation by inversion was performed by nonlinear regression using PEST (Doherty, 2010; 2014a).

In the process of inversion, parameter values are estimated by minimizing the error between the measured values and their simulated model equivalents using a measurement objective function. To reduce the potential for unrealistic parameter estimates, a second objective function can be added in a process known as regularization, which measures the deviation of parameter values from a preferred condition. With regularization, improvements in model fit must be balanced by adherence to parameter values that are realistic. In the calibration of the Columbia County groundwater-flow model, the measurement and regularization objective functions were minimized in tandem, using the "PHIMLIM" variable in PEST to control the trade-off in model fit between the observational data and conceptual model.

The above steps were performed iteratively as more was learned about the system and shortcomings were identified in the conceptual model, observation dataset, and parameterization scheme.

Observations

A total of 4,034 weighted observations were used in the model calibration. Datasets included 2,995 hydraulic-head measurements from spatially located WCRs. A total of 944 hydraulic-head measurements from within the model domain were selected from the National Water Information System (NWIS) database (http://nwis.waterdata.usgs.gov; USGS, 2017). Hydraulic-head measurements and four vertical hydraulic-head differences were obtained from wells CO-783 and CO-779 (fig. 12). Stream baseflow measurements used as calibration targets included 54 average stream baseflows from the statewide recharge study of Gebert and others (2011). An additional 37 streamflow calibration targets were selected from 42 streamflow measurements collected by WGNHS in 2009 during low-flow conditions (appendix 2).

The calibration dataset spans many years, whereas this steady-state model simulates single values that represent long-term averages. To create calibration targets representative of model outputs, average values (for the period after 1970, if available) were used for wells with multiple hydraulic-head observations. Long-term average baseflows obtained from Gebert and others (2011) were estimated for 1970 to 1999 using techniques of baseflow separation at stream gages and regression modeling that related partial records or one-time measurements to conditions at index stream gages.

Targets based on vertical differences in hydraulic head were developed for calibration using the packer test results collected by WGNHS from wells CO-783 and CO-779 (fig. 12). At both locations, the depth and thickness of identifiable strata within the upper bedrock and Elk Mound aquifers were determined on the basis of borehole geophysical data. Hydraulic-head measurements within each packed interval were averaged to obtain a head representative of each unit. These values were compared to their simulated counterparts in model layers 3, 4, and 6.

The absolute hydraulic-head values at these locations were assigned to the same group as the NWIS "good" hydraulic heads (see "Observation weighting," below). Targets were also developed for the difference in the vertical hydraulic head by subtracting the hydraulic-head values in layer 4 from layer 3, and in layer 6 from layer 4, at both of these locations. At well CO-779, the casing extends into the Elk Mound aquifer; therefore, packer tests could not be completed for the upper bedrock aquifer. The hydraulic-head value for the upper aquifer at this location was estimated from measurements in nearby wells and assigned a weight of half the value assigned to the other vertical head difference targets.

Observation weighting

Observations in the calibration dataset were weighted to reflect differences in information content and measurement uncertainty related to measurement quality, location uncertainty, and temporal variability. Generally, observation weights were assigned to promote the most reliable (most certain) observations and to balance the contributions of different observation types to the objective function. The overall goal of the weighting was to maximize the transfer of information from the observation dataset to the estimated parameters (see Doherty and Hunt, 2010).

Observations were grouped based on the different sources listed above and then by their quality. Hydraulic-head observations from the NWIS database were categorized as "good," "fair," or "poor" on the basis of the number of measurements at each location, the time period covered, wellhead elevation accuracy, and other ancillary notes in the database. WCRs were separated into two groups (WCRs1 and WCRs2) on the basis of a "location confidence" radius estimated by the WGNHS. WCRs with a location accuracy of less than 200 ft were placed in the WCRs1 group and those with a location accuracy of 200 ft or greater were assigned to the WCRs2 group.

Estimates of average baseflows from Gebert and others (2011) were categorized by size under the assumption that measurements of large flows were less prone to error. Streamflow measurements collected for this project (appendix 2) were placed in a separate category.

The weights in each group were initially assigned to be inversely proportional to an estimated representative measurement uncertainty for the group. For example, hydraulic heads in the NWIS "good" category were initially assigned weights of 0.2 (uncertainty of ±5 ft), whereas hydraulic heads in the NWIS "fair" and WCRs1 categories were given initial weights of 0.03 (uncertainty of ±33 ft). Baseflow measurements were initially weighted as inversely proportional to their value multiplied by a coefficient of variation (CV) expressing the estimated uncertainty for each measurement. The average baseflow estimates from Gebert and others (2011) were initially assigned a CV of 0.14, reflecting a standard error of 14 percent in the regression technique used in their estimation. The one-time measurements collected for this project, which were not converted to average baseflow estimates, were subject to additional uncertainty because they may not have been collected under average conditions. These observations were assigned CVs of 0.5 to 1.0. Initial and final weights and observation groups are available in the data release (Leaf and others, 2021).

Placing a pump discharge pipe for hydraulic tests.

After the observation groups and their initial uncertainty-based weighting were developed, multipliers were applied to each group to balance the objective function (phi; see Doherty and Hunt, 2010). At the start of the final calibration run, the hydraulic-head and baseflow observation groups were weighted so that they contributed approximately 30 and 41 percent of phi, respectively. The vertical hydraulic-head difference targets were assigned to their own group, which was weighted to make up 28 percent of phi (Leaf and others, 2020). This approach was used to prioritize an important aspect of the conceptual model in the nonlinear regression: vertical gradients resulting from the presence of aquitards at the base of the Tunnel City Group and in fine-grained facies of the Eau Claire Formation. WGNHS hydrogeologists collected the measurements for the vertical hydraulic-head differences and corrected for elevation errors; therefore, the vertical hydraulic-head differences had significantly less uncertainty compared to the hydraulic-head measurements from other sources.

Recharge

Initial recharge (deep infiltration) values were developed from the SWB model results (Schoephoester and Gotkowitz, 2012; fig.16) for Columbia County. Calibrated recharge values were selected from the Dane County Groundwater Model (Parsen and others, 2016) for areas outside of Columbia County where the two model domains intersected. For areas outside of these two model domains, the initial values were based on average values from the SWB model of Schoephoester and Gotkowitz (2012) for similar Quaternary units.

Recharge was parameterized using multiplier values set initially to 1. For the areas with SWB results, this parameterization allowed the overall volume of recharge to be adjusted to match baseflows while maintaining the spatial distributions estimated by SWB. The recharge multiplier parameters were regularized in the inversion process using preferred values of 1, which introduced a penalty (increase) in the regularization for increasing or decreasing the volume of recharge from the initial estimates.

Streambed vertical hydraulic conductivity

A single parameter value was assigned to estimate the uniform streambed vertical hydraulic conductivity term as described in the "Parameter estimation results" section, below.

Hydraulic conductivity

A horizontal hydraulic conductivity (K_h) parameter was assigned to each hydraulic conductivity (K) zone in layers 1 and 2 (derived from fig. 17). In the underlying layers, K_h was parameterized using pilot points (Doherty, 2003; Doherty and Hunt, 2010) spaced on a regular grid every 90 model cells, which represents approximately 5.1 mi. Ordinary kriging interpolation was then used to populate each model cell with a K_h value based on the values assigned to the surrounding pilot points. A single exponential variogram was used, with a range of three pilot point spacings (an "*a*" parameter of one spacing; see Doherty, 2014b; Doherty and others, 2010), a sill of 1, and a nugget of 0. The interpolation between pilot points was performed on a zoned basis; for example, the interpolated K_h values within the zone representing the Eau Claire aquitard were independent of the pilot points in the zone representing the undifferentiated Elk Mound aquifer.

A corresponding vertical anisotropy value (A_v) was estimated as the ratio of K_v to K_h for each K_h parameter, where K_v represents vertical hydraulic conductivity. In doing so, we assumed that the K_h and K_v values were correlated within a hydrogeologic unit and should be estimated together (see "Regularization" below).

The initial values for the K_h parameters were based on the geometric means for the respective zones determined from an analysis of the WCRs (fig. 10; table 3). The upper and lower bounds for the K_h parameters were also based on the hydraulic conductivity estimates from the WCRs as two log-space standard deviations above and below the geometric means. The A_v pilot points were assigned a default value of 0.1 (one-tenth the value of K_h), except for those in the Tunnel City Group, where a value of 0.05 was used on the basis of a comparison of the model results to the vertical hydraulic-head gradient targets and previous work that had shown the Tunnel City Group to be more anisotropic.

Regularization

The K_h parameters for zones in layers 1 and 2 were regularized using the K estimates from the WCRs as preferred values in a manner similar to the parameterization of the recharge zones, which meant that parameter estimates that deviated from these values resulted in an improvement in the model fit that outweighed the regularization penalty. The A_v values for layers 1 and 2 were regularized to their initial values.

The pilot point parameters were regularized using preferred differences of 0, which meant that the homogenous parameter fields within each zone were preferred. This approach to parameterization results in the introduction of variability only where it is supported by the observation dataset.

The regularization function is weighted against the measurement objective function in the parameter estimation process using the PHIMLIM variable in PEST (Doherty, 2010), which controls the trade-off between honoring the observation data instead of the conceptual model. An appropriate PHIMLIM value was set following the procedure in Doherty and Hunt (2010).

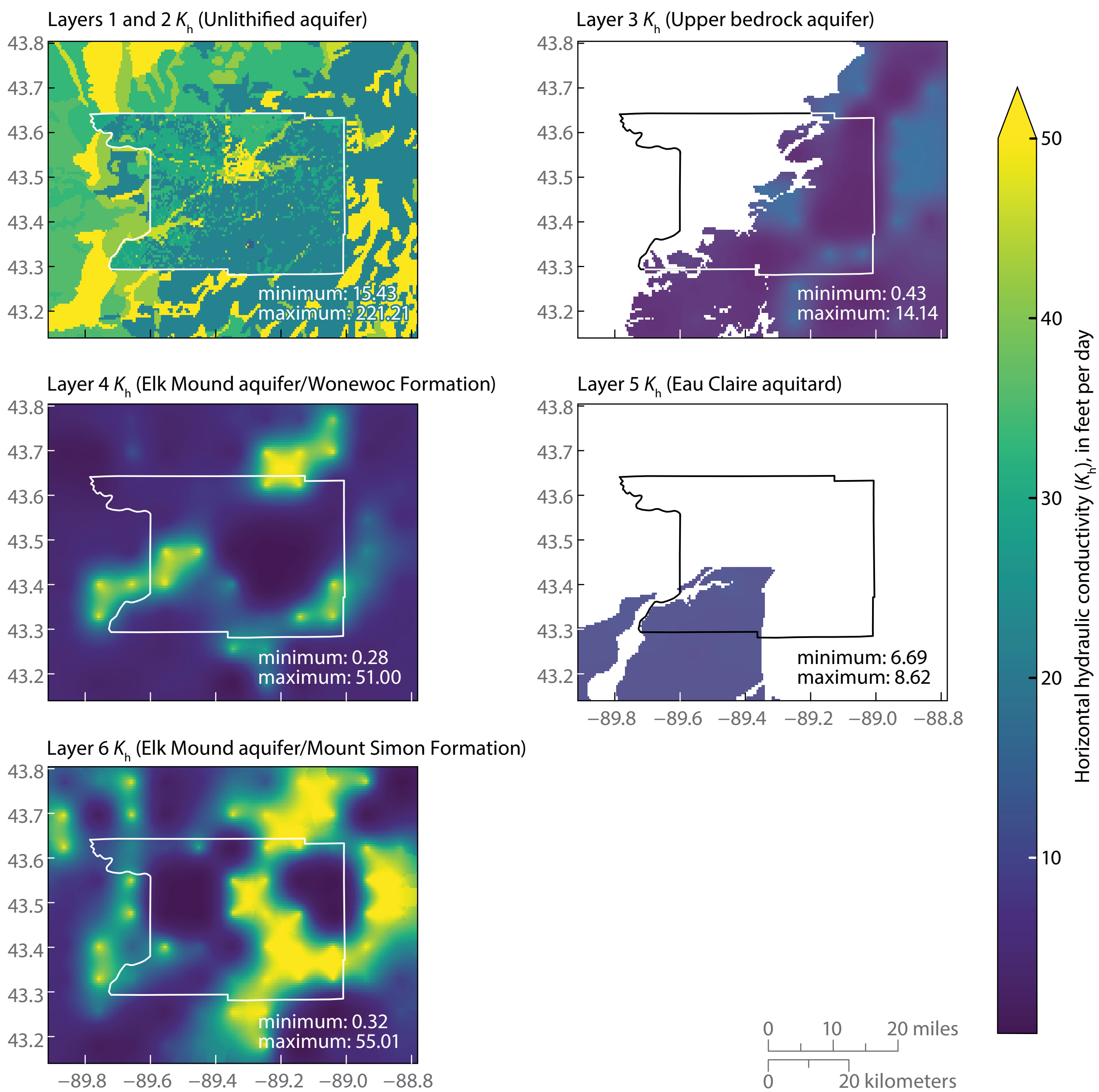
Parameter estimation runs

The measurement and regularization objective functions were minimized in tandem using PEST with the SVD-Assist functionality (Doherty, 2010). For more details on SVD-Assist and regularized inversion, see Doherty and Hunt (2010) and Anderson and others (2015). Additional details are available in the parameter estimation run files in the accompanying data release (Leaf and others, 2021).

Parameter estimation results

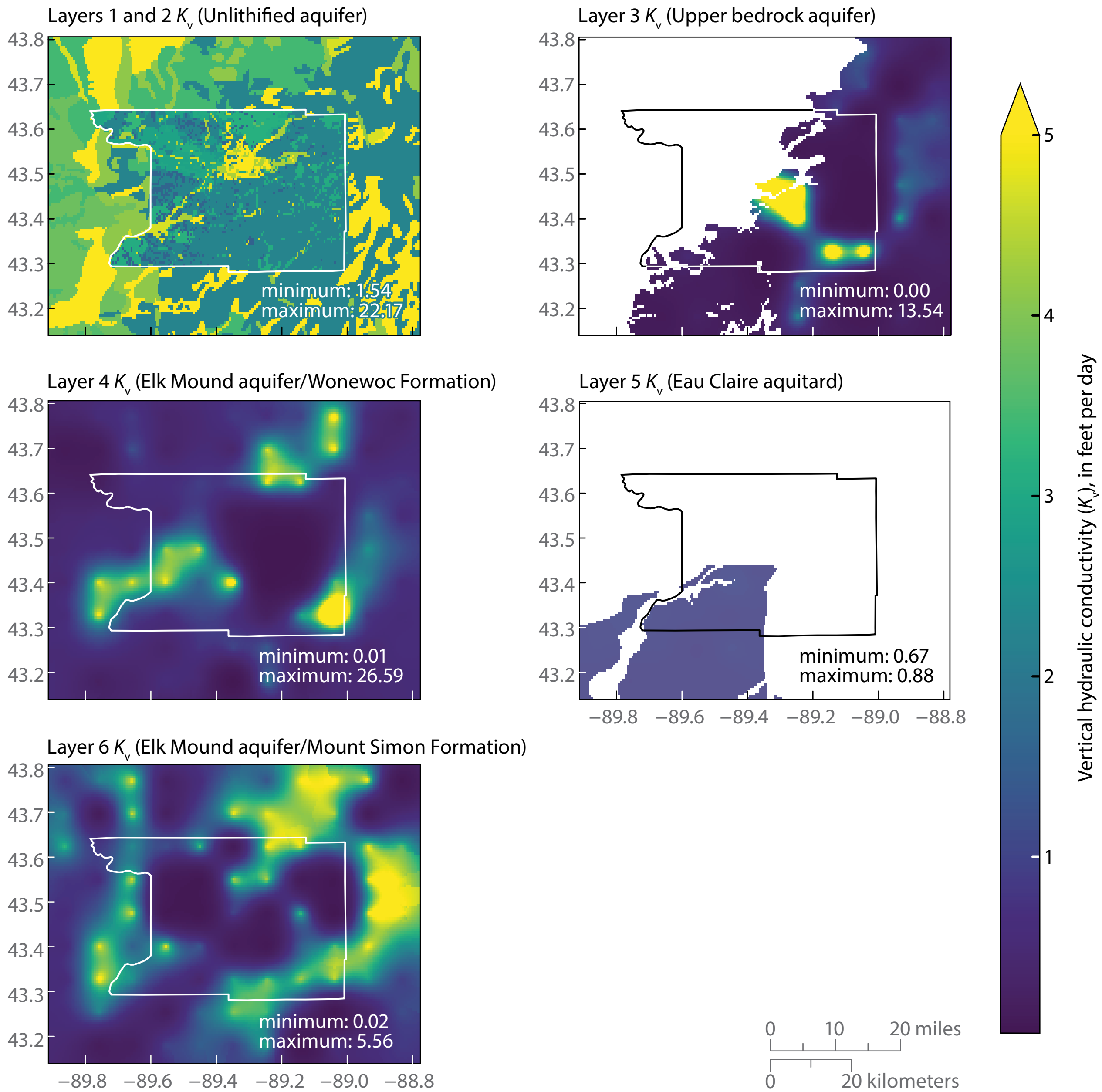
Parameter estimation resulted in (1) a good correspondence between the groundwater flow model output and the equivalent field observations and (2) reasonable hydraulic conductivity values. All recharge multiplier values remained at 1, indicating that the groundwater-flow observation data were usually consistent with the recharge rates estimated by the SWB model. The estimated horizontal and vertical hydraulic conductivity fields are shown in figures 18 and 19, respectively. The horizontal hydraulic conductivity values are within the ranges estimated in the specific capacity analysis (fig. 10).

Figure 18. Estimated horizontal hydraulic conductivity (K_h) fields.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Political boundaries: Wisconsin Department of Natural Resources, 2011.

Figure 19. Estimated vertical hydraulic conductivity (K_v) fields.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Political boundaries: Wisconsin Department of Natural Resources, 2011.

Areas of especially low or high estimated hydraulic conductivity in layers 3, 4, 5, and 6 may reflect either real field conditions or a structural error in the model. For example, the Precambrian surface topography is relatively uncertain due to limited borehole data. Areas where the Precambrian surface elevation was simulated too high may have led to unrealistically low transmissivities in the model, which PEST may have compensated for by increasing hydraulic conductivity. This type of error may have been the case in results for the Baraboo Hills, where the Precambrian bedrock is near the surface and the model layers are therefore thin. Estimates indicating high hydraulic conductivity in this area may simply reflect an error in the model layer thickness (overall transmissivity is still realistic). Similarly, high vertical hydraulic conductivities in layer 3 in the center of Columbia County may indicate an absence of the upper bedrock aquifer in those areas or an error in the layer elevations (vertical hydraulic conductivity estimates in layer 4 in this same area are low). One advantage of distributed parameterization using pilot points in this instance was that such structural errors and their effect on model predictions were locally compartmentalized. With large, piecewise-constant zones, the same structural errors may have resulted in an unknown bias in model predictions across larger areas. This effect can be seen in the larger baseflow residuals outside of Columbia County, where recharge was applied to large zones extending across the model area (see “Fit to observations,” below).

The initial parameter estimation runs produced some pilot point values that exceeded 50 ft/day in the zones representing the Elk Mound aquifer. Although some specific capacity tests exceeded this value (table 2), these results were attributed to locally fractured intervals observed through geophysical logging and described by Sellwood and others (2015). An analysis of flow logs collected at CO-784 indicated hydraulic conductivity on the order of 1 to 10 ft/day in unfractured intervals of this aquifer (table 3). In the groundwater model, each pilot point represents an area of the flow system on the order of 26 square miles, a scale at which porous media flow rather than fracture flow is likely to dominate groundwater flow. This consideration was the basis for subsequently limiting the upper bound in these zones to 50 ft/day.

The streambed vertical hydraulic conductivity was estimated at 0.18 ft/day, which corresponded to a resistance value of 5.6 days, with the assigned uniform streambed thickness of 1 ft. This resistance is at the upper end of the range used by Gotkowitz and others (2005) and higher than the values reported by Krohelski and others (2000). This estimate of streambed vertical hydraulic conductivity may not have been very robust as this parameter is often insensitive in regional models and also correlated with the behavior of the UZF package. With the UZF package, higher riparian heads result in an increase in the surface leakage routed to streams, which offsets any of the decrease in groundwater discharge to streams that is due to higher streambed resistance.

Fit to observations

Figures 20 and 21 show the correspondence between the simulated and observed hydraulic heads. A mean error of 0.01 ft and a mostly uniform spatial distribution of positive and negative residuals indicate an overall lack of bias in the model solution. Concentrations of negative resid-

Figure 20. Comparison of simulated and observed groundwater levels. Colors for individual hex bins indicate the number of observations that fall within the bin. MAE, mean absolute error; RMSE, root mean square error.

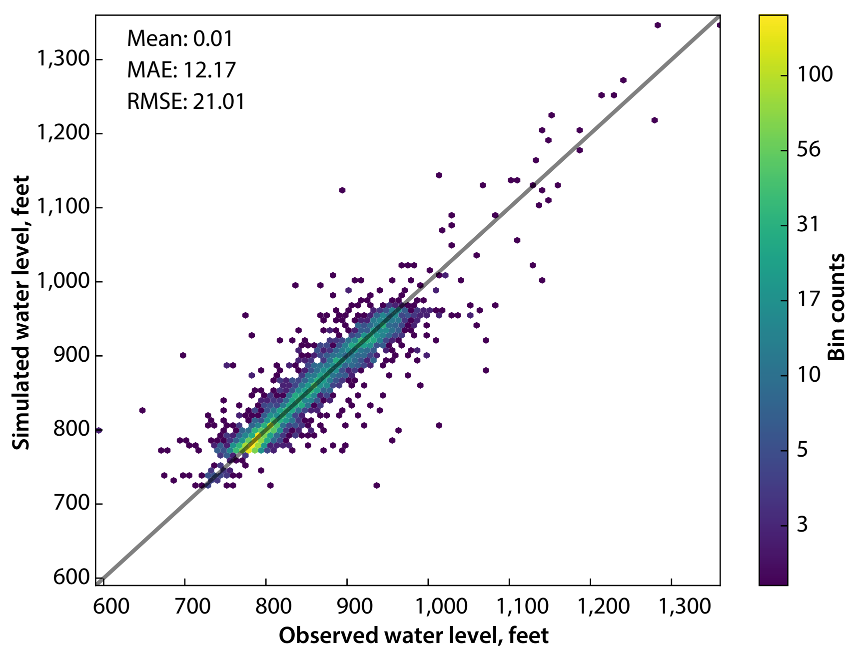
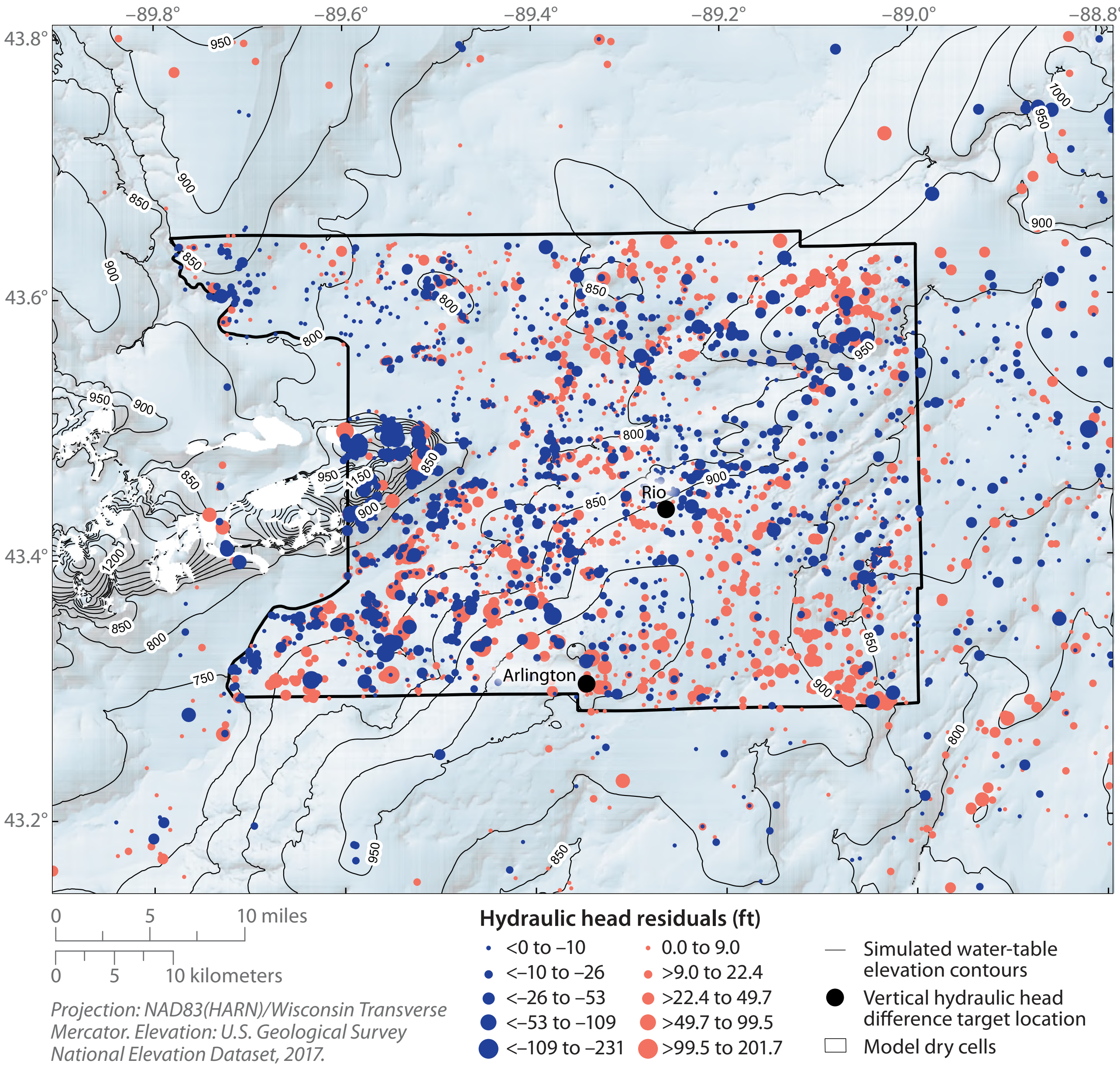


Figure 21. Spatial distribution of hydraulic-head residuals. Negative residuals (blue circles) indicate simulated values that are higher than their corresponding observations. An even distribution of positive and negative residuals indicates an unbiased solution. The shaded relief illustrates the simulated water-table surface, with a contour interval of 50 feet. White areas (in the Baraboo Hills region to the west) are where all model layers are dry.



uals around the Baraboo Hills and positive residuals in the southeastern and northeastern parts of Columbia County indicate structural deficiencies in the model in these areas. Groundwater levels in the Baraboo Hills are likely sensitive to fine-scale variability in the thickness and extent of both shallow surficial deposits, which were not well resolved in the model, and fracture networks in the Precambrian bedrock, which were not included in the model. Concentrations of positive residuals in the eastern part of the county mostly occurred in observations located in the upper bedrock and unlithified aquifers (model layers 3 and above). The upper bedrock aquifer contains six different stratigraphic units that function individually as both aquifers and aquitards and vary spatially in their extents. With a single model layer, it was not possible to accurately represent vertical hydraulic gradients within this sequence. Positive residuals in these locations may indicate lower vertical hydraulic conductivities in the upper bedrock aquifer than those simulated in the model. The positive residuals could also indicate the presence of a perched water table. Simulation of these phenomena, while beyond the scope of this study, may be important in characterizing flow and transport for site-specific issues. Figure 22 shows that the correspondence between the vertical hydraulic-head difference targets at CO-783 and CO-779 are also in good agreement.

Figures 23 and 24 show the relationship between simulated and observed baseflows. The mean error of 1.64 cubic ft per second (cfs)—or 9 percent of the average baseflow observation—indicates a small bias toward the simulation of lower-than-observed streamflows. Several large residuals in the Fox River and Crawfish River Basins outside of Columbia County contribute appreciably to this bias and may indicate (1) a structural error in the zoning of recharge in these areas outside of Columbia County or (2) boundary groundwater flow estimates from the GFLOW model used along the MODFLOW boundary that are biased low. The largest residual in stream flow targets within Columbia County is at site 05404033 on Duck Creek (fig. 24), which was oversimulated by 22 cfs in the model. This observation value was estimated by Gebert and others (2011) by relating partial records to a continuous record index site. It is not known when the underlying low-flow measurements for site 05404033 were collected (no data are available in NWIS or Gebert and others, 2011).

Figure 22. Comparison of simulated and observed vertical hydraulic head differences in well CO-779 in Arlington and well CO-783 in Rio.

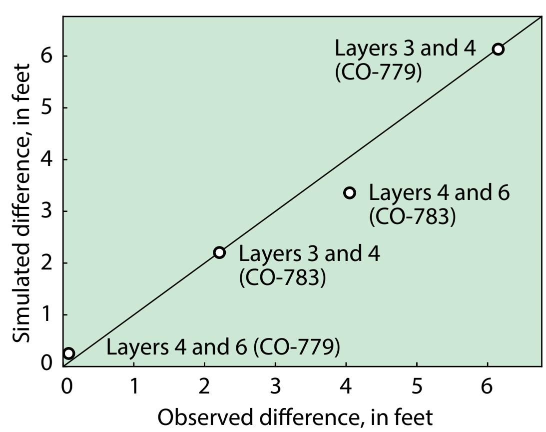


Figure 23. Comparison of simulated and observed baseflows. Data represented by circles are from this study and are presented in appendix 2; data represented by triangles are from Gebert and others (2011). MAE, mean absolute error; RMSE, root mean square error.

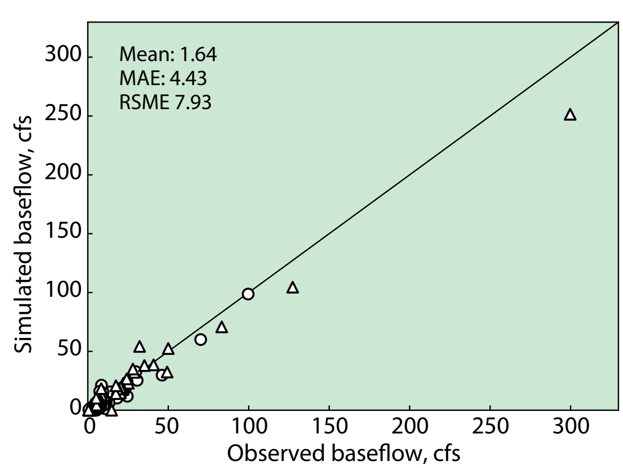
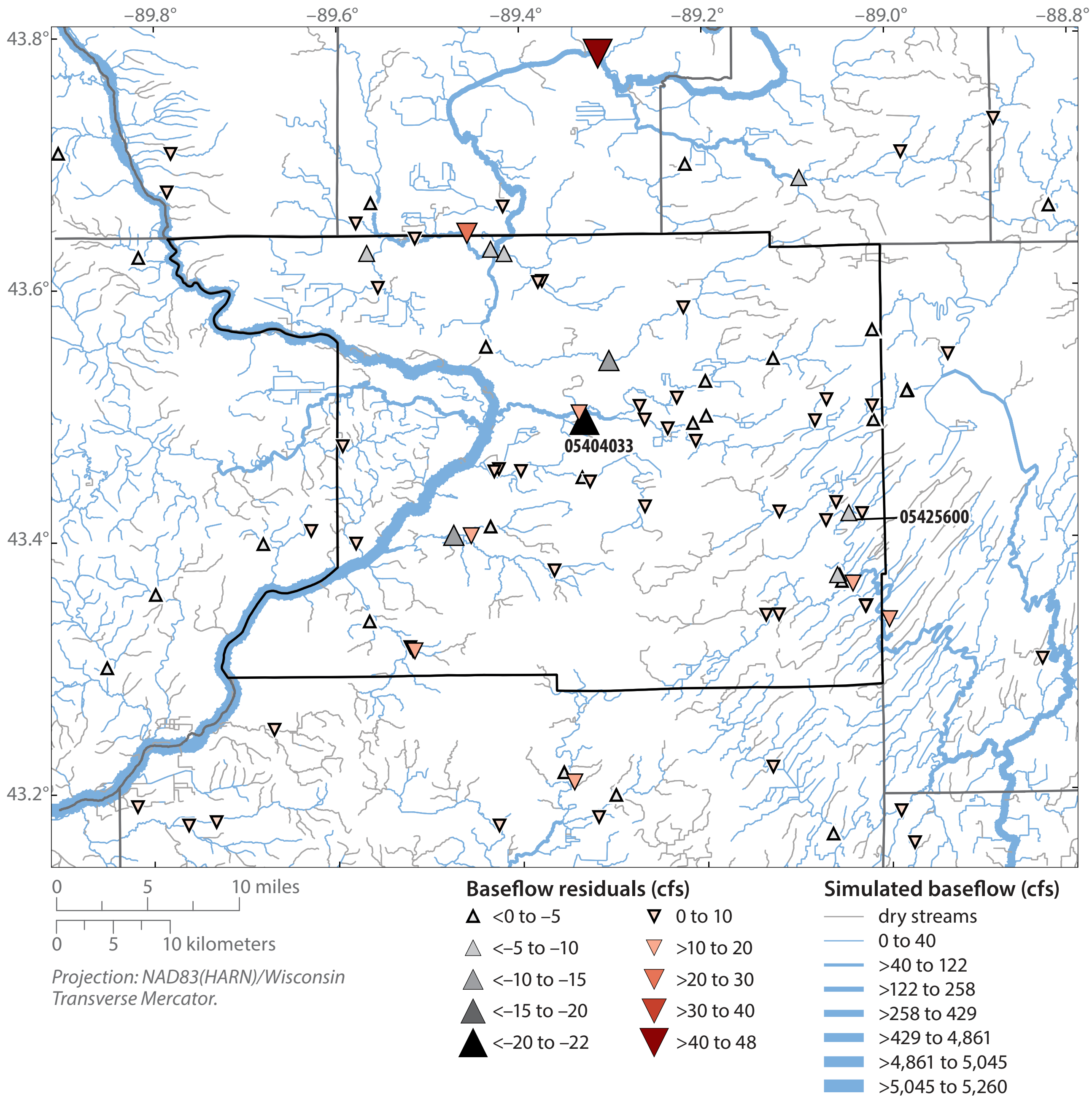


Figure 24. Spatial distribution of baseflow residuals, with simulated baseflows. Negative residuals (gray triangles) indicate simulated values that are higher than their corresponding observations. The simulated magnitude of baseflow along streams is also shown, indicating the relative size of streams, including those that receive no simulated groundwater discharge ("dry streams"). cfs, cubic feet per second.



However, the observation value appears to be biased low because 10 other observations on Duck Creek and its tributaries—including both estimates from Gebert and others (2011) and measurements collected for this study (appendix 2)—all agree with the model to within a few cubic feet per second.

The low-flow measurements collected for this project (appendix 2) are also mostly undersimulated. These flow measurements were included in the model as-is, without any attempt to normalize them to long-term flow conditions (for example, by using index gages, as in Gebert and others, 2011). These measurements may have been collected under higher than average baseflow conditions. For example, site 05425600 on the North Branch of the Crawfish River (fig. 24), from Gebert and others (2011), is oversimulated, but an adjacent WGNHS measurement is undersimulated, as are three upstream WGNHS measurements. Regardless, there is overall good agreement with the values in Columbia County from Gebert and others (2011), and this, along with the estimated recharge multiplier of 1, lend confidence to the overall accuracy of the mass balance simulated by the groundwater flow model.

Model results

Mass balance

The simulated mass balance is shown in table 5 and indicates that the overall error for the solution was 0.12 percent. The largest source of water to the model was groundwater recharge. Streams provided inflow to and outflow from the model, although groundwater discharge to streams was much greater than stream loss to the groundwater system. Overall, the mass balance was consistent with (1) Columbia County's position at a triple hydraulic divide between the Wisconsin, Fox, and Rock River Basins and (2) its relatively high density of streams. Groundwater within the county generally originates as recharge and flows towards streams within the three basins. Flow across the model's perimeter, both into and out of the domain, was relatively minor. In comparing the relative flow across simulated boundaries, the stream network and topography controlling discharge in the UZF package was more important than flow across the model's perimeter.

Outflows from the groundwater system include discharge to (1) streams and other surface-water features and (2) wells. The largest simulated outflow was the surface leakage component simulated by the UZF package, which represented groundwater flow to model cells that did not contain a stream reach but where the water table was close to the land surface. This component of the mass balance accounted for discharge to lakes, riparian wetlands, and small streams and seeps that were not explicitly simulated in the model. There are many such features in the study area, and the areas of simulated surface leakage generally corresponded well with mapped lakes and wetlands (fig. 25). For example, large areas of surface leakage were simulated in Green Lake and Dodge Counties (fig. 1) where broad lakes were simulated as narrow streams. Because of the well-developed drainage network in Columbia County, the vast majority of groundwater-fed wetlands are connected to the stream network. In the model, almost all (98.6 percent) surface leakage was routed to the stream network (SFR package) with the remainder likely constituting discharge occurring near the model boundary in catchments where a stream was not simulated in the model. Pumping from high-capacity wells represented the smallest outflow of groundwater simulated in the model.

Table 5. Simulated mass balance.

	Inflow (cfs)	Percent
Recharge	1,582.1	83.5
Leakage from streams	223.0	11.8
Lateral flow across model boundaries	89.1	4.7
Total	*1,894.2*	
	Outflow (cfs)	**Percent**
Discharge to streams	589.3	31.1
Surface leakage[1]	1,221.0	64.4
Lateral flow across model boundaries	47.0	2.5
Pumping from high-capacity wells	39.2	2.1
Total	*1,896.4*	
Percent discrepancy	**0.12**	

Abbreviation: cfs = cubic feet per second

[1] Groundwater discharge simulated by the unsaturated zone flow (UZF) package where the water-table elevation is above the land-surface. In reality, this represents groundwater discharge to riparian wetlands, seeps, and small streams that are not represented in the Streamflow Routing (SFR2) package's stream network.

Simulated baseflow

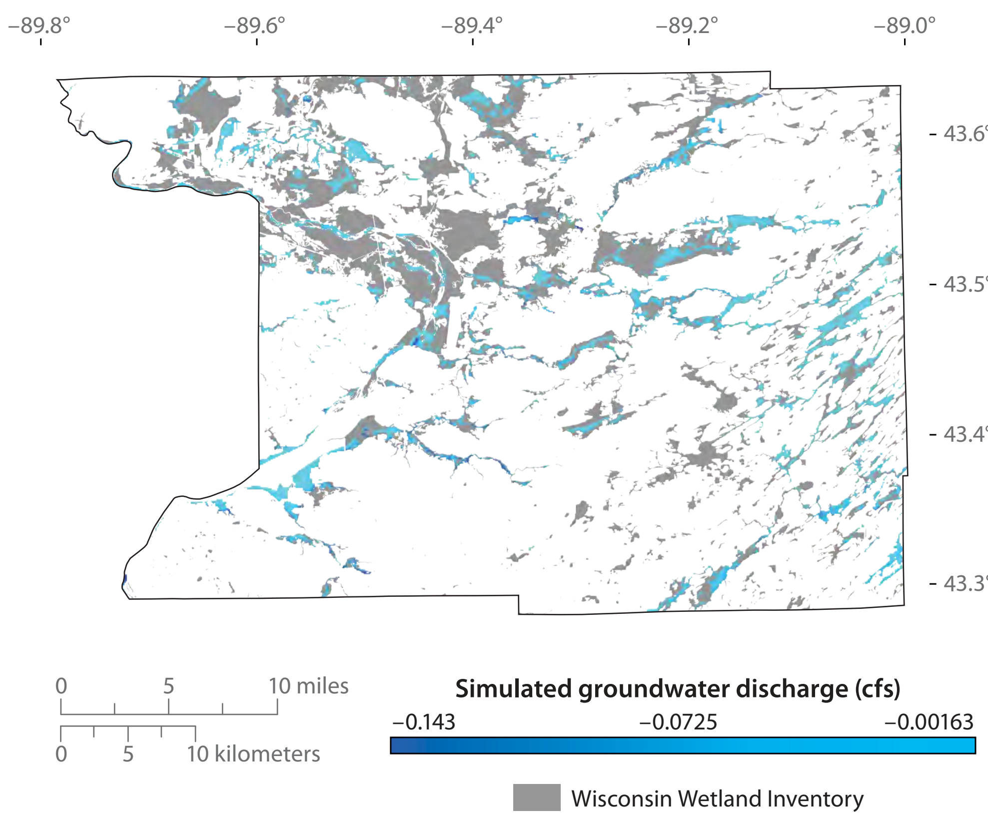
Figures 24 and 25 show simulated baseflows. Approximately 72 percent of stream reaches represented in the model were simulated as perennial (having baseflow under normal conditions). Of the 28 percent that were simulated as dry, 75 percent were first-order streams, which is typical for Wisconsin.

Simulated water table

The simulated water-table surface (fig. 26) reflected the regional surface-water divides between the Wisconsin, Rock, and Fox River Basins (fig. 2), as well as the strong influences of perennial streams and geology. For example, the model indicated that many of the incised areas in eastern Columbia County coincided with locations where (1) the unlithified aquifer is thin or not present (fig. 8) and (2) the upper bedrock aquifer is near the land surface and has a low hydraulic conductivity (fig. 18). Similarly, the model simulated parts of the Baraboo Hills as dry where the Precambrian surface (a no-flow boundary) reaches the land surface.

The simulated water table generally corresponded to the surface topography, with the lowest water-table elevations (about 750 to 790 ft above sea level) along the Wisconsin River and Lake Wisconsin and the highest water-table elevations (over 1,400 ft above sea level) in the Baraboo Hills region. High water-table elevations in areas of the Baraboo Hills, where saturated conditions were simulated, may reflect the higher elevations of the presumed aquifer base (the Precambrian surface). In some areas, the Precambrian surface may act as an effective base; in others, the actual aquifer may extend into fracture networks within the Precambrian bedrock. Other areas of the model that indicated higher gradients in the water table generally corresponded to variable streambed elevations created by erosional topography in the Paleozoic bedrock. In contrast, the water table

Figure 25. Comparison of simulated groundwater discharge (surface leakage) with mapped wetlands from the Wisconsin Wetland Inventory (gray; Wisconsin Department of Natural Resources, 2016). Areas of groundwater discharge were compared to the distribution of wetlands as a qualitative indicator of model results. The model generally simulates groundwater discharge in wetland areas and, as expected along the Wisconsin River, and indicates a good match between simulated and actual conditions. cfs, cubic feet per second.



Projection: NAD83 (HARN)/Wisconsin Transverse Mercator.

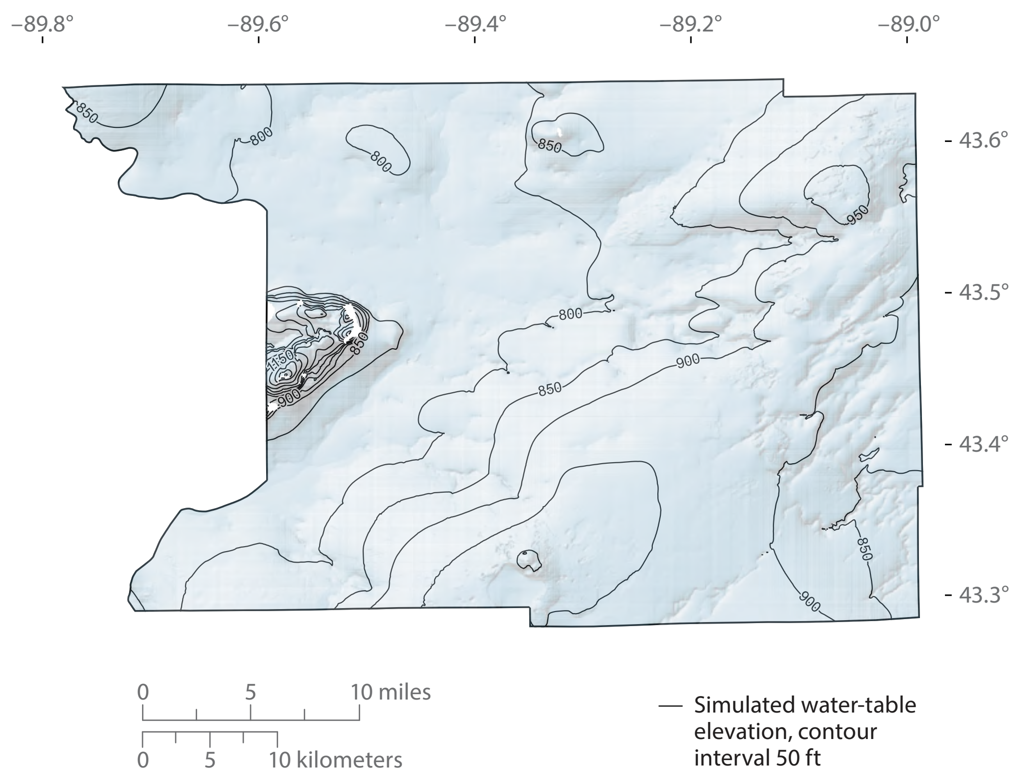
was modeled as low-lying with a relatively flat gradient along Duck Creek, a tributary of the Wisconsin River, where there is low topographic relief. Along the eastern boundary of Columbia County, the modeled water table appeared as a northeast-southwest linear trend, which broadly reflected the orientation of the drainage network and the historical direction of ice flow. Within this area, drumlins influenced the location and shape of surface-water features, which in turn affected the configuration of the water table.

Groundwater recharge

The multiplier of 1 for recharge, arrived at through calibration, supported the use of the SWB model to estimate the values of recharge across Columbia County (fig. 16). The SWB results (Schoephoester and Gotkowitz, 2012) applied to the groundwater model were based on the 1981 precipitation year because total precipitation that year was close to the long-term average value of about 33 in. for 1941 to 2016 (fig. 3). The SWB results yielded a county-wide average recharge rate of 8 in./yr. Soil characteristics exerted a strong control on the recharge estimates for Columbia County, with soils characterized by a high-infiltration capacity generally correlating to areas of greatest recharge. In general, hydrologists regard wetland areas as likely having relatively low groundwater recharge rates because their fine-grained soil types retain water rather than allow it to quickly drain, and shallow water-table depths often preclude recharge in wetland settings. In the SWB model, the simulated retention in areas with wetland soil types resulted in more water use by plants and less recharge to groundwater.

Schoephoester and Gotkowitz (2012) also used the SWB model to estimate recharge for very dry and very wet years. The precipitation records from 1963, during which precipitation totaled 21.6 in., resulted in a county-wide average recharge rate of 1.5 in/yr. In contrast, in 2008 when total precipitation in Portage reached 50.8 in., the SWB estimate of average recharge was 14 in/year. Incorporating this long-term variability in recharge into the groundwater flow model might better represent a broad range of climatic conditions but was beyond the scope of this project.

Figure 26. Simulated water-table surface, with 50-foot elevation contours. White areas in the Baraboo Hills indicate dry conditions through the entire vertical extent of the model, where the surface of the Precambrian bedrock is above the water table.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator.
Elevation: U.S. Geological Survey National Elevation Dataset, 2017.

Model limitations

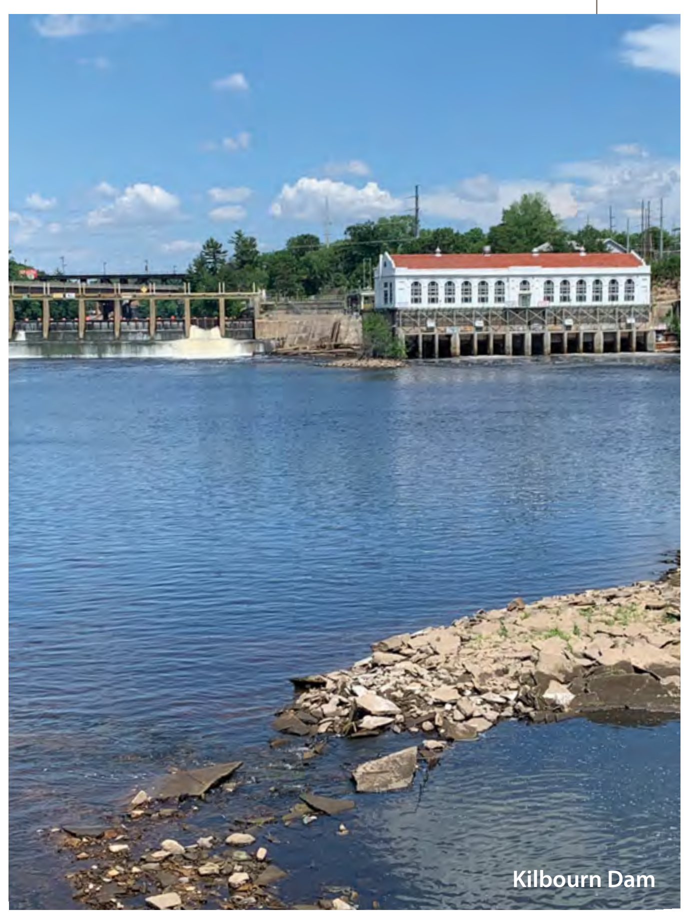
As with all models, the Columbia County groundwater-flow model is a simplification of a complex natural system. This model's results are uncertain because of the chosen model structure and simplifying assumptions, uncertainty in the input parameter values, and uncertainty in the supporting data. Generally, uncertainty in the model's results was lower within Columbia County, which is represented in more detail than the surrounding areas, and lowest in areas with the most supporting data (for example, borehole data that provided layer elevations and water levels or streamflow observational data).

The model discretization, parameterization, and layer surfaces all included simplifying assumptions:

- Each model cell represents average conditions over an area of 90,000 square feet and up to several hundred vertical feet of thickness.
- Each pilot point's hydraulic conductivity estimate represented an area of approximately 26 square miles and hydraulic conductivity was assumed to vary smoothly between individual pilot points within a zone.
- The spatial distribution of recharge estimated by the SWB model for Columbia and Dane Counties was not altered; only the magnitude of recharge was adjusted through global multiplier values. In the areas of the model outside of Columbia County and the area simulated in the Dane County Groundwater Flow Model, recharge was assumed to be homogenous throughout zones that covered large areas of the model.

In reality, hydraulic conductivity and recharge varied locally at much smaller scales, both laterally and vertically. For example, we documented the presence of hydraulically active bedding-plane-parallel fractures, which result in several orders of magnitude variation in hydraulic conductivity within a well that intersects the upper bedrock aquifer (well CO-784, table 3). In the model, this setting is represented by a single value of hydraulic conductivity in layer 3. The histograms of hydraulic conductivity estimates (fig. 10) demonstrate the variation in hydraulic conductivity throughout the study area. The SWB estimates indicated a range of variability in recharge across the domain, but the accuracy of these estimates may vary in specific areas. Potential sources of error in the SWB model include (1) an assumption that there was no Dunnian runoff or saturation excess because of a shallow water table and (2) many input parameters (runoff curve number, rooting depth, and so on) that were correlated and (or) difficult to measure in the field.

The differences between the local conditions and the simplified representation in the model constitute a form of structural error, which may have biased some model predictions that were sensitive to those differences. The ability of the model to accurately simulate a particular area depended on the amount of supporting data in that location. Supporting data can reduce model uncertainty by informing both the model structure and the input parameter values. Areas with more water-level and borehole data were better constrained than areas with sparse data, which was especially true for the interpretation of the Precambrian surface elevation (fig. 6) that was developed for the bottom boundary of the model. As noted previously, some of the anomalous hydraulic conductivity estimates may indicate errors in the modeled surface elevations of the Precambrian or



other layers (and therefore simulated aquifer thickness), which were compensated for in the parameter estimation process through adjustments to hydraulic conductivity.

The well locations and pumping rates included in the model for calibration represented long-term, steady-state conditions from approximately 1970 to 2010; the steady-state model did not reflect the number of wells in operation at any one point in time. Using the best available pumping information may be beneficial in any additional model applications.

In some locations, such as the Baraboo Hills or the upper bedrock aquifer in the eastern part of the county, the model structure may be inadequate for simulating groundwater levels and flow directions. In reality, groundwater flow in the Baraboo Hills is likely sensitive to the fine-scale variability in surficial deposits and shallow fracture networks, which were poorly resolved in the groundwater-flow model. In the upper bedrock aquifer, local conditions vary considerably, depending on the presence of the St. Peter Formation, Jordan Formation, and Tunnel City Group. Locally extensive aquitards, such as the St. Lawrence Formation or the fine-grained intervals of the Tunnel City Group, are known to influence the groundwater-flow paths at the scale of individual wells. In the model, however, these units were lumped into a single layer. Local-scale studies in these areas may benefit from (1) incorporating changes to the model structure, such as additional model layers to represent locally important hydrostratigraphic units, and (2) refining the surface elevations of each model layer.

Streambed and stream stage elevations simulated in the model were approximate; both these and surface leakage simulated by the UZF package were limited by the grid discretization of 300 ft. In reality, the interactions between groundwater and surface water are affected by local topography at smaller scales. Uncertainty in surface elevations may have affected the accuracy of the simulated groundwater discharge apportioned between the stream leakage and surface leakage components of the model's mass balance. Therefore, these components warrant consideration together as the overall discharge to and from the surface-water network.

Simulated surface leakage conveyed to the SFR package is applied evenly among the reaches in the receiving stream segment. In SFR segments with dry reaches, this can result in the misapplication of surface leakage to reaches that in reality should not receive groundwater discharge. For example, dry upper reaches in a headwater segment that are not conceptualized as receiving any flow would receive an equal share of any riparian discharge, producing flow in stream reaches that are above the water table and would otherwise be simulated as dry. In the Columbia County model, the overall effects of this simplification are likely small and localized to headwater areas. In a similar modeling study set in northern Wisconsin, Leaf and others (2015) reported about 5% of total discharge being misallocated in affected stream segments.

Extensive bedding plane fractures in an outcrop near Rio. Fracture networks such as these likely control local groundwater flow paths in the upper bedrock aquifer.

Conclusions

The geologic formations that compose Columbia County's groundwater system are of variable thickness across the region. The unlithified aquifer is an important source of water to wells in the Wisconsin River valley. The upper bedrock aquifer is present only in the eastern and central parts of the county. The Elk Mound aquifer generally varies from about 200 to 600 ft in thickness but is absent in several locations where Precambrian basement rocks are at the surface.

The Eau Claire aquitard, present over large parts of neighboring counties, is limited to the southwestern portions of Columbia County. The lower facies of the Tunnel City Group, at the base of the upper bedrock aquifer, appears to restrict vertical groundwater flow to the underlying sandstone of the Wonewoc Formation. Aquitards can offer natural protection for groundwater quality in underlying aquifers. Data presented in this report indicate that the Tunnel City Group may provide this function where it is present. In these areas, wells cased through the upper bedrock system into the underlying Elk Mound aquifer may be less susceptible to contamination. However, wells that are open across the base of the Tunnel City Group may provide a pathway for contamination in shallow groundwater to reach deeper portions of the groundwater system. Additional characterizations of the extent and hydraulic properties of the Tunnel City Group in Columbia County may be useful to support the design and construction of wells where groundwater in the upper bedrock aquifer is of poor quality.

The three-dimensional regional groundwater-flow model documented in this report may be useful in supporting the management of groundwater resources in Columbia County. The steady-state model is calibrated to a large dataset generally representative of average conditions between 1970 and 2010. The use of the USGS's MODFLOW-NWT code provided explicit simulation of the surface water with streamflow routing, whereas the application of the UZF package accounted for groundwater discharge to wetlands and other surface-water bodies that were not explicitly simulated.

The water balance derived from the model supports the conclusion that groundwater resources are abundant in Columbia County. Groundwater discharge in low-lying areas supports numerous wetlands. Other areas with shallow depths to groundwater may be prone to groundwater flooding during wet periods that cause the water table to rise. The estimates from the SWB model indicate that recharge to the water table averages about 8 in./yr across the area. Groundwater use from high-capacity wells is low relative to recharge. However, pumping from wells completed near streams and springs intercepts groundwater that would otherwise discharge to these features and may cause decreases in surface-water flow. Locations and depths of new wells designed with consideration of these factors may reduce the potential for effects to streams or interference with existing wells.

The groundwater-flow model developed here is a tool to support water-resource management in Columbia County. Applications include designing wells to support high-quality drinking water, developing wellhead-protection areas, quantifying groundwater contribution to streams, and characterizing the potential effects of new wells or changes in pumping rates on existing wells (Gotkowitz, 2021). The model is also useful for assessing general groundwater-flow directions near areas where septage, manure, or industrial waste has been applied to the land surface. Limitations of the model, such as the representation of porous media flow rather than fracture flow, may affect its utility for some types of analyses. For example, the model is not designed to simulate transport or preferential flow that is affected by the bedding-plane fractures discussed in the "Hydrostratigraphy" section. The model may be suitable for updating as more hydrogeologic information becomes available; updates may improve the representation of heterogeneity in the hydraulic properties of the primary aquifers and aquitards.

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References

Anderson, M.P., Woessner, W.W., and Hunt, R.J., 2015, Applied groundwater modeling: simulation of flow and advective transport (5th ed.): San Diego, Calif., Academic Press, 564 p.

Aswasereelert, W., Simo, J.A., and LePain, D.L., 2008, Deposition of the Cambrian Eau Claire Formation, Wisconsin: Hydrostratigraphic implications of fine-grained cratonic sandstones: Geoscience Wisconsin, v. 19, no. 1, p. 1–21.

Barnes, H.H., 1967, Roughness characteristics of natural channels: U.S. Geological Survey Water-Supply Paper 1849, 213 p., https://doi.org/10.3133/wsp1849.

Bradbury, K.R., and Rothschild, E.R., 1985, A computerized technique for estimating the hydraulic conductivity of aquifers from specific capacity data: Ground Water, v. 23, no. 2, p. 240–246.

Center for Watershed Science and Education, 2019, Well Water Quality Viewer: Private well data for Wisconsin: Center for Watershed Science and Education, University of Wisconsin—Stevens Point web page accessed October 30, 2019 at https://www.uwsp.edu/cnr-ap/watershed/Pages/WellWaterViewer.aspx.

Clayton, L., and Attig, J.W., 1990, Geology of Sauk County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 67, 68 p., 2 pls., scale 1:100,000.

Cotter, R.D., 1969, Water resources of Wisconsin—Rock-Fox River basin: U.S. Geological Survey Hydrologic Investigations Atlas 360, 4 pls.

Doherty, John, 2003, Ground water model calibration using pilot points and regularization: Ground Water, v. 41, no. 2, p. 170–177, https://doi.org/10.1111/j.1745-6584.2003.tb02580.x.

Doherty, John, 2010, PEST, Model-independent parameter estimation—user manual (5th ed., with slight additions): Brisbane, Australia, Watermark Numerical Computing, [333 p.], accessed November 13, 2014, at http://www.pesthomepage.org/Downloads.php.

Doherty, John, 2014a, Addendum to the PEST manual: Brisbane, Australia, Watermark Numerical Computing [316 p.], accessed November 13, 2014, at http://www.pesthomepage.org/Downloads.php.

Doherty, John, 2014b, Groundwater data utilities; part A, overview: Brisbane, Australia, Watermark Numerical Computing [73 p.], accessed November 13, 2014, at http://www.pesthomepage.org/Downloads.php.

Doherty, J.E., Fienen, M.N., and Hunt, R.J., 2010, Approaches to highly parameterized inversion: Pilot-point theory, guidelines, and research directions: U.S. Geological Survey Scientific Investigations Report 2010–5168, 36 p.

Doherty, J.E., and Hunt, R.J., 2010, Approaches to highly parameterized inversion—A guide to using PEST for groundwater-model calibration: U.S. Geological Survey Scientific Investigations Report 2010–5169, 59 p.

Dunne, T., and Black, R.G., 1970, An experimental investigation of runoff production in permeable soils: Water Resources Research, v. 6, p. 478–490.

Feinstein, D.T., Hunt, R.J., and Reeves, H.W., 2010, Regional groundwater-flow model of the Lake Michigan Basin in support of Great Lakes Basin water availability and use studies: U.S. Geological Survey Scientific Investigations Report 2010–5109, 379 p.

Gebert, W.A., Walker, J.F., and Kennedy, J.L., 2011, Estimating 1970–99 average annual groundwater recharge in Wisconsin using streamflow data: U.S. Geological Survey Open-File Report 2009–1210, 14 p., plus appendixes, http://pubs.usgs.gov/ofr/2009/1210/.

Gotkowitz, M.B., 2012, Groundwater recharge, Columbia County, Wisconsin: Wisconsin Geological and Natural History Survey Educational Series 52–2, 2 p.

Gotkowitz, M.B., 2021, Simulations of groundwater flow in Columbia County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2021–06, 15 p.

Gotkowitz, M.B., and Mauel, S.W., 2012a, Groundwater susceptibility, Columbia County, Wisconsin: Wisconsin Geological and Natural History Survey Educational Series 52–3, 2 p.

Gotkowitz, M.B., and Mauel, S.W., 2012b, Groundwater susceptibility map of Columbia County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2012–03, scale 1:100,000.

Gotkowitz, M.B., Zeiler, K.K., Dunning, C.P., Thomas, J.C., and Lin, Y.F., 2005, Hydrogeology and simulation of groundwater flow in Sauk County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 102, 43 p.

Haitjema, H.M., 1995, Analytic element modeling of groundwater flow: San Diego, Calif., Academic Press, 394 p.

Harr, C.A., Trotta, L.C., and Borman, R.G., 1978, Ground-water resources and geology of Columbia County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 37, 30 p.

Hindall, S.M., and Borman, R.G., 1974, Water resources of Wisconsin—lower Wisconsin River basin: U.S. Geological Survey Hydrologic Investigations Atlas 479, 3 pls.

Hooyer, T.S., Mode, W.N., and Clayton, L., 2021, Quaternary geology of Green Lake, Marquette, and Columbia Counties, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 114, 38 p., 1 pl., scale 1:100,000.

Hooyer, T.S., Mode, W.N., Clayton, L., and Attig, J.W., 2015, Preliminary Quaternary geology of Columbia, Green Lake, and Marquette Counties, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2015–01, scale 1:100,000.

Hunt, R., Anderson, M., and Kelson, V., 1998, Improving a complex finite-difference ground water flow model through the use of an analytic element screening model: Ground Water, v. 36, no. 6, p. 1011–1017, http://dx.doi.org/10.1111/j.1745-6584.1998.tb02108.x.

Johnson, S., and Gotkowitz, M., 2012, Evaluation of groundwater pumping to reduce the level of Crystal Lake in Columbia County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2012–05, 14 p.

Juckem, P.F., 2009, Simulation of the regional ground-water-flow system and ground-water/surface-water interaction in the Rock River Basin, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2009–5094, 38 p.

Konikow, L.F., Hornberger, G.Z., Halford, K.J., and Hanson, R.T., 2009, Revised multi-node well (MNW2) package for MODFLOW ground-water flow model: U.S. Geological Survey Techniques and Methods 6–A30, 67 p.

Krohelski, J.T., Bradbury, K.R., Hunt, R.J., and Swanson, S.K., 2000, Numerical simulation of groundwater flow in Dane County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 98, 31 p.

Krohelski, J.T., Lin, Y.-F., Rose, W.J., and Hunt, R.J., 2002, Simulation of Fish, Mud, and Crystal Lakes and the shallow ground-water system, Dane County, Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 2002–4014, 17 p.

Kucharik, C.J., Serbin, S.P., Vavrus, S., Hopkins, E.J., and Motew, M.M., 2010, Patterns of climate change across Wisconsin from 1950 to 2006: Physical Geography, v. 31, no. 1, p. 1–28.

Lacombe, S., Sudicky, E.A., Frape, S.K., and Unger, A.J.A., 1995, Influence of leaky boreholes on cross-formational groundwater flow and contaminant transport: Water Resources Research, v. 31, no. 8, p. 1871–1882.

Leaf, A.T., Fienen, M.N., Hunt, R.J., and Buchwald, C.A., 2015, Groundwater/surface-water interactions in the Bad River Watershed, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2015–5162, 110 p., http://dx.doi.org/10.3133/sir20155162.

Leaf, A.T., Gotkowitz, M., Haserodt, M.J., 2021, MODFLOW-NWT and GFLOW model of groundwater flow and groundwater/surface-water interactions in Columbia County, Wisconsin: U.S. Geological Survey data release, https://doi.org/10.5066/F7HM57NS.

Leaf, A.T., Hart, D.J., and Bahr, J.M., 2012, Active thermal tracer tests for improved hydrostratigraphic characterization: Ground Water, v. 50, no. 5, p. 726–735.

Lineback, J.A., Bleuer, N.K., Mickelson, D.M., Farrand, W.R., Goldthwait, R.P., Richmond, G.M., and Fullerton, D.S., 1983, Quaternary geologic map of the Chicago 4° × 6° quadrangle, United States: U.S. Geological Survey Map I–1420 (NK–16), scale 1:1,000,000.

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p., http://dx.doi.org/10.3133/cir1405.

McKay, L., Bondelid, T., Dewald, T., Johnston, J., Moore, R., and Rea, A., 2012, NHDPlus version 2—User guide: Washington, D.C., U.S. Environmental Protection Agency, 173 p., https://nctc.fws.gov/courses/references/tutorials/geospatial/CSP7306/Readings/NHDPlusV2_User_Guide.pdf.

Meyer, J.R., Parker, B.L., and Cherry, J.A., 2008, Detailed hydraulic head profiles as essential data for defining hydrogeologic units in layered fractured sedimentary rock: Environmental Geology, v. 56, no. 1, p. 27–44.

National Oceanic and Atmospheric Administration, 2017, Climate Data Online, https://www.ncdc.noaa.gov/cdo-web/.

Niswonger, R.G., Panday, S., and Ibaraki, M., 2011, MODFLOW–NWT—A Newton formulation for MODFLOW–2005: U.S. Geological Survey Techniques and Methods 6–A37, 44 p.

Niswonger, R.G., and Prudic, D.E., 2005, Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams—A modification to SFR1: U.S. Geological Survey Techniques and Methods 6–A13, 50 p.

Niswonger, R.G., Prudic, D.E., and Regan, R.S., 2006, Documentation of the Unsaturated-Zone Flow (UZF1) Package for modeling unsaturated flow between the land surface and the water table with MODFLOW–2005: U.S. Geological Survey Techniques and Methods 6–A19, 62 p.

Olcott, P., 1968, Water resources of Wisconsin—Fox-Wolf River basin: U.S. Geological Survey Hydrologic Investigations Atlas 321, 4 pls.

Ostrom, M.E., 1978, Stratigraphic relations of Lower Paleozoic rocks of Wisconsin, in Odom, I.E., Ostrom, M.E., Byers, C.W., Morris, R.C., and Adams, R.A., Lithostratigraphy, petrology, and sedimentology of Late Cambrian–Early Ordovician rocks near Madison, Wisconsin: University of Wisconsin–Extension Geological and Natural History Survey, Field Trip Guide Book 3, p. 3–22.

Paillet, F.L., 2001, Hydraulic head applications of flow logs in the study of heterogeneous aquifers: Ground Water, v. 39, no. 5, p. 667–675.

Parsen, M.J., Bradbury, K.R., Hunt, R.J., and Feinstein, D.T., 2016, The 2016 groundwater flow model for Dane County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 110, 56 p.

Perry, M., 2017, Rasterstats, version 0.12: conda-forge web page accessed July 5, 2017 at https://conda-forge.org/.

Poff, R.J., and Threinen, C.W., 1965, Surface water resources of Columbia County: Madison, Wisconsin Conservation Department, 55 p.

Public Service Commission of Wisconsin, 2011, E-Services Portal, Annual Reports: Water, Electric, Gas and Sewer: web page accessed October 15, 2011, at https://apps.psc.wi.gov/ARS/annualReports/content/listingWEGS.aspx.

Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., and Alexander, S.C., 2006, Hydrostratigraphic characterization of intergranular and secondary porosity in part of the Cambrian sandstone aquifer system of the cratonic interior of North America: Improving predictability of hydrogeologic properties: Sedimentary Geology, v. 184, no. 3–4, p. 281–304.

Schoephoester, P.R., and Gotkowitz, M.B., 2012, Groundwater recharge map of Columbia County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2012–02, scale 1:100,000.

Sellwood, S.M., 2012a, Preliminary water-table elevation map of Columbia County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2012–04, scale 1:100,000.

Sellwood, S.M., 2012b, Water-table elevation: Wisconsin: Wisconsin Geological and Natural History Survey Educational Series 52–1, 2 p.

Sellwood, S.M., 2015, Characterization of groundwater flow in sandstone aquifers using heat as an in-well tracer: Madison, University of Wisconsin, Ph.D. dissertation, 122 p.

Sellwood, S.M., Hart, D.J., and Bahr, J.M., 2015, An in-well heat-tracer-test method for evaluating borehole flow conditions: Hydrogeology Journal, v. 23, no. 8, p. 1817–1830.

Swanson, S.K., Bahr, J.M., Bradbury, K.R., and Anderson, K.M., 2006, Evidence for preferential flow through sandstone aquifers in Southern Wisconsin: Sedimentary Geology, v. 184, no. 3–4, p. 331–342.

Thwaites, F.T., 1957, Buried Pre-Cambrian of Wisconsin: Wisconsin Geological and Natural History Survey Map 31, 1 page-sized map, https://wgnhs.wisc.edu/pubs/000356/.

U.S. Census Bureau, 2020, Quick facts; Columbia County, Wisconsin: U.S. Census Bureau web page accessed July 6, 2020 at https://www.census.gov/quickfacts/columbiacountywisconsin

U.S. Environmental Protection Agency, 2000, National Primary Drinking Water Regulations: Ground Water Rule, 40 CFR Parts 141 and 142: Federal Register, v. 65, no. 91, p. 30194–30274.

U.S. Geological Survey, 2009, National Elevation Dataset: U.S. Geological Survey web page accessed in 2009 at http://ned.usgs.gov/.

U.S. Geological Survey, 2013, National Elevation Dataset: U.S. Geological Survey web page accessed June 18, 2013, at http://ned.usgs.gov/.

U.S. Geological Survey, 2017, USGS water data for the Nation: U.S. Geological Survey National Water Information System database accessed October 2, 2017, at https://doi.org/10.5066/F7P55KJN.

Wahl, K.L., and Wahl, T.L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas, in Texas Water '95, A Component Conference of the First International Conference on Water Resources Engineering, Water Resources Engineering Division, American Society of Civil Engineers, San Antonio, Tex., August 16–17, 1995, Proceedings: San Antonio, American Society of Civil Engineers, p. 77–86. http://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0708.pdf.

Wisconsin Department of Natural Resources, 2016, Wetland Mapping; Wisconsin Wetland Inventory: Wisconsin Department of Natural Resources web page accessed May 16, 2016, at http://dnr.wi.gov/topic/wetlands/inventory.html.

Weidman, S., and Schultz, A.R., 1915, The underground and surface water supplies of Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 35, 664 p.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB—A modified Thornthwaite-Mather Soil-Water-Balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods 6–A31, 61 p.

Young, H.L., 1992, Hydrogeology of the Cambrian-Ordovician aquifer system in the northern Midwest: U.S. Geological Survey Professional Paper 1405–B, 108 p., 1 pl., scale 1:2,500,000.

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Kenneth R. Bradbury, Director and State Geologist

Wisconsin Geological and Natural History Survey
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The Survey conducts earth-science surveys, field studies, and research. We provide objective scientific information about the geology, mineral resources, water resources, soil, and biology of Wisconsin. We collect, interpret, disseminate, and archive natural resource information. We communicate the results of our activities through publications, technical talks, and responses to inquiries from the public. These activities support informed decision making by government, industry, business, and individual citizens of Wisconsin.