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The 2016 Groundwater Flow Model for Dane County, Wisconsin

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Sue Swanson

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Appendices are provided in an Excel file.

Abstract

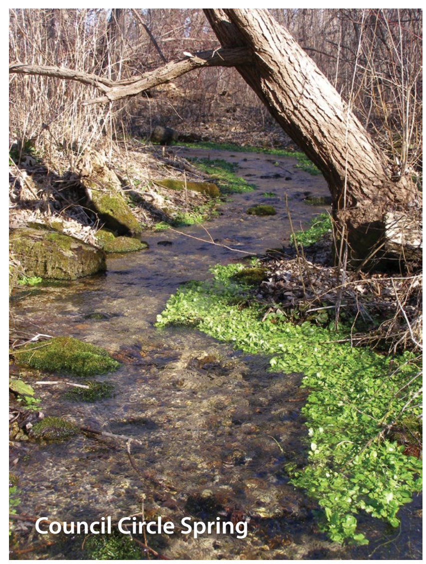
A new groundwater flow model for Dane County, Wisconsin, replaces an earlier model developed in the 1990s by the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS). This modeling study was conducted cooperatively by the WGNHS and the USGS with funding from the Capital Area Regional Planning Commission (CARPC). Although the overall conceptual model of the groundwater system remains largely unchanged, the incorporation of newly acquired high-quality datasets, recent research findings, and improved modeling and calibration techniques have led to the development of a more detailed and sophisticated model representation of the groundwater system. The new model is three-dimensional and transient, and conceptualizes the county's hydrogeology as a 12-layer system including all major unlithified and bedrock hydrostratigraphic units and two high-conductivity horizontal fracture zones.

Beginning from the surface down, the model represents the unlithified deposits as two distinct model layers (1 and 2). A single layer (3) simulates the Ordovician sandstone and dolomite of the Sinnipee, Ancell, and Prairie du Chien Groups. Sandstone of the Jordan Formation (layer 4) and silty dolostone of the St. Lawrence Formation (layer 5) each comprise separate model layers. The underlying glauconitic sandstone of the Tunnel City Group makes up three distinct layers: an upper aquifer (layer 6), a fracture feature (layer 7), and a lower aquifer (layer 8). The fracture layer represents a network of horizontal bedding-plane fractures that serve as a preferential pathway for groundwater flow. The model simulates the sandstone of the Wonewoc Formation as an upper aquifer (layer 9) with a bedding-plane fracture feature (layer 10) at its base. The Eau Claire aquitard (layer 11) includes shale beds within the upper portion of the Eau Claire Formation. This layer, along with overlying bedrock units, is mostly absent in the preglacially eroded valleys along the Yahara River valley and in northeastern Dane County. Layer 12 represents the Mount Simon sandstone as the lowermost model layer. It directly overlies the Precambrian crystalline basement rock, whose top surface forms the lower boundary of the model.

The model uses the USGS MODFLOW-NWT finite-difference code, a standalone version of MODFLOW-2005 that incorporates the Newton (NWT) solver. MODFLOW-NWT improves the handling of unconfined conditions by smoothing the transition from wet to dry cells. The model explicitly simulates groundwater–surface-water interaction with streamflow routing and lake-level fluctuation. Model input included published and unpublished hydrogeologic data from recent estimates of aquifer hydraulic conductivities. A spatial groundwater recharge distribution was obtained from a recent GIS-based, soil-water-balance model for Dane County. Groundwater withdrawals from pumping were simulated for 572 wells across the entire model domain, which includes Dane County and portions of seven neighboring counties—Columbia, Dodge, Green, Iowa, Jefferson, Lafayette, and Rock. These wells withdrew an average of 60 million gallons per day (mgd) over the 5-year period from 2006 through 2010. Within Dane County, 385 wells were simulated with an average withdrawal rate of 52 mgd.

Model calibration used the parameter estimation code PEST, and calibration targets included heads, stream and spring flows, lake levels, and borehole flows. Steady-state calibration focused on the period 2006 through 2010; the transient calibration focused on the 7-week drought period from late May through July 2012.

This model represents a significant step forward from previous work because of its finer grid resolution, improved hydrostratigraphic discretization, transient capabilities, and more sophisticated representation of surface-water features and multi-aquifer wells.



Mike Parsen

Potential applications of the model include evaluation of potential sites for and impacts of new high-capacity wells, development of wellhead protection plans, evaluating the effects of changing land use and climate on groundwater, and quantifying the relationships between groundwater and surface water.

Introduction

The 2016 Dane County regional groundwater model is part of an ongoing effort to improve understanding of the hydrologic system within Dane County, Wisconsin. This model replaces a 1996 regional groundwater flow model (Krohelski and others, 2000). The new model builds upon improvements in our understanding of the hydrogeology of Dane County and takes advantage of additional data collection efforts as well as advances in computer capabilities, data management, groundwater modeling, and calibration.

Following its development, the original 1996 model has been regularly used to evaluate a host of questions ranging from long-term impacts of groundwater pumping and well siting to numerous site-specific research and applied environmental investigation studies. Although the 1996 model has remained a valuable tool for assessing groundwater resources, our understanding of hydrogeology across the county has improved, as has the data management, modeling, and calibration software. Furthermore, certain simplifications of the 1996 model, including no transient calibration, fixed lake and stream levels, and relatively coarse discretization, provided additional motivation to build an improved model.

Although many of the same groundwater modeling needs remained relevant to the development of the 2016 model, new societal concerns have emerged over the past decade as our understanding of Dane County's hydrologic system has improved. The recent interest in groundwater–surface-water interactions, which require greater spatial resolution for accurate representation, and the need for a transient model with improved model calibration methods were the primary drivers motivating the development of an updated regional groundwater flow model. The release of countywide lidar (*li*ght + ra*dar*) data in 2010, long-term baseflow estimates by USGS researchers in 2011 (Gebert and others, 2011), the availability of numerous high-quality geophysical logs, and a countywide groundwater recharge model (Hart and others, 2012) developed by the WGNHS in 2009 provided further opportunities to leverage existing data sets and update the groundwater flow model.

The regional-scale groundwater modeling of Dane County has been made possible through ongoing funding by the CARPC, the Dane County Land and Water Resources Department, the Madison Metropolitan Sewerage District, the Madison Water Utility, and other municipalities and public water utilities across Dane County. This continued support has led to the development, use, and regular improvement of the groundwater model, ensuring its applicability and utility as a decision-support tool for years to come.

The WGNHS partnered with the USGS Wisconsin Water Science Center for this modeling project.

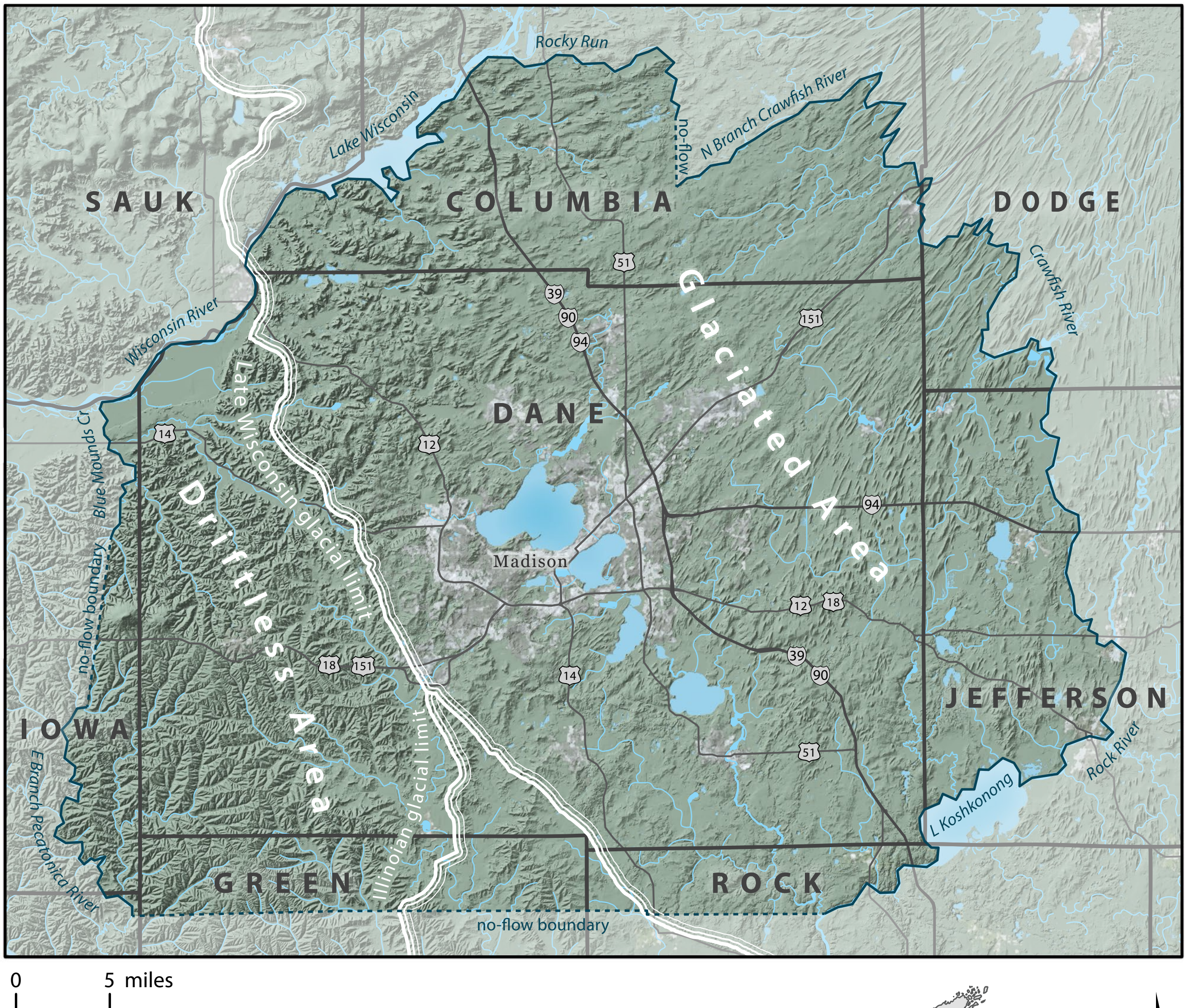
Spring Creek

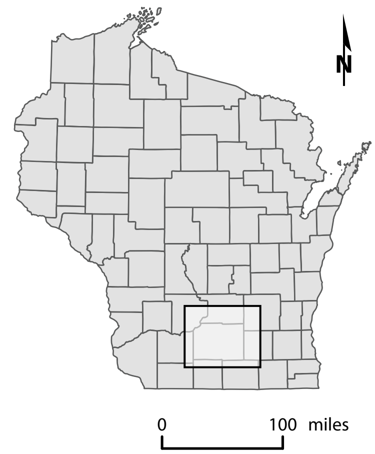
Mike Parsen

Scope

The model area, shown in figure 1, comprises Dane County and parts of seven adjacent counties (Columbia, Dodge, Green, Iowa, Jefferson, Lafayette, and Rock). Including neighboring counties was necessary because the hydraulic boundaries of the groundwater system extend outside Dane County. Water-use data for high-capacity wells and subsurface hydrogeologic data for areas beyond Dane County's borders were compiled and used in the updated model. When available, we also used existing data for neighboring counties, such as recharge estimates for Columbia County. In the absence of additional information, data and published maps for Dane County were extrapolated into neighboring counties.

Figure 1. Location and extent of the Dane County model showing edge boundary conditions.





Setting

Dane County is located in south-central Wisconsin and straddles the boundary between the Driftless Area of southwestern Wisconsin and the area covered by the Laurentide Ice Sheet during the Wisconsin Glaciation (Clayton and Attig, 1997). The western part of the county is located within the Driftless Area, a region of older landscapes not modified by glacial ice. The Driftless Area typically contains dissected uplands and well-developed surface-water drainage systems. Hills are generally flat-topped and are often used for pastureland and row crops. Slopes are steep and commonly forested. In contrast, the glaciated eastern two-thirds of the county is characterized by rolling, moderately hilly topography. The eastern part of the county contains numerous drumlins. The drainage system is not as well developed and the region contains lakes and marshes.

According to the National Climatic Data Center, the average annual precipitation in Dane County, as measured at the Dane County Regional Airport, was 34.48 inches per year between 1981 and 2010. For the same period, the mean annual air temperature was 46.5°F, with an average monthly maximum of 81.6°F in July and an average monthly minimum of 11.1°F in January (http://www.ncdc.noaa.gov/oa/climate/normals/usnormals.html). Sixty percent of annual precipitation falls between May and September.

Land use in Dane County is predominantly agricultural, with most activity directed toward dairy farming and row crops. The centrally located Madison metropolitan area, composed of the city of Madison and the adjacent cities of Monona, Middleton, Fitchburg, and Verona, is the largest population center in the county. As of the 2010 census, the total population of Dane County was 488,000 (U.S. Census Bureau, 2012).

Objectives

This project had three major objectives:

1. **Collect data to support model improvement**, including refining hydrostratigraphy, characterizing aquifer properties, updating water-use data, and refining recharge rates.
2. **Refine the conceptual and numerical model**, including improving simulation detail through finer grid spacing than used in previous models, adding simulations of springs plus groundwater interactions with the Yahara Lakes, and calibrating to transient conditions.
3. **Develop a simulation tool for informing management decisions** regarding groundwater use and development in Dane County. Typical uses include simulating contributing areas for municipal wells, examining current groundwater levels and flow directions, and establishing a starting point for future site-specific studies using refined models.

Important features of the new model

Although the overall area simulated by the 2016 model is essentially the same as was simulated in the 1996 model, the new model incorporates the following improvements to the conceptualization and numerical representation of the groundwater system:

Additional data

- Re-evaluation of existing hydrogeologic and hydraulic data and incorporation of recently acquired high-quality datasets including geophysical logs, water-level and vertical-head-difference measurements, borehole-flow measurements, pumping test results, and stream baseflow measurements.
- A more complete evaluation of countywide water-use data, including all active and inactive high-capacity wells through 2010 (historical, industrial, agricultural, commercial, and municipal).
- Use of more-detailed estimates of recharge distribution from recently published soil-water-balance modeling for Dane County (Hart and others, 2012).
- Incorporation of recent laboratory and field testing to better estimate effective porosity of different aquifer and aquitard units.
- Incorporation of recently acquired lidar data on county topography, which was particularly useful for developing the streamflow routing network used in the model.

Improvements to the numerical model

- Refined grid spacing from 1,320 to 360 feet (ft) horizontally and from 3 layers to 12 layers vertically to provide greater spatial resolution.
- Simulation of all significant streams in the county using the MODFLOW Streamflow-Routing (SFR2) package (Niswonger and Prudic, 2005). The 1996 model simulated streams using the less-sophisticated River (RIV) package, where stream-aquifer interactions are not constrained by a water balance in the stream, and streamflow routing is not explicitly simulated. The SFR2 package simulates a water balance in each stream cell, which includes streamflow routing components, and can simulate inflows and outflows between streams and lakes. Stream stage is computed from the water balance, and can limit stream-aquifer interactions (for example, losing streams can go dry, shutting off leakage to the aquifer).
- Simulation of major lakes in the county using the MODFLOW Lake (LAK3) package. The 1996 model simulated lakes as static constant-head features. The new model allows lake levels to fluctuate dynamically in response to a simulated lake-water balance, which includes groundwater flow, precipitation, evaporation, as well as stream inflow and outflow. The LAK3 package also allows lake area, volume, and stream outflow to vary as a function of stage.
- Improved simulation of multi-aquifer or cross-connecting wells using the MODFLOW Multi-Node Well (MNW2) package.
- Use of MODFLOW-NWT (Niswonger and others, 2011), a stand-alone version of the USGS MODFLOW 2005 code (Harbaugh, 2005) that incorporates a Newton solver package, which greatly improves model stability by allowing dry nodes in the model to remain part of the model solution (for an example, see Feinstein and others, 2012).
- Transient capabilities to allow seasonal predictions of water levels and streamflow.
- Advanced calibration using a highly parameterized approach (Doherty and Hunt, 2010) for both steady-state and transient models.

Model distribution and use

The groundwater flow model described here is in the public domain. The model files are available both in native MODFLOW and in proprietary Groundwater Vistas (Environmental Simulations, Inc.) formats. A companion user's guide (Bradbury and others, 2016) includes detailed lists of files required and instructions for running the model.

Acknowledgments

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U.S. Geological Survey staff contributing to this project include Cheryl Buchwald, Mike Fienen, Jim Kennedy, Rich Niswonger, Jason Smith, and John Walker.

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Study methods

Review of previous studies

The initial phase of the project involved review of geological and hydrogeological studies conducted within Dane County over the past several decades. Early groundwater modeling (McLeod, 1975) served as a historical reference point for development of more recent models in Dane County. Regional-scale groundwater characterization by the USGS and WGNHS in the 1990s and 2000s (Bradbury and others, 1999; Krohelski and others, 2000) represented a major improvement in the conceptual model and numerical representation of the groundwater system. A series of inset models based on the regional Dane County model were subsequently developed to investigate flow in fractured bedrock and spring systems at local scales. The inset models led to improved understanding of preferential flow through fracture features and their importance for regionally fed spring systems (Hunt and Steuer, 2000; Parent, 2001; Swanson, 2001, 2007; Swanson and others, 2001, 2006; Anderson, 2002), and other areas of interest such as Fish and Crystal Lakes (Krohelski, 2002). Work by McLeod (1974), Meyer (2005, 2013), Meyer and others (2008), Macholl (2007), Bahr and others (2010), Gellasch and others (2013), and Sellwood and others (2014) further demonstrated the importance of preferential flow through fracture networks and better characterized groundwater flow within the county.

Foundational research on the regional geology and hydrology by Cline (1965), Ostrom (1965), Olcott (1972), and Day and others (1985) provided a basis for reinterpreting the hydrostratigraphy of Dane County. More recent geologic mapping by Clayton and Attig (1997) and Brown and others (2013), and studies by Fritz (1996) and Aswasereelert and others (2008) also provided insight into the regional hydrogeology. The development of improved techniques for estimating recharge by Dripps and Bradbury (2007) and Westenbroek and others (2010) and their application to Dane County by Hart and others (2012) also improved understanding of the spatial distribution of recharge within the county.

Location and identification of public and private wells

The location and pumping rates of both public and private high-capacity wells were compiled by the USGS into a water-use database. A high-capacity well is, by definition, any well that is constructed on a high-capacity property, where the pumping rate from all combined wells is equal to or exceeds 70 gallons per minute, or roughly 100,000 gallons per day (gpd) (Wisconsin Administrative Code NR 812.07).

Water-use estimates were made for all wells based on data available from the Wisconsin Public Service Commission (PSC) and from individual water utilities. Pumping rates were averaged over the 5-year period of 2006 through 2010 for the steady-state model. Historical pumping rates were also obtained, from as early as the late 1800s, for the purposes of evaluating changes in pumping since predevelopment.

The steady-state model includes 572 wells. The locations and well construction characteristics of each well were checked against records in the DNR well construction reports (WCRs) as well as information maintained by the WGNHS.

Geophysical logging

Modern downhole geophysical logging is an important tool for understanding subsurface hydrostratigraphy. Numerous geophysical logs have been collected in Dane County over the past several decades, typically including vertical profiles of temperature, fluid conductivity, resistivity, natural gamma radiation, and borehole diameter (caliper). Many more recent logs also include optical and acoustic borehole imaging as well as borehole-flow measurements. These additional data can provide more detailed information about hydrostratigraphy, including the spatial extent and thickness of aquitards and evidence for preferential flow along apparent bedding-plane fractures. Appendix 1 contains an example of a complete suite of geophysical logs.

The high quality of geophysical logs, compared to other sources of subsurface data, such as well construction reports and geologic logs from drill cuttings, make them a primary source of data for delineating distinct hydrostratigraphic units.

Water-use survey and data compilation

Following the collection and compilation of pumping data for all high-capacity wells, a water-use survey was sent to all 27 public water utilities within Dane County during the spring of 2012. Results from this survey confirmed the location and pumping rate for each municipal well and provided information about future pumping. Wells that had recently become inactive or selected for future abandonment were identified and modified accordingly in the water-use database.

A survey was also conducted for all Dane County municipal wastewater treatment facilities in the spring of 2012 to estimate discharge rates to surface water during 2010. Of the 15 treatment plants surveyed in Dane County, the following 12 reported effluent data: Belleville, Blue Mounds, Cambridge, Cross Plains, Deerfield, Madison Metropolitan Sewerage District (MMSD), Marshall, Mazomanie-Arena, Mount Horeb, Oregon, Stoughton, and Sun Prairie. For the remaining three, we estimated discharge rates by applying a 6 percent increase (that is, the average percent increase for the reporting treatment plants between 2000 and 2010) to the 2000 rates published by CARPC (Dane County Regional Planning Commission, 2004). The MMSD treatment plant discharges to two locations, one on Badfish Creek and another at the headwater of Badger Mill Creek, raising the total number of Dane County discharge locations accounted for by the model to 16.

A final water-use survey was conducted during the fall of 2012 to obtain transient pumping data for the drought period from late May to July 2012 from all municipal water utilities. We obtained withdrawal data from the following 11 water utilities in Dane County: DeForest, Fitchburg, Madison, McFarland, Middleton, Mount Horeb, Oregon, Stoughton, Sun Prairie, Verona, and Waunakee. These data were then extrapolated to other wells for which no withdrawal data were available for this period.

Stream and spring flow measurements

Baseflow measurements for perennial streams in Dane County were used to calibrate the model. A statewide study to estimate average annual recharge from 1970 to 1999 by the USGS (Gebert and others, 2011) provided estimates of baseflow for 66 partial-record stations and eight long-term stream gaging stations across the study area. During the course of the modeling project, the WGNHS made 23 one-time streamflow measurements and 18 one-time spring flow measurements within the study area. In most cases these measurements were made under low-flow conditions and at least several days after a rainfall event. For a DNR study to evaluate the aquatic health of stream habitats across Dane County (Diebel and others, 2014), over 100 flow measurements were made within the study area. Eighty of these measurements were located along perennial streams and included in model calibration. Four additional estimates of streamflow representing a 75 percent flow exceedance (Q75) at the outlets of Lakes Mendota, Monona, Waubesa, and Kegonsa were calculated based on an evaluation of historical time-series streamflow data from USGS stream gaging stations along the Yahara River.

Recharge estimation

Groundwater recharge in Dane County comes from precipitation (rain and snowmelt) at the land surface. A recent investigation estimated recharge across Dane County (Hart and others, 2012) using the soil-water-balance code (SWB) (Westenbroek and others, 2010). SWB uses readily available soil type, land cover, topographic, and climatic data to estimate groundwater recharge. The SWB recharge model accounts for precipitation, evapotranspiration, interception, surface runoff, soil-moisture storage, and snowmelt at daily time steps. The spatial distribution of groundwater recharge was estimated for both present and past climate and land-use conditions. The results indicated significant temporal variability in average annual infiltration to the unsaturated zone in response to climatic variability.

Starkweather Creek—stream gaging

Mike Parsen

Estimated recharge varied spatially across the county from less than 5 inches to more than 15 inches in a typical year.

Hydrostratigraphy

Hydrostratigraphic interpretation was important for discretizing the model layering. Geologic and hydrogeologic data were compiled, including well construction reports with driller's lithological descriptions, geological logs of drill cuttings and core as described by WGNHS geologists, geophysical logs collected by WGNHS staff and other researchers, as well as Pleistocene, bedrock geology, and bedrock elevation maps for Dane County. Geophysical logs represented the highest quality and most reliable set of subsurface data. An initial interpretation of hydrostratigraphic contact elevations for bedrock was made using geophysical logs. The lateral extent and thickness of each hydrostratigraphic unit was then constrained using the remaining subsurface point data and existing geologic, depth-to-bedrock, and bedrock elevation maps.

Numerical simulation methods

The model uses the USGS MODFLOW-NWT finite-difference code (Harbaugh, 2005; Hunt and Feinstein, 2012), with a Newton solver to improve the handling of unconfined conditions by smoothing the fluctuation of wet and dry cells. The model is transient and three-dimensional. It explicitly simulates groundwater–surface-water interaction with streamflow routing and lake-level fluctuation. The Groundwater Vistas graphical user interface was used to facilitate model input and visualize model output. The model was calibrated using parameter estimation code (PEST) and guidelines outlined by Doherty and Hunt (2010). Calibration targets used for history matching included heads, stream and spring flows, lake levels, and borehole flows. Steady-state calibration focused on the period between 2006 and 2010; the transient calibration simulated a 7-week drought period between late May and July 2012.


Culver Springs

Ken Bradbury

Geology, hydrostratigraphy, and hydrology of Dane County

Quaternary geology and hydrostratigraphy

Dane County straddles the boundary between the glaciated area to the east and the unglaciated, or Driftless, area to the west (fig. 1). Weathering and glacial processes over the past tens of thousands of years have created a diverse range of landforms, surface-water features, and deposits of glacial, fluvial, lacustrine, and eolian materials across the landscape, over the bedrock. Several geologists, including Alden (1918), Mickelson (1983), and Clayton and Attig (1997) have described these deposits and provide a framework for interpreting their hydrogeologic significance.

Across the county, the overall depth of Pleistocene sediment varies from absent to a thin cover of windblown and hillslope sediment on the uplands and valley walls of the Driftless Area, to several hundred feet of unlithified sediments within the Yahara River and Wisconsin River valleys (Clayton and Attig, 1997). Most of the Pleistocene sediment in Dane County is composed of till of the Horicon Member of the Holy Hill Formation, which was deposited by the Green Bay Lobe of the Laurentide Ice Sheet during the Late Wisconsin glaciation. Earlier deposits from the early and middle Pleistocene are believed to be present in some of the deeper preglacial valleys beneath the modern-day Yahara and Wisconsin Rivers. These earlier sediments would have been deposited on the preglacial, erosional topography that was carved into the Paleozoic bedrock surface millions of years before glaciers first reached Dane County. As glaciers moved into eastern Dane County, they ground down a surface topography comparable to that of the Driftless Area; lowering hills and filling low-lying areas with debris and sediment (Clayton and Attig, 1997). Modern-day fluvial and lacustrine sediments were subsequently deposited in lakebeds and along river and stream channels in both the glaciated and Driftless Area.

The till dominating the eastern portion of the county consists primarily of gravelly, clayey, silty sand, which exhibits a relatively uniform range of hydraulic conductivity of about 0.5–0.7 ft/day in field tests (Rayne and others, 1996). Offshore sediment of glacial lakes and postglacial, pre-modern lakes also form important landscape features in central and eastern Dane County. In several areas, these deposits of fine-grained silt and clay overlie coarser-grained till, forming a confined or partially confined aquifer within the unlithified sediments (Clayton and Attig, 1997). The presence of this confined unlithified aquifer system was mapped by Fritz (1996).

Bedrock geology and hydrostratigraphy

The bedrock geology of Dane County consists of Precambrian age crystalline rock overlain by successive units of younger Paleozoic age sandstone and dolomite (fig. 2). Cline (1965) and Ostrom (1965) describe these units in detail, while more recent mapping by Brown and others (2013) interprets the spatial extent of these units. Investigations by Mickelson (1983) and Clayton and Attig (1997) also discuss these bedrock units.

The base of the system consists of igneous and metamorphic rocks of Precambrian age. The top of this Precambrian surface varies in elevation between roughly 400 ft below and 400 ft above mean sea level within Dane County. This surface elevation was developed by using information from 58 wells in Dane County and an additional 300 wells from across southern Wisconsin and northern Illinois, which were drilled to Precambrian bedrock. Although little is known about the hydrogeologic properties of the crystalline bedrock in Dane County, it is known to have little porosity and limited hydraulic conductivity (Bradbury and others, 1999). The Precambrian surface is directly beneath several hundred feet of permeable sandstone, and, for the purposes of this model, represents the base of the aquifer system.

Paleozoic bedrock of the Elk Mound Group overlies the Precambrian crystalline rocks throughout all of Dane County. The Elk Mound Group consists of units of sandstone and shale including, from oldest to youngest, the Mount Simon, Eau Claire, and Wonewoc Formations. The Mount Simon Formation is made up of coarse- to medium-grained sandstone, which ranges in thickness across Dane County from roughly 100 ft in the northeast to 800 ft in the south. Across most of the county, the Mount Simon ranges from 300 to 600 ft thick. The Mount Simon is a major aquifer, which serves as the water supply for many of the largest high-capacity wells in Dane County. The coarse- to medium-grained sandstone of the Mount Simon Formation gradually transitions upwards to the fine-grained, silty sandstone of the Eau Claire Formation. Interbedded shales occur in the lower quarter of the Mount Simon, and the formation

Figure 2. Bedrock stratigraphy and corresponding layers in the 1996 and 2016 groundwater models. (General bedrock stratigraphy adapted from Brown and others, 2013.)

GENERAL BEDROCK STRATIGRAPHY				GROUNDWATER FLOW MODEL				
Age		Stratigraphic name		Model layers, names				Type
Era	Period	Group	Formation	1996 model		2016 model		
				1	Sand and gravel	1	Unlithified I (fine-grained lake deposits within glacial Lake Yahara area; elsewhere, till and meltwater stream deposits)	aquifers
						2	Unlithified II (till and meltwater stream deposits)	
Paleozoic	Ordovician		Maquoketa	2	Upper bedrock	3	Upper bedrock	
		Sinnipee	Galena					
			Decorah					
			Platteville					
		Ancell	Glenwood					
			St. Peter					
		Prairie du Chien						
	Cambrian	Trempealeau	Jordan			4	Jordan	
			St. Lawrence			5	St. Lawrence	
		Tunnel City	Lone Rock, Mazomanie			6	Tunnel City—upper	
						7	Tunnel City *(fracture layer)*	
						8	Tunnel City—lower	
		Elk Mound	Wonewoc			9	Wonewoc	
						10	Wonewoc *(fracture layer)*	
			Eau Claire	—[a]	Confining unit	11	Eau Claire	aquitard
			Mount Simon	3	Lower bedrock	12	Mount Simon	aquifer
Precambrian		Various unnamed units		No-flow boundary				

[a] *In the 1996 model, the shaley part of the Eau Claire Formation was represented by a leakance term to account for the unit's vertical hydraulic conductivity and thickness.*

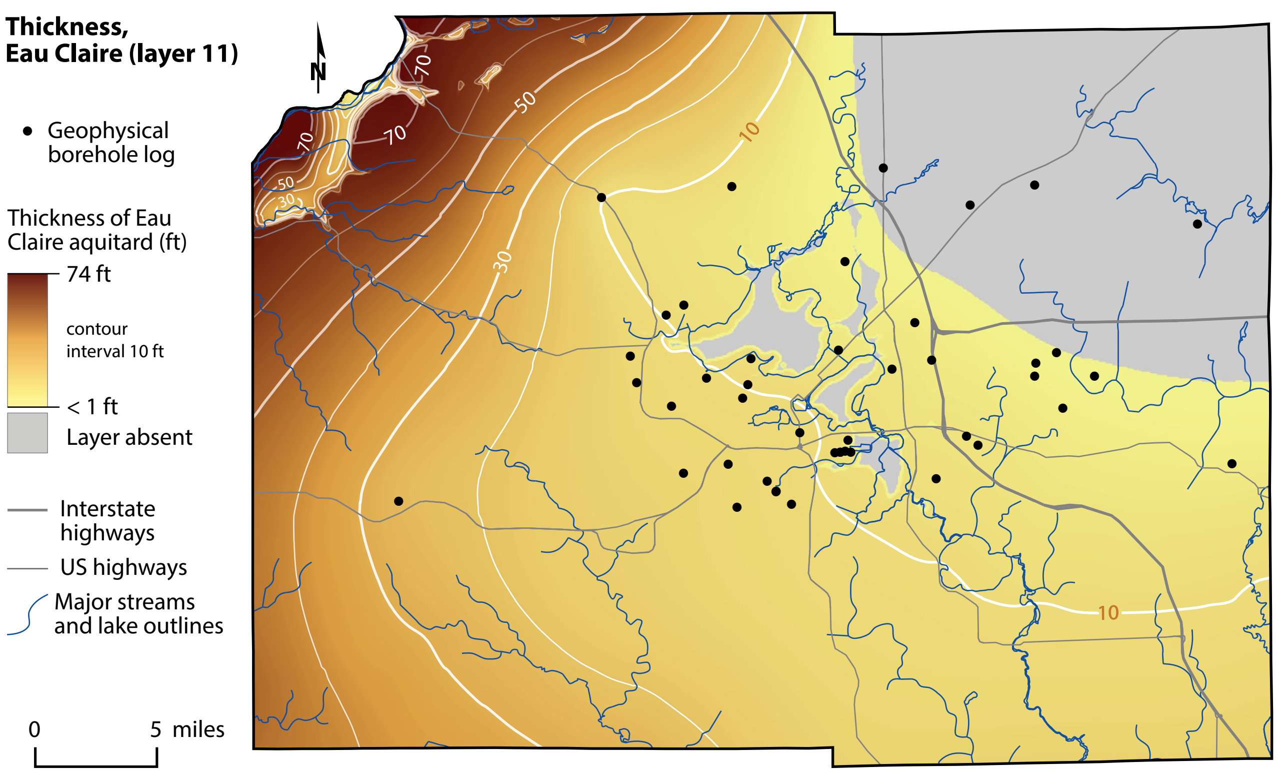
coarsens and contains numerous pebbles near its basal contact with the underlying Precambrian rocks.

The upper portion of the Eau Claire Formation contains significant amounts of shale and siltstone, forming an important aquitard, known as the Eau Claire aquitard, across much of the county. The shaley interval near the top of the Eau Claire Formation is absent in well logs in northeastern Dane County. This shaley interval is also absent beneath portions of central Dane County where erosion along the pre-glacial Yahara River valley scoured down through this layer into the Mount Simon aquifer. The Eau Claire aquitard ranges in thickness from absent to over 70 ft in western Dane County (fig. 3). A geophysical log of WGNHS test hole along County Highway A in eastern Iowa County (WGNHS ID: 25000512), indicates that the shaley facies interval of the Eau Claire Formation is roughly 70 ft thick in that vicinity. This shale interval is particularly distinct from the natural gamma signature in numerous geophysical logs. The absence of this gamma signature in northeastern Dane County suggests the absence of the Eau Claire aquitard in these areas. The top-of-bedrock elevation surface developed by Olcott (1972) suggests that the Eau Claire aquitard is also absent beneath parts of the Yahara Lakes.

The overlying Wonewoc Formation consists of medium- to fine-grained sandstone, forming an important regional aquifer system above the Eau Claire aquitard. Sandstone of the Wonewoc Formation varies in thickness from absent to roughly 200 ft. The Wonewoc is absent within portions of the Yahara River, Black Earth Creek, and Wisconsin River valleys where the preglacial erosional surface fell below this layer. Outcrops of the Wonewoc are exposed along the banks of the Wisconsin River valley. Recent studies at multiple field sites within Dane County provide evidence for preferential flow of groundwater along bedding-plane fracture features within the sandstone of the Wonewoc Formation (Anderson, 2002; Macholl, 2007; Bahr and others, 2010; Gellasch and others, 2013; Sellwood and others, 2014).

The Tunnel City Group overlies the Elk Mound Group and consists of medium to very fine-grained glauconitic sandstone. In Dane County, the Tunnel City Group ranges from absent to roughly 140 ft thick. Although these rocks yield less than the underlying sandstones of the Elk Mound Group, the sandstone of the Tunnel City Group is an important source of groundwater to wells in many parts of Dane County. In central

Figure 3. Thickness and extent of the Eau Claire aquitard. Includes locations of geophysical borehole logs used in the interpretation.



Mike Parsen

Dane County, the Tunnel City Group outcrops at or near the level of the principal lakes within the Yahara watershed. In many areas, the Tunnel City Group sandstone is the first bedrock unit encountered at depth along the Madison Isthmus and other low-lying areas near the Yahara lakes. Recent investigations by Swanson (2001, 2007), Swanson and others (2006), and Meyer and others (2008) demonstrated the existence of discrete bedding-plane fractures within the Tunnel City Group that contribute to the preferential flow of groundwater. Many of the larger spring features in central Dane County, for example Nine Springs, Culver Springs, Frederick Springs, and several springs around Lake Wingra are likely associated with these fracture features.

The upper Cambrian bedrock units of the Trempealeau Group is made up of the St. Lawrence and Jordan Formations. The St. Lawrence is classified as a silty dolostone or dolomitic siltstone, contains trace amounts of glauconite (Brown and others, 2013), and exhibits relatively low hydraulic vertical conductivity. The sandstone of the Jordan Formation lies just above this unit and acts as a minor aquifer where saturated. The combined thickness of these two bedrock units varies from absent to roughly 60 ft thick across Dane County.

The uppermost Paleozoic units of Ordovician age are above the water table in most of the county and were lumped into a single model layer. This layer includes dolostone of the Prairie du Chien Group, dolostone and sandstone of the Ancell Group, shale and dolostone of the Sinnipee Group, and shale of the Maquoketa Formation, which forms a thin cap at the top of the highest ridge at Blue Mounds State Park.

Bedding-plane fractures

Over the past decade, downhole investigations using video logs, optical-borehole imaging (OBI), borehole flow meters, and other technology have regularly detected permeable horizontal discontinuities in bedrock wells in Dane County and elsewhere. These discontinuities usually appear coincident with bedding planes and are typically nearly horizontal in orientation. These features range in thickness from about 0.05 to 0.5 ft when imaged in borehole walls and can transmit significant quantities of water. Gellasch and others (2013) showed that such fractures can dominate the transmissivity of an individual borehole in Madison and reported hydraulic conductivities ranging from 26 to 1,560 ft/day measured using short-interval (2.3 feet) straddle packers. Swanson and others (2006) observed similar fractures in an investigation of the Nine Springs basin in Dane County. They reported fracture hydraulic conductivities as high as 1,130 ft/day and were able to simulate springs in a numerical flow model by including a fracture layer having a hydraulic conductivity of 400 ft/day. WGNHS scientists have commonly observed such fractures in bedrock wells installed in the county. These fractures, which appear to correlate from well to well, are generally found about midway between the top and bottom of the Tunnel City Group and within a few feet of the bottom of the Wonewoc Formation.

Surface-water features

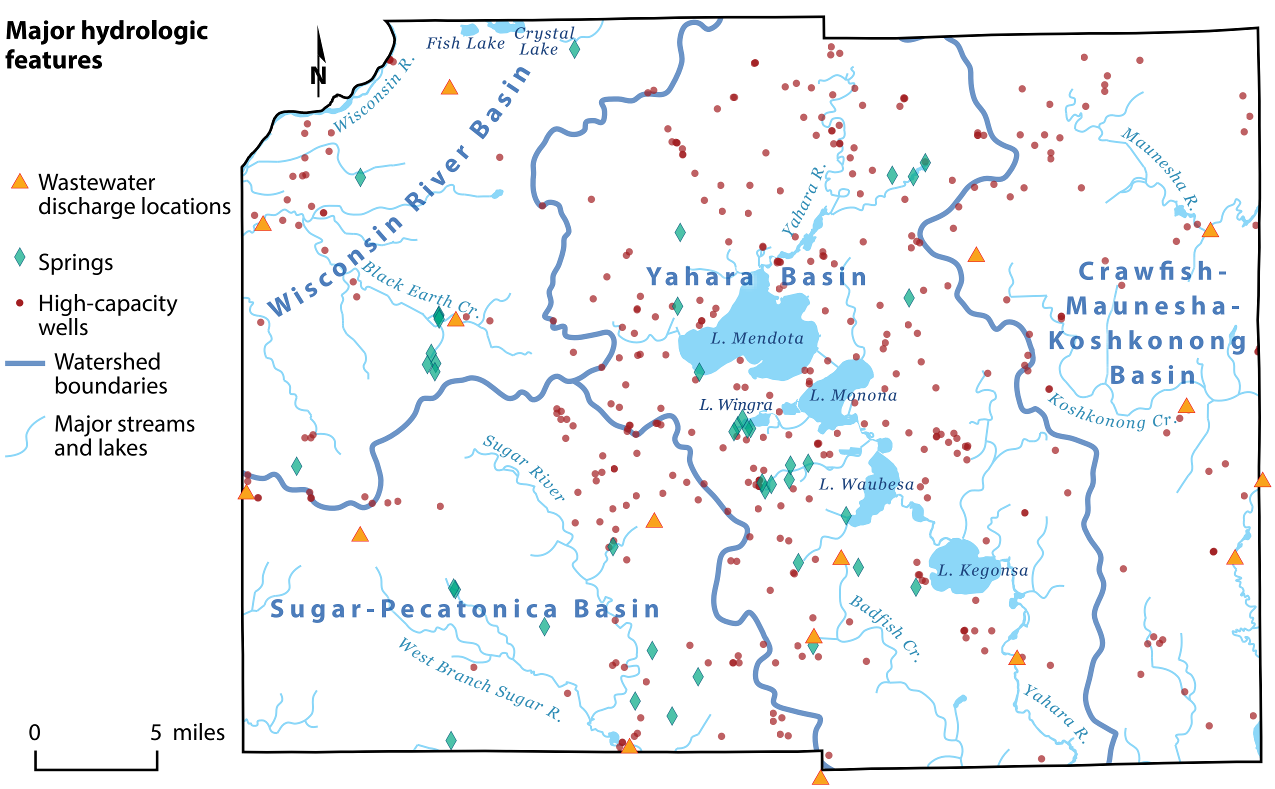
Dane County contains a diversity of geomorphologic landforms that influence the distribution of surface-water features across the county. The county consists of five distinct physiographic areas including the Wisconsin River valley, valleys and ridges of the Driftless Area, hills and hummocks between the Johnstown and Milton moraines, the Yahara River Valley, and drumlins and marshes of eastern Dane County (Day and others, 1985). Within these areas, four principal surface watersheds are commonly demarcated: the Wisconsin River basin in the northwest; the Sugar and Pecatonica River basins to the west and south; the Yahara River basin forming a central corridor from north to south; and the Crawfish River, Koshkonong Creek, and Maunesha River basin to the east (fig. 4) (Day and others, 1985). Each basin contains a variety of surface-water features including lakes, wetlands, streams, and springs. There are also a number of municipal treatment plants whose treated effluent contributes to the flow of various streams across the county.

Lakes and wetlands

The largest lakes in Dane County are located within the central Yahara River corridor and form a chain connected by the Yahara River and a series of smaller streams, lakes, and wetlands. From north to south the Yahara River enters Lake Mendota through Cherokee Marsh, a broad wetland area that receives additional streamflow from Token Creek and the watershed upstream of Cherokee Marsh. At the outlet of Lake Mendota, the Yahara River abruptly drops 5 ft in elevation as water passes through the lock and dam structure at Tenney Park and makes its way across the Madison Isthmus to Lake Monona. Lake Wingra, which is fed by several local springs near the UW-Madison Arboretum, is also connected to Lake Monona via Wingra Creek. From Lake Monona, the gradient flattens and the Yahara River flows through several marshes and shallow lakes before entering Lake Waubesa near McFarland. Due to the low hydraulic gradient between these lakes, backwater effects (where water backs up due to an obstruction) are common along this stretch of the Yahara River. At the outlet of Lake Waubesa, the Yahara River again passes through several wetlands and shallow lakes before entering Lake Kegonsa north of Stoughton. Once the Yahara River leaves Lake Kegonsa, it continues south until joining the Rock River southwest of Edgerton.

In addition to the five major lakes within the Yahara River watershed, there are dozens of smaller named lakes. Most named lakes are located within kettles, low-lying marsh areas, or behind impoundments and dams. Lakes at higher elevations in the watershed are typically isolated seepage lakes with no natural stream outlets or headwater lakes that feed perennial streams. Lakes lower in the landscape are usually flow-through lakes connected to streams or low-lying seepage lakes. Fish and Crystal Lakes, seepage lakes in northwest Dane County, are the two largest lakes outside of the Yahara River basin that are within the model domain. Water levels in Fish and Crystal Lakes have varied significantly over the past decades with more recent flooding (Krohelski, 2002).

Figure 4. Major hydrologic features in Dane County.



Rivers and streams

Rivers and streams within Dane County lie within four principal surface watersheds (fig. 4). Within the Wisconsin River watershed, several streams drain the northern flanks of Military Ridge and the western edge of the terminal moraine west of Middleton, Springfield, and Dane. The major perennial stream networks include Dunlap Creek, Black Earth Creek, Blue Mounds Creek, and several smaller tributaries to Black Earth and Blue Mounds Creeks. Wastewater discharges at Cross Plains and Mazomanie contribute to streamflow along Black Earth Creek; discharge at Roxbury is directed to the Wisconsin River through a dedicated canal and does not enter any streams within the county.

The Sugar River and Pecatonica River watershed, within southwest Dane County, drains the southern slopes of Military Ridge and the western edge of the terminal moraine. The primary streams include the Sugar River, Sugar River West Branch, Mount Vernon Creek, and a few tributaries of the Pecatonica River in southwest Dane County. Wastewater discharges at Blue Mounds join the Pecatonica River system to the west; discharges at Mount Horeb, Verona, and Belleville contribute to flow within the Sugar River system.

Within the Yahara River watershed, many of the tributaries feed directly into the Yahara lakes. Token Creek west of Sun Prairie, Pheasant Branch Creek in Middleton, Wingra Creek at the outlet of Lake Wingra, Nine Springs Creek near Fitchburg, and Starkweather Creek in Madison are important spring-fed creeks that contribute flow to the Yahara River. Wastewater discharges at Badfish Creek, Oregon, Brooklyn, and Stoughton all contribute to surface-water flow along the lower Yahara River.

The Crawfish River, Koshkonong Creek, and Maunesha River watershed within eastern Dane County is a relatively low-hydraulic-gradient system characterized by the presence of many drumlins and low-lying wetlands and marshes. The principal streams are tributaries of the Koshkonong River, south of Sun Prairie and east of Cottage Grove, and the Maunesha and Crawfish Rivers, in the northeast. Streams meander considerably more than in the western and central portions of Dane County and are often connected to drainage ditches and fed by field tiles that were installed to manage water levels and convert wetland areas to cultivated acreage. Wastewater discharge from Sun Prairie, Deerfield, Cambridge, and Rockdale contribute flow to the Koshkonong River, while discharge from Marshall contributes to the Maunesha River.

Within each of the four principal watersheds, the natural hydrological system has been altered by humans to manage water levels and streamflows, preferentially draining water from certain areas while maintaining elevated water levels in others.

Common methods for lowering water levels and increasing streamflow include channelizing creeks, installing ditches and tile drains, as well as harvesting aquatic plants and removing debris from stream and river channels. In contrast, techniques for maintaining higher water levels in lakes and streams commonly include the installation of dams and impoundments. As an example, along the Yahara River, dam structures at the outlets of Lakes Mendota, Waubesa, and Kegonsa are used to manage maximum and minimum lake levels while extensive weed cutting maintains more consistent water flow during the summer months.

Springs

Springs are important hydrologic features in Dane County and support diverse ecosystems by providing a steady supply of cool, clear water to many streams and lakes. In 2007, an inventory of Wisconsin's springs identified 230 springs in Dane County based on historical records going back decades (Macholl, 2007). Of these, over 100 had recorded flow rates of less than 0.01 cubic feet

Grace Graham

per second (cfs) or 4.5 gpm. Of the remaining springs, 20 had recorded flows of 0.1 cfs to 0.25 cfs (45 gpm to 112 gpm), and 20 had recorded flows of greater than 0.25 cfs (112 gpm). This set of principal springs is concentrated within the Yahara River, Wisconsin River, and Sugar-Pecatonica River watersheds (fig. 4), with over half occurring within the Yahara River basin. Springs are notably absent from the Crawfish-Maunesha-Koshkonong River watersheds. Work by Swanson and others (2006) suggests that preferential groundwater flow along bedding-plane fractures could contribute to the location of these spring features. Springs tend to be located in areas where bedrock units containing bedding-plane fractures, such as the Tunnel City Group, outcrop at the surface or are truncated by younger unlithified sediments at depth. Overlying unlithified materials could then serve as vertical conduits to flow, transporting groundwater to its surface outlet at the spring.

Water use and wastewater discharge

Within Dane County, the average groundwater withdrawal rate during the period from 2006 to 2010 was estimated to be 52 million gallons per day (mgd) from a total of 385 high-capacity wells (fig. 4). Although some residents obtain water from private low-capacity wells (wells with a pumping capacity less than 70 gallons per minute), the vast majority of Dane County's residents, businesses, industries, and farmers rely on high-capacity wells for their water supply. Groundwater withdrawal rates were compiled for all public and private high-capacity wells within the model domain based on responses to water-use surveys. For those utilities that did not respond to the survey, withdrawal rates and well locations were obtained from PSC, WGNHS, or USGS records. These records reflect the highest quality data available at the time of model construction.

Of the 52 mgd pumped from high-capacity wells in Dane County, 46 mgd are attributable to pumping from 104 municipal supply wells within the county. For the entire active model domain, which includes portions of seven neighboring counties, the total number of high-capacity wells is 572 with an average pumping rate between 2006 and 2010 of 60 mgd.

Much of the water produced from wells eventually reaches a wastewater plant for treatment. Once treated, wastewater is discharged to nearby streams where it reenters the hydrologic system as surface water. In Dane County there are 15 wastewater treatment plants that process approximately 53 mgd of water and discharge it to 16 outlet locations (the Madison Metropolitan Sewerage District treatment plant discharges to two locations) (fig. 4). The amount of water discharged at these locations is rarely the same as the amount of groundwater originally withdrawn due to evaporation and gains and losses from the sanitary sewer system before it reaches the wastewater treatment plant. A portion of pumped groundwater is commonly applied directly to the land for irrigation or watering lawns and gardens, and never reaches the sanitary sewer system. By contrast, heavy rains or rapid snowmelt can contribute runoff to wastewater. Leaky sanitary sewers can also lead to groundwater entering the sewer system or wastewater leaking from the sewer, leading to gains or losses in the total amount of wastewater arriving at the treatment plant.

The largest discharge of treated wastewater in Dane County is from the Madison Metropolitan Sewerage District (MMSD), which releases water to the headwaters of Badfish Creek near Oregon (41.7 mgd) and Badger Mill Creek near Verona (3.3 mgd). The discharge to Badger Mill Creek was designed to return groundwater pumped from within the Sugar River watershed, near Verona and Fitchburg, back to that same watershed as surface water. The next-largest discharges of treated wastewater are from Sun Prairie to Koshkonong Creek (3.2 mgd), followed by Stoughton to the Yahara River (1.2 mgd), and Oregon to Badfish Creek (1.1 mgd). The remaining 11 wastewater treatment plants discharge a combined total of 2.5 mgd to surface water. See appendix 2 for a full list of treatment plants and discharge volumes.

Conceptualization of the groundwater system

A conceptual model of the groundwater system is a synthesis and interpretation of what is known about the study area, and/or a collection of hypotheses about how the groundwater system functions, which are subsequently tested and refined in the modeling process (Anderson and others, 2015). The conceptualization of regional aquifers, aquitards, and boundary conditions outlined in the 1996 model (Krohelski and others, 2000) served as the starting point for updating the conceptual model of the hydrogeologic system. Figure 5 illustrates the updated conceptual model and figure 2 compares the hydrostratigraphy of the two models.

In the 2016 model, the unlithified materials were divided into two units to account for locally confined conditions created by the presence of shallow, fine-grained glacial and post-glacial lacustrine deposits within the greater Yahara River valley. Outside of the Yahara River valley, the unlithified materials are present across much of the glaciated portion of the county and within narrow alluvial valleys of the Driftless Area. In these areas, the distinction between the unlithified units is not applicable and both layers were assigned the same hydraulic properties. The distinction between these two unlithified aquifer units was based on previous hydrogeologic mapping of the shallow sand and gravel aquifer system (Fritz, 1996).

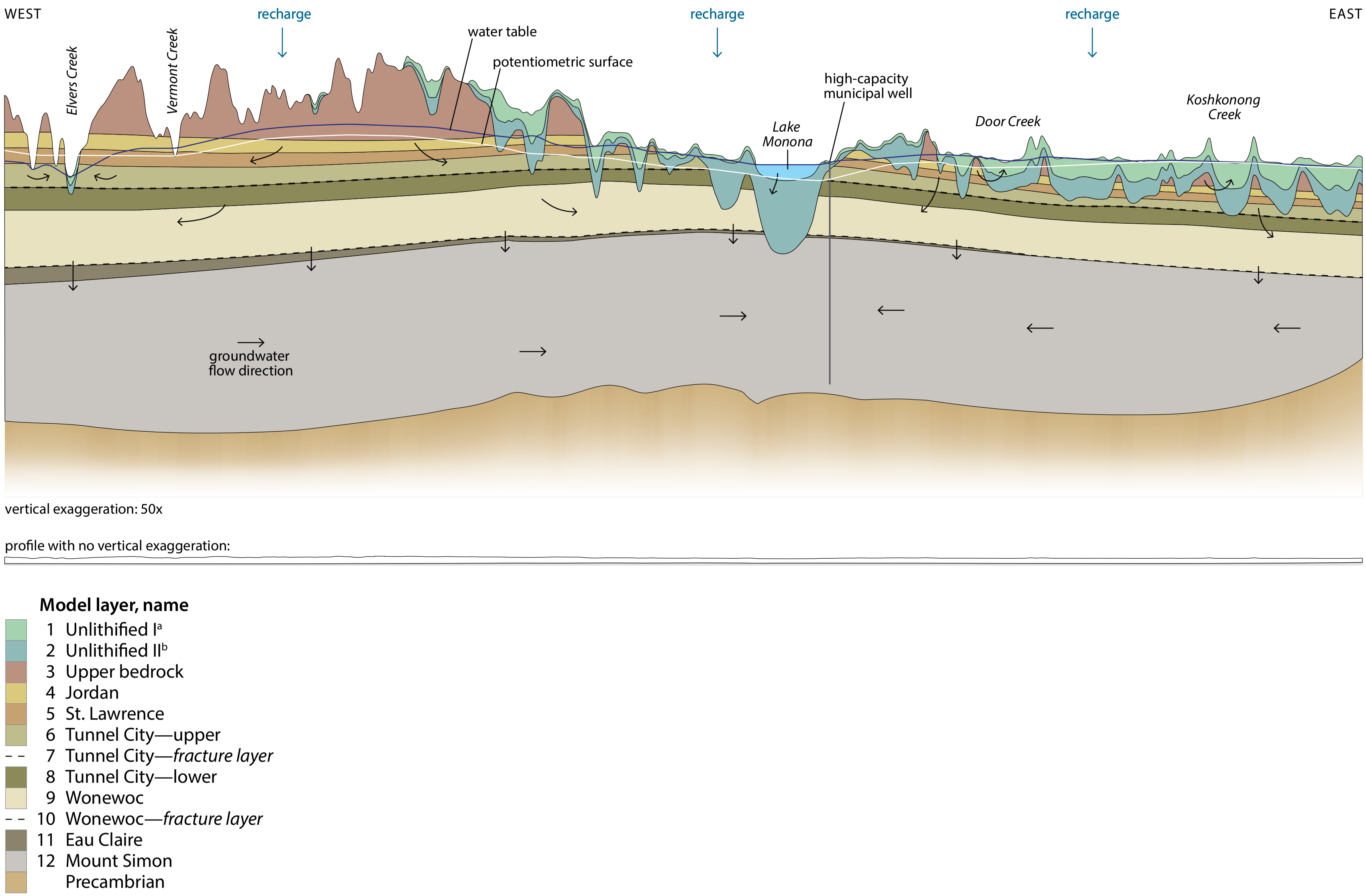
The upper bedrock aquifer system (rock units above the Eau Claire aquitard) was lumped as a single unit in the 1996 model. The current model subdivides the upper Paleozoic into eight layers (fig. 2) and accounts for preferential groundwater flow along bedding-plane fractures within the Tunnel City Group and Wonewoc Formation. The Eau Claire shale underlies the Wonewoc sandstone aquifer and serves as an important regional aquitard between the upper and lower aquifer systems. The Eau Claire shale is largely absent within the northeastern portion of Dane County as well as along the preglacially eroded valleys of the Yahara lakes area. The underlying Mount Simon aquifer, which consists of sandstones of both the Mount Simon Formation and the lower part of the Eau Claire Formation, beneath the shaley interval, forms the lower bedrock aquifer. The Mount Simon aquifer overlies the Precambrian crystalline basement rock, which is assumed to be impermeable and forms the lower boundary of the groundwater flow system.

Vertical hydraulic gradients, where hydraulic heads vary significantly with depth, occur in Dane County. Upward gradients, and upward flow, often occur beneath natural discharge areas such as the Wisconsin River, the Yahara River, and major springs in the county. However, near the main pumping centers there is often a strong potential for downward ambient borehole flow from the shallow aquifer system to the Mount Simon. Numerous flow meter logs in these cross-connecting wells have documented these flows, which can be as high as 100 gpm.

Water intersecting fracture networks within the sandstones of the Tunnel City Group and the Wonewoc Formation moves preferentially along these horizontal features until reaching a well, flowing into the unlithified aquifer, or discharging directly to the surface. Many of the major spring networks in Dane County are located in areas where the fracture network within the sandstone of the Tunnel City Group outcrops directly at the surface or subcrops (that is, where it is truncated at depth by unlithified deposits). In areas where the Tunnel City Group subcrops, the unlithified deposits are believed to serve as preferential conduits for water to flow vertically to surface springs (Swanson and others, 2006).

Water enters the groundwater flow system as recharge to the water table. Recharge rates vary across the county depending on the topography, soil type, and land use. When water falls on the land surface as rain or snow melt, a portion infiltrates and reaches the water table as recharge. Once part of the groundwater system, water moves horizontally and vertically toward discharge areas such as streams, lakes, wetlands, and pumping wells. Water within shallow groundwater aquifers, such as unlithified deposits or shallow bedrock, typically circulates through the groundwater system on the scale of years to hundreds of years depending on the proximity to discharge features. The closer recharging water is to a discharge feature, the shorter its flow path, and the more quickly, on average, it travels through the groundwater system and discharges to the surface. In contrast, water in the deeper Mount Simon aquifer typically takes hundreds to thousands of years to circulate through the groundwater system unless captured by a well.

Figure 5. Conceptual model of the groundwater system shown with and without vertical exaggeration.



[a] *Unlithified I = fine-grained lake deposits within glacial Lake Yahara area; elsewhere, till and meltwater stream deposits*

[b] *Unlithified II = till and meltwater stream deposits*

Three-dimensional model construction and simulation of the groundwater flow system

Model grid

The three-dimensional finite-difference groundwater flow model covers a 50- by 60-mile land area subdivided into 3,056,020 nodes (479 rows, 638 columns, and 12 layers). To allow for additional node refinement within Dane County, while maintaining acceptable run times, the model grid is divided into near-field and far-field areas. The near-field area encompasses all of Dane County and has uniform row and column dimensions of 360 x 360 ft. The area of a single model cell is approximately 3 acres. By contrast, the far-field node dimensions are non-uniform and increase in length using a multiplier of 1.4, effectively stretching each node dimension with distance from the near-field boundary. The far-field area extends outward from the near-field boundary into the seven neighboring counties (Columbia, Dodge, Jefferson, Rock, Green, Lafayette, and Iowa). For comparison, the previous Dane County model (Krohelski and others, 2000) used uniform node dimensions of 1312.4 x 1312.4 ft (roughly 40 acres) throughout the entire model grid. The number of active nodes in each model layer varies slightly because the active extent of each model layer is slightly different.

Model construction

Each component of the hydrogeologic system, including hydrostratigraphic units (aquifers, fracture layers, and aquitards), boundary conditions (streams, lakes, and springs), groundwater withdrawals, wastewater treatment plant discharges, and hydrologic properties, is associated with discretized cells that constitute a three-dimensional numerical grid. The following sections describe how each of these components was incorporated into the model. Figure 2 shows the relation of geologic units to model layers. Maps of the extent and thickness of each model layer are shown in figures 6 and 7, respectively. Figure 8 shows the model layering in cross section.

Fractured dolomite near Fitchburg

Mike Parsen

Hydrostratigraphic units

Layering approach and treatment of pinchouts

The Dane County numerical model uses the concept that each model layer represents a single hydrostratigraphic unit. This layering philosophy is convenient for keeping track of the properties of multiple units, but poses problems where the units pinch out due to erosion or nondeposition because model layers must be continuous across the model domain. Where hydrostratigraphic units pinch out or are absent, the layer was assigned a nominal thickness of 0.2 ft and given vertical hydraulic conductivity (Kv) and horizontal hydraulic conductivity (Kh) comparable to adjacent layers. When overlying layers are pinched beginning with layer 1, Kv and Kh of the first unpinched underlying layer were assigned. For example, if layer 1 was pinched, Kv and Kh of layer 2 were assigned to layer 1; or if layers 1 and 2 were pinched, Kv and Kh of layer 3 were assigned to layers 1 and 2. In contrast, if underlying layers are pinched, Kv and Kh of the first unpinched overlying layer were assigned to all underlying pinched cells. For example, if only layer 3 was pinched, Kv and Kh of layer 2 were assigned to layer 3; or if layers 3 and 4 were pinched, Kv and Kh of layer 2 were assigned to layers 3 and 4. These pinchout layers were used, for example, across the Driftless Area of western Dane County where Quaternary sediments are absent. They were also used below the Madison lakes where the pre-glacial lake basin is eroded down through the younger Paleozoic rocks.

Figure 6. Extents and elevations for key model layer surfaces.

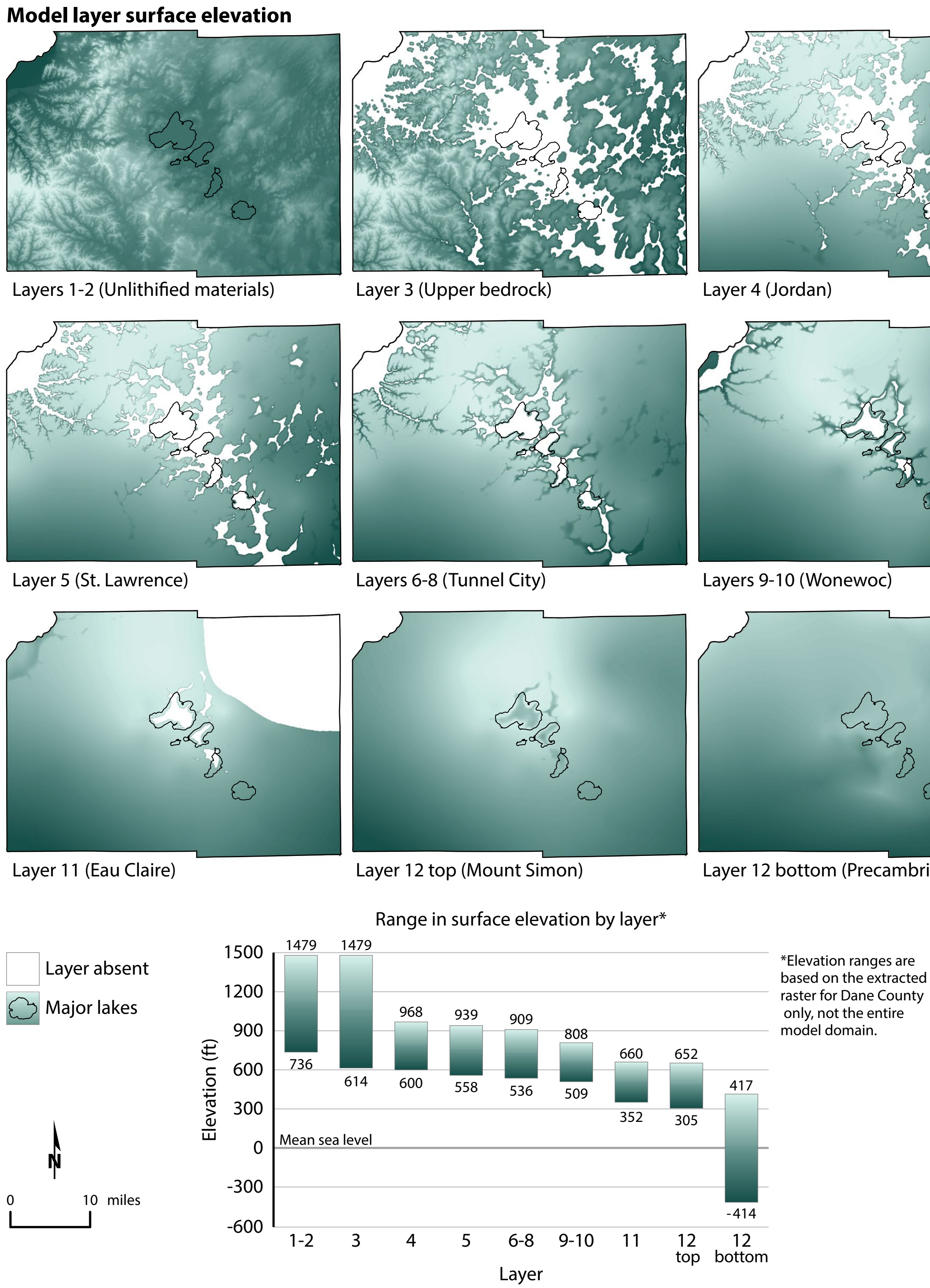


Figure 7. Model layer thicknesses for key model layers.

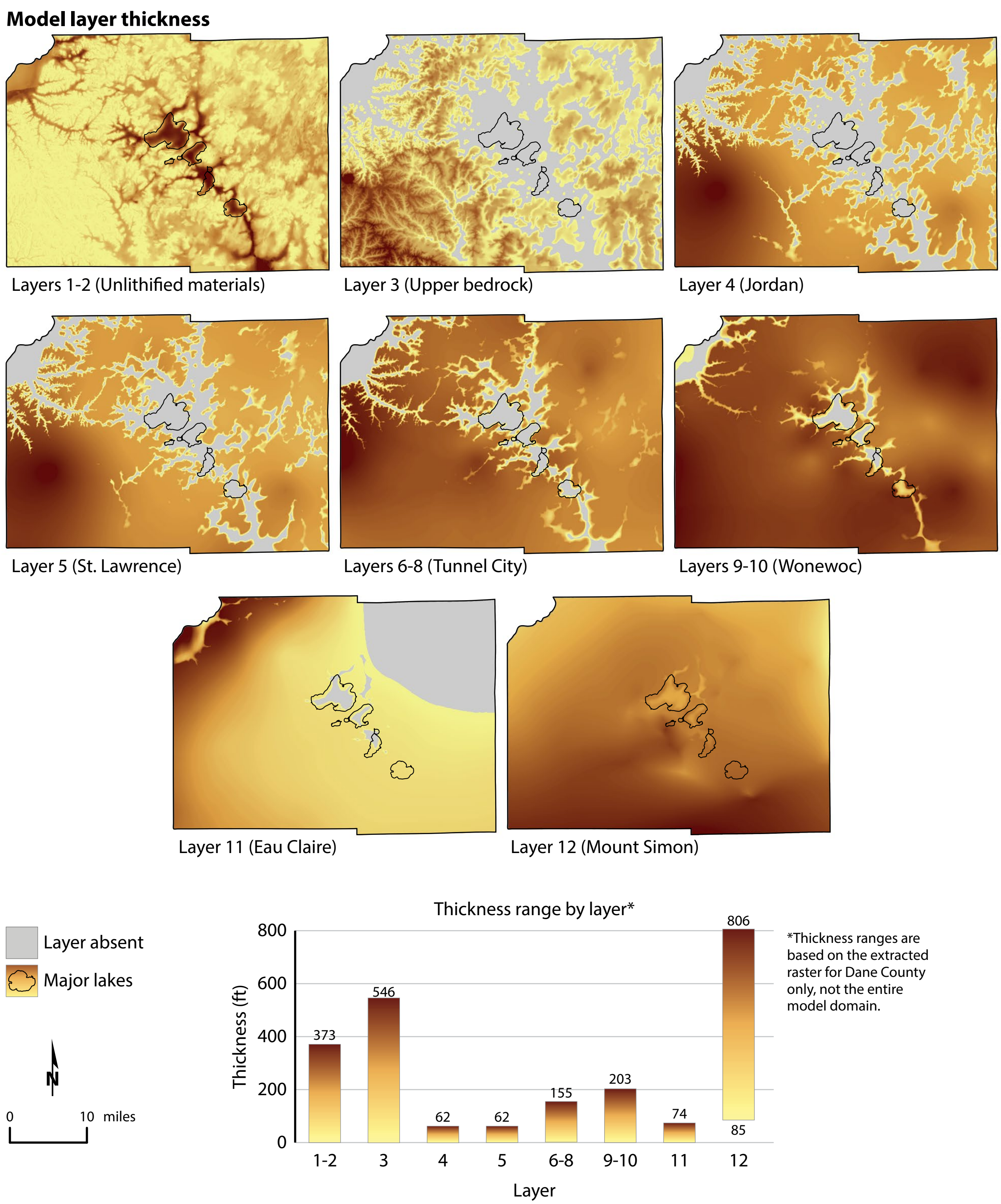
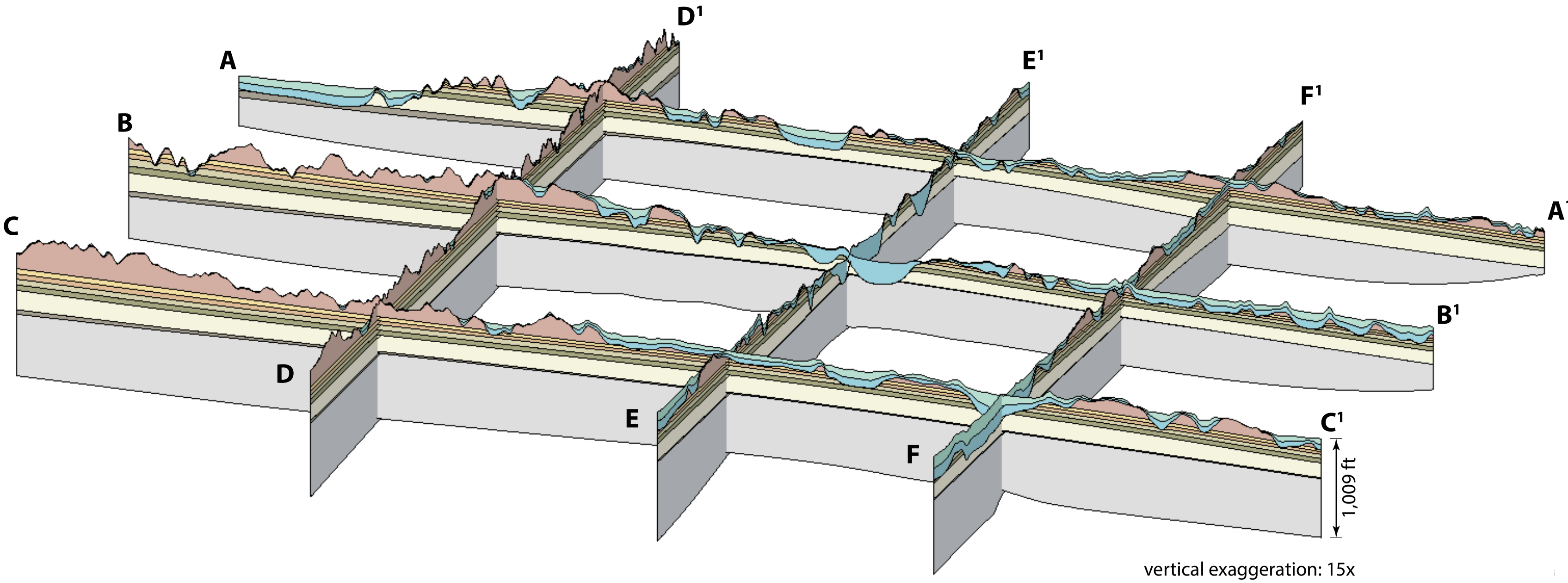


Figure 8. Hydrostratigraphic cross sections across Dane County.

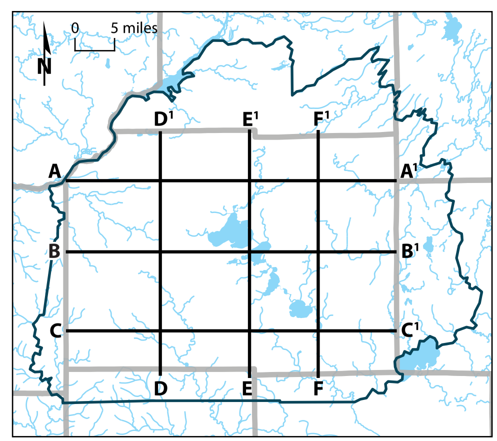


Model layer, name

- 1 Unlithified I[a]
- 2 Unlithified II[b]
- 3 Upper bedrock
- 4 Jordan
- 5 St. Lawrence
- 6 Tunnel City—upper
- 7 Tunnel City—*fracture layer* (not shown)
- 8 Tunnel City—lower
- 9 Wonewoc
- 10 Wonewoc—*fracture layer* (not shown)
- 11 Eau Claire
- 12 Mount Simon
- Precambrian

[a] *Unlithified I = fine-grained lake deposits within glacial Lake Yahara area; elsewhere, till and meltwater stream deposits*

[b] *Unlithified II = till and meltwater stream deposits*



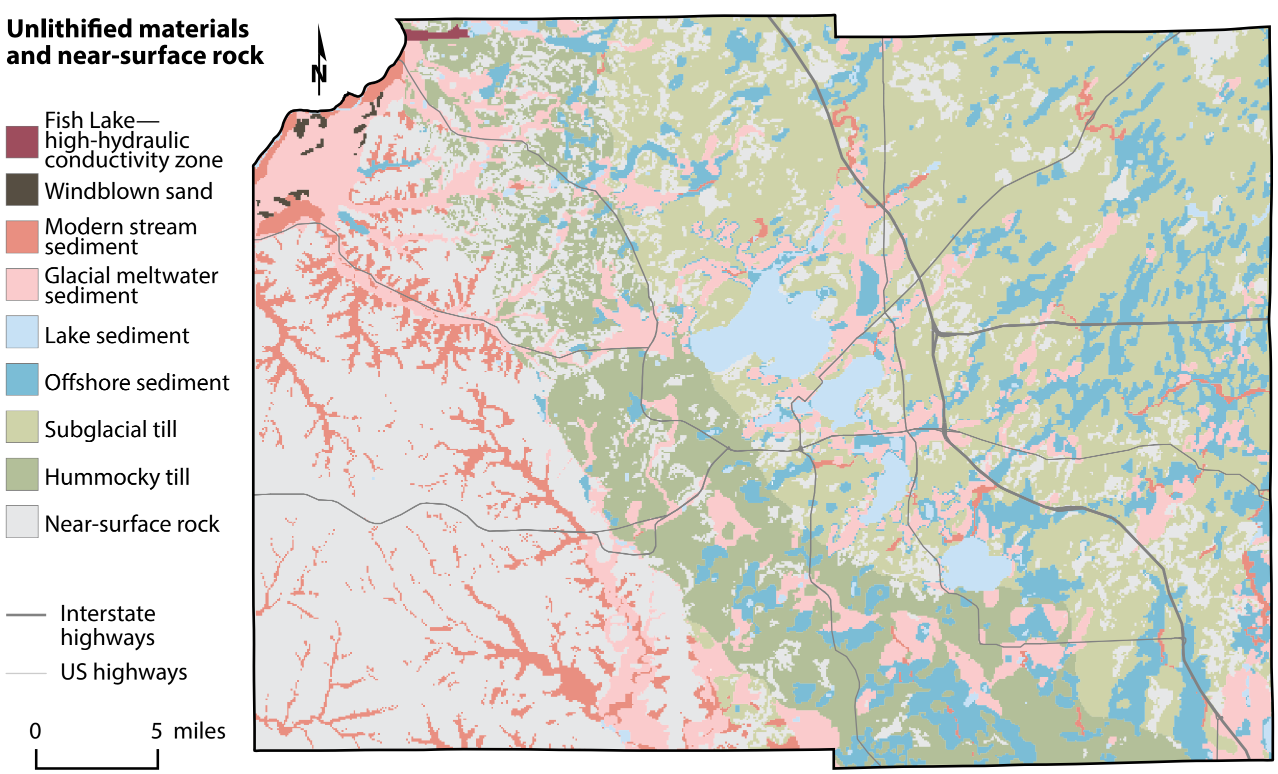
Unlithified materials

Model layers 1 and 2 represent the unlithified materials between land surface and the top of bedrock. These unlithified sediments were divided into two hydrostratigraphic units based on geologic mapping by Clayton and Attig (1997) and Fritz (1996), as well as WCR data. The presence of extensive lacustrine deposits, associated with the emplacement of Glacial Lake Yahara and Glacial Lake Middleton, provided justification for subdividing the hydrostratigraphy within the Yahara lakes corridor. The thickness of these silt and clay-rich lacustrine deposits was estimated from WCR data within central Dane County. For the five principal Yahara lakes and Fish and Crystal Lakes, lake bathymetry is used as the top of layer 1. Where lacustrine deposits were mapped within the Yahara lakes corridor, layer 1 is assigned a thickness of 10 ft and assigned distinct hydraulic properties (described in the Hydraulic Properties section). Outside this corridor, the thickness of layers 1 and 2 are equally divided and the same hydraulic properties are assigned to both layers. Figure 9 shows the distribution of materials in model layers 1 and 2. The model simulates both layers as convertible between confined and unconfined depending on the head in the cell.

Bedrock units

The upper bedrock units, of Ordovician age, were combined into a single hydrostratigraphic unit in model layer 3. All units are not found across the county, and insufficient information exists to subdivide these units hydrostratigraphically. The underlying Jordan and St. Lawrence aquifers were each interpreted as distinct hydrostratigraphic units and were identified as model layers 4 and 5, respectively. The model treats layers 3 through 5 as convertible because each of these layers either outcrops or can be dewatered somewhere in the model domain. Layers 6 through 12 are simulated as always confined because they remain saturated everywhere in the model through all model runs. The sandstone of the Tunnel City Group was subdivided into three model layers, layer 6 for the upper massive section, layer 7 for the bedding-plane fracture near the middle of the formation, and layer 8 for the lower massive section. Two layers, 9 and 10, represent sandstone of the Wonewoc Formation. Layer 9 represents the upper Wonewoc Formation, with layer 10 simulating the bedding-plane fracture at the

Figure 9. Distribution of unlithified materials and near-surface rock in model layers 1 and 2.



base of the formation. Layer 11 represents the Eau Claire aquitard. The Mount Simon aquifer is simulated as a single hydrostratigraphic unit (layer 12) below the Eau Claire aquitard (where present). The Mount Simon is the lowest hydrostratigrapic unit in the model, with the Precambrian crystalline bedrock forming a lower no-flow boundary beneath it (Krohelski and others, 2000).

Bedding-plane fractures

Numerous hydrogeologic investigations (for example, Swanson, 2007; Gellasch and others, 2013; Sellwood and others, 2014) have identified high-conductivity near-horizontal fractures associated with bedding planes in the Tunnel City Group and the Wonewoc Formation in Dane County. The model simulates these bedding-plane fracture features as two continuous model layers, each 0.1-ft thick. Layer 7 simulates a fracture within the Tunnel City Group, and layer 10 simulates a fracture within the sandstone of the Wonewoc Formation. This conceptualization represents a simplification of reality because there is likely more than one fracture in each of these stratigraphic positions, and a single continuous fracture is unlikely to extend across the entire county. However, the abundance of field evidence suggests that higher-conductivity features do commonly occur at these stratigraphic positions. This simulation approach has been successfully used in the past in regional models (Rayne and others, 2001).

High-conductivity zone near Fish and Crystal Lakes

Fish and Crystal Lakes are set in the northwest corner of Dane County and are characterized by atypical changes in lake levels (Krohelski, 2002). This area of Dane County has few wells for subsurface information, and the interaction of these lakes with groundwater is incompletely understood. During model calibration (described later), the current extrapolation of Dane County hydrostratigraphy was not able to simulate the lake levels and steep hydraulic gradients observed near the lakes. To address the error in the conceptual model, a high-conductivity zone was created in model layers 1 through 10 (see fig. 9) and adjusted between the lake area and the Wisconsin River to the west. This modification allowed both the steep gradient and lake levels to be acceptably simulated. However, the evidence that there is enhanced hydraulic conductivity in this area is based on indirect hydrologic data rather than direct geological characterization.

Boundary conditions

Streams

The SFR2 package (Niswonger and Prudic, 2005) simulates streamflow along perennial streams and through minor named lakes[1] which are connected to the perennial river system. The package simulates each stream as a number of connected segments and tracks the gains and losses to groundwater along each segment. In SFR2, a reach is defined as a section of a stream associated with a specific finite-difference model cell, and a segment is a group of reaches having uniform or linearly changing properties (such as streambed elevation, streambed thickness, streambed hydraulic conductivity, or stream width). Stream segments are linked to form drainage networks, and also link directly with simulated lakes. The calculation of groundwater exchange with each stream node depends on the vertical hydraulic gradient, the vertical hydraulic conductivity (Kv), and thickness (b) of the streambed, as well as the area (A) that the stream occupies within the model cell. There are a total of 11,440 SFR2 nodes in the model. The SFR2 stream network includes all the streams shown within the county in figures 4 and 10.

A streambed conductance term governs the exchange of water between surface-water features and the groundwater system. SFR2 calculates both stream stage and fluxes for each individual reach (SFR2 model cell) allowing for a detailed mass balance at each model node along the stream.

The surface water network used in the groundwater model was based on the perennial stream network as mapped by the Dane County Land and Water Resources Department. High-resolution surface-elevation data from a 2009 lidar survey of Dane County was subsequently used to route the perennial stream network. Lidar data was obtained from the Dane County Land Information Office.

A regression expression was used to calculate stream width for each SFR2 cell based on the total stream length upstream of that particular cell. The regression equation used is $Y = 0.0091 * X^{0.7103}$, where X represents stream length in feet and Y represents stream width in feet, with $R^2 = 0.68$. This regression expression was developed using stream length data from GIS evaluation of the perennial stream network and stream width data from a historical study on surface-water features of Dane County (Poff and Threinen, 1961).

Stream slope was estimated for SFR2 nodes depending on whether the stream was located within the Driftless Area or the glaciated area of the model. An average stream slope was calculated for both areas and then applied to all perennial

[1] *Minor lakes are those lakes which are not modeled using the LAK3 package. The LAK3 package was only used to model the main Yahara lakes (Mendota, Wingra, Monona, Waubesa, and Kegonsa) as well as Fish and Crystal Lakes in northwestern Dane County.*

streams within each area. Stream slope data was obtained from the same 1961 report as stream width. Streams within the Driftless Area were assigned an average slope of 0.0048 ft/ft (25.3 ft/mile), while streams in glaciated areas were assigned an average slope of 0.0018 ft/ft (9.4 ft/mile).

Lakes

The LAK3 package (Merritt and Konikow, 2000) was used to simulate the major Dane County lakes within the Yahara River watershed (Mendota, Wingra, Monona, Waubesa, and Kegonsa), and Fish and Crystal Lakes in northwestern Dane County (fig. 10). The LAK3 package simulates lake level in terms of the lake bathymetry and the balance of water inflows and outflows. The water budget accounts for inflows such as precipitation on the lake surface, direct groundwater baseflow, and contributions from tributary streams. The budget also accounts for outflows from the lake including evaporation from the lake surface, losses to groundwater, streamflow to an outlet, and any direct diversion of lake water. As an example of streamflow routing, the SFR2 package routes streamflow from the Yahara River into Lake Mendota, between Lakes Mendota and Monona and so forth down the Yahara River basin. There are a total of 6,697 LAK3 nodes in the model covering over 19,000 acres. Smaller named lakes, such as Cherokee Lake, Indian Lake, and Stewart Lake, were included as SFR2 rather than LAK3 nodes.

Springs

The model simulates 18 prominent spring systems across Dane County (fig.10). Simulated springs were initially selected based on information from the Wisconsin Springs Inventory (Macholl, 2007) and through conversations with local water-resources professionals and Dane County landowners. Springs with an estimated historical flow greater than 0.2 cfs (approximately 90 gpm or 17,280 cfd) were considered for inclusion in the model and evaluated in the field. Spring Harbor spring, which today has a low flow, was included because of its higher historical flow. Spring locations were recorded by GPS and new flow measurements were collected for springs where possible. Historical flow measurements were used for several springs that have been studied in greater detail by other researchers. Examples include Frederick Springs at Pheasant Branch (Hunt and Steuer, 2000) and Culver Springs at Token Creek (Parent, 2001).

The model simulates springs using the MODFLOW SFR2 package. Each spring included in the model is connected to a surface-water feature and routed as part of the SFR2 stream network. Many of the prominent spring networks in Dane County consist of multiple spring boils and groundwater seeps, and many spring features are distributed among several SFR2 nodes. Most major (high-flow) springs were connected to underlying aquifers by initially setting the vertical hydraulic conductivity (Kv) of model nodes directly below the spring to a high value. Allowing flexibility in vertical conductivity under the springs was required in order to match measurements of spring discharge.

Specified-head boundaries

Surface-water features along the perimeter of the active model domain are simulated as specified-head boundaries. Specified-head nodes in the model form a buffer around Dane County coinciding with the Wisconsin River, Lake Wisconsin, Rocky Run, Crawfish River, Rock River, Lake Koshkonong, Pecatonica River East Branch, and Blue Mounds Creek (fig. 1). Although specified-head features can serve as sources or sinks for groundwater (depending on the direction of the hydraulic gradient), the lakes represented as constant heads are located in the far-field of the model domain and have little impact on the numerical solution within the near-field of the model. The area of the model most sensitive to the specified heads is the near-field boundary in northwest Dane County along the Wisconsin River and Lake Wisconsin. During the calibration phase it was observed that changes in specified heads or hydraulic conductivity impacted the water levels in nearby Fish and Crystal Lakes.

No-flow boundaries

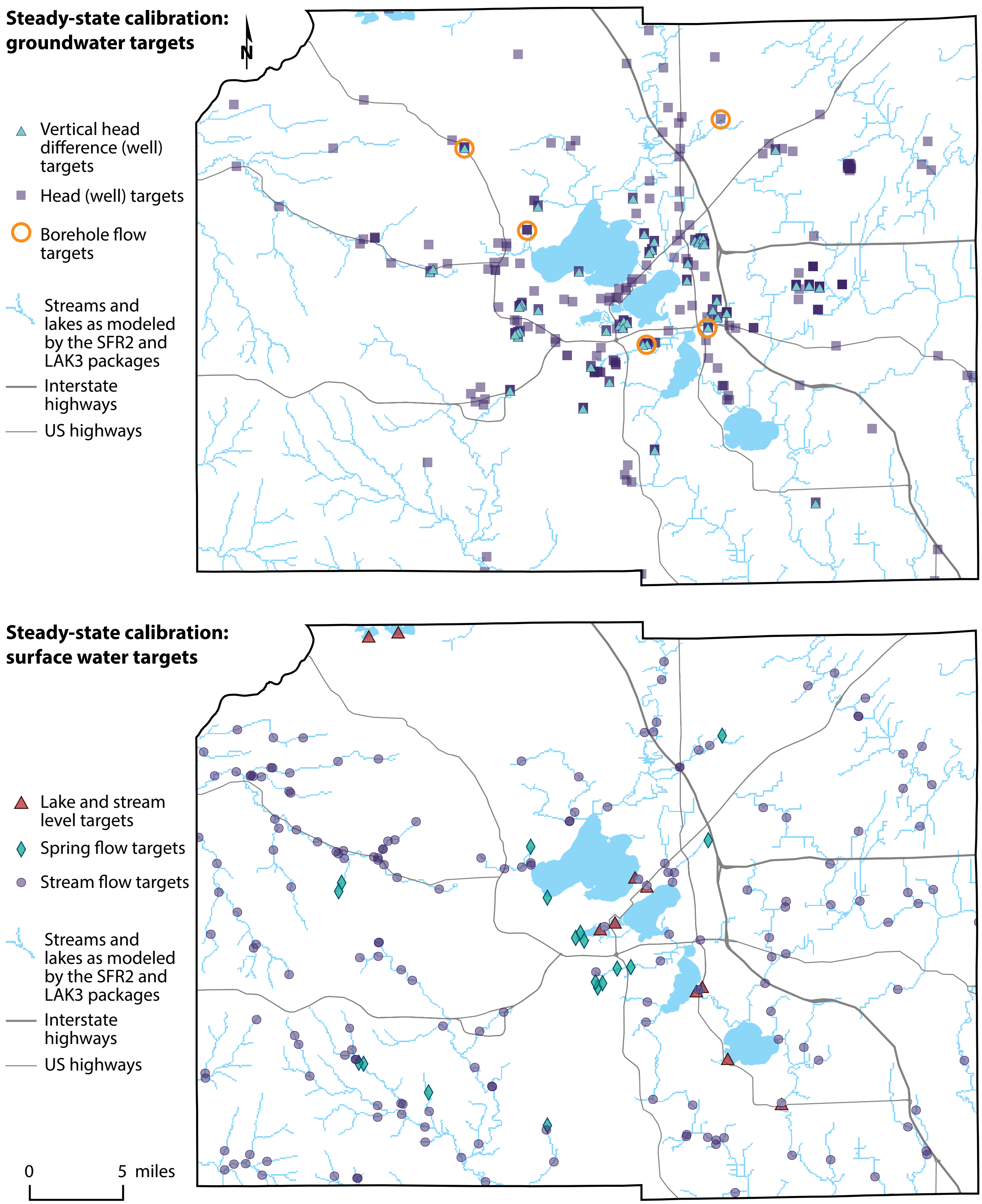
No-flow boundaries represent places where groundwater cannot cross the model boundary. No-flow boundaries were placed along the perimeter of the model near groundwater divides outside of the county along the northern model perimeter between Rocky Run and North Branch Crawfish River, along the southern perimeter between the Rock River and East Branch Pecatonica River, and along the western perimeter between the East Branch Pecatonica River and Blue Mounds Creek (fig. 1). The base of the model (top of Precambrian crystalline rock) is also a no-flow boundary.

Sources and sinks of water

Recharge

The largest source of water to the model is recharge at the land surface. Recharge was applied to the uppermost active layer in the model. Initial estimates of recharge for Dane County were based on results from the 2009 Dane County recharge model (Hart and others, 2012), which used a soil-water-balance (SWB) model approach. Results of SWB models also provided estimates of recharge for Iowa and Columbia Counties. In neighboring Dodge, Green, Jefferson, Lafayette, and Rock

Figure 10. Location of all steady-state calibration targets. Streams and lakes shown as modeled by the SFR2 and LAK3 packages.



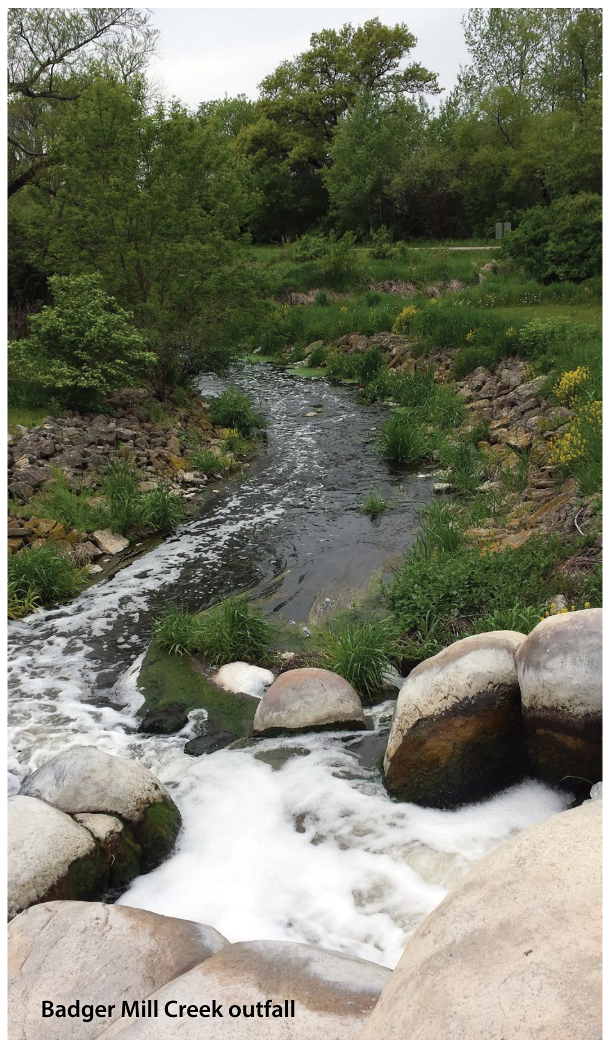
Counties, for which SWB models have not been developed, uniform distributions of recharge were used based on values obtained from areas modeled using a SWB model. The initial estimates of the recharge were varied piecewise by multipliers across the model domain during history matching. Therefore, calibrated recharge rates maintain the relative recharge distribution calculated by Hart and others (2012) but have different actual recharge rates.

Wastewater treatment discharges

Wastewater discharges from 14 wastewater treatment plants corresponding to 15 outlet locations were directly added to the SFR2 package as stream inflow (MMSD accounts for one plant and two outlets). Discharges from wastewater treatment plants were estimated based on actual reported discharge rates from 2010. The Roxbury wastewater treatment plant discharge was not included in the SFR2 package because it discharges to a tributary of the Wisconsin River. The Wisconsin River serves as a constant head boundary which is negligibly impacted by this discharge. A list of all wastewater treatment plants in Dane County and those included in the model is provided in appendix 2.

Groundwater withdrawals

The location of all high-capacity withdrawal wells in Dane County are included in figure 4 and a detailed table with corresponding well data is included in appendix 3. Withdrawal rates for each well were averaged over the 5-year period from 2006 to 2010 to obtain a representative rate. Average withdrawal rates were used to avoid outliers that were particularly high during dry years or particularly low during wet years. A common past well construction practice (still sometimes used) in Dane County was to drill wells into the Mount Simon Formation but to case the well only partway through the overlying Paleozoic units. This construction technique maximized well yields but left an open conduit for groundwater to flow vertically across the Eau Claire aquitard into the Mount Simon aquifer. Well withdrawals are represented in the model using the MODFLOW multi-node well (MNW2) package (Konikow and Harbaugh, 2009). This package accounts for the exchange of groundwater between a well and each model layer open to the well. This is particularly important in Dane County given the large number of high-capacity wells that span multiple aquifers. Model output includes a detailed accounting of node-by-node mass balance and hydraulic head for each multi-node well simulated.


Badger Mill Creek outfall

Madison Metropolitan Sewerage District

Hydraulic properties of the groundwater flow system

Hydraulic conductivity and storage

Hydraulic conductivity and storage properties (confined storativity and specific yield) of the aquifer and aquitard units are fundamental model parameters. The model inputs are in the form of hydraulic conductivity (ft/day), specific storage (1/ft), and specific yield (dimensionless).

Initial hydraulic properties for each model layer were determined through a review of the numerous reports and theses cited elsewhere in this document and earlier model information (Bradbury and others, 1999; Krohelski and others, 2000). The areal variation of hydraulic conductivity in the two major aquifer units—the Wonewoc and Mount Simon Formations—was also initially estimated by using specific-capacity test data from several hundred water-supply wells. The TGUESS code (Bradbury and Rothschild, 1985), which treats specific capacity data as short-term single-well pumping tests, was used to convert these tests to hydraulic conductivity estimates.

During model calibration (described in the Model Calibration section) the initial hydraulic property estimates were varied within reasonable ranges to achieve an acceptable fit between measured and simulated water levels and stream and spring flows. Table 1 summarizes the layering and hydraulic properties used in the model.

Parameterization of unlithified material properties

Parameterization refers to the assignment of hydraulic properties to spatially variable geologic materials, and is a key part of model development. The distribution of unlithified materials (sand and gravel, clay, and till) in the model is based on the most recent Quaternary mapping in Dane County (Clayton and Attig, 1997), and these detailed map units were translated into piecewise-constant zones of uniform hydraulic conductivity and specific yield in layers 1 and 2. Geologic materials having similar hydraulic properties were combined. Because the thickness of saturated unlithified materials in the county is generally small compared to the total thickness of the bedrock aquifer system, the hydraulic properties of layers 1 and 2 were specified identically. However, in the vicinity of the Madison lakes, Fritz (1996) delineated an area where well- to moderately well-sorted sand and gravel lies beneath clayey lacustrine sediment. In this area, these coarser-grained sediments were incorporated in model layer 2 as a piecewise-constant zone. Everywhere else, the hydraulic properties of layers 1 and 2 were assigned to be the same as the properties of the uppermost bedrock. Table 2 and figure 9 show how the various Quaternary map units were combined and assigned to hydraulic units.

Table 1. Hydraulic properties of hydrostratigraphic units used in the model.

		HYDRAULIC CONDUCTIVITY				STORAGE PARAMETERS				
		Initial		Calibrated		Initial		Calibrated		
Model layer(s)	Hydrostratigraphic unit	Kh (range) (ft/day)	Kv (range) (ft/day)	Kh (range) (ft/day)	Kv (range) (ft/day)	Ss (range) (1/day)	Sy (range)	Ss (1/day)	Sy	Estimated n
1, 2	Near-surface rock	$1e^{-10}$	10,000	Layer takes properties of uppermost bedrock		$1e^{-3}$ ($1e^{-5}$–$1e^{-3}$)	0.01 (0.01–0.3)	$9.1e^{-4}$	0.01	0.0001
	Modern stream sediment	30	30	20.0	3.8	$1e^{-3}$ ($1e^{-5}$–$1e^{-3}$)	0.1 (0.1–0.4)	$1.9e^{-3}$	0.26	0.10
	Subglacial till	3	3	5.0	5.0	$1e^{-3}$ ($1e^{-5}$–$1e^{-3}$)	0.05 (0.01–0.2)	$5.0e^{-3}$	0.015	0.10
	Glacial meltwater sediment	20 (1.6–26)	20	25.4	25.4	$1e^{-3}$ ($1e^{-5}$–$1e^{-3}$)	0.2 (0.1–0.4)	$7.1e^{-5}$	0.11	0.15
	Offshore sediment	1 (1–3)	0.1	10.0	1.4	$1e^{-3}$ ($1e^{-5}$–$1e^{-3}$)	0.1 (0.01–0.3)	$1.4e^{-4}$	0.066	0.10
	Hummocky till	5 (3–28)	5 (3–28)	0.5	$5e^{-3}$	$1e^{-3}$ ($1e^{-5}$–$1e^{-3}$)	0.1 (0.01–0.2)	$1.1e^{-4}$	0.068	0.05
	Lake sediment	1	1	0.1	$1e^{-3}$	$1e^{-3}$ ($1e^{-5}$–$1e^{-3}$)	0.1 (0.01–0.2)	$2.5e^{-4}$	0.3	0.05
	Windblown sand	30	30	332	167	$1e^{-3}$ ($1e^{-5}$–$1e^{-3}$)	0.1 (0.01–0.4)	$2.1e^{-4}$	0.073	0.30
3	"Upper bedrock" (Ordovician)	10 (1–20)	1 (0.1–2)	13.5	0.1	$1e^{-3}$ ($1e^{-5}$–$1e^{-3}$)	0.01 (0.01–0.3)	$1.0e^{-4}$	0.0035	0.05
4	Jordan	1 (0.3–1)	1 (0.1–2)	0.3	0.01	$1e^{-3}$ ($1e^{-7}$–$1e^{-3}$)	0.01 (0.01–0.4)	$5.0e^{-5}$	0.07	0.10
5	St. Lawrence	50 (1–60)	0.5 (0.1–2)	60	0.01	$1e^{-3}$ ($1e^{-7}$–$1e^{-3}$)	0.01 (0.01–0.3)	$7.2e^{-5}$	0.07	0.05
6	Tunnel City—upper	3.6 (1–10)	0.5 (0.1–1)	1	0.5	$1e^{-4}$ ($1e^{-7}$–$1e^{-3}$)	—	$1.6e^{-4}$	—	0.05
7	Tunnel City *(fracture layer)*	—	—	29.3 (0.49–1,000)	4.3 (0.5–9.3)	$1e^{-4}$ ($1e^{-7}$–$1e^{-4}$)	—	$2.6e^{-4}$	—	0.001
8	Tunnel City—lower	1.3 (1–5)	0.5 (0.1–1)	1.0	0.5	$1e^{-4}$ ($1e^{-7}$–$1e^{-3}$)	—	$1.2e^{-5}$	—	0.05
9	Wonewoc	1.1 (1–10)	0.1 (0.1–5)	5.7 (0.031–237)	1.0	$2e^{-4}$ ($1e^{-7}$–$1e^{-3}$)	—	$2.6e^{-5}$	—	0.10
10	Wonewoc *(fracture layer)*	—	—	10.4 (0.02–2,680)	3.8 ($5e^{-4}$–2,380)	$1e^{-4}$ ($1e^{-7}$–$1e^{-4}$)	—	$2.1e^{-4}$	—	0.001
11	Eau Claire	$5e^{-3}$ ($5e^{-4}$–$5e^{-2}$)	$5e^{-4}$ ($5e^{-5}$–$5e^{-3}$)	0.015	$2.8e^{-3}$ ($4e^{-4}$–$5e^{-2}$)	$1e^{-4}$ ($1e^{-7}$–$1e^{-3}$)	—	$8.3e^{-6}$	—	0.001
12	Mount Simon	12 (1–30)	0.1 (0.01–10)	8.1 (0.015–2,330)	0.2 ($2e^{-3}$–5,060)	$2e^{-4}$ ($1e^{-7}$–$1e^{-3}$)	—	$2.4e^{-5}$	—	0.15
1–10	Fish and Crystal Lakes, high-hydraulic cond. zone	—	—	300.0	150.0	Same as model layer		Same as model layer		Same as model layer

Abbreviations: Kh = horizontal hydraulic conductivity, Kv = vertical hydraulic conductivity, Ss = specific storage, Sy = specific yield, n = effective porosity, — = not assigned.

Clayton's and Attig's Quaternary mapping extends only to the boundaries of Dane County. Materials outside the county were interpreted from recent studies in Iowa County (Batten and Attig, 2010), unpublished maps of Columbia County, and regional Quaternary maps.

Parameterization of bedrock properties

Parameterization of hydraulic conductivity (K) and specific storage (Ss) varies by layer in the bedrock units (model layers 3–12); table 1 summarizes these values. The model simulates layers 3, 4, 5, 6, and 8 using single values of parameters for the entire layer (as shown in table 1). This single-value approach recognizes that there is little or no spatial data (layer-specific head or K measurements) to guide more detailed parameterization for these stratigraphic intervals. Where the formations represented by these layers are absent or eroded away, the model cells in the eroded layer take on the properties of adjacent layers, as described earlier in the treatment of pinchouts (p. 18).

In contrast to the layers above, the model varies the hydraulic conductivity in layers 7, 9, 10, 11, and 12 continuously by location. Such spatially variable K fields are more geologically realistic than the single-value approach used in the overlying layers and is justified by the availability of field data (head measurements, specific capacity tests, packer tests) over parts of these units. In addition, these model layers represent the main aquifers present in Dane County and model output is more sensitive to their properties than to properties of the upper, less continuous layers. The distribution of hydraulic conductivity (both Kh and Kv) in these spatially variable layers uses the pilot point approach. Pilot points represent locations where the parameter of interest (K in this case) is either measured or estimated. Each pilot point is treated as a variable parameter in the calibration process (described below), and an interpolated hydraulic conductivity field based on these point values represents the layer hydraulic conductivity. See Doherty and others (2010) for details regarding the pilot point method.

Table 2. Conversion between map units defined by Clayton and Attig (1997) and hydrogeologic materials in model layers 1 and 2. See table 1 for hydraulic property assignments for these materials.

Map units	Description
gd, ge, h	Little or no Quaternary material—use upper bedrock properties
sm, sp	Modern stream sediment
gs, gt, gb, gp	Subglacial till
su, se, so, sc	Glacial meltwater sediment
og, op, or	Offshore sediment
gh, gk	Hummocky till
wtr	Lake sediment
w	Windblown sand

Parameterization of streambed and lakebed properties

Vertical hydraulic conductivity (Kv) of streambeds (assuming bed thickness equal to 1 foot) was previously measured in the field at 12 sites in the upper Yahara and Sugar Rivers as well as the Koshkonong, Sixmile, Black Earth, Garfoot, and Pheasant Branch Creeks (Bradbury and others, 1999). Streambed Kv from these measurements varied from 1.6 ft/day to 37 ft/day, with a mean of 8.1 ft/day. The MODFLOW stream conceptualization divides streambed Kv by thickness to calculate streambed conductance. Both Kv and bed thickness are generally poorly known and vary along the length of the stream. Assuming a 1-foot thickness means that all variability in streambed conductance is ascribed to Kv, and while this is not strictly true in the field it is an appropriate assumption for the purposes of simplifying the stream network at a regional scale.

The combination of the vertical hydraulic conductivity of the lakebed sediment and the thickness of these materials in the lakebed regulates the rate of lake-water exchange with groundwater. This lumped parameter is called leakance, and is defined as Kv/b, where Kv is the vertical hydraulic conductivity of the lakebed and b is the thickness of these materials above an aquifer. Leakance values were assumed uniform over nearshore and offshore zones in each lake, where the nearshore consisted of a single node width (360 feet) adjacent to the lake shore and the offshore consisted of the remainder of the lake area, but varied among lakes.

Model calibration

Calibration strategy

A calibrated model is one that has: (1) an acceptable history matching where the model approximates a series of field-measured calibration targets, and (2) reasonable parameters used to obtain the history-matching fit (Anderson and others, 2015). There were two history-matching steps in the development of the Dane County model. The first, and most extensive, step calibrated the model to steady-state conditions by varying recharge, hydraulic conductivity, and stream and lakebed properties. The second step was a transient calibration to the drought conditions of late May to July 2012. During the transient calibration only storage parameters (specific storage and specific yield) were varied to match observed data.

Steady-state model calibration

The steady-state calibration was generally based on average hydrogeologic conditions between 2006 and 2010. This time period represented the most updated data record, included a variety of high-quality calibration targets, and reduced the influence of particularly wet or dry years. This evaluation of the steady-state period is critical because it defines average equilibrium conditions, and served as the starting point for transient calibration. The objective of the steady-state history matching was to obtain the best match of time-averaged field observations and to obtain reasonable parameter estimates from the observation data.

Steady-state calibration targets

Measurements from wells and surface-water features were used for the steady-state calibration. Calibration targets from wells consisted of water levels (i.e., hydraulic heads, or heads), vertical head differences, and borehole flows. Target data from surface-water features included lake levels, spring flows, and streamflows (fig. 10). Each target was classified into one of 15 groups (summarized in table 3) and assigned an observation weight based on the general reliability of the measurement, number of measurements in that group, and importance for model objectives. Weights are important for emphasizing (higher weight) or de-emphasizing (lower weight) a calibration target during history matching. When more than one measurement was available for a single well, water levels were averaged to determine a single calibration target value.

Table 3. Steady-state calibration target list.

Target group	Name	Description	Sources	Number of targets
Water level	head_1	Research wells	WGNHS, other researchers	65
	head_4	Wisconsin groundwater-level monitoring network wells	USGS	16
	head_11	Wisconsin surface water network	USGS	10
	head_19	Prime research wells	Univ. of Guelph, WGNHS, other researchers	79
	head_23	Remediation and site investigation wells	DNR, other sources	181
Vertical-head difference	head_2	Miscellaneous wells	Various sources	5
	head_21	Research wells	WGNHS, other researchers	38
	head_22	Remediation and site investigation wells	DNR, other sources	45
Borehole flow	bh_flow	Research wells	WGNHS	16
Lake level	lake_1	Lakes Mendota, Wingra, Monona, Waubesa, and Kegonsa	USGS	5
	lake_2	Fish and Crystal Lakes	USGS	2
Spring flow	springs	Research measurements	WGNHS, other researchers	18
Streamflow	flux	Research measurements	WGNHS, DNR, other researchers	128
	flux1	Surface water gaging stations	USGS	8
	flux2	Surface water partial record stations	USGS	66

Water-level and vertical-head-difference targets include field measurements collected from a variety of sources within the model domain. Many measurements were obtained from ongoing groundwater research projects by WGNHS and USGS staff, UW-Madison faculty and graduate students, researchers from the University of Guelph (Ontario, Canada), as well as ongoing remediation efforts by local environmental consultants, and the City of Madison Engineering Department. A total of 351 water-level targets, 88 vertical-head-difference targets, and 16 borehole-flow targets were included in model calibration. Field measurements obtained by the USGS, WGNHS, or other researchers were generally given the highest weights due to high level of documentation of measuring point elevation, data collection, and data archiving. In contrast, measurements collected as part of ongoing groundwater remediation/investigation projects or other research projects were assigned lower calibration weights because these are considered more uncertain. Water-level targets recorded by the Wisconsin DNR's well construction report program were not weighted due to their higher level of uncertainty relative to other calibration targets. Zero weight means such targets were evaluated visually but did not formally factor into the calculation of a best fit during history matching. A list of all head targets and associated weights used for parameter estimation is included in appendix 4.

Mike Parsen

Borehole-flow targets represent a unique category of calibration target not included in the calibration of the previous Dane County model. Since 2000, borehole-flow measurements have increasingly been collected during geophysical evaluations of wells across Dane County. The measurement consists of lowering and raising a probe, such as a spinner flow meter or heat-pulse flow meter, in the well and correcting for borehole diameter to determine the vertical flow of groundwater within the uncased section of the borehole. When taken at multiple depths in the well, flow measurements provide information about the vertical direction of flow and the rate of groundwater flow from the aquifer into the borehole. Sudden jumps in flow rate are typical signatures of preferential flow along bedding-plane fractures, while steady changes in flow rate are more characteristic of matrix flow through porous media. An example of a borehole-flow log is included in the geophysical log in appendix 1. Sixteen borehole-flow targets from three different wells were included in the steady-state calibration. Flow measurements for each well were targeted for periods under ambient, non-pumping, conditions within the borehole to best represent background groundwater flow conditions. In each instance, the measured vertical flow rates across a particular hydrostratigraphic unit were compared to fluxes simulated by the MNW2 package for the corresponding model layer. A list of all borehole-flow targets, their corresponding model layers, and associated weight used for parameter estimation is included in appendix 5.

Lake-level targets were included for each of the principal Yahara lakes (Mendota, Wingra, Monona, Waubesa, and Kegonsa), as well as Fish and Crystal Lakes. These levels were obtained from historical measurements made by the USGS and represent lake levels under average conditions. Zero weight was given to the Fish and Crystal Lakes targets due to steep observed horizontal hydraulic gradients that were difficult to simulate with numerical stability; however, the history matching to these zero-weighted targets was still acceptable (see Results section). A list of all lake-level targets and associated weight used for parameter estimation is included in appendix 6.

Spring-flow targets were included for 18 of the principal spring systems within Dane County. Due to the challenge of accurately simulating these features in a finite-difference grid, observed flow rates at certain springs were history matched by comparing simulated flow over several SFR2 nodes to combined observed flow from multiple spring boils. The group of SFR2 nodes represented cumulative flow from the entire spring complex, not just one particular outlet feature such as a spring boil. Spring flow measurements were compiled from a variety of sources including the WGNHS, USGS, DNR, UW-Madison researchers, and historical measurements from the Wisconsin Springs Inventory. The WGNHS and DNR measurements were made during 2010 and 2011 while the other measurements were made between 1997 and 2003. A list of all spring flow targets and associated weights used for parameter estimation is included in appendix 7a, and a list of SFR2 nodes representing flow contribution for each spring complex is included in appendix 7b.

Streamflow targets included USGS statistical estimates of baseflow at long-term stream and partial-record gaging stations, as well as synoptic one-time streamflow measurements made by the WGNHS and DNR. The most highly weighted streamflow targets were the USGS baseflow estimates at eight long-term gaging stations (Gebert and others, 2011). The second most highly weighted targets were USGS baseflow estimates at 66 USGS partial-record stations (Gebert and others, 2011). The lowest target weights were assigned to one-time streamflow measurements performed by WGNHS and DNR staff under baseflow conditions during 2010 and 2011, as well as streamflow averages for USGS gaging stations that were not included in the 2011 Gebert study. While WGNHS measurements were obtained especially for the Dane County groundwater modeling project, DNR measurements were conducted as part of a separate surface-water modeling study for Dane County (Diebel and others, 2014). Four estimates of streamflow were included for the outlets of Lakes Mendota, Monona, Waubesa, and Kegonsa. Based on time series evaluations of streamflow, the Q75 duration period was selected to represent long-term baseflow through these lakes.[2] While the total discharge from the Yahara Lakes system is well represented, the local distribution of flow between lakes is not as well constrained. These estimates were based on historical time-series streamflow data from USGS stream gaging stations along the Yahara River, downstream from Lakes Mendota, Waubesa, and Kegonsa. Since no stream gaging station is located at the outlet of Lake Monona, streamflow data near the outlet of Lake Waubesa was used as a surrogate. A list of all streamflow targets and associated weights used for parameter estimation is included in appendix 8.

Steady-state calibration parameters

Model calibration was undertaken at the U.S. Geological Survey Wisconsin Water Science Center by using PEST (Doherty and others, 2010; Doherty and Hunt, 2010). The Dane County model calibration effort adjusted 2,580 parameters during steady-state history matching. Therefore, it is considered a highly parameterized model (Hunt and others, 2007) that provides more flexibility to model calibration. Such flexibility allows the history-matching process to extract more information from the observed data, but requires additional computational power.

History matching was performed on a large parallel computer array at the USGS Wisconsin Water Science Center. During this phase of the history matching, the following parameters were adjusted:

Recharge: Recharge varies spatially across the landscape. The initial spatial distribution of recharge was taken from Hart and others (2012), and then adjusted regionally using one multiplier over the glaciated area and another multiplier over the unglaciated areas of the model domain. This approach maintained the initial distribution of relative recharge rates of Hart and others (2012) within the two regions while providing the flexibility needed to obtain a good history match to observed measurements.

Horizontal hydraulic conductivity: During history matching, hydraulic conductivity was estimated at pilot point locations and then hydraulic conductivity values were assigned to individual model cells by interpolation between the pilot points using kriging. The calibration process adjusted both horizontal and vertical hydraulic conductivity in each active model layer, using the initial values shown in table 1. In the unlithified sediment layers 1 and 2, horizontal hydraulic conductivity varied piecewise by material units as shown in figure 9. These two layers were parameterized into zones that aligned with the material units. Upper bedrock layers 3, 4, 5, 6, 8, and 11 were parameterized using single values of hydraulic conductivity corresponding to each

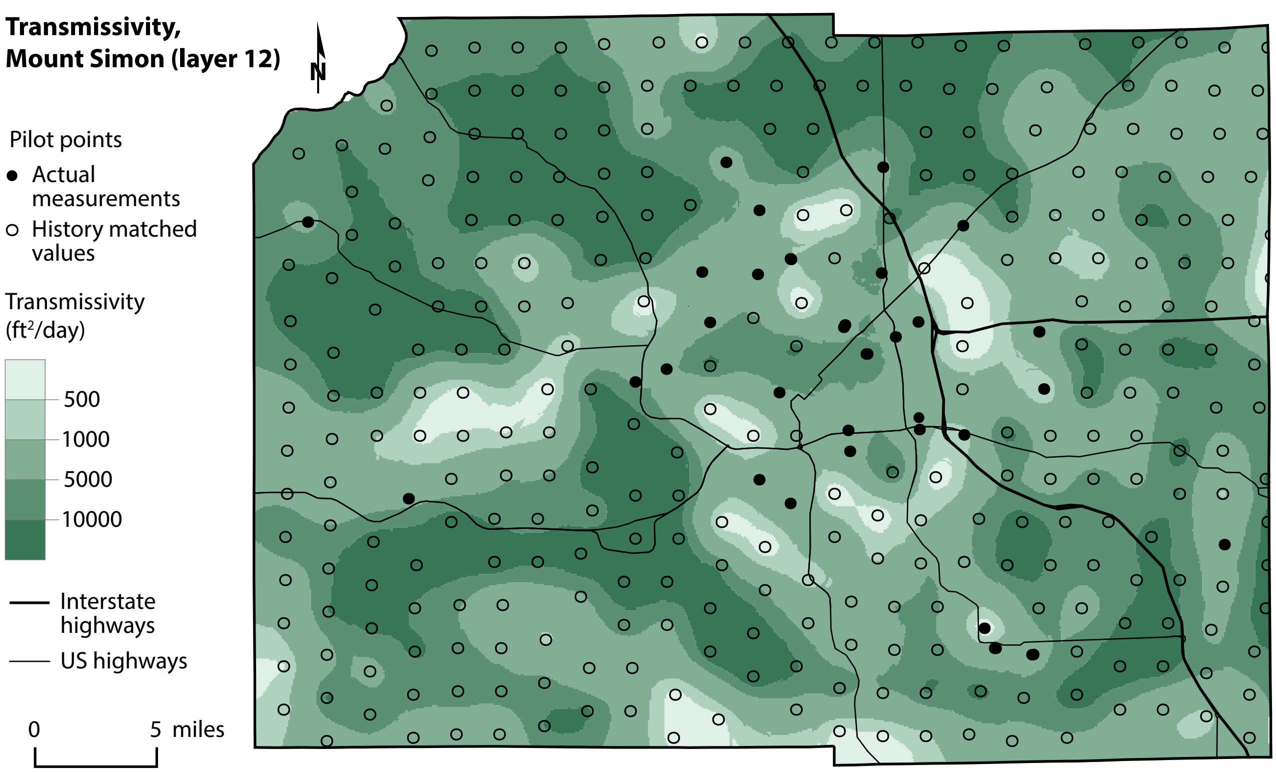
[2] The Q75 value for a stream is the flow rate (Q) which occurs or is exceeded at least 75% of the time.

of the Paleozoic bedrock hydrostratigraphic units. In the remaining layers (7, 9, 10, and 12), a highly parameterized approach was used and hydraulic conductivity was represented using pilot points (Doherty and others, 2010) assigned to the Paleozoic bedrock in each layer. Pilot points were used to simulate the Wonewoc and Mount Simon aquifers (layers 9 and 12, respectively), and the Tunnel City and Wonewoc fracture layers (layers 7 and 10, respectively). Horizontal hydraulic conductivity was estimated at over 1,800 pilot points in these four layers, which allowed hydraulic conductivity to vary spatially within the hydrostratigraphic unit.

In the Dane County model, field measurements of hydraulic conductivity were formally considered during calibration in wells where specific capacity data were used (Bradbury and Rothschild, 1985) to estimate horizontal hydraulic conductivity. Only field-based estimates from wells with open (uncased) well intervals in either the Mount Simon or upper Wonewoc aquifer were included. For the Wonewoc, TGUESS values of hydraulic conductivity were used for initial values in 337 co-located pilot points but then they, along with 260 other pilot points, were allowed to vary during history matching. For the Mount Simon aquifer, TGUESS values from 37 locations were used to set collocated pilot point hydraulic conductivity to a constant value, and history matching then varied the remaining 305 pilot point values (point distribution shown in fig. 11). Thus, Mount Simon TGUESS measurements were more strictly enforced during the history matching to ensure final calibrated parameters agreed with measured values. The more strict application of TGUESS is consistent with the Mount Simon being a primary aquifer that is costly to drill; thus, directly measured values are likely more important for citing future wells than indirect values inferred during history matching to sparse head observations.

Vertical hydraulic conductivity: In a similar manner to horizontal hydraulic conductivity, initial vertical hydraulic conductivity values (table 1) were adjusted during history matching. In the unconsolidated sediment layers 1 and 2, vertical hydraulic conductivity was varied by the piecewise-constant zones representing the geologic units as shown in figure 9. Vertical hydraulic conductivity in bedrock layers 3 through 10 was parameterized using single values of vertical hydraulic conductivity applied to the entire unit and corresponding to the Paleozoic bedrock hydrostratigraphy. Vertical hydraulic conductivity in the

Figure 11. Location of layer 12 (Mount Simon aquifer) Kx pilot points used during steady-state model calibration.



Eau Claire aquitard and Mount Simon sandstone are represented using 308 and 443 pilot points, respectively.

Streambed and lakebed conductance: Streambed properties were varied using single multipliers for two regions of the model domain reflecting the glaciated and unglaciated areas. Lakebed leakance values were divided into two zones for each lake using lake bathymetry—a shallow water nearshore zone which is relatively more transmissive, and the remaining lake nodes representing a less transmissive offshore zone. During history matching, the entire lakebed leakance was adjusted using a single multiplier parameter for each lake. This maintained the relative leakance difference within the lake while allowing history matching flexibility to account for differences in lake hydrogeologic setting.

To ensure that calibration parameters stayed within geologically reasonable ranges, we used "soft knowledge", or Tikhonov Regularization, to constrain parameter variation (Doherty and Hunt, 2010). Soft knowledge was interjected into the calibration by limiting the hydraulic conductivity values to be within pre-calibration estimated ranges, limiting the Kh/Kv ratio to be greater than 1 for every unit, setting measured Kh as initial values for pilot points associated with TGUESS measurements, and maintaining reported well production for pumping wells. Assisted singular value decomposition (SVDA) (Doherty and Hunt, 2010) was used to ensure that the calibration problem was mathematically solvable (that is, to create a well-posed problem from a highly parameterized ill-posed problem).

Steady-state calibration results

The final steady-state calibration consisted of a good model fit for most observations and reasonable values for the 2,580 calibration parameters. Figure 12 shows the calibrated recharge distribution. The average calibrated recharge rate over the model domain is 7.7 in/yr with a range of 0.0 to 35.4 in/yr, with most less than 12 in/yr. For comparison, recharge estimates using stream baseflow for selected basins in the county range from 1.1 to 15 in/yr (Gebert and others, 2011), with estimates from the largest basins in the range of 5.8 to 9.5 in/yr.

Cross plots of observed versus simulated hydraulic heads, vertical head differences, and lake levels (fig. 13) show good agreement, with some outliers.

Figure 12. Calibrated steady-state recharge distribution.

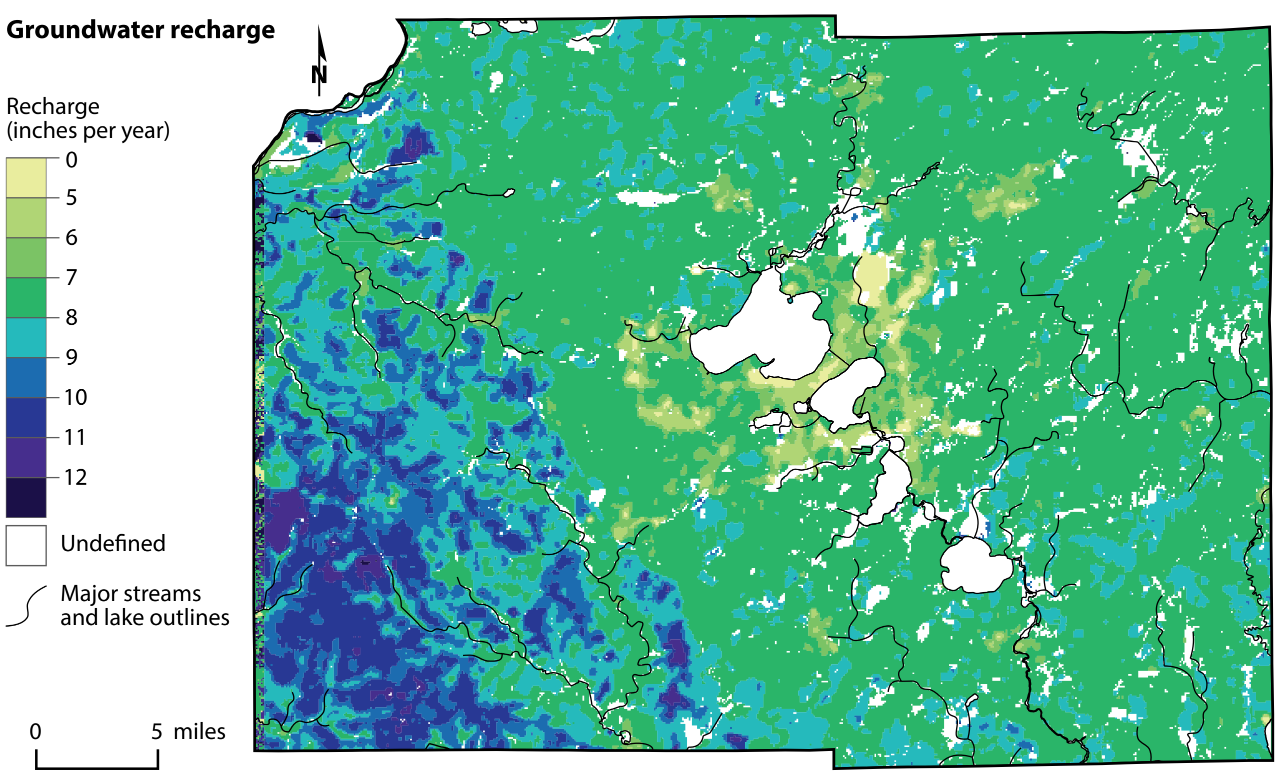
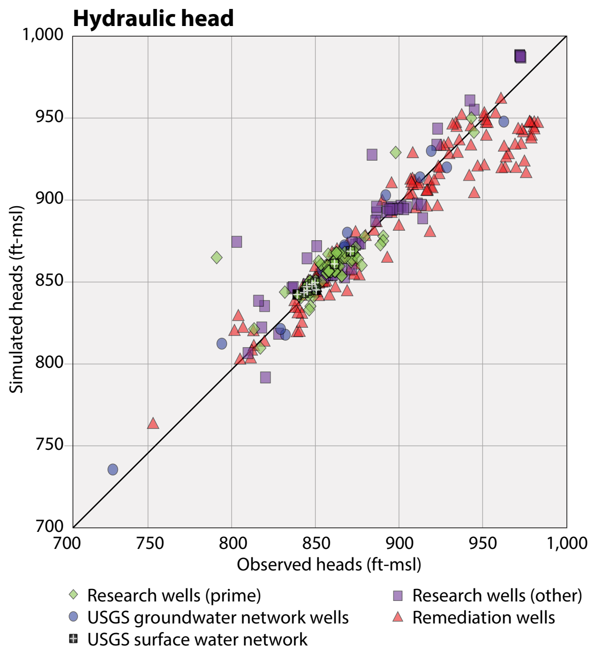
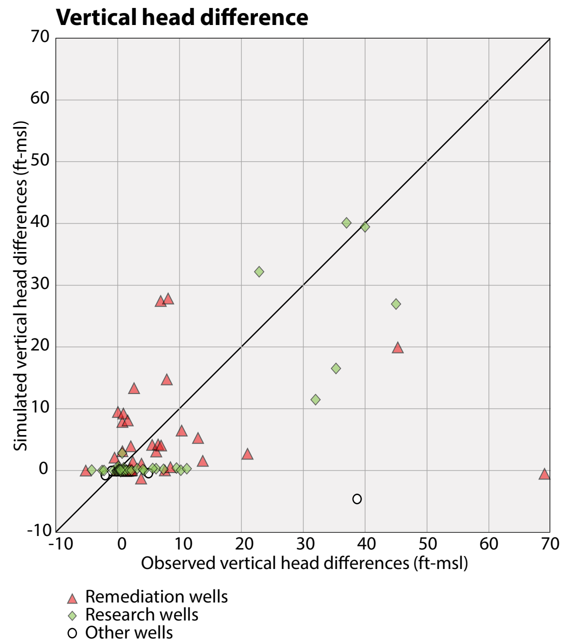
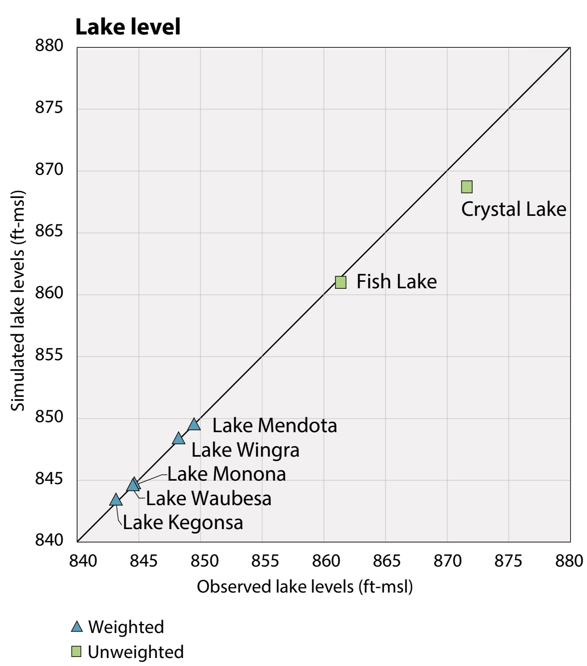


Figure 13. Steady-state hydraulic head, vertical head difference and lake-level calibration results with calibration summary statistics.







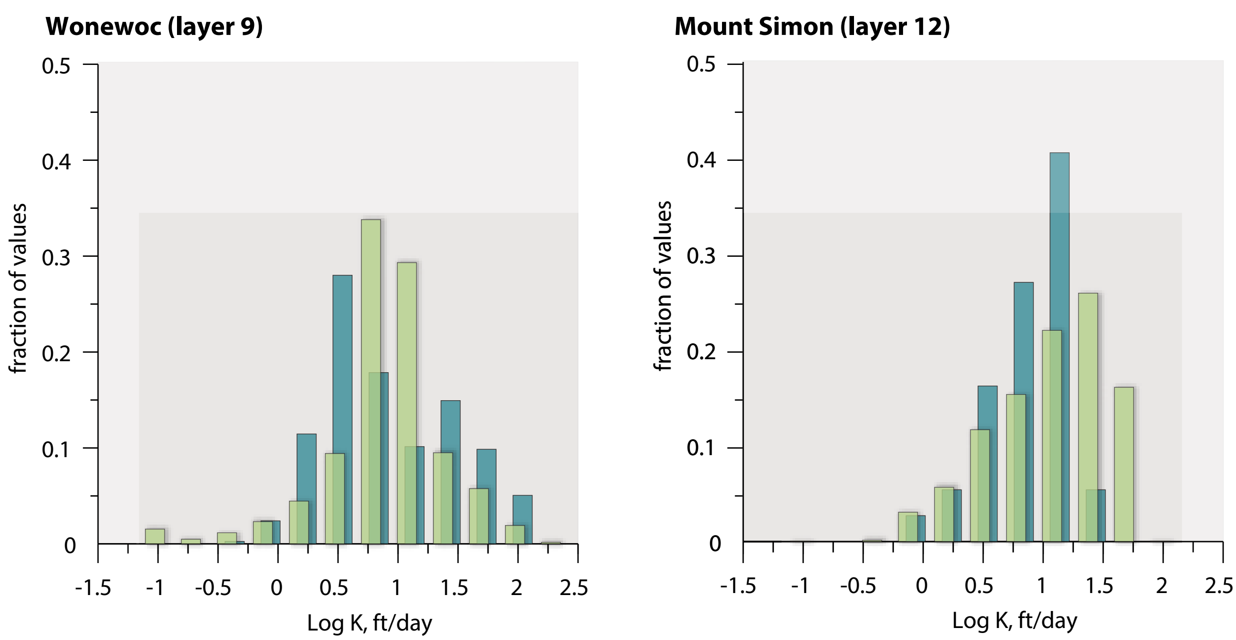
Calibration summary statistics

Measurement	Head	Head difference
Residual mean	3.92	2.58
Absolute residual mean	9.26	6.1
RMS error	15.48	11.64
Range of observations	287.06	877.89
Number of observations	355	86

Histograms (fig. 14) comparing field measurements of hydraulic conductivity with the spread of node-by-node calibration results for layers 9 and 12 show that the calibration appropriately reproduces the range and distribution of the field data.

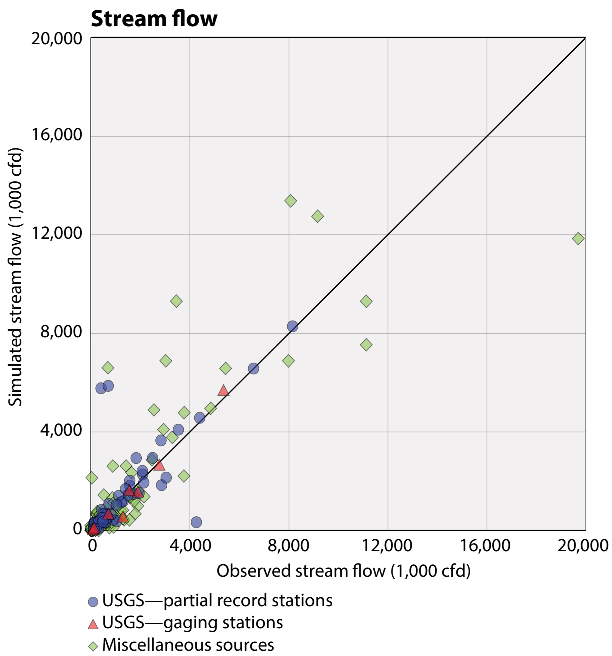
In figure 14, the calibrated mean hydraulic conductivity for the Mount Simon aquifer (layer 12) is about 65 percent higher than the mean from the TGUESS estimates. This apparent discrepancy is likely due to the relatively small number of reliable specific capacity tests in the Mount Simon and the clustering of these tests in the Madison area. Commonly, hydraulic conductivity values appropriate for regional models are significantly larger than values derived from single well pumping tests (Bradbury and Muldoon, 1990). It was also noted that enhanced hydraulic conductivity in the fractures in layers 7 and 10 did not persist beyond the glaciated area. Rather, in the unglaciated areas these layers retained the properties of the vertically adjacent unfractured bedrock. The model also generally reproduces field-measured streamflows and spring discharges well across the county (fig. 15).

Figure 14. Histograms of hydraulic conductivity for the Wonewoc (layer 9) and Mount Simon (layer 12) aquifers.



	Wonewoc	Mount Simon
FIELD DATA		
Geometric mean (ft/day)	5.6	4.9
Log geometric mean	0.75	0.69
Number of tests	375	37
CALIBRATION DATA		
Geometric mean (ft/day)	5.7	8.1
Log geometric mean	0.76	0.91

Figure 15. Steady-state flow calibration results.



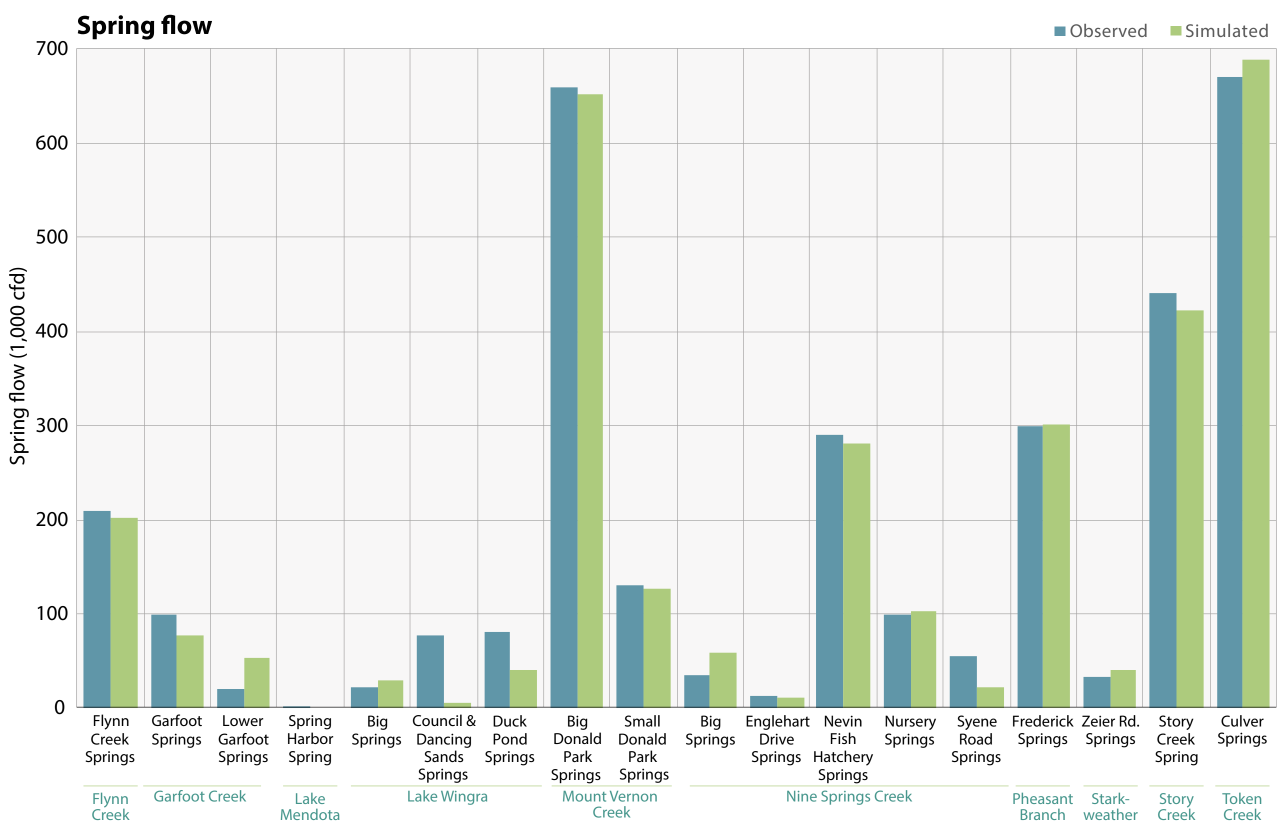


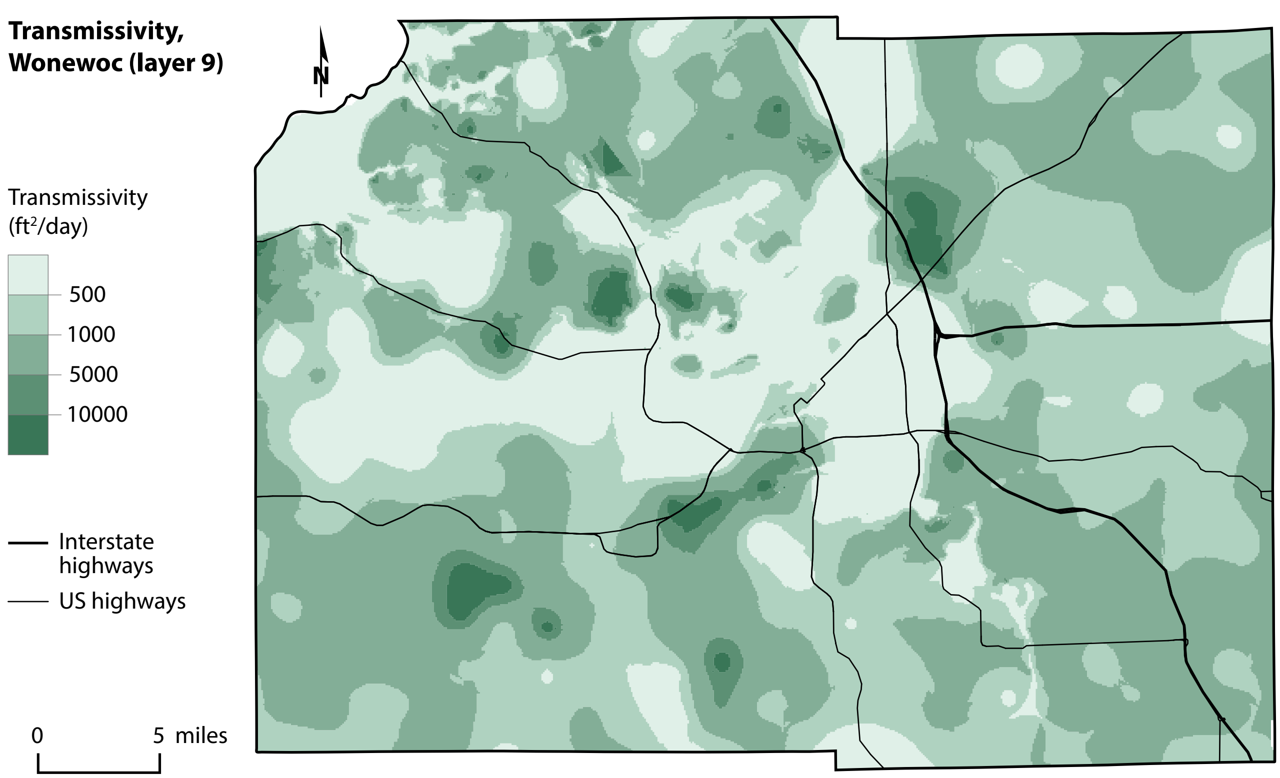
Figure 16 shows calibrated transmissivity distributions for layer 9 (Wonewoc aquifer); and figure 11 shows distributions for layer 12 (Mount Simon aquifer).

After model calibration, streambed Kv in the calibrated model (again, assuming a bed thickness equal to 1 ft) ranged from 2 to 40 ft/day, with an overall average of 7.7 ft/day. Streambed Kv was set at 15 ft/day for streams in the glaciated area of Dane County and 2 ft/day in the unglaciated area. Table 4 shows the lake sediment leakance values that regulate the rate of lake water exchanged with groundwater for the lakes simulated with the LAK2 package.

Table 4. Simulated lakes and calibrated leakance values.

Model number, lake name		Calibrated leakance: Nearshore (1/day)	Calibrated leakance: Offshore (1/day)
1	Mendota	1.3	0.1
2	Wingra	0.8	0.08
3	Monona	0.9	0.09
4	Waubesa	2.1	0.2
5	Kegonsa	1.0	0.1
6	Fish	1.1	1.0
7	Crystal	2.1	2.0

Figure 16. Calibrated transmissivity distribution for layer 9 (Wonewoc aquifer).



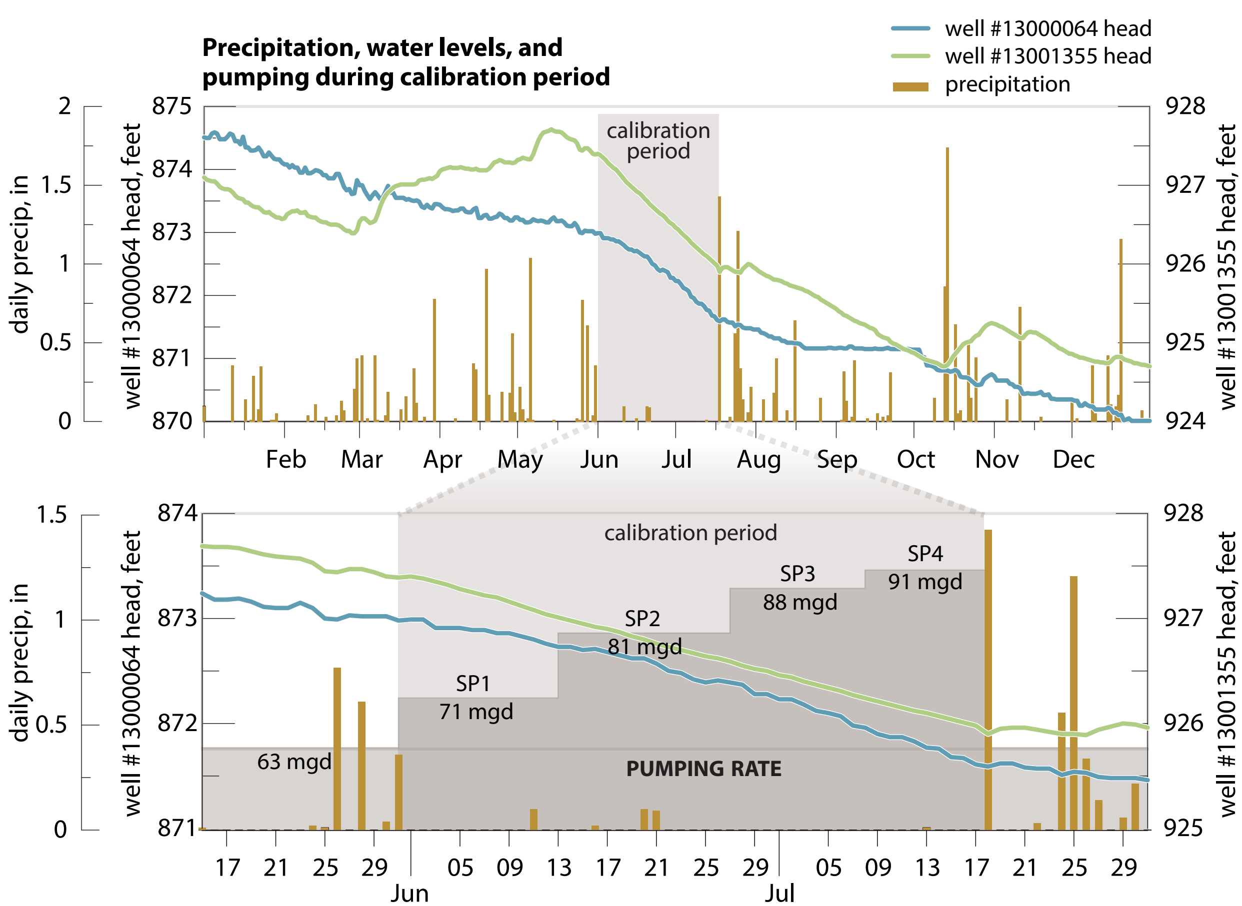
Transient model calibration

Transient models are needed to simulate field data where head or flow changes with time. Simulating transient groundwater flow was an important objective of the modeling project as many societal questions cannot be adequately addressed using a steady-state model. A transient model was derived from the steady-state model to simulate drought conditions of May 31 to July 18, 2012. As shown in figure 17, during this 7-week drought, only two small rainfall events occurred and regional groundwater levels steadily declined due to an absence of recharge and an increase in groundwater pumping. The figure also shows an expanded view of the transient calibration period. During this period, regional groundwater levels declined by several feet, while total county groundwater pumping increased from about 63 mgd in May to nearly 91 mgd in July. History matching focused on transient changes in hydraulic head and associated groundwater–surface-water exchange in response to changes in pumping rates and the absence of recharge. Because any changes to calibrated hydraulic conductivity values would only degrade the steady-state calibration results, the transient calibration focused on only the values of the storage terms, specific storage and/or specific yield, for hydrogeologic units included in the model domain. The model simulates changes in hydrologic stress such as recharge and lake evaporation.

Transient calibration targets

Transient head and flow targets consisted of time-series measurements of water levels in wells, lake levels, and flow in streams (appendix 9). Time series are relatively sparse compared to steady-state targets in Dane County. Groundwater recharge during the 2012 drought (May 31–July 18) was assumed to be zero, consistent with the period occurring during the height of the growing season when available soil moisture was likely removed by evapotranspiration. Calibration targets for the transient

Figure 17. Precipitation, water levels, and pumping during the 2012 calibration period.



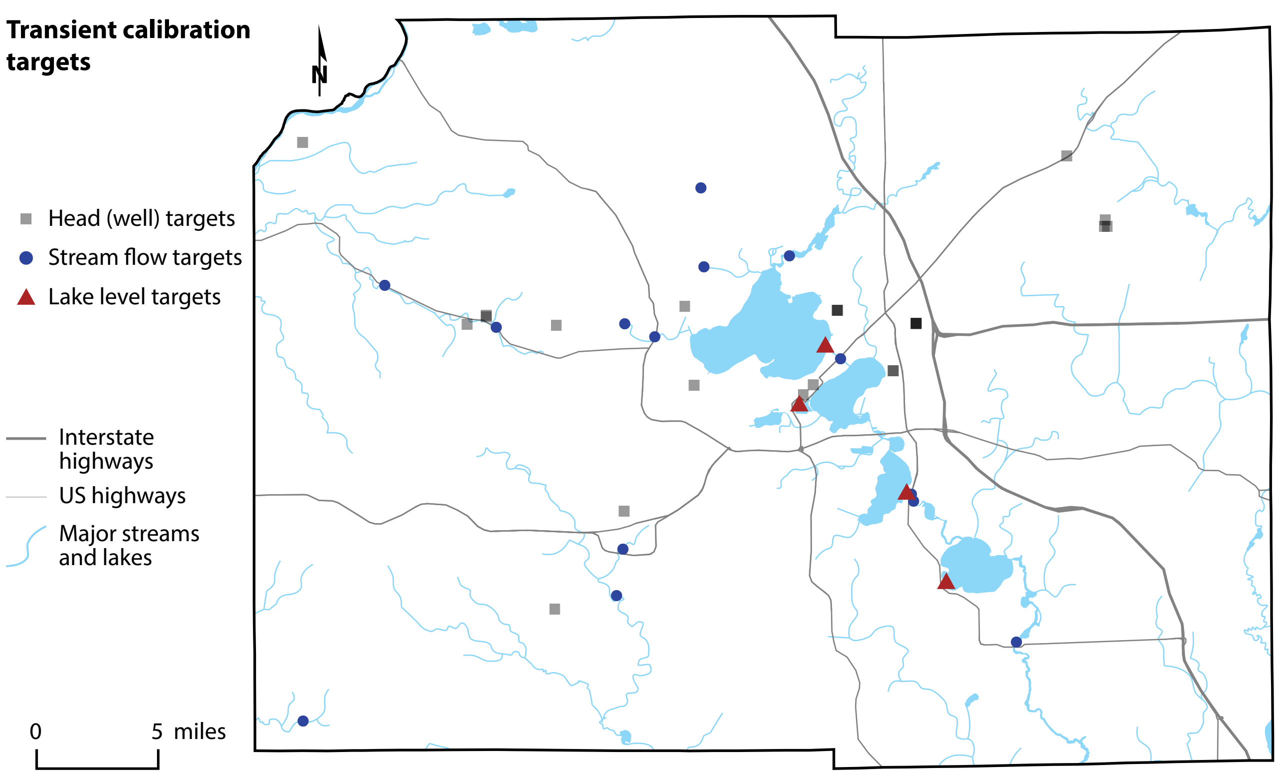
calibration consisted of water-level measurements at 25 wells and four lakes, and flow records at 14 streams (fig. 18). At each site, continuous time-series records were converted to period mean and ranges (lake levels) and daily mean and daily difference (that is, the difference between adjacent daily values) for comparison with model results. Temporal differencing of observed data is needed to ensure the history matching focuses on dynamics of the groundwater system and does not simply reflect the parameter's need to overcome shortcomings in the steady-state model (Doherty and Hunt, 2010). Observation weight varied by target type and length of observed time series; transient observed data and simulated results were pre- and post-processed using a time-series processor (TSPROC) (Westenbroek and others, 2012)).

Transient stress periods

The transient calibration run used the calibrated steady-state model as the starting condition. Recharge was set to zero, as was precipitation on lake surfaces. Lake evaporation rates were initially set to typical summer values of 0.15 to 0.23 inches per day. To estimate groundwater withdrawal rates during the transient calibration runs, we sent a water-use survey to major public water utilities in the fall of 2012. These data were then extrapolated to other wells for which no withdrawal data was obtained. Withdrawal data were obtained from 11 water utilities in Dane County: DeForest, Fitchburg, Madison, McFarland, Middleton, Mount Horeb, Oregon, Stoughton, Sun Prairie, Verona, and Waunakee. These records represent approximately 12 percent of the high-capacity wells within the model domain. Although this is a relatively small percentage of wells, they account for over 70 percent of total pumping within the model domain and are assumed to represent general water demand trends.

Although operations varied from well to well, analysis of the pumping records showed that the pumping generally fell into four stress periods, specifically May 31–June 13 (14 days), June 14–27 (14 days), June 28–July 8 (11 days), and July 9–18 (10 days), for a total of 49 days. During each of these stress periods, simulated pumping for wells with records was set to actual reported rates when possible; pumping rates for wells lacking records was estimated to increase proportionally to the rates in the wells having records. For the calibration runs shown in figure 17, stress periods (SP1–4) were divided into time steps equal to the number of days in each period (14, 14, 11, and 10 days, respectively); the time step length was increased from 0.5 days at

Figure 18. Locations of all transient calibration targets.



the initial step in each stress period to 1.5 days in the final step to facilitate numerical convergence.

Transient calibration parameters

Specific storage, specific yield (for convertible layers that can change from confined to unconfined), and lake surface evaporation were adjusted during transient history matching while holding all other model parameters constant. These storage parameters were zoned according to hydrostratigraphic unit, and varied uniformly within an individual unit. Initial and final calibration values are shown in table 1. A total of 33 parameters, including lake evaporation for the four stress periods and 29 storage parameters, were adjusted during transient calibration.

Transient calibration results

The overall transient history matching was deemed acceptable, though was not as well matched as the steady-state calibration. A lesser fit is expected because the actual magnitude and time of important changes to stress, such as pumping rate, were only approximately known. In addition, fewer parameters were allowed to vary during the history matching. The transient calibration must trade-off fit between multiple observation types (for example, between fitting predicted streamflows and predicted water levels) as well as possible across the entire county. Figures 19 and 20 (heads and flows, respectively) show typical comparisons between measured and simulated targets. For water levels in wells (fig. 19), it is important to note that matching the slopes of the head decline was the objective of transient calibration rather than matching the head values themselves. For some wells, such as Savannah Valley and Madison city well #21, the match is considered close, while a poor match in other wells (Pheasant Branch, for example) suggests that the transient model stress regime did not accurately reflect actual stresses such as local pumping changes. Likewise, predicted baseflows and lake levels (fig. 20) are in close agreement for some targets (such as Lake Monona) while the match is rather poor for others (such as Black Earth Creek). Lake levels are particularly difficult to match because the measured lake level responds to multiple factors other than groundwater interaction, such as wind, dam operation, and weed growth in the Yahara River—processes that are not included in the transient groundwater model. Therefore, while the model can reliably represent groundwater–lake interactions, it is not intended for use as a transient lake-level model.

The calibrated values for specific storage (table 1) for the sandstone aquifer layers (layers 9 and 12) are in the range of 10^{-5} 1/ft, which is within the range of the expected specific storage for sandstone (Li and Bradbury, unpub. data), and the observation that some (but not all) of the simulated transient head declines shown in figure 19 are less steep than observed declines suggests that, at least locally, the actual specific storage might be less than the calibrated values. The final transient calibration is a compromise fit among all model targets and viewed as acceptable for the purposes of this model and for the relatively short calibration period chosen. Application of the model to problems where transient results are critical will likely require additional evaluation of storage parameters.

Figure 19. Transient calibration results for selected well targets.

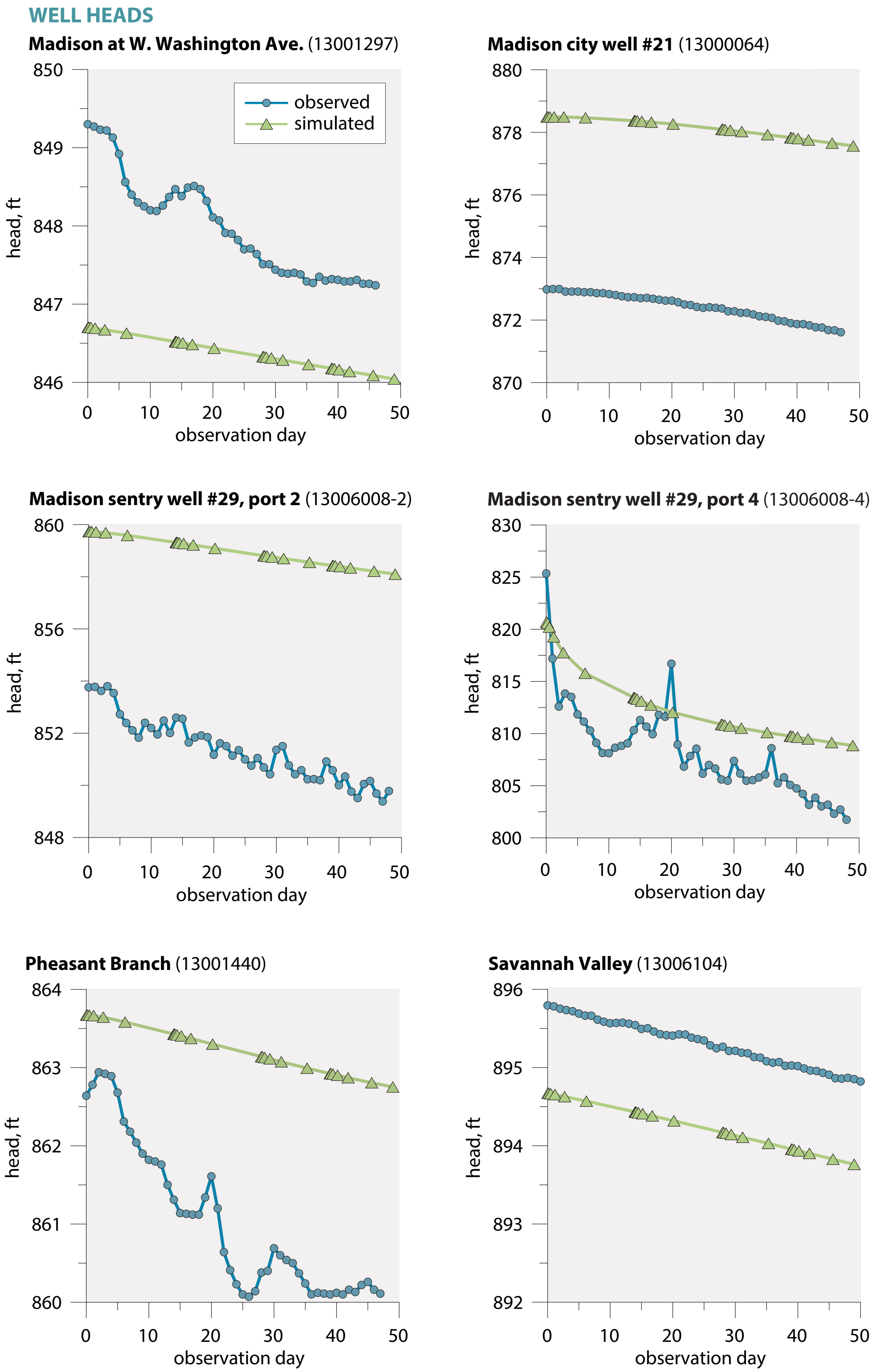
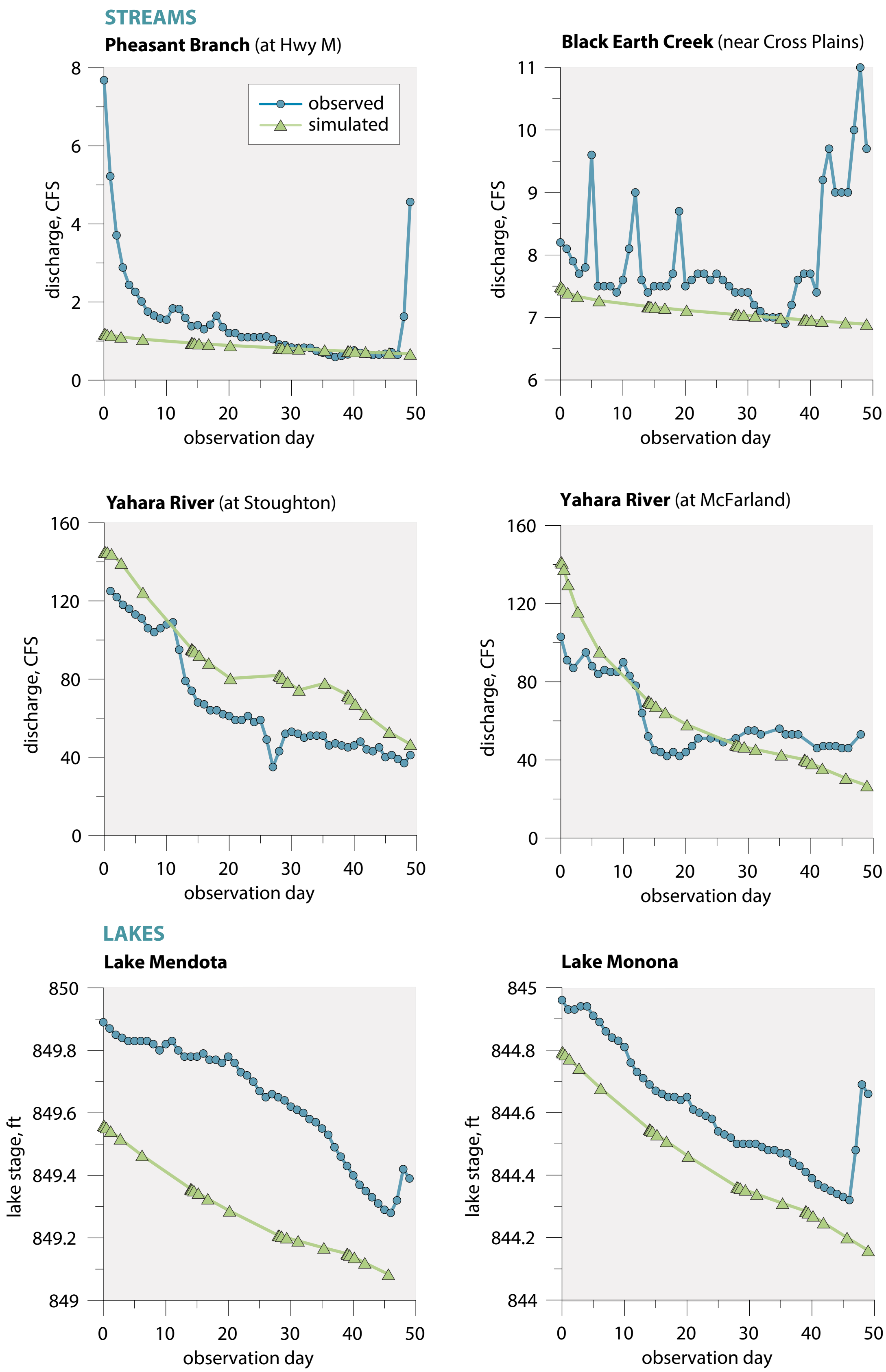


Figure 20. Transient calibration results for selected flow and lake-level targets.



Model results

Model solution and numerical mass balance

Using the Newton solver, the calibrated steady-state model converges in about 3 minutes on a 64-bit computer using an Intel Core i7 2.8GHz processor. The overall mass-balance error for the solution is less than 0.02 percent, using a head-change criterion of 0.01 (steady-state) and 0.3 (transient) ft and a global flux criterion of 20,000 (steady-state) and 9,000 (transient) cfd.

An overall mass-balance summary (table 5) shows inputs and outputs of water to the model. Lakes and streams can act as both sources and sinks of water depending on their location relative to pumping wells and their position in the landscape. Cross-connecting wells can also be a water source, transferring a net amount of over 4 cfs between model layers.

Table 5. Steady-state mass balance summary.

Boundary	Inflow (cfs)	Outflow (cfs)
Recharge	1,090.2	0.0
Specified head	10.3	150.4
Lake	11.2	19.9
Well	6.4	97.5
Stream	20.4	871.6
Storage	0.0	0.0
TOTAL	1,138.5	1,139.4

Comparison of 2010 and predevelopment simulations

Water levels and drawdown

Comparison of simulated steady-state predevelopment conditions to the 2010 calibration shows how groundwater conditions in Dane County have changed over the past century. Predevelopment here refers to conditions prior to the use of high-capacity wells in the county. This simulation is identical to the 2010 steady-state calibration simulation except that all wells were removed and the wastewater treatment discharges to selected streams were eliminated. It assumes recharge equal to present-day conditions. More detailed hindcast simulation of changes in the hydrology of the county (such as wetland drainage, dam construction, and land-use change) is possible but was beyond the scope of this project.

Figure 21 shows the simulated water table and Mount Simon potentiometric surface for predevelopment conditions. The water table has significant complexity, particularly in the western Driftless Area, because the numerous surface-water features are well-connected to groundwater. Lows in the Mount Simon potentiometric surface reflect topographic lows, and this potentiometric surface is much smoother than the water table because the Mount Simon is not directly connected to surface-water features. The simulation clearly shows the divides between the Yahara River basin and the Wisconsin River and Sugar-Pecatonica River basins to the west, represented as highs on the predevelopment water table and potentiometric surface contour maps.

Figure 22 shows simulated steady-state conditions during the 2010 calibration run. This simulation includes all high-capacity wells pumping at 2010 average rates, with the rates shown by the relative diameters of the circles on the figure (see appendix 3 for a list of wells and pumping rates). The water table is very similar to the predevelopment water table (fig. 21 - top) except for drawdown near the Madison area (discussed later). The Mount Simon potentiometric surface shows inflection or bull's-eyes around the pumping wells in the Madison area, showing the impact of deep pumping in lowering heads in the deep aquifer.

Present-day pumping has caused significant drawdown near the Madison metropolitan area, in the center of the county. Figure 23 shows drawdown for the water table and Mount Simon potentiometric surface (calculated as the difference between predevelopment and 2010 conditions). Simulated water-table declines (fig. 23 - top) range from less than 5 ft to more than 40 ft in the Madison area, but the Madison lakes and Yahara River maintain the water table where they occur, so there is negligible decline at the lakeshore or below the lakes. More significant declines occur in the Mount Simon potentiometric surface (fig. 23 - bottom) which simulations show has declined more than 70 ft in parts of Madison, including a nearly 50-ft decline below the Madison lakes. Other smaller cones of depression occur in outlying cities such as Verona, Stoughton, and Sun Prairie; little or no drawdown occurs near the county boundaries. These overall patterns are consistent with simulations of the earlier Dane County model of Krohelski and others (2000).

Figure 21. Simulated steady-state results under predevelopment conditions (no pumping).

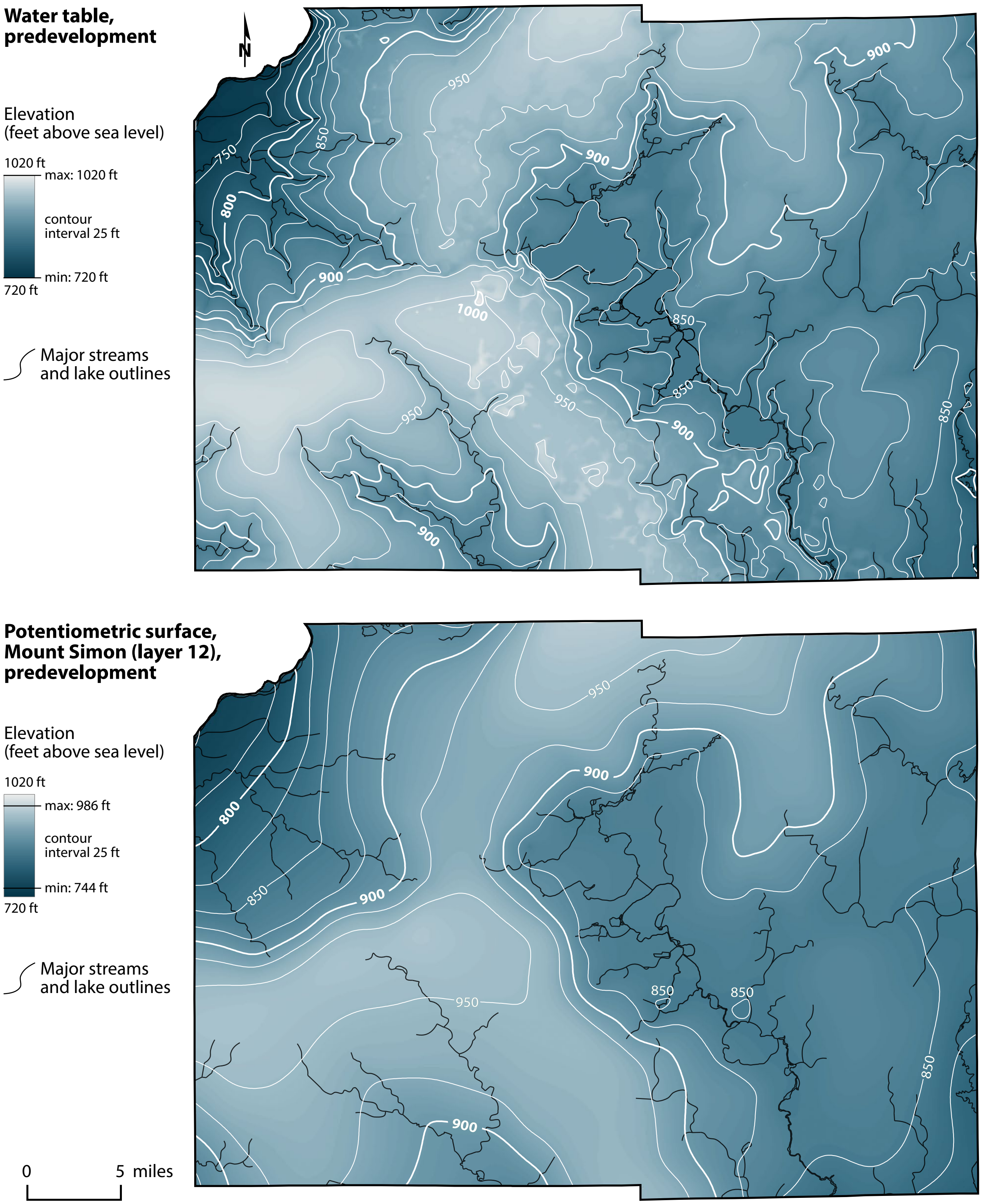


Figure 22. Simulated steady-state results under 2010 conditions (pumping).

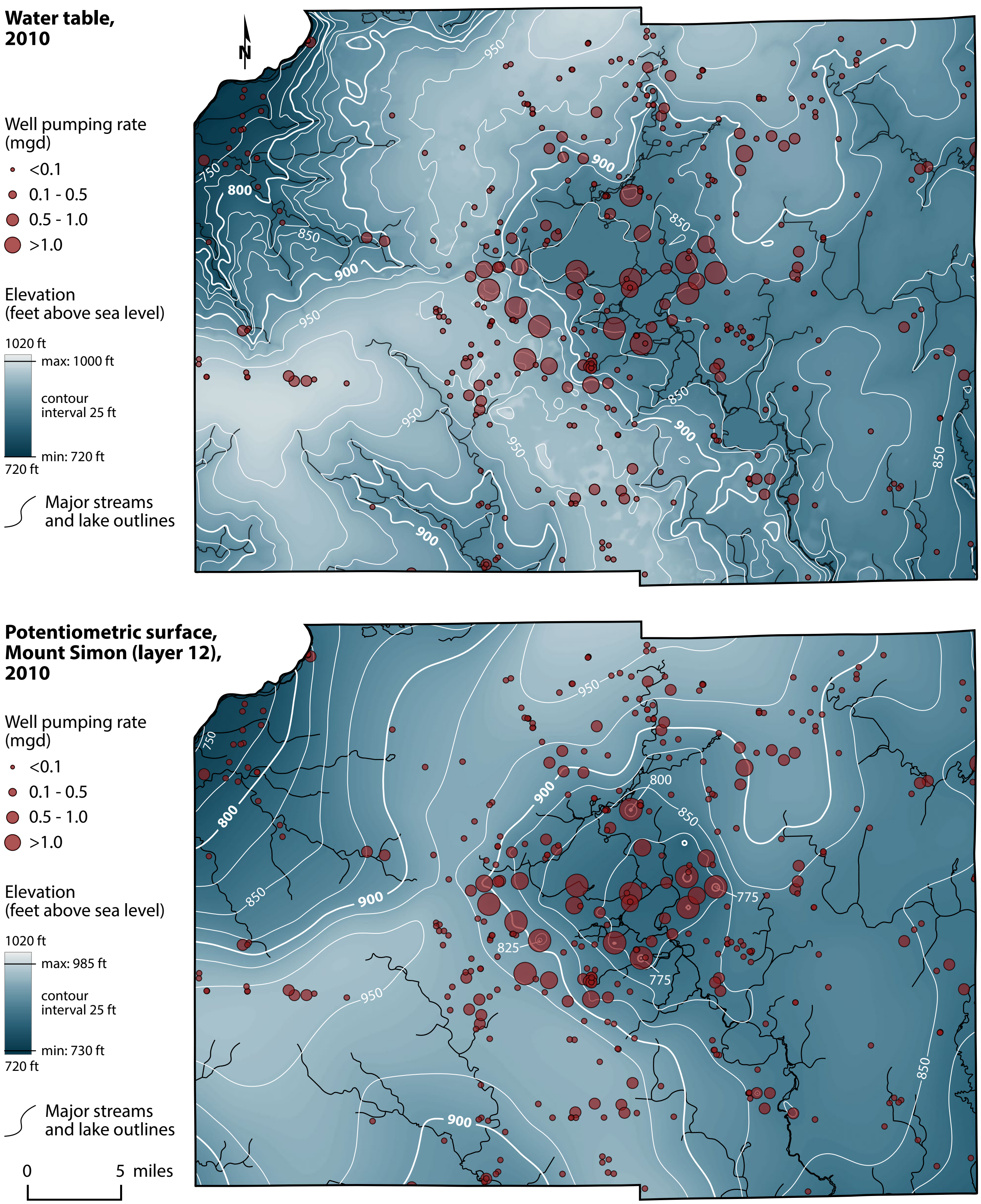
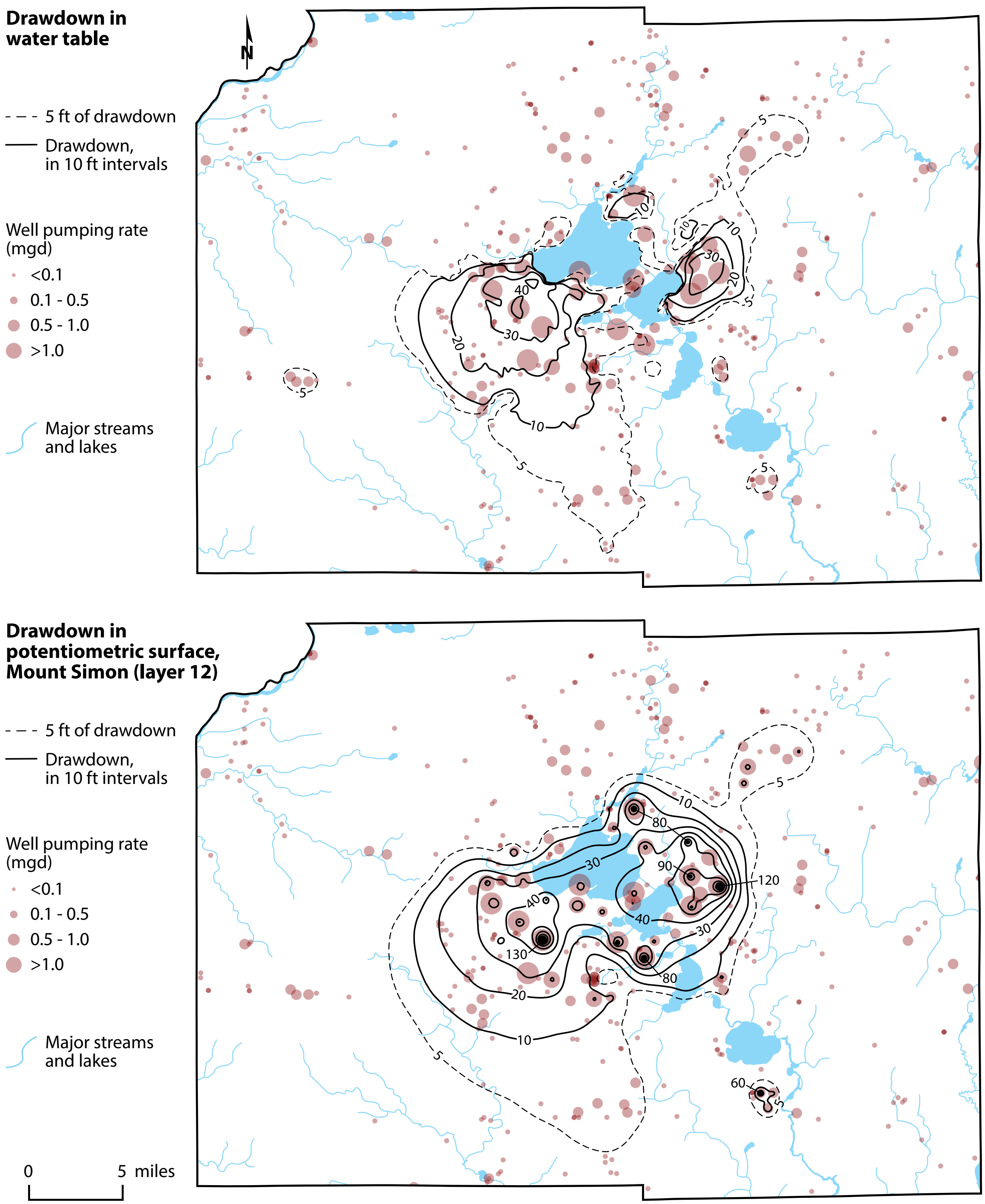


Figure 23. Simulated steady-state drawdown, comparing predevelopment and 2010 conditions.

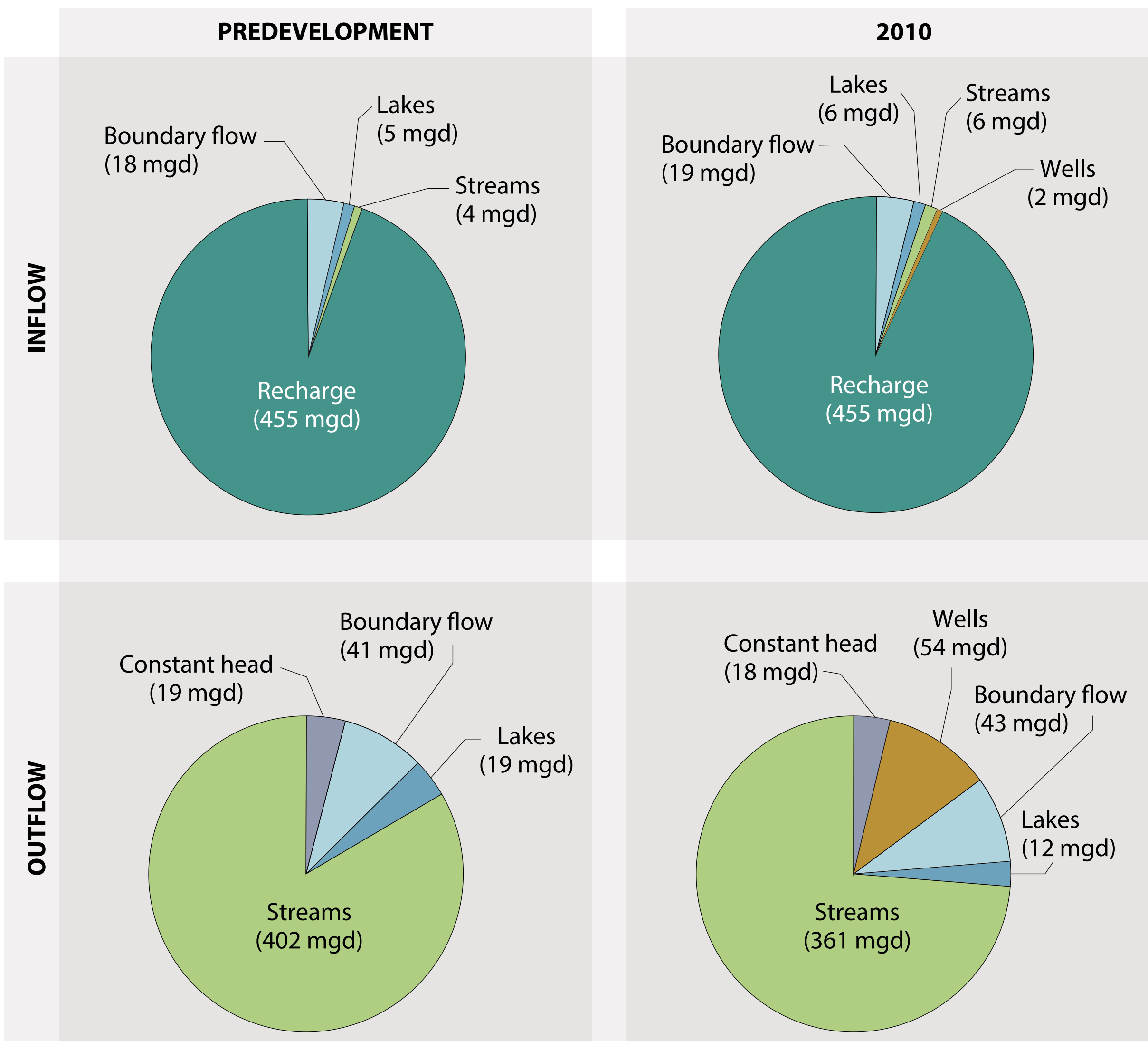


Mass balance and flow to surface water

The model quantifies the overall mass balance of groundwater and how that mass balance has changed from predevelopment to the present. Figure 24 compares predevelopment to 2010 conditions for Dane County, using pie charts to illustrate the changes to different components of the water balance. For both conditions the largest source of groundwater is recharge, and the largest sink of groundwater is discharge to streams. With the addition of pumping from wells totaling 52 mgd countywide, recharge remains the largest source and streams the largest sink, but groundwater discharge to streams decreases by over 40 mgd, and discharge to lakes declines from 19 mgd to 12 mgd. Figure 24 shows 2 mgd of inflow from wells in 2010. This 2010 inflow arises from ambient borehole inflow (flow from wells into aquifers) in wells open to more than one aquifer. An equal amount of ambient borehole outflow (flow from aquifers into wells) also occurs, and this flow is lumped together with the pumping outflow (52 mgd) to yield the total well outflow (54 mgd) shown in figure 24.

The impact of pumping on individual streams varies according to proximity to the drawdown and stream size. CARPC requested a compilation of streamflow impacts from pumping at specific locations relevant for regional planning decision-making (M. Kakuska, CARPC, personal com-

Figure 24. Steady-state water balance, comparing predevelopment and 2010 conditions.



munication). Table 6 summarizes the simulated changes in streamflow at 23 locations. Declines in streamflow from predevelopment to 2010 range from 0.31 mgd to 33.24 mgd (0.51 cfs to 51.43 cfs). In terms of percentages of total simulated streamflow, the percent declines range from less than 3 percent to over 75 percent. For several of the streams, the simulated flows increased from predevelopment to 2010 due to contributions from wastewater treatment plants. Badfish Creek is a prime example (table 6). Badfish Creek receives about 42 mgd (64 cfs) of treated effluent from the Nine Springs Wastewater Treatment plant (see appendix 2). As a result, its flow in 2010 was significantly greater than predevelopment flow. Note, though, that changes to streamflow between the two periods refer only to baseflow, not total streamflow.

Similarly, the impacts of pumping on individual spring flows varies across Dane County. Table 7 summarizes the changes in spring flow at 18 spring locations simulated in the model from predevelopment to 2010. Declines in spring flow from predevelopment to 2010, range from as little as 0.01 mgd to 1.54 mgd (0.02 cfs to 2.38 cfs). Overall, the percentages of total simulated spring flow, range from declines of less than 2 percent to 100 percent (completely dry).

Figure 25 depicts the change in flow for the entire streamflow routing (SFR2) network between predevelopment and 2010 conditions. The largest percent decreases in flow occur in streams located within central Dane

Table 6. Simulated predevelopment and 2010 streamflows at selected sites in Dane County.

Stream/river	Measurement location (at or near area listed)	Simulated predev. flow (cfs)	Simulated 2010 flow (cfs)	Difference (cfs)	Difference (mgd)	Difference (%)
Badfish Creek	CTH-A	11.58	75.47*	63.89	41.30	551.7
Badger Mill Creek	STH-69	3.63	4.21*	0.58	0.38	16.1
Black Earth Creek	Stagecoach Rd. near Cross Plains	4.94	3.52	−1.42	−0.92	−28.8
	Black Earth	33.24	31.28*	−1.96	−1.27	−5.9
Dorn Creek	CTH-M	6.27	5.65	−0.62	−0.40	−9.9
Koshkonong Creek	Deerfield	27.35	29.79*	2.43	1.57	8.9
	Hoopen Rd. near Rockdale	62.52	64.66*	2.14	1.38	3.4
	Bailey Rd. near Sun Prairie	0.77	5.02*	4.25	2.75	549.8
Maunesha River	Greenway Rd. south of US-151	17.25	16.43	−0.82	−0.53	−4.8
Mount Vernon Creek	STH-92	19.15	18.49	−0.67	−0.43	−3.5
Nine Springs Creek	US-14	12.17	6.87	−5.30	−3.42	−43.6
Pheasant Branch	Parmenter St, Middleton	2.85	1.19	−1.66	−1.07	−58.3
Sixmile Creek	North Madison St, Waunakee	5.96	5.11	−0.85	−0.55	−14.3
Spring Creek	Lodi	22.44	21.92	−0.51	−0.33	−2.3
Starkweather Creek	East Branch—at Milwaukee St.	3.01	0.73	−2.28	−1.47	−75.7
	West Branch—at Milwaukee St.	8.85	4.16	−4.69	−3.03	−53.0
Sugar River	above Badger Mill Creek near Riverside Rd.	21.16	18.60	−2.55	−1.65	−12.1
	West Branch—at STH-92 near Mt. Vernon	18.96	19.19*	0.24	0.15	1.2
Token Creek	US-51	20.34	17.98	−2.36	−1.53	−11.6
Wingra Creek	Beld St., Madison	3.77	1.82	−1.95	−1.26	−51.6
Yahara River	Lake Windsor Country Club	6.77	6.28	−0.49	−0.31	−7.2
	Stoughton	207.94	156.51*	−51.43	−33.24	−24.7
	Lake Waubesa outlet at Stoughton Rd.	157.60	109.04	−48.57	−31.39	−30.8

Abbreviations: *cfs = cubic feet per second, mgd = million gallons per day*

* *Includes discharge from wastewater treatment plants; see appendix 2 for outfall locations and volumes.*

Table 7. Simulated predevelopment and 2010 spring flows at principal springs in Dane County.

Stream/lake	Spring name	Simulated predev. flow (cfs)	Simulated 2010 flow (cfs)	Difference (cfs)	Difference (mgd)	Difference (%)
Flynn Creek	Flynn Creek Springs	2.41	2.33	–0.08	–0.05	–3.3
Garfoot Creek	Garfoot Springs	0.95	0.88	–0.06	–0.04	–6.8
	Lower Garfoot Springs	0.85	0.62	–0.22	–0.14	–26.3
Lake Mendota	Spring Harbor Spring	0.11	0.00	–0.11	–0.07	–100.0
Lake Wingra	Big Springs	0.57	0.34	–0.23	–0.15	–40.5
	Council Circle & Dancing Sands Springs	0.18	0.06	–0.12	–0.08	–66.8
	Duck Pond Springs	0.81	0.48	–0.34	–0.22	–41.6
Mount Vernon Creek	Big Donald Park Springs	7.69	7.54	–0.15	–0.10	–1.9
	Small Donald Park Springs	1.50	1.48	–0.02	–0.01	–1.5
Nine Springs Creek	Big Springs	1.01	0.68	–0.34	–0.22	–33.5
	Englehart Drive Springs	0.35	0.13	–0.23	–0.15	–64.2
	Nevin Fish Hatchery Springs	5.63	3.25	–2.38	–1.54	–42.2
	Nursery Springs	1.68	1.19	–0.49	–0.32	–29.2
	Syene Road Springs	0.60	0.25	–0.35	–0.22	–58.1
Pheasant Branch	Frederick Springs	4.14	3.48	–0.66	–0.43	–16.0
Starkweather Creek	Zeier Road Springs	1.09	0.47	–0.62	–0.40	–57.0
Story Creek	Story Spring	5.48	4.88	–0.61	–0.39	–11.0
Token Creek	Culver Springs	8.91	7.97	–0.94	–0.61	–10.6

Abbreviations: *cfs = cubic feet per second, mgd = million gallons per day*

County, which are coincident with the regional cone of depression. In contrast, the smallest percent decreases in flow are concentrated within western and eastern Dane County, outside of the main groundwater withdrawal centers. Stream reaches simulated as dry (zero flow) during both predevelopment and 2010 conditions are areas which were included in the model as streams but did not receive groundwater discharge during either simulation period. These streams are concentrated in headwater areas and represent ephemeral streams that flow during wet periods of the year but often become dry during baseflow conditions. Streams that gained flow between predevelopment and 2010 conditions are those that currently receive treated effluent from wastewater treatment plants across Dane County. The most noticeable gains in flow are associated with effluent discharges to Badger Mill Creek at Verona, Badfish Creek north of Oregon, the West Branch of the Sugar River south of Mount Horeb, and the Koshkonong Creek south of Sun Prairie.

Demonstration of transient model response

One potential use of the transient model is for evaluation of the time-variant impacts of new high-capacity wells. To demonstrate this capability, we added a hypothetical new well in the vicinity of Story Creek in the Town of Oregon in the southern part of Dane County. Story Creek begins at a spring complex, which discharges approximately 4 cfs. The hypothetical well is located 3,000 ft east of the creek and spring complex (fig. 26), simulated as cased through the Eau Claire aquitard, and open to the entire thickness of the Mount Simon sandstone. The model simulates the pumping well at 1,200 gpm, a typical rate for large high-capacity wells in southern Wisconsin. The model simulates drawdown and spring flow prior to pumping, after 30 days of pumping, and at steady-state. The model also simulates the transient response of the well and the spring during and after a 30-day pumping period.

Figure 25. Comparison of changes in streamflow between predevelopment and 2010 conditions.

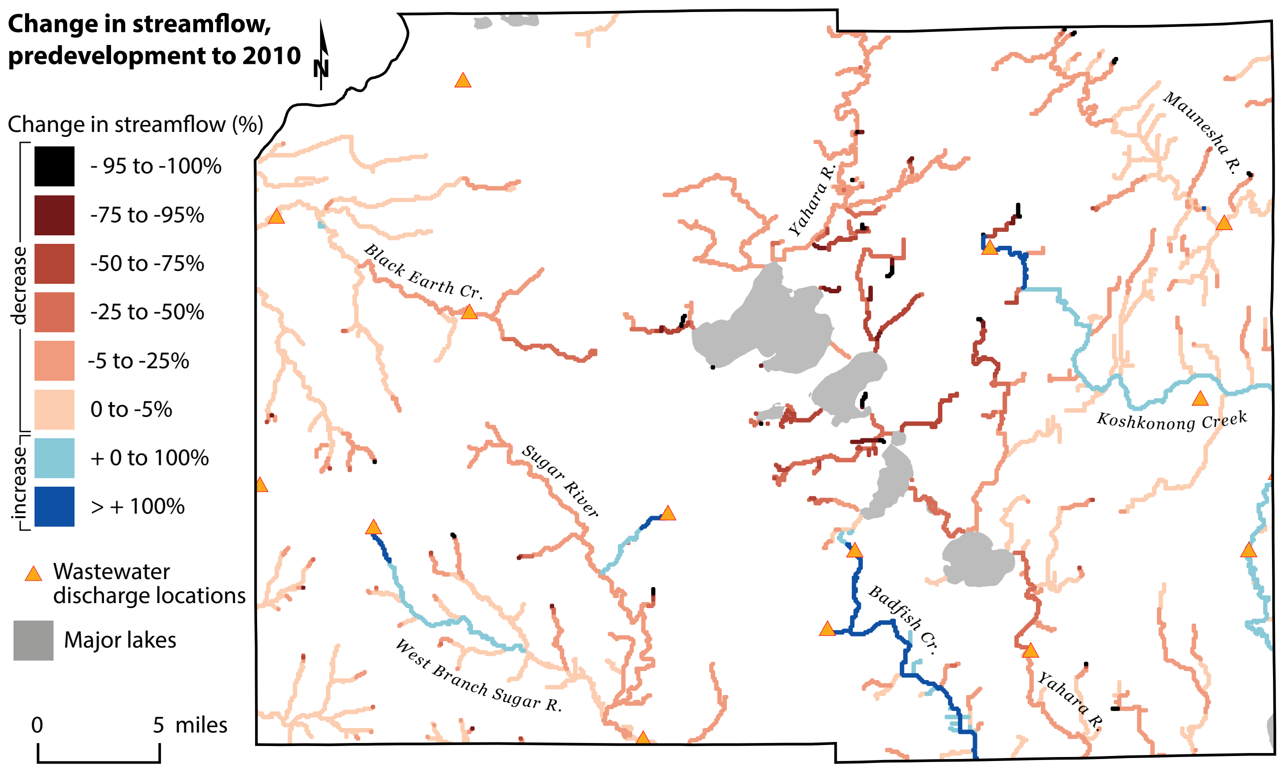
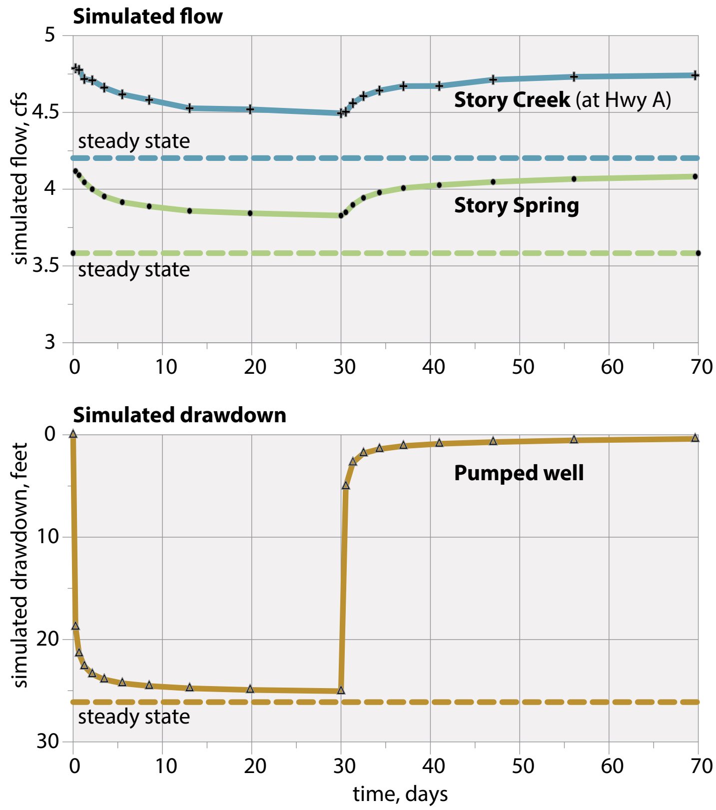


Figure 26. Transient drawdown simulation for a hypothetical well near Story Creek in southern Dane County.

The simulated hydrograph (fig. 27) shows that following the initiation of pumping, the water level in the pumped well falls nearly 25 ft and continues to decline slowly throughout the 30-day pumping period. Following the cessation of pumping after 30 days, the water level in the pumped well rebounds rapidly and continues to rise slowly throughout the 40-day recovery period (fig. 27). Even though the spring complex is over 3,000 ft from the well and in the surficial aquifer, its flow declines by about 0.25 cfs during the pumping period and recovers once the well is turned off. It is interesting to note that the decline and recovery of spring flow happens more slowly than the decline and recovery in the pumping well, a result which is consistent with hydrogeologic theory.

Figure 27. Detailed results for the hypothetical well showing drawdown for the creek, spring, and pumped well.



Model limitations

Overview

The current model is a state-of-the-art representation of the groundwater system and groundwater–surface-water interactions in Dane County at the county or regional scale. The model is intended to inform questions at the regional scale and is very well suited to problems involving regional pumping, water balance, and groundwater–surface-water interactions. The model is not intended for site-scale questions and problems that involve small stresses to the regional system (such as the effects of additional pumping from a new private well), where the prediction of interest depends on fine-scale details that are not well represented in the regional model. Although it simulates flow between groundwater and surface water, the model is not a surface-water model, and can only simulate the groundwater component of issues such as flooding, stormwater runoff, and stream management. This model provides a regional foundation for smaller-scale studies, however, and can be used as a starting point for refined study and simulation of site-specific problems. The following sections summarize model limitations.

Limitations related to discretization

The hydrogeologic system in Dane County has been significantly simplified during model discretization. The smallest horizontal grid dimension in the model is 360 ft, and cannot capture geologic complexity, such as facies changes, erosional channels, sand and gravel lenses, silt layers, fractures, and other features that occur at smaller areal dimensions. Similarly, the vertical discretization of the groundwater system into 12 discrete layers required significant lumping of hydrogeologic properties and does not represent features that exist at finer scales.

This model contains two layers (layers 6 and 10) intended to represent bedding-plane fractures that are present across the entire county. The existence of such features is now well documented (Swanson, 2001, 2007; Swanson and others, 2006; Gellasch and others, 2013), but the field appearance of these fractures is of numerous horizontal features over a limited stratigraphic zone rather than a single continuous feature. Although such detail is not important for groundwater flow at the county scale, the model's omission of detail in these fracture features at the site scale might lead to inaccurate model predictions, particularly with respect to transport of contaminants.

The discretization of time represents another model limitation. Steady-state simulations assume that hydrologic conditions, including pumping and recharge, are constant over time. Pumping and recharge are both obviously transient phenomena, and so the results of steady-state simulations represent long-term averages. The transient model is suitable for time-dependent problems; however, the transient calibration documented here reflects a relatively simple drought scenario and a limited observed data set for history matching. Therefore, the model's ability to simulate more complex transient stresses and responses in areas without observed transient data will vary, both in space and with complexity of the specified transient stress.

Limitations related to model stability

The Dane County model features a number of mathematically nonlinear processes such as groundwater-lake interaction, surface-water routing and groundwater exchange, and wetting and drying of model cells. Although the Newton solver offers improved handling of these nonlinearities (Hunt and Feinstein, 2012), certain reasonable combinations of model parameters can cause the model solver settings used for the calibration documented here to be non-optimal. When the solver settings are not properly specified, the model can become unstable, require very long run times, or fail to converge. This problem is especially troublesome for transient simulations. Therefore, modifications to the base steady-state and transient model stresses and/or parameters may require the user to explore a range of solver settings to obtain acceptable results.

Limitations related to a lack of hydrogeologic knowledge

Fish and Crystal Lakes

The model was unable to satisfactorily simulate the stages and fluctuations of Fish and Crystal Lakes, in northwest Dane County, using stratigraphy extrapolated from farther south in the county, and sparse stratigraphic information near the lakes. Successful calibration of these lakes required insertion of a high-hydraulic conductivity zone extending from the lakes to the Wisconsin River in model layers 1–10. Therefore, the model's simulation capabilities in the area of these two lakes are uncertain. Additional hydrostratigraphic characterization and subsequent modeling is needed to more accurately resolve the local groundwater flow system and its interaction with these lakes.

Parameter uncertainty

All models are simplifications of an unknowably complex natural system. As such, there can be no expectation of a model forecast without some uncertainty (Hunt and Zheng, 2012). Uncertainty in model parameters is one well-recognized source of forecast uncertainty. Even after calibration, hydrogeologic parameters can only be approximately known, and the level of uncertainty varies across the county because the density of calibration targets is spatially uneven. Parameters that are not sensitive to the calibration data, and those that take on surrogate values to compensate for other model deficiencies add further model uncertainty.

The hydrogeologic data, especially pumping tests and specific capacity estimates of hydraulic conductivity, are most abundant in populated areas such as the Madison metropolitan area, and much less abundant in outlying rural areas where water-supply wells are scarce. In addition, the hydraulic data are heavily biased toward the most-used aquifers of the Wonewoc and Mount Simon Formations. Parameters in areas of sparse calibration targets are relatively more uncertain. If, as intended, this model is used as a basis for creation of more detailed inset models, additional data collection and re-calibration will usually be necessary.

Streamflow and lake level along the Yahara River

Due to the low hydraulic gradient and management of lakes along the Yahara River, from Lake Mendota to Lake Kegonsa, it was not feasible to develop rating curves that could accurately attribute flow rates to specific lake-level elevations. The combination of backwater effects between the lakes and engineering management decisions to maintain lake levels above winter minimums and summer maximums (for example, raising and lowering dam outlet elevations, aquatic plant cutting practices), contributed several variables that could not be adequately resolved at the temporal and spatial resolution used in this modeling effort.

Wetland drainage

From predevelopment to the present day, Dane County has experienced significant alteration of its landscape. One very significant hydrologic alteration has been the drainage of wetlands and the construction of networks of agricultural drainage ditches and field tiles. These constructed features route water directly to streams and away from the groundwater system, with the effect of decreasing groundwater recharge where they occur. An offsetting effect is that draining wetlands has reduced evapotranspiration losses. Accounting for drainage ditches and field tiles was considered beyond the scope of the current model and not explicitly simulated in the model. They were, however, indirectly accounted for by the recharge multiplier, which constrains the magnitude of recharge to achieve a "best fit" to the baseflow stream targets, as well as SWB, which uses present-day land-cover conditions. Omitting the dynamics of these hydraulic features probably has little impact on the overall model solution but increases model uncertainty near ditches and wetlands.

Summary

The 2016 groundwater flow model for Dane County, Wisconsin, exemplifies state-of-the-art model construction and calibration. The model was developed by a team of WGNHS and USGS scientists with support from the Capital Area Regional Planning Commission, and replaces an earlier model developed in the 1990s. The new model is three-dimensional and transient, and conceptualizes the county's hydrogeology as a 12-layer system including major hydrostratigraphic units and two known high-conductivity fracture zones.

The model uses the USGS MODFLOW-NWT finite-difference code, with a Newton solver to improve the handling of unconfined conditions by more robustly handling the transition between wet and dry cells. The model explicitly simulates groundwater–surface-water interactions with streamflow routing and lake-level fluctuation. Model calibration used the parameter estimation code PEST, and calibration targets included heads, stream and spring flows, lake levels, and borehole flows. Steady-state calibration focused on the 5-year period of 2006 through 2010; the transient calibration focused on the 7-week drought period from late May through July 2012.

This model represents superior simulation capabilities of the groundwater system over previous work because of its finer grid resolution, improved representation of hydrostratigraphy, transient capabilities, and focus on sophisticated handling of surface-water features.

As a tool for sustainably managing Dane County's groundwater resources, the model has many potential applications. These can include evaluation of potential sites for and impacts of new high-capacity wells, development of wellhead protection plans, evaluating the effects of changing land use and climate on groundwater, and quantifying the relationships between groundwater and surface water.

Pond in Story Creek headwaters

Ken Bradbury

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