Wisconsin Geological
and Natural History Survey
UNIVERSITY OF WISCONSIN–MADISON

Groundwater Flow Model *for* Western Chippewa County, Wisconsin

Including analysis of water resources related to industrial sand mining and irrigated agriculture

Bulletin 112 • 2019

Michael J. Parsen
Paul F. Juckem
Madeline B. Gotkowitz
Michael N. Fienen

Wisconsin Geological and Natural History Survey

Kenneth R. Bradbury, *Director and State Geologist*

WGNHS staff

Carsyn Ames, *samples coordinator*
Amber Boudreau, *GIS technician*
Eric C. Carson, *geologist*
Peter M. Chase, *geotechnician*
Linda G. Deith, *editor*
Stefanie Dodge, *project geologist*
Anna C. Fehling, *hydrogeologist*
Ana Genthe, *field and lab asst. geologist*
Brad T. Gottschalk, *archivist*
Grace E. Graham, *hydrogeologist*
David J. Hart, *hydrogeologist*
Irene D. Lippelt, *water resources spec.*
Sushmita S. Lotlikar, *assistant director of administration*
Stephen W. Mauel, *GIS specialist*
M. Carol McCartney, *outreach manager*
Michael J. Parsen, *hydrogeologist*
Jill E. Pongetti, *office manager*
J. Elmo Rawling III, *geologist*
Caroline M.R. Rose, *GIS specialist*
Kathy Campbell Roushar, *GIS specialist*
Peter R. Schoephoester, *assistant director*
David M. Sibley, *web developer*
Esther K. Stewart, *geologist*
and approximately 20 graduate and undergraduate student workers

Research associates

Jean M. Bahr, *University of Wisconsin–Madison*
Mark A. Borchardt, *USDA–Agricultural Research Station*
William F. Cannon, *U.S. Geological Survey*
Michael Cardiff, *University of Wisconsin–Madison*
William S. Cordua, *University of Wisconsin–River Falls*
Daniel T. Feinstein, *U.S. Geological Survey*
Michael N. Fienen, *U.S. Geological Survey*
Timothy J. Grundl, *University of Wisconsin–Milwaukee*
Paul R. Hanson, *University of Nebraska–Lincoln*
Karen G. Havholm, *University of Wisconsin–Eau Claire*
Randy J. Hunt, *U.S. Geological Survey*
John L. Isbell, *University of Wisconsin–Milwaukee*
Mark D. Johnson, *University of Gothenburg*
George J. Kraft, *Central Wisconsin Groundwater Center*
Evan R. Larson, *University of Wisconsin–Platteville*
John A. Luczaj, *University of Wisconsin–Green Bay*
J. Brian Mahoney, *University of Wisconsin–Eau Claire*
Shaun Marcott, *University of Wisconsin–Madison*
Joseph A. Mason, *University of Wisconsin–Madison*
Daniel J. Masterpole, *Chippewa Co. Land Conservation Dept.*
David M. Mickelson, *University of Wisconsin–Madison (emeritus)*
Donald G. Mikulic, *Illinois State Geological Survey*
William N. Mode, *University of Wisconsin–Oshkosh*
Maureen A. Muldoon, *University of Wisconsin–Oshkosh*
Todd W. Rayne, *Hamilton College*
Randall J. Schaetzl, *Michigan State University*
Madeline E. Schreiber, *Virginia Tech*
Susan K. Swanson, *Beloit College*
Kent M. Syverson, *University of Wisconsin–Eau Claire*
Lucas Zoet, *University of Wisconsin–Madison*

The Wisconsin Geological and Natural History Survey also maintains collaborative relationships with a number of local, state, regional, and federal agencies and organizations regarding educational outreach and a broad range of natural resource issues.

Wisconsin Geological and Natural History Survey
UNIVERSITY OF WISCONSIN–MADISON

Bulletin 112 ▪ 2019

Groundwater Flow Model *for* Western Chippewa County, Wisconsin

Including analysis of water resources related to industrial sand mining and irrigated agriculture

Michael J. Parsen
Wisconsin Geological and Natural History Survey

Paul F. Juckem
U.S. Geological Survey, Wisconsin Water Science Center

Madeline B. Gotkowitz
Wisconsin Geological and Natural History Survey

Michael N. Fienen
U.S. Geological Survey, Wisconsin Water Science Center

Suggested citation:

Parsen, M.J., Juckem, P.F., Gotkowitz, M.B., and Fienen, M.N., 2019, Groundwater flow model for western Chippewa County, Wisconsin—including analysis of water resources related to industrial sand mining and irrigated agriculture: Wisconsin Geological and Natural History Survey Bulletin 112, 74 p.

The use of company names in this document does not imply endorsement by the Wisconsin Geological and Natural History Survey or by the U.S. Geological Survey.

Published by and available from:

Wisconsin Geological and Natural History Survey

University of Wisconsin-Madison Division of Extension
3817 Mineral Point Road ▪ Madison, Wisconsin 53705-5100
608.262.1705 ▪ WisconsinGeologicalSurvey.org
Kenneth R. Bradbury, Director and State Geologist

ISBN: 978-0-88169-980-7
ISSN: 0375-8265

Contributors

Editor: Linda Deith
Graphics: Caroline Rose (maps), Kristen Rost (graphs)
Cover photos: Front cover—Duncan Creek, by Michael Parsen; Back cover—Wonewoc Formation outcrop, by Michael Parsen
Layout: Kristen Rost

Contents

Figures

Tables

Appendices

(Appendices are available at http://wgnhs.org/pubs/b112)

Abstract

A groundwater flow model for western Chippewa County, Wisconsin, was developed by the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS) using the computer program MODFLOW. The model is the result of a five-year groundwater study commissioned by Chippewa County in 2012 to evaluate the effects of industrial sand mining and irrigated agriculture on the county's water resources. The study incorporates existing data and newly acquired data from fieldwork conducted within the study area. The groundwater model may be useful for future investigations, such as evaluation of proposed high-capacity well sites, development of municipal wellhead protection plans, and studies that seek to further quantify surface water-groundwater relationships.

The model conceptualizes the hydrostratigraphy of western Chippewa County as six stacked layers. Each layer is distinct, beginning with unlithified glacial material at the surface, and alternating between sandstones (that act as aquifers) and shale units (that serve as aquitards). The model is bounded below by Precambrian crystalline bedrock and its perimeter was derived from a regional-scale groundwater flow model.

The MODFLOW model represented average conditions during 2011–2013 with "steady-state" assumptions, meaning that simulated water levels do not fluctuate seasonally or from year to year. Steady-state models simplify natural variability, making results of scenario simulations easier to interpret and compare while also maximizing effects of stressors because the simulated stress is always applied (not halted after a few months or years). Model calibration used the parameter estimation code (PEST), and calibration targets included heads (groundwater levels) and streamflows. Calibration focused on 2011–2013 because a large amount of head and streamflow data were available for that period.

The MODFLOW model explicitly simulates all sources and sinks of water, including groundwater/surface-water interaction with streamflow routing. Model input included estimates of aquifer hydraulic conductivity and a spatial groundwater recharge distribution developed using a GIS-based soil-water-balance (SWB) model applied to the model area. Groundwater withdrawals were simulated for 269 high-capacity wells

Michael Parsen

Jerry Clark

across the entire model domain, which includes western Chippewa County and adjacent portions of Dunn, Barron, and Rusk Counties. Collectively, these wells withdrew about 1.14 million gallons per year between 2011 and 2013.

Once the model was calibrated, it was applied to two distinct scenarios of increased groundwater withdrawals: one evaluating hydrologic effects of more intensive industrial sand mining and the second evaluating the hydrologic effects of more intensive agricultural irrigation practices. Each scenario was developed with input from Chippewa County and a stakeholder group established expressly for this study. The scenarios were designed to represent reasonable future buildout conditions for both mining and irrigated agriculture. The mining scenario underscores the potential hydrologic effects related to changing land-use practices (i.e., hilltops and farmland becoming sand mines), while the irrigated agriculture scenario illustrates the potential hydrologic effects of intensifying existing land-use practices (i.e., installing new wells to irrigate farm fields).

While each scenario evaluated distinctly different conditions, modeling results demonstrated the potential of both scenarios to lower the water table and reduce baseflows in headwater streams within the modeled area. In the case of irrigated agriculture, hydrologic effects were associated directly with groundwater withdrawals. By assuming that irrigation did not decrease, this steady-state simulation represented a sustained future effect. By contrast, hydrologic effects of industrial sand mining were the result of both groundwater withdrawals at mines and land-use changes that effectively reduced recharge to groundwater over distinct phases of active mining. This scenario included a post-mining phase, during which groundwater withdrawals stopped and mined areas were reclaimed to undeveloped prairie grass cover. If reclamation to undeveloped prairie indeed occurs as simulated, long-term increases in the water table and stream baseflows are possible. In this sense, the scenario representing build out of irrigated agriculture led to long-term baseflow declines while the future buildout of industrial sand mining led to declines that dissipated following mine reclamation to undisturbed prairie.

Future investigations in similar hydrogeologic settings may find the following insights gleaned from this study useful:

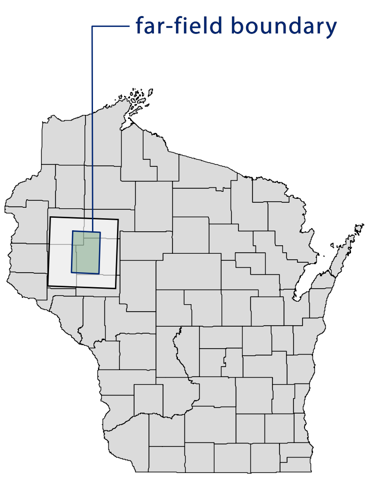
- The characterization of hydrogeologic properties, delineation of hydrogeologic units, and calibration of groundwater flow models benefited from incorporation of accurate well construction reports, high-quality borehole geophysical logs, and streamflow gaging data.
- Infiltration testing performed in active mining areas provided evidence that reducing the degree and extent of compaction and enhancing areas designed to retain and infiltrate stormwater runoff could potentially reduce runoff and increase groundwater recharge.
- Similarly, reclaiming mined areas to prairie grasses would be expected to reduce runoff and increase groundwater recharge by reducing compaction and improving soil structure and vegetation that can slow runoff and enhance infiltration.

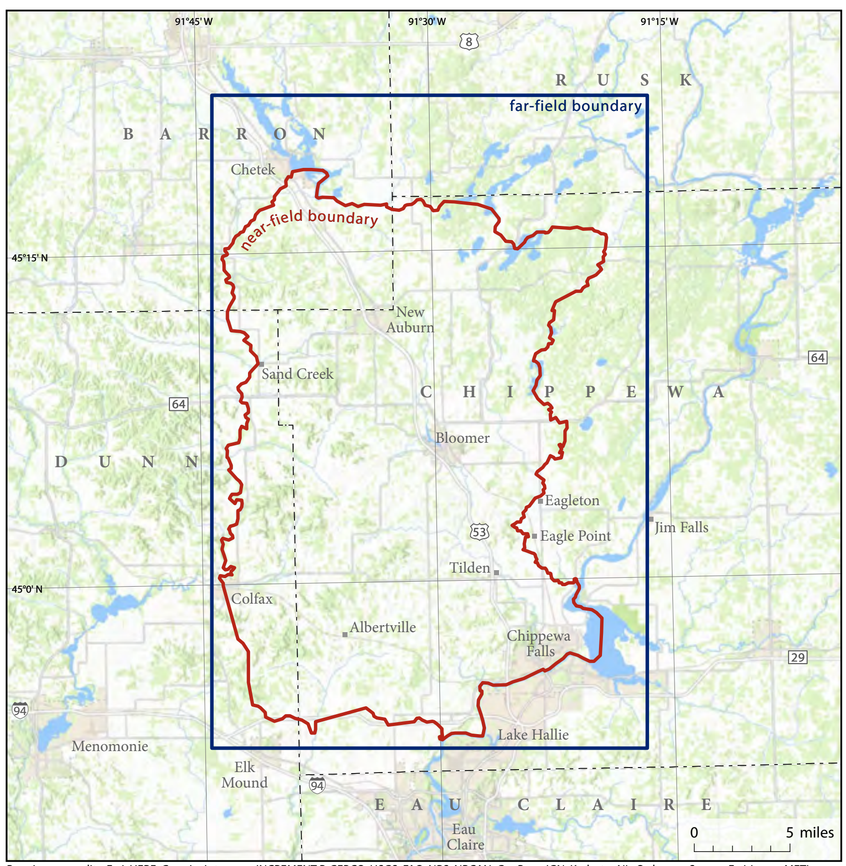
Introduction

The quantity of surface water and groundwater resources is important to the ongoing quality of life and economic well-being of residents and businesses in Chippewa County, Wisconsin. Over the past decade, greater demands have been placed on the land and natural resource base of west-central Wisconsin. For example, parts of this region are experiencing an increase in the number of acres of irrigated cropland (WDNR, n.d.-b; R.A. Smail, WDNR, oral communication, 2013). Coincident with these changes in agricultural practices, trends in global demand for energy have resulted in an increase in demand for industrial silica sand, commonly referred to as frac sand, from Wisconsin (Benson and Wilson, 2015). Frac sand is injected into gas and oil production wells to prop open fractures in bedrock, increasing well yields. While Wisconsin has no oil- or gas-producing wells, our sand is in high demand in other regions of the United States. To meet demand, numerous industrial sand mines are being permitted and developed to extract high-quality sand from the Wonewoc Formation (R.A. Walls, WDNR, oral communication, 2013; Parsen and Zambito, 2014). This sandstone formation extends throughout upland areas in west-central Wisconsin.

Residents, local officials, and other concerned citizens recognize these changes in land use and are interested in understanding potential cumulative effects of changes in groundwater recharge and groundwater use on water resources in west-central Wisconsin. Changes in recharge could occur due to active mining and reclamation techniques. Changes in groundwater use may result from an expansion of irrigated agriculture, industrial sand mining, and other high-capacity groundwater withdrawal operations.

The study seeks to develop a better understanding of groundwater resources in western Chippewa County (fig. 1). The project includes development of a soil-water-balance (SWB) model that integrates with a groundwater flow model to evaluate the effects of changes to groundwater recharge and withdrawal on the hydrologic system. This study will benefit water resources management efforts in the region by characterizing hydrogeologic conditions and incorporating this characterization into a computer model capable of





Base image credits: Esri, HERE, Garmin, Intermap, INCREMENT P, GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 1. Study area location in west-central Wisconsin.

evaluating a set of scenarios associated with alternative management plans and/or hydrologic conditions. The results will provide interested parties with technical information to support informed decision-making regarding water resources within western Chippewa County.

The regional-scale groundwater modeling of western Chippewa County has been made possible through funding by Chippewa County and the Chippewa County Board of Supervisors with support from the Chippewa County Department of Land Conservation and Forest Management, and the U.S. Geological Survey Cooperative Water Program.

Study extent

The model area, shown in figure 1, is centered on western Chippewa County and extends into parts of three adjacent counties (Barron, Dunn, and Rusk). The near-field portion of the model, for which calibration was performed, is limited to Chippewa, Barron, and Dunn Counties. Data collection efforts also extended southward into Eau Claire County.

The project focuses on western Chippewa County due to the increase in groundwater use and changes to the landscape related to industrial sand mines and irrigated agriculture. The proximity of additional groundwater withdrawals to streams and rivers poses potential challenges to water resource management. The development of a groundwater flow model requires that data collection and analysis extend to the hydraulic boundaries of the groundwater system and in many cases beyond the boundary of Chippewa County.

Scope

The study was comprised of two core components: (1) a technical investigation, which included the development of hydrologic models to estimate groundwater recharge and regional groundwater flow, and (2) a sustained outreach and reporting effort to communicate findings to the public throughout the project. A stakeholders group was formed at the onset of the project to assist and provide feedback regarding both of these components.

Technical investigation and modeling

The technical investigation consisted of several phases that included data collection and interpretation, recharge estimation, groundwater modeling, scenario testing, and identification of principles that would be transferable to groundwater studies in similar areas. The data collection and interpretation phase focused on readily available hydrologic and geologic data but also included new field measurements and observations performed specifically for this project. The recharge estimation phase applied an SWB model (Westenbroek and others, 2010) to evaluate groundwater recharge under current and future conditions. During the groundwater modeling phase, a three-dimensional steady-state model was developed for the study area and calibrated to ensure that output was consistent with observed water levels and streamflows. Results from the SWB model were incorporated into the groundwater flow model. The next phase utilized the recharge and groundwater flow models to test scenarios illustrating the potential effects of expanded industrial sand mining and irrigated agriculture on groundwater resources. The final transferability phase summarized key findings regarding potential hydrologic changes due to pumping and recharge associated with industrial sand mining and irrigated agriculture in west-central Wisconsin.

Public outreach and report

In addition to this final report, the public outreach and reporting component of the study included the development of a fact sheet (Parsen and Gotkowitz, 2013), an

Farm field and neighboring mine

Paul Juckem

interim report (Parsen and Gotkowitz, 2015), and several presentations to the general public and project stakeholders. The goal of these reports and presentations was to educate the public about Chippewa County's groundwater and surface water resources and communicate details regarding the objectives, methods, and outcomes of the study. The fact sheet was published during the early phases of the project and provided a resource for interested parties throughout the course of the five-year study period. Copies of all project-related presentations and reports are available from the WGNHS or Chippewa County Department of Land Conservation and Forest Management upon request.

Stakeholders group

The stakeholders group was formed to provide technical feedback and assist with communicating study results to their representative groups and the general public. The group included representatives from all industrial sand mining companies in the study area, local citizens, Trout Unlimited, the Wisconsin Department of Natural Resources (WDNR), and the Wisconsin Farmers Union. Stakeholders participated in regular meetings, collected and supplied data for use in the models, and provided valuable insights about industrial sand mining and agricultural practices that informed scenario testing.

Setting

Chippewa County is located in west-central Wisconsin in the Chippewa River drainage basin. Many glacial ice advances covered this area, beginning about 780,000 years ago (Syverson, 2007). The western part of the county is characterized by upland hills and ridges with relatively well-developed surface-water drainage systems. Hills and ridges are commonly forested. Land adjacent to hills and ridges consists of extensive tracts of pastureland and row crops. Sand mines and processing facilities have been constructed at several locations that were previously forested hilltops.

According to the National Climatic Data Center, the average annual precipitation in Chippewa County, as measured in Bloomer, Wis., was 31.6 inches per year (in/yr) between 1981 and 2010. For the same period, the mean annual air temperature was 43.5°F, with an average monthly maximum of 81.9°F in July and an average monthly minimum of 3.1°F in January (https://www.ncdc.noaa.gov/cdo-web/datatools/normals). Sixty two percent of annual precipitation falls between May and September with 80 percent falling between April and October.

Land use in western Chippewa County is predominately agricultural, with most activity directed toward row crops. Population centers within the study area are primarily found along the Highway 53 corridor extending from Chippewa Falls north to Bloomer, the Village of New Auburn, and Chetek (Barron County). Other outlying population centers within the study area include the villages of Colfax and Elk Mound and the unincorporated community of Sand Creek in Dunn County as well as the unincorporated communities of Albertville, Eagle Point, and Eagleton in Chippewa County. The model area encompasses six municipal groundwater supply systems; these are operated by the communities of Bloomer, Chetek, Chippewa Falls, Colfax, Lake Hallie, and New Auburn.

Objectives

Major objectives of this project are as follows:

- Develop recharge estimates and a groundwater flow model to evaluate the effects of current and future water use and land use on the hydrologic system;
- Evaluate effects of current groundwater use for frac sand mining, irrigated agriculture, and municipal supplies to water resources;
- Evaluate potential effects on water resources from future scenarios of irrigation and industrial sand production, including peak frac sand production, post-mine reclamation, and potential expansion in irrigated lands;
- Disseminate the study results to project stakeholders and the general public;
- Transfer the study results to similar geologic/hydrologic settings as appropriate.

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.[1] The Groundwater Vistas file and most MODFLOW files are available on the WGNHS website; MODFLOW files required to reproduce all simulations described in this report are available from the USGS model archive (https://doi.org/10.5066/F7TB15DB).

[1] *The Wisconsin Geological and Natural History Survey obtains its Groundwater Vistas licenses from ESI; however, several other providers also distribute the software. The WGNHS does not endorse one product over others. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.*

Acknowledgments

We are indebted to the many agencies and individuals who provided help, cooperation, and feedback on this project. Specifically, the authors thank the Chippewa County Department of Land Conservation and Forest Management for their support of this work, including Seth Ebel (now with Dane County Land and Water Resources Department), Dan Masterpole, David Nashold, Christien Huppert, Joan Schemenauer, and Jane Tetzloff-Jensen. The following people also provided valuable input: Jerry Clark of Extension Chippewa County; Mark Hazuga, Stacy Steinke, Bob Smail, Deb Dix, and Roberta Walls of the Wisconsin Department of Natural Resources; Kent Syverson and John Tinker of UW–Eau Claire; Holly Dolliver of UW–River Falls; Jim Aiken and Sara Welna of Barr Engineering; and Barry Graham of Roberts Irrigation.

Our thanks to Lee Boland, Tony Christopherson, Dave and Dan Stiehl, and Tony Pecha, who provided access to their property and wells. Steve Hilger graciously led the research team on a tour of agricultural irrigation through western Chippewa County. Bruce Brown, Andrew Chikowski, and Marty Lehman of Badger Mining Corporation provided access and assistance with measuring infiltration rates at the company's Taylor mine. Amanda Lierman and Sharon Masek of Superior Silica Sands, and Bryan Wurzer of Fred Weber Inc., provided access and assistance with measuring infiltration rates at the company's mines in Chippewa and Barron Counties. Steven Schimmel of Chippewa Sand Company provided access and assistance with measuring infiltration rates at the company's mine in Chippewa County. We also thank Chippewa Sand Company, EOG Resources, Preferred Sands, Superior Silica Sands, Taylor Creek Transit, West Wisconsin Sand Company, Great Northern Sand, Hi-Crush, and Fairmount Santrol for data sharing. Local citizens, Trout Unlimited, and the Wisconsin Farmers Union also contributed to the project. All stakeholders who served on the stakeholder advisory panel provided timely feedback and made important contributions to the study.

Pete Chase, Jake Krause, Irene Lippelt, and Pete Schoephoester, of the WGNHS, and Cheryl Buchwald, Patrick Farrel, Andrew Leaf, Josef Schuler, Zachary Vande Slunt, and Benjamin Torrison, of the U.S. Geological Survey, contributed their technical expertise to this study. Steve Mauel, of the WGNHS, compiled the well construction databases and provided technical support. Esther Stewart, WGNHS, served as technical editor, and Ken Bradbury and Dave Hart, also of the WGNHS, and Andrew Leaf, USGS, made important contributions to the manuscript review. And finally, our thanks to Caroline Rose, WGNHS, for her work improving the map figures, and to Linda Deith, WGNHS, for her attention to detail editing the manuscript.

Study methods and data sources

Review of previous studies

The initial phase of this project involved review of prior geological and hydrogeological studies conducted within the study area. Geologic mapping and research by Ostrom (1966), Ostrom and others (1970), Brown (1988), Mudrey (1987), Mudrey and others (1987), Havholm and others (1998), and Syverson and others (1998) provided a basis for interpreting the general geology of Chippewa County and neighboring areas. Pleistocene geologic maps of Chippewa County (Syverson, 2007) and Barron County (Johnson, 1986), and depth-to-bedrock maps for Wisconsin (Trotta and Cotter, 1973), Chippewa County (Lippelt, 1988), Dunn County (Lippelt and Fekete, 1988), Barron County (Zaporozec, 1987), and Eau Claire County (Johnson, 1993) provided insights into the spatial extent of bedrock and the overlying unconsolidated sediments. Land surface mapping consisted of the updated National Elevation Dataset 10-m digital elevation model (Gesch, 2007; Gesch and others, 2002).

Well construction reports

Well construction reports (WCRs) are routinely submitted to the WDNR by well drillers to satisfy Wisconsin well-drilling requirements. These records contain basic information about the well's location, date of drilling, observed water level, and construction methods (e.g., well-casing depth and diameter). They may also contain results of specific capacity testing (such as maximum observed drawdown, pumping duration, and pumping rate) and the lithology of materials encountered with depth while drilling. The location and quality of information contained in each well construction report varies depending on the thoroughness of the driller.

WGNHS retrieved and compiled a set of all available WCRs from the WDNR's water well database (WDNR, n.d.-a). Well locations were verified by WGNHS personnel and improved wherever possible, using available plat maps and parcel-address records to move locations from the center of the Public Land Survey System section to a house, barn, or other structure described by the driller. For wells within Chippewa County, the Department of Land Conservation and Forest Management had previously verified many well locations, an effort that reduced the workload for WGNHS staff. WGNHS personnel assigned a location confidence to each well record point during this location checking and improvement process (WGNHS, unpublished data).

Once well locations were improved, data contained in the WCRs were used to constrain the hydrostratigraphic interpretation and inform model parameterization. Specific capacity data were used to estimate hydraulic transmissivity (discussed in greater detail in the Groundwater Flow Model Construction section) and water-level data provided head targets for model calibration. Despite variable record quality, sometimes inadequate for use, the large sample size of available WCRs provides valuable information to model calibration at a regional scale when used with discretion.

High-capacity wells

The location and pumping rates of both public and private high-capacity wells and surface water withdrawal points were obtained from the WDNR (WDNR, n.d.-c; R.A. Smail, WDNR, oral communication, 2015). The model contains 293 high-capacity wells. High-capacity wells are defined as wells capable of pumping more than 70 gallons per minute or 100,000 gallons per day (Wis. Admin. Code § NR 812.07 (October 2016)). As with WCRs, high-capacity well locations were improved as needed; initial details for these types of wells are commonly more accurate than for the WCRs.

Geophysical logging

Modern downhole geophysical logging is an important method for understanding subsurface hydrostratigraphy. Logs typically include vertical profiles of temperature, fluid conductivity, resistivity, natural gamma radiation, and borehole diameter (caliper). Optical and acoustic borehole imaging, as well as borehole-flow measurements, provide further details about hydrogeological conditions. Seven geophysical logs were collected in or near the study area—six by WGNHS staff and one by Preferred Sands at the LaGesse Mine west of Bloomer (fig. 2 shows a sample log; appendix A provides all logs used in the study).

Geophysical logs were processed using the WellCAD software by ALT Technologies. A GIS environment using Esri ArcGIS 10.1 software was used to visualize and create model input layers from geologic maps and digital elevation models.

Interpretation of borehole geophysical logs can identify preferential flow along fractures or high-conductivity zones, and the spatial extent and thickness of aquitards (geologic formations that restrict groundwater flow) and aquifers (geologic formations that readily transmit groundwater). The high quality of geophysical logs compared to other sources of subsurface data, such as WCRs, makes them a primary source of data for subsurface characterization.

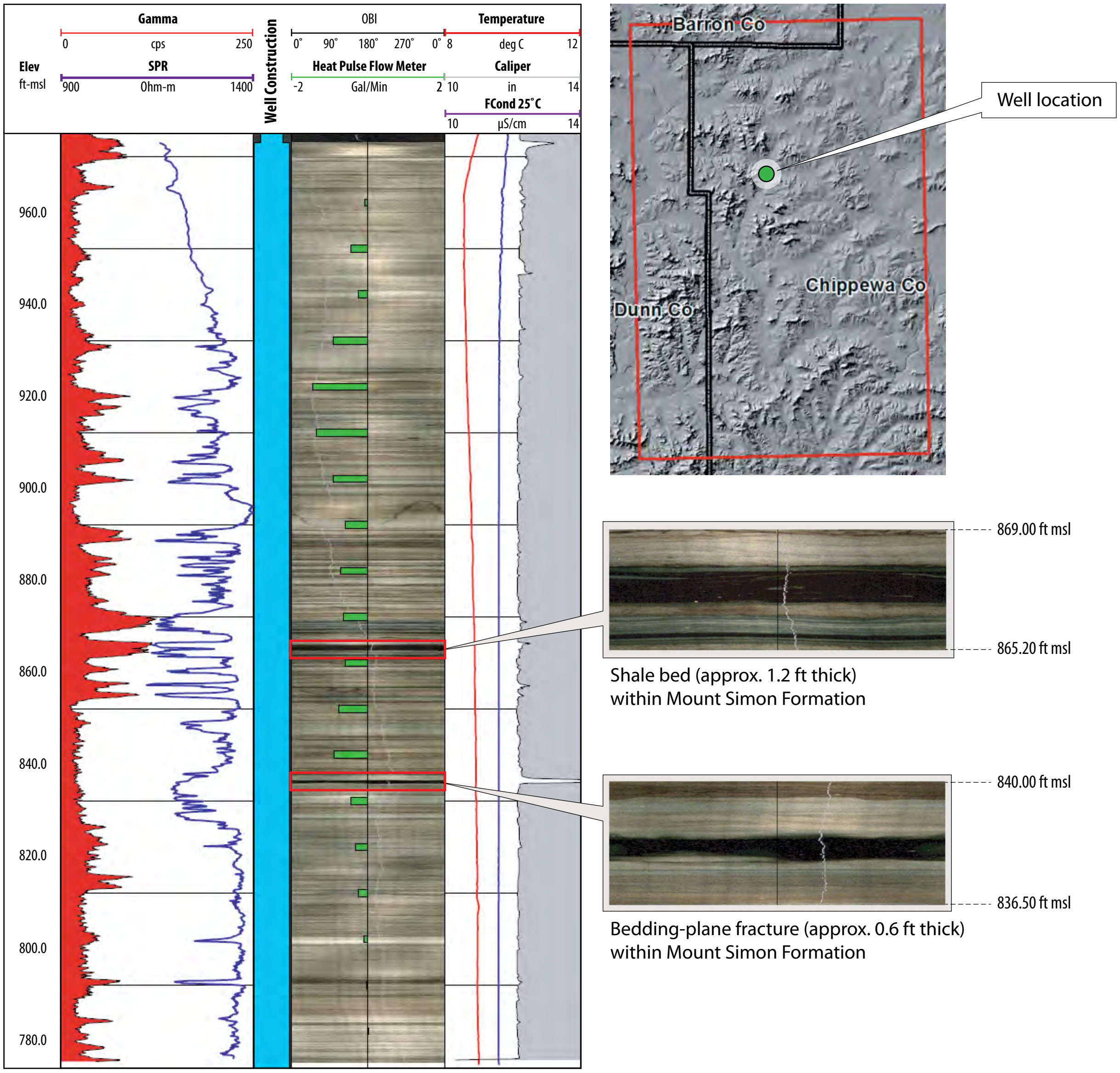


Figure 2. Example borehole geophysical log. High-resolution imagery from the optical borehole imaging (OBI) tool reveals a shale bed and a bedding-plane fracture within the Mount Simon Formation. From the Superior Silica Sands Culver mine (WGNHS ID 9000341).

Geologic outcrops

Geologic outcrop descriptions were reviewed and approximately 30 outcrops were visited throughout the study area to improve understanding of the regional geology and geologic units with potential frac sand resources. These field visits also provided a framework for hydrostratigraphic interpretation, as many geologic units that outcrop in the eastern portion of the study area are at or below the water table farther to the west. Geologic cross sections by Mudrey and others (1987) and Brown (1988) provide a generalized interpretation of the regional stratigraphy that was viewed in outcrop. Furthermore, considering that the regional strike and dip of geologic units are relatively consistent across the study area, as confirmed by geologic well logs and borehole geophysical logs, observations of relative thickness of stratigraphic units informed interpretation of the thickness of hydrostratigrahic units and ultimately model layers. At each geologic outcrop, vertical extent of stratigraphic units and elevation of stratigraphic contacts were recorded.

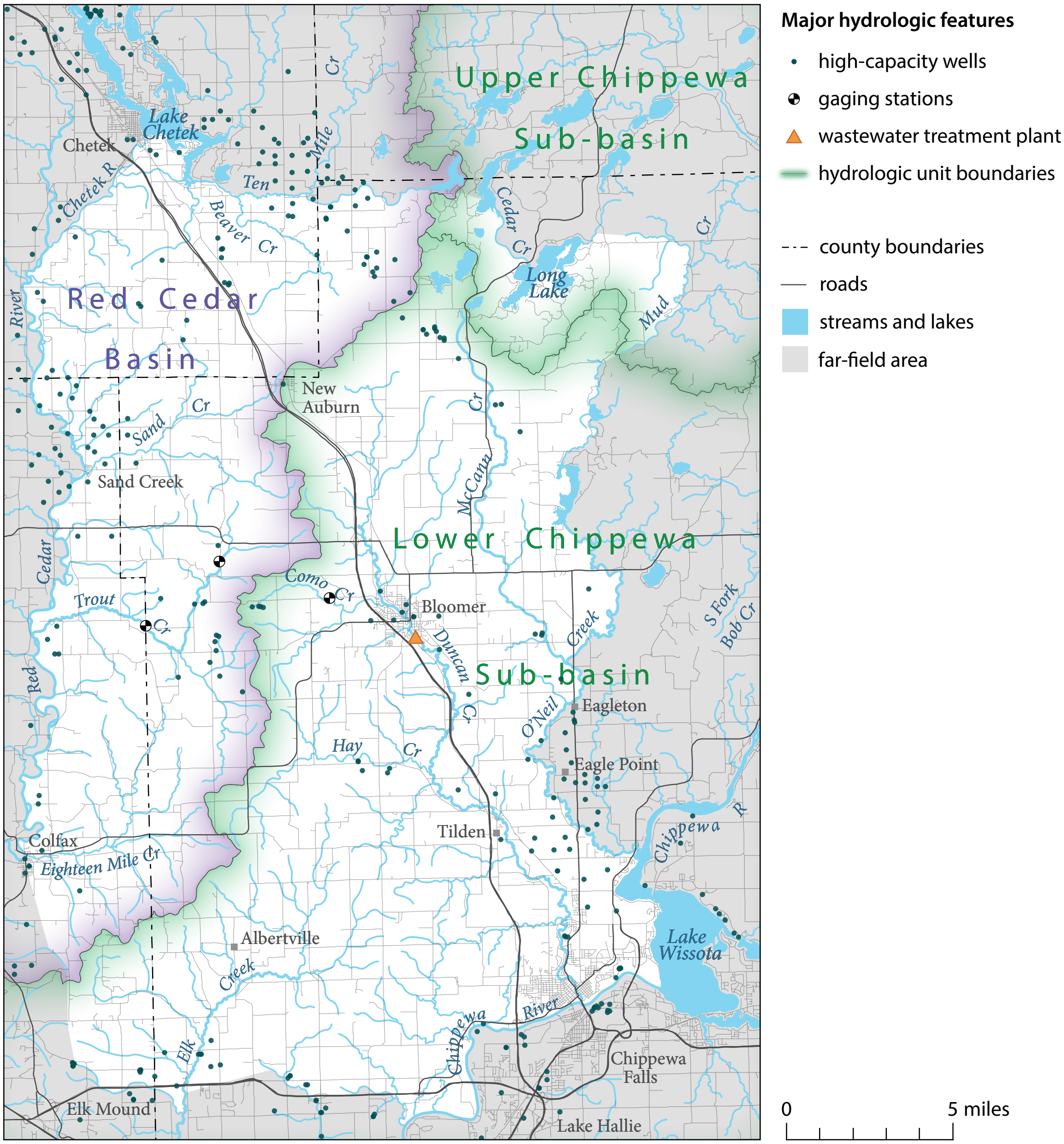


Figure 3. Major hydrologic features of the study area.

Streamflow measurements

Three continuously recording streamflow gages were installed within the study area during 2011 and 2012. The gages were installed on Como and Trout Creeks (fig. 3), west of Bloomer, to provide baseline data on streamflow, temperature, and specific conductance. Baseflow, or the portion of total streamflow that comes from groundwater discharge into streams, was estimated and used as a calibration target for each gage. The BaseFlow Index, modified method (Wahl and Wahl, 1995; Institute of Hydrology, 1980a, 1980b), was used to separate stormflows from baseflows through implementation of the USGS Groundwater Toolbox (Barlow and others, 2014) with turning-point intervals of two days for all three gages. Average baseflows from October 2011 to September 2014 were used for the Trout Creek gage at Hwy DD (site 053674962) and the Como Creek gage near Bloomer (site 05364422), and from the first full month of operation (Sept. 1, 2012) to the end of September 2014 for the Trout Creek gage at Tenth

Street (site 053674967). The 1-year period from October to September is defined by the USGS as a "water year" and is used as the annual transition in streamflow gaging and model calibration since it coincides well with baseflow conditions.

Thirty-four synoptic streamflow measurements were made in local streams throughout the study area on October 11 and 12, 2012. Synoptic measurements are collected within a short period and under specific conditions; they provide a "snapshot" of the distribution of baseflow for use as targets throughout the model domain. Long-term average baseflow was estimated for the 34 one-time measurements using a statewide multiple-regression relationship (Gebert and others, 2011) that incorporated drainage area and a baseflow factor referenced to the 90-percent flow duration (flow that is equaled or exceeded 90 percent of the time) for the Hay River gage at Wheeler (site 05368000) from October 2011 to September 2014. The Hay River gage was chosen as the reference for long-term baseflow estimation because it was active throughout the measurement period and its drainage basin shares characteristics with most of the 34 measured sites (located in areas that were glaciated prior to the Wisconsin Glaciation).

Recharge estimation

Groundwater recharge was estimated across the study area using the SWB code (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. Average annual recharge was estimated for the study area under pre-existing conditions, active mining, and reclaimed conditions. Field tests of infiltration collected in mined and reclaimed areas provided data in support of recharge estimates. These estimates were incorporated into the groundwater flow model during model calibration and subsequent scenario testing.

Hydrostratigraphy

Hydrostratigraphic interpretation was important for developing the model layering. To do so, we compiled all available geologic and hydrogeologic data, including WCRs with lithological descriptions made by drillers; geological logs of drill cuttings as described by WGNHS geologists; geophysical logs collected by WGNHS staff; outcrop descriptions; and Pleistocene, bedrock geology, and bedrock elevation maps available within the study area. Mining companies also contributed geophysical logs and geologic observations from several active industrial sand mines.

While geological contacts observed in outcrop provided a framework for the hydrostratigraphic interpretation, geophysical logs provided high quality, consistent and reliable 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 with information from WCRs and geologic logs, and existing geologic, depth-to-bedrock, and bedrock elevation maps.

Groundwater flow simulation

Groundwater flow was simulated with the USGS MODFLOW-NWT finite-difference code (Harbaugh, 2005; Niswonger and others, 2011), which uses a Newton solver to improve the handling of unconfined conditions by smoothing the transition between wet and dry conditions in model cells. The model is steady state and three-dimensional and explicitly simulates groundwater/surface-water interaction with streamflow routing. The model was calibrated using a parameter estimation code (PEST) and guidelines outlined by Doherty and Hunt (2010). Briefly, PEST performs a non-linear inversion, or history matching, by adjusting model parameters (for example, hydraulic conductivity) within predefined limits until weighted discrepancies between simulated and measured target values are minimized. Calibration targets used for history matching were heads (water levels) and streamflows. The steady-state calibration focused on the 3-year period between 2011 and 2013.

Hydrogeology of western Chippewa County

Quaternary geology and hydrostratigraphy

Depositional processes that produced spatial patterns in the texture of sedimentary bedrock and glacially modified unconsolidated sediment, commonly referred to as hydrostratigraphy, affect how groundwater flows through aquifers and aquitards in the study area. The study area lies to the north of the unglaciated Driftless Area and was therefore covered at times by glacial ice during the Pleistocene (2.6 million to 11,700 years before present). The earliest known period of glaciation in Chippewa County dates to 780,000 years ago. The Chippewa Lobe of the most recent glaciation was present in Chippewa County from approximately 24,000 to 21,500 years before present, before permanently retreating northward (Mickelson and Attig, 2017). The lobe reached its southernmost extent near the northern and eastern perimeter of the study area roughly 24,000 years before present. The core of the study area in the western uplands of Chippewa County was not glaciated during the Wisconsin Glaciation but contains both proglacial outwash from that period as well as remnant outwash deposits from earlier glaciations.

The oldest Pleistocene deposits observed in Chippewa County are lacustrine sediments of the Kinnickinnic Member of the Pierce Formation, which date to more than 780,000 years before present. Although these lacustrine deposits have not been observed at land surface, they have been identified in WCRs and are present in river valleys of the Chippewa River and Elk Creek (Syverson, 2007).

The next youngest deposits include till of the Superior and Chippewa Lobes of the River Falls Formation, which is considered to have been deposited more than 130,000 years before present (Syverson, 2007). These sediments were deposited when the glacial ice margin extended southward to southern Dunn and Eau Claire Counties, completely covering Chippewa County with ice. As the ice retreated, till and meltwater stream sediment was deposited across Chippewa County. In western Chippewa County, outwash sediment of the River Falls Formation is present at depth in valleys as well as upland areas and has been extensively weathered and eroded, abutting sandstone bedrock in areas (Syverson, 2007). The contact between outwash of the River Falls Formation and the Cambrian sandstones can be sharp in areas and hard to discern based strictly on the hillslope geometry or land surface elevation. In recent years, deposits of River Falls Formation outwash have been encountered in upland areas west of Bloomer by sand mining companies performing exploratory borings to delineate the lateral extent of Cambrian-age sandstone deposits (B.B. Kelly, Red Flint Group, oral communication, 2013).

The eastern margin of the model area is dominated by hummocky, high-relief deposits of the Chippewa moraine, which form the terminal moraine of the Chippewa Lobe within the model area (Syverson, 2007). The relief of the moraine ranges from 50 to 100 ft; it is thought that the thickness is similar to the sediment thickness that was present on the glacial surface when the moraine was originally forming (Clayton, 1967; Syverson, 2007). This moraine contains hummocks, kettles, and ice-walled-lake plains and is home to many small lakes and immature stream systems (Syverson, 2007). The Chippewa moraine is largely underlain by sediment of the Copper Falls Formation. This moraine area is largely outside the near-field of the model domain; however, it forms an important feature on the landscape and is contained within the model area.

The youngest meltwater-stream deposits within the study area are those of the Copper Falls Formation, which dominate the principal river valleys, forming broad outwash plains, and extend into tributary valleys. In the upland areas of western Chippewa County, the meanders of modern-day perennial streams are largely contained within the lateral extent of these deposits (Syverson, 2007). These meltwater-stream sediments may be up to 100-ft thick, are largely composed of sand and gravel, and serve as an important surficial aquifer for domestic and high-capacity well withdrawals in the study area (Syverson, 2007). Post-glacial stream sediments consist of silty sand, sand, and gravelly sand which can contain peat (Syverson, 2007; Johnson 1986).

The proglacial outwash of the Wisconsin Glaciation and remnant outwash deposits from earlier glaciations contain extensive surficial aquifer systems. These aquifers support groundwater withdrawals along the principal river and stream valleys within the study area.

The overall depth of Quaternary sediments varies from absent or thin cover of soil in the western Cambrian sandstone uplands to more than 350 ft along the southern margin of the study area (fig. 4). The thickest deposits are located in a deeply incised trench west of the Chippewa River in the southeast corner of the

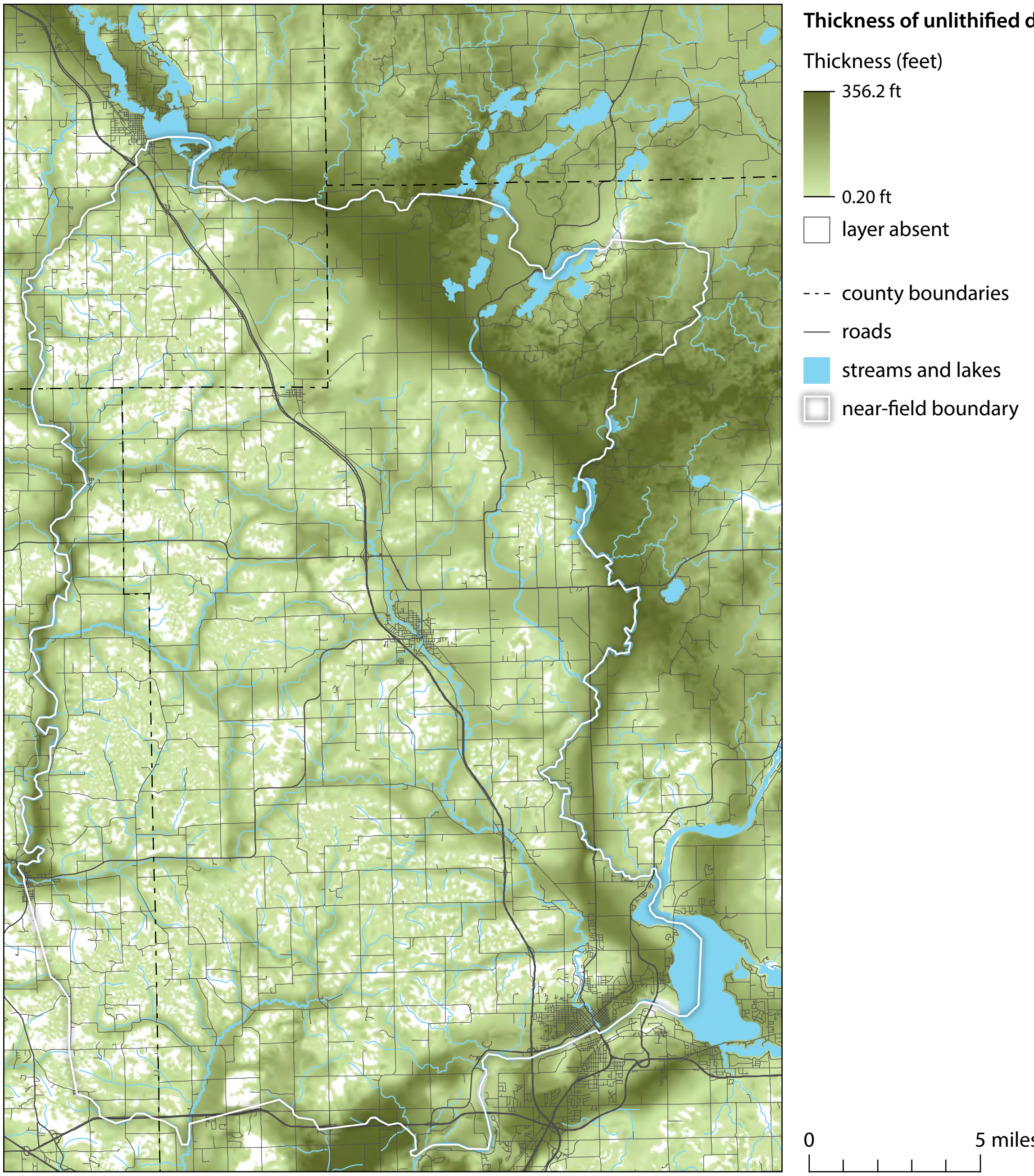


Figure 4. Thickness of unlithified deposits.

study area. Other deeply incised areas include the Red Cedar River valley and areas along the western margin of the Chippewa Moraine near the border with Barron and Rusk Counties. Lithologic information from nearly 3,900 location-verified wells within the model area and over 5,600 location-verified wells across the entire study area were used to constrain the thickness of the unlithified Quaternary deposits (fig. 4) and to estimate the top-of-bedrock surface elevation (fig. 5). The Natural Neighbor interpolation tool in ArcGIS 10.1 was used to construct a top of bedrock raster surface based on existing depth-to-bedrock maps and available geologic datasets. Contour lines representing the interpolated surface were then edited manually to incorporate geologic interpretation. The thickness of unlithified deposits was calculated by subtracting the final bedrock-surface elevations from land-surface elevations.

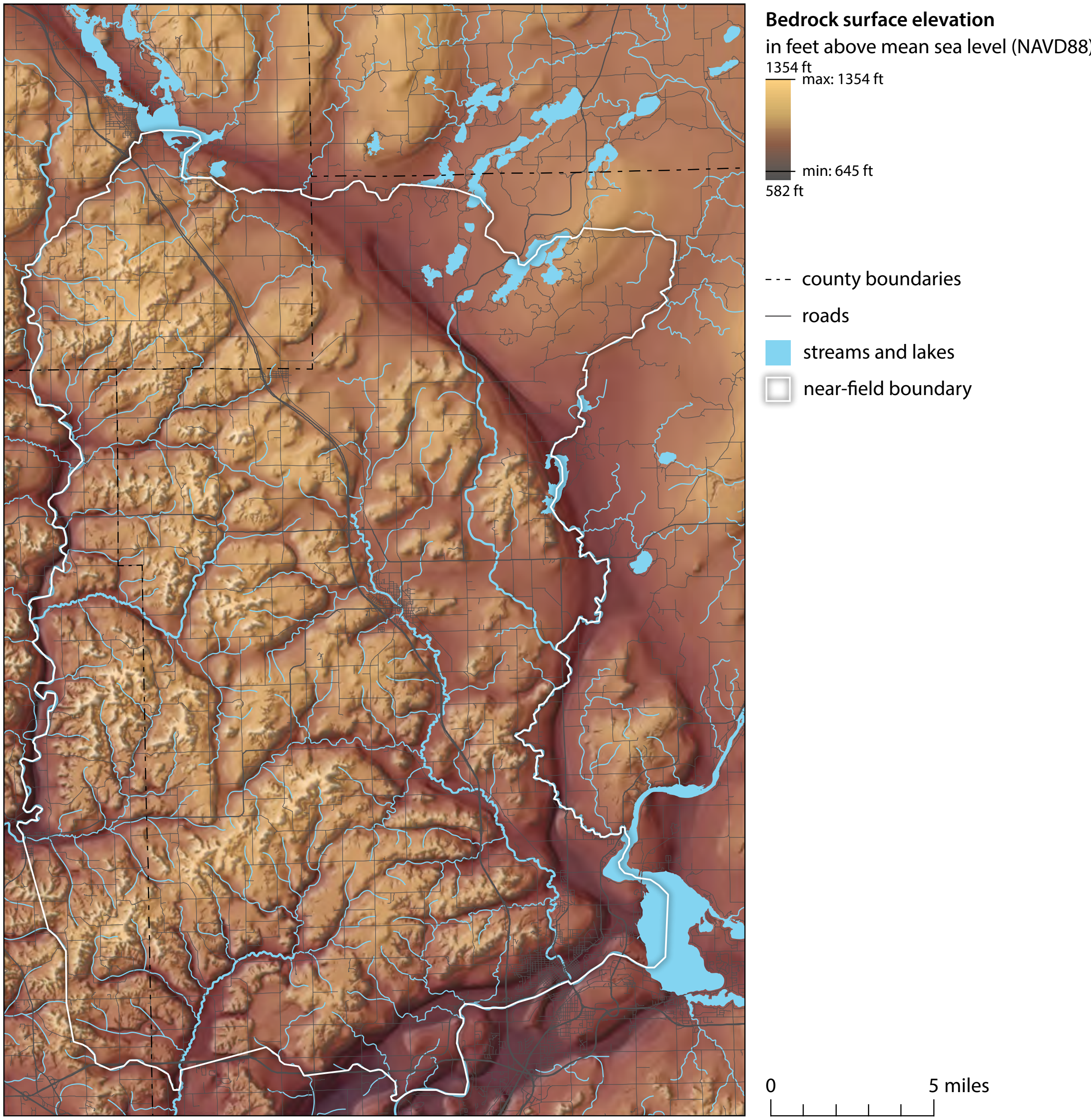


Figure 5. Bedrock surface elevation.

Bedrock geology and hydrostratigraphy

The bedrock geology of western Chippewa County and neighboring Barron, Dunn, Eau Claire, and Rusk Counties consists of Precambrian age crystalline rock overlain by a succession of younger Paleozoic age sandstone units. Ostrom (1966) describes these units in detail and more recent geologic mapping by Mudrey (1987), Mudrey and others (1987), and Brown (1988) interprets the spatial extent of these units. Investigations by Johnson (1986), Havholm (1998), and Syverson (2007) also discuss these bedrock units within the specific context of west-central Wisconsin.

Igneous and metamorphic rocks of Precambrian age represent the base of the bedrock geologic system. Across the model area, the top of the Precambrian surface ranges in elevation from roughly 580 to 1,100

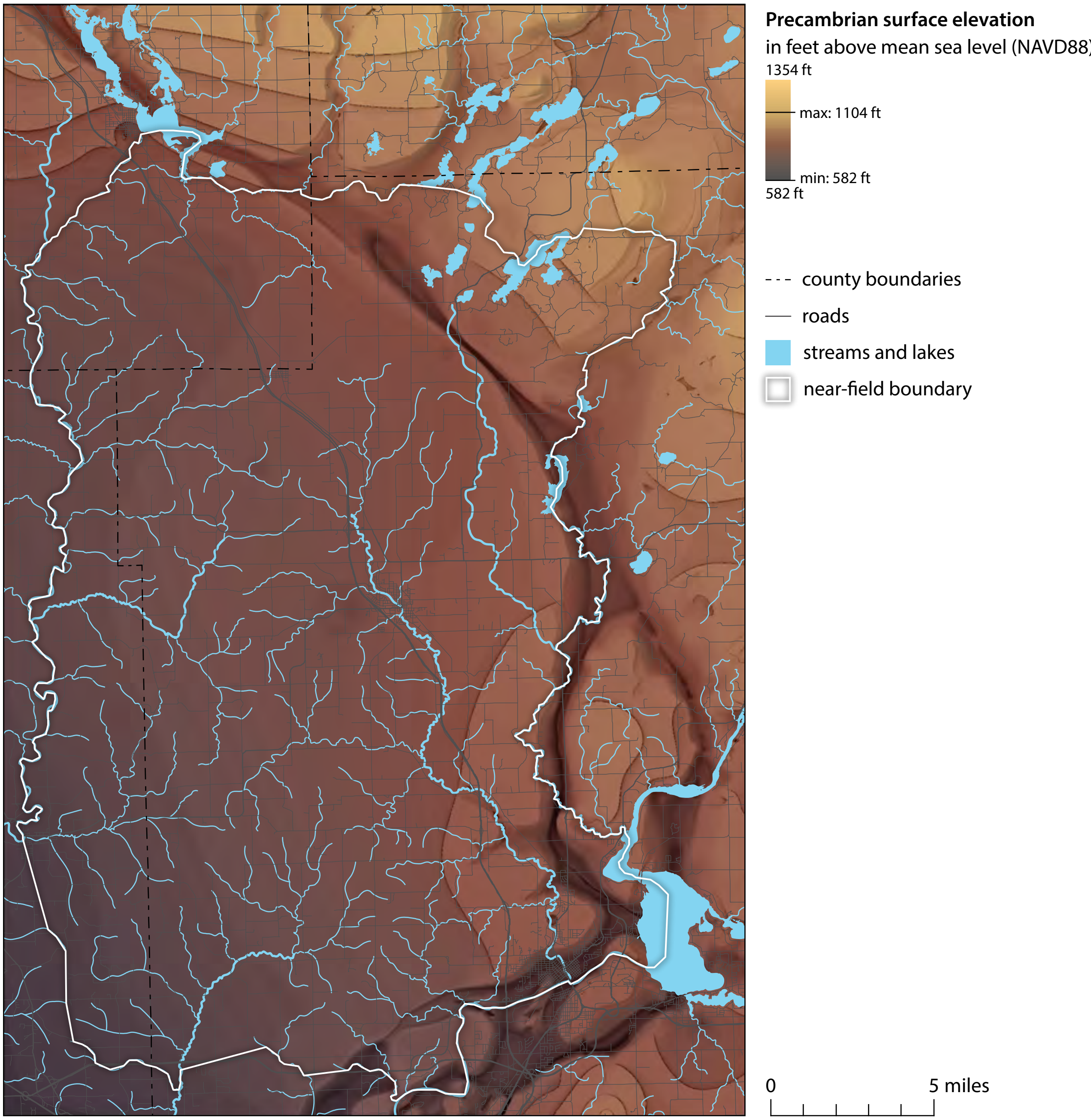


Figure 6. Precambrian surface elevation.

ft above mean sea level (fig. 6). This surface outcrops along parts of Duncan Creek and the Chippewa River near Chippewa Falls. At depth, the Precambrian surface forms the uppermost bedrock unit in areas where Paleozoic bedrock units were completely eroded away. The full extent of this deeply incised bedrock valley is observable in well records but does not consistently follow modern-day surface water features; especially in the northeastern portion of the study area where the trench runs parallel to the margin of the Chippewa moraine. The elevation of the Precambrian surface was estimated by incorporating mapped outcrops of this rock unit, along with well construction reports, geologic logs, and geophysical logs that intersected Precambrian crystalline rock. Close to 160 wells within the modeling area and 1,300 wells from across the study

Michael Parsen

area of Barron, Chippewa, Dunn, Eau Claire, and Rusk Counties intersected Precambrian rock and were used to refine the Precambrian surface elevation (fig. 6). In addition to these wells, lithologic information from roughly 3,800 location-verified wells within the model area and over 5,300 location-verified wells across the entire study area, were used to estimate the bedrock surface elevation (fig. 5) and constrain the Precambrian surface elevation. Even though most wells did not intersect Precambrian at depth, they helped constrain the maximum possible surface elevation for the Precambrian surface. In areas where Paleozoic bedrock units are eroded away, Precambrian crystalline rock forms the top-of-bedrock surface. Similar to the bedrock surface elevation, the Natural Neighbor interpolation tool in ArcGIS 10.1 was used to construct the top of Precambrian elevation surface based on the above-mentioned datasets.

In Wisconsin, the Precambrian crystalline bedrock is generally regarded as a very low-permeability environment compared to overlying sandstone formations. In the model area, the Precambrian surface is conceptualized as the base of the groundwater flow system and is represented in the groundwater model as a no-flow boundary.

Where present, Paleozoic bedrock of the Elk Mound Group overlies Precambrian crystalline rocks. All formations of the Elk Mound Group are present within the study area. From oldest to youngest, they are the Mount Simon, Eau Claire, and Wonewoc Formations.

The Mount Simon consists mainly of medium- to coarse-grained quartz-rich sandstone as well as minor amounts of pebble conglomerate and fine-grained shale-rich layers (Havholm, 1998). The Mount Simon ranges in thickness within the model area from absent within the deeply incised Precambrian bedrock valleys to roughly 250 ft in the southwest near Elk Mound, Wisconsin. Within the Red Cedar River valley, the Mount Simon Formation has been significantly incised, with as little as 50 ft of sandstone in place above Precambrian crystalline rock.

The Mount Simon is a major aquifer within this region and provides a significant supply of water to high-capacity wells used for industrial sand mining and agricultural purposes. Geophysical logs (appendix A) were used to delineate five distinct hydrostratigraphic units within the Mount Simon Formation (figs. 7 and 8): Four layers at the top and bottom of the formation (Mount Simon—I, II, IV, and V) represent aquifers and the shale-rich middle layer (Mount Simon—III) behaves as an aquitard. Hydrostratigraphic units between aquitards and aquifers were considered transitional (Mount Simon—II and V). In the groundwater flow model, the five Mount Simon hydrostratigraphic units were reduced to three model layers (fig. 7). For more on the incorporation of hydrostratigraphic layers into the MODFLOW model, see the Groundwater Flow Model Construction section.

The Mount Simon transitions upward to the Eau Claire Formation, a fine- to very fine-grained sandstone, siltstone, and shale. The Eau Claire Formation is present in outcrop as both clay drapes and laterally continuous beds (Havholm, 1998). It ranges in thickness within the model area from absent within the deeply incised Precambrian bedrock valleys to roughly 120 ft beneath upland areas in the west and southwest. Unlike the Mount Simon, the Eau Claire is completely eroded away at depth within the Red Cedar River valley as well as the valleys containing Elk, Trout, and Eighteen Mile Creeks in the western part of

General bedrock stratigraphy				Hydrostratigraphy			Groundwater flow model			
Age		Stratigraphic name								
Era	Period	Group	Formation	Units	Names	Type	Layers	Zones	Names, lithology	Type
				1	Unlithified deposits	aquifer	1	1, 2	**Unlithified deposits** (glacial and valley fill)	aquifer
Paleozoic	Cambrian	Tunnel City	Lone Rock	2	Tunnel City	n/a	2		**Upper bedrock** (sandstone: Tunnel City Group, Wonewoc Fm., upper Eau Claire Fm.)	aquifer
		Elk Mound	Wonewoc	3	Wonewoc	aquifer				
			Eau Claire	4	Eau Claire—I	aquitard	3	1, 3, 33	**Eau Claire** (shale)	aquitard
				5	Eau Claire—II	transition				
			Mount Simon	6	Mount Simon—I	aquifer	4	1, 4, 44	**Mount Simon—upper** (sandstone: lower Eau Claire Fm., upper Mount Simon Fm.)	aquifer
				7	Mount Simon—II	transition				
				8	Mount Simon—III	aquitard	5	1, 5, 55	**Mount Simon—middle** (shaley intervals)	aquitard
				9	Mount Simon—IV	aquifer	6	1, 6, 66	**Mount Simon—lower** (sandstone)	aquifer
				10	Mount Simon—V	transition				
Precambrian		Various unnamed units		No-flow boundary			No-flow boundary			

Figure 7. Bedrock stratigraphy and corresponding hydrostratigraphic units and model layers in the groundwater flow model.

the study area. Several outcrops of the Eau Claire are present within the model area, along road cuts in the Town of Tilden (Ostrom, 1988) and farther to the west near Colfax (Havholm and others, 1998) (fig. 1).

Interpretations of geophysical logs performed within the study area were used to delineate two hydrostratigraphic units within the Eau Claire (figs. 7 and 8). The lower unit was interpreted as containing interbedded sandstone and shale; it represents a transitional unit into the Eau Claire from the upper Mount Simon aquifer unit. The upper Eau Claire unit was interpreted as containing thicker and tighter shale beds, as evidenced by an elevated gamma signature and a correspondingly low resistivity signature in the geophysical logging data. These two hydrostratigraphic units were consistently present in borehole geophysical logs across the model area, suggesting that they are laterally continuous where the Eau Claire is present. The lateral extent of this shale-rich interval led to its classification as an aquitard feature in the model. Moreover, a synoptic streamflow survey found increases in baseflow to streams along most reaches, except immediately downstream of where the Eau Claire Formation was eroded away. This streamflow pattern further indicates that the Eau Claire Formation likely functions as an aquitard, resisting the downward flow of groundwater. The two hydrostratigraphic units of the Eau Claire are combined as a single layer in the groundwater flow model (fig. 7).

The Wonewoc Formation overlies the Eau Claire Formation and consists of poorly cemented fine- to coarse-grained sandstone with little to no shale layering present (Havholm, 1998). Within the model area, the Wonewoc ranges in thickness from absent within most of the perennial stream valleys to 120 ft in western upland areas. The Wonewoc is the target sandstone deposit for industrial sand mining companies within Chippewa County as its characteristics consistently meet specifications for use as a proppant in hydraulic fracturing for oil and gas outside of Wisconsin. The deposit contains a high concentration of quartz sand grains which are well rounded, highly spherical, extremely hard, and of a specific size range making them prized as a nonmetallic industrial mining resource (Parsen and Zambito,

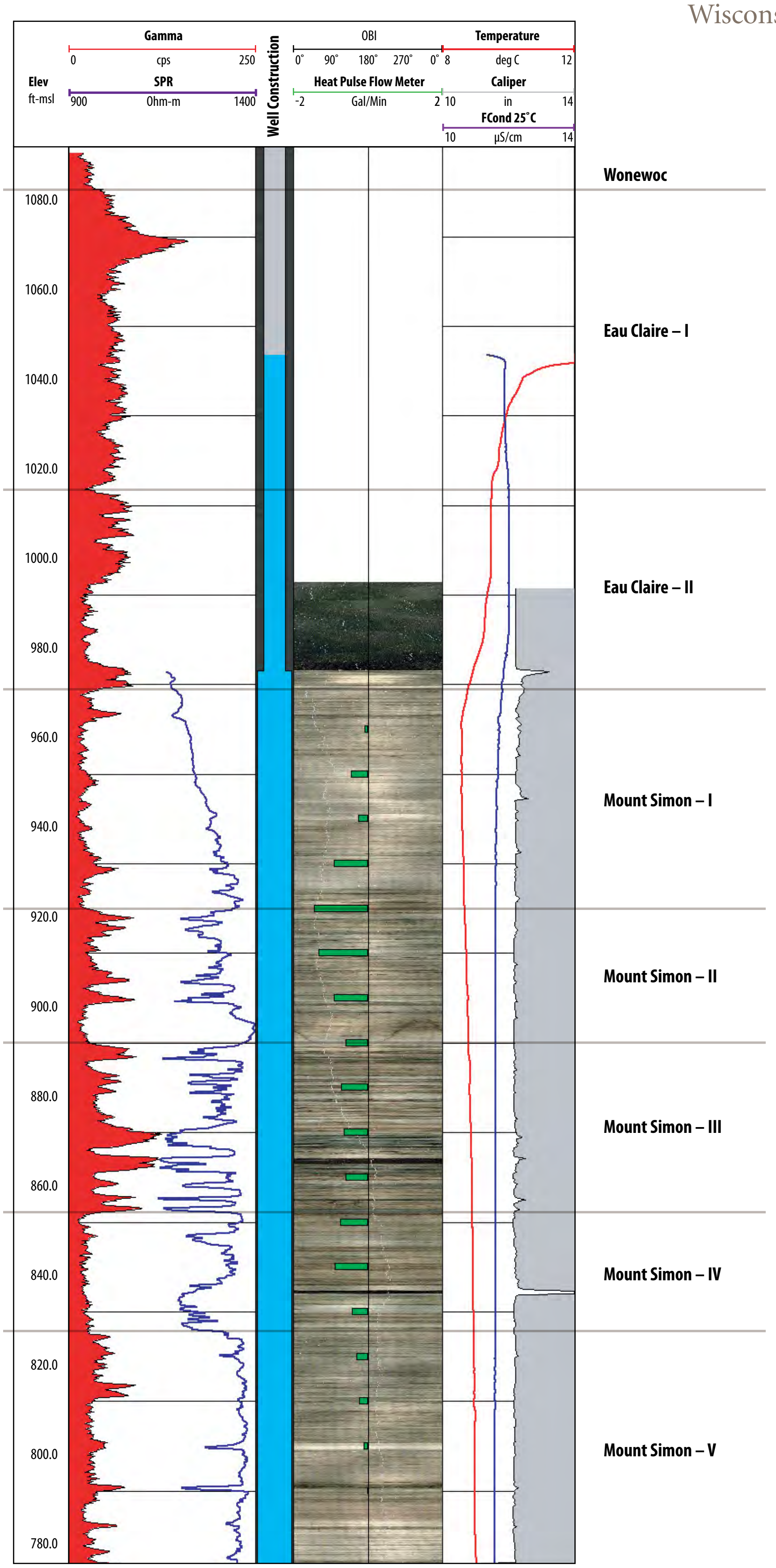


Figure 8. Hydrostratigraphic units from a borehole geophysical log. (See fig. 2 for additional information about this log.)

2014). The upward transition from the Eau Claire to the Wonewoc Formation is difficult to observe in outcrop, as it is typically located below land surface, and infrequently encountered in driller's logs, as wells are often too far from hills and ridges to intersect this contact. Recent exploratory borings by sand mining companies provide additional information about the elevation of this contact. For the purposes of this study a limited number of exploratory drilling logs were obtained from sand mining companies as this type of information is typically considered proprietary.

The Wonewoc Formation is located at or above the water table within the model area and is not considered to serve as an important groundwater resource although the lower portions of this unit can become saturated during periods of elevated groundwater levels. The hydrostratigraphic contact between the Wonewoc and Eau Claire was estimated based almost entirely on field observations in industrial sand mines, records obtained from industrial sand mining companies, and geophysical logs performed by WNGHS staff. The Wonewoc hydrostratigraphic unit includes sandstone of the upper Eau Claire Formation and is considered to be an aquifer where saturated. In the groundwater flow model, the Wonewoc hydrostratigraphic unit is combined with the overlying Tunnel City unit to form the upper bedrock model layer (fig. 7).

The Lone Rock Formation of the Tunnel City Group conformably overlies the Wonewoc Formation and consists of fine-grained glauconitic sandstone with interbedded shales (Havholm, 1998). Geologic mapping by Mudrey and others (1987) and Brown (1988) suggest that fine-grained sandstone, siltstone, and shale of the St. Lawrence as well as fine- to coarse-grained sandstone of the Jordan Formation may form a thin cap on the highest ridges in the western most parts of the model area, but these units were not observed in outcrop during this project or by Syverson (2007).

The Tunnel City hydrostratigraphic unit was not observable in geophysical logs as the unit occurs higher on the landscape than the high-capacity wells that were investigated for this study. The use of the term "hydrostratigraphic unit" to describe the Tunnel City Group may seem like a misnomer as it occurs above the water table; however, the unit exhibits a distinct lithology and is associated with discrete groundwater seeps observed at high elevations in the landscape.

The extent of the Tunnel City unit was relevant to the groundwater modeling scenario involving the progressive mining of the Wonewoc sandstone and associated removal of the overlying Tunnel City (see the industrial sand mining buildout scenario in the Scenario Testing section). The contact of the Tunnel City with the underlying Wonewoc Formation was apparent in outcrops along road cuts and within active sand mines. The distinct facies change between the fine-grained glauconitic sandstone of the Tunnel City and coarser-grained glauconite-free sandstone of the Wonewoc often forms a bench in roadside outcrops (Havholm and others, 1998) and serves as the top of the principal economic sandstone deposit in most industrial sand mines.[2]

For this study, any bedrock units overlying the Tunnel City Group were considered to have no effect on model results and therefore were not identified as a distinct hydrostratigraphic unit.

Surface-water features

Lakes and wetlands

The study area contains a number of lakes which are largely concentrated along the Chippewa moraine as well as several flowage (reservoir) lakes located along the Chippewa River and its tributaries (fig. 3). The lakes present on the moraine are often irregularly shaped, owing to the hilly topography. Many of these lakes are located along or adjacent to the far-field model boundary. The core of the near-field model area, in the older glaciated areas of west-central Chippewa County, contains only a handful of lakes that are generally shallow, marshy, and often ephemeral (Sather and Threinen, 1963).

The largest lake within the model area is Lake Wissota, located east of Chippewa Falls. The lake was formed in 1917 when a hydroelectric dam was constructed on the Chippewa River (fig. 3). Lake Wissota is a reservoir, covering an area of roughly 6,000 acres to a maximum depth of 64 ft (WDNR, n.d.-d). The upper portion of the lake extends up to Jim Falls where another dam forms Old Abe Lake, located directly east of the model area.

In the northeast corner of the model area, near Long Lake, a number of kettle lakes dot the hummocky landscape. Many of these lakes are near wetlands and connected to perennial stream systems that slowly drain this recently glaciated landscape.

To the northwest, Lake Chetek is the principal lake along a flowage above the dam at Chetek. Below the dam, these waters form the Chetek River which flows downstream to join the Red Cedar River.

Rivers and streams

The model area consists of two major watersheds: the Chippewa River basin to the east and the Red Cedar River basin to the west (fig. 3). The upland area in western Chippewa County serves as the surface-water divide separating these two basins which are characterized by meandering streams within relatively well-developed stream valleys.

The Chippewa River basin can be divided further into the upper Chippewa sub-basin to the northeast and the lower Chippewa sub-basin in the east central and southeast areas of the model domain. The principal tributaries to the Chippewa River within the study area include Duncan, McCann, and O'Neil Creeks. Duncan Creek flows from north to south and joins the Chippewa River at Chippewa Falls, incorporating flow from Como Creek near Bloomer and from Hay Creek near Tilden. South-flowing McCann Creek is located several miles to the east of Duncan Creek and joins O'Neil Creek east of Bloomer. O'Neil Creek continues southward before flowing into the Chippewa River at Lake Wissota. Elk Creek, located in the southern part of the study area, joins the Chippewa River south of the model area. Within the upper Chippewa sub-basin, Mud Creek drains water east, while Cedar Creek flows west through Long Lake and then north through McCann Lake before discharging to the Chippewa River.

Within the model area, the principal tributaries to the Red Cedar River are the Chetek River, Trout Creek, Sand Creek, and Eighteen Mile Creek. The Chetek River is fed by water emanating from the Lake Chetek flowage system which includes significant contributions from Ten Mile Creek

[2] The Tunnel City sandstone was mined by some industrial sand mining operations within the study area due to the suitability of this sand for livestock bedding as well as a fine-grained industrial proppant following additional processing to remove undesirable fines such as glauconite (D.J. Masterpole, Chippewa County, oral communication, 2013).

and Beaver Creek. Sand, Trout, and Eighteen Mile Creeks each receive contributions from smaller perennial feeder streams that flow out of the upland areas of western Chippewa County. These high-gradient groundwater-fed streams provide a steady supply of clean, cool water throughout the year, support high-quality stream habitat, and are home to many Class 1 and Class 2 trout streams.[3]

The thickness of unconsolidated sediments beneath streams varies significantly within the study area. Unconsolidated material below upstream reaches of tributary streams (such as Como, Duncan, Eighteen Mile, Elk, Hay, McCann, Sand, and Trout Creeks) are typically on the order of 50–100 ft thick (fig. 4). Farther downstream, Duncan, Elk, and Sand Creeks are underlain by upwards of 200 ft of unconsolidated sediment. Beneath the Chippewa River, O'Neil Creek, and the Red Cedar River, these deposits can exceed 200–300 ft. The thick unconsolidated sediments within these incised bedrock valleys are commonly used to supply irrigation water, and have aided development of one of the densest irrigation districts in the state over the past several decades (R.A. Smail, WDNR, oral communication, 2014).

Water use

Groundwater pumped from aquifers in western Chippewa County is used primarily for agricultural irrigation, public water supply, industrial processing (including for industrial sand), and to a lesser extent for dairy operation, electrical generation, domestic consumption, and other activities. Well pumping for domestic consumption and other non-intensive uses is below the 70 gallons-per-minute threshold for high-capacity wells, is often obtained from relatively shallow aquifers, and, in unsewered areas, the water is returned to the local groundwater system via on-site septic systems. As a result, domestic wells generally have a minor effect on regional groundwater flow systems and were not considered for this study. Conversely, high-capacity wells that are permitted to pump more than 70 gallons-per-minute for irrigation, public supply, and industrial uses are often drilled deeper into groundwater systems. Moreover, discharge from municipal and industrial supply wells is typically returned to surface water following wastewater treatment; only a percentage of the water pumped for irrigation is returned to the water table through re-infiltration. Therefore, water use in this study focused on high-capacity pumping wells.

The combined average annual withdrawal of groundwater for irrigation, public supply, and industrial use in the study area totaled about 3.12 billion gallons per year between 2011 and 2013. As shown in figure 9, during 2011–2013, most high-capacity withdrawal in the study area was for agricultural irrigation (71 percent), followed by public water supply (21 percent) and industrial uses (6 percent). Most of the water pumped in 2013


Center-pivot irrigation

Jerry Clark

[3] *Class 1 trout streams are defined as waters that have sufficient natural reproduction to sustain wild trout populations without the need for stocking of hatchery trout, while Class 2 trout streams require stocking to maintain sufficient sport fishery trout populations but exhibit good survival and carryover of adult trout (WDNR website).*

(86 percent) was withdrawn during the summer growing season of June, July, August, and September (fig. 10). This seasonality was driven primarily by agricultural irrigation, although all water-use categories exhibited some seasonal variability. Seasonal increases in withdrawal can amplify the effect of pumping on the groundwater flow system and related stream baseflows, especially when pumping is coincident with a drought. For this study of long-term average conditions and scenario testing, annual pumping from 2011 to 2013 (fig. 11) was simulated in the groundwater flow models.

While the 3.12 billion gallons of average annual withdrawal between 2011 and 2013 represents less than 2 percent of all groundwater moving through the study area, the effect of groundwater pumping is best understood in terms of how such withdrawals reduce natural discharge to springs, streams, or lakes; a process often referred to as capture (Winter and others, 1998; Alley and others, 1999; Barlow and Leake, 2012). Thus, effects of potential future high-capacity pumping, as described in the Scenario Testing section, focused on the percent change in baseflow along river segments associated with various scenarios.

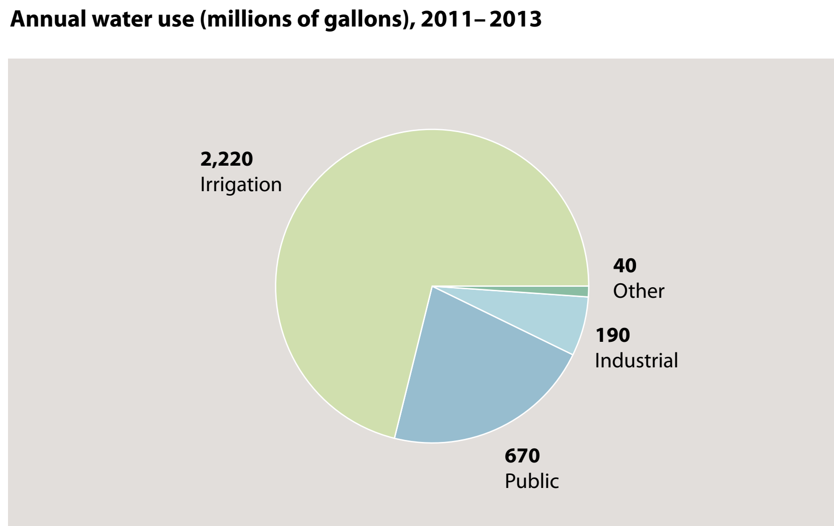


Figure 9. Average annual groundwater withdrawal from high-capacity wells, 2011–2013.

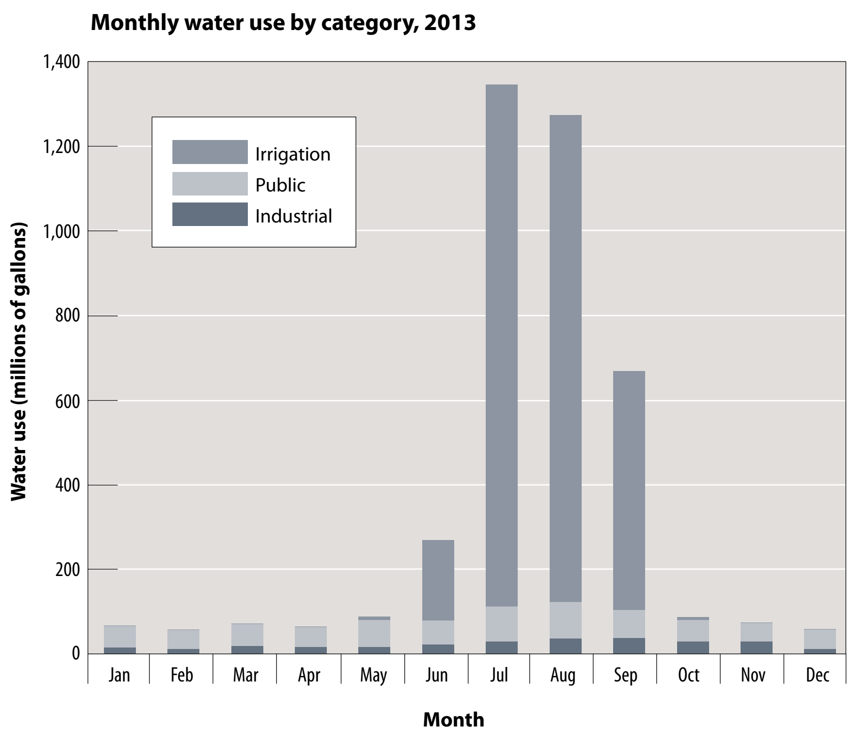


Figure 10. Monthly water use, 2013.

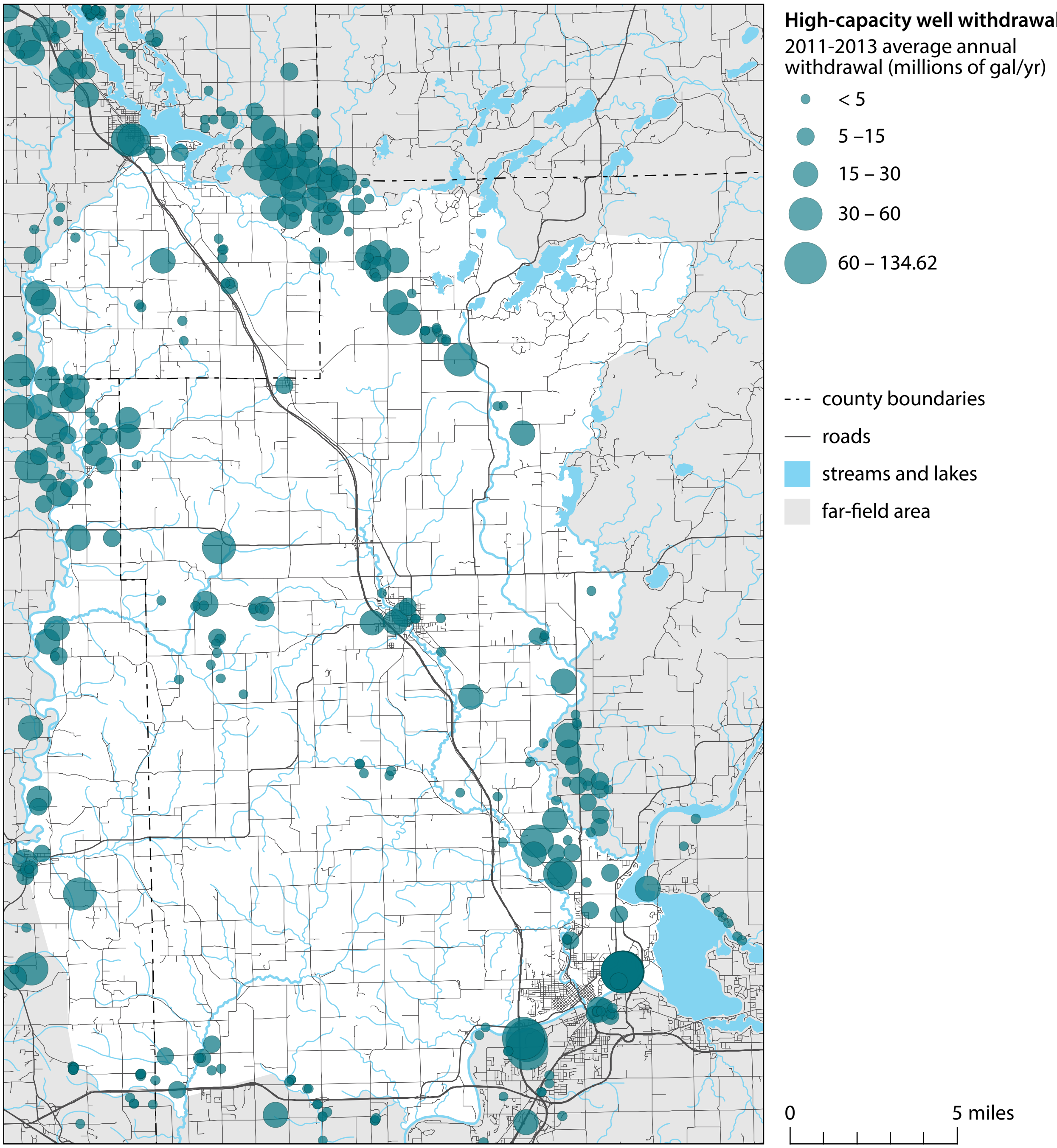


Figure 11. Average annual groundwater withdrawal from high-capacity wells, by location, 2011–2013.

Conceptualization of the groundwater system

Construction of a groundwater flow model starts with the development of a conceptual understanding of how groundwater flows through the hydrostratigraphic system (aquifers and aquitards) as well as how groundwater interacts with water sources and sinks (such as surface-water bodies and wells). A simplified hydrostratigraphic cross section (fig. 12) was used to develop the conceptual model for the study area. Groundwater/surface-water interactions were expected to occur mostly within shallow unconsolidated sediments that fill bedrock valleys in the western part of the study area and within thick glacial sediments in the eastern part of the study area.

Groundwater flows through two primary aquifer types in the study area—surficial unconsolidated sediment and sedimentary bedrock. Although the entire study area was glaciated by older, pre-Wisconsin glaciations, the western upland area was not covered by ice during the most recent Wisconsin Glaciation and retains large bluffs of Cambrian sandstone that protrude hundreds of feet above streams (Attig and others, 2011). The eastern part of the study area exhibits glacial features, such as a north–south trending deep buried valley adjacent to the Chippewa moraine and predominately gently rolling topography at the land surface, with hummocky terrain and numerous lakes that formed on top of the Chippewa moraine. These glacial deposits serve as the primary aquifer where sedimentary bedrock is thin or absent, though the permeability of the glacial sediments is highly variable.

In the western portion of the study area, sedimentary bedrock units act as major aquifers. These Cambrian-aged units consist of alternating layers of sandstones and shales that dip slightly toward the southwest. Several of the upper bedrock units, including the Wonewoc Formation, the primary source rock for industrial silica sand production, are only present within ridges that rise above the local stream elevation. As a result, the hydraulic connection of any groundwater within these upper bedrock units to streams is complex because local and ephemeral perched water tables and related seeps along the slopes may occur. Conceptually, if saturated conditions exist within the Wonewoc or other overlying stratigraphic horizons, downward gradients will result in flow into underlying bedrock units or adjacent glacial deposits before discharging to streams. This phenomenon was observed at a location within the study area, with small seeps emanating from the Tunnel City sandstone within an incised valley. The water infiltrated into the soil and colluvium before reaching the headwaters of the nearby perennial stream.

In the western upland bedrock areas, the water table is generally located near the base of the Wonewoc and the top of the Eau Claire sandstone. Groundwater in the Eau Claire and underlying Mount Simon sandstones is conceptualized to flow primarily horizontally until reaching an eroded valley filled with unconsolidated material where the water can discharge to a regional hydrologic feature such as a perennial river. Indeed, although there is about 300 ft of vertical topographic relief in the study area, groundwater flow is predominately horizontal because the aquifers cover hundreds of square miles and streams (where most groundwater discharges) are commonly miles apart.

Sources of water to the aquifers include areally extensive recharge at the water table and local exchange between streams and the aquifers. Sinks of groundwater from the aquifers include discharge to streams and wells. The streams continually transport water out of the study area, thus their water levels strongly influence the water table in their local vicinity. For example, the Red Cedar River serves as a hydraulic boundary along the western edge of the groundwater flow model because groundwater flowing from east and west of the river discharges into it. Groundwater also is withdrawn by wells for industrial, agricultural, domestic, and municipal use. High-capacity wells withdraw water from both the glacial deposits and sedimentary bedrock. Crystalline bedrock (for example, granite) that underlies the sedimentary bedrock yields little water to wells and forms a lower boundary to the groundwater flow system. In addition, groundwater flows within these aquifers cross the perimeter of the study area.

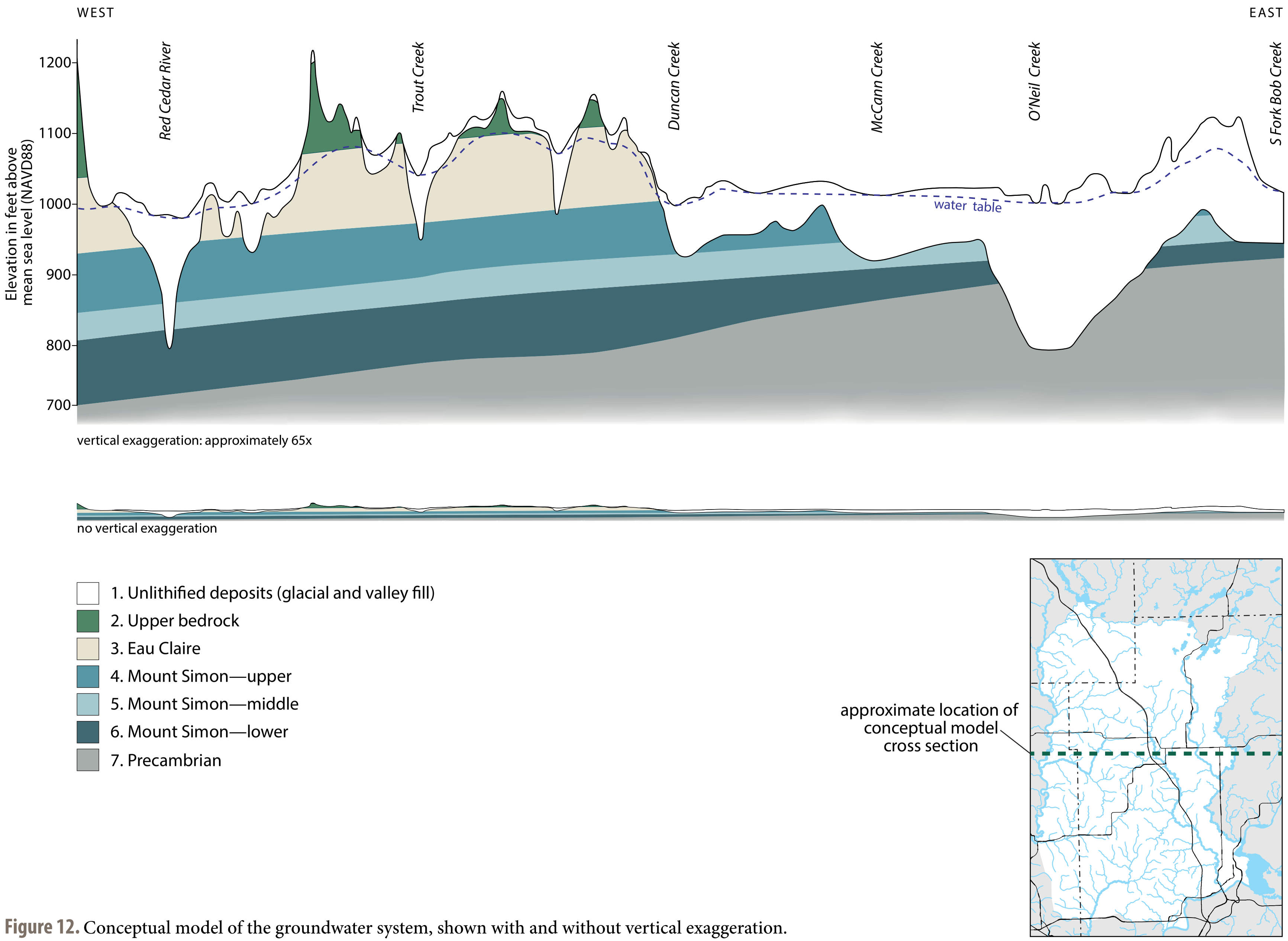


Figure 12. Conceptual model of the groundwater system, shown with and without vertical exaggeration.

Infiltration and recharge

Groundwater recharge is water that reaches the water table and becomes part of the groundwater flow system. Estimates of recharge are an important step in developing a groundwater flow model because recharge is the primary source of water to the groundwater system.

Recharge is difficult to measure directly because it varies spatially (due to changes in soil, vegetation, and topography) and temporally (due to daily and seasonal differences in climate). An alternative to measuring recharge to the water table is to model infiltration of precipitation through soil. One can then assume that deep infiltration, or water that passes through the root zone, flows through the unsaturated zone (the vadose zone) to reach the water table. This is a reasonable assumption for the Chippewa County area, where climatic conditions are typical of the humid Upper Midwest and evaporation is relatively low, and where the water table is generally close to land surface.

We selected the SWB computer code (Westenbroek and others, 2010) to estimate recharge across the study area. This method provides estimates of deep infiltration based on precipitation, which varies over time, and soil type and land use, which vary spatially across the landscape.

The SWB model applies a mass-balance approach, meaning that all precipitation that reaches the land surface is accounted for. The model tracks diversions of precipitation prior to it reaching the water table by accounting for four physical processes:

1. Interception of water by the plant canopy,
2. Runoff that flows across the land surface,
3. Evapotranspiration of water through evaporation or use by plants, and
4. Soil moisture capacity, the amount of water that may be retained in soil pores.

The SWB model applies GIS computer techniques to overlay a grid of cells on digital maps of soil, land use, and topography. The model calculates a value of recharge at a daily time step in each model cell:

Recharge = precipitation – interception – runoff – evapotranspiration – change in soil moisture storage

In a cell with no available soil moisture storage, excess precipitation (that is, precipitation that is not intercepted, evapotranspired, or stored in soil pores) is routed to the adjacent downstream cell as runoff. The runoff may infiltrate or transpire in this cell or continue as runoff to the next downstream cell. This determination is made on the basis of available soil-moisture capacity in each cell. Precipitation and temperature are input to the model as daily time steps. Temperature is tracked over time to determine periods of snowfall and frozen ground, both of which decrease infiltration. The model uses the daily temperature record to calculate the rate of water use by plants. Westenbroek and others (2010) provide additional detail.

One challenge in use of the SWB model is developing a conceptual model for estimating recharge in active areas of industrial sand mines, and in mined areas that have undergone reclamation. The following aspects of mine development, operation, and reclamation planning were considered in this effort:

- Soil structure is altered during excavation, storage, and eventual replacement of soil in reclaimed areas.
- During active mining, exposed bedrock and heavily trafficked and compacted areas can generate large volumes of stormwater runoff, diverting precipitation that might otherwise recharge groundwater.
- As portions of the mine footprint are reclaimed, drainage and infiltration will increase over time as plants are established and roots, worms, and other biological activity lead to development of soil structure and macropores.

Field infiltration tests (described below), conducted in 2014 and 2015, informed this conceptual model of recharge in active and reclaimed areas. The use of the SWB model to estimate changes in recharge related to mining and reclamation are based in part on results of infiltration tests.

Data sources

The SWB model used the following data sets:

- Daily climate conditions. Precipitation and temperature records were available from Bloomer, Wisconsin; missing climate records were supplemented with those available from Eau Claire, Wisconsin (Menne and others, 2012).
- Topographic data. Topographic data is used to route runoff. To achieve reasonable model computation times, the updated 30-m digital elevation model was obtained from the National Elevation Dataset (Gesch, 2007; Gesch and others, 2002). Its spatial resolution is approximately 98 ft.
- Soil characteristics. The soil hydrologic group and the available water storage values came from the Soil Survey Geographic Database (SSURGO) provided by the Natural Resources Conservation Service (2013).
- Land-use data. Land use is needed to calculate interception, runoff, evapotranspiration, and root zone depth. This model used the 2006 National Land Cover Database (U.S. Geological Survey, 2011).

Field investigation of infiltration rates

Infiltration rates were measured during the summer and fall of 2014 and 2015 in Barron, Chippewa, and Jackson Counties (fig. 13). The sites were selected to encompass a variety of land-use conditions including unmined forest, warm-weather native prairie, cool-weather bromegrasses, and agricultural fields. In areas subject to mining activity, three testing environments were used: an active excavation of the target sand, areas previously mined and used at the time of the field investigation for staging equipment and stockpiling sand, and reclaimed areas of various ages.

With the exception of the reclaimed mine sites (described below), infiltration test sites were selected within the study area. Many of the tests on agricultural, forested, and grassland/prairie lands were completed at the Superior Silica Sands Culver mine in Chippewa County, but were sited at locations that had not been mined. A total of seven tests were completed at three forested locations, five tests were completed at three sites planted to restored prairie or grassland, and eight tests were conducted at four agricultural fields planted in corn, soybeans, or alfalfa.

Field investigations at an active mine were facilitated by the Chippewa Sand Company, which provided access to their mine in Chippewa County. Seven infiltration measurements were completed within an active sand excavation area. At the time of testing, this area was covered by 1–2 ft of loose, disturbed Wonewoc Formation sandstone. Although excavation was extensive, there appeared to have been limited use of heavy equipment, and the sand at the surface was not noticeably compacted. Additional tests completed at the Chippewa Sand Company mine targeted areas of the facility that were used to stockpile sand and stage equipment. These areas had been mined in previous years and appeared to be heavily compacted. Two infiltration tests each were conducted at two of these staging areas.

Field investigations also included work at two reclaimed mines. The Badger Mining Corporation's Taylor mine in Jackson County, located south of the study area, was selected

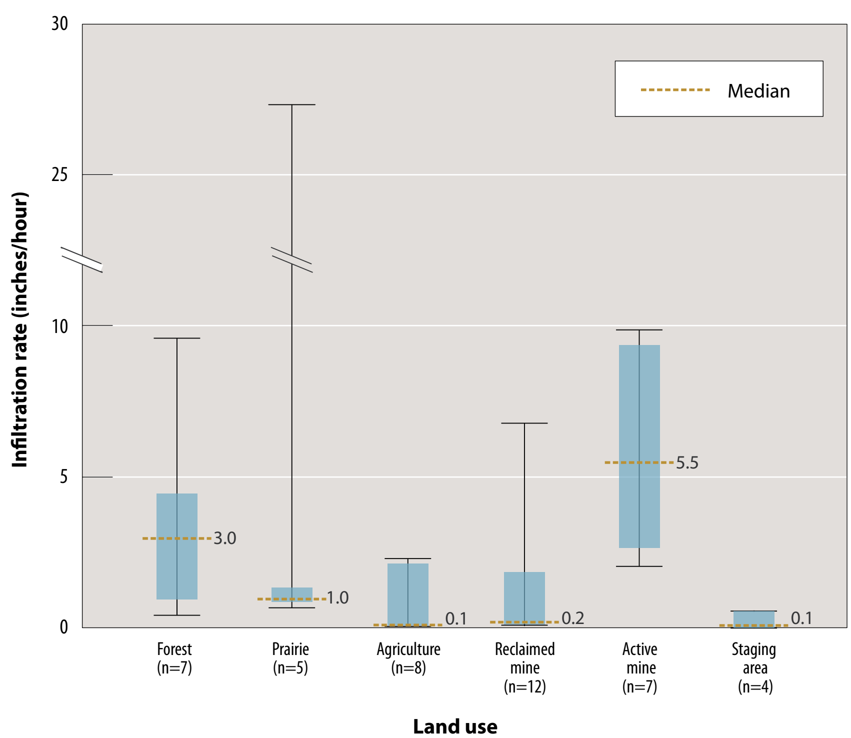


Figure 13. Infiltration rate, by land use. Vertical lines ("whiskers") show minimum and maximum values, boxes show upper and lower quartiles, and dashed lines show medians.

because it included areas that had been in reclamation for up to 30 years. A total of 10 tests were completed at five reclaimed areas within the Taylor mine. The plantings at these five locations were less than 1, 2, 12, 20, and 30 years old. The Superior Silica Sands Thompson mine in Barron County was also made available for infiltration tests on a reclaimed area. Reclamation and seeding had been established for less than a year at this facility. Two tests were completed at this reclaimed area.

The Taylor mine reclaimed areas were planted with native warm-weather prairie grass mixtures, except for plots that were less than one year post-reclamation activity. The newly reclaimed fields, which included one at the Taylor mine and one at the Thompson mine, were planted in an oats-dominated cover crop. The oats are planted initially to reduce erosion and to facilitate establishment of prairie plants in following years, after which the oats are naturally replaced by prairie plants.

A double-ring infiltrometer was used to measure infiltration rather than a percolation (or perc) test. The infiltrometer was preferred because it reduces soil disturbance and can accommodate infiltration through macropores, such as wormholes or channels from decayed plants. In contrast, a perc test requires augering or digging a hole for infiltration, which disturbs the soil structure. Each test was initiated by hammering a 12-inch diameter inner ring and a 24-inch diameter outer ring at least an inch into the soil to ensure a tight seal. Each ring was then filled with enough water to cover the soil. The time required for the water level to decline over ¼-inch increments was recorded, with additional water added as necessary to maintain standing water above the soil. For sloped sites, this required frequent refilling to maintain water at the highest ¼-inch interval so that up-slope soils remained saturated. As water infiltrated into the ground from the two concentric rings, water from the outer ring prevented the subsurface horizontal flow of water from the inner ring. This ensured that measurements made from the inner ring represented vertical, one-dimensional infiltration. During most tests, water level decline in the inner ring was monitored over several decline/refill cycles until the infiltration rate dropped to a constant value. The exception to this was at sites with very slow infiltration, where the water level decline was monitored for a minimum of 2 hours and the change in water level was measured with a tape if it had declined less than ¼ inch.

Infiltration rates varied from less than 1 in/hr to more than 26 in/hr. The range of results within each land use is displayed in figure 13. Outliers, values that exceed 1.5 times the upper quartile of the range of measurements, reflect heterogeneity in the soil or surficial material in each setting. While double-ring infiltrometers sample a larger area than methods such as the perc test, the measurement still represents a relatively small portion of the land surface and macropores within the ring can dominate a measurement. The single highest value, 26.3 in/hr, is attributed to such a macropore at one of the prairie sites. While this measurement is a statistical outlier, it illustrates the high potential infiltration rate provided by well-developed, undisturbed soils.

The forest, prairie, and active mine excavation areas had median values of 3.0, 1.0, and 5.5 in/hr, respectively, an order of magnitude larger than those in agricultural, reclaimed, and staging areas (0.1, 0.2, and 0.1 in/hr, respectively). Low infiltration rates in the agricultural setting are attributed to soil compaction that results from modern cultivation practices (Hamza and Anderson, 2005). All four of the infiltration rates measured in the staging areas were very low and were likely a result of compaction by heavy equipment used in mining operations.

Infiltration rates relative to the age of plantings in reclaimed mining areas are illustrated in figure 14. The two locations tested in each age of planting area were in good agreement, and infiltration rates generally increased with the age of the reclaimed area. This is attributed to macropore development over time as plantings mature; however, differences in soil texture may also affect infiltration in each area. These results inform the conceptualization of recharge under future mining conditions, as more land is reclaimed following excavation.

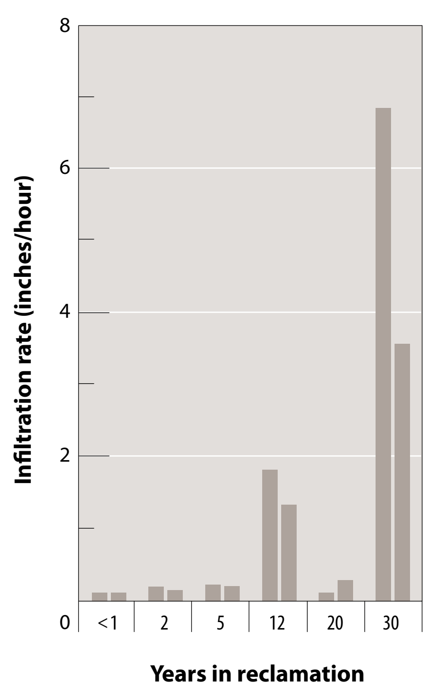


Figure 14. Infiltration rate, by years in reclamation (Jackson County sites).

Soil-water-balance model implementation

The SWB model was used in two distinct modes for this project. It was applied to the entire study area to evaluate recharge from 1950 to 2015. This characterized recharge patterns in the region under a variety of climate patterns and allowed the determination of a "typical" recharge year for input into the groundwater model. The SWB model was also used to assess potential changes to infiltration and groundwater recharge as active mining and reclamation activities take place in areas permitted for these activities. These results were incorporated into the future industrial sand mining buildout scenario.

Results

Recharge in the study area prior to mine development

A 66-year period, 1950–2015, was simulated with the SWB model. This extended time period provides insight into recharge over the study area under a variety of climate patterns. During this period, total annual precipitation in Bloomer averaged 31.3 inches, ranging from a minimum of 16.9 to a maximum of 44.6 inches (fig. 15). The average annual groundwater recharge during this time period, averaged over the study area, ranged from 2.4 to 15.2 inches with an average of 8.3 inches.

The SWB simulation over this period illustrates the relationship between climate and recharge. Figure 15 shows an increase in recharge in 2001 and 2002, coincident with high precipitation from 2000 to 2002. Relatively dry conditions experienced in 1987–1989 resulted in several low-recharge years. The timing and intensity of precipitation also affect recharge, affecting runoff, infiltration, and evapotranspiration. For example, August rainfall on growing crops, under relatively high summer temperatures, will be subject to more evapotranspiration than October rainfall on bare fallow land. These effects are simulated in the SWB model and can be seen in figure 16, which shows the relationship between precipitation and estimated recharge. Although recharge generally increases with annual precipitation, the scatter along the best-fit line illustrates that recharge

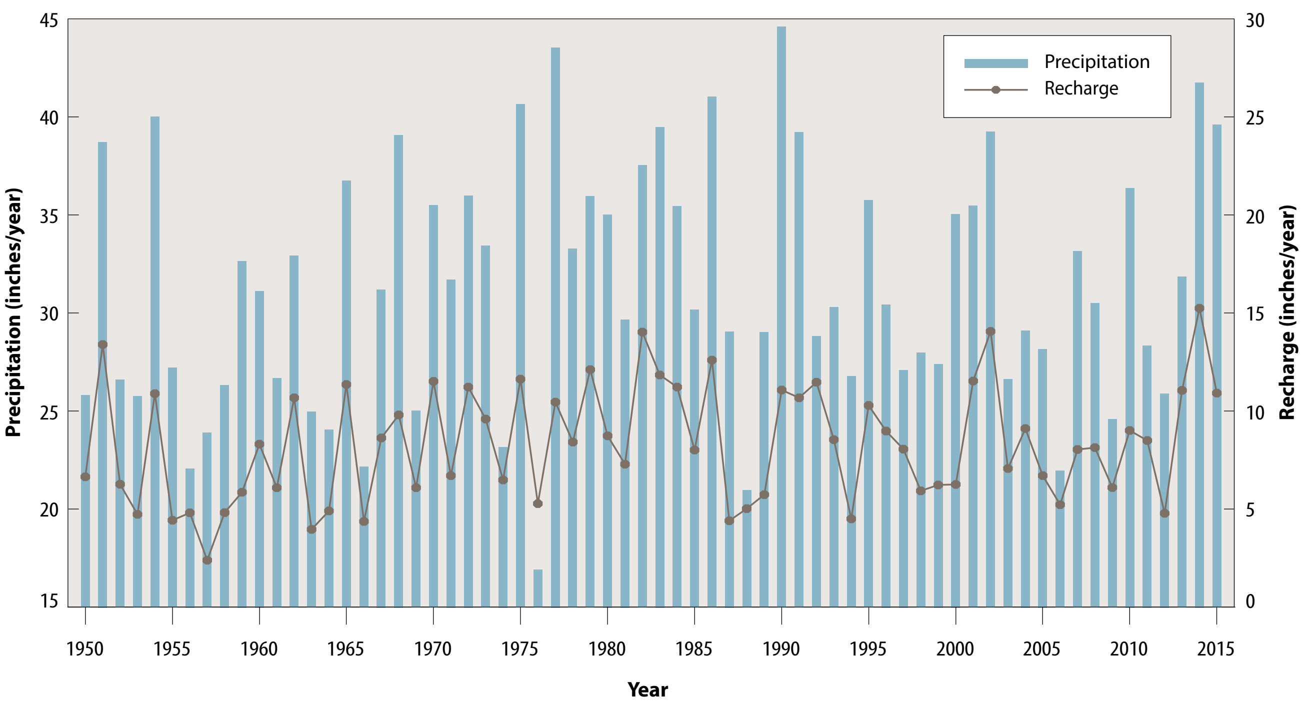


Figure 15. Precipitation and SWB-estimated recharge for study area, 1950–2015.

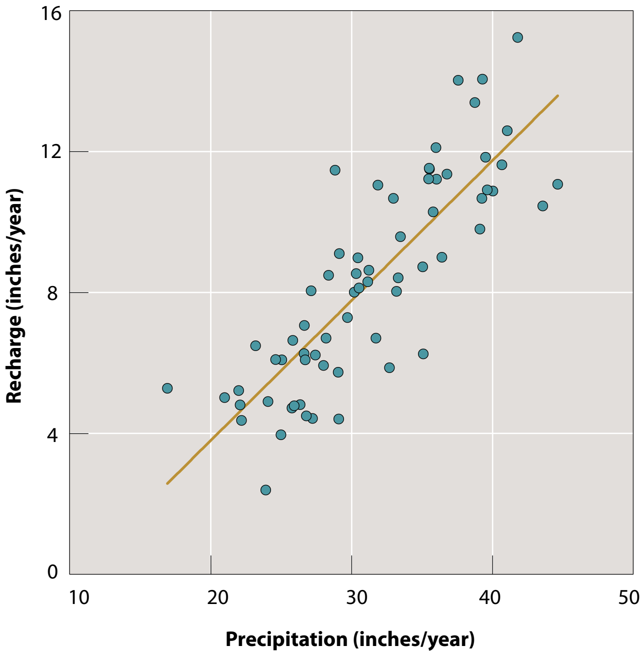


Figure 16. Annual precipitation and SWB-estimated recharge for study area.

varies somewhat in years of similar total precipitation. For example, at an annual precipitation rate of 30 in/yr, estimated recharge over the study area varies from about 7.5 to 9 inches. The variation in estimated recharge is related to several factors, including antecedent soil moisture, the extent of frozen ground during spring snowmelt, the magnitude of individual rainstorms, and temperatures during the growing season.

Deep infiltration, or recharge, varies spatially across the study area, as illustrated in figure 17. This map shows SWB-simulated recharge in 1993, during which precipitation and recharge approximated long-term average conditions. These conditions represent a typical recharge year in the study area and were incorporated into the groundwater flow model. (For more about the model's recharge component, refer to the Groundwater Flow Model Construction section.) Under these conditions, estimated recharge varies by about 12 inches across the region. Climate patterns during other years result in different recharge estimates, but the overall pattern across the landscape is similar to that shown in figure 17.

Spatial variation in recharge reflects soil type (sandy soils lead to increased infiltration compared to soil with more silt or clay) and land use (forested land generally allows higher infiltration compared to cropped land or urban areas) across the study area. Areas of open water are labeled as undefined in figure 17. These areas are hydrologically complex, and the SWB model is not well-suited to estimate recharge patterns at lakes and streams. In arid regions, surface water is more likely to lose water to underlying groundwater systems. In the humid conditions prevalent in Wisconsin and the Upper Midwest, low-lying lakes and streams are generally areas of groundwater discharge to surface water.

Soil type and land use affect groundwater recharge, and this is reflected in estimates from the SWB model. SWB results at 12 specific locations within the study area are illustrated in figure 18 for dry (1994), average (1993), and wet (2002) years. Although these 12 sites were selected for evaluation and comparison because they are permitted for mining, or had applied for a mining permit, these results estimate recharge prior to mining activity. This was done to illustrate spatial and temporal differences across the study area under long-term climate patterns and existing land uses. Recharge varies at each site from year to year by more than 10 inches due to climatic conditions. For example, at Preferred Sands LaGesse mine, the SWB model simulates recharge of 6.0 inches in a dry year and 17.6 inches in a wet year. Soil at the Mine 2 site (referred to as such because the site was not permitted at the time of evaluation) is less permeable than soil at the LaGesse property. Thus, recharge is lower at Mine 2 under each weather pattern, ranging from 4.0 to 13.0 inches.

Recharge estimated at actively mined and reclaimed areas

Use of the SWB model included assessment of potential changes in recharge for the industrial mine build-out scenario (for more details about the scenario, refer to the Scenario Testing section). The conceptual model incorporates observations of conditions at operating facilities and results of the infiltration tests. This section also describes implementation of the conceptual model in the SWB model.

The SWB model was configured to estimate recharge at permitted mines during operation and at two stages of reclamation, referred to as "early" and "mature." These three phases were informed by visual inspection of runoff during and after large rainfall events, and from the infiltration measurements described above.

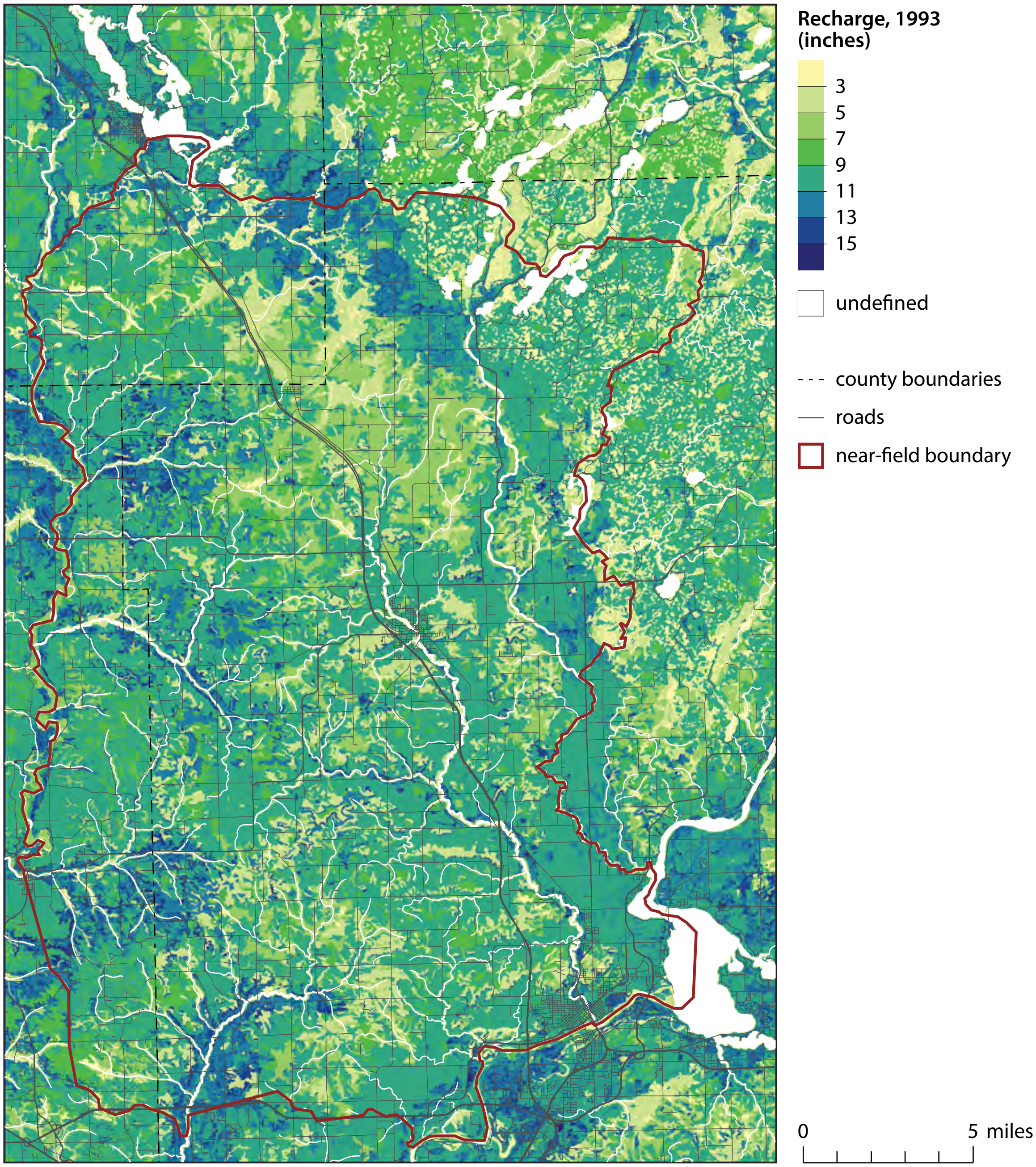


Figure 17. Recharge estimated with SWB model, 1993.

At any given time, operational mines have limited exposures of quarry floor and active excavation areas. Large portions of the permitted area are used for stockpiling excavated material, staging equipment, and driving heavy equipment to excavate and transport material. Such areas have very low infiltration rates. Thus, operational mine footprints are dominated by compaction with little infiltration capacity, and precipitation generally ponds or runs off of these areas via stormwater control features.

Following the operational phase, there are two phases of reclamation. Infiltration measurements indicated that during the early years of reclamation plantings, infiltration rates are similar to those found in row crop agriculture. Rates tend to be higher on undisturbed reclaimed soils after approximately 10 years of prairie soil development. This timing is similar to observations from research on redevelopment of soil structure following disturbance in the Driftless Area (Knighton, 1970). Therefore, after 10 years, it was assumed that reclaimed areas would have developed more

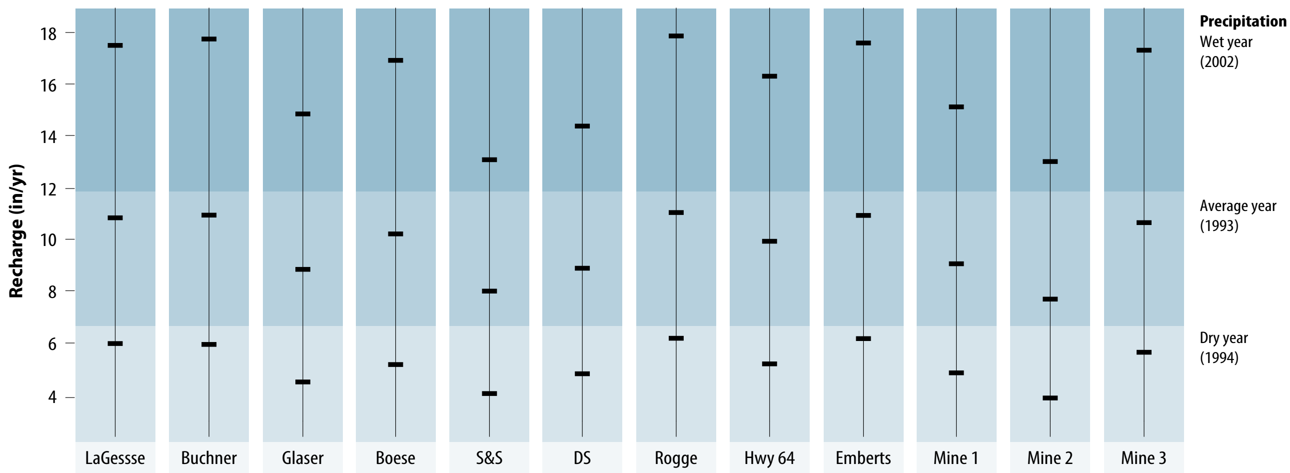


Figure 18. SWB-estimated recharge during wet, average, and dry years at 12 mine sites under pre-mining land use. Example shows differences from site to site and from year to year.

infiltration capacity, similar to that of prairie and grassland or forested settings. This approach was also based off of established reclamation plans for most mines that have been permitted in the study area, which reference grassland or prairie as the intended reclaimed land cover type (D.J. Masterpole, Chippewa County, written communication, Nov. 3, 2017). Reclamation to other land covers or more intensive land uses could deviate from the assumptions of high infiltration rates approximately a decade after reclamation, thereby potentially reducing anticipated recharge rates.

This conceptual model was implemented in the SWB model by adjusting the maximum daily infiltration rates applied in the model. The maximum infiltration rate, expressed in in/day, is the model's upper limit on potential recharge at the daily time step; it represents the maximum amount of infiltrating water that can exit the base of each SWB cell and enter the groundwater system in a day. The spatial scale simulated in the SWB model is much larger than the area tested by the double-ring infiltrometer, and this accounts for the difference between the measured rate (in/hour) and that applied by the model for a daily time step.

Reducing the maximum daily infiltration rate in the SWB limits simulated recharge in cases where there is excess water in a model cell. The SWB model is typically implemented with the maximum infiltration rate determined by the soil type. This is reasonable because soil hydrologic classification is related to permeability (Cronshey and others, 1986). The maximum infiltration rates used in SWB for the historical evaluation of pre-existing conditions (1950–2015) vary with the soil hydrologic class (that is, A, B, C, or D) assigned in the soil survey and range from 2.0 to 0.12 in/day (table 1). For active mining operations and reclaimed land uses, maximum infiltration rates in SWB were changed to evaluate new recharge patterns. Land under active mining was assigned a maximum infiltration rate of 0.12 in/day, regardless of the pre-existing hydrologic class. This is appropriate because staging areas and roadways extend over large areas of the operational area, and soil is removed prior to mining, exposing bare quarry floor or highly compacted surficial material. Low infiltration rates measured in staging areas further support the low rate set for active mining. For the early reclamation stage, applied to the first 10 years of reclamation activity, potential infiltration is limited to 0.42 in/day. This rate falls within the measured values and is about midway

Table 1. Maximum infiltration rates for simulating mined and reclaimed areas.

Development stage	Reference land use	Soil hydrologic class	Max. infiltration (inches/day)
Pre-existing conditions	Pre-existing	A	2.00
		B	0.60
		C	0.24
		D	0.12
Active mining	Quarry	—	0.12
Early reclamation	Cultivated crops	—	0.42
Mature reclamation	Grassland	—	1.30

Table 2. Successive land use over 30 years showing percent difference in recharge. Recharge differences of less than 100 percent indicate a decrease in estimated recharge compared to original land use; differences greater than 100 indicate an increase.

	Land use, difference from average recharge estimate (%)					
Years	Parcel 1		Parcel 2		Parcel 3	
1–5	Active mining	38	Pre-existing conditions	99	Pre-existing conditions	101
6–10	Early reclamation	94	Active mining	38	Pre-existing conditions	102
11–15	Early reclamation	94	Early reclamation	95	Active mining	40
16–20	Mature reclamation	123	Early reclamation	95	Early reclamation	106
21–25	Mature reclamation	122	Mature reclamation	125	Early reclamation	107
26–30	Mature reclamation	122	Mature reclamation	124	Mature reclamation	140

between the maximum values applied to hydrologic classes B and C in the evaluation of pre-existing conditions. Land in reclamation for more than 10 years is considered mature and is assigned a maximum potential infiltration rate of 1.3 in/day (midway between the maximum values applied to hydrologic classes A and B). This is consistent with the increase in measured infiltration at some of the older reclaimed areas.

Application of the SWB model to characterize recharge during mining and reclamation required rotating parcels of land through stages of land use, from existing conditions to active mining, early reclamation and mature reclamation. The Chippewa County Department of Land Conservation and Forest Management provided a map of permitted and proposed permits as of 2013. A portion of the study area that encompasses all of those sites was selected for further evaluation. This significantly shortened computational run time of the SWB model and was instrumental to the development and testing of this approach.

The land use rotation was implemented by identifying parcels ranging from 50 to 100 acres within each permitted area. One parcel in each permitted area was assigned a mining condition for a 5-year period, resulting in a mining rate of 10–20 acres/year. Each parcel at a permitted area advanced through 5 years of mining to 10 years of early reclamation followed by 5–15 years of mature reclamation, as shown in table 2. This succession resulted in a 30-year simulation period consisting of six 5-year periods. One 5-year climate record was selected and repeatedly applied during the 30-year SWB run, effectively holding climate steady so that the progressive change in land use at permitted sites dominated this evaluation. The 1995–1999 climate record, reported in table 3, was selected for this because it falls within the 25th and 75th percentile of annual recharge estimated from 1950 to 2015 (fig. 15). Thus, the repeated climate record does not include extremely high or low estimates of recharge.

The SWB estimates under the 30-year progression, applying the infiltration rates in table 1, show a decrease in recharge followed by a rebound after land goes into reclamation. As shown in table 2, recharge decreases to about 40 percent of the estimate of pre-existing conditions within the actively mined parcel. Results show that the adjacent portions of the permitted area that remain in the prior land use are affected to a slight degree. As reclamation progresses, recharge returns to about 95–105 percent of historic values. This results from applying a maximum infiltration rate to the early reclaimed phase that is similar to that of cultivated crops. Finally, under mature reclamation conditions, the SWB results indicate that recharge may increase by about 20–40 percent above land use for pre-existing conditions. The simulated increase in recharge occurs because the conceptual model implemented in SWB reflects the infiltration rates measured in mature reclaimed areas (fig. 14).

The results presented here for changes in recharge under mining operations and reclaimed conditions reflect changes that occur over approximately 50- to 100-acre parcels. The groundwater system underlying each parcel is a small portion of the entire aquifer extent within a watershed. The estimated effect of changes in recharge at a permitted facility presented in this section are limited to the mined footprint. Potential changes at the watershed

Table 3. Precipitation and recharge values, 1995–1999.

Year	Precipitation (inches/year)	Recharge (inches/year)
1995	35.8	10.3
1996	30.5	9.0
1997	27.1	8.1
1998	28.0	5.9
1999	27.4	6.2

scale are evaluated below, in the Scenario Testing section describing the sand mining buildout scenario.

Limitations of recharge estimates

The SWB model has several limitations, briefly summarized here. Hart and others (2012) provide more details about these aspects of SWB.

One limitation concerns the accuracy of SWB estimates, which are affected by the uncertainty and resolution of the information supplied to the model. For example, the model uses a daily precipitation amount to calculate a daily recharge value. Thus, the model does not differentiate between a 2-inch rainfall that occurs over a 15-hour period and a 2-inch rainfall that occurs in 2 hours. In reality, runoff would be greater in the 2-hour duration storm than the 15-hour storm.

A second limitation was the inability to verify the SWB model, due in part to the difficulty in directly measuring recharge. This limitation was tempered somewhat during development of the regional groundwater flow model, because SWB recharge estimates were adjusted during model calibration to match stream baseflow targets. The same fractional adjustment was applied to SWB results for mine operation and reclamation conditions. Furthermore, the limitation of directly measuring recharge was mitigated by using field infiltration measurements to inform the SWB model. Although a total of 43 measurements were collected with the double-ring infiltrometer, the variability and heterogeneity within each land use may not be fully characterized due to the relatively small number of tests (4–12) in each category and the relatively small test area associated with this method.

The SWB model was limited in application where runoff flowed into model cells containing closed depressions in the digital elevation model. Including such closed depressions in the model could lead to erroneously high recharge estimates because the model cannot route runoff out of such low areas, nor does the SWB model simulate ponding of surface water in these areas. In applying the SWB model to the study area, this problem was overcome by altering the digital elevation model to eliminate closed depressions. Thus, runoff was routed continuously along a flow path until it reached a cell with some soil moisture capacity or until it reached a surface water body that accepted the runoff.

A further simplification applied in the SWB model related to land use in the study area. Although the simulated climate conditions spanned from 1950 to 2015, land use was held constant over this 66-year period to represent conditions described in the 2006 National Land Cover Database (2011). This was a reasonable assumption for this area because of limited growth in urban areas across this region.

Groundwater flow model construction

Construction of the three-dimensional MODFLOW groundwater flow model involved generating input arrays (gridded data) that represent recharge to the aquifers, hydraulic conductivity of the aquifers, top and bottom elevations of each model layer, groundwater withdrawal by wells, mapping curvilinear rivers onto square model cells, and developing perimeter boundary conditions. The model design was built upon the conceptual model shown in figure 12, with details of the construction process described here.

All of the files necessary to run the final models (including scenarios) are publicly available from an online model archive available at https://doi.org/10.5066/F7TB15DB (Juckem and others, 2019).

Numerical simulation methods

In addition to the SWB model described below in the Recharge section, two groundwater flow models were constructed for this study: the primary MODFLOW model, and a secondary large-scale two-dimensional analytic element model (GFLOW; Haitjema, 1995). This secondary GFLOW model was developed to produce hydraulic boundaries for the perimeter of the more detailed, three-dimensional MODFLOW model that was used for the scenario simulations described later in the Scenario Testing section. A complete description of the analytic-element method is beyond the scope of this report, but Strack (1989) and Haitjema (1995) have written detailed descriptions of the method. Hydraulic boundaries (specified flow) for the MODFLOW model were extracted from the GFLOW model using methods described by Hunt and others (1998a, 1998b).

GFLOW

The GFLOW model (fig. 19) was constructed by including features (streams, recharge, hydraulic conductivity) that affect groundwater flow as mathematical elements or strings of elements in the model.

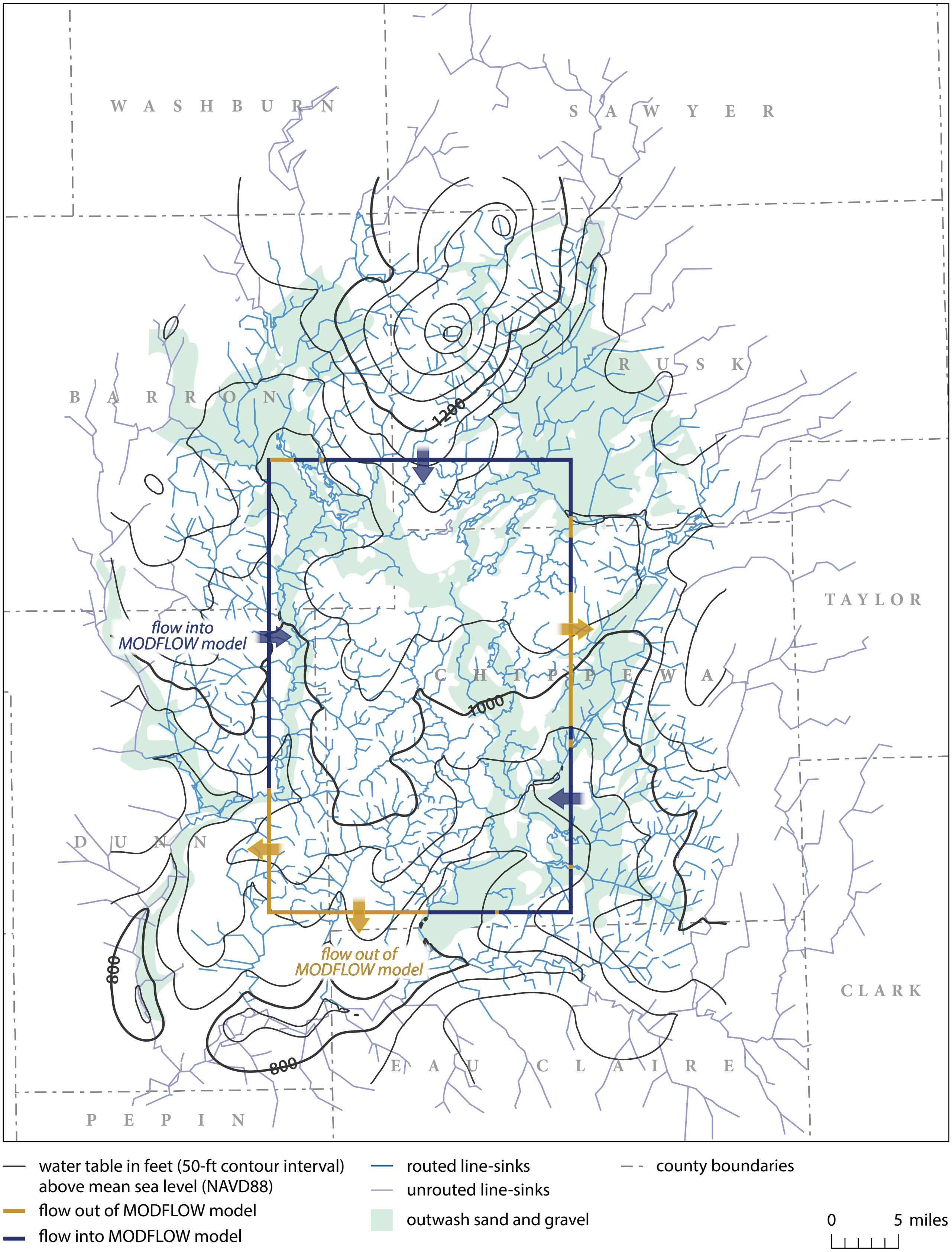


Figure 19. GFLOW model line-sinks showing direction of groundwater flow across model boundaries.

Each element was represented by an analytic solution, with the effects of these solutions added together using super-position to arrive at a two-dimensional, steady-state solution for the groundwater flow system. The geometry of the single-layer GFLOW model included a uniform bottom elevation of 450 ft above NAVD88 and an upper boundary simulated as the water table for an unconfined aquifer representing all glacial and sandstone aquifers. Streams were simulated using line-sinks. All line-sinks within about 3 miles of the MODFLOW model domain were routed, meaning that any loss of streamflow to the underlying aquifer was limited to upstream simulated baseflow. These routed line-sinks were simulated with a streambed resistance of 2.2 days (1-ft-thick sediment with a hydraulic conductivity of 0.45 ft/day) and widths ranging from about 5 to 350 ft. (For an expanded discussion of simulation methods and terminology, refer to Haitjema, 1995.) No high-capacity pumping wells were simulated with the GFLOW model as this well withdrawal was anticipated to have a relatively minor effect on regional groundwater flow direction compared to groundwater discharge to streams.

The calibrated GFLOW model had a uniform recharge rate of 9.2 in/yr, a hydraulic conductivity of 8.2 ft/day across most of the model domain, and a hydraulic conductivity of 46 ft/day in areas mapped as glacial sand and gravel deposits by Goebel and others (1983). Calibration targets included water levels and stream baseflows developed for the MODFLOW model; they are described fully in the Parameter Estimation section. While the GFLOW model was used only to provide hydraulic boundaries for the MODFLOW model, the model simulated heads and baseflows reasonably close to measured values. The GFLOW model was calibrated prior to the MODFLOW model, so measurement errors were used to weight all available targets (no targets were purged), except baseflow targets greater than 1 cubic ft/second, which were given four times their measurement-error calculated weights because the main goal of the GFLOW model was to properly simulate the mass of groundwater moving through the aquifer system. The mean difference and mean absolute difference between simulated and measured ground water levels were –3.6 and 14 ft; between simulated and measured baseflows they were 0.5 and 1.3 cubic ft/second, respectively.

MODFLOW

The primary tool used to evaluate the groundwater system was the computer program MODFLOW-NWT (Niswonger and others, 2011). This version of MODFLOW uses an upstream-weighted block-centered finite-difference method to solve the groundwater flow equations, which partially mitigates challenges associated with simulating thin unconfined aquifers that are susceptible to numerical instability due to dewatering of model cells during the iterative solution process. Dewatered cells (dry cells) occur when the simulated water level falls below the layer bottom; MODFLOW-NWT minimizes this problem during the solution process by assigning a very small minimum saturated thickness to each cell. The model was simulated using steady-state assumptions (no change in input stresses or water levels over time for a given simulation—inputs and results reflect long-term average conditions). Steady-state conditions were deemed appropriate because of the long-term focus of the study (as opposed to seasonal extremes) and because the timing of future stresses in the final scenarios are highly uncertain. Thus, a steady-state model allows for representation of the full effect of a hydraulic stress because the response is not muted by transient storage of water within the aquifer system. Detailed descriptions of the finite-difference method, MODFLOW input requirements, steady-state assumptions, and the methods employed to ameliorate dry cell problems with MODFLOW-NWT are provided by McDonald and Harbaugh (1988), Anderson and others (2015), and Niswonger and others (2011).

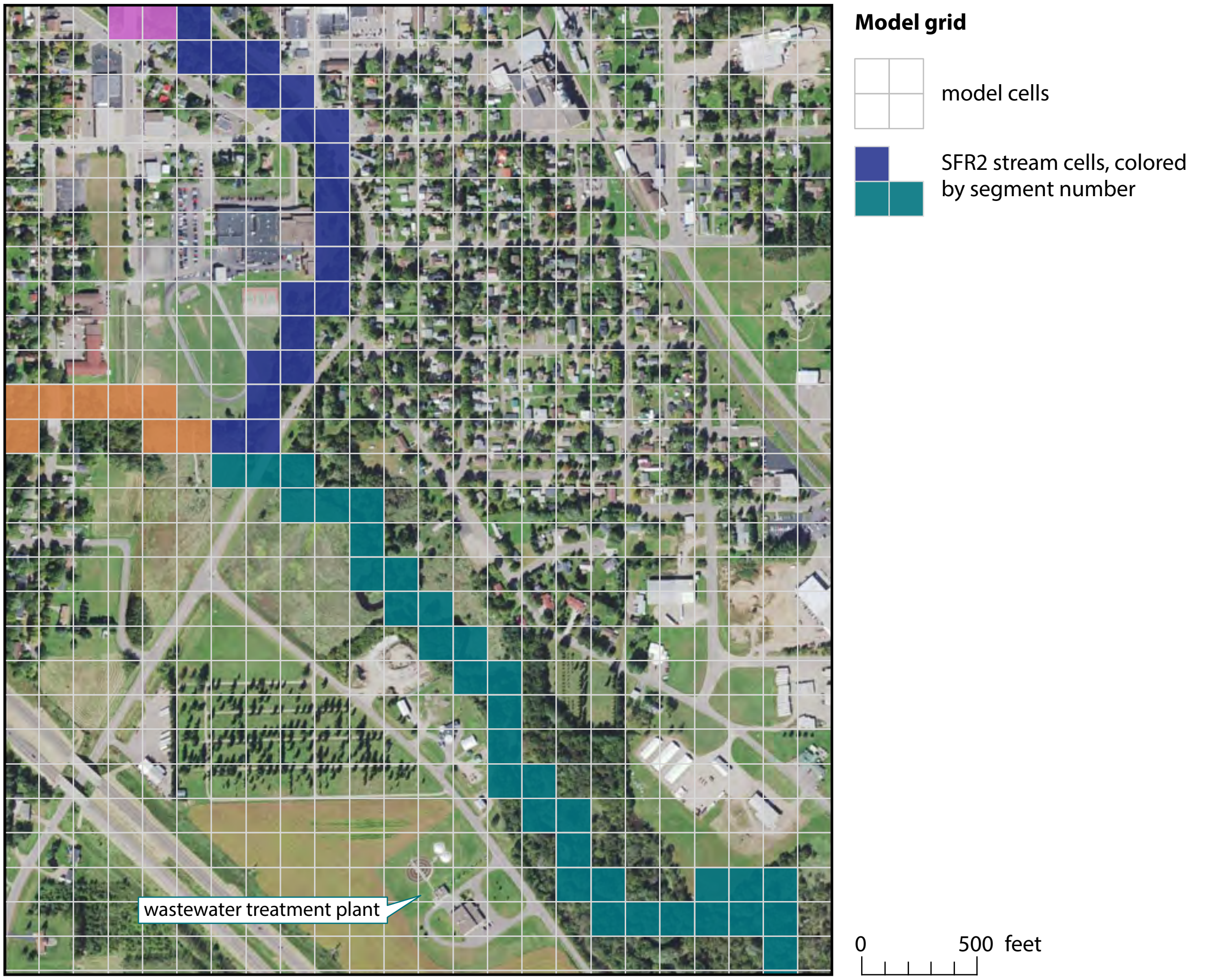
Model grid

The MODFLOW model was designed with square cells spanning 150 ft on each side, resulting in 1,200 rows and 800 columns of cells per layer (960,000 cells per layer), covering 775 square miles. This level of model resolution was chosen as a compromise between detailed representation of groundwater/surface-water interactions and reasonable constraints on computer resources required to construct and solve the model (fig. 20).

The model perimeter extended hundreds to thousands of feet beyond the near-field study area (fig. 3) to ensure that groundwater divides surrounding the near field were directly simulated within the model. This approach buffers effects from boundary conditions and possible changes in how those boundaries respond to scenario stressors on simulated results within the study area for the calibrated model as well as scenario simulations.

Hydrostratigraphic units

Several regionally extensive bedrock surfaces were identified from WCRs and geophysical logs in and around the study area. To simulate groundwater flow through these aquifers and aquitards, the stratigraphic surfaces were combined and integrated into the MODFLOW grid design. Similarly,



Imagery: National Agricultural Imagery Program (NAIP), U.S. Department of Agriculture, 2016

Figure 20. Example MODFLOW grid near the city of Bloomer, Wisconsin. Model cells are 150 ft on each side, colored cells are simulated stream segments.

unlithified material from glacial deposits and the erosion and deposition of bedrock in stream valleys was incorporated into the MODFLOW model such that all major hydrogeologic units in the study area were simulated with the model.

Layering approach and treatment of pinchouts

The 10 hydrostratigraphic units shown in figure 7 were combined into six layers in the MODFLOW model. These model layers represented surficial unconsolidated deposits (glacial sediment and eroded sandstone and sediment in valleys) and regionally identifiable hydrostratigraphic aquifers and aquitards. The top layer of the model, layer 1, represented the bulk of unlithified deposits; layers 2–6 represented bedrock layers as described in figure 7. An exception to this "one lithology per layer" approach occurred where bedrock units were very thin or absent. That is, a minimum thickness of 2 ft was enforced for all layers to maintain layer continuity and model stability. Such "pinched-out" areas in bedrock layers were designated as unlithified material and assigned hydraulic properties accordingly.

The top of the MODFLOW model was computed as the mean elevation of all pixels from a 10-meter (about 30 ft) by 10-meter digital elevation model of the land surface that occurred within each 150-ft by 150-ft model cell. The top of the MODFLOW model was used only as a check on the bottom elevation of model layers below; the simulated water table is the functional top of the mathematical model. The bottom elevations of all layer cells were similarly computed as the mean value of all pixels for individual hydrostratigraphic unit surfaces that occurred within each model cell. The bottom of layer 1 was computed from the top-of-bedrock surface, so that model layer 1 generally represented unlithified material. The bottom of layer 2 was computed from the bottom surface of the Wonewoc hydrostratigraphic unit, so that model layer 2 coincided with the Wonewoc and overlying Tunnel City units, where present. The basal surface of the Eau Claire hydrostratigraphic units was used to compute the bottom elevation of layer 3. Similarly, layers 4, 5, and 6 represent the Mount Simon hydrostratigraphic units, with layer 5 representing the shale-rich intervals (fig. 7). Where interpolation and averaging resulted in MODFLOW model layers less than 2-ft thick (pinched-out layers), the bottom elevation of each layer was moved downward on a cell-by-cell basis until all cells in the model had a minimum thickness of 2 ft. This minimum thickness was expected to have a minor effect on the overall model transmissivity (hydraulic conductivity times saturated thickness) but allowed for the required maintenance of layer continuity in MODFLOW-NWT and improved numerical stability of the model.

Hydrostratigraphic zones

To facilitate model calibration, each model cell was assigned to a hydrostratigraphic zone based on the interpolated bedrock surfaces. The goal was to directly match the MODFLOW model to the conceptual model (fig. 12). This worked well for most cells, but the methods used to interpolate bedrock surfaces from well construction information (discussed in Hydrogeology of Western Chippewa County section) and average those surfaces onto the MODFLOW grid caused minor irregularities in the extent of mapped bedrock areas within some layers.

The first irregularity was that portions of layers 5 and 6 appeared to be pinched out below areas in which layer 4 was not pinched out, meaning that the upper Mount Simon appeared to be present in this area, but the lower units were absent. In these locations, the underlying layers were designated as being at least 2-ft thick (not pinched out) and assigned to the hydrostratigraphic zone number representing the bedrock unit for that model layer (zone 5 or 6) rather than for the overlying layer (zone 4).

The second irregularity was that many small areas contained bedrock that was only slightly thicker than the 2-ft pinch-out criteria, particularly in layers 1, 2, and 3. To minimize the resulting granularity in bedrock hydrostratigraphic zones, we used an algorithm (the image erosion function from the Python skimage library (Van der Walt and others, 2014)) to smooth the contact between bedrock and unlithified material zones. Only the 50 largest bedrock zones, or "islands," within each model layer were retained; all remaining islands were assigned to zone 1, unlithified deposits. The largest contiguous zone in each layer (identified using the label function in SciPy's ndimage library (Jones and others, 2001)) was assigned the primary hydrostratigraphic zone number for that unit. This identified the area over which pilot points would be used to estimate hydraulic conductivity values during the subsequent calibration process. The remaining 50 (or fewer) bedrock islands were assigned two-digit model layer numbers based on their primary zone number: 33, 44, 55, 66. These numbers were used to assign spatially uniform bedrock hydraulic conductivity values during the calibration process. The decision to retain only the 50 largest bedrock islands as bedrock hydrostratigraphic zones was determined by manually testing a range from 20 to 100 and visually compar¬ing the results; a value of 50 was deemed to provide the most appealing result for all layers.

Boundary conditions

Perimeter hydraulic boundaries for the MODFLOW model were derived from the two-dimensional GFLOW model. Groundwater flow extracted from the GFLOW model was distributed across MODFLOW model layers for each perimeter model cell based on the relative transmissivity of each cell within a vertical column. Transmissivity was computed using hydraulic conductivity values from a preliminary MODFLOW model that was calibrated using only spatially uniform hydraulic conductivity zones. Boundary flows in the MODFLOW model were simulated using the well (WEL) package (Harbaugh, 2005). According to the regional GFLOW model, more than twice as much groundwater flows into the MODFLOW model domain than flows out through the model perimeter—5.9 million cubic ft/day of groundwater enters the model domain compared with 2.3 million cubic ft/day leaving across the boundaries. However, MODFLOW-NWT reduces groundwater withdrawals from the well package when simulated water levels approach the bottom elevation of a cell. As a result, groundwater outflow from the MODFLOW model through perimeter boundary conditions was reduced from 2.3 to 1.8 million cubic ft/day in the final calibrated model. Given the fact that the primary study area was buffered from the perimeter model domain by tens to hundreds of model cells and typically one or more simulated streams (internal boundary

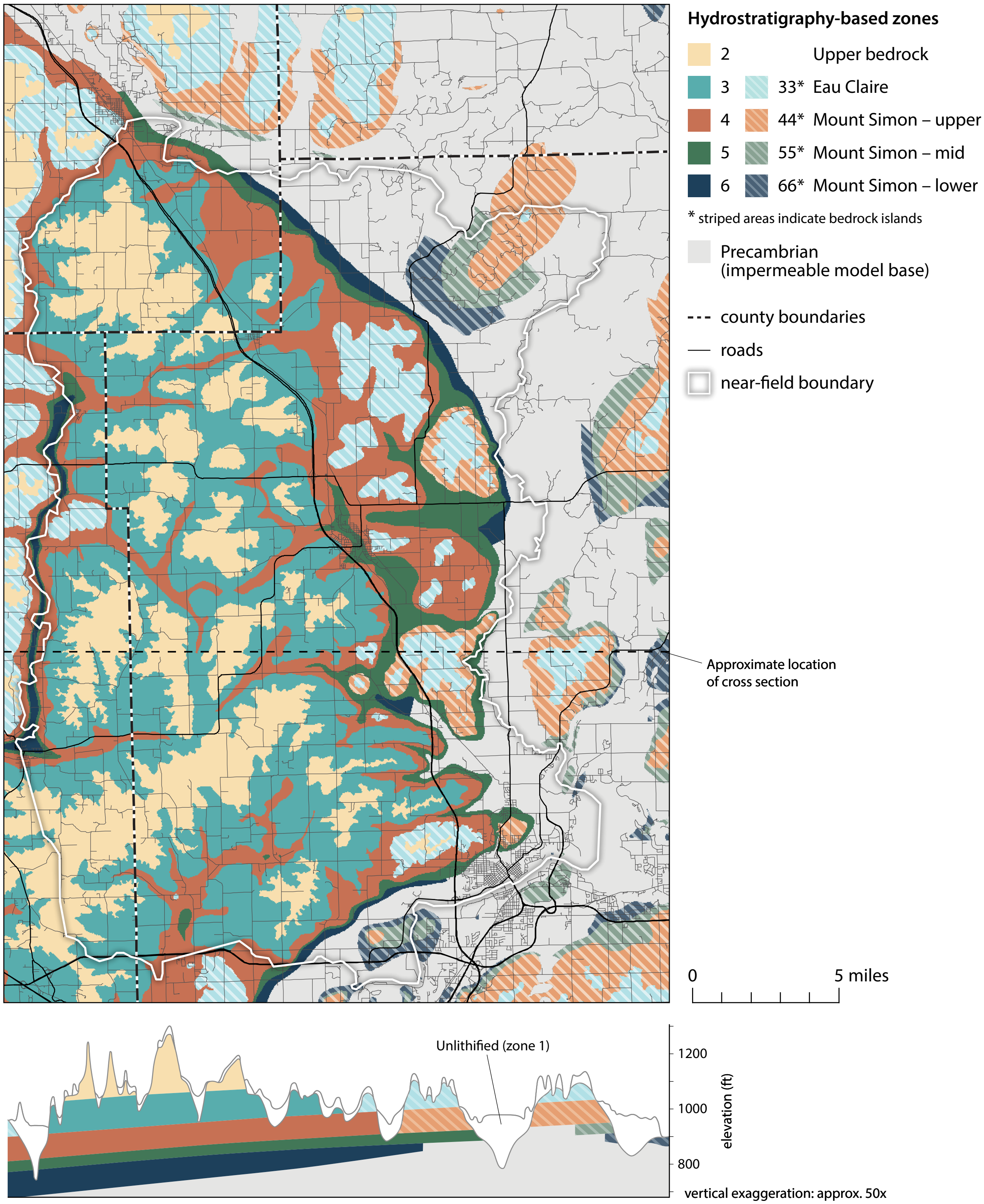


Figure 21. Hydrostratigraphic zones used to calibrate hydraulic conductivity. All zones represent areas where the associated bedrock is at least 2-ft thick. Zone 1, unlithified deposits, covers the entire model and is not shown in the map.

conditions), this internal modification of the perimeter boundary flow by MODFLOW-NWT is expected to have minimal influence on the model calibration or scenario simulations.

Surface water network

Streams in the MODFLOW model were simulated with the streamflow-routing (SFR2) package (Niswonger and Prudic, 2005). The SFR2 package routes water from upstream to downstream cells to accumulate flow and solve for water levels in the streams (fig. 20). The SFR2 file was developed from the National Hydrography Dataset Plus (NHDPlus; McKay and others, 2012), which guided the locations of stream segments and their downstream connections. Two small headwater segments were manually added where a pre-calibrated version of the model showed simulated water levels above the land surface and aerial photographs illustrated the presence of perennial streams. The streambed in each cell was assumed to be about 1-ft thick.

Hydraulic conductivity of streambeds was set equal to the horizontal hydraulic conductivity of the underlying glacial material in layer 1 of the model for the dominant reach in each model cell, which was subsequently adjusted during calibration via a single multiplier value for all SFR2 segments.

For model cells with overlapping SFR2 cells, an artificially low hydraulic conductivity (1×10^{-8} ft/day) was assigned to all cells except for the one "dominant" cell that was associated with the most downstream segment, ensuring that only the most downstream SFR2 cell interacted with the aquifer. The stream length for each SFR2 cell was determined from the length of the associated NHDPlus polyline fragment crossing the model cell. Stream width was calculated using an arbolate sum (Bartošová and others, 2004) algorithm that was based on a relation between measured stream widths and the downstream distance from the headwater origin, as originally developed by Feinstein and others (2010).

Elevations of the streambed in each SFR2 cell were derived from the lowest elevation of all values from a 10-meter resolution DEM (U.S. Geological Survey, 2014) that overlapped with the MODFLOW cell containing the associated SFR2 cell. Streambed elevations were subsequently refined, such that all streambed elevations decreased from headwater reaches to the most downstream reach of the stream networks. These refined elevations were then used to compute the stream slope for each SFR2 cell, with the stream slopes further constrained by a maximum slope of 0.2 ft/ft to improve model solution stability.

The stream slope and channel roughness coefficient, specified as 0.037 for all SFR2 cells, were combined with the stream width and total simulated flow to compute stream stage via Manning's equation in each SFR2 reach (Prudic and others, 2004). The channel roughness coefficient represents an approximation for the resistance to flow in stream channels. The value used in this study was guided by tables and analyses by Arcement and Schneider (1989), and informed from observations of sediment composition and streambed forms, in-stream and channel bank vegetation, and the general degree of stream meandering in the study area.

Paul Juckem

Recharge

Deep infiltration estimated by the SWB model for the year 1993 was input as groundwater recharge in the MODFLOW model through the recharge (RCH) package (Harbaugh, 2005). Recharge for 1993 was chosen for the baseline, or long-term average steady-state model, because the annual recharge computed by SWB for that year was the closest to the long-term average recharge for the SWB simulation. A representative "average" year was chosen because 2011 and 2012 were relatively dry compared to the long-term average, in turn affecting SWB estimates during the primary study years (2012–2014). However, the modeling objective was to simulate long-term average conditions with the calibrated model. Even though the magnitude of recharge for the calibrated model was adjusted with a multiplier parameter during calibration, an "average" recharge year was desirable to ensure that the spatial distribution of recharge (which can be affected by wet and dry cycles due to differing patterns of soil infiltration capacities) was also representative of the long-term average spatial pattern. Given the calibrated recharge multiplier of 0.88 and ignoring all cells with zero recharge (water bodies), the resulting average calibrated recharge applied to the model domain was 7.6 in/yr and ranged spatially from 0.2 to 13.7 in/yr. The average recharge rate is within the range reported by Gebert and others (2011) for watersheds in northwestern Chippewa County.

Groundwater withdrawals

Annual pumping rates for high-capacity wells in the model area were obtained from the WDNR (n.d.-b; R.A. Smail, WDNR, oral communication, 2013) for 2011–2013 (fig. 11). Locational information for each well was refined, and well construction information such as casing and well depth were checked against WCRs and updated as necessary. For model calibration, average pumping rates were used for 2011–2013 because they represented the most complete dataset for pumping and because surface-water flow measurements were available for the same period.

High-capacity wells were simulated with the multi-node well (MNW2) package (Konikow and others, 2009). Well construction information was used to designate elevations for the top and bottom of the open interval for each well. This allowed the model to identify which layers each well spanned and apportion pumping to each model layer based upon their relative saturated transmissivity. Most active wells (197 of 274) in the water-use database included depth of casing and depth of well information, which was used to compute the open interval for each well. Wells that lacked this information were adjusted such that: (1) the well casing for all wells was simulated as being at least 25 ft below the average land surface within each model cell, (2) the bottom of the well was at or above the bottom of the model, and (3) the bottom of the well was at least 2.5 ft deeper than the casing. Inactive wells, or those with zero average pumping, and five wells in the southeastern portion of the model (outside of the near-field area) that caused numerical challenges for the model solver were removed from the MNW2 package, resulting in 269 active groundwater withdrawal wells in the model.

The MNW2 package computes the water level in each well as part of the iterative MODFLOW solution in order to compute the saturated thickness for layers that cross the open interval of the well. Due to differences in the width of individual wells compared to the width of a model cell, the simulated water levels for wells are expected to differ from water levels in the cells (Konikow and others, 2009). For this model, the water level in each MNW2 well was computed using the Thiem equation (Thiem, 1906) to account for cell-to-well corrections to the simulated water level in the pumping wells. While the simulated water level in individual wells was not used to limit overall well pumping via the MNW2 package, the MODFLOW-NWT solver automatically limits well pumping when water levels in cells that contain MNW2 wells fall below a small percentage of the cell thickness (the default 5 percent was used for this model). When an aquifer could not maintain a specified pumping rate, the simulated rate was reduced by the MNW2 package to an amount that could be met by the aquifer. For the calibrated model, less than 4.5 percent of the total specified pumping was reduced; the reductions were concentrated outside of the near-field area near the city of Chippewa Falls where thin unlithified material directly overlays nearly impermeable Precambrian crystalline rock. The total simulated groundwater withdrawal from high-capacity wells in the calibrated model was 2.98 billion gallons per year.

Table 4. Range and mean hydraulic conductivity estimates from prior studies near Chippewa County.

Hydrostratigraphic unit	Hydraulic conductivity, range [mean] (ft/day)			
	Feinstein and others, 2006	Juckem, 2009	Juckem and Robertson, 2013	This report
Unlithified deposits	1–20	13–272 [73.3][a]	1–120	1–300 [110]
Wonewoc	5	—	—	9.6
Eau Claire		—	—	0.2–4
Mount Simon		—	21	0.7–40[b]

[a] Data from specific capacity tests from 19 municipal wells in the unlithified deposits in Polk, Barron, Burnett, and Washburn Counties, Wisconsin.

[b] Range uses layers 4–6 from the groundwater flow model.

Wastewater treatment discharges

A portion of the groundwater that is pumped for use in municipal systems is commonly discharged to streams following treatment at wastewater treatment plants. This discharge typically remains relatively constant and functions similar to baseflow in a stream. Wastewater discharge is useful to track when calibrating groundwater flow models to stream baseflow targets. The City of Bloomer (fig. 3) has the only municipal pumping and wastewater discharge that occurs upstream of a baseflow target within the model domain. The utility provided total annual wastewater discharge for 2009–2013. That discharge was assigned as overland runoff to the SFR2 segment and reach along Duncan Creek that is associated with the location of the utility outfall (fig. 20). Thus, all high-capacity pumping and return flow in the near-field area of the model was simulated directly within the groundwater flow model. Discharges to streams outside the near-field area, for example at Chippewa Falls (Chippewa River) and Colfax (Red Cedar River), were not simulated as there were no baseflow targets downstream of the outfalls; therefore, those wastewater discharges had no effect on the model calibration.

Hydraulic conductivity

Estimates for the reasonable range of hydraulic conductivity values in the model were developed from prior studies of groundwater flow in the region (table 4) and from pumping test reports and specific capacity data from WCRs. One aquifer pumping test came from Preferred Mine in the study area. The test evaluated changes in water levels in monitoring wells completed in the shallow and deep portions of the Mount Simon aquifer to pumping from a well completed in the deep portion of the Mount Simon aquifer, which approximately corresponds with layer 6 of the model. The pumping test estimated the hydraulic conductivity of the basal Mount Simon aquifer as approximately 39 ft/day. Because this estimate was higher than previous estimates, it was used as the initial hydraulic conductivity value for the Mount Simon aquifer zone in layer 6 of the MODFLOW model.

Specific capacity data from WCRs also were used to estimate hydraulic conductivity based on the methods of Bradbury and Rothschild (1985). Hydraulic conductivity values ranged over several orders of magnitude, but specific capacity data from most wells corresponded with hydraulic conductivity values between about 1–1,000 ft/day for wells open to glacial material and 0.1–100 ft/day for wells open to Mount Simon sandstone. Estimates from WCRs were used to inform limits on acceptable hydraulic conductivity values produced during the model parameter estimation process.

It was assumed that hydraulic conductivities were horizontally isotropic (for example, no difference in north–south directions compared with east–west directions) and vertically anisotropic (lower hydraulic conductivity in the vertical direction compared with horizontal directions).

Parameter estimation

Parameter estimation is the process of adjusting model parameters so that model inputs and outputs acceptably fit both "hard" knowledge (observations of water levels and flows) as well as "soft" knowledge (professional experience and judgment) about the model domain. Parameter estimation of the Chippewa County model involved adjustment of uncertain model parameters and comparison of results to an array of model targets, a process called history matching. This term refers to the specific aspect of calibration that was used in this work, and it is used interchangeably with the term calibration in this report.

Parameter estimation strategy

The parameter estimation process used for the Chippewa County groundwater flow model was performed in multiple steps. These steps, outlined broadly, were (1) assembling available data, (2) assigning weights to data, (3) defining hydraulic parameterization (discretization and zoning), (4) conducting manual trial-and-error history matching to determine initial parameter values, (5) iteratively exchanging parameter values between parameter estimation steps, and (6) revising the conceptual model and observation weights. These steps do not necessarily follow in sequence from one to the other because feedback throughout the process identifies shortcomings and indicates changes that cascade throughout the process. The final model is based on the results at each step, as described in this section. (Appendix B describes the parameter estimation algorithm and provides context for each of the steps.)

History matching involves a systematic adjustment of parameter values to improve the fit between measured observation values and model outputs. An objective function is formed from the sum of the squared differences between model outputs and measured observation values, each multiplied by a weight. The goal is to minimize the value of the objective function. However, fit can come at the expense of reasonable parameter values, so a "penalty" is added to the objective function. As fit decreases (because parameter values have strayed too far from a preferred condition) the penalty increases the objective function. This provides a balance between fit and prior knowledge of hydrogeologic conditions.

History matching was first performed using a zoned version of the model. This provides a starting point for a more highly parameterized approach using pilot points for hydraulic conductivity parameters and a general adjustment to the SWB recharge array. The following parameters were estimated: (1) pilot points for horizontal and vertical hydraulic conductivity, (2) a recharge multiplier applied to the entire SWB-derived recharge array, and (3) a multiplier applied to vertical hydraulic conductivity in stream cells to calculate streambed conductance.

Model parameter estimation

Parameter estimation target dataset

The model was calibrated to 37 baseflow targets and 658 water-level targets (fig. 22). Baseflow targets included data from three gaging stations established for this study and 34 synoptic one-time measurements.

Baseflow, or the portion of total streamflow derived from groundwater discharge, for the three gaging stations was estimated using the baseflow separation program, BFI (Wahl and Wahl, 1995). The BFI program is based on a method that combines a local minimum analysis and a recession-slope test (Institute of Hydrology, 1980a, 1980b; Wahl and Wahl, 1995) to separate baseflow and runoff components of a streamflow hydrograph. The modified BFI method was applied using the default recession constant of 0.98 with 2 days of recession between points for all three gages. For the one-time synoptic streamflow measurements, target baseflow values were computed by adjusting the streamflows measured on October 11 and 12, 2012 to the baseflow at Hay Creek at Wheeler (a nearby long-term gage located in a similar geographic and hydrogeologic setting). Streamflows were adjusted using the statewide baseflow equation (Gebert and others, 2007, 2011) and the 90 percent flow duration from October 2011 to September 2014. Flow duration is the flow of water equaled or exceeded on 90 percent of the days for a given period of time. Synoptic flows were adjusted in this manner to better represent long-term conditions during the study period.

Water-level targets included wells with drillers' WCRs and wells with water-level measurements provided by mining companies. Wells with WCRs used the measured water level recorded by the driller at the time of drilling as the target values. For observation wells at mining sites, the average measured water levels from October 2010 to September 2013 were used as the target values. Each well was initially assigned to a model

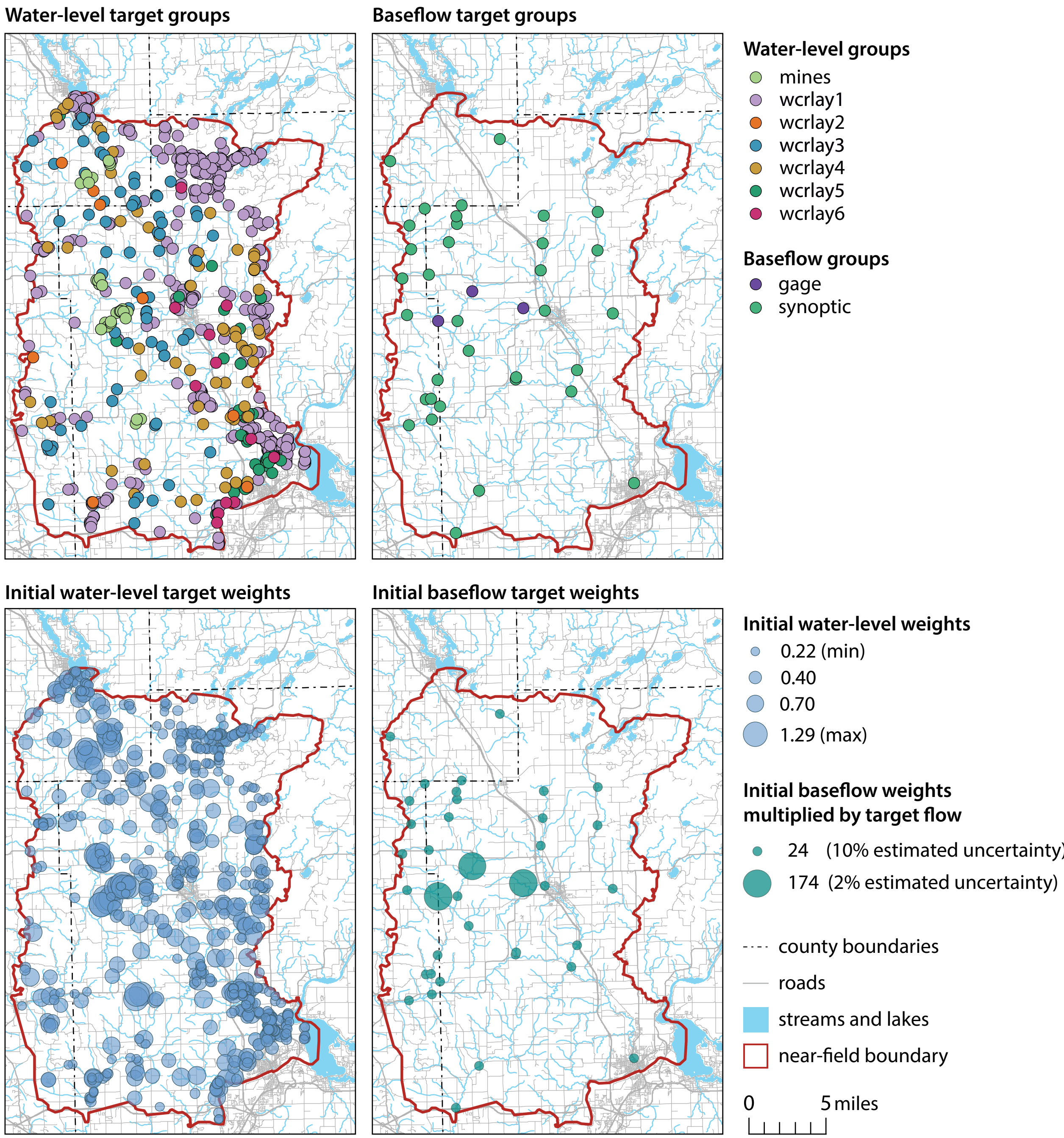


Figure 22. Simulated water levels for layers of the calibrated MODFLOW model.

layer based on the elevation of the center of each well's open interval. The layer designation was used to subdivide the WCR targets into observation groups for PEST. However, a transmissivity-weighting method was ultimately used to compute the simulated water level for each water level target. That is, well construction information was used to calculate the transmissivity of each layer spanned by either a well screen or open borehole (e.g., the thickness of the open interval intersecting each model layer multiplied by the horizontal hydraulic conductivity of the layer). The simulated water level for each target well was then computed as the sum of the simulated water level in each layer times the percent of total transmissivity for the respective layer at each well's location.

Observations were assigned to groups to allow for balancing as discussed below. The groups are:

- mines: water levels supplied by the mining companies
- wcrlay1–6: data from WCRs in layers 1–6
- gage: baseflow observations at the three gage locations
- synoptic: baseflow observations at the one-time observation locations spread throughout the near-field area

Parameter estimation target weights

Weights were initially assigned to targets based on an assumption of their accuracy (fig. 22). They were then iteratively adjusted by group to balance the objective function to account for disparate units among different types of observation data and variable numbers of observations in each group.

For head targets, in general, initial weight was based on two factors: the accuracy of the ground elevation from which depths to water were measured, and how representative a measurement was of changing conditions over time. (Accuracy of ground elevation is discussed below in the context of well construction reports.) For temporal conditions, if a single measurement was made to represent long-term conditions, a standard deviation of 5 ft was assumed. If multiple measurements were made over time, the average water level was used and a standard deviation of 1 ft was assumed.

For the mines group, elevation at ground surface was assumed to be accurate (boreholes and wells were located with surveying equipment or a survey-grade GPS system), so the only source of error was temporal water level fluctuation. As a result, initial weights were based on either a 1- or 5-ft standard deviation.

The wcrlay groups span a much larger time and a much greater range of quality than the mine targets. Most WCRs represent a single measurement made when the well was drilled, so a 5-ft standard deviation was typically used as the starting point; a standard deviation of 1 ft was used if multiple measurements were available. WCRs are also located laterally with varying degrees of accuracy. Within the uncertainty of the lateral location, it is possible to estimate the range of ground elevations. In other words, a WCR that is accurately located in a steep area may have less vertical accuracy than a WCR located in a relatively flat area with less certain lateral accuracy. To account for this, the standard deviation of the digital elevation model within a radius of accuracy around each WCR was calculated. If the vertical variability was less than or equal to 10 ft, the standard deviation of the ground elevation near the well was added to the 1- or 5-ft value representing the variability due to temporal water level fluctuations. If vertical variability was more than 10 ft, the WCR was deemed too inaccurate to use and was assigned a weight of 0.0. WCR targets for which the simulated water level appeared to be influenced by nearby high-capacity pumping were also assigned weight of zero.

For flow targets, the accuracy was assumed to be a standard deviation of 2 percent of the flow for gages and 10 percent of flow for synoptic measurements.

In all cases, weights were initially assigned as the reciprocal of these assumed standard deviation values. Adjustments were then made to balance the objective function. Specifically, multipliers were assigned to group contributions to the objective function to account for varying numbers of targets in a group, target units, and subjective factors. The initial weights, the adjusted weights, and the implied error when recalculated from the adjusted weights are presented in appendix C.

The weight adjustment process is illustrated in figures 23–25. Figure 23 shows the makeup of the objective function with weights based on the assumed error values discussed above. Subjectively, this figure shows an imbalance in particular with the contribution from the mines group eclipsing the flow observations of the gage and synoptic groups. Figure 24 shows the contributions rebalanced with the mines, gage, and synoptic groups each making up 25 percent of the objective function with the remainder spread among the six WCR head observation groups. Figure 25 shows the makeup of the objective function following history matching. The final balance is the result of differential reduction in the objective

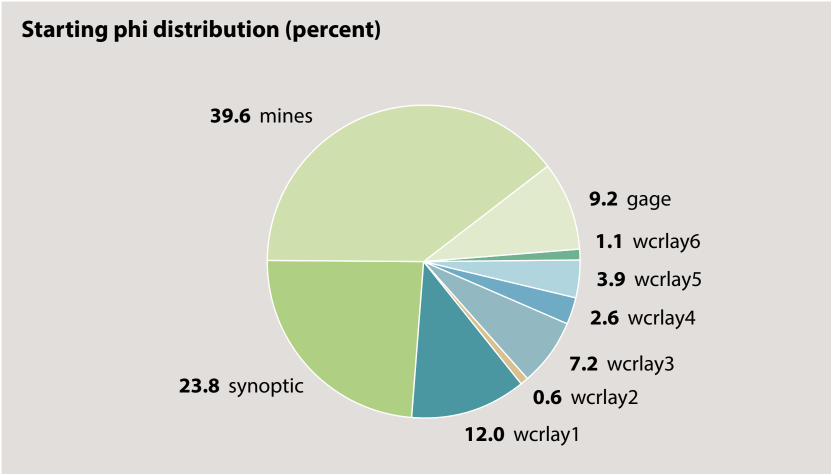


Figure 23. Initial phi distribution among observation groups using total error weights.

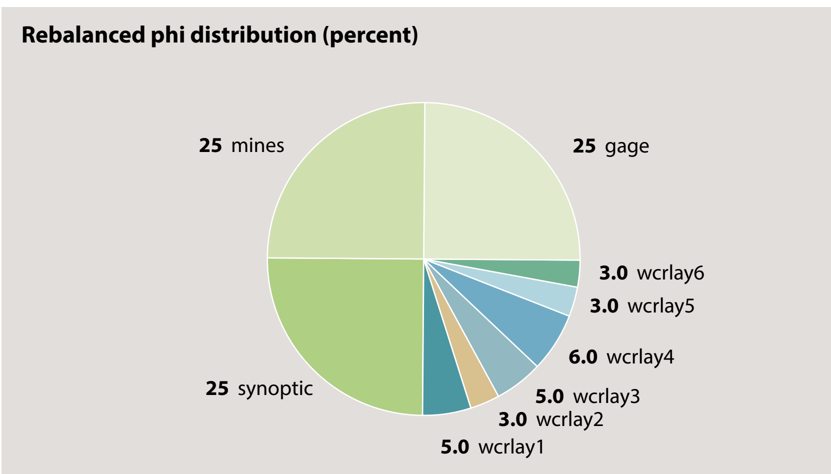


Figure 24. Rebalanced phi distribution, observation groups weighted equally.

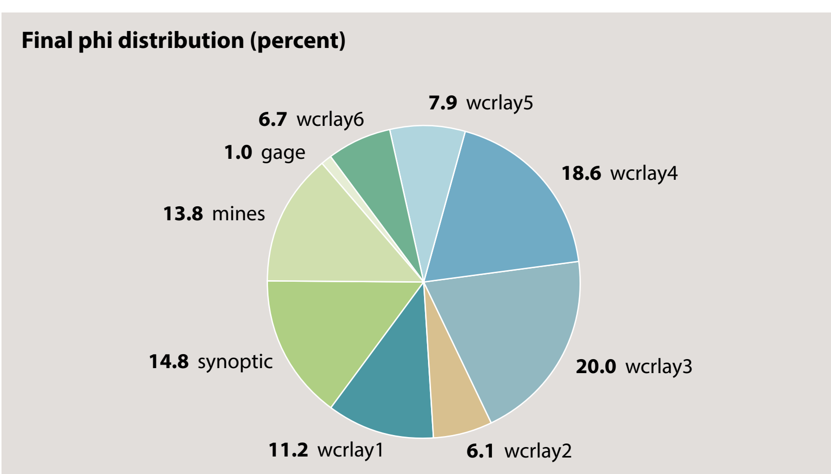


Figure 25. Final phi distribution, calibrated using rebalanced observation weights.

function among the various groups, but the objective function remained reasonably distributed among all the groups, which indicates no group dominated the history-matching process. This final objective function is also indicative of which groups experienced the greatest reduction in phi.

Parameterization of unlithified material and bedrock properties

Horizontal hydraulic conductivity for unlithified material and bedrock was parameterized using a combination of zones of uniform hydraulic conductivity and pilot points. Pilot points allow for estimation of hydraulic conductivity at several points in the parameter field as guided by information from the observations during history matching. Hydraulic conductivity values are then interpolated between the pilot points, filling the zone with values.

On all but one layer, the main geologic body was parameterized using pilot points. (Layer 2 has no pilot points because it has too few saturated areas.) Bedrock islands, those portions of the layer that are separated from the main body, were treated as homogeneous zones with a single parameter value estimated for the lithology type during history matching. Islands contain fewer observations, which diminishes the level of information that would justify the flexibility of pilot points.

Pilot points were placed at variable spacing based qualitatively on the assumed heterogeneity and the amount of data supporting their estimation in history matching. The spacing was 12,000 ft in zone 1; 12,750 ft in zone 3; 15,000 ft in zones 4 and 5; and 22,500 ft in zone 6 (figs. 26 and 27). For each zone, an exponential variogram was used with range set to two times the maximum spacing of pilot points in the zone

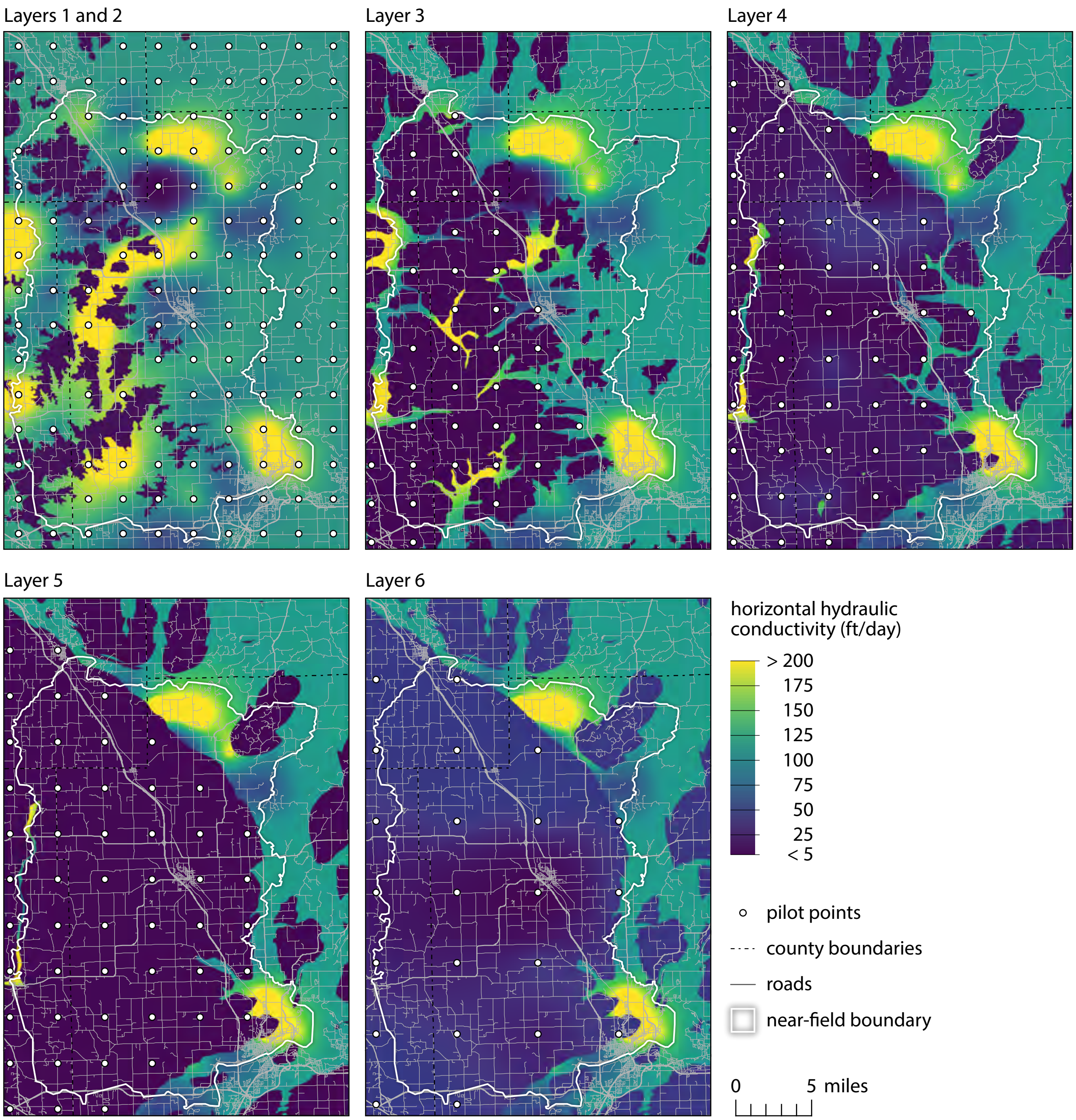


Figure 26. Calibrated horizontal hydraulic conductivity, by model layer. Layers 1 and 2 are combined because they have the same hydraulic conductivity values. Layer thickness is 2 ft wherever a unit is absent within a model layer.

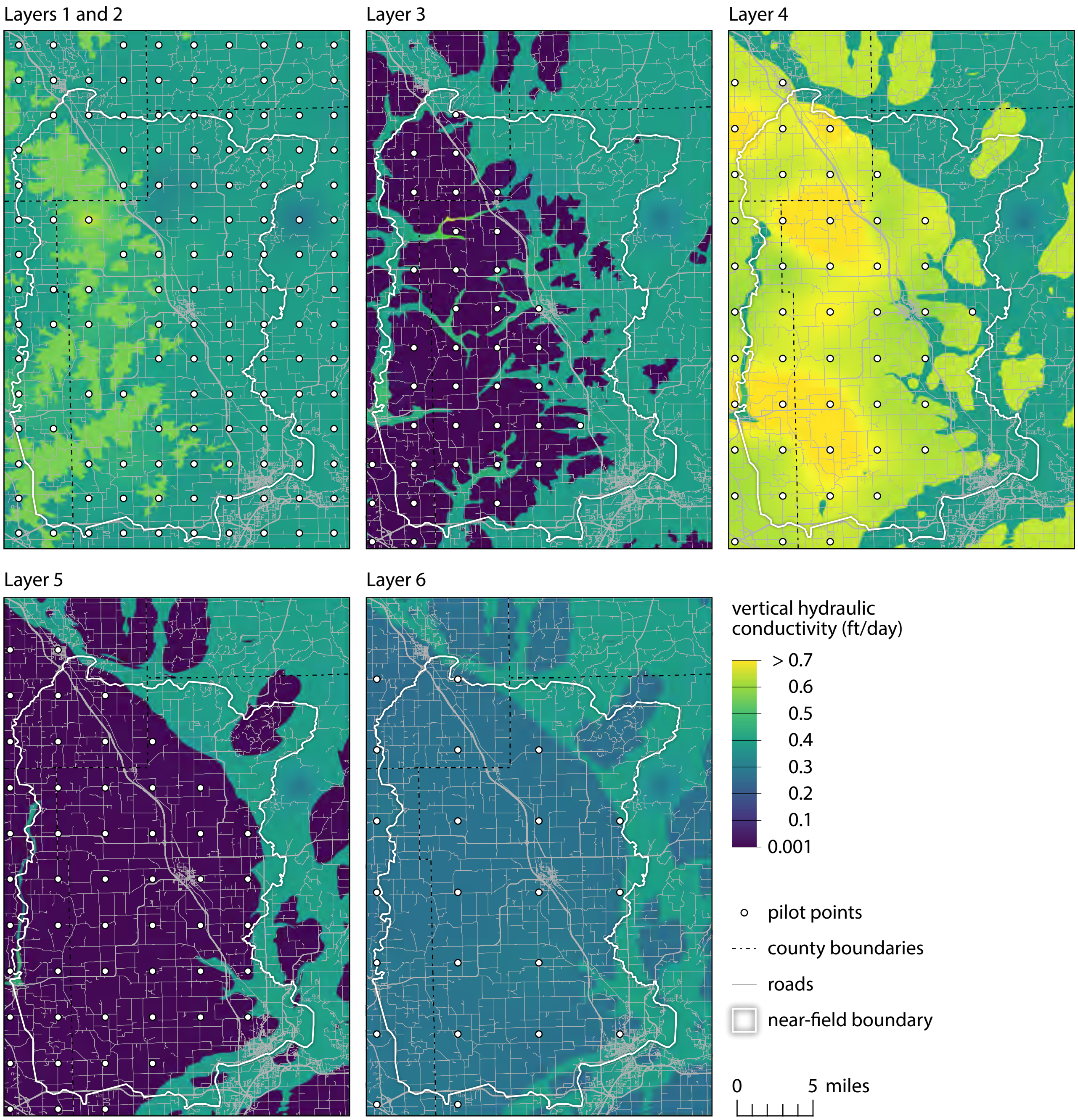


Figure 27. Calibrated vertical hydraulic conductivity, by model layer. Layers 1 and 2 are combined because they have the same hydraulic conductivity values. Layer thickness is 2 feet wherever a unit is absent within a model layer.

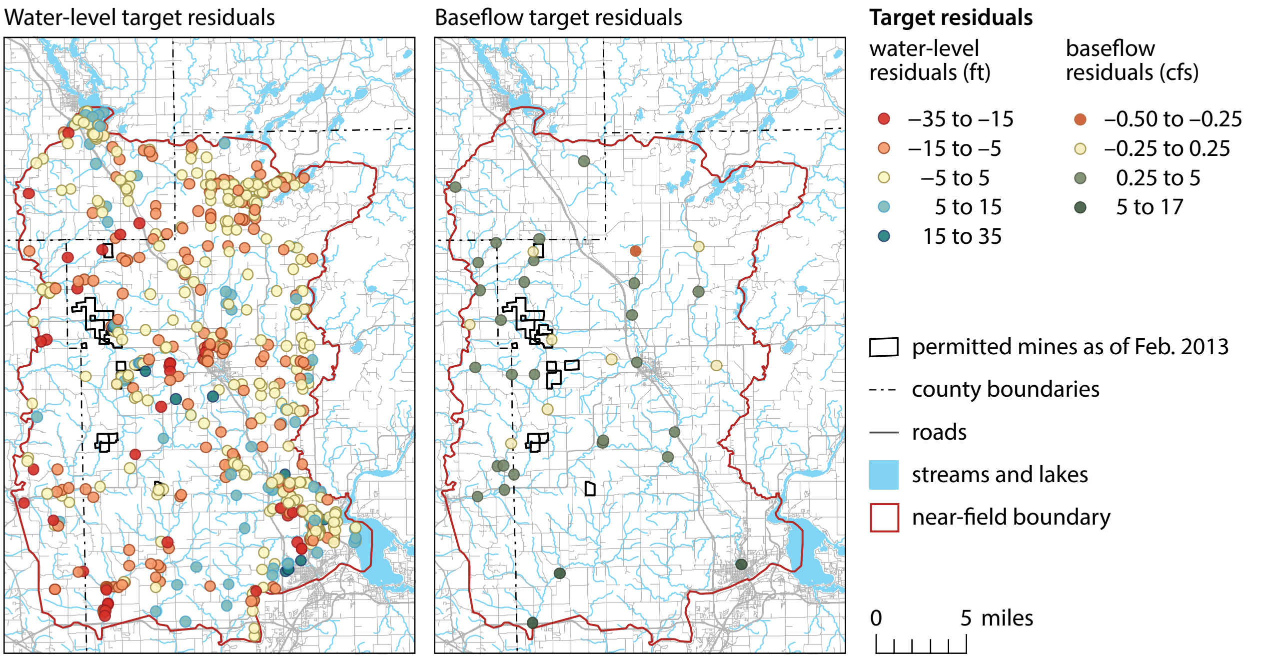


Figure 28. Target residuals. Negative residuals represent simulated results larger than target values; positive residuals represent simulated results smaller than target values.

(Doherty, Fienen, and Hunt, 2010). Tikhonov regularization was also implemented using the same variogram as a penalty such that candidate solutions with excessive variability in history matching are ruled out by the algorithm in favor of smoother solutions made up of parameter values with limited spatial variability. This provides a balance between model fit to the data and hydrogeologic knowledge of the region.

Parameterization of streambed properties

Streambed hydraulic conductivity can influence the local hydraulic gradient between groundwater and streams, thereby influencing local groundwater discharge. Such local groundwater/stream exchange is difficult to measure, so streambed hydraulic conductivity is commonly estimated during the calibration process. As described earlier, streambed hydraulic conductivity was set equal to the simulated hydraulic conductivity of the aquifer in layer 1 for each cell of the SFR2 package. While this is a reasonable initial estimate, a multiplier parameter was estimated during the calibration process. A value of 1.0 was used for the initial multiplier estimate, with lower and upper limits set at 0.001 and 1.0, respectively. The upper limit was set to 1.0 because it is unlikely that streambed sediments would be more permeable than aquifer material across the model domain. The calibrated multiplier value remained at 1.0, indicating that streams appear to be well connected with the aquifers.

History matching results

Evaluating parameter-estimation results requires analysis of model fit and parameter values. Model fit is the agreement between modeled values and their associated measured observations. The calibration process also must ensure that the estimated parameters fall within realistic ranges. There is a tradeoff between model fit and parameters. Excellent fit values can often be obtained with parameters that are inconsistent with knowledge of the geology of an area. Care must be taken to properly strike the balance between fit and realistic parameter values. In the remainder of this section, we first discuss the fit to observation data, and then provide context of the quality of estimated parameters.

History matching: Fit to observations

The observations, as discussed above, were water levels and baseflows (fig. 28). Water levels in the mines group were assigned 25 percent of the starting objective function due to their quality and importance for the project. Figure 29 shows the correspondence between modeled and measured values. The error bars indicate the a priori assumed standard deviation. The mean absolute error is 5.84 ft, indicating reasonable correspondence—especially in this region of steep hillsides. Figure 30 shows the residuals multiplied by their weights, which indicates their contribution to the objective function. Residuals are defined as the measured value minus modeled value. There is a small positive bias in the weighted residuals, driven in part by the least-certain values.

Figure 31 shows the correspondence between modeled and measured values for all the WCR observations in aggregate, which made up 25 percent of the objective function when balanced. Error bars are not presented because this figure uses a heat map with colors indicating multiple values at a given location on the plot since so many overlap. The mean absolute error of 6.3 ft is slightly higher than for the mines but also reasonable. Figure 32 shows the residuals.

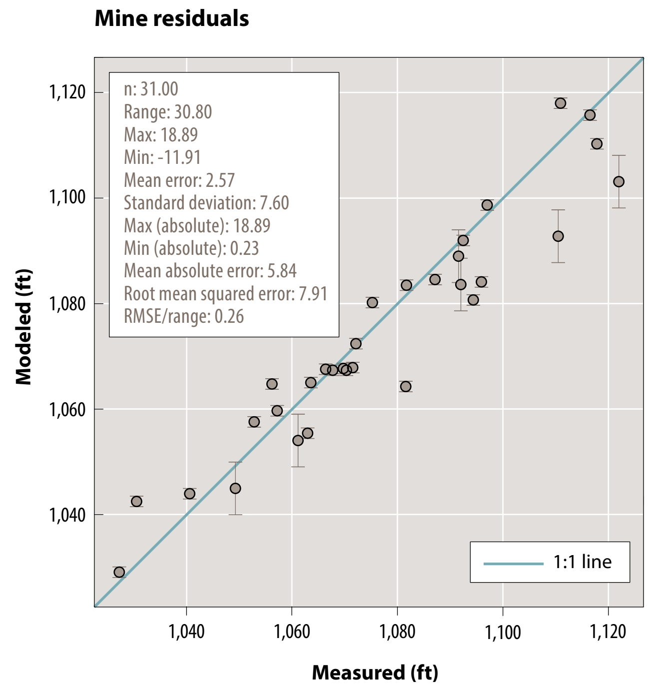


Figure 29. Mine residuals.

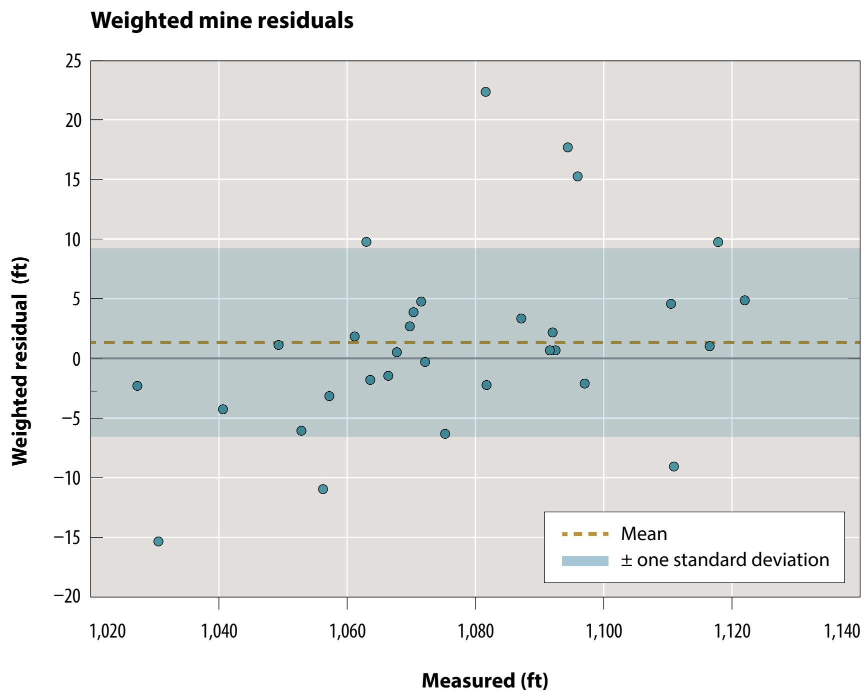


Figure 30. Mine residuals, weighted.

History matching: Estimated parameters

Hydraulic conductivity fields generated during the parameter estimation process improved the match to water level and baseflow targets, while maintaining a reasonable range in values (as identified in table 4) and associated spatial patterns (figs. 26 and 27). For example, unlithified material in all layers, exhibits a large degree of heterogeneity with values ranging from 2 to 300 ft/day through several smoothed transition areas. Moreover, differences among layers followed expected patterns with aquifers in layers 1, 4, and 6 having higher values than aquitards in layers 3 and 5. Vertical hydraulic conductivity values follow similar patterns, with even larger differences among aquifers and aquitards.

The estimated multiplier for recharge was 0.88. This multiplier was applied to the entire recharge array as calculated by SWB. This parameter serves to correct potential discrepancies in the mass balance when matching head and flow conditions over a long range of time with recharge that was necessarily calculated in a single representative year with the SWB model. A value between 0.85 and 1.15 was subjectively considered a reasonable adjustment.

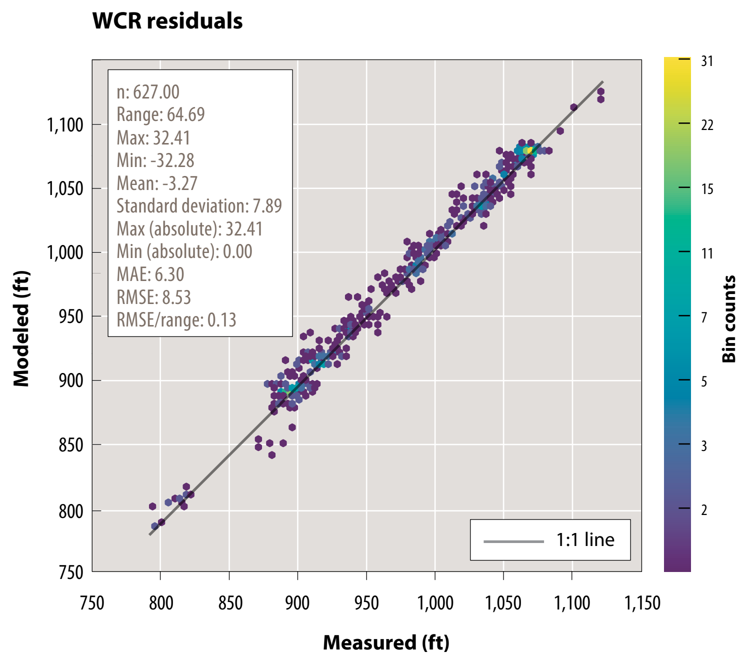


Figure 31. WCR residuals.

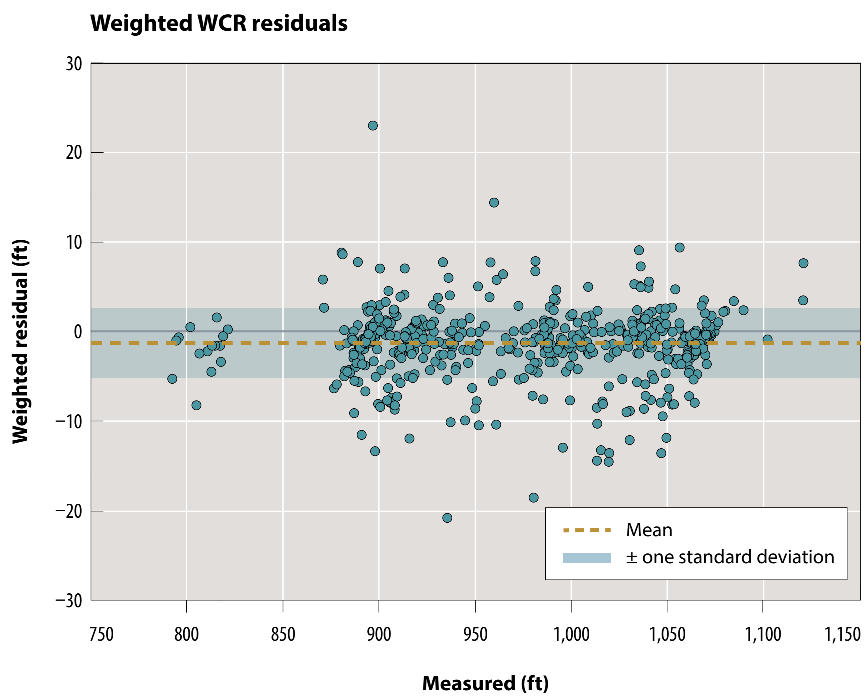


Figure 32. WCR residuals, weighted.

Base model results

The MODFLOW model was solved iteratively until convergence criteria for both maximum water level change and water volume change between iterations were satisfied. The final percent error in the water budget for the model was less than 0.01 percent, indicating that the model had reached a stable solution. The largest source of water to the aquifers is recharge at the water table; the largest sink of water out of the aquifers is discharge to streams (table 5). Model results suggest that approximately one third of groundwater that discharges to streams re-infiltrates into aquifers within downstream model cells. While natural re-infiltration within the hyporheic zone below streams (where groundwater and stream water mix) is ecologically important, the accuracy of the simulated hyporheic exchange may be limited by the 150-ft cell size used for the model.

Simulated results for the baseline calibrated model include baseflow through streams and water levels (fig. 33). Simulated water levels in layer 1 illustrate the strong connection between shallow aquifers and streams, with contours of the water table wrapping around perennial streams in the model. Deeper in the system, water-level contours are smoother and illustrate how overlying aquitards dampen the influence of streams on water levels. Flow directions, as illustrated by arrows in figure 33, convey similar concepts in that flow directions tend to change direction over shorter distances in the upper aquifers whereas in deeper units flow directions are primarily toward the largest streams in the area—the Chippewa River along the southern extent, the Red Cedar River along the western extent, and Duncan Creek near the center of the study area. Simulated baseflows form the foundation for evaluating changes through scenario testing.

Table 5. Water budget summary for the MODFLOW model.

Water budget category	Total flow (ft^3/day)	Percent of total (%)
Flow into model		
Perimeter flow from GFLOW model	5,942,259	8.9
Recharge to the water table	36,053,300	53.8
Re-infiltrated water from streams	24,993,838	37.3
Total inflow	*66,989,397*	*100.0*
Flow out of model		
Perimeter flow to GFLOW model, calibrated	1,839,043	2.8
Groundwater discharge to streams	64,059,636	95.6
Net withdrawal from high-capacity wells	1,090,483	1.6
Total outflow	*66,989,162*	*100.0*
Difference (inflow–outflow)	235	< 0.01

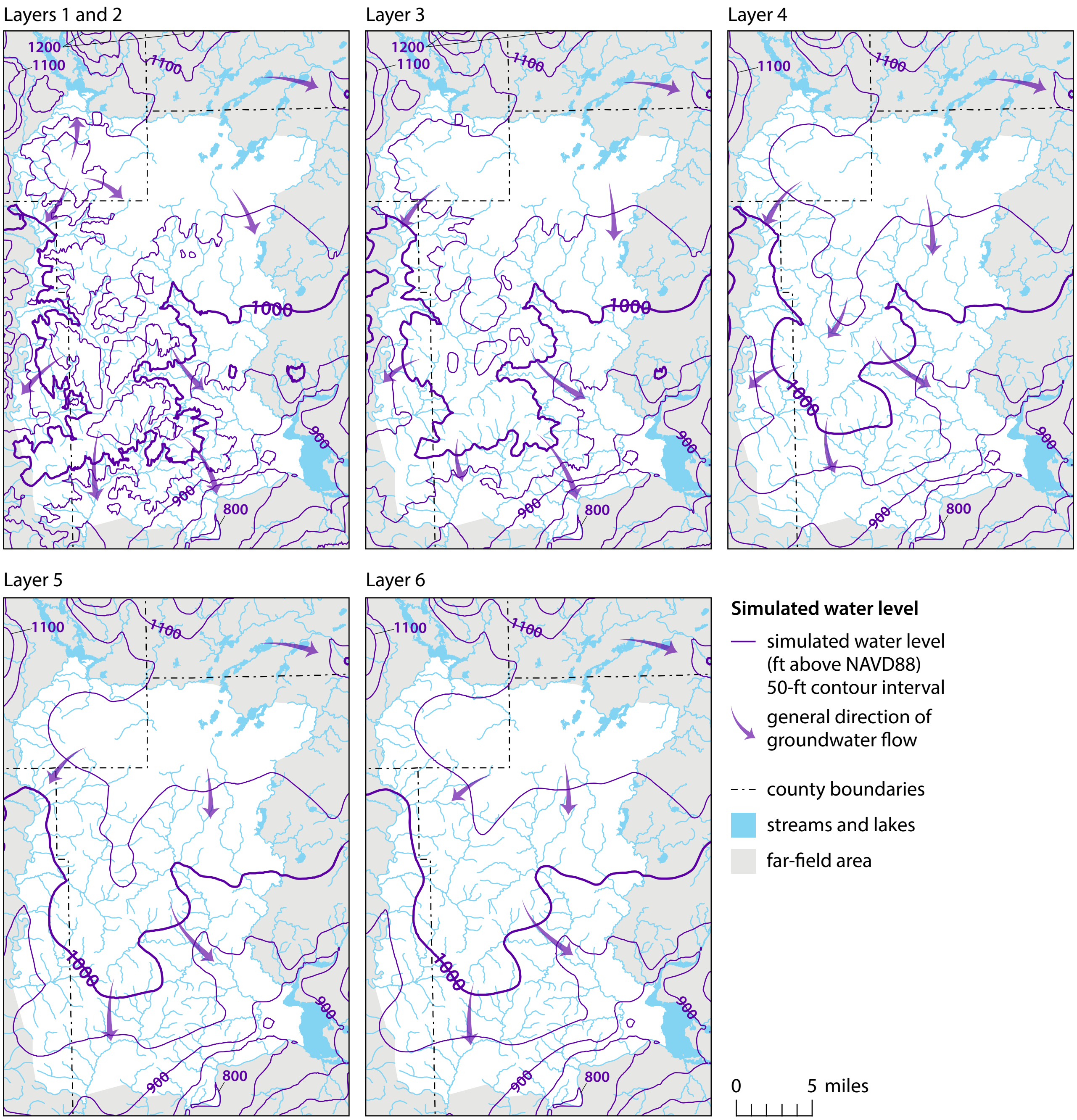


Figure 33. Simulated water levels, by model layer.

Scenario testing

Overview

The two main future stresses affecting water resources considered in this study are sand mining activity and expansion of irrigated agriculture. Scenarios were constructed for both stresses to evaluate their potential effects. The scenarios were constructed to represent the possible maximum stress that each activity could exert on the water resources of Chippewa County.

The scenarios cannot anticipate all factors that may affect the degree of development of mining or irrigated agriculture. Market forces and individual business decisions, combined with societal pressures, greatly affect land-use decisions. As a result, these scenarios should be evaluated as possible maximum buildout representations rather than a specific prediction of the future. The results should help inform which water resources are most susceptible to change from future land use. From this information, more focused forecast models could be developed to evaluate specific potential future land and water use scenarios.

For the agriculture scenarios, stakeholders indicated a potential maximum footprint of future irrigation. However, they also indicated that only 80 percent of that footprint was likely to be developed, demonstrating the uncertainty related to future conditions. Rather than making specific assumptions about which 80 percent would be developed, a Monte Carlo approach was adopted whereby samples of 80 percent development were generated and evaluated. Details are provided below.

For the mining scenario, stakeholders assisted with identifying the likely extent of minable source rock, or the minable area. Timing and extent of mining was less clear, making it difficult to formally analyze uncertainty as part of this scenario. Instead, a few instances were selected along a range from no additional mining to full and simultaneous implementation of mining throughout the minable area. Thus, the model uncertainty discussion in the following section is focused on the agricultural irrigation scenarios only.

Industrial sand mining buildout scenario

Scenario development

To develop a reasonable future buildout scenario for industrial sand mining, the WGNHS and Chippewa County staff evaluated the spatial relationships between (1) mapped sandstone deposits which meet specifications for use as industrial sand, (2) existing industrial sand mining activity, and (3) areas that are unlikely to be developed for mining due to public ownership (e.g., county, state), or special land designation. This was important to determine the overall footprint of minable sand to incorporate into the buildout scenario. One of the key assumptions for this scenario was the fact that industrial mining of the Wonewoc sandstone is actively occurring in the region and has demonstrably met the threshold for economic viability.

Following the initial evaluation, the resulting footprint was reviewed by the stakeholders group and modified accordingly. The following sections present the methodology that was used to identify locations where mining might be reasonably anticipated under the industrial sand mining buildout scenario. The information also documents the approach taken when incorporating the minable sand footprint into the scenario runs.

To determine the buildout scenario for industrial sand mining expansion, a GIS analysis was performed. This analysis used the following core assumptions:

- The Wonewoc and Tunnel City sandstones are economically viable deposits for industrial sand mining due to the properties of the sand and the proximity to available transportation corridors.
- There will be a sustained market demand for these deposits and mining will continue over at least the next 30 years.
- The location of mining may be constrained by deposit size, location, and cultural factors.

The analysis used the full extent of the Tunnel City Group and the Wonewoc Formation, identified as hydrostratigraphic units 2 and 3 in figure 7. The total minable area of the deposit is roughly 42,000 acres.

To determine the potential buildout mining scenario, certain criteria were used to exclude areas from the mapped extent of the Tunnel City and Wonewoc sandstones (WGNHS and USGS, 2016). Feedback from stakeholders helped determine the criteria. Excluded areas are

- not economically viable for mining (that is, the lower 40 ft of the Wonewoc hydrostratigraphic unit),
- noncontiguous deposits smaller than 100 acres,

- subject to mining restrictions (e.g., parcels are owned by Chippewa County and Wisconsin or are part of the state's Farmland Preservation program),
- lack overlying Tunnel City deposits (its presence means that the full thickness of Wonewoc sandstone is also present; Tunnel City sandstone also has potential as a marketable industrial sand reserve), or have
- more than five houses per 100 acres nearby.

Implementation in MODFLOW

Implementation of the mining buildout scenario involved altering both recharge and groundwater withdrawal across the potentially minable area. To create a baseline for comparison, a model run with no mines (neither future nor current groundwater withdrawals or alteration of recharge associated with existing mines) was simulated. This was done because in the timeline of future development, it is likely that existing mines will be at various stages of mining or reclamation as new mining activity begins. As a result, comparisons with baseline are intended to evaluate the composite effect of differing levels of simultaneous mining or reclamation.

Mine propagation

Following identification of the final minable sandstone footprint, a strategy was developed for dividing the resource into minable sections, or hypothetical mining sites. Staff from Chippewa County estimated that mines operating during 2012–2014 in the study area mined and processed approximately 10 acres of sandstone per year. Given the 5-year stages of mining and early and mature reclamation used with the SWB model to evaluate potential changes in recharge, the minable sandstone footprint was manually divided into 471 sections of approximately 50 acres each. Each section was catalogued as one of three development stages, with progression generally advancing from the perimeter of minable ridges toward the center. Each set of three 50-acre stages (1, 2, and 3) was then combined into an individual hypothetical mine site. This resulted in 155 mine sites, each of which contained approximately 150 acres of minable sandstone (fig. 34). Conceptually, hypothetical mines could cover additional acreage to facilitate processing and storage of mined sandstone, but such non-minable "support" areas were not considered for these scenarios because their size and location varies unpredictably among individual mine sites.

The pace and final maximum extent of industrial sand mine propagation in the study area is unknown. Given this uncertainty, a range of maximum buildout and mine-reclamation scenarios were simulated, consisting of 10, 25, 50, 75, and 100 percent of the potential minable area. For each of these scenarios, the appropriate percent of the 155 hypothetical mine sites were selected at random for simulating the effects of groundwater withdrawal for mining and successive change in recharge through mining and reclamation.

Groundwater withdrawal

Pumped groundwater is used in the sand mining process during several steps, often including the transport of sand and sorting into desired textural classes. While the source and amount of this process water differs somewhat among existing mines within the study area, all mines in the study

Industrial sand stockpile

Paul Juckem

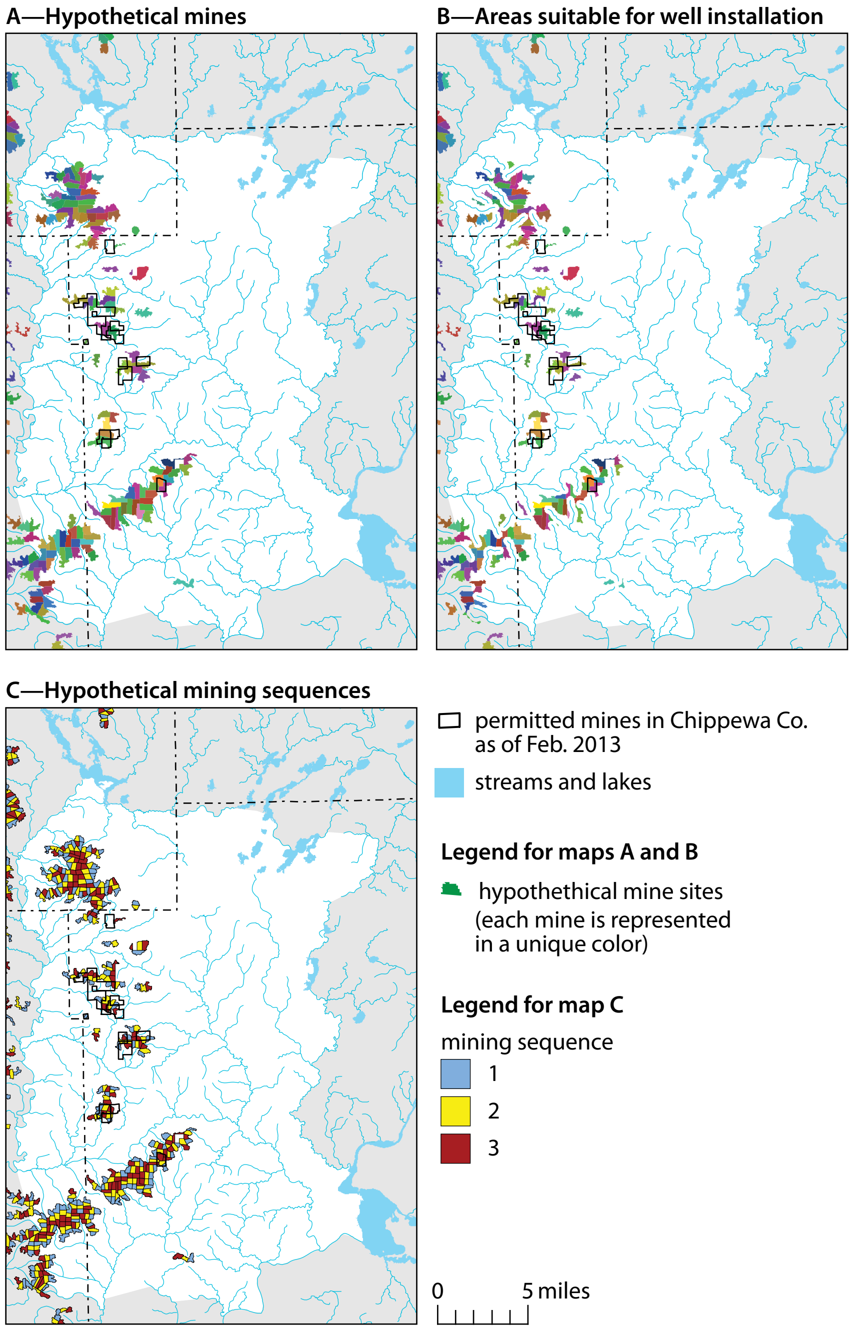


Figure 34. Mine buildout maps showing (A) the minable Wonewoc resource segmented into 155 hypothetical mines of approximately 150 minable acres each, (B) segments with well locations at least 1,200 feet from a stream, and (C) hypothetical three-step mine development sequences.

area used some amount of pumped groundwater for their mining or sand processing operations.

The average amount of groundwater used at five mines in the study area that pumped water from on-site wells for 2012–2014 was computed as 35 million gallons per year per mine site. This pumping rate was assumed to be representative of the annual groundwater withdrawal needs for an average mine site in the study area.

For each maximum buildout scenario, one pumping well per selected hypothetical mine site was added to a model cell within the 150-acre mine site. The individual model cell was chosen randomly from all cells within the minable sandstone footprint associated with each hypothetical mine site, excluding model cells that were within 1,200 ft of a stream. The buffer distance of 1,200 ft was used to conform to Wisconsin's high-capacity citing limitations (Wis. Admin. Code § NR 820 (February 2017)).

Wells were simulated using the MNW2 package and assigned top and bottom elevations that resulted in the wells being open to the entire Mount Simon aquifer (layers 4–6). For the reclamation scenarios associated with each of the five buildout scenarios, all groundwater withdrawal for mine sites was eliminated from the model.

Recharge

Changes in recharge from the calibrated model conditions are expected for both the mine buildout and mine reclamation scenarios because these significant changes in land use involve altering soil conditions and, subsequently, infiltration.

For the mine buildout scenarios, all hypothetical mine sites were assumed to be in the "Years 11–15" stage of the mine development process (table 2). That is, parcels 1 and 2 were simulated as being in the early reclamation phase and parcel 3 as being actively mined. Recharge for early reclamation areas is estimated at about 95 percent of the land's original recharge rate, and recharge for actively mined areas is about 40 percent of the original. (Table 2 shows measured differences in recharge for each parcel.) To simulate these changes in recharge with the MODFLOW model, each mine parcel or the corresponding randomly selected hypothetical mine sites (10–100 percent of mine sites) were assigned an updated recharge rate computed as the product of the calibrated recharge and the associated percent reduction (95 or 40 percent) from the calibrated recharge rate for each mine cell. This led to an overall decrease in simulated recharge for all mine buildout scenarios.

For the reclamation scenarios, the hypothetical mine areas selected for the buildout scenarios were transitioned to "Years 26–30" of the mine development process (table 2). That is, all parcels (1, 2, and 3) were simulated as having a mature reclaimed soil condition associated with prairie plant cover. The SWB model estimated a recharge rate of approximately 129 percent of the calibrated recharge rate for these previously mined areas. Thus, recharge was increased by 29 percent above the calibrated rate for hypothetical mine areas in all reclamation scenarios. This was a key assumption in this evaluation and depends on implementation of reclamation plans such that mature prairie plants would ultimately cover all mined areas. This assumption favors simulations of higher recharge; it may be used to inform best-management practices if high recharge through reclaimed materials is a desired outcome. If actual reclamation includes land cover with lower infiltration rates than prairie cover, recharge would presumably be less than that used for the reclamation scenarios described in this report.

Results

Results of the mine buildout and reclamation scenarios are displayed in terms of decreases or increases in stream baseflow as compared against the baseline simulation in which the calibrated model was simulated without any pumping from mines (figs. 35 and 36). For these results, only streams that were flowing during the baseline simulation are shown, and larger stream widths correspond with larger baseflows in the baseline simulation. Percent changes in baseflow between the baseline simulation and the buildout or reclamation scenarios are illustrated through a color scale. The minimum visualized change (plus or minus 10 percent change in baseflow) in figures 35 and 36 was loosely based on the results of Zorn and others (2008), who found that baseflow reductions as small as 10–20 percent of the mean August baseflow could result in reduced abundance of brown and brook trout (among other species), particularly in cold-transitional streams.

For the mine buildout scenarios, increased pumping from the Mount Simon aquifer combined with reductions in recharge associated with mining activity and initial soil development on early reclaimed areas resulted in reductions in baseflow for all scenarios. The largest reductions in baseflows are consistently focused in headwater streams, with some headwater reaches showing the potential to go dry (100 percent decrease) in scenarios with greater simultaneous expansion of mining (fig. 35, parts d and e). The range of results associated with increasing proportions of simultaneous mine expansion (10–100 percent) illustrates how the magnitude of baseflow reduction would be expected to vary according to the extent of simultaneous mine development. Regardless, for all mine buildout scenarios, headwater streams near major sources of minable sandstone show the greatest potential reductions in baseflow. While the magnitude of the reductions for some stream reaches are within the range of natural variability over the course of a season, the simulated reductions would represent a new, lower baseflow condition upon which seasonal and longer-term variability would overprint.

For post-mine reclamation, baseflow increased for all five scenarios due to elimination of pumping and increased recharge from expected soil structure development below mature prairies (fig. 36). Indeed, the locations and magnitudes of change mimic those seen for the mine buildout scenarios, but in the opposite direction. That is, the largest increases in baseflow are focused in headwater streams, especially near major ridges that would have been largely mined and subsequently reclaimed to prairie. Similar to the mine buildout scenarios, the simulated increases in baseflow would represent a new, higher baseflow condition upon which seasonal and longer-term variability would overprint. As noted previously, if mine reclamation results in land use other than mature prairies, the simulated increase in recharge and associated baseflows would likely be less than the results illustrated in figure 36.

Regardless of future conditions and the assumptions inherent to these scenarios, the consistent spatial patterns shown in figures 35 and 36 highlight the sensitivity of headwater streams to land use along bluffs in the study area.

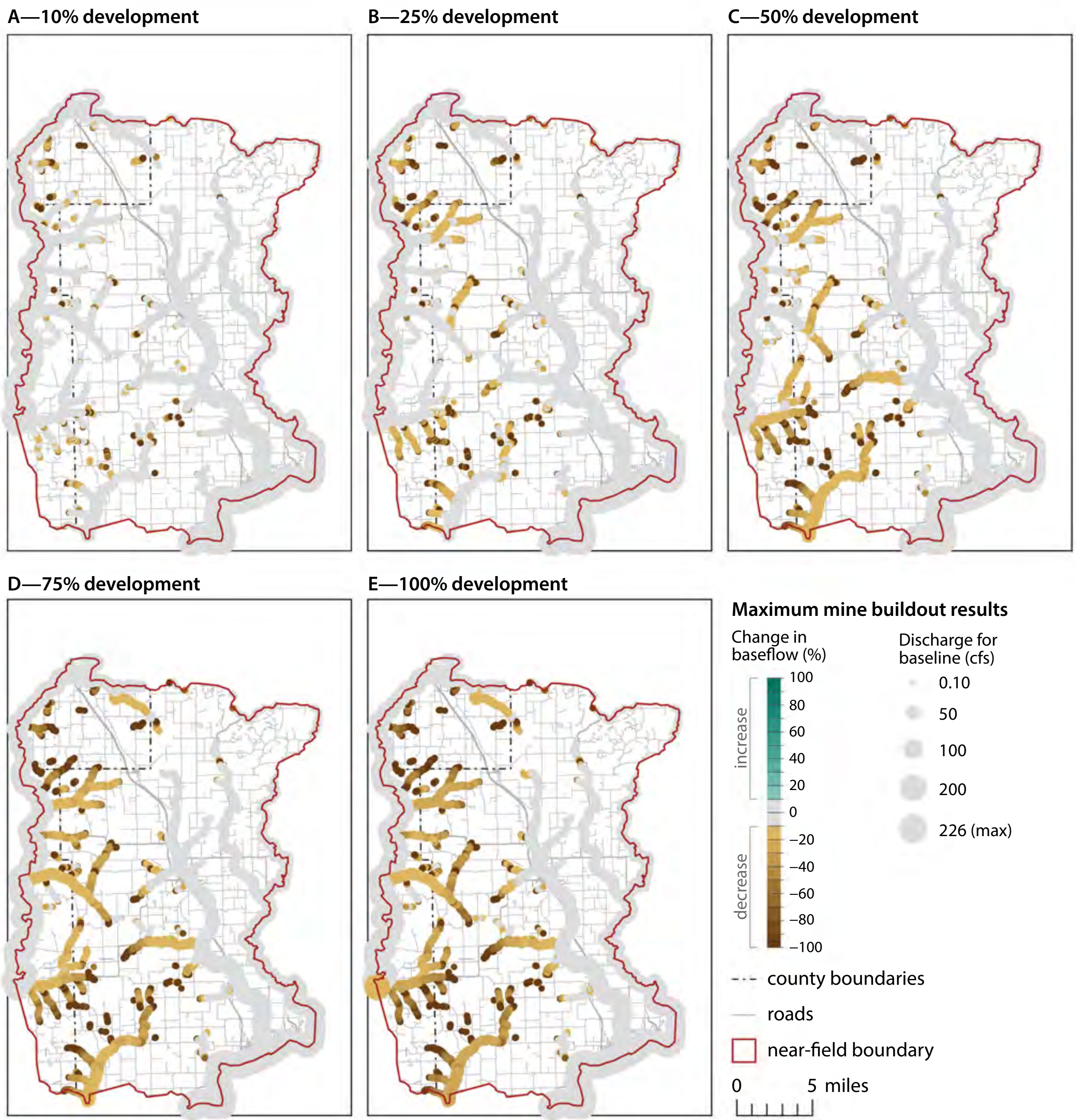


Figure 35. Percent baseflow change due to simultaneous mine development at different percentages of the minable Wonewoc resource.

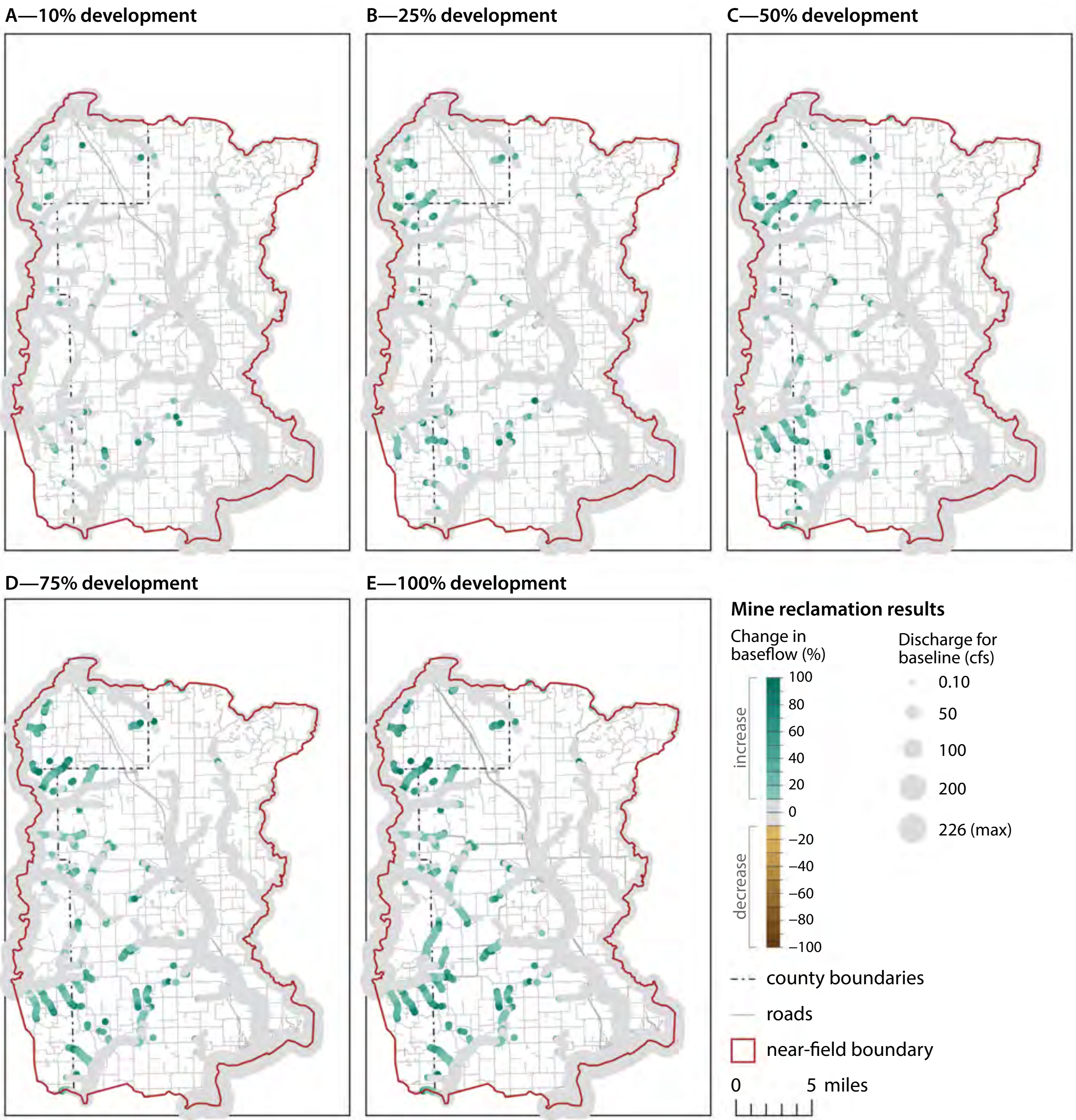


Figure 36. Percent baseflow change due to long-term prairie reclamation following simultaneous mine development of the minable Wonewoc resource.

Irrigated agriculture buildout scenario

Scenario development

To develop a reasonable future buildout scenario for irrigated agriculture, the WGNHS and Chippewa County staff evaluated the relationship between the location of existing high-capacity irrigation wells and both soil properties and land-use types within the study area.

Following the initial GIS evaluation, the results were shared with the stakeholders group to solicit their feedback so that improvements could be made to the buildout footprint of potentially irrigable lands. The following sections present the final stakeholder-informed and supported methodology that was used to identify the potential locations where irrigation could reasonably be anticipated under the irrigated agriculture buildout scenario.

Michael Parsen

Existing high-capacity irrigation wells are typically found in areas that are classified as agricultural lands and have well-drained soil with low to moderate slopes. These features served as selection criteria for identifying lands that would be well suited for future agricultural irrigation and could therefore be included in the future irrigated-ag buildout (i.e., expansion) scenario performed for this study.

The following sections identify the source of each dataset and explain the methodology of how the data was used to determine potential locations for adding new irrigation wells under the future irrigated agriculture buildout scenario. The final section describes how these data were combined to determine potential distribution of future wells.

Water-use data

The WDNR high-capacity water-use database was used as the basis for identifying the location of existing irrigation withdrawals (WDNR, n.d.-c; R.A. Smail, WDNR, oral communication, 2015). This database contained all high-capacity withdrawal points as of December 2013. The WDNR's water-use identifier for irrigation withdrawals was used to distinguish high-capacity irrigation withdrawals from other high-capacity withdrawals.

Soil data

The USDA-NRCS SSURGO 2014 soil map was used to generate a coverage of soil data across the study area (Soil Survey Staff, 2014). The most useful soil data categories for this evaluation included soil drainage and soil slope. These two soil categories are strongly related to the location of existing high-capacity irrigation wells and provide a basis for identifying lands potentially suitable for future agricultural irrigation.

The selection criterion for soil drainage used soils that are classified as excessively drained, somewhat excessively drained, well drained, and moderately well drained. These well-drained soils are strongly related to the location of existing high-capacity irrigation wells. Roughly 90 percent of existing high-capacity irrigation wells are located in soils with excessively drained to moderately well-drained soils.

The selection criterion for soil slopes included soils which are classified as A (0–3 percent grade), B (0–6 percent), and C (6–12 percent) slopes. These low to moderately sloped soils are strongly related to the location of existing high-capacity irrigation wells. Roughly 96 percent of existing high-capacity irrigation wells are located in soils with A, B, or C slopes. Conversations with irrigation experts with experience in western Wisconsin confirmed that modern irrigation and center pivot systems can efficiently irrigate soils on slopes up to 12 percent (J. Panuska, UW–Madison, oral communication, 2015; B. Graham, Robert's Irrigation, oral communication, 2015).

Based on feedback from farmers in the study's stakeholders group, the following soil types were removed from consideration because they were considered to not require irrigation: SgA and SgB (Seaton silt loam, 0–2 and 2–6 percent slopes); TeB (Tell silt loam, 1–6 percent slopes) in areas west and south of Bloomer near Cooks Valley; and ScB (Scott Lake sandy loam, 1–6 percent slopes) and SdA (Scott Lake loam, 0–3 percent slopes) in areas east of Bloomer. For the purposes of this regional study, it was agreed that all occurrences of these soil types be removed from the scenario calculation within the entire model area, not just the select areas they were identified by farmers east and west of Bloomer (D.J. Masterpole and S. Ebel, Chippewa County, oral communication, 2015).

Land-use data

The National Land Cover Database (Homer and others, 2011) land-use map was used to generate a coverage of land-use data across the study area. Mapped agricultural lands are closely related to the location of high-capacity irrigation wells and provide a basis for identifying lands potentially suitable for future agricultural irrigation.

The selection criterion for land-use type included lands which were classified as either row crop or hay/pasture. Roughly 91 percent of existing high-capacity irrigation wells are located in or within 100 ft of agricultural lands classified as row crop or hay/pasture. For the purposes of this evaluation, it was assumed that the future footprint of agricultural lands will not dramatically change from the 2011 coverage.

Determination of percent-irrigable lands and distribution of future wells

Soil drainage, soil slope, and land-use selection criteria were combined using ArcGIS mapping software to determine which land areas satisfied all three criteria and were therefore potentially irrigable. This map of potentially irrigable land was gridded using quarter-quarter sections (approximately 40 acres each) to provide a property-based assessment. The percentage of potentially irrigable lands, referred to as "percent-irrigable", was calculated for every 40-acre grid cell. This gridded map of percent-irrigable lands provided a basis for distributing irrigation wells under the future irrigated agriculture buildout scenario.

The final step was to determine a reasonable threshold of percent-irrigable land within any given 40-acre grid cell that would justify adding a new well during the irrigated agriculture buildout scenario. This was done by determining which grid cells contained the largest number of existing high-capacity irrigation wells. The percentage of irrigable land within each cell was categorized into one of 10 groups, or deciles. The deciles represent an index of irrigation suitability, ranging from least suitable (0–10 percent) to most suitable (90–100 percent).

As shown in figure 37, the largest number of existing high-capacity wells were located in the uppermost decile (90–100 percent), or most-suitable category. The total number of wells decreased markedly at smaller percent-irrigable deciles, stabilizing at about 10 wells between the 0 and 70 percent deciles. Based on this evaluation, grid cells with at least 70 percent irrigable land were considered reasonable locations for distributing new wells in a future irrigated agriculture buildout scenario.

We set a minimum buffer of 1,200 ft between the placement of potential future wells and the stream network. This decision was based on stakeholder feedback and on current WDNR well-siting criteria (Wis. Admin. Code § NR 820 (February 2017)). For the purposes of the future irrigation scenario, quarter-quarter sections located entirely within the 1,200-ft buffer were deemed unsuitable for placement of a high-capacity well and removed from consideration.

Implementation

The irrigated agriculture buildout scenarios were generated to be consistent with stakeholder-informed likely future conditions. This section describes the implementation details that were applied.

A key component of the analysis stipulated that no more than 80 percent of potentially irrigable land would make up the maximum footprint. In other words, 20 percent of potentially irrigable land would be held back from irrigation due to economic or social considerations. The stakeholders did not indicate specifically which parcels would be in that 80 percent, so random samples were evaluated. Initially, 2,000 Monte Carlo realizations (samples) were made of the future agricultural conditions. For the cases including model uncertainty through null-space Monte Carlo (NSMC), 2,000 realizations of model parameters were also generated. To create a baseline for comparison, a model run with no irrigation (neither future nor current irrigation) was evaluated. This was done to account for the possibility that some existing irrigation may

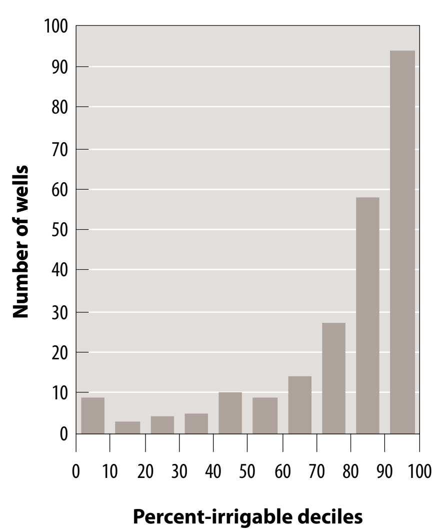


Figure 37. Number of existing high-capacity irrigation wells, by percent-irrigable decile.

cease or be transferred; comparisons with the baseline allow evaluation of the aggregate effect of irrigation.

Irrigation suitability

Based on the metrics discussed above, all quarter-quarter sections with an irrigation suitability index of 70 percent or greater were included in the potential footprint of future irrigation. These quarter-quarter sections, shown in figure 38, were then sampled with equal probability with each realization comprising 80 percent of the footprint.

Crop selection

The three most commonly farmed crops in the modeling area are corn (57.5 percent), soy (26.9 percent), and alfalfa (15.6 percent) (J.R. Clark, UW–Extension, oral communication, 2016). These crop distributions were maintained in the future scenarios by sampling a discrete probability distribution using the same percentages.

Pumping rates and excess irrigation return

To simulate irrigation pumping, statewide average rates of pumping (R.A. Smail, WDNR, oral communication, 2016) were applied, based on assumed future crop selection, to each quarter-quarter section in the scenario. These rates were 7.9, 7.0, and 7.4 in/yr for corn, soy, and alfalfa, respectively. Not all water pumped for irrigation is consumed by evaporation, transpiration, or uptake into vegetable matter. In most fields, some irrigation water returns as recharge. Comparing irrigated to non-irrigated crop coverages in the Little Plover River Basin, excess recharge was estimated to be 1.5, 0.5, and 1.0 inches for corn, soy, and alfalfa, respectively (M.L. Kniffin, WGNHS, written communication, 2016). In both cases, the water amounts were converted to model units of cubic ft/day. The rates were then applied to a region of 31.4 acres for each field (the portion of a 40-acre field irrigated using a center-pivot irrigation system).

Target layer for irrigation well

Two possible depths for irrigation wells were evaluated: the shallowest and the deepest layers that can support pumping. The shallowest layer was chosen to minimize the amount of lift required for pumping; thus, potentially, limiting electrical costs for operation. Installation costs at the shallower depth were also expected to be lower. Conversely, deep layers were expected to have a more reliable and consistent water supply.

The MODFLOW-NWT modeling code (Niswonger and others, 2011) reduces simulated pumping from wells as the simulated water table drops to the bottom of or below model cells containing wells to simulate the condition that wells in dry model cells cannot sustain pumping. Analysis comparing the two well depths suggests that placing the wells in the shallow layers may result in insufficient water production.

We analyzed the sustainability of the two pumping depths. The model found that for the shallow simulation, 30.7 percent of requested pumping went unmet; for the deep simulation, only 0.2 percent of requested pumping went unmet. This behavior is location-specific—some areas of the model domain would be less affected by reduced pumping. To perform the model-wide analysis, only the deep scenario was retained.

Model uncertainty

In addition to the inherent uncertainty of future conditions, there is also underlying uncertainty in the model parameters as estimated by history matching. The uncertainty in the model parameters was formally evaluated to explore the effect model uncertainty has relative to uncertainty about future agricultural conditions. The null-space Monte-Carlo (NSMC) technique (Tonkin and Doherty, 2009; Doherty, Hunt, and Tonkin, 2010) was used, as implemented in pyEMU, a Python framework for environmental model uncertainty analysis (White and others, 2016). The technique creates samples, or realizations, of model parameters exploring values that are not directly informed by observations in the history-matching process. In this way, information from history matching is honored and parameter values that are not constrained by observations are tested to ensure that their variability is reasonable for the parameter. For example, hydraulic conductivity in a region with a paucity of observation data informing its estimated value will be allowed to vary more than a hydraulic conductivity value that has nearby observations constraining it. The uncertainty in model parameters is propagated through the model and can affect model outputs.

Results

In the case of NSMC, a cutoff of the objective function was chosen above which scenarios were considered unrealistic. In this process, 709 scenarios were dropped. In some cases, extremely high anomalous baseflow results were simulated due to model instability. As a result, any scenarios with a maximum baseflow greater than 110 percent of the highest baseline baseflow value were rejected. This amounted to 123 for the NSMC scenarios and 172 for the non-NSMC scenarios. The discrepancy is due to some of the scenarios with anomalously high baseflow results being already rejected due to high objective function in the NSMC case.

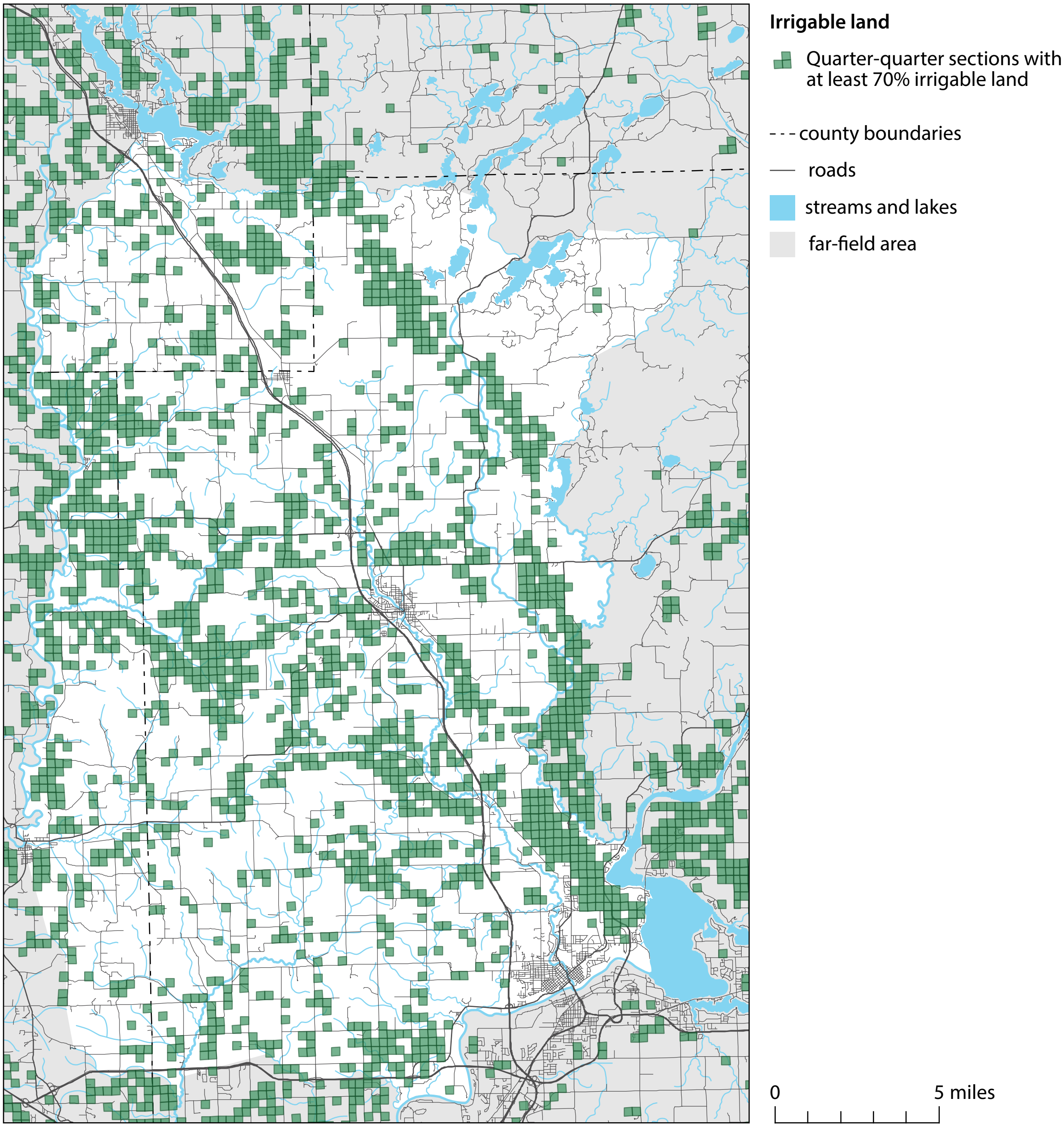


Figure 38. Potential future irrigation fields. Highlighted cells (quarter-quarter sections) contain at least 70 percent irrigable land and have a portion that is at least 1,200 ft from a stream.

Figure 39 presents a summary of percent reductions in baseflow in simulated streams relative to baseline baseflow, with the minimum visualized change set to plus or minus 10 percent change in baseflow as described for the mine buildout scenarios. Panels A and B show the results when only future agricultural stressors were considered; panels C and D show the results with both future agricultural stressors and model uncertainty using NSMC. In both cases, median baseflow reduction is modest (especially in the larger streams) with most streams showing reductions less than 20 percent. As expected, greater percent reductions are noticed in the headwater streams which, with low flows in any case, are the most vulnerable to changes of conditions. In the non-NSMC scenarios, the standard deviation is less than 10 percent except for segments in Elk Creek and its tributaries in the south of the model domain. This relatively low standard deviation indicates that the mean behavior of the realizations is relatively consistent. Incorporating model parameter uncertainty contributes to much greater variability in baseflow estimates (see fig. 39, panel D) and also higher levels of baseflow reduction, particularly in the headwater streams. Note that in a few cases, increases in recharge due to parameter uncertainty even show potential for the median baseflow to increase slightly in a few of the most variable headwater stream reaches.

Comparison of base model to future scenarios

The mine-buildout, mine-reclamation, and irrigation-buildout scenarios were not designed to represent specific predictions of future conditions. This is partially because several factors could not be reliably predicted, such as the cyclical demand for industrial sand, effects on infiltration and recharge related to implementation of reclamation practices, and actual location, depth, and withdrawals for irrigation wells. Instead, the scenarios were designed around stakeholder insights and measurable characteristics (for example, average withdrawal rates, extent of sand deposits, and irrigation patterns). Thus, the scenarios inform general understanding of how changes in land use could potentially affect groundwater recharge and discharge to streams.

The industrial sand mine and irrigated agriculture scenarios were not designed for direct comparison to each other for several reasons. First, uncertainty related to specific future conditions limits direct comparison. Second, differences in the rate and timing of development were expected—mine-buildout scenarios depended on the level of simultaneous development of minable areas followed by reclamation; irrigation-buildout scenarios anticipated a continual increase toward a potential maximum. Third, information provided by stakeholders resulted in different approaches to mining and irrigation scenarios. For example, irrigation expansion patterns were relatively well informed with approximate percent values associated with many decisions. In contrast, mine expansion rates were expected to depend on market conditions and there was little historical information to quantify market cycles and rates of mine expansion.

The mine- and irrigation-buildout scenarios illustrate a few common phenomena related to water resources that may occur in the study area.

1. Headwater streams appear to be the most sensitive stream reaches to groundwater withdrawals and changes in recharge associated with expansion of these industries, as illustrated by larger percent changes in headwater areas compared with many downstream reaches.
2. Baseflow reductions are expected to increase as groundwater withdrawal increases or recharge declines, with greater baseflow reductions occurring near local withdrawals (or recharge declines) compared with distant withdrawals (or recharge declines).
3. Simulated reductions in baseflow due to expanded irrigation or mining (or any activity that increases withdrawals or reduces recharge) are systematic and form a lower baseline of streamflow from which natural seasonal variability will occur. That is, seasonal variability (drought, floods, etc.) may be larger than some of the changes simulated in the scenarios, thus obfuscating some direct observations, especially periodic or short-term observations. Nonetheless, the simulated buildout results demonstrate that long-term baseflow conditions would be expected to decline such that seasonal low-flow conditions could be exacerbated in the future, depending on actual expansions.

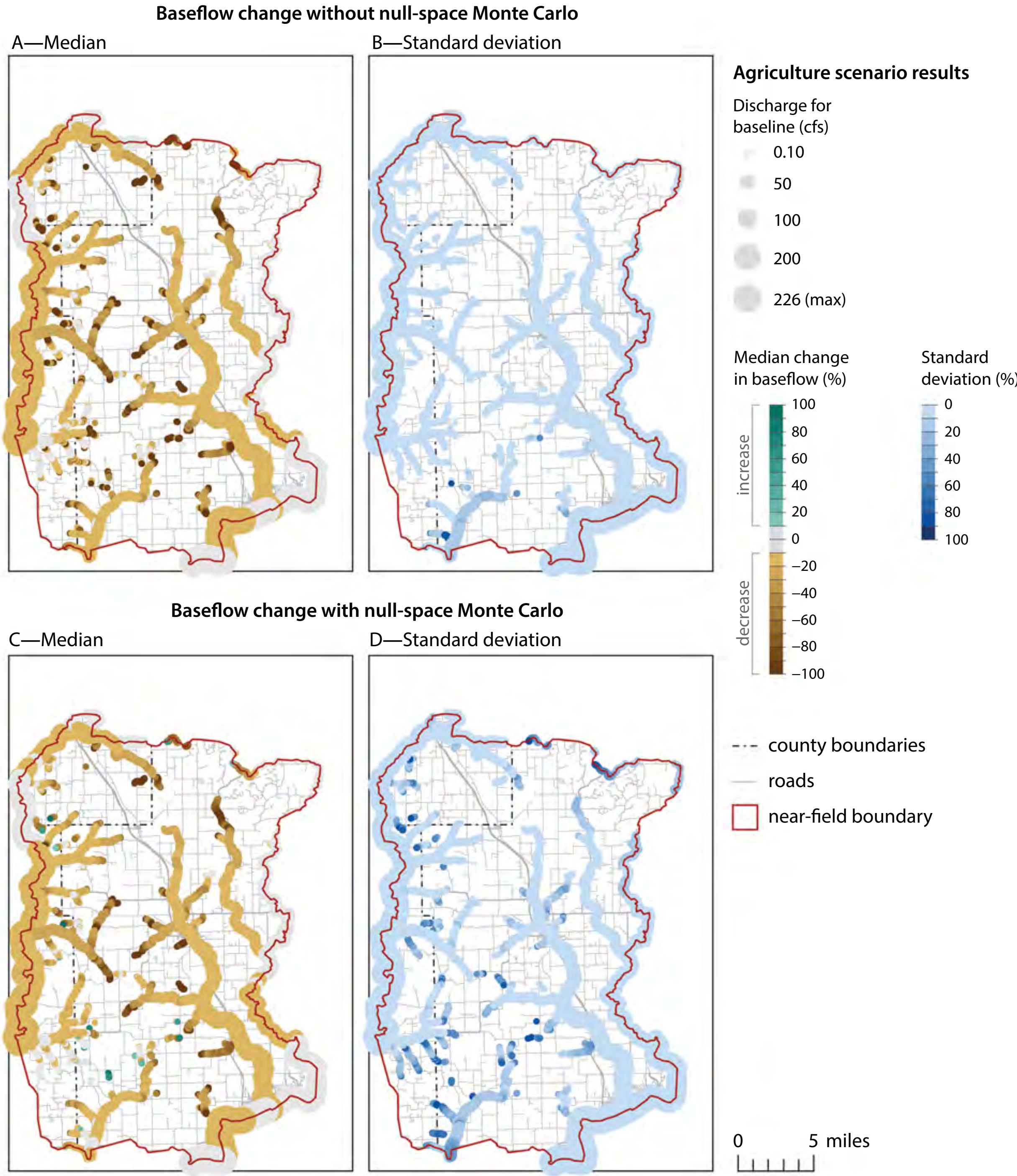


Figure 39. Percent baseflow change results expressed as median (panels A and C) and standard deviation (panels B and D) of the Monte Carlo simulation model runs. All results consider the uncertainty of future agricultural stressors and the results shown in panels C and D additionally incorporate model parameter uncertainty considered using Null-Space Monte Carlo. Inclusion of model parameter uncertainty increases the variability of simulated baseflow in many headwater streams.

Note that carefully planned expansion of water withdrawals and mine reclamation could help to mitigate some of the simulated effects of increased groundwater withdrawals or reductions in recharge. Some examples of management considerations include (1) locating pumping as far away as possible (both horizontally and with depth) from sensitive groundwater-dependent areas, (2) staggering mine development over time, and (3) reclaiming mined areas to high-infiltration land covers and land uses, such as planting prairie grasses with deep roots that enhance macropore development and limiting compaction from vehicular use. This list is not exhaustive and ideal approaches would likely incorporate local insight and feedback.

Finally, the study provides a foundation from which management considerations tied to ecological thresholds (Foley and others, 2015) could be evaluated. That is, transference of the scenario results described in this report to ecological thresholds is currently limited by the long-term average steady-state nature of the simulations and the generalized nature of the buildout scenarios. These limitations could be addressed in future applications of the models by incorporating seasonal variability into the MODFLOW model and evaluating actual development and reclamation practices or permit applications as compared with the generalized buildout scenarios. For example, simulating seasonal baseflow variability is important for evaluating ecological thresholds because the sensitivity of many fish communities to flow alteration is greatest during August (or during other summer droughts), when streamflows are often near annual lows and stream temperatures are often near annual highs (Zorn and others, 2008). Fish species that rely upon stream sections known as riffles (shallow, fast-moving sections with few fine-grained deposits) may be particularly sensitive to flow alterations, especially those inhabiting cold-transition streams (intermediate between cold "trout" steams and warm-water streams) (Zorn and others, 2008). Lyons and others (2009) classified several streams in the study area as potentially cold-transitional (or "coolwater") stream types. Extending hydrologic simulations to ecological thresholds would also likely benefit from continued ecological and streamflow monitoring, as well as from stakeholder discussions about ways to incorporate ecological thresholds into future decision making (Foley and others, 2015).

Michael Parsen

Transferability

While the groundwater flow model and scenarios described in this report were designed to account for the hydrogeologic conditions specific to western Chippewa County, a number of principles emerged from this study that may be generally transferable and worthy of consideration in similar hydrogeologic settings beyond the study area. Many of these principles involve hydrogeological site characterization methods, while others relate to on-site best-management practices for reducing runoff, monitoring groundwater levels and streamflows, and anticipating potential effects to groundwater and surface water features. The following discussion presents several key findings from this study and is intended to serve as a starting point for future investigations.

Site characterization methods

Groundwater flow models are comprehensive tools that are useful for evaluating effects of stressors on water resources. The models described in this report incorporated many forms of data and information, such as hydrostratigraphy and aquifer properties, streamflows and water levels, groundwater pumping rates, and recharge informed from precipitation, soil properties, and land cover. As a result, the quality of the data fed into the model underpins the quality of the model itself. Accurate measurements and record-keeping are critical components of any investigation. The following discussion describes how high-quality site assessments and careful measurements can facilitate subsequent analyses of potential development (mining, agriculture, urban, or other activity).

Well construction reports

Well construction reports are routinely submitted to the WDNR by well drillers every time a well, both low and high capacity, is drilled in Wisconsin. These reports often serve as the sole source of information about the well over its lifetime and are only as useful as the quality of information recorded by the well driller. If thoroughly completed, the well construction report includes basic information about the well such as the location, date of drilling, observed groundwater level, and construction (e.g., well/casing depth and diameter). Detailed WCRs also include information about specific capacity testing (e.g., maximum observed drawdown, pumping duration, pumping rate) and the lithology of materials encountered with depth while drilling.

Based on this study, the following observations were developed regarding the verification and usefulness of WCRs:

- The information contained in the WCR is only as good as the location confidence. For example, if the depth to bedrock is listed as 50 ft but the location of the well is off by 1,000 ft, the depth measurement can be very misleading if the land surface elevation changes significantly over that 1,000-ft distance. The location confidence of a well is contained in the WCR; efforts to improve locations should be tracked by providing an updated estimate of location confidence.
- The level of lithological detail contained in WCRs can vary significantly, with some records containing many observations and others none at all. Irrespective of the level of lithological detail, WCR data is marginally helpful for delineating geologic or hydrogeologic contacts. The most useful lithologic information from WCRs is often the contact between unlithified materials and bedrock or between Paleozoic sedimentary bedrock and Precambrian crystalline rock.
- In western Wisconsin, where the Paleozoic record consists of a succession of sandstones, it is often challenging to distinguish between sandstones of the Elk Mound Group (Mount Simon, Eau Claire, and Wonewoc Formations) or where unlithified sand directly overlies poorly cemented sandstone. Furthermore, since drilling is often performed using wet-drilling methods, the finer-grained materials (silts and clays) are preferentially washed away and commonly underrepresented in drillers' samples. For this reason, lithological descriptions from WCRs are typically biased towards coarser materials, making identification of potential aquitard features more difficult.
- Specific capacity test data included in WCRs is useful for roughly estimating the transmissivity of hydrostratigraphic units or model layers, particularly when applied to a large dataset. The methodology for this calculation is described by Bradbury and Rothschild (1985) and also outlined in earlier sections of this report.

- Water-level data included in WCRs are often mediocre; however, when taken in the aggregate over an entire study area, they represent an important source of calibration data. The location confidence of a well is also a consideration when using water-level data because incorrect well locations can result in incorrect land-surface elevations, leading to incorrect water-level estimates.

Stream surveys and surface water observations

Streamflow gaging and other surface water observations are particularly useful for developing a conceptual model of the hydrogeologic system and calibrating groundwater flow models. In this temperate and humid region of the United States, surface water features are often inextricably connected to groundwater systems and knowledge about streamflows during baseflow conditions (when streams are largely supported by groundwater discharge) aid in calibrating groundwater flow models.

Based on this study, the following observations were developed regarding the value of streamflow gaging data and other surface water characteristics:

- Continuous streamflow gages, such as those installed along Como and Trout Creeks, provide high-quality measurements of streamflow and allow for baseflow to be calculated from the annual record.
- Synoptic streamflow measurements performed over a short period of time (days), along multiple streams, during dry conditions provide a distribution of baseflow targets throughout the study area. Although measured streamflows may not represent long-term average baseflow conditions, they can be adjusted closer to long-term averages by means of a statewide multiple-regression analysis (Gebert and others, 2011) for a nearby reference gaging station when appropriate.
- Observations of gaining and losing stream reaches during synoptic surveys can provide insights into the hydrogeologic role of aquifers and aquitards. In western Chippewa County, perennial streams were observed to lose water in areas where the Eau Claire shale became eroded in the downstream direction, suggesting the Eau Claire shale can serve as an aquitard and maintain elevated groundwater levels where it is present.
- Observations of small upland seeps can inform the conceptual model and guide flow model development. Seeps observed within the study area suggested that perched groundwater flow may occur within upper bedrock units along reduced conductivity (e.g., shale-rich) intervals. However, water seeping from these outcrop faces was observed to re-infiltrate nearby, suggesting that the seeped water ultimately rejoins the regional groundwater system before discharging to streams. Because of this re-infiltration into the regional system, incorporation of perched aquifers or seeps/springs was not justified for this study. Nonetheless, hydrogeologic settings in other areas could merit additional evaluation of perched aquifers.

Geophysical logs

Geophysical logging surveys represent one of the more powerful tools for characterizing hydrogeologic properties, developing a conceptual model of the regional hydrogeology, delineating hydrostratigraphic units, and building model layers. These surveys provide information about the hydrogeologic properties of the rock, such as evidence for preferential flow along fractures or high-conductivity zones, and the spatial extent and thickness of aquifers and aquitards. Geophysical logs routinely include fluid temperature and conductivity, resistivity, natural gamma, and borehole caliper data. More specialized logs such as optical borehole imaging (OBI), acoustic borehole imaging (ABI), and borehole flow can also be performed and provide considerably more detail, especially regarding hydrogeologic conditions.

The following observations were developed regarding the value of geophysical logging surveys:

- While one or two geophysical logs are informative, multiple logs over an extended area provide a framework for making hydrostratigraphic picks and delineating model layers. The best logs are obtained in wells with a diameter of 6–18 inches (to ensure proper deployment of the geophysical tools and collection of high-quality data) and from below the bottom of the well casing in the open interval of bedrock wells, where the borehole wall is clean and the borehole is free of obstructions.
- The ideal time to perform a geophysical log is often shortly after the well is drilled but before the pump is installed or while a pump is removed for service or to rehabilitate the well. Maintaining close working relationships with well drillers and landowners is a good way to secure access to newly drilled or soon-to-be modified wells.

- Gamma logs and resistivity logs are particularly useful for identifying the presence of shale layers which may denote the location of aquitards and define the upper and lower extent of aquifers.
- Borehole flow logs can provide evidence of upward or downward hydraulic gradients in the formations surrounding a well, leading to insights about the hydrogeological system.
- The combination of geophysical logs with lithological observations from WCRs or detailed geologic logs provide additional evidence for characterizing hydrogeological properties and delineating hydrostratigraphic units and model layers.

Stakeholder engagement

The establishment of a stakeholders group that represented the diversity of interests within the study area was critical to the overall success of this groundwater study. Stakeholders provided technical feedback to the study team and helped communicate study results to their representative groups as well as the general public. Active stakeholder participation throughout the study ensured continuity of project development and allowed for new findings and insights to be shared with the project team. Data and site-specific knowledge from farmers, mine operators, land owners, scientists, consultants, regulators, UW–Extension specialists, and the general public all provided valuable insights that informed model development and scenario testing.

The following observations were developed regarding stakeholder engagement:

- Work with project sponsors began early in the study design and was intended to bring together a group of well-respected stakeholders that represented the diverse set of interest groups relevant to the study.
- Regular updates were provided to stakeholders through in-person meetings, webinars, emails, letters, and technical reports. Meetings and events documented progress and created opportunities for stakeholders and the public to give feedback and inform future work.
- Stakeholders and active citizens were consulted regarding their field observations. These observations were later confirmed through field trips and site visits.
- Flexibility was built into the study design to ensure ample time for incorporating stakeholder feedback. Input by stakeholders resulted in the need to refine build-out scenarios and prompted the collection of additional field data.

Infiltration and groundwater recharge

Infiltration measurements and observations of ponded water on some mine sites demonstrated that compaction during mining and reclamation can increase runoff and reduce groundwater recharge at mines. The following practices could presumably mitigate some of these effects:

- Reducing the severity of compaction in the active mine area and reclamation areas, or subsequent tilling could potentially mitigate some of the effects of compaction.
- Establishing cover vegetation over exposed soils could potentially slow runoff and erosion, although increases in recharge associated with mature soil structure may require years or decades to fully develop.

Groundwater development

Consideration of the three-dimensional distance between sensitive areas and proposed groundwater development (withdrawals) is an important component of permitting and land-management planning. Such three-dimensional considerations include understanding of well and casing depths in relationship to aquitards, the magnitude and seasonality of withdrawals, and the sensitivity of water bodies to hydrologic alteration. For example, a shallow well pumping at a high rate during a summer drought adjacent to a headwater stream could logically have a substantial effect on the stream. Conversely, a deep well completed below an aquitard and located a moderate distance from a large river would be expected to have less effect on the river than the example above.

Model limitations

The model is a three-dimensional representation of the groundwater system and groundwater/surface-water interactions in western Chippewa County at the regional scale. The model is intended to inform questions at the regional scale and is 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 a regional model. Although the model simulates flow between groundwater and surface water, it is not a surface-water model—the model can only simulate baseflow, it cannot simulate flooding and stormwater runoff. Nonetheless, this model provides a regional foundation for smaller-scale studies and can be used as a starting point for refined evaluations of site-specific problems. The following sections summarize additional model limitations.

Limitations related to discretization

The hydrogeological system in western Chippewa County was strategically simplified during model discretization. The smallest horizontal grid dimension in the model is 150 ft, and cannot capture some geologic complexities, such as facies changes, erosional channels, sand and gravel lenses, thin silt lenses, fractures, and other features that occur at smaller dimensions. Similarly, the vertical discretization of the groundwater system into six layers required strategic lumping of hydrogeologic properties and does not represent features that exist at finer scales.

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 transient phenomena, and so the results of steady-state simulations represent long-term average conditions. Conversely, steady-state models neglect storage within aquifers that can provide a short-term buffer against hydrologic stressors. Finally, calibration of a steady-state model to data that was collected at different intervals over an extended time period required an assumption that, in aggregate, the calibration dataset was representative of average conditions during the study period. While water levels and baseflow at the gaging stations generally coincided with the study period, synoptic streamflow measurements were measured on a single date. These measurements were adjusted using flow data from a nearby long-term gage to better approximate average conditions during the study period.

Limitations related to model scenarios

Several assumptions were invoked for the scenario simulations due to limited knowledge of future trends and patterns. Specifically, a single representative pumping rate was applied for all mines and for each specific crop type, ignoring local variability and design considerations. Similarly, withdrawals were assigned uniformly to specific model layers (a surrogate for well depth) for each scenario, although current and future well depths do and are expected to vary.

For the mining scenarios, all mines were assumed to cover similar acreage and progress in three discrete stages that consisted of active mining,


Land reclamation at active mine

Christien Huppert

early reclamation, and mature reclamation. Moreover, no consideration was given to areas surrounding minable Wonewoc sandstone, which have been used for staging, processing and storing sand and water at several mines in the study area. This additional area was intentionally omitted because of the variability among contemporary mines and the limited ability to predict future development or reclamation of this area. Had this surrounding area been included, it is expected that the simulated scenario results could have illustrated somewhat larger magnitudes of change compared with the base model.

The mine reclamation scenario assumed that all mine parcels would be reclaimed to prairie grass. Following initial seeding, prairies are typically not cultivated and the plants develop deep roots that create macropores; these characteristics are attributed with increased infiltration capacity compared with cultivated crops grown in similar soils. Reclamation of mines to cultivated crops would likely produce less of an increase in baseflow compared to prairie restoration, and could possibly result in a decline in recharge compared with the simulated scenario results, although such a scenario was not evaluated. Reclamation to forests also was not evaluated. Like prairie soils, forest soils also develop macropores and are seldom subject to vehicular compaction, though potentially higher transpiration rates than prairie grasses could presumably result in somewhat subdued recharge rates compared with the simulated reclamation scenarios described in this report.

The irrigated agriculture scenarios were based on estimated likely future conditions that were informed both by current conditions and the understanding of the system provided by stakeholders in the county. Uncertainty as to which specific parcels are likely to convert to irrigated agriculture within the 80 percent of likely parcels estimated by stakeholders could be further refined with more stakeholder information. The analysis in this work, however, reflects the uncertainty inherent in attempts to forecast the future accurately.

Finally, groundwater flow models are useful tools for evaluating the effect of existing or proposed changes, such as well withdrawals, on both the groundwater flow system itself and also connected surface water features. Moreover, simulated scenario results could potentially be extended to predict or evaluate effects on ecological communities, such as the variety and abundance of fish species. For example, Foley and others (2015) and Zorn and others (2008) provide insight into how groundwater model scenario simulations could potentially be used to evaluate ecological responses and assess the potential for a system to cross an ecological threshold. However, the existing steady-state model is not ideally suited for direct extension to ecological threshold evaluations. Rather, the model provides a framework from which necessary enhancements could be added, such as seasonal transience, which would better facilitate such assessments.

Limitations related to hydrogeologic 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). Model-parameter uncertainty 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 model area because the density of calibration targets is spatially uneven. The degree of uncertainty in parameters that also affects forecasts is largely a function of the information content and spatial density of observations used for calibration.

The hydrogeologic data, especially specific capacity estimates of hydraulic conductivity, are most abundant in more densely populated areas 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 unconsolidated sand and gravel system and the Mount Simon Formation. Parameters in areas of sparse calibration targets have a higher relative level of uncertainty. If this model is used as a basis for creating more detailed inset models, additional data collection and recalibration may be necessary.

Summary

The groundwater flow model described in this report for western Chippewa County, Wisconsin, was funded by Chippewa County with additional funding from the USGS Cooperative Water Program. The county's Department of Land Conservation and Forest Management coordinated the overall study, including establishing the stakeholders group and facilitating meetings. The principal goal of the study was to evaluate the potential future effects of expanded industrial sand mining and irrigated agriculture on the county's groundwater resources.

The three-dimensional steady-state groundwater flow model conceptualizes the hydrogeology of western Chippewa County as a six-layer system. The model uses the USGS MODFLOW-NWT finite-difference code, with a Newton solver to improve the handling of unconfined conditions by smoothing the fluctuation of wet and dry cells. Boundary conditions for the MODFLOW model were generated from an analytic element model (GFLOW) that was constructed and calibrated for the study area. A GIS-based soil-water balance (SWB) model estimated the spatial distribution of groundwater recharge, which was applied to the MODFLOW model. The model simulates groundwater/surface-water interactions with streamflow routing and incorporates pumping stresses from high-capacity wells. Model calibration (or history matching) was performed using the parameter estimation code PEST and included groundwater levels (heads) and streamflows. Calibration focused on the 3-year period from 2011 to 2013.

Future buildout scenarios for industrial sand mining and irrigated agriculture were developed with input by Chippewa County and a stakeholders group to evaluate the potential hydrologic effects associated with future expansion and intensification of these activities. The mining scenario underscores the potential hydraulic effects related to changing land-use practices (i.e., hilltops and farmland becoming sand mines followed by reclamation to prairie grasses), while the irrigated agriculture scenario illustrates the potential hydraulic effects of intensifying existing land-use practices (i.e., installing new wells to irrigate additional farm fields).

The following list summarizes key points from the study:

- Infiltration measurements demonstrate that active land activities (for example, cultivation and mining) can limit infiltration rates compared with passive activities (undisturbed vegetation), which influences groundwater recharge and associated discharge to streams. Some activities (for example, compaction) can result in concurrent reductions in infiltration rates; other activities (for example, prairie planting) can take several years or decades to produce substantial increases in infiltration rates.
- Deep infiltration and groundwater recharge naturally vary in space and time; rates ranged from around 0.2 to 15 inches during a typical year in the study area.
- Between 2011 and 2013, groundwater withdrawals totaled 3.12 billion gallons per year in the study area, or about 2 percent of the total water moving through the aquifers. Pumping from agricultural wells accounted for about 71 percent of the total water used, public supply wells used 22 percent, and industrial supply wells used 6 percent. Regardless of total or individual well withdrawals, the effect of pumping is often best evaluated in terms of the reduction in water that would otherwise discharge to springs, streams, or lakes (Barlow and Leake, 2012).
- Scenarios developed for projected growth of industrial sand mines and irrigated agriculture showed that stream baseflow reductions ranged from negligible to 100 percent in some stream sections. Simulated baseflow reductions tended to be highest in headwater streams where baseline streamflows were small compared with downstream segments. These simulated baseflow reductions were most pronounced near areas with highest development.
- For the industrial sand mine scenarios, the magnitude of baseflow reductions increased as the percent of simultaneous development increased. In simulations of mine reclamation to undisturbed prairie grasses and halting of withdrawals, stream discharge increased several decades after completion of mine reclamation. The increases mimicked the pattern and, to a lesser extent, the magnitudes of reductions simulated with the development scenarios.
- For the irrigation scenarios, inclusion of model uncertainty illustrated that the simulated magnitude of baseflow reductions is least certain in headwater reaches. However, the headwater areas exhibited relatively greater median percent reductions than downstream reaches, regardless of whether or not model uncertainty was incorporated.

The current study was designed to evaluate potential effects on groundwater and surface water resources from expansion of water and land uses in the study area, providing results that illustrate broad development scenarios rather than specific predictions or site evaluations. The model also forms a framework from which additional evaluations could be expanded, such as source-water assessments (where does pumped water come from?), water-use optimization (maximize use while minimizing effects), or evaluating groundwater developments in terms of ecological thresholds (Foley and others, 2015). Re-application of the groundwater model for these secondary purposes could require specific enhancements to the model or additional data collection.

Literature cited

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 79 p.

Anderson, M.P., Woessner, W.W., and Hunt, R.J., 2015, Applied groundwater modeling (2nd ed.): San Diego, Calif., Academic Press, 564 p.

Arcement, G.J., Jr., and Schneider, V.R., 1989, Guide for selecting Manning's roughness coefficients for natural channels and flood plains: U.S. Geological Survey Water-Supply Paper 2339, 38 p.

Attig, J.W., Bricknell, M., Carson, E.C., Clayton, L., Johnson, M.D., Mickelson, D.M., and Syverson, K.M., 2011, Glaciation of Wisconsin (4th ed.): Wisconsin Geological and Natural History Survey Educational Series 36, 4 p.

Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p.

Barlow, P.M., Cunningham, W.L., Zhai, Tong, and Gray, Mark, 2014, U.S. Geological Survey groundwater toolbox, a graphical and mapping interface for analysis of hydrologic data (version 1.0): User guide for estimation of base flow, runoff, and groundwater recharge from streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. B10, 27 p., http://doi.org/c4qb.

Bartošová, A., McConkey, S., Lin, Y., and Walker, D., 2004, Using NHD to estimate stream geometry characteristics for MODFLOW, *in* American Water Resources Association Spring Specialty Conference, Nashville, Tenn., May 17–19, 2004: Nashville, Tenn., Geographic Information Systems and Water Resources III, 7 p.

Benson, M.E., and Wilson, A.B., 2015, Frac sand in the United States—a geological and industry overview: U.S. Geological Survey Open-File Report 2015–1107, 78 p.

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

Brown, B.A., 1988, Bedrock geology of Wisconsin, west-central sheet: Wisconsin Geological and Natural History Survey Map M104, scale 1:250,000.

Clayton, L., 1967, Stagnant-glacier features of the Missouri Coteau in North Dakota, in Clayton, Lee, and Freers, T.F., eds., Glacial geology of the Missouri Coteau and adjacent areas: North Dakota Geological Survey Miscellaneous Series 30, p. 25–46.

Cronshey, R., McCuen, R.H., Miller, N., Rawls, W., Robbins, S., and Woodward, D., 1986, Urban hydrology for small watersheds: Natural Resources Conservation Service, Conservation Engineering Division, Technical Release 55, variously paged.


Clearing hilltop for sand mining

Paul Juckem

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

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

Doherty, J.E., Hunt, R.J., and Tonkin, M.J., 2010, Approaches to highly parameterized inversion: A guide to using PEST for model-parameter and predictive-uncertainty analysis. U.S. Geological Survey Scientific Investigations Report 2010-5211, 71 p.

Feinstein, D.T., Buchwald, C.A., Dunning, C.P., and Hunt, R.J., 2006, Development and application of a screening model for simulating regional ground-water flow in the St. Croix River Basin, Minnesota and Wisconsin: U.S. Geological Survey Scientific Investigations Report 2005–5283, 41 p.

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

Foley, M.M., Martone, R.G., Fox, M.D., Kappel, C.V., Mease, L.A., Erickson, A.L., Halpern, B.S., Selkoe, K.A., Taylor, P., and Scarborough, C., 2015, Using ecological thresholds to inform resource management: Current options and future possibilities: *Frontiers in Marine Science*, v. 2, no. 95, 12 p., http://doi.org/gft34m.

Gebert, W.A., Radloff, M.J., Considine, E.J., and Kennedy, J.L., 2007, Use of streamflow data to estimate base flow/ground-water recharge for Wisconsin: *Journal of the American Water Resources Association*, v. 43, no. 1, p. 1–17, http://doi.org/b6fknn.

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

Gesch, D.B., 2007, The national elevation dataset, in Maune, D., ed., Digital elevation model technologies and applications: The DEM user's manual (2nd ed.): Bethesda, Md., American Society for Photogrammetry and Remote Sensing, p. 99–118.

Gesch, D.B., Oimoen, M.J., Greenlee, S.K., Nelson, C.A., Steuck, M.J., and Tyler, D.J., 2002, The National Elevation Dataset: Photogrammetric engineering and remote sensing: Bethesda, Md., American Society for Photogrammetry and Remote Sensing, v. 68, no. 1, p. 5–11.

Goebel, J.E., Mickelson, D.M., Farrand, W.R., Clayton, L., Knox, J.C., Cahow, A., Hobbs, H.C., and Walton, M.S., Jr., 1983, Quaternary geologic map of the Minneapolis 4 degrees x 6 degrees quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series Map I-1420(NL-15), accessed February 21, 2018, https://pubs.usgs.gov/imap/i-1420/nl-15/.

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

Hamza, M.A., and Anderson, W.K., 2005, Soil compaction in cropping systems: A review of the nature, causes and possible solutions: *Soil and Tillage Research*, v. 82, no. 2, p. 121–145.

Harbaugh, A.W., 2005, MODFLOW-2005, The U.S. Geological Survey modular ground-water model—the ground-water flow process: U.S. Geological Survey Techniques and Methods 6-A16, variously paged.

Hart, D.J., Schoephoester, P.R., and Bradbury, K.R., 2012, Groundwater recharge in Dane County, Wisconsin: Estimating recharge using a GIS-based water-balance model: Wisconsin Geological and Natural History Survey Bulletin 107, p. 11.

Havholm, K.G., 1998, Pre-Quaternary geologic history of western Wisconsin, with an emphasis on the Cambrian sandstones, *in* Syverson, K.M., and Havholm, K.G., eds., 1998, Geology of western Wisconsin: Guidebook for 61st Annual Tri-State Geological Field Conference and University of Wisconsin System Geological Field Conference, p. 3–14.

Havholm, K.G., Mahoney, J.B., Hooper, R.L., Golding, H., Jenson S., and Paddock, J., 1998, Wonewoc and Lone Rock Formations, Colfax, Wisconsin, *in* Syverson, K.M., and Havholm, K.G., eds., 1998, Geology of western Wisconsin: Guidebook for 61st Annual Tri-State Geological Field Conference and University of Wisconsin System Geological Field Conference, p. 73–79.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 2015, Completion of the 2011 National Land Cover Database for the conterminous United States—Representing a decade of land cover change information: *Photogrammetric Engineering and Remote Sensing*, v. 81, no. 5, p. 345–354.

Hunt, R.J., Anderson, M.P., and Kelson, V.A., 1998a, Improving a complex finite-difference ground water flow model through the use of an analytic element screening model: *Ground Water*, v. 36, no. 6, p. 1011–1017.

Hunt, R.J., Kelson, V.A., and Anderson, M.P., 1998b, Linking an analytic element flow code to MODFLOW—Implementation and benefits, *in* MODFLOW 98: Proceedings of the 3rd International Conference of the International Groundwater Modeling Center: Golden, Colo., Colorado School of Mines: p. 497–504.

Hunt, R.J., and Zheng, C., 2012, The current state of modeling: *Groundwater*, v. 50, no. 3, p. 329–333.

Institute of Hydrology, 1980a, Low flow studies report no. 1, research report: Wallingford, U.K., Institute of Hydrology, 42 p.

Institute of Hydrology, 1980b, Low flow studies report no. 3, catchment characteristic estimation manual: Wallingford, U.K., Institute of Hydrology, 27 p.

Johnson, D.M., 1993, Depth to bedrock of Eau Claire County, Wisconsin: Wisconsin Geological and Natural History Survey Map M122, scale 1:100,000.

Johnson, M.D., 1986, Pleistocene geology of Barron County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 55, 42 p., 1 plate, scale 1:100,000.

Jones, E., Oliphant, E., Peterson, P., and others, 2001, SciPy: Open source scientific tools for Python: accessed September 13, 2017, http://www.scipy.org/.

Juckem, P.F., 2009, Simulation of the groundwater-flow system in Pierce, Polk, and St. Croix Counties, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2009–5056, 53 p.

Juckem, P.F., Fienen, M.N., and Haserodt, M.J., 2019, MODFLOW-NWT model data sets for simulating effects of groundwater withdrawals on streamflows in northwestern Chippewa County, Wisconsin: U.S. Geological Survey Data Release, https://doi.org/10.5066/F7TB15DB.

Juckem, P.J., and Robertson, D.M., 2013, Hydrology and water quality of Shell Lake, Washburn County, Wisconsin, with special emphasis on the effects of diversion and changes in water level on the water quality of a shallow terminal lake: U.S. Geological Survey Scientific Investigations Report 2013-5181, 77 p., 2 app., http://doi.org/c4qf.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resource Investigations, book 2, chap. E-2, 149 p.

Knighton, M.D., 1970, Forest floor characteristics in southwestern Wisconsin: U.S. Forest Service Research Note, NC-102, 2 p.

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

Lippelt, I.D., 1988, Depth to bedrock of Chippewa County, Wisconsin: Wisconsin Geological and Natural History Survey Map M098, scale 1:100,000.

Lippelt, I.D., and Fekete, T.E., 1988, Depth to bedrock of Dunn County, Wisconsin: Wisconsin Geological and Natural History Survey Map M099, scale 1:100,000.

Lyons, J., Zorn, T., Stewart, J., Seelbach, P., Wehrly, K., and Wang, L., 2009, Defining and characterizing coolwater streams and their fish assemblages in Michigan and Wisconsin, USA: *North American Journal of Fisheries Management*, v. 29, no. 4, p. 1130–1151, http://doi.org/dbv4r5.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A-1, 586 p.

McKay, L., Bondelid, T., Dewald, T., Johnston, J., Moore, R., and Rea, A., 2012, NHDPlus version 2—user guide: U.S. Environmental Protection Agency, 182 p.

Menne, M.J., Durre, I., Korzeniewski, B., McNeal, S., Thomas, K., Yin, X., Anthony, S., Ray, R., Vose, R.S., Gleason, B.E., and Houston, T.G., 2012, Global Historical Climatology Network - Daily (GHCN-Daily): NOAA National Climatic Data Center, http://doi.org/c4qc, accessed June 2013.

Mickelson, D.M., and Attig, J.W., 2017, Laurentide Ice Sheet: Ice-margin positions in Wisconsin (2nd edition): Wisconsin Geological and Natural History Survey Educational Series 56, 46 p.

Mudrey, M.G., Jr., 1987, Bedrock geology of Barron County, Wisconsin: Wisconsin Geological and Natural History Survey Map M095-plate 3, scale 1:250,000.

Mudrey, M.G., Jr., LaBerge, G.L., Myers, P.E., and Cordua, W.S., 1987, Bedrock geology of Wisconsin, northwest sheet: Wisconsin Geological and Natural History Survey Map M094, scale 1:250,000.

Natural Resources Conservation Service, 2013, Soil Survey Geographic (SSURGO) Database for Chippewa, Dunn, and Barron Counties, Wisconsin: U.S. Department of Agriculture, Natural Resources Conservation Service, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053627, accessed June 2013.

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

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

Ostrom, M.E., 1966, Cambrian stratigraphy in western Wisconsin: Prepared for the Michigan Basin Geological Society Annual Field Conference, May 21 and 22, 1966, by the Wisconsin Geological and Natural History Survey Information Circular 7, 79 p.

Ostrom, M.E., 1988, Outcrop descriptions: Tilden, Wisconsin—contact of Mount Simon and Eau Claire Formations (upper Cambrian): Wisconsin Geological and Natural History Survey, OUT-CH03, 4 p.

Ostrom, M.E., Davis, R.A., Jr., and Cline, L.M., 1970, Field trip guide book for Cambrian–Ordovician geology of western Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 11, 131 p.

Parsen, M.J., and Gotkowitz, M.B., 2013, Managing Chippewa County's groundwater—today and tomorrow: Evaluating the impacts of industrial sand mines and irrigated agriculture on the county's water resources: Wisconsin Geological and Natural History Survey Factsheet 7, 4 p.

Parsen, M.J., and Gotkowitz, M.B., 2015, Chippewa County groundwater study—interim report: Report prepared for the Chippewa County Department of Land Conservation and Forest Management by the Wisconsin Geological and Natural History Survey, 34 p., 7 geophysical logs.

Parsen, M.J., and Zambito, J.J., 2014, Frac sand in Wisconsin: Wisconsin Geological and Natural History Survey Factsheet 5, 2 p.

Prudic, D.E., Konikow, L.F., and Banta, E.R., 2004, A new Streamflow-Routing (SFR1) Package to simulate stream-aquifer interaction with MODFLOW-2000: U.S. Geological Survey Open-File Report 2004-1042, 95 p.

Sather, L.M., and Threinen, C.W., 1963, Surface water resources of Chippewa County: Wisconsin Conservation Department, 154 p.

Soil Survey Staff, 2014, Gridded Soil Survey Geographic (gSSURGO) Database for Wisconsin: United States Department of Agriculture, Natural Resources Conservation Service, accessed April 22, 2015, https://gdg.sc.egov.usda.gov.

Strack, O.D.L., 1989, Groundwater mechanics: Englewood Cliffs, N.J., Prentice Hall, 732 p.

Syverson, K.M., 2007, Pleistocene geology of Chippewa County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 103, 53 p., 2 plates.

Syverson, K.M., and Havholm, K.G., eds., 1998, Geology of western Wisconsin: Guidebook for 61st Annual Tri-State Geological Field Conference and University of Wisconsin System Geological Field Conference, p. 92.

Thiem, G. 1906, Hydrologische methoden: Leipzig, Germany, J.M. Gebhart, 56 p.

Tonkin, M.J., and Doherty, J., 2009, Calibration-constrained Monte-Carlo analysis of highly parameterized models using subspace techniques: *Water Resources Research*, v. 45, no. 12, W00B10, http://doi.org/cjqx58.

Trotta, L.C., and Cotter, R.D., 1973, Depth to bedrock in Wisconsin: Wisconsin Geological and Natural History Survey Map M051, scale 1:1,000,000.

U.S. Department of Agriculture, 2016, National Agriculture Imagery Program (NAIP) 3.75 x 3.75 minute—downloadable data collection, Chippewa County, Wis.: Accessed November 25, 2016, https://www.sciencebase.gov/catalog/item/51355312e4b0e1603e4fed62.

U.S. Geological Survey (USGS), 2011, National Land Cover Database—2006 land cover: U.S. Geological Survey, http://www.mrlc.gov/.

U.S. Geological Survey, 2014, National Elevation Dataset (NED) 1/3 arc-second—downloadable data collection: Accessed November 25, 2016, https://www.sciencebase.gov/catalog/item/4f70aa9fe4b058caae3f8de5.

Van der Walt, S., Schönberger, J.L., Nunez-Iglesias, J., Boulogne, F., Warner, J.D., Yager, N., Gouillart, E., and Yu, T., and contributors, 2014, Scikit-image: Image processing in Python: *PeerJ* v. 2, e453, http://doi.org/gftp3s.

Wahl, K.L., and Wahl, T.L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas, *in* Proceedings of Texas Water 95, August 16-17, 1995, San Antonio, Tex: American Society of Civil Engineers, p. 77–86.

WDNR (Wisconsin Department of Natural Resources), n.d.-a, Well construction reports: accessed September 10, 2012, https://prodoasext.dnr.wi.gov/inter1/watr$.startup.

WDNR (Wisconsin Department of Natural Resources), n.d.-b, Water withdrawal reporting dataset: accessed January 7, 2013, http://dnr.wi.gov/wateruse/pub_v3_ext/source/.

WDNR (Wisconsin Department of Natural Resources), n.d.-c, Water withdrawal reporting dataset: accessed January 5, 2015, http://dnr.wi.gov/wateruse/pub_v3_ext/source/.

WDNR (Wisconsin Department of Natural Resources), n.d.-d, Lake Wissota, Chippewa County: accessed August 15, 2017, https://dnr.wi.gov/lakes/lakepages/LakeDetail.aspx?wbic=2152800.

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

White, J.T., Fienen, M.N., and Doherty, J.E., 2016, A Python framework for environmental model uncertainty analysis: *Environmental Modelling & Software*, v. 85, p. 217–228, http://doi.org/c4qd.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water; a single resource: U.S. Geological Survey Circular 1139, 79 p.

Wisconsin Geological and Natural History Survey and U.S. Geological Survey, 2016, Chippewa County groundwater study—5th stakeholders group meeting, April 20, 2016: Presentation prepared by the Wisconsin Geological and Natural History Survey and U.S. Geological Survey for the Chippewa County Land Conservation and Forest Management, 57 p., https://www.co.chippewa.wi.us/home/showdocument?id=10633.

Wisconsin State Climatology Office, 2017, North-central Wisconsin climate normals (1971–2000): Wisconsin State Climatology Office, http://www.aos.wisc.edu/~sco/clim-history/division, accessed May 30, 2017.

Zaporozec, A., 1987, Depth to bedrock in Barron County, Wisconsin: Wisconsin Geological and Natural History Survey Map M095-plate 4, scale 1:100,000.

Zorn, T.G., Seelbach, P.W., Rutherford, E.S., Wills, T.C., Cheng, S.-T., and Wiley, M.J., 2008, A regional-scale habitat suitability model to assess the effects of flow reduction on fish assemblages in Michigan streams: Michigan Department of Natural Resources, Fisheries Research Report 2089, 46 p.

Bulletin 112 ▪ Groundwater Flow Model for Western Chippewa County, Wisconsin ▪ 2019

Published by and available from:

Wisconsin Geological and Natural History Survey

University of Wisconsin–Madison Division of Extension
3817 Mineral Point Road ▪ Madison, Wisconsin 53705-5100
608.263.7389 ▪ www.WisconsinGeologicalSurvey.org
Kenneth R. Bradbury, Director and State Geologist

This report is an interpretation of the data available at the time of preparation. Every reasonable effort has been made to ensure that this interpretation conforms to sound scientific principles; however, the report should not be used to guide site-specific decisions without verification. Proper use of the report is the sole responsibility of the user.

The use of company names in this document does not imply endorsement by the Wisconsin Geological and Natural History Survey.

ISBN: 978-0-88169-980-7
ISSN: 0375-8265

Our Mission

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