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Characterization of groundwater resources in the Chequamegon-Nicolet National Forest, Wisconsin: Nicolet Unit

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Summary report prepared for the U.S. Forest Service
Prepared in cooperation with the U.S. Geological Survey

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List of abbreviations

CNNF Chequamegon-Nicolet National Forest

DEM digital elevation model

SWB soil-water balance

USFS U.S. Forest Service

USGS U.S. Geological Survey

WCR well construction report

WDNR Wisconsin Department of Natural Resources

WGNHS Wisconsin Geological and Natural History Survey

Executive summary

The Chequamegon-Nicolet National Forest (CNNF) in northern Wisconsin contains many groundwater-dependent water resources such as streams, lakes, springs, and wetlands. However, hydrogeologic data in the CNNF are sparse and to date there has been no comprehensive analysis of the groundwater system. Additionally, there is growing concern about the potential hydrologic effects of climate change, new high-capacity wells, mining, and land development. Management of the CNNF would benefit from improved characterization of the interactions of groundwater with surface water and from the the development of tools to evaluate the sensitivity of hydrologic flows and temperature to future climate and land-use changes. To address these issues, in 2010 the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS), cooperatively with the U.S. Forest Service (USFS), initiated a comprehensive review and analysis of groundwater resources in the CNNF. The study was divided by location into four reports corresponding to the four main CNNF contiguous land units: Medford, Nicolet, Park Falls, and Washburn/Great Divide. This report documents the study results within the Nicolet Unit in Florence, Forest, Langlade, Oconto, Oneida, and Vilas Counties.

The project consists of an inventory of available data and development of tools to improve the understanding of aquifer characteristics and the groundwater flow regime, more clearly define interactions of groundwater with surface water, evaluate the vulnerability of aquatic resources to climate change, and provide a basis to support future studies in the forest.

The four primary components of this study correspond to the sections in this report:

1. **Hydrogeologic data.** Inventory and interpretation of existing geologic and hydrogeologic data in the Nicolet unit, assembled into a spatial database. Results include the distribution of physical and hydraulic aquifer properties and water-use data.
2. **Groundwater potential recharge.** Construction of a soil-water balance model for predicting spatial and temporal distribution of potential recharge.
3. **Baseline water chemistry.** Geochemical sampling and analysis for characterizing current water chemistry in the forest.
4. **Groundwater flow model.** Construction of a groundwater flow model that can be used as a tool for evaluating future scenarios and for development of a water-table map.

The initial portion of the study inventoried and analyzed available hydrogeologic data, which was assembled into a spatial database. Data sources included well construction reports, high-capacity-well pumping rates, and groundwater-level measurements. These data were analyzed to produce maps of bedrock elevation, depth to bedrock, and saturated aquifer thickness and to produce estimates of hydraulic conductivity. The assembled data as well as previous studies of the regional geology indicate that subsurface materials in the unit consist of unlithified glacial sediments over crystalline bedrock. The spatial analysis suggests that surficial glacial deposits form an aquifer with low to moderate productivity. This aquifer ranges from zero to about 200 feet (ft) thick, changing largely with topography and absent in local areas. The horizontal hydraulic conductivity estimates for this aquifer ranged from 0.2 to 1,200 feet per day (ft/d) and have a mean of 27 ft/d. About 80 percent of wells in the unit draw their water from this aquifer. The glacial aquifer has the potential to support high-capacity wells in some areas; the approximate average potential yield is 100–200 gallons per minute (gpm). Crystalline bedrock beneath the glacial materials can supply adequate water to low-capacity wells in areas where the glacial deposits are too thin or too fine grained. The bedrock has mean horizontal hydraulic conductivity estimates about an order of magnitude lower than those of the overlying glacial deposits. The bedrock aquifer has a low likelihood of supporting high-capacity wells; its approximate average potential yield is about 20 gpm. Of the bedrock wells, most pump from the top 140 ft of bedrock, although some pump from as deep as 300 ft. Specific capacities (discharge divided by drawdown) are generally low throughout the forest unit, although some wells have high yields with specific capacities greater than 10 gallons per minute per foot (gpm/ft).

Few high-capacity wells are present in this region. There are 26 active high-capacity wells in the Nicolet Unit, most of which obtain their water from the glacial aquifer. Although these wells are permitted to pump more than 70 gpm, most pump at lower rates. On average, each of the wells within the unit withdraws about 5 million gallons of groundwater per year (equivalent to about 9 gpm, if a constant pumping rate is assumed); the total withdrawal in the unit is 125 million gallons annually (240 gpm). In the broader region represented in the regional groundwater model, high-capacity wells pump at a slightly higher average of 24 gpm and cumulatively at 5,500 gpm. Groundwater levels in a long-term monitoring well are similar to those measured in 1967. More recent water levels in three wells have risen since a regional drought about 2010. These wells provide important baseline data that can be used for future studies.

For the second part of this study, potential recharge was estimated by using a soil-water balance (SWB) model. This modeling effort produced temporally and spatially variable estimates of deep drainage in the Nicolet Unit for the years 2000 through 2010. The mean annual potential recharge simulated by this model throughout the model domain for this time period was 4.6 inches per year (in/yr), and it ranged from 2.9 to 8.4 in/yr, largely owing to changes in precipitation. The SWB model results reflect mapped variability in soil types but are low in magnitude compared to other reported values. In addition, the model may overestimate recharge in wetlands, which cover about one-third of the unit. The SWB model results were calibrated to measured baseflow by using a groundwater flow model. During calibration, a regional multiplier was applied to the SWB grid, resulting in an overall mean recharge value of 7.1 in/yr for the northern part of the unit and 7.5 in/yr for the south; these values are consistent with previously reported recharge estimates.

The third part of this study was a basic inventory of surface-water and groundwater geochemistry, in order to better characterize current water quality in the unit. Water samples from groundwater wells, spring ponds, streams, and one lake were analyzed for major ion chemistry, basic nutrients, and the stable isotopes oxygen-18 (^{18}O) and deuterium (^{2}H). The results show that water in the forest unit is relatively unaffected by human activities and has low concentrations of most dissolved constituents. Groundwater in the Nicolet Unit is distinguished from surface water by higher electrical conductivity, greater alkalinity, and greater concentrations of dissolved ions such as calcium and magnesium. Water samples from several wells exceeded the Wisconsin preventive action limit for dissolved arsenic, and a water sample from one well exceeded the preventive action limit for lead. These trace elements might originate from natural sources, from well or plumbing fixtures, or from local anthropogenic sources. Although concentrations remain below the maximum concentration specified by safe drinking water standards, we recommend additional sampling and testing of these wells.

Groundwater well samples have an average conductivity of 249 microsiemens per centimeter (µS/cm) and alkalinity of 108 milligrams per liter (mg/L); for comparison, the lake sample has a conductivity of 31 µS/cm and alkalinity of 8 mg/L. Isotopes of hydrogen and oxygen can also be used to distinguish groundwater, which is isotopically lighter, or more negative, than surface water. This can be used to evaluate where wells may be drawing from surface water or, conversely, where surface-water features may be predominantly groundwater fed. Some samples contained moderately elevated levels of chloride, suggesting the local influence of land-use activities such as road salting.

The fourth part of this study was the construction of a regional groundwater flow model for the Nicolet Unit by using the analytic element model code GFLOW. The flow model provides key aquifer properties, simulated water table elevations, flow paths, flow rates, and discharge zones. The regional groundwater divide is similar to the surface-water divide. Most groundwater in the unit flows southeast; the far western part of the unit drains south to the Wolf and Wisconsin River basins. The model can be a powerful decision-support tool for water resource management. Potential uses for the model include delineating areas contributing groundwater to surface-water features, determining the expected drawdown from a new well, and evaluating how changes in pumping or land use change streamflow and water levels.

The results of the inventory, modeling, and analysis described in this report are available in an electronic database for public use (see Data availability).

Introduction

Background

The Chequamegon-Nicolet National Forest (CNNF) in northern Wisconsin is home to an abundance of water resources including streams, lakes, springs, and wetlands that depend on the recharge and discharge of groundwater. Groundwater discharge is a primary factor in the establishment, persistence, and survival of groundwater-dependent ecosystems. In addition, groundwater-derived baseflow is the limiting factor for many recreational uses such as fishing and canoeing. Understanding groundwater in the forest is also important for assessing the feasibility and potential effects of multi-use projects such as mines, timber extraction, and agriculture. However, traditional groundwater studies rely on data from groundwater wells which are sparse in the undeveloped forest, and to date there has been no comprehensive data inventory or analysis of the groundwater system in the CNNF. An improved understanding of Nicolet Unit hydrology would help protect and manage these resources.

There is also growing concern about the hydrologic impacts of future changes in climate and the landscape. The CNNF can expect increases in developmental pressure on private lands within and near the forest, such as proposals for high-capacity wells, metallic mineral extraction, and other land use changes. The potential effects on water resources from these changes has not been documented. Management of the CNNF would benefit from improved characterization of the interactions of groundwater with surface water and development of tools to evaluate the sensitivity of hydrologic flows and temperature to future climate and land use changes.

To improve the baseline understanding of forest-wide resources, in 2010 the U.S. Forest Service (USFS) requested that the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS), acting jointly, review and analyze groundwater resources in the CNNF. This multi-year hydrogeological study presents an innovative approach to studying hydrogeology in undeveloped areas with sparse datasets. The study is divided by location into four reports corresponding to the four main CNNF contiguous land units: Medford, Nicolet, Park Falls, and Washburn/Great Divide. This report documents the results of this study within the Nicolet Unit (fig. 1), which comprises approximately 1,500 square miles (mi^2) in Florence, Forest, Langlade, Oconto, Oneida, and Vilas Counties, Wisconsin.

Purpose and goals

The purpose of this study is to integrate existing hydrologic knowledge of the entire CNNF system and to provide a comprehensive quantitative framework for describing how the hydrologic system works under current land use and climatic conditions. The project consists of an inventory of available data and development of tools with the following goals:

- Improve the understanding of aquifer characteristics and the groundwater flow regime;
- More clearly define interactions between groundwater and surface water;
- Refine the identification of groundwater-dependent ecosystems;
- Provide better groundwater information for CNNF and project-level planning;
- Help evaluate the vulnerability of aquatic resources to climate change; and
- Provide a basis to support future studies in the forest.

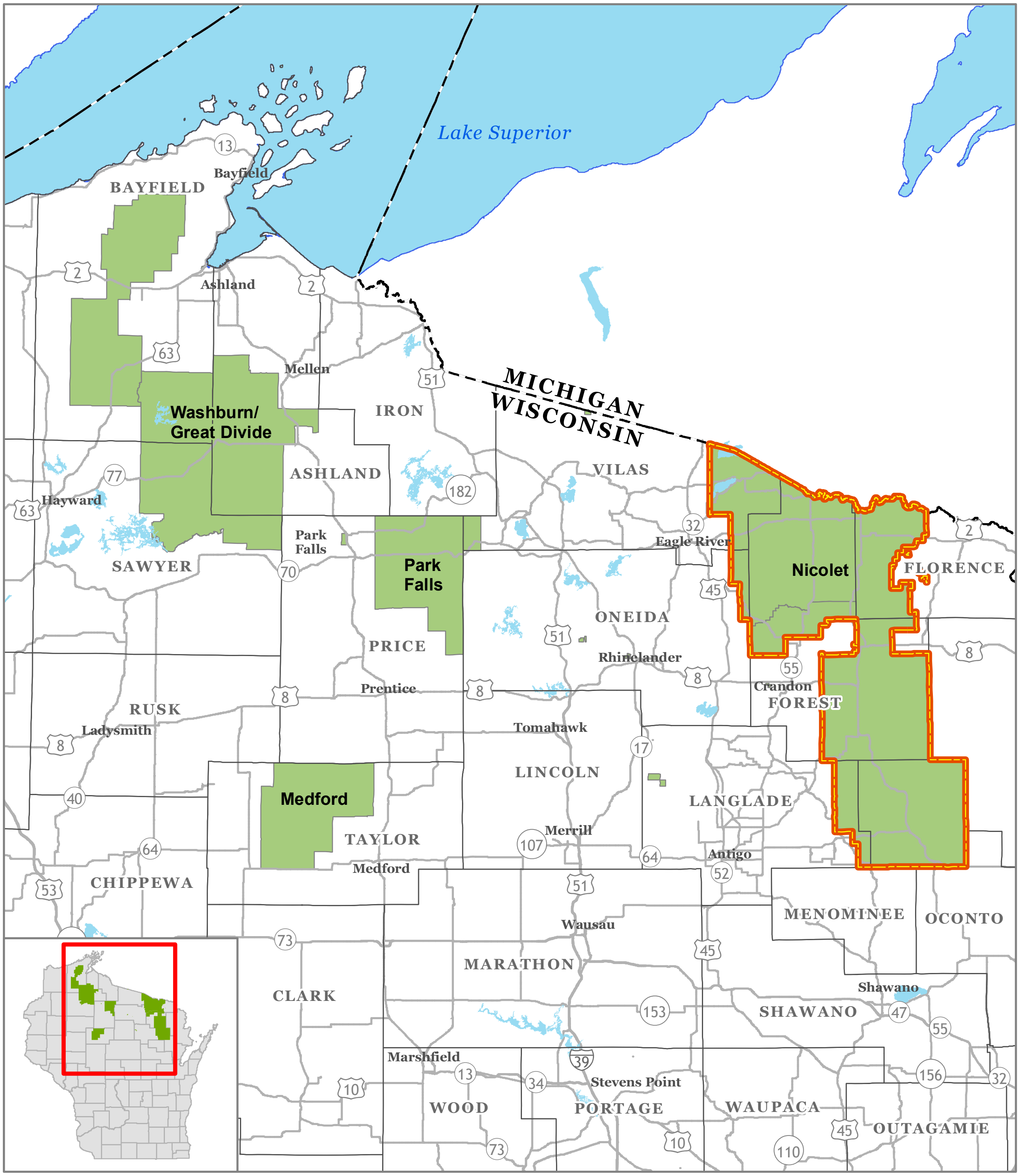
Study approach

The four primary components of this study correspond to the sections in this report:

1. **Hydrogeologic data.** Inventory and interpretation of existing geologic and hydrogeologic data in the unit, assembled into a spatial database. Results include the distribution of physical and hydraulic aquifer properties and water-use data.
2. **Groundwater potential recharge.** Construction of a soil-water balance model for predicting spatial and temporal distribution of potential recharge.
3. **Baseline water chemistry.** Geochemical sampling and analysis for characterizing current water chemistry in the forest.
4. **Groundwater flow model.** Construction of a groundwater flow model, which can be used as a tool for evaluating future scenarios, and development of a water table map.

These components meet the goals of the project by summarizing key elements of the existing hydrologic system throughout the CNNF, such as aquifer characteristics, potential recharge distribution, and surface-water–groundwater interactions. The flow model was needed to provide a quantitative framework for simulating heads, flows, flow paths,

Figure 1. Chequamegon-Nicolet National Forest, Wisconsin, and location of Nicolet Unit.



Nicolet Unit

Chequamegon–Nicolet National Forest Units

Miles

0 20

Political boundaries from Wisconsin DNR, 2011. National Forest boundaries from the USDA Forest Service, 2011. Roads from U.S. Census Bureau, 2015. Hydrography from National Hydrography Dataset, 2012.

and responses to potential stress. The model can be used to show general directions of groundwater flow, identify areas contributing to high-priority surface-water reaches, and evaluate baseflow contribution distributed through the CNNF subbasins. This study also highlights areas where more data or other types of data are needed to contribute to the understanding of the system. The analysis and models presented here are broad in scope, but they provide an important base from which to develop future site-specific analyses.

The products of this investigation are also available in an electronic database for public use (see Data availability).

Previous work

Regionally, a number of water-related studies have been done in and around the CNNF, although none of these includes a comprehensive analysis across the entire region. Juckem and Hunt (2007, 2008) and Lenz and others (2003) describe groundwater flow models that include the western and southwestern portion of the CNNF, respectively. Fitzpatrick and others (2005) characterized the Fish Creek watershed north of the CNNF, and Krohelski and others (2002) describe a groundwater flow model in eastern areas of the CNNF. More recently, a groundwater flow model was developed for the Bad River watershed northeast of the Washburn/Great Divide Unit (Leaf and others, 2015). In addition, a long history of groundwater modeling is present for Vilas County as part of the National Science Foundation–funded Long-Term Ecological Research and the USGS Water Energy Biogeochemical Budgets site at Trout Lake, as well as models constructed in nearby Forest and Langlade Counties in support of permitting the proposed Crandon Mine. The WGNHS has mapped the Quaternary geology of portions of the CNNF in Florence, Forest, Langlade, Oconto, Oneida, Taylor, and Vilas Counties at the 1:100,000 scale. These county maps are supported by unit descriptions and cross sections. Modern Quaternary mapping is available at the more generalized 1:250,000 scale for Ashland, Bayfield, and limited parts of Rusk and Sawyer Counties.

Within the Nicolet Unit, prior to this study little comprehensive information existed on groundwater conditions. Although the glacial geology of the entire Nicolet Unit is mapped at 1:100,000, no modern county-scale maps of bedrock geology is available for the unit. Greenberg and Brown (1984) mapped the regional bedrock geology of northeast Wisconsin at 1:250,000 scale, and their map includes the Nicolet Unit. County-scale glacial geology maps are available for Florence, Forest, Langlade, northern Oconto, and Vilas Counties (Attig, 1985; Attig and Ham, 1999; Clayton, 1986; Mickelson, 1986; Simpkins and others, 1987). The entire unit is included in a larger 1:1,000,000-scale glacial map by Richmond and Fullerton (2001).

Groundwater and surface water have been studied locally in portions of the unit, and Lidwin and Krohelski (1993) documented the hydrology in the Forest County Potawatomi Indian Reservation. Reports on the water resources of Vilas and Langlade Counties were completed by Patterson (1989) and Batten (1987), respectively. As discussed above, a proposed metallic mineral mine in Crandon, Wisconsin, prompted the creation and review of a groundwater flow model in that vicinity (Krohelski and Carlson, 2005). The USFS has actively collected ecological and surface-water data in the Nicolet Unit, such as water temperature, streamflow, and basic water quality for selected streams and lakes. Locations of springs and spring-fed surface-water features, here called spring ponds, in the Nicolet Unit were compiled as part of a statewide springs inventory (Macholl, 2007).

Setting

The Nicolet Unit (fig. 1) comprises about 1,500 mi^2 in Florence, Forest, Langlade, Oconto, Oneida, and Vilas Counties, Wisconsin. Of this region, approximately 1,000 mi^2 are managed by the USFS. The Nicolet Unit is mostly forested and is characterized by numerous wetlands, springs, lakes, and streams; approximately a third of the unit is covered by wetlands (U.S. Geological Survey, 2011a). In the majority of the unit, surface water drains to the east or southeast into (from north to south) the Brule, Menominee, Peshtigo, and Oconto Rivers. The far western part of the unit drains south to the Wolf and Wisconsin Rivers. The headwaters of several regional rivers originate in the northwest portion of the unit, including the Wisconsin, Wolf, Peshtigo, and Oconto. Land-surface elevation ranges from 1,800 ft above sea level at the northwest corner to 850 ft at the southeast corner. The climate is humid and temperate; the northeastern region of Wisconsin that includes the Nicolet Unit receives an average precipitation of 31.5 in/yr (Wisconsin State Climatology Office, 2017).

Geology

Surficial materials in the Nicolet Unit mostly consist of sediment deposited during glaciations between about 22,000 and 12,000 years ago (Simpkins and others, 1987). Glacial geology in the Nicolet Unit mapped by Richmond and Fullerton (2001) is shown on plates 1 and 2 and summarized in table 1. Broadly, tills dominate the northwest (noncalcareous sandy loamy till, unit tdb) and southeast (loamy till, unit tly) regions of the unit. Outwash sand and gravel (unit gg) is present throughout in lowlands and is more common in the central region.

More detailed glacial geology reports and maps are available for most counties within the Nicolet Unit (Attig, 1985; Attig and Ham, 1999; Clayton, 1986; Mickelson, 1986; Simpkins and others, 1987). These reports document outwash and till deposits from the Nashville Member of the Copper Falls Formation in the north and from the Holy Hill and Kewaunee Formations in the south. Pronounced relief in the bedrock topography as well as multiple glaciations resulted in irregular thickness and type of glacial deposits. Tills are commonly present in uplands, while sand and gravel has filled valleys. Numerous bedrock knobs crop out in the southeast corner of unit; in other places glacial sediment is as much as 100 m thick. Owing to the lack of data points in much of the northern and central parts of the unit, the distribution of glacial thickness is poorly known.

The glacial sediments overlie Precambrian igneous and metamorphic bedrock, as shown on plate 3 and in table 2 (Greenberg and Brown, 1984). Bedrock in the northern and central parts of the unit is primarily composed of Early Proterozoic (now termed Paleoproterozoic) gneiss and metavolcanic rocks, whereas the southern quarter is dominantly intrusive rocks of Middle Proterozoic (now termed Mesoproterozoic) age associated with the Wolf River batholith. The oldest rock in the unit is Archean gneiss (unit PAgn) located near the northwest boundary. A number of faults have been documented in this region, including the Niagara Fault located at the northern boundary of the unit.

Table 1. Late Wisconsin glacial geology units, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Fluvial and lacustrine material	
gg	Outwash sand and gravel
kg	Ice-contact sand and gravel
lca	Lake silt and clay
hp	Peat and muck
Loamy till	
tlx	Ground moraine
tly	End moraine
Calcareous sandy loamy till	
tdx	Ground moraine
tdy	End moraine
Noncalcareous sandy loamy till	
tdbx	Ground moraine
tdby	End moraine

Modified from Richmond and Fullerton, 2001. Units distinguished with different colors on the original map were given unique 2- or 3-letter identifiers.

Table 2. Bedrock geology units, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Era	Unit	Description
Paleozoic	Cu	Undivided Cambrian sedimentary rock—mostly clastic rock
Mesoproterozoic	Pwb	Belongia Granite
	Pwg	Wolf River Granite
	Pwh	Hager Porphyry
	Pwm	Mangerite
Paleoproterozoic	Pqz	Quartzite and conglomerate
	Pgr	Granitic intrusive rocks
	Pdi	Dioritic intrusive rocks
	Pgn	Gneiss
	Pmg	Mafic intrusive rocks
	Pms	Metasedimentary rocks
	Pif	Iron formation
	Pvn	Metavolcanic rocks—mafic to bimodal metavolcanic rocks north of the Niagara Fault
	Pvs	Metavolcanic rocks—mafic, intermediate, and felsic metavolcanic rocks south of the Niagara Fault
Neoarchean	PAgn	Gneiss

Modified from Greenberg and Brown, 1984

Trending east-west across the center of the unit is a belt of Paleoproterozoic rocks with potential for mining economically valuable minerals such as copper, gold, silver, and zinc. A massive sulfide deposit within this belt, known as the Crandon deposit, was discovered in 1975 approximately 5 mi south of Crandon, Wisconsin (Erickson and Côté, 1996). A proposal to mine the Crandon deposit was submitted to the Wisconsin Department of Natural Resources (WDNR) in 1994 but was ultimately unsuccessful, and the Chippewa and Potawatomi tribes purchased the land in 2003 (see http://dnr.wi.gov/topic/Mines/Projects.html). The potential for future hardrock prospecting and mining in and near the Nicolet Unit is an additional motivation for improving the understanding of local hydrogeology and baseline water quality in the Nicolet Unit of the CNNF.

Acknowledgments

This report is divided into chapters corresponding to each of the four main objectives. Owing to the extensive scope of the study, the objectives were coordinated but completed separately by different staff. The primary authors are acknowledged as follows: section 1, Stephen W. Mauel and Anna Fehling; section 2, Peter R. Schoephoester; section 3, Anna Fehling; section 4, Andrew T. Leaf, Randall J. Hunt, and Paul F. Juckem; project coordination and synthesis, Anna Fehling and Kenneth R. Bradbury.

Section 1: Hydrogeologic data

Objectives

The initial portion of the study inventoried and analyzed available hydrogeologic data, in order to characterize key aquifer properties. The primary output is a compilation of spatial data within a geographic information system database, which includes hydraulic properties, hydrostratigraphy, and water levels. Additionally, the compiled data supported the subsequent construction of a groundwater flow model (section 4).

Data sources

Data sources compiled and analyzed for this project included publicly available well construction reports, geologic records, and water-use data. These sources are described in further detail below.

Well construction reports

Well construction reports (WCRs) form the primary database for the hydrogeologic study of the Nicolet Unit. WCRs are one-page reports prepared by water-well drillers upon the completion of any new water well in Wisconsin. WCRs contain information about the well location, date drilled, owner's name, well depth, subsurface materials, and water levels. These WCRs can be used to interpret spatial hydrogeologic information such as regional water levels and bedrock depth. Although the data quality may vary greatly between records, the WCRs as a group can provide valuable insight into the hydrogeology of a region. WCRs are shown as "Located wells" on plate 4. The plate also shows the locations of mapped springs, spring-fed surface-water features here called spring ponds (Macholl, 2007), and other relevant data points.

The WCR dataset used in this study comes from several sources. Most of the WCRs were obtained from a digital database maintained by the WDNR. This database of WCR records extends back to about 1988 and typically identifies wells by a Wisconsin Unique Well Number. Most WCRs filed prior to 1988 are not in the WDNR database but instead are stored as scanned images on file at the WGNHS. These wells generally do not have a Wisconsin Unique Well Number but instead are identified by WGNHS image numbers, keyed to Wisconsin counties. Information about water wells in Michigan were obtained from the Michigan Department of Environmental Quality Statewide Ground Water Database (Michigan Department of Environmental Quality, 2013).

Using the WCRs and Esri ArcGIS software, WGNHS staff prepared a geographic information system database for the Nicolet Unit. This database was the fundamental tool used for storing spatial data for the project. Because the WCR records generally locate wells only to the nearest quarter-quarter section or to a lot number, it was necessary to manually move records to the correct location in a process called geolocation. Using aerial photography and land ownership records, WGNHS staff examined individual wells and digitized the most likely location of the wells in relation to visible buildings, roads, and other landscape features identified on the NAD83 Wisconsin Transverse Mercator projection. Each well record was also evaluated for the confidence in the selected location. The study area, which extended outside the Nicolet Unit boundary, contained parts of Florence, Forest, Iron, Langlade, Lincoln, Marathon, Marinette, Menominee, Oconto, Oneida, Shawano, and Vilas Counties in Wisconsin; and Dickinson, Gogebic, Iron, and Ontonagon Counties in Michigan. In all, this process located 19,951 wells in the study area to within an estimated 750 ft of their true location, of which 15,858 wells were located to within 200 ft. Many of the wells are located outside the study area. Physical data associated with each of these wells were assembled in the database.

About 80 percent of the 19,951 located wells within the Nicolet Unit are screened in the sand and gravel aquifer; these wells have an average bottom depth of about 80 ft, although some are nearly 300 ft deep. The average bedrock well pumps from the top 140 ft of bedrock, although some pump from as deep as 300 ft. Of the bedrock WCRs, depth to bedrock averages about 60 ft and may be as much as about 220 ft; the total well depth averages 200 ft and may be as much as 400 ft.

Geologic records

The WGNHS maintains a digital database of geologic records in the state of Wisconsin (wiscLITH) that is available for public use (Wisconsin Geological and Natural History Survey, 2012). This database contains detailed descriptions of lithology and stratigraphy compiled from more than 45,000 paper records of well or exploratory drilling and can provide a valuable source of information on bedrock depth to supplement the WCRs. The data have not been peer reviewed but their rock descriptions merit a higher level of confidence than those in WCRs, and some are located in areas where supply wells are not ordinarily drilled. Records with information on depth to bedrock were assembled for this report and included in the database.

Water use

Records of monthly water use for high-capacity wells (wells capable of pumping at 70 gallons per minute (gpm) or more) have been maintained by the WDNR since 2011. As of 2014, the WDNR database contains records of 26 active (average pumping rate exceeds 0.01 gpm) high-capacity wells within the Nicolet Unit (table 3) (R. Smail, written communication, 2016). Plate 4 shows all permitted wells, even those those that are inactive or pumping at very low rates. Although many high-capacity wells in Wisconsin pump rates in the hundreds of gallons per minute, most wells in the Nicolet Unit pump at much lower rates. On average, each of the wells within the unit withdraws about 5 million gallons of groundwater per year (equivalent to about 9 gpm, if a constant pumping rate is assumed); the total withdrawal in the unit is 125 million gallons annually (240 gpm). About 90 percent of the high-capacity wells with available construction records are screened in the sand and gravel aquifer and are an average 100 ft deep. Outside of the unit, high-capacity wells are more common but still pump at relatively low rates. Active high-capacity wells represented in the regional groundwater model (section 4) pump at an average 24 gpm and cumulatively at about 5,500 gpm.

Methods

Interpolation of hydrostratigraphic layers

Information in the WCR database was interpolated to produce three map layers: bedrock surface elevation, depth to bedrock, and saturated thickness of unlithified materials.

The bedrock surface layer was created by interpolating depth-to-bedrock values from WCRs and geologic records. Elevations of wells and surfaces were taken from the 10-meter digital elevation model (DEM). The DEM is a raster representation of land elevation of Wisconsin, derived from the U.S. Geological Survey's 10-meter National Elevation Dataset (U.S. Geological Survey, 2013). This dataset is a seamless mosaic of best-available elevation data. Elevations were assigned to wells by using interpolation tools available in Esri ArcMap software. Because the bedrock elevation at each well depends on the elevation assigned to the land surface, wells with higher confidence in spatial location also have a higher confidence in bedrock elevation. The DEM resolution, WCR location confidence, and spatial distribution of WCRs are all sources of uncertainty in developing the bedrock surface layer.

The bedrock surface was interpolated using a triangular irregular network (TIN) algorithm in Groundwater Modeling System (GMS) software. The TIN algorithm connects the data points (wells or outcrops) with triangles and interpolates elevations along the triangle surfaces. This method has the advantage of exactly honoring the data points. The resulting TIN surface was then manually edited and refined so that it was consistent with local topography and landforms. This step was needed to eliminate problems such as the bedrock surface being interpolated above the known land surface in areas where data points were sparse. Following this correction, the TIN was converted to a smooth raster grid and imported into Esri ArcMap software for contouring and plotting.

The depth-to-bedrock raster surface was calculated by subtracting the bedrock surface raster from the land surface elevation. The saturated thickness coverage was calculated by subtracting bedrock surface elevation from the water table surface obtained from the groundwater flow models (section 4). Two groundwater flow models were developed due to the size of the unit. The results from these models were merged into a single continuous raster and then manually refined for consistency. These surfaces were also imported into Esri ArcMap or Surfer software for contouring and plotting.

Estimation of hydraulic properties

Many WCRs report the results of specific capacity testing, which can be used to estimate hydraulic properties of subsurface materials. Specific capacity, which is defined as well yield divided by drawdown, can indicate aquifer productivity. For the Nicolet Unit, specific capacity results were used to estimate transmissivity and hydraulic conductivity by using the TGUESS method described by Bradbury and Rothschild (1985). TGUESS treats the specific capacity information reported by well drillers as a short-duration pumping test and includes correction for partial penetration and well loss. Although specific capacity reports commonly contain numerous errors and spurious data, our experience of many years suggests that these estimates, used in a statistical manner and including many well tests, provide reasonable estimates of transmissivity and hydraulic conductivity for regional applications. The TGUESS program uses parameters obtained from well construction reports and from aquifer thickness. Aquifer thickness for wells finished in unconsolidated materials was estimated as the difference between the water level reported by the driller and the interpreted bedrock elevation surface. For wells completed in bedrock, the aquifer thickness was set to the depth of open-borehole penetration below the bedrock surface.

Table 3. High-capacity well withdrawals, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

High-capacity well no.	WI unique well no.	Depth (feet)	Material reported by driller	Total annual water use (gallons)				
				2011	2012	2013	2014	Average 2011-14
Public supply								
387	No record located			4,125,000	298,000	618,000	560,000	1,400,250
1091	EJ759	157	Sand and gravel	7,669,800	7,844,900	10,251,700	15,345,600	10,278,000
2038	KY560	101	Sand	7,443,000	5,270,000	3,939	4,164,000	4,220,235
67616	JC223	55	Sand	57,309	62,193	70,685	72,881	65,767
67617	SX643	81	Sand and gravel	48,000	11,000	47,500	55,500	40,500
73364	FF725	290	Gravel	—	—	—	20,160	5,040
73475	AH040	103	Granite	—	—	132,647	132,724	66,343
73476	OU679	No record located		—	—	20,353	48,860	17,303
3477	JC117	38	Sand	—	—	28,486	51,310	19,949
73479	YJ931	260	Granite	—	—	—	116,100	29,025
778645	BF827	57	Sand and gravel	24,994,000	22,548,000	23,596,000	27,896,000	24,758,500
78646	BF828	95	Sand	6,341,646	8,444,438	7,260,142	5,043,073	6,772,325
87244	BH109	75	Sand and gravel	5,219,000	5,421,000	4,115	5,754,000	4,099,529
Commercial								
955	EN082	93	Sand and gravel	1,032,000	1,032,000	10,584,000	517,800	3,291,45
Domestic supply								
73360		No record located		—	—	—	40,000	10,000
Industry								
1658		No record located		1,363,611	1,443,010	1,758,840	1,342,485	1,476,987
1659	KQ535	145	Sand	3,181,899	2,706,254	2,513,507	2,637,031	2,759,673
Irrigation								
388		No record located		290,000	4,125,000	604,600	256,800	1,319,100
15008	BC327	78	No record	19,103,300	25,639,000	12,981,000	14,069,000	17,948,075
20701	BC583	No record located		12,960,000	13,932,000	9,720,000	6,048,000	10,665,000
20702	BC584	No record located		12,960,000	13,932,000	9,720,000	6,048,000	10,665,000
20703	BC585	No record located		12,960,000	13,932,000	9,720,000	6,048,000	10,665,000
70503	WX008	20	Sand and gravel	7,878,700	24,628,000	11,071,000	8,483,000	13,015,17
73365	XG642	98	Sand	—	—	—	102,615	25,654
83001	BG500	No record located		32,000	—	380,000	—	103,000
Other								
4176	RB720	177	Sand	—	60,000	3,240,000	—	825,000

Wells with specific capacity measurements were sorted into two groups: glacial (unlithified) wells and bedrock wells. The data were reviewed for errors, and wells with missing or obviously incorrect data were removed from the analysis. Wells were also removed if the tests were apparently influenced by casing storage effects. The final data set contained 7,483 wells in unlithified materials and 781 wells finished in bedrock.

Water level measurements

As part of this study, a monitoring well in each unit measured continuous water levels. Water levels in the Nicolet Unit were obtained at monitoring well FR-908 (plate 4a). The wells were installed as part of this project and became part of the Wisconsin groundwater monitoring network in October 2011. The USGS maintains daily water level records which are publicly available from its National Water Information System website under site number 455646089012601. Records for this well are available online at http://waterdata.usgs.gov/wi/nwis/inventory/?site_no=455646089012601. The well is approximately 15 ft deep and screened in unlithified sand and gravel. Well construction information and a site sketch are included in the electronic data associated with this report (see Data availability).

Currently, two other wells in the Nicolet Unit are being monitored daily as part of the Wisconsin groundwater monitoring network: FR-87 (plate 4a) and FR-656 (plate 4b). Both wells are screened in sand and gravel and are 102 ft and 34 ft deep, respectively. Records for these wells are available on the National Water Information System website at http://waterdata.usgs.gov/wi/nwis/inventory/?site_no=455620088593901 and https://waterdata.usgs.gov/wi/nwis/inventory/?site_no=452726088434401.

Results

Hydrostratigraphic layers

Elevation of the interpolated bedrock surface in the Nicolet Unit is shown on plate 5. The bedrock surface generally slopes to the southeast, as does the surface topography, and it ranges from 800 to 1,650 ft above mean sea level. The bedrock surface of the Paleoproterozoic metavolcanic rocks in the north and central regions of the unit has the highest elevation in the unit; it generally slopes gently down to the east. A ridge overlies the southern border of Forest County at the contact with the Wolf River batholith, south of which the bedrock dips to the south and east. The lowest bedrock elevation, about 800 ft, is located at the southeast corner.

Depth to bedrock ranges from zero to approximately 200 ft (plate 6). The deepest bedrock is present in eastern Vilas County and southwestern Forest County, corresponding to topographic highs. With the exception of the bedrock ridge trending east–west along the contact with the Wolf River batholith, most topography in the unit is developed on glacial deposits. Shallow bedrock is present throughout the unit where glacial deposits are thin, particularly near the southeast corner of the unit.

The saturated thickness of unlithified materials in the unit ranges from zero to approximately 200 ft, similar to the depth to bedrock; thicker zones lie near topographic highs (plate 7). Saturated glacial materials are thin to absent in some areas where bedrock is shallow.

Hydraulic properties

Plates 1–3, figure 2, and table 4 illustrate the results of the hydraulic conductivity estimates. About 90 percent of the analyzed wells draw their groundwater from unlithified materials. Bedrock wells are most commonly completed where sandy materials are not present, either where glacial materials are fine grained (for example, loamy till of moraines) or where glacial deposits are thin or absent. As seen on plates 1 and 2, glacial wells are much more commonly completed in outwash deposits and, as a result, the unlithified hydraulic conductivities may be skewed toward higher values. Because the results are log-normally distributed, the geometric mean was used to evaluate the central tendency of the data. Hydraulic conductivities

Table 4. Summary of hydraulic estimates for wells, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Wells	Specific capacity (gpm/ft)	Transmissivity (ft^2/day)	Hydraulic conductivity (ft/day)
In unlithified materials (n = 7,483)			
Minimum	0.009	7	0.2
Maximum	200	71,000	1,200
Geometric mean	0.9	1,700	27
Bedrock (n = 781)			
Minimum	0.006	1	0.004
Maximum	25	5,800	360
Geometric mean	0.3	70	1

Abbreviations: gpm/ft = gallons per minute per foot; ft^2/d = square feet per day; ft/d = feet per day

Figure 2a. Hydraulic conductivity estimated from specific-capacity tests in the Nicolet Unit.

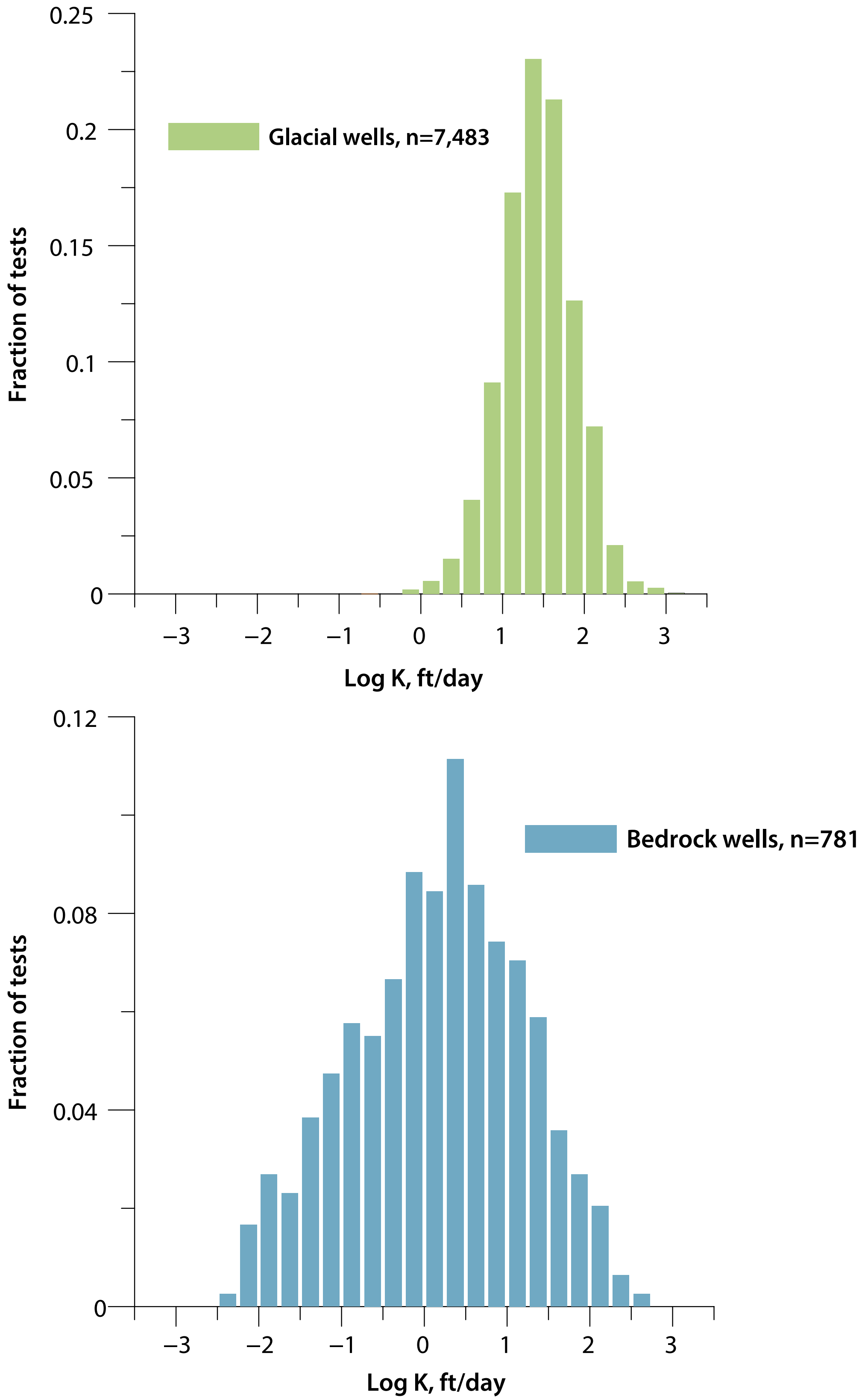


Figure 2b. Transmissivity estimated from specific-capacity tests in the Nicolet Unit.

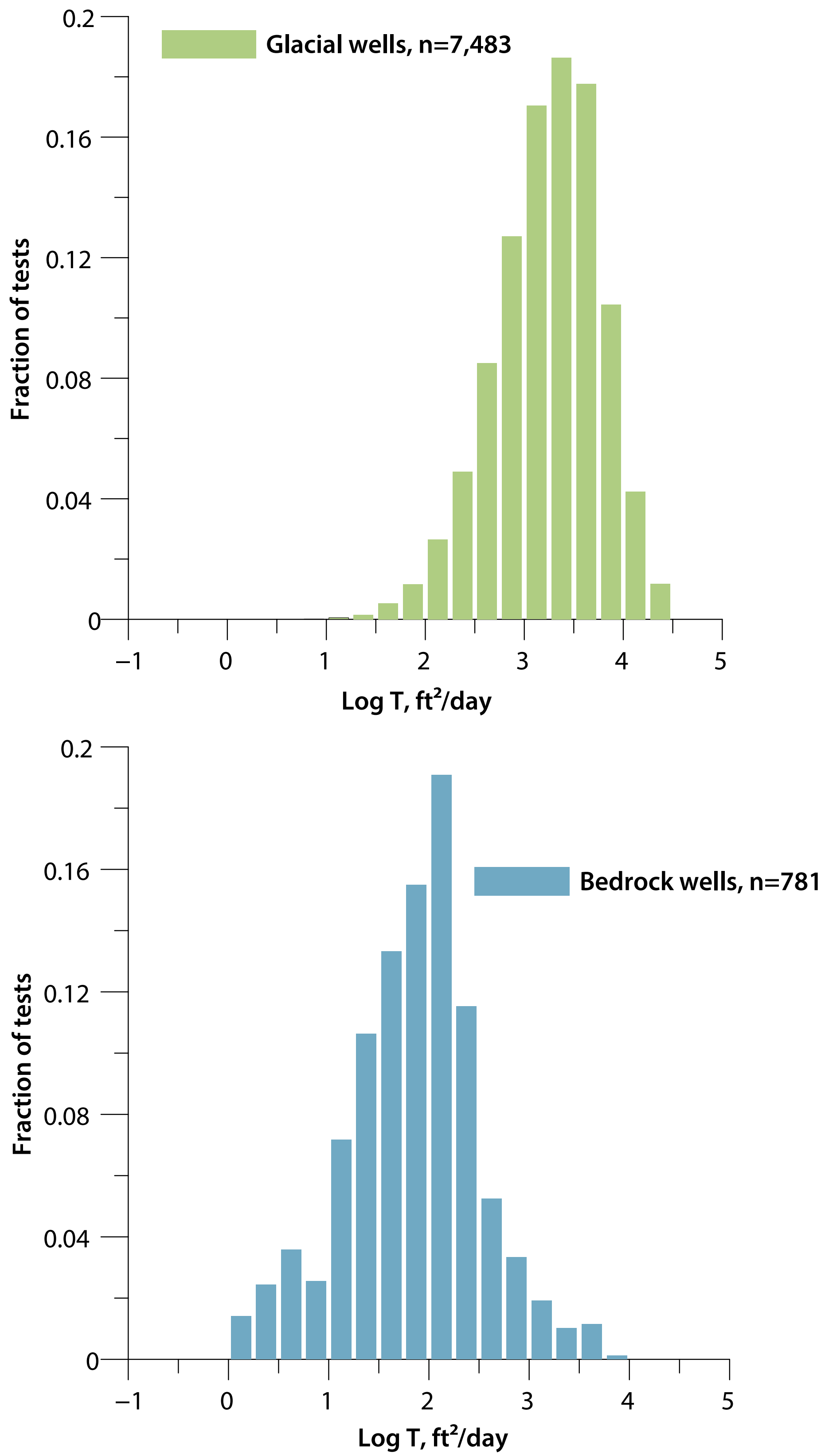
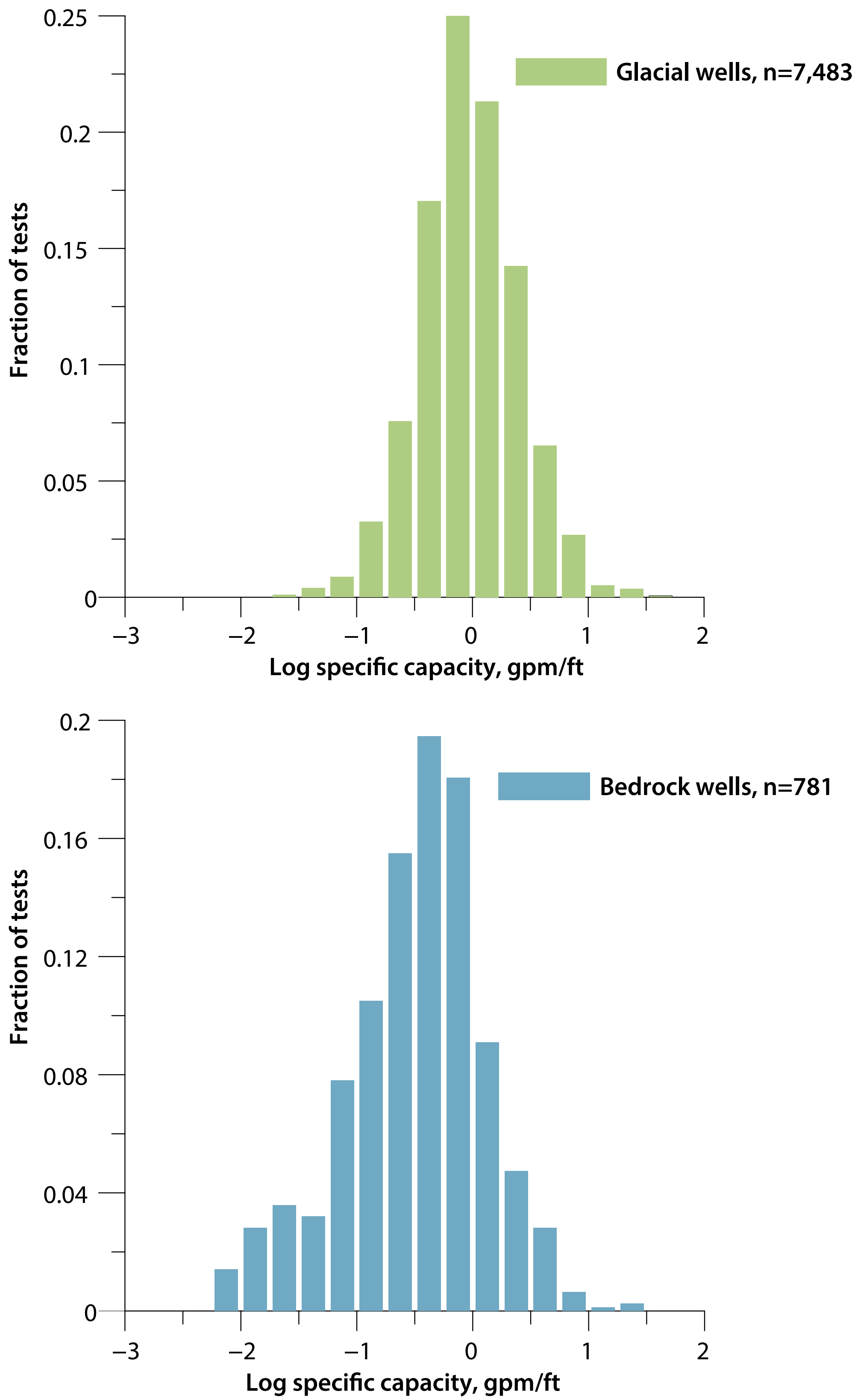


Figure 2c. Specific capacity estimated from specific-capacity tests in the Nicolet Unit.



were moderate in the unlithified materials (mean, 27 ft/d; range 0.2–1,200 ft/d). In general, the hydraulic conductivities in bedrock are about an order of magnitude lower than hydraulic conductivities in glacial materials; the mean hydraulic conductivity is 1.4 ft/d and the range is 0.04 to 360 ft/d. These estimates are similar to hydraulic properties reported in other studies (Batten, 1987; Krohelski and Carlson, 2005; Patterson, 1989).

Aquifer yield depends on hydraulic conductivity as well as aquifer thickness. Transmissivity (plate 1), the product of aquifer thickness and hydraulic conductivity, was therefore used to evaluate potential aquifer yield. Mean transmissivity was 1,700 ft^2/d in the glacial materials and 70 ft^2/d in the bedrock. If we assume mean transmissivity and a drawdown of 30 ft (on the basis of average aquifer thickness of analyzed glacial wells), in many places the glacial aquifer could support a typical yield of 100–200 gpm, above the 70 gpm minimum for high-capacity wells. A similar analysis for the bedrock aquifer that uses 70 ft of drawdown suggests that it could support a yield of about 20 gpm. Yields of several hundreds of gallons per minute are possible in either aquifer where transmissivity is greater than about 1,300 ft^2/d (assuming a drawdown of 30 ft). This analysis suggests that the glacial aquifer has the potential to support high-capacity wells in areas of higher transmissivity, but in general those wells could not produce much more than several hundred gallons per minute. Other studies suggest that higher yields of 500–1,000 gpm are possible in the central portion of the unit where outwash deposits are thick, whereas yields of more than 100 gpm are unlikely in till deposits (Batten, 1987; Devaul, 1975). The bedrock aquifer is unlikely to support high-capacity wells.

Specific capacities (discharge divided by drawdown during a well completion test) are generally low throughout the Nicolet Unit, which suggests low to moderate aquifer productivity, although some wells in both glacial materials and bedrock do have high yields with specific capacities greater than 10 gallons per minute per foot (gpm/ft). By using the same assumptions for drawdown, a typically constructed well in this area could support a yield of about 25 gpm in the bedrock aquifer and 30 gpm in the glacial aquifer. Specific capacity depends on well construction and most wells in the forest are designed for low use; higher yields are possible with larger diameter wells.

Specific capacity did not appear to correlate with glacial material. This lack of correlation may be due to the heterogeneity of glacial deposits on a relatively small scale, the uneven distribution of well records, and the potential for wells to be completed in materials that differ from surficial geology.

Water levels

Groundwater levels in the unit fluctuate seasonally on the order of 5 ft in response to changes in precipitation, evaporation, and evapotranspiration. A hydrograph of well FR-908 (fig. 3) shows the 30-day moving average of groundwater elevation and precipitation measured at the Florence climate station about 50 mi to the east (National Centers for Environmental Information, 2016). The groundwater levels fluctuated about 3 ft with precipitation during the last 5 years, ranging from about 1,712 to 1,715 ft above mean sea level.

The longer-term records at FR-87 and FR-656 are shown in figures 4 and 5. Water levels at FR-87 range from just below 1,672 to nearly 1,677 ft; at well FR-656 they range from about 1,587 to 1,591 ft. The longest record at FR-87 has fluctuated with time, but the current water level is similar to the earliest measurement in 1967. Following a period of regional drought, water levels have continued to increase in all three wells from about 2010 to the present, 2016. These wells provide important baseline data representative of the general study area that can be used for future analyses.

Discussion

Compilation and analysis of available data as shown on plates 1–7 lead to the following general observations.

Hydrogeologic data are sparse throughout large areas of the unit. Review of the data distributions on plates 1, 2, and 4 shows almost no subsurface records for the central parts of the unit in Forest and Florence Counties. Numerous lakes and streams in these areas reflect the elevation of the water table, but measurements of subsurface materials are essentially absent.

Glacial outwash and till deposits form a shallow aquifer, referred to in this report as the glacial aquifer, with low to moderate productivity. The aquifer is thin, ranging from zero to about 200 ft thick. The hydraulic conductivity estimated by using TGUESS ranged from 0.2 to 1,200 ft/d, with a mean of 27 ft/d.

Crystalline bedrock beneath the glacial materials can supply adequate water to low-capacity wells in areas where the glacial deposits are too thin or too fine grained. In general, the bedrock aquifer has hydraulic conductivities about an order of magnitude lower than hydraulic conductivities in the overlying glacial deposits.

The glacial aquifer has the potential in some areas to support high-capacity wells, with an approximate average potential yield of about 100–200 gpm. The bedrock aquifer has an approximate average potential yield of 20 gpm and is unlikely to support high-capacity wells.

About 80 percent of the located wells within the Nicolet Unit are screened in the glacial aquifer at an average depth of about 80 ft. The average bedrock well pumps from the top 140 ft of bedrock, although some pump from as deep as 300 ft.

There are records of only 26 active high-capacity wells within the Nicolet Unit. About 90 percent of these wells are screened in the sand and gravel aquifer and are an average of 100 ft deep. Although these wells are permitted to pump more than 70 gpm, the wells within the unit pump at an average 9 gpm; the total withdrawal in the unit is 240 gpm. In the broader region represented in the regional groundwater model (section 4), high-capacity wells pump at a higher average of 24 gpm and cumulatively at 5,500 gpm.

Groundwater levels measured within the period of this study in a long-term monitoring well are similar to those measured in 1967. More recent water levels in three wells have risen about 3 ft since a regional drought about 2010. These wells provide important baseline data that can be used in future studies.

Subsurface data within the Nicolet Unit are sparse, and additional data collection could improve our understanding of these groundwater resources.

Figure 3. Hydrograph of monitoring well FR-908 showing 30-day running average and monthly precipitation at Florence climate station

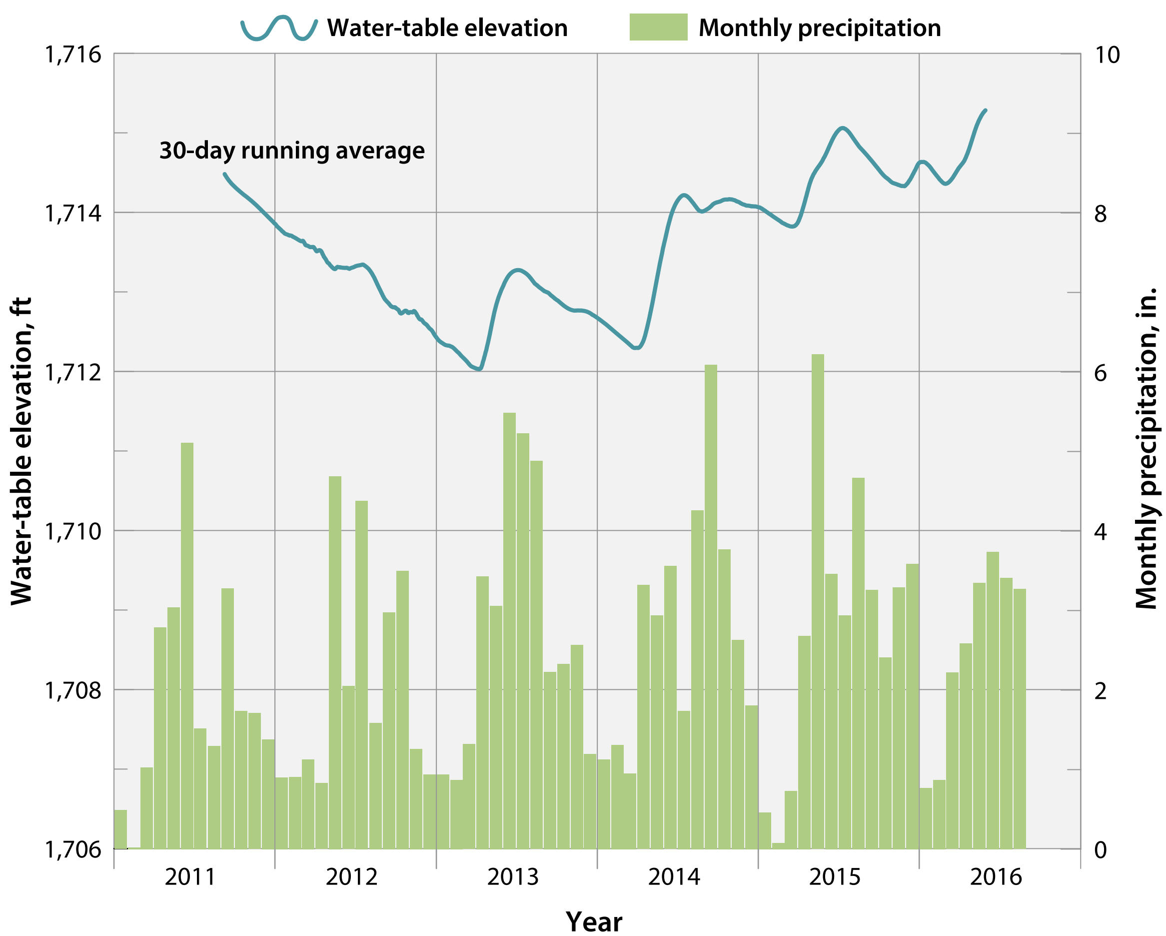


Figure 4. Hydrograph of monitoring well FR-87 from the USGS National Water Information System (NWIS)

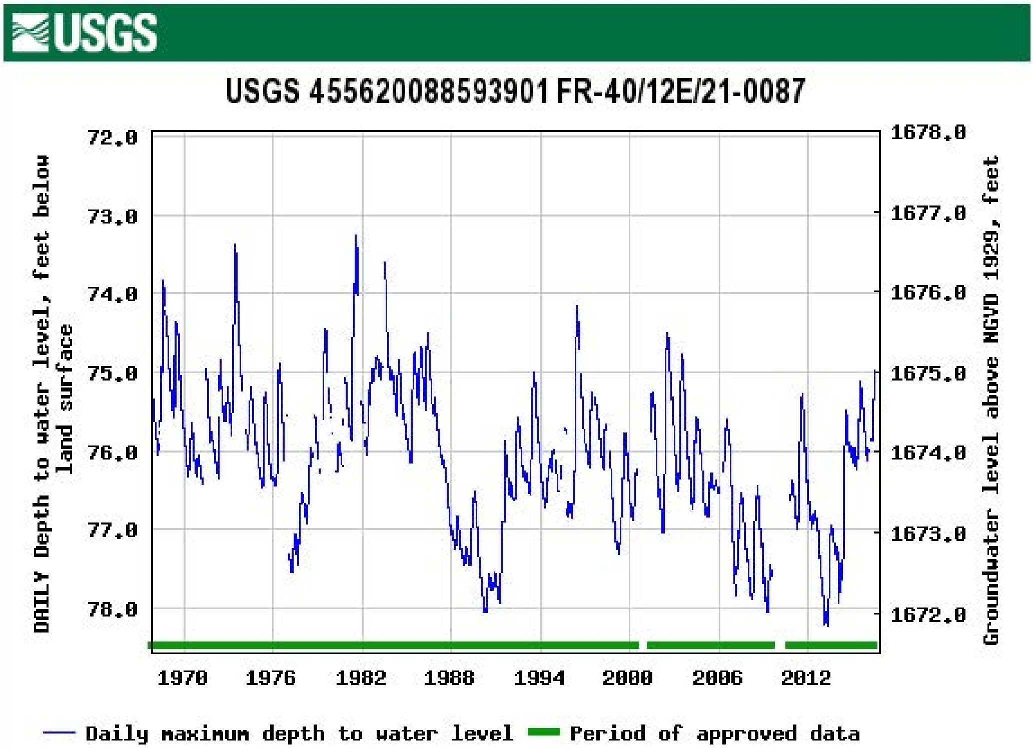
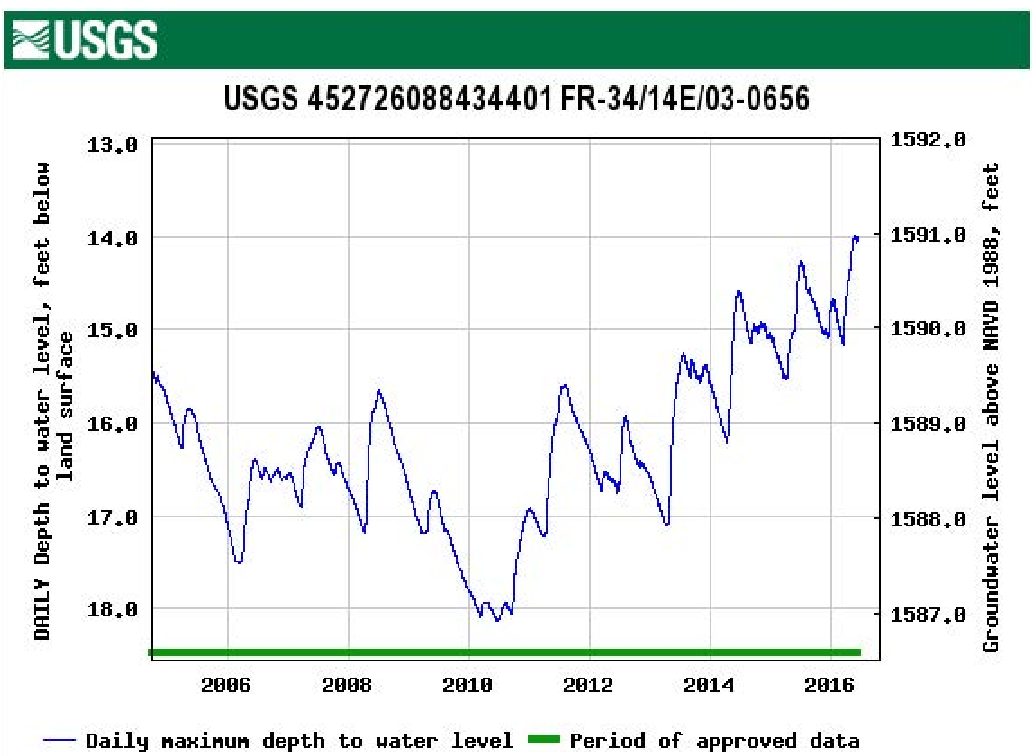


Figure 5. Hydrograph of monitoring well FR-656 from the USGS National Water Information System (NWIS)



Section 2: Potential recharge to groundwater

Objectives

As part of this study, the WGNHS used a soil-water balance (SWB) model to simulate deep infiltration, which can be used as an estimate of potential groundwater recharge, equated to deep drainage from the soil zone. The purpose of this modeling was to produce temporally and spatially variable estimates of deep drainage in the Nicolet Unit, here called potential recharge. The primary output is a summary map showing the general distribution of potential recharge in the Nicolet Unit. The electronic files produced by this analysis are included in the file geodatabase discussed in section 1 (see Data availability).

The SWB model results also provided input for development of a groundwater flow model (section 4). During flow model calibration, the potential recharge grid was modified by use of a multiplier that provided the best match to observed groundwater data. This method allows the groundwater model to incorporate spatially variable recharge and provides a way to calibrate the deep drainage calculated by the SWB model to observed groundwater conditions.

Methods

Overview

Groundwater potential recharge was estimated through application of a SWB model (Westenbroek and others, 2010) to an area encompassing the Nicolet Unit. Figure 6 shows the model extent: an area of more than 6,000 mi^2 covering the unit and all intersecting watersheds of the 12-Digit Watershed Boundary Dataset (Natural Resources Conservation Service, 2014a).

The model estimates the distribution of potential groundwater recharge through time by use of a modified Thornthwaite-Mather method to track soil moisture storage and flow on a spatially referenced grid at daily time increments. Inputs to the SWB model include map data layers for land surface topography and soil and land cover characteristics, as well as tabular climate records. Model outputs include datasets of annual potential recharge for the model grid and time period.

The model calculates recharge for each grid cell on a daily time step by using the following water budget equation:

Recharge = (precipitation + snowmelt + inflow) – (interception + outflow + evapotranspiration) – Δ soil moisture

where (see Westenbroek and others, 2010)

Recharge = deep drainage below the root zone, assumed to become groundwater;

Precipitation = atmospheric rainfall (not including snowmelt);

Snowmelt = water derived from melting snow, on the basis of a temperature index method governing the timing of melting;

Inflow, outflow = surface-water flow onto or off of the grid cell, based on a topographic model;

Interception = water trapped and used by vegetation or evaporated or transpired from plant surfaces;

Evapotranspiration = loss of moisture from land surfaces and plants and to the atmosphere; and

Δ soil moisture = the amount of soil moisture held in storage for a particular grid cell.

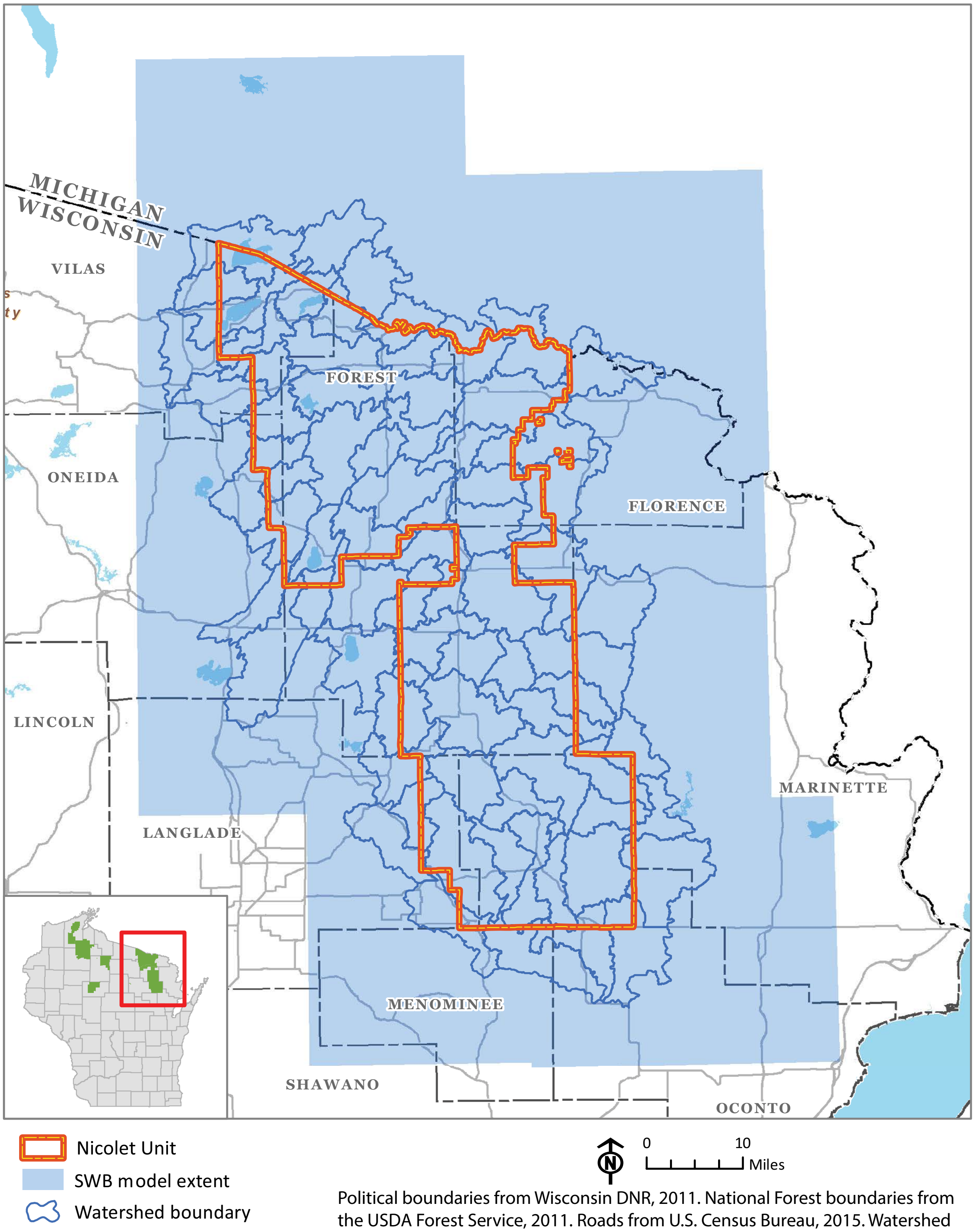
The model calculates runoff from each cell (outflow) and routes it to adjacent cells (inflow) by using a flow-direction grid. Runoff is partitioned in each daily time step; it either becomes infiltration (inflow in the equation above) in a downslope grid cell through runoff routing, or, if there is no downslope cell (at the boundaries of the simulated area), it is removed from the model. Runoff is also removed when it reaches a surface water body; cells assigned a land use of "open water" are set to have zero recharge.

The model calculates daily values of interception and evapotranspiration to account for water trapped and used by vegetation, as well as changes in soil moisture. Any excess water inputs are converted to recharge.

Because all runoff is used up in each time step, the SWB model code does not allow ponding. For closed depressions in the flow-direction grid, recharge is the primary mechanism for removing water from the cell, and focused areas of unrealistically high recharge values may result. However, all closed depressions were removed from this model (see Data sources—Flow direction). To account for model assumptions that may result in local instances of unrealistically high recharge, infiltration rates were limited to 100 in/d. Such high rates might occur within very small areas of closed depressions following intense storms or runoff, but in the large domain of the model this assumption affects the results very little.

Unlike the SWB models for other forest study areas, the Nicolet SWB model takes advantage of a newer feature that allows the user to input climate data in a gridded format rather than manually tabulating from

Figure 6. Extent of Nicolet soil-water balance model.



Political boundaries from Wisconsin DNR, 2011. National Forest boundaries from the USDA Forest Service, 2011. Roads from U.S. Census Bureau, 2015. Watershed boundaries and hydrography from National Hydrography Dataset, 2011–12.

climate station records. The Nicolet model also uses a different method, the Hargreaves-Samani (1985) method, for calculating evapotranspiration. This newer capability of the SWB code is intended for use with gridded climate data. The method has the advantage of producing spatially variable estimates of potential evapotranspiration by use of daily minimum and maximum temperatures. Other available methods produce only spatially uniform estimates. For a more detailed discussion of evapotranspiration methods, see Westenbroek and others (2010).

Data sources

Flow direction

The SWB model uses digital topographic data to determine surface-water flow direction and properly route runoff. Flow direction was calculated by using a 30-m DEM from the U.S. Geological Survey's National Elevation Dataset (U.S. Geological Survey, 2013) and a standard flow direction routine. Although more-detailed elevation data are available for the area, the 30-m resolution was selected as most appropriate given the scale of this study. Because DEMs typically include closed depressions that confound simple flow planes used for surface routing of flow, a standard closed-depression fill routine was applied to the DEM before the final calculation of the flow-direction input grid. Several fill thresholds were tested, and a complete fill was determined to be the most appropriate. True closed depressions were estimated to account for approximately 10 percent of the model area. Although true closed depressions are present in the model area, the identification, verification, and incorporation of these data were beyond the scope of this effort but could be incorporated into future site-specific studies.

Hydrologic soil group and available water storage

Digital soil map data from the Natural Resources Conservation Service Soil Survey Geographic Database were used for two input datasets to the SWB model, hydrologic group and available water storage (Natural Resources Conservation Service, 2014b). The hydrologic group is a classification of the infiltration potential of a soil map unit and is used in the SWB model in runoff calculations. The primary categories range from A to D, representing low to high runoff potential. Several map units in the model domain were classified with dual designations, such as "A/D," where the lower runoff designation typically indicates artificially drained land. Any infiltration in this situation would ultimately be available downslope as runoff, and for this reason all dual-designation soil map units were reassigned to the higher runoff category. The available water storage characteristic is a measure of the amount of water-holding potential in a specified soil thickness and is used by the model to account for root zone moisture.

Land cover

The 2006 land cover map from the National Land Cover Database (U.S. Geological Survey, 2011a) provides land cover data for the model area. These data are used to calculate interception, runoff, and evapotranspiration and to estimate vegetation root-zone depth. Runoff curve numbers, rooting depth estimations, and other parameters were reviewed and adjusted to best approximate conditions in the model area.

Daily temperature and precipitation

The SWB model uses tabulated daily temperature and precipitation observations as inputs to specify precipitation, track snow cover and melt, determine frozen-ground conditions, and estimate potential evapotranspiration. Given the large extent of the model area, gridded climate data were used to provide climate inputs, similar to the approach used for other regional SWB models (such as Smith and Westenbroek, 2015). Gridded climate data were obtained from Daymet, a collection of daily gridded climatological data created by interpolating individual observations (Thornton and others, 2012).

The simulation period of the model, 2000–2010, represents recent climate conditions while also showing variability in total annual precipitation. Variability in precipitation will cause variability in recharge to the groundwater system; a model period of more variable precipitation can indicate the long-term variability in potential recharge. The same time interval was selected for all four national forest units studied for this project after we compared precipitation statistics: the goal was to select a single, recent, and relatively short time period that represented the average and extremes of a longer time period. According to Daymet data, from 2000 to 2010, the model area had an average precipitation of 33 in/yr and a range of 29 to 41 in/yr (fig. 7). The annual average precipitation compares favorably with the 30-year average precipitation for northeast Wisconsin (31.5 in/yr, Wisconsin State Climatology Office, 2017). However, areas of higher precipitation in the south suggest potential spatial bias in the gridded dataset.

Running the SWB model

Data grids for the four map inputs (flow direction, hydrologic group, available water storage, and land cover) were generated from the source datasets for input to the model. Daily climate data for minimum, maximum, and average temperature and for total precipitation were input from the gridded climate data. The full model extent was subdivided, and six sub-models with distinct climate inputs were run for the period 1999 through 2010; the year 1999 was used to develop antecedent moisture conditions for year 2000.

Results

Discussion

Each of the sub-models simulated the daily soil-water budget during the model period and was configured to output grids of annual recharge and summary tables of the water balance. The grids were converted to raster format for further aggregation and analysis. For each model year the output of the sub-models was mosaicked to a single grid covering the full model extent. In addition, to better understand average recharge conditions, the 11 grids (one for each of the 11 years simulated) were averaged to produce a grid of mean annual groundwater potential recharge during the model period. This grid was further processed to fill in any "no-data" cells with the mean of the surrounding grid cells.

The mean potential recharge simulated throughout the model domain for the period 2000 through 2010 was 4.6 in/yr. The average simulated values for each parameter in the water balance equation are included in table 5. The average values are on the low end of other reported recharge for these and nearby areas (for example, Batten, 1987; Gebert and others, 2011, fig. 2; Krohelski and Carlson, 2005; Neff and others, 2005; Patterson, 1989). The reasons for the low potential simulated recharge in this forest unit are unclear. It may be that the model's calculation of evapotranspiration affected the overall results. The Nicolet Unit model used a different method for calculating evapotranspiration (Hargreaves-Samani, 1985) than was used in the other national forest units to take advantage of the ability to model spatially variable evapotranspiration and to use gridded datasets rather than manually tabulating data from several climate stations. However, the simulated evapotranspiration is higher in the Nicolet Unit (25 in) than in other modeled national forest units, making up about 75 percent of the water balance compared to 45 to 55 percent in the other units. Although this value is within the range of typical values in Wisconsin, studies in northern Nicolet report lower estimated or modeled values closer to 20 in (Patterson, 1989; Vano, 2005). Soil type is another factor that may contribute to the low mean recharge. Differences in hydrologic soil group classification in Michigan's Upper Peninsula and in Wisconsin create an unrealistic contrast in potential recharge at the state border. In Michigan, soils in the model area are classified as having higher runoff potential than soils in Wisconsin, resulting in lower estimated recharge. The higher potential recharge results in Wisconsin are more consistent with other estimates of recharge in this region and are interpreted to imply a more appropriate hydrologic soil group classification. The lower estimates in Michigan further reduce the overall simulated mean potential recharge for the entire model. This spatial contrast as well as the low recharge magnitude of the SWB dataset were addressed during groundwater flow modeling to produce a calibrated recharge map (plate 8).

During development of the groundwater model (section 4), the SWB model recharge estimates were adjusted to calibrate to groundwater targets (water levels and streamflow). This adjustment reduced the overall low bias while maintaining

Table 5. Soil-water balance model approximate average water balance parameters, years 2000–2010[1], Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Water balance parameter	Average value (in/yr)
Precipitation	34
Interception	2
Runoff from grid	1
Evapotranspiration	25
Recharge	5
Runoff to surface water[2]	2

Abbreviations: in/yr = inches per year

[1]Based on daily water balance statistics output for the full model grid, including areas outside the forest unit, weighted by area for each submodel.

[2]Runoff to surface water is not explicitly calculated by the model; this term was calculated as the remainder of the water balance.

the spatial distribution of SWB model results. Low values of recharge at the Michigan border were manually adjusted to be more consistent with the higher potential recharge in Wisconsin. The SWB grid was downsampled, or generalized, for import into the groundwater flow model. Lastly, the grid was adjusted by using a multiplier to calibrate it to measurements of groundwater heads and stream baseflows. As described in section 4 of this report, two groundwater flow models were created, one each for the northern and southern parts of the Nicolet unit. The recharge multipliers were 1.72 and 1.36, respectively, resulting in modeled mean recharge values of 7.1 in/yr and 7.5 in/yr for the portions of the Nicolet Unit represented in the North and South models (table 6); these manipulated values are more consistent with recharge reported in nearby areas. Plates 8a and 8b depict the calibrated mean annual groundwater recharge for the northern and southern watersheds of the Nicolet Unit, respectively. Groundwater flow model calibration is discussed in more detail in section 4.

The general trend in the distribution of recharge within the unit generally correlates with surficial geology through soil characteristics. Throughout the whole unit, local areas of higher recharge correlate with sandy soils and forest cover, and areas of lower recharge correlate with finer soils and wetland cover. This pattern is consistent with our understanding of the groundwater system; precipitation enters the groundwater system as recharge at high points in the landscape (forest cover) and exits, or discharges, at low points such as wetlands, streams, or lakes. It is a common misconception that wetlands are always important groundwater recharge areas, when in fact they are often areas of discharge or low recharge. The mean calibrated recharge for the north and south flow models is similar but slightly higher in the south. This difference is more pronounced in the raw SWB model potential recharge, and higher recharge in the south commonly corresponds to areas of higher precipitation in the gridded input data. However, any potential bias from spatial variations in the precipitation data was reduced by calibrating the north and south parts of the unit separately. In certain cells of the recharge grid, recharge rates are higher than is typically considered appropriate for large-scale areal groundwater recharge. Plate 8 displays these values as greater than 15 in/yr.

Although the overall SWB model results for the Nicolet unit appear to be biased low, the results provide detail in spatial and temporal variation that is not captured in the calibrated recharge grid shown on plate 8. Because the grid was generalized for import into the flow model, the SWB model results include more detail in spatial resolution than the calibrated recharge plate. These results also include yearly grids of potential recharge from 2000 to 2010. Mean potential recharge variability during this time period is summarized in figure 7. This graph shows total annual average gridded precipitation along with average potential recharge. Annual potential recharge is correlated with precipitation and varied from 2.9 to 8.4 in/yr for the 11 years between 2000 and 2010. The raster grids for each modeled year are included in the electronic database for public use.

Assumptions and limitations

The recharge estimates reported here are subject to several important limitations and assumptions. Most important, the SWB model does not include a groundwater component, and it is not directly linked to the groundwater system. The deep drainage calculated by the SWB model may differ from true groundwater recharge where hydraulic gradients in the groundwater system are upward and recharge therefore cannot enter the groundwater system, or in areas where the unsaturated zone is very thick and redistributes and stores large volumes of water.

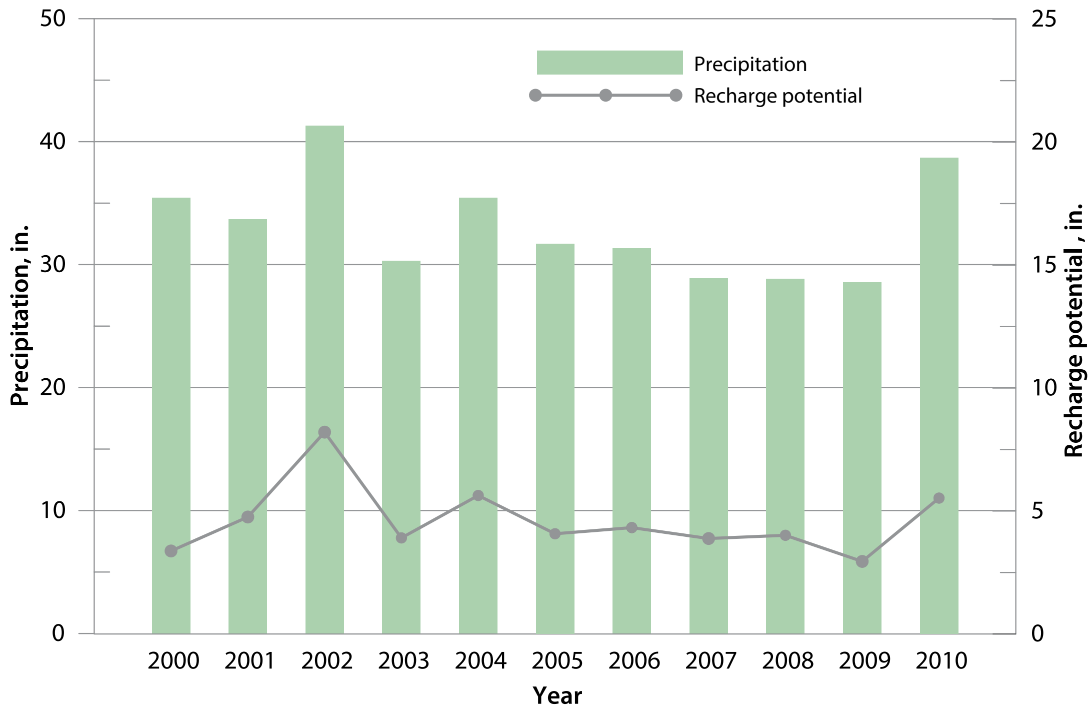
Table 6. Soil-water balance model mean annual recharge results, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Variant soil-water balance model	Recharge (in/yr)		
	Entire unit	North model	South model
Original model (includes wetland recharge)	4.6	—	—
Assuming zero wetland recharge	3.5	—	—
Calibrated to GFLOW model (by using multiplier of 1.7 and 1.4)[1]	—	9.3	6.5

Abbreviations: in/yr = inches per year; SWB = soil-water balance

[1] *The SWB grid used in GFLOW has a slightly different extent than the SWB model and therefore does not correlate exactly to mean SWB model values reported here.*

Figure 7. Total annual precipitation at the Florence climate station and mean potential recharge.



Overall simulated potential recharge for the Nicolet Unit appears to be biased low; however, this bias was reduced by calibrating the groundwater flow model to produce more realistic groundwater recharge rates. The calibrated recharge grid, as well as the raw SWB grids, are included in the report dataset. Users of the SWB model dataset should consider applying a multiplier to adjust for the low bias, similar to the approach that we used in the groundwater flow model.

Model results near the state border between Michigan and Wisconsin are unrealistic owing to differing hydrologic soil group classifications between the two states. The lower results in Michigan are inconsistent with other estimates of recharge and are interpreted to be less reliable than those in Wisconsin.

Recharge in wetlands and other areas where the water table is shallow may be overestimated by the SWB model. When the water table is near the root zone, water continually leaves the system through evapotranspiration. However, the SWB model does not simulate the nearly saturated conditions in wetland areas and thus doesn't simulate the high evapotranspiration from these areas. As a result, the model may overestimate recharge in these areas. Wetlands cover about a third of the Nicolet Unit but determining which of these wetlands contribute to recharge was outside the scope of this study. Assuming zero recharge in wetlands produces an average forest-wide potential recharge of 3.5 in/yr. Because wetlands do account for some recharge, the assumption of zero recharge provides a lower bound for estimated potential recharge. Given the low bias in the model, any overestimation of recharge in wetlands in the Nicolet model is unlikely to materially influence the results.

Although true closed depressions likely exist in the model domain, such depressions were filled in the SWB model to improve the functionality of the flow-direction grid. Recharge is potentially underestimated for some of these true closed depressions. Additionally, the model does not account for dewatering in pits and quarries, which affects recharge in these areas. The few gravel pits in the project area are not anticipated to change the overall results. Additional details on model limitations are outlined in Hart and others (2012).

Section 3: Baseline water chemistry

Objectives

The third part of this study inventoried basic surface-water and groundwater geochemistry in the unit. The WGNHS systematically sampled water in the Nicolet Unit during 2013 through 2016, with the objective of understanding current water chemistry in the unit. Samples were taken chiefly from groundwater wells and springs but also from two streams and one lake. Water samples were analyzed for major ion chemistry, basic nutrients (nitrate and phosphorus), and the stable isotopes oxygen-18 (^{18}O) and deuterium (^{2}H). This report summarizes the water chemistry data collected and is not intended to be a comprehensive analysis of the geochemistry of the Nicolet Unit. The sample site locations and laboratory results are described in the file geodatabase (see Data availability).

Methods

Selection of sampling sites

Water samples were collected at 40 sites in the unit of four types: wells, spring ponds, streams, and a lake. The sites (26 wells, 11 spring ponds, 2 streams, and 1 lake) were generally distributed both spatially and by type of water source, as well as accessible for sampling. Some preference was given to sampling spring ponds because they are much more prevalent in the Nicolet Unit than in other national forest units studied. Because the focus of this study was on groundwater, the project scope did not allow for more thorough sampling of surface-water features. Most of the wells selected for groundwater sampling are operated by the USFS at campgrounds and picnic areas. If a discrete discharge point was present, samples from spring ponds were obtained as near to the discharge point as possible. Stream samples were obtained near road access points. Samples from the lake were obtained at a campground beach. Figure 8 shows all sampling points in the Nicolet Unit, and table 7 lists information about the specific wells sampled. Most of the sampled wells are 50–100 ft deep and are open to the unconsolidated glacial aquifer; five of the wells are screened in bedrock.

Sampling procedures

Samples were collected in October 2013, July 2014, and May 2016. Groundwater samples were collected directly from hand pumps or electric pumps installed in USFS wells. Wells were purged of approximately one well volume prior to sampling. Samples from spring ponds, streams, and the lake were collected by dipping a sample bottle directly into the water. Samples were placed in prepared bottles provided by the laboratory. For ion samples, three containers were used. For analysis of major cations and anions (Ca, Mg, Na, and Cl), water was passed through a membrane filter with 0.45 micron pore size and stored in 15-milliliter (mL) vials preacidified with nitric acid. A second, filtered sample to be analyzed for nutrients was placed into 125-mL polyethylene bottles preacidified with HCl. A third, nonfiltered, sample to be analyzed for alkalinity was placed in a nonacidified 125-mL polyethylene bottle. Unfiltered samples for isotopes were placed in separate 250-mL polyethylene bottles. All samples were immediately placed on ice in coolers in the field. Geochemical samples were transported to the laboratory within 48 hours of sampling. Isotope samples were refrigerated at the WGNHS, Madison, Wisc., prior to shipment to the laboratory.

Analytical procedures

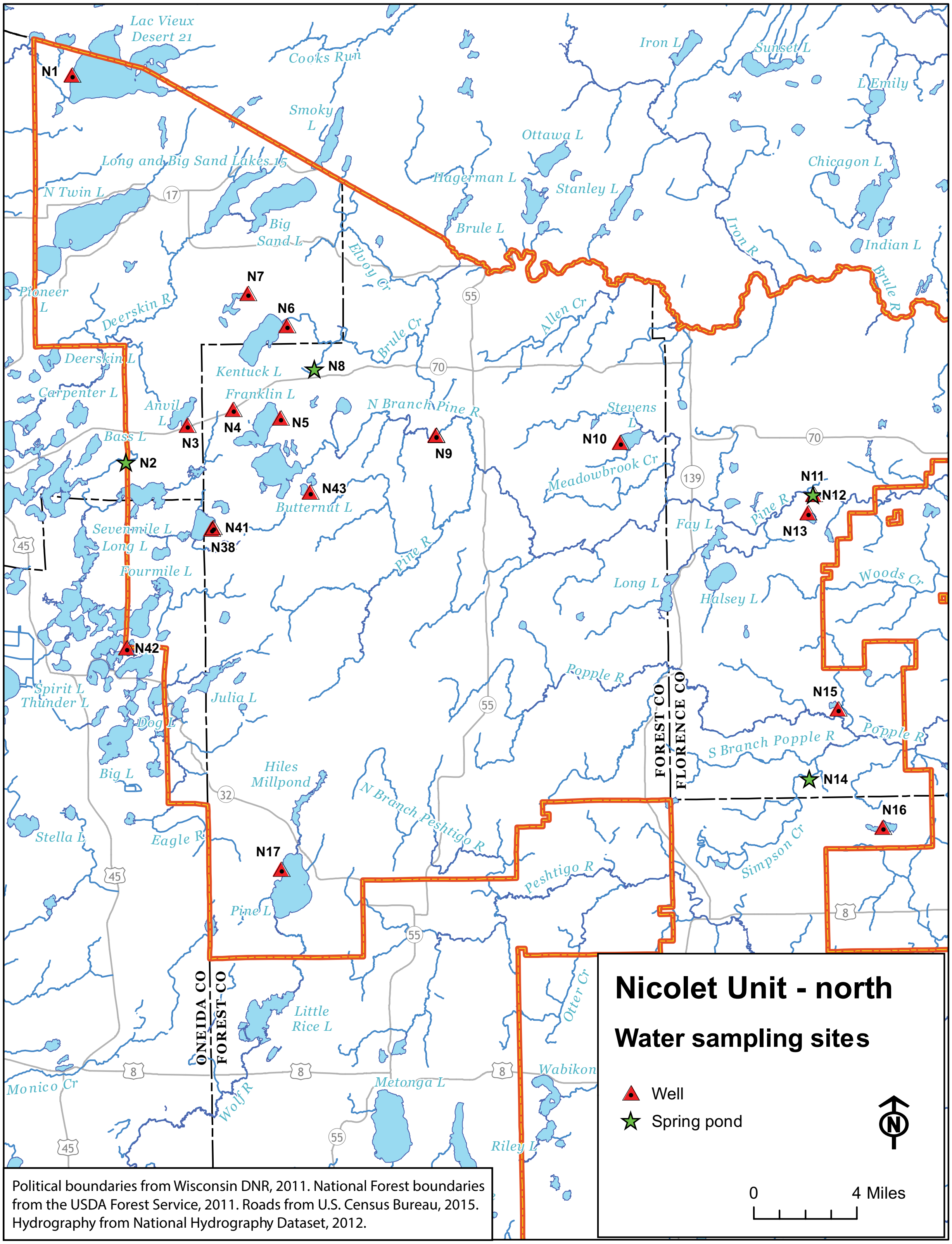
For all samples, electronic field meters measured temperature, pH, and electrical conductivity in the field immediately after sampling. Dissolved oxygen was measured by either an electronic field meter or colorimetric field kit. Major ions, nutrients, and laboratory alkalinity samples were submitted to the Water and Environmental Analysis Laboratory at the University of Wisconsin-Stevens Point (https://www.uwsp.edu/cnr-ap/weal). Oxygen-18 and deuterium were analyzed at Iowa State University Stable Isotope Lab (https://www.ge-at.iastate.edu/research/climate-quaternary/siperg/).

Results

Major ion chemistry

Electrical conductivity is commonly used to estimate total dissolved solids. On the basis of electrical conductivity values less than 300 microsiemens per centimeter (µS/cm), groundwater and surface water both are low in dissolved solids, with nearly neutral to slightly basic pH and similar distribution of ion concentrations. Groundwater is distinguished from surface water by higher conductivity, alkalinity, and magnitude of ion concentrations such as calcium and magnesium. Table 8 contains field chemistry results, table 9 contains the major ion results, and table 10 shows average results for each source type. Groundwater and surface water in the Nicolet Unit are dominantly a Ca-Mg-HCO_3 type (see tables 10 and 11 and fig. 9). To calculate sample averages, samples with non-detect results were assumed to have a concentration of half the detection limit. Water quality results are consistent with results in previous studies in the region (Batten, 1987; Patterson,

Figure 8a. Water sampling locations in the northern Nicolet Unit.



Political boundaries from Wisconsin DNR, 2011. National Forest boundaries from the USDA Forest Service, 2011. Roads from U.S. Census Bureau, 2015. Hydrography from National Hydrography Dataset, 2012.

Figure 8b. Water sampling locations in the southern Nicolet Unit.

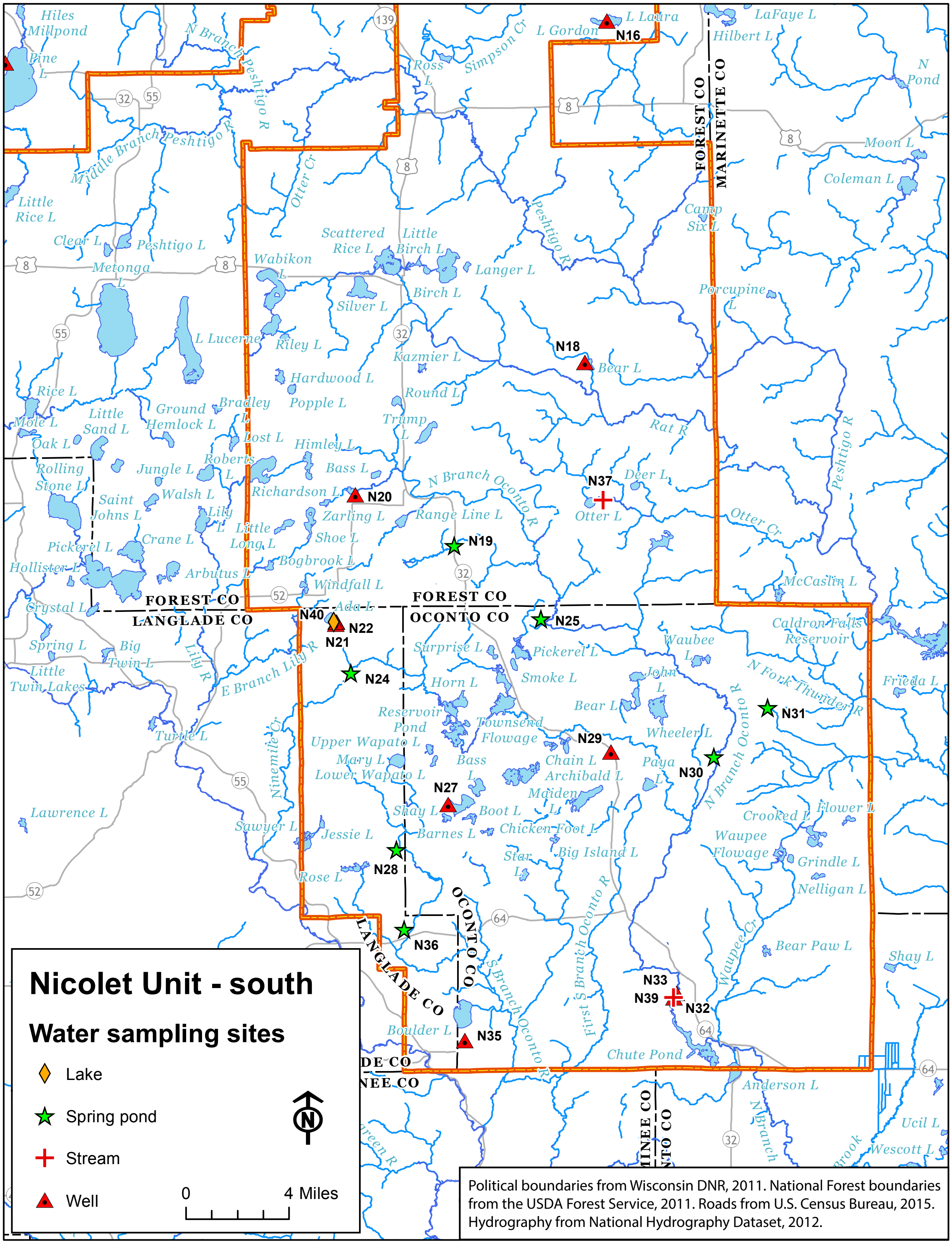


Table 7. Information about wells sampled, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Well sampled	Site number[1]	Project ID[2]	WI unique well no.[3]	Total depth (feet)	Material, reported by driller
Ada Lake Campground—deep	N21	4717	GP647	144	Red granite
Ada Lake Campground—shallow	N22	4716	GP646	123	Sand and gravel
Anvil Lake Campground	N3	37998	GP592	48	Sand
Anvil Lake monitoring well FR-9083	N4	Shallow monitoring well		15	Sand and gravel
Bagley Rapids Campground—deep	N33	17369	JC786	156	Granite
Bagley Rapids Campground—shallow	N32	17370	JC785	79	Granite
Bear Lake Campground	N18	1797	AV191	67	Sand and gravel
Boot Lake Campground	N27	17366	JC842	31	Sand
Boulder Lake Campground	N35	17346	JC835	109	Sand and gravel
Chipmunk Rapids Campground	N12	30	JB618	57	Sand
Franklin Lake Campground	N5	1799	GP594	86	Hardpan and sand
Kentuck Lake Campground	N6	1782	HO900	81	Gravel
Lac Vieux Desert boat launch well	N1	38023	GP582	48	Sand and gravel
Laura Lake Campground	N16	4639	GP644	—	Not recorded
Laurel Lake well	N42	26834	GP598	52	Sand and gravel
Lost Lake Campground	N13	8	CI805	77	Sand and gravel
Luna-White Deer Campground	N43	4642	GP588	51	Not recorded
Morgan Lake Campground	N15	34	JD795	85	Sand
Pine Lake Campground	N17	1806	GP641	100	Granite
Richardson Lake Campground	N20	1767	AV192	42	Sand and gravel
Sevenmile Lake—deep	N38	1808	GP596	141	Sand
Sevenmile Lake—shallow	N41	1807	GP595	97	Sand and gravel
Spectacle Lake Campground	N7	37948	GP583	66	Sand and gravel
Stevens Lake well	N10	1815	GP637	42	Bedrock
USFS Lakewood ranger station	N29	17384	QQ953	120	Sand and gravel
Windsor Dam Campground	N9	1809	GP586	34	Sand and gravel

[1]*Arbitrary number assigned to each water sampling site*

[2]*Object ID in Located WCR geodatabase*

[3]*Monitoring well installed for this project. Number indicates WGNHS geologic log number. Well construction information included in appendix 1.*

Table 8. Water chemistry field results, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Site number	Water source and location sampled	Date sampled	Temp. (°C)	Conductivity (µS/cm)	Dissolved oxygen (ppm, mg/L)	pH
Well						
N1	Lac Vieux Desert boat launch well	10/14/2013	10.7	220	1.8	7.7
N3	Anvil Lake Campground	10/14/2013	8.5	274	11	7.1
N4	Anvil Lake monitoring well FR-908	7/9/2014	6.5	27	8.9	6.2
N5	Franklin Lake Campground	7/8/2014	8.8	201	4.7	7.8
N6	Kentuck Lake Campground	10/14/2013	9.9	230	3.8	7.7
N7	Spectacle Lake Campground	10/14/2013	8.0	323	0.9	7.6
N9	Windsor Dam Campground #1	10/14/2013	8.0	228	8.4	8.2
N9	Windsor Dam Campground #2	7/8/2014	7.6	155	5.4	9.4
N10	Stevens Lake well	10/15/2013	9.1	387	7.5	8.4
N12	Chipmunk Rapids Campground	10/15/2013	8.5	430	4.2	8.1
N13	Lost Lake Campground	10/15/2013	9.4	169	2.0	8.1
N15	Morgan Lake Campground	10/15/2013	8.8	201	2.5	8.4
N16	Laura Lake Campground	10/15/2013	8.8	196	1.2	8.1
N17	Pine Lake Campground	10/15/2013	9.1	261	5.1	7.3
N18	Bear Lake Campground	10/15/2013	8.4	275	8.1	8.1
N20	Richardson Lake Campground	10/16/2013	7.4	253	7.8	7.8
N21	Ada Lake Campground—deep	10/16/2013	8.7	140	4.1	8.8
N22	Ada Lake Campground—shallow #1	7/10/2014	11.6	228	7.6	8.3
N22	Ada Lake Campground—shallow #2	5/10/2016	8.3	253	4	8.3
N27	Boot Lake Campground	10/16/2013	8.1	284	3.9	7.7
N29	USFS Lakewood ranger station	7/10/2014	12.4	337	7.3	8.6
N32	Bagley Rapids Campground—shallow	5/9/2016	7.7	359	4	9.2
N33	Bagley Rapids Campground—deep	10/16/2013	9.5	340	8.5	8.6
N35	Boulder Lake Campground	10/16/2013	11.5	412	7.8	7.8
N38	Sevenmile Lake—deep	7/8/2014	10.9	211	5.5	8.0
N41	Sevenmile Lake—shallow	10/15/2013	9.1	211	2.1	8.6
N42	Laurel Lake well	10/15/2013	9.0	208	2.0	8.5
N43	Luna-White Deer Campground	10/15/2013	7.5	150	1.5	7.7
Spring pond						
N2	Spring Meadow spring	7/7/2014	20.7	112	—	6.8
N8	Brule Springs	5/10/2016	5.6	289	6–8	7.7
N11	Chipmunk Springs	7/9/2014	7.9	397	6.1	7.9
N14	Simpson Creek Pond	7/9/2014	18.2	236	9.3	9.0
N19	Torpee Creek Seeps	7/9/2014	18.7	269	9.4	8.6
N24	McCaslin Spring	10/16/2013	9.4	260	8.6	7.8
N25	Hemlock Spring Pond	5/10/2016	12.3	297	6–8	8.1
N28	Saul's Spring	5/9/2016	15.1	304	8–10	8.5
N30	Sullivan Spring	7/10/2014	20.7	264	8.2	8.5
N31	Forbes spring	7/10/2014	20.1	313	8.7	8.2
N36	Roix Springs	5/10/2016	8.5	305	6	8.0

Abbreviations: °C = degrees Celsius; µS/cm = microsiemens per centimeter; DO = dissolved oxygen; mg/L = milligrams per liter

(continued)

Table 8. Water chemistry field results, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin *(continued).*

Site number	Water source and location sampled	Date sampled	Temp. (°C)	Conductivity (µS/cm)	Dissolved oxygen (ppm, mg/L)	pH
Stream						
N37	Otter Creek	7/9/2014	21.3	233	7.1	7.9
N39	Bagley Rapids, North Branch Oconto River	5/9/2016	15.2	269	6–8	8.3
Lake						
N40	Ada Lake beach	5/10/2016	11.7	31	6	7.2

Abbreviations: °C = degrees Celsius; µS/cm = microsiemens per centimeter; DO = dissolved oxygen; mg/L = milligrams per liter

1989). Charge balance calculations showed that although most samples satisfy standard criteria for acceptable lab analyses, 11 samples had unacceptable charge balance errors (table 9). The criteria for determining acceptable charge balances depend on the sum of the anions. The balance was considered acceptable if (1) the cation-anion difference was within 0.2 milliequivalents per liter (meq/L) for anion sums 0–3 meq/L, (2) the charge balance was within 2 percent for anion sums 3–10 meq/L, or (3) the charge balance was within 5 percent for anion sums of 10–800 meq/L. The dilute nature of the water contributes to these percentage balance errors; when the overall sum of cations or anions is small even a small analytical error in one constituent can result in a large overall percentage error in the balance. Results from samples having unacceptable charge balance errors should be used with caution.

As expected (although on the basis of only three surface-water samples), groundwater is considerably more alkaline than surface water, and it has higher electrical conductivity. Groundwater well samples have an average alkalinity of 108 mg/L (range 12–208 mg/L) and conductivity of 249 (range 27–430) µS/cm. Water from monitoring well FR-908 at Anvil Lake (site N4, fig. 8a) is anomalous, having appreciably lower conductivity, alkalinity, temperature, pH, and ion concentrations than water from other wells, and its isotopic signature is characteristic of cold recharge conditions (see Isotope section below). It is possible that shallow groundwater at this site reflects early spring recharge from snowmelt. Other wells with somewhat lower conductivity and alkalinity, such as the deep bedrock well at Ada Lake Campground (site N21, fig. 8b) may be drawing from nearby surface waters. Interestingly, water from a shallow sand-and-gravel well also located at Ada Lake (site N22, fig. 8b) has higher alkalinity and conductivity than both the lake and the deep bedrock well, as well as an isotopic signature more typical of groundwater.

The 11 springs and spring ponds have relatively high electrical conductivity and alkalinity typical of groundwater samples. The average alkalinity was 136 mg/L (range 36–188 mg/L) and the conductivity was 277 (range 112–397) µS/cm. Spring Meadow (site N2) has the lowest values, and it may be somewhat influenced by surface water.

Surface waters such as lakes and streams commonly contain a mix of groundwater inflow and runoff. The two stream samples (Otter Creek and the North Branch of the Oconto River) have relatively high electrical conductivity (233 and 269 µS/cm) and alkalinity (144 and 131 mg/L), similar to the groundwater wells, suggesting that these streams have appreciable groundwater inputs. The sample from Ada Lake had far lower electrical conductivity (31 µS/cm) and alkalinity (8 mg/L), suggesting that it is dominated by rainwater and snowmelt.

Plate 9 shows the spatial distribution of alkalinity and electrical conductivity in the sampled streams and spring ponds and the lake. Blue and green symbols indicate water features that are more likely fed by groundwater, whereas red and yellow symbols indicate surface-runoff-dominated features. Geochemistry results agree well with modeled groundwater flow paths and stream discharge (plate 9 and section 4). Samples with higher conductivity and alkalinity (for example, those from site N11 (fig. 8a) and sites, N28, N36 (fig. 8b)) typically align with discharge areas (near the ends of groundwater flow arrows), whereas runoff-dominated features such as Ada Lake (site N40, fig. 8b) are located in upland recharge areas. The relative concentrations of various ions for each water source are shown on Stiff diagrams (fig. 9). In these diagrams, average ion concentrations are converted to electron milliequivalents. Cations plot on the left side of the diagrams and anions plot on the right. The width of the resulting polygon indicates the concentration of dissolved constituents, whereas the shape indicates the relative importance of individual ions. The plots illustrate that groundwater (wells, spring ponds, and groundwater-dominated streams) typically contains a

Table 9. Water chemistry laboratory results, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Site number[1]	NO_2+NO_3 (N) (mg/L)	Chloride (mg/L)	Alkalinity (mg/L)	As (mg/L)	Ca (mg/L)	Cu (mg/L)	Fe (mg/L)	K (mg/L)	Mg (mg/L)
Wells									
N1	<0.1	4.8	84	<0.004	19.57	0.012	0.130	3.77	5.65
N3	1.1	3.3	44	<0.004	9.84	0.005	1.243	1.01	2.95
N4	<0.1	<0.5	12	<0.004	1.45	<0.002	0.027	0.59	0.57
N5	<0.1	<0.5	108	<0.004	25.31	<0.002	0.782	1.04	7.67
N6	<0.1	<0.5	40						
N7	<0.1	4.9	92	<0.004	14.86	0.004	0.351	0.72	9.35
N9, #1	<0.1	6.5	80	<0.004	15.82	0.003	0.009	0.65	9.12
N9, #2	<0.1	4.7	64	<0.004	10.92	<0.002	0.012	0.73	7.56
N10	2.1	19.2	140	<0.004	27.63	0.008	0.136	0.83	15.63
N12	<0.1	9.8	180	0.005	44.82	0.006	0.022	1.49	21.91
N13	<0.1	<0.5	76	0.006	17.39	<0.002	1.408	0.90	4.34
N15	<0.1	2.8	88	<0.004	15.79	0.009	0.461	0.95	12.25
N16	<0.1	1.1	92	0.005	21.06	0.039	0.552	0.81	6.81
N17	<0.1	<0.5	124	<0.004	27.50	0.008	0.110	1.69	10.17
N18	<0.1	<0.5	120						
N20	1.3	1.3	112	0.005	26.25	0.006	0.016	0.87	11.97
N21	<0.1	<0.5	68	<0.004	10.50	<0.002	0.042	1.28	5.09
N22, #1	<0.1	2.7	132	<0.004	25.29	0.015	0.007	0.78	12.27
N22, #2	0.6	0.8	124	<0.003	26.76	0.008	0.007	0.94	13.28
N27	<0.1	7.9	128						
N29	<0.1	<0.5	184	<0.004	39.32	0.010	0.009	1.91	18.93
N32	<0.1	2.2	199	<0.003	3.28	0.049	1.106	1.91	1.14
N33	<0.1	2.7	160	<0.004	15.72	0.004	0.005	1.69	8.16
N35	0.4	1.6	208						
N38	<0.1	0.8	116	<0.004	25.46	<0.002	<0.003	2.07	9.28
N41	<0.1	<0.5	100	0.004	22.42	0.004	0.250	2.01	8.54
N42	<0.1	1.5	88	<0.004	20.88	0.009	0.078	4.90	8.79
N43	<0.1	<0.5	60	<0.004	10.36	<0.002	4.648	2.44	5.45
Spring pond									
N2	<0.1	6.4	36	<0.004	9.10	<0.002	0.068	0.44	4.13
N8	1.1	26.7	90	<0.003	22.07	<0.0005	<0.003	0.75	10.51
N11	<0.1	9.6	188	<0.004	45.14	0.005	0.009	1.52	22.26
N14	<0.1	1.4	128	<0.004	27.78	<0.002	0.027	0.79	13.82
N19	<0.1	1.3	148	<0.004	33.32	<0.002	0.020	0.68	14.31
N24	<0.1	1.6	124	<0.004	30.96	0.009	0.188	1.39	13.66
N25	<0.1	<0.5	150	<0.003	35.59	0.001	0.011	1.30	15.52
N28	<0.1	<0.5	167	<0.003	36.33	0.005	0.008	1.33	16.45
N30	<0.1	5.1	136	<0.004	30.36	<0.002	0.066	1.26	13.69
N31	<0.1	1.5	172	<0.004	37.96	<0.002	0.021	1.91	16.87
N36	<0.1	<0.5	154	<0.003	36.33	<0.0005	0.008	1.32	15.26
Stream									
N37	<0.1	2.1	144	<0.004	28.28	<0.002	0.028	0.76	12.43
N39	<0.1	4.7	131	<0.003	30.64	0.001	0.064	1.35	13.18
Lake									
N40	<0.1	0.8	8	<0.003	1.60	<0.0005	0.013	0.56	0.86

Abbreviations: mg/L = milligrams per liter; meq/L = milliequivalents per liter

Table 9 reads across two pages.

Site number[1]	Mn (mg/L)	Na (mg/L)	P (mg/L)	Pb (mg/L)	SO_4 (mg/L)	Zn (mg/L)	Charge balance[2] (%)
Wells							
N1	0.035	6.3	0.072	<0.004	3.2	0.069	1.3
N3	0.178	2.8	<0.006	<0.004	5	2.881	3.5
N4	0.003	1.9	0.013	<0.005	2.6	0.003	14.6
N5	0.544	2.1	0.012	<0.005	2.9	0.078	3.6
N6							
N7	0.120	3.9	<0.006	<0.004	3.3	0.153	8.6
N9, #1	0.014	3.5	<0.006	<0.004	4.4	0.015	4.6
N9, #2	0.006	3.1	0.014	<0.005	3.5	0.003	5.9
N10	0.005	15.5	0.007	<0.004	6.4	0.159	2.0
N12	0.026	1.5	<0.006	<0.004	17.6	0.08	1.1
N13	0.292	1.2	0.073	<0.004	<0.04	0.02	5.0
N15	0.027	1.7	0.009	<0.004	9.8	0.39	2.9
N16	0.171	0.9	0.012	<0.004	<0.04	0.159	4.6
N17	0.222	3.3	0.018	<0.004	3.4	0.058	2.7
N18							
N20	0.005	1.5	0.023	<0.004	7.2	0.356	1.0
N21	0.040	5.5	0.006	<0.004	<0.04	0.02	5.4
N22, #1	0.008	1.9	0.021	<0.005	4.7	0.009	8.3
N22, #2	0.009	2.0	0.009	<0.002	5.9	0.017	1.7
N27							
N29	0.002	2.3	<0.008	<0.005	9.9	0.007	2.8
N32	0.017	75.5	0.004	0.004	10.4	0.013	7.9
N33	0.002	45.2	<0.006	<0.004	12	0.081	0.8
N35							
N38	0.108	1.5	0.081	<0.005	3.3	1.073	4.4
N41	0.043	1.7	0.011	<0.004	3.9	0.116	2.9
N42	0.061	2.9	0.038	<0.004	11.2	0.032	0.1
N43	0.193	1.2	0.257	<0.004	3.2	2.047	3.5
Spring pond							
N2	0.010	2.6	<0.008	<0.005	4.5	0.006	3.7
N8	0.000	14.2	0.023	<0.002	6.7	0.002	1.9
N11	0.027	2.2	<0.008	<0.005	18.2	0.005	2.2
N14	0.025	1.8	0.017	<0.005	8.7	0.003	2.9
N19	0.005	2.3	0.014	<0.005	7.5	<0.002	3.2
N24	0.019	1.0	0.013	<0.004	9.8	0.157	0.6
N25	0.001	1.9	0.004	<0.002	9.7	<0.002	0.5
N28	0.002	2.0	0.004	<0.002	9.0	0.005	3.5
N30	0.020	3.2	0.017	<0.005	8.5	0.005	3.8
N31	0.002	1.5	<0.008	<0.005	6.6	<0.002	3.1
N36	0.002	1.5	<0.003	<0.002	7.4	<0.002	1.0
Stream							
N37	0.009	1.5	0.012	<0.005	7.3	<0.002	10.1
N39	0.018	3.2	0.006	<0.002	6.5	0.005	1.7
Lake							
N40	0.002	0.9	<0.003	<0.002	3.9	<0.002	12.8

[1]See table 8 for site locations. Site numbers with two samples indicated.

[2]Unacceptable charge balance errors are highlighted. The criteria for determining acceptable charge balances depends on the sum of the anions. The balance was considered acceptable if (1) the cation-anion difference was within 0.2 meq/L for anion sums 0–3 meq/L, (2) the charge balance was within 2% for anion sums 3–10 meq/L, (3) the charge balance was within 5% for anion sums 10–800 meq/L.

Table 10. Average water quality results,[1] Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Site type	Samples (no.)	Conductivity (µs/cm)	Dissolved oxygen (mg/L)	pH	Alkalinity (mg/L $CaCO_3$)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	Cl (mg/L)	SO_4 (mg/L)
Well	28	249	5.1	8.1	108	19.9	9.0	7.9	1.50	0.476	0.089	2.9	5.6
Spring pond	11	277	7.9	8.1	136	31.4	14.2	3.1	1.15	0.039	0.010	4.9	8.8
Stream	2	251	7.1	8.1	138	29.5	12.8	2.4	1.06	0.046	0.013	3.4	6.9
Lake	1	31	6	7.2	8	1.6	0.9	0.9	0.56	0.013	0.002	0.8	3.9

Abbreviations: µs/cm = microsiemens per centimeter; mg/L = milligrams per liter

[1]*Non-detect results were assigned a value of half the detection limit to calculate averages.*

higher concentration of dissolved ions, but that the relative concentrations of these constituent ions are about the same for all water sources. The lake, which is interpreted as surface-runoff dominated, has much lower concentrations of ions.

Water quality indicators

The geologic setting of the Nicolet Unit, glacial deposits over crystalline bedrock, contains few natural sources of dissolved nutrients such as chloride, nitrate, and phosphorus. For this reason, water samples with elevated concentrations of Cl, NO_3, or P likely represent places where land use or cultural activities are degrading water quality. The majority of water samples collected contained low (less than 5 mg/L) concentrations of chloride, and low or non-detectable concentrations of nitrate and phosphorus (table 9). However, eight of the 42 samples collected were slightly elevated in chloride (greater than 5 mg/L). Elevated Cl concentrations might result from nearby road salting to reduce winter ice. Road salting would allow Cl to enter the groundwater system near roads and move laterally through the aquifer. At Brule Springs (27 mg/L) and the Stevens Lake well (19 mg/L) (sites N8, N10 (fig. 8a)), Cl is considerably higher than in most other samples from the Nicolet Unit. At Brule Springs the most likely Cl source is salt used on Highway 70, a major highway about 1,000 ft south of the spring. In contrast, the Cl source at the Stevens Lake well is uncertain, because there is no major highway nearby. Chloride is also elevated above 5 mg/L at Spring Meadow Spring, Windsor Dam Campground well, Chipmunk Springs, Chipmunk Rapids Campground well, Boot Lake Campground well, and Sullivan Spring (sites N2, N9, N11, N12 (fig. 8a) and sites N27, N30 (fig. 8b)). The specific causes of elevated concentrations at each of these sites are not known. Although these Cl concentrations are slightly higher than background values, they are well below the maximum concentration allowed by safe drinking water standards and thus not a cause for concern.

Concentrations of arsenic and lead in several groundwater samples in the Nicolet Unit were slightly in excess of the Wisconsin NR140 preventive action limit for arsenic, and one sample failed to meet the preventive action limit for lead (table 9). In Wisconsin, the preventive action limit for these elements is set at 10 percent of the drinking water standard, and it is intended as an early warning that constituent concentrations are elevated. Concentrations in excess of the arsenic preventive action limit of 0.001 mg/L were measured in samples from wells at Chipmunk Rapids (site N12; 0.005 mg/L), Lost Lake (site N13; 0.006 mg/L), Laura Lake (site N16; 0.005 mg/L), Richardson Lake (site N20; 0.005 mg/L), and Sevenmile Lake (site N41; 0.004 mg/L). The sample from Bagley Rapids campground well (site N32; 0.004 mg/l) failed to meet the lead preventive action limit of 0.0015 mg/L. In all of these samples, the concentrations of arsenic or lead are still very low, and they are near the level of detection for the analytical methods used. The source of the arsenic and lead is unknown; it might be from natural minerals in the region, plumbing and pipe fixtures, or other anthropogenic sources. We recommend that these wells be retested periodically to determine whether well water still meets standards for drinking water quality.

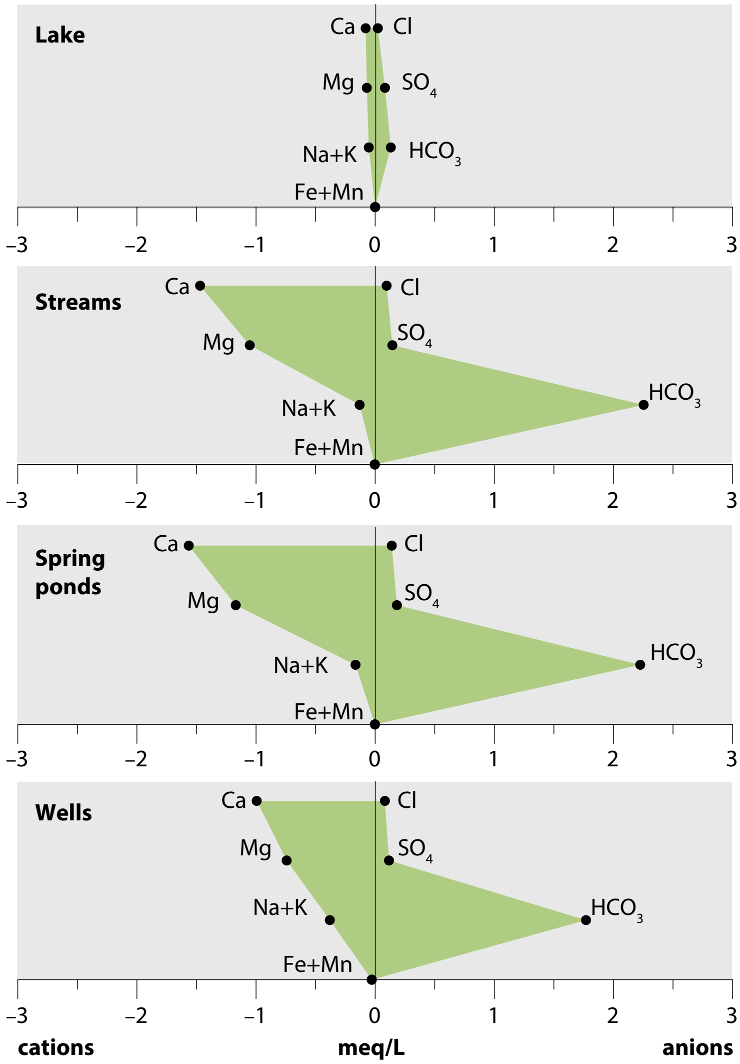
Some groundwater samples also had ion concentrations higher than the Wisconsin NR140 preventive action limit, and in some cases the enforcement standard, for manganese, nitrate + nitrite, iron, and zinc (table 9). The manganese enforcement standard of 0.3 mg/L was not met in the Franklin Lake Campground well (site N5; 0.54 mg/L); the preventive action limit of 0.06 mg/L was not met in seven additional wells. The iron enforcement standard of 0.3 mg/L was not met in eight wells, of which the highest iron concentration was found in the Luna–White Deer Campground well (site N43; 4.6 mg/L). Concentrations slightly above the preventive action limit of 2 mg/L for nitrate and 2.5 mg/L for zinc were observed in one well each. Manganese, iron, zinc, and

Table 11. Isotope data, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Sample location	Site number	Sample date	$\delta^{18}O$ (per mil SMOW)	$\delta^{2}H$ (per mil SMOW)
Wells				
Ada Lake Campground—deep	N21	10/16/2013	−6.82	−53.64
Ada Lake Campground—shallow #1	N22	7/10/2014	−7.51	−56.23
Ada Lake Campground—shallow #2	N22	5/10/2016	−10.15	−71.12
Anvil Lake Campground	N3	10/14/2013	−11.54	−79.47
Anvil Lake monitoring well FR-908	N4	7/9/2014	−14.12	−99.25
Bagley Rapids Campground—deep	N33	10/16/2013	−11.00	−74.31
Bagley Rapids Campground—shallow	N32	5/9/2016	−11.20	−77.29
Bear Lake Campground	N18	10/15/2013	−11.30	−76.97
Boot Lake Campground	N27	10/16/2013	−9.08	−65.35
Boulder Lake Campground	N35	10/16/2013	−10.68	−71.70
Chipmunk Rapids Campground	N12	10/15/2013	−11.96	−82.29
Franklin Lake Campground	N5	7/8/2014	−11.03	−75.88
Kentuck Lake Campground	N6	10/14/2013	−7.50	−58.58
Lac Vieux Desert boat launch well	N1	10/14/2013	−11.92	−84.52
Laura Lake Campground	N16	10/15/2013	−4.39	−43.73
Laurel Lake well	N42	10/15/2013	−11.67	−79.30
Lost Lake Campground	N13	10/15/2013	−3.33	−39.79
Luna–White Deer Campground	N43	10/15/2013	−12.21	−84.54
Morgan Lake Campground	N15	10/15/2013	−11.49	−78.41
Pine Lake Campground	N17	10/15/2013	−11.29	−76.49
Richardson Lake Campground	N20	10/16/2013	−11.57	−79.26
Sevenmile Lake—deep	N38	7/8/2014	−11.30	−77.07
Sevenmile Lake—shallow	N41	10/15/2013	−11.21	−73.92
Spectacle Lake Campground	N7	10/14/2013	−11.49	−79.40
Stevens Lake well	N10	10/15/2013	−11.83	−80.52
USFS Lakewood ranger station	N29	7/10/2014	−11.39	−74.29
Windsor Dam Campground #1	N9	10/14/2013	−11.81	−80.87
Windsor Dam Campground #2	N9	7/8/2014	−11.87	−80.15
Spring pond				
Brule Springs	N8	5/10/2016	−11.75	−81.30
Chipmunk Springs	N11	7/9/2014	−11.93	−81.03
Forbes Spring	N31	7/10/2014	−10.58	−70.61
Hemlock Spring Pond	N25	5/10/2016	−10.75	−73.97
McCaslin Spring	N24	10/16/2013	−9.81	−64.81
Roix Springs	N36	5/10/2016	−10.45	−72.28
Saul's Spring	N28	5/9/2016	−10.70	−73.47
Simpson Creek Pond	N14	7/9/2014	−11.52	−78.53
Spring Meadow Spring	N2	7/7/2014	−9.49	−67.09
Sullivan Spring	N30	7/10/2014	−9.96	−68.64
Torpee Creek Seeps	N19	7/9/2014	−10.71	−72.76
Stream				
Bagley Rapids	N39	5/9/2016	−10.13	−71.96
Otter Creek	N37	7/9/2014	−9.73	−67.81
Lake				
Ada Lake beach	N40	5/10/2016	−4.99	−47.28

Abbreviations: $\delta^{18}O$ = $^{18}O/16O$; $\delta^{2}H$ = deuterium; SMOW = Standard Mean Ocean Water standard

Figure 9. Stiff plots of average major ion constituents from the Nicolet Unit, categorized by water source.



nitrate have been found in similar concentrations in this region (for example, Patterson, 1989).

Isotopes of hydrogen and oxygen

The content of the stable isotopes deuterium (^2H) and oxygen-18 (^{18}O) in groundwater and surface water can provide information on water mixing (groundwater with surface water), age, and source areas. These isotopes are extremely scarce in comparison to the more common hydrogen (^1H) and oxygen (^{16}O) atoms in the environment. Isotopes of hydrogen and oxygen are fractionated through evaporation and condensation as air masses move over continents from the oceans. Lighter isotopes evaporate preferentially and, consequently, inland waters are commonly enriched in the lighter isotopes compared to ocean water. Isotopic concentrations are reported relative to isotopic concentrations in ocean water (in units per mil or parts per thousand notation) symbolized by δ (delta) SMOW, where SMOW stands for Standard Mean Ocean Water. Typically, inland waters have negative δ values because they are isotopically lighter than ocean water. The covariance between $\delta\ ^2H$ and $\delta\ ^{18}O$ in precipitation is called the meteoric water line (MWL), a formulation of the ratio of ^2H to ^{18}O found in unevaporated precipitation. Isotope concentrations in precipitation depend on location, and as a result it is important to evaluate samples against a locally derived MWL. Samples that plot along the lower left part of the line (fig. 10; lighter precipitation) typically result from precipitation during colder months. Water samples plotting off the MWL are interpreted as having been exposed to surface water evaporation or to other physical processes. In groundwater studies, deuterium and oxygen-18 concentrations are commonly used to distinguish groundwater from surface water.

Figure 10 and table 11 show the isotope results from water samples collected in the Nicolet Unit. The MWL is based on samples from northern Vilas County (Krabbenhoft and others, 1990). The groundwater well samples cluster along the lower-left side of the plot, indicating recharge derived from precipitation that fell during colder months. Most of the groundwater and surface-water samples do not fall precisely on the local MWL, possibly because the meteoric water line established by Krabbenhoft and others (1990) is taken from precipitation samples collected as much as 120 mi northwest of the Nicolet Unit. Additionally, the Krabbenhoft MWL was derived by using data from November 1985 to August 1987, whereas the Nicolet samples were obtained during three discrete sampling periods that may not reflect seasonal variations in the MWL. The minor deviation to the left of the MWL cannot be explained, but this deviation is minimal and does not affect the interpretations and discussion below.

Ada Lake and several wells plot to the right of the MWL, characteristic of water that has undergone open-water evaporation. Lost Lake and Laura Lake Campground wells (sites N13, N16 (fig. 8a)) have isotopic signatures characteristic of mixing of groundwater and surface water, because they plot far to the right of the MWL on figure 10. The two wells, which have moderate alkalinity and electrical conductivity compared to the other wells sampled, are likely drawing some water rapidly through the ground from nearby lakes.

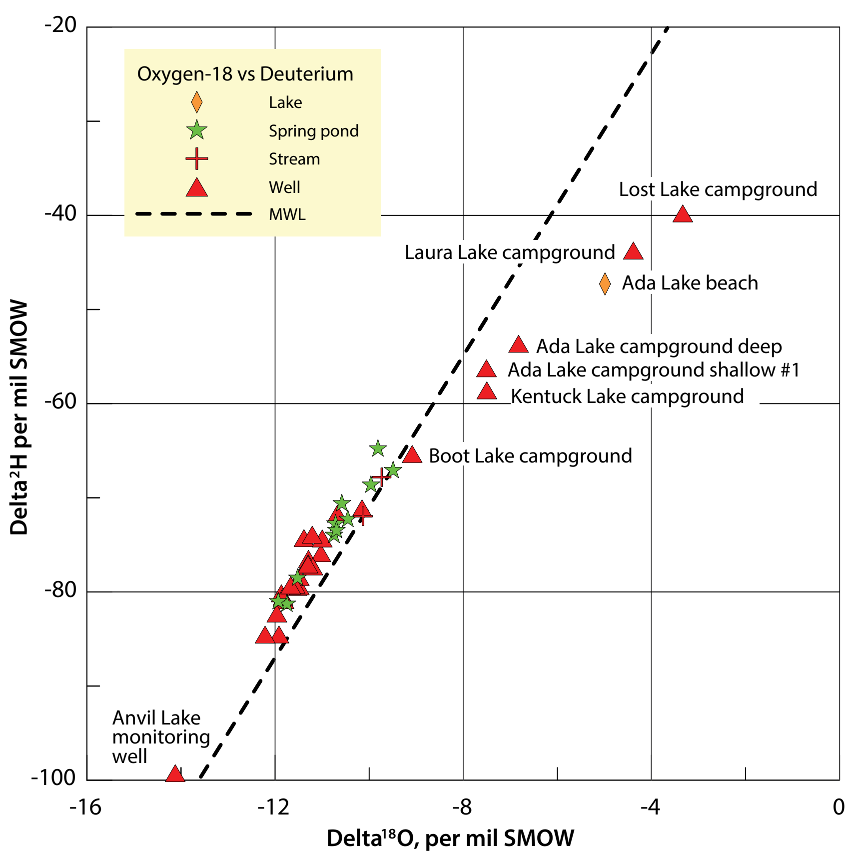
Along the MWL, the streams and spring ponds generally plot to the right and above the well samples (fig. 10). These streams may receive a higher percentage of isotopically heavy summer precipitation than the deeper groundwater system. Most groundwater has a "light" signature (plots along the lower left section of the MWL) because groundwater is predominantly recharged by isotopically lighter winter precipitation and snowmelt. In the summer, precipitation undergoes evapotranspiration and therefore less is available for groundwater recharge. However, some of this isotopically heavy summer precipitation may flow through shallow wetlands and discharge to a nearby stream or spring. The isotopic signature of these samples—heavier than groundwater but unevaporated—could reflect flow through these shallow wetlands (Hunt and others, 1996; Zimmerman and others, 1967).

Water in the Anvil Lake monitoring well FR-908 (site N4; fig. 8a) has a much lighter isotopic signature than water in other wells (plots far down and to the left). Although samples with signatures this light can indicate groundwater recharged in a colder climatic period, such as the Wisconsin glaciation around 10,000 years ago, it is unlikely that water this old is present in a shallow (15 ft deep) sand and gravel well. The specific reason for anomalous results at this well is not clear. One hypothesis is that this well samples young, shallow groundwater that recharged the previous spring and has undergone little or no mixing with the surrounding groundwater. This water maintains its isotopic signature of cold recharge and has not been in the aquifer long enough to dissolve many ionic constituents, which would explain the low ion concentrations in this well.

Discussion

The results show that water in the Nicolet Unit, which is relatively unaltered by human activities, has low concentrations of most constituents. Groundwater is distinguished from surface water by higher electrical conductivity (average 249 vs. 31 µS/cm) and alkalinity (108 vs. 8 mg/L). Concentrations of dissolved ions such as calcium and magnesium are also higher in groundwater. Isotopes of hydrogen and oxygen can show whether features have undergone open-water evaporation, and they can distinguish surface water (isotopically heavier, less negative) from groundwater (isotopically lighter, more negative). Geochemistry results agree well with modeled groundwater flow paths and stream discharge (see section 4). Several samples contained elevated chloride, suggesting the local influence of land-use activities such as road salting. This overview also provides a basis for future geochemical investigations of specific areas in the Nicolet Unit.

Figure 10. Oxygen-18 vs. deuterium for water samples from the Nicolet Unit, and meteoric water line.



Section 4: Groundwater flow model

Objectives

The data inventory and analysis described in the previous sections were incorporated into two groundwater flow models of the Nicolet Unit. The construction of two models was necessitated by the large size of the Nicolet Unit, the density of surface-water features, and the limitations of the analytic element modeling technique. The northern model (North model) (fig. 11a) covers the Eagle River–Florence District and northernmost part of the Lakewood–Laona District; the southern model (South model) covers the remaining part of the Lakewood–Laona District (fig. 11b). The models were constructed by using the analytic element groundwater modeling program GFLOW (Haitjema, 1995). Construction of the flow models supports the goals of this project by providing key aquifer properties, simulated water table elevations, flow paths, flow rates, and discharge zones. The two calibrated regional models can be refined to analyze site-specific concerns as they arise and to evaluate data needs to guide future monitoring programs.

Model construction

Overview

The two-dimensional groundwater flow models used for this study were developed by using the analytic element groundwater-flow modeling program GFLOW (Haitjema, 1995). Hunt (2006) reviews applications of the analytic element method, and Haitjema (1995) discusses in detail the underlying concepts and mathematics of the method. The analytic element technique is briefly described below.

An infinite aquifer is assumed in analytic element modeling. Features important for controlling groundwater flow (for example, wells and surface-water features) are entered as mathematical elements or strings of elements. The amount of detail specified for the features depends on distance from the area of interest and the purpose of the model. Each element is represented by an analytic solution to the groundwater flow equation. The effects of these individual solutions are superposed to form a solution for any location in the simulated groundwater flow system. Because the solution is not confined to a grid, heads and flows can be computed anywhere in the model domain without interpolating between grid cells. In the GFLOW model used here, the analytic elements are two dimensional and are used only to simulate steady-state conditions—that is, simulated water levels and flows that are time invariant. The analytic element method and comparisons of analytic element to finite-difference numerical model techniques have been discussed by others (Haitjema, 1995; Hunt and others 1998; Hunt and others, 2003).

Conceptual model

In humid climates, groundwater flow patterns are influenced by the pattern of surface-water features, such as rivers and lakes that intersect the water table, and by aquifer transmissivity, recharge to the aquifer, and pumping. Conceptualization of the hydrologic system forms the framework for the development of mathematical models and simplifies the groundwater system into important component parts. Steps in the development of the conceptual model are as follows: (1) characterization of the aquifer or aquifers; (2) identification of sources and sinks of water; and (3) identification and delineation of hydrologic boundaries in the area of interest.

The shallow regional groundwater system in the Nicolet Unit is contained in a relatively thin aquifer composed mostly of glacially deposited materials but in places also incorporating a fractured and weathered zone of the upper bedrock. This aquifer ranges in thickness from less than 50 to about 250 feet, overlying comparatively impermeable Precambrian igneous and metamorphic rocks (section 1). The underlying crystalline bedrock has comparatively low permeability, and transmissivities are more than an order of magnitude smaller in bedrock than in the glacial deposits (section 1). Aquifer transmissivity varies throughout the glacial deposits, according to saturated thickness and lithology. Lateral variability in aquifer transmissivity is incorporated in the model in piecewise-constant zones that represent areas where glacial till, outwash, shallow fractured bedrock, or anomalies in saturated thickness predominate (plate 1a,b). Groundwater moves from higher to lower hydraulic potential (areas of higher groundwater elevation to areas of lower groundwater elevation). As a result, water generally enters the groundwater system in uplands throughout the study area and discharges to surface-water features or, to a lesser extent, to pumping wells. Therefore, accurate locations and elevations of surface-water features and pumping wells, along with accurate estimates of average baseflow, are critical to simulating the groundwater system.

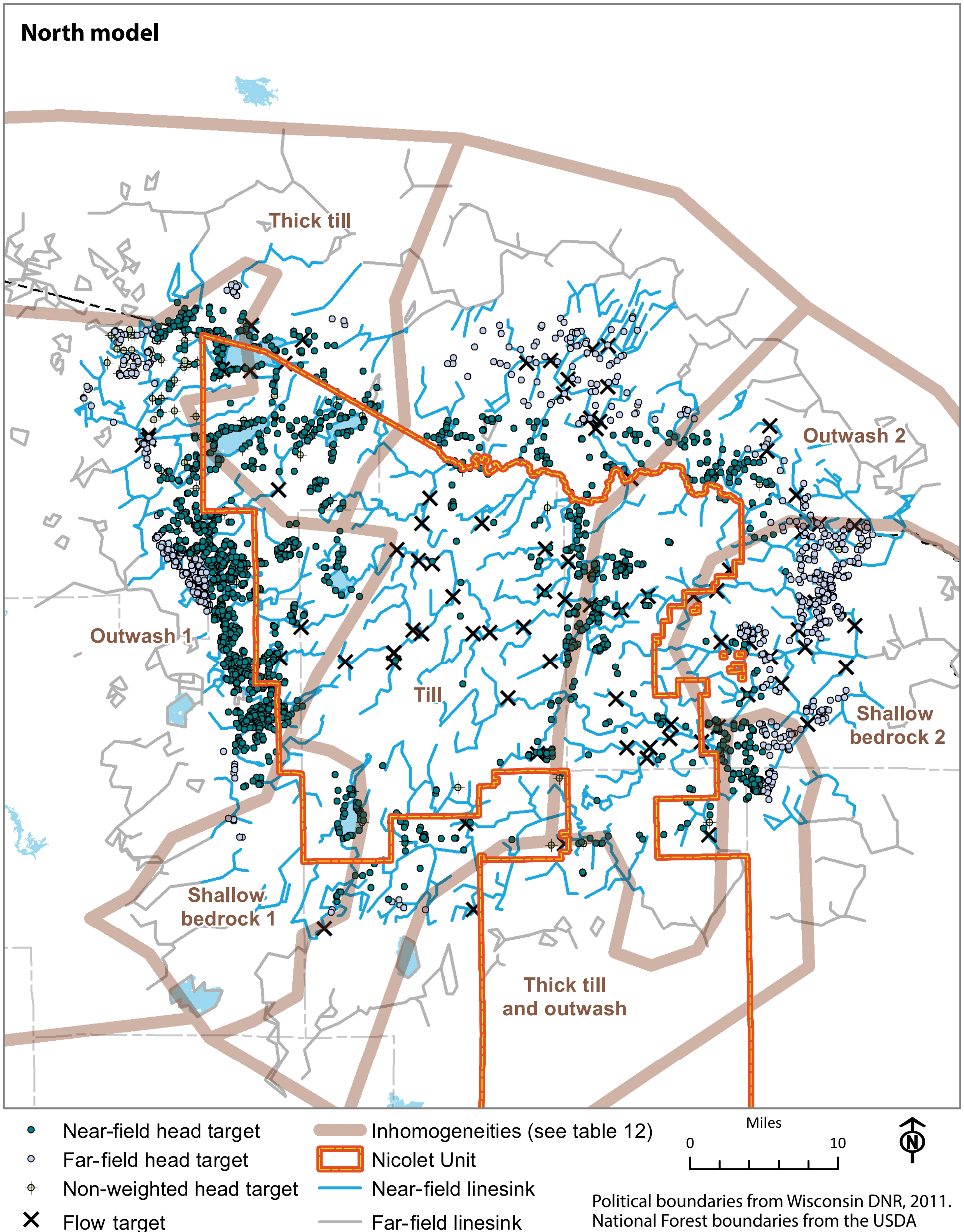
Description of the GFLOW model

Development of the initial model required that we delineate hydraulic conductivity zones and estimate starting parameter values such as hydraulic conductivity values for the zones, a base elevation for the simulated groundwater system, and a global resistance value for linesink elements representing streams and lakes. Resistance is defined as the stream or lakebed thickness divided by the vertical hydraulic conductivity of the sediment; its unit is days (d). A value of 10.0 d corresponds to a 1-ft sediment thickness and a vertical hydraulic conductivity of 0.1 ft/d. Gridded potential recharge results were imported from the SWB model (section 2) and given a global multiplier parameter to allow for adjustment of the total volume of water entering the groundwater system. In two-dimensional areal models, groundwater flow is simulated by using the aquifer transmissivity of a single layer, where transmissivity represents hydraulic conductivity multiplied by saturated thickness. Hydraulic conductivity values are set to represent regional averages, and saturated thickness is calculated from the height of the simulated water table above the model's base elevation, which is assumed to be horizontal (a sloping base elevation is not supported in GFLOW). As such, transmissivity varies throughout the model domain. Although both base elevation and hydraulic conductivity affect transmissivity, calibrating horizontal hydraulic conductivity led to the most robust and stable model solution (for example, Feinstein and others, 2006).

Elevations of 1,000 ft (North model) and 600 ft (South model) above NAVD 88 were chosen to approximate the true aquifer base (which in reality varies throughout the model domains) without causing regions of zero saturated thickness (where the simulated water table drops below the base). The North model base of 1,000 ft is approximately 30 ft below the most downstream segment of the Menominee River in the southeast corner of the model (in a zone representing shallow bedrock) and is approximately 600–800 ft below streams in the western and northern parts of the model. The South model base of 600 ft is approximately 50 ft below the lowest stream elevation (North Branch of Beaver Creek) in the southeast corner of the model and is approximately 1,000 ft below streams in the northwestern part of the model. The sloping water table surface and uniform base results in a simulated transmissivity gradient across the model domain (saturated thickness, and therefore transmissivity, varies as a function of the height of the water table above the uniform base). In reality, transmissivity would be more uniform if the bedrock surface were more closely aligned with the water table (and the general trend of the landscape). Simulated transmissivity gradients resulting from the uniform-base assumption are somewhat mitigated at the model scale by the hydraulic conductivity zones, which modify the hydraulic conductivity parameter. However, within the piecewise-constant zones, the uniform-base assumption can still produce an artificial transmissivity gradient, especially in areas with greater topographic relief in the bedrock surface. Deeper base elevations in the model can also minimize this effect, by reducing relative spatial variation in saturated thickness. Deeper base elevations than those chosen were tested but found to have a small effect on the quality of the model calibration to the head targets. See Juckem and Dunning (2015, p. 12) for further discussion of base elevation and its implications.

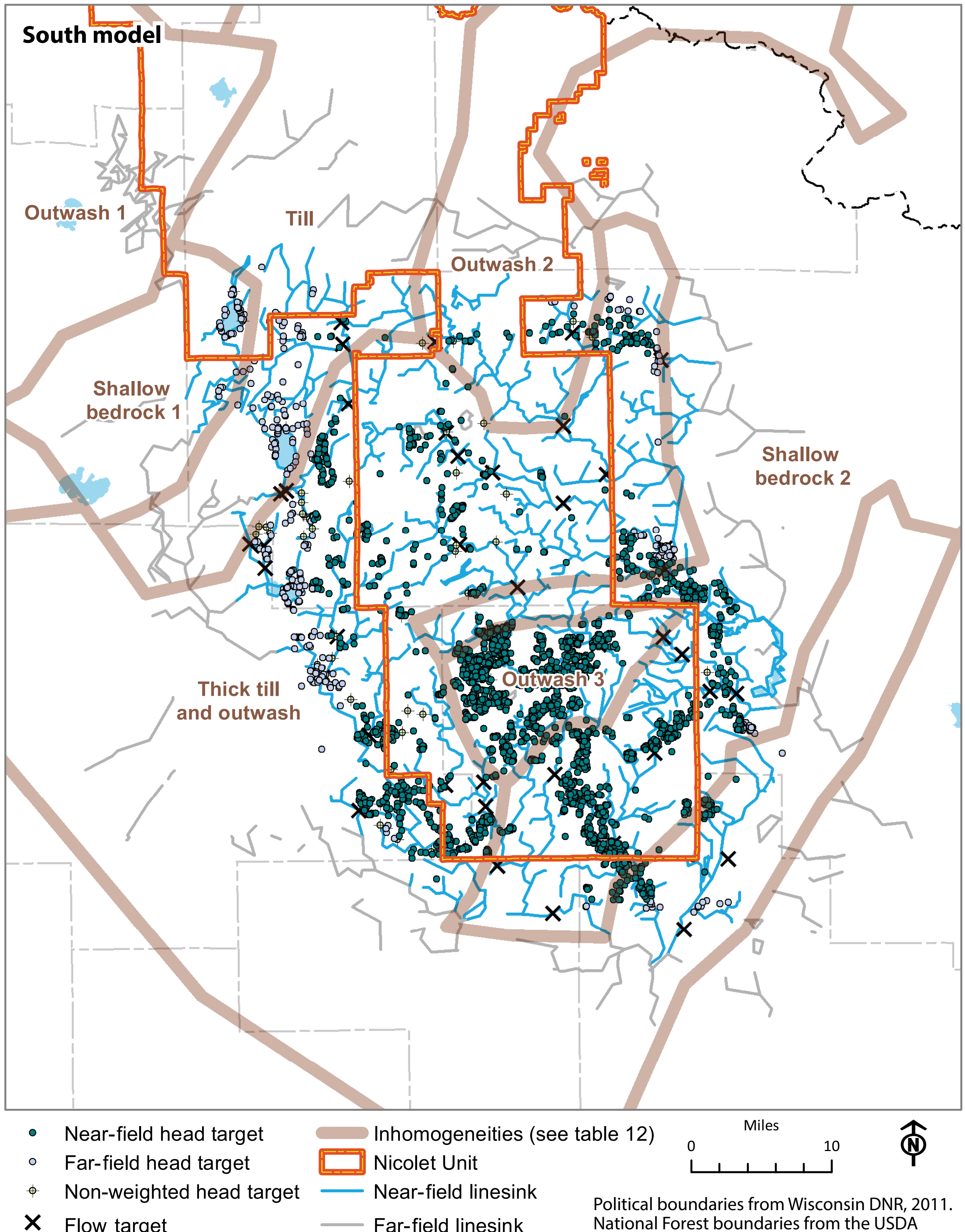
The model domain was divided into eight zones of differing aquifer hydraulic conductivity (fig.11 and table 12) on the basis of mapped variations in the surficial geology (Soller and others, 2012) as well as WCRs and depth-to-bedrock maps assembled as part of this report (section 1). Recharge was applied to the model by down-sampling the SWB results to a 1-kilometer resolution, and then importing them into the GFLOW graphical user interface by means of the Hybrid GFLOW-MODFLOW sequential coupling feature (Haitjema, 2015). Sequential coupling—linking models in a sequence—uses the output of one model (in this case the SWB simulation) as input into another. Sequential coupling allows for a more realistic representation of groundwater recharge by incorporating the physical processes represented in the SWB model and climatic inputs that are more easily measured. MODFLOW refers to the USGS modular groundwater flow modeling code (Harbaugh, 2005); although this project did not use the MODFLOW code, it did use an interface developed to work with that code. We believe that the SWB model results in areas of Iron County and other parts of Michigan with lower recharge potential are biased low relative to SWB model results in Wisconsin, owing to differences in hydrologic soil group classification in the underlying datasets (fig. 12; see section 2 for more detailed discussion). Although these areas are outside of the Nicolet Unit, they are important for matching baseflow targets along the Brule River and properly simulating groundwater flows along the northern boundary of the forest unit. The following steps were taken to mitigate these discrepancies.

Figure 11a. Features of the GFLOW models for North model.



Political boundaries from Wisconsin DNR, 2011. National Forest boundaries from the USDA Forest Service, 2011. Hydrography from National Hydrography Dataset, 2012.

Figure 11b. Features of the GFLOW models for South model.



Political boundaries from Wisconsin DNR, 2011. National Forest boundaries from the USDA Forest Service, 2011. Hydrography from National Hydrography Dataset, 2012.

Table 12. Calibrated parameter values for groundwater flow models, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Recharge

Parameter name	Model	Grid file name	Optimized parameter value	Average simulated recharge (in/yr)	Description
rgrid_mult	North	nn1.rta	1.72	7.1	Recharge multiplier for SWB model results
rgrid_mult	South	ns1.rta	1.36	7.5	Recharge multiplier for SWB model results

Hydraulic conductivity

Representative zone[1]	Calibration status	GFLOW identifier	Average simulated saturated thickness[2] (ft)	Optimized parameter value[3]	Approx. simulated transmissivity (ft^2/d)	Representative actual saturated thickness[4] (ft)	Effective average hydraulic conductivity[5] (ft/d)	Description
North model								
Outwash 1	Fixed	Outwash1	652	6.2	4,000	80	50	Coarse-grained deposits 100–200 ft thick, west of unit
Outwash 2	Adjustable	Outwash2	461	5.5	2,500	40	60	Coarse-grained deposits, northeast Nicolet
Shallow bedrock 1	Adjustable	ShallowBR1	654	6.2	4,000	40	100	Glacial deposits less than 50 ft thick, west of unit
Shallow bedrock 2	Adjustable	ShallowBR2	327	3.4	1,100	30	40	Glacial deposits less than 50 ft thick, east of unit
Thick till and outwash	Adjustable	ThickGlacial	471	8.0	3,700	80	50	Till and outwash deposits, generally more than 100 ft thick
Till	Adjustable	Till	710	5.7	4,100	130	30	Dominantly till deposits, northern Nicolet
Thick till	Adjustable	ThickTill	569	2.9	1,600	40	40	Till deposits 100–200 ft thick
South model								
Outwash 1	Fixed	Outwash1	—	3.8	—	—	—	Zone outside of model domain fixed to approximately equivalent transmissivity from North model
Outwash 2	Adjustable	Outwash2	891	1.8	1,600	60	30	Coarse-grained deposits, northeast Nicolet
Outwash 3	Adjustable	Outwash3	674	6.4	4,300	80	50	Coarse-grained deposits 100–200 ft thick, southern Nicolet
Shallow bedrock 1	Adjustable	ShallowBR1	1,078	1.3	1,400	70	20	Glacial deposits less than 50 ft thick, west of unit
Shallow bedrock 2	Adjustable	ShallowBR2	384	6.2	2,400	30	80	Glacial deposits less than 50 ft thick, east of unit
Thick till and outwash	Adjustable	ThickGlacial	763	2.9	2,200	80	30	Till and outwash deposits, generally more than 100 ft thick
Till	Adjustable	Till	1,057	0.4	400	90	4	Dominantly till deposits, northern Nicolet
Thick till	Fixed	ThickTill	—	3.7	—	—	—	Zone outside of model domain fixed to approximately equivalent transmissivity from North model

Abbreviations: ft = feet; yr = year; in = inches; SWB = soil-water balance

[1] *Zones shown on figure 11a and 11b. Zones were slightly modified for South model.*

[2] *Mean modeled water table elevation in each zone minus GFLOW base elevation.*

[3] *Modeled hydraulic conductivity value in GFLOW. Effective hydraulic conductivity for each zone is shown in separate column.*

[4] *Mean modeled water table elevation minus actual bedrock surface elevation. Represents saturated thickness of unlithified materials only; the thickness of zones that include a fractured bedrock aquifer could be underestimated.*

[5] *The effective hydraulic conductivity for bedrock zones may be overestimated as a result of transmissivity from fractured bedrock not captured in saturated thickness estimates; see note 2.*

A threshold recharge rate of 0.0015 ft/d (6.57 in/yr) was chosen, and areas with recharge below this threshold were adjusted to reduce the effect of soil type. The threshold was selected so that the adjustments were applied only to areas with lower recharge potential.

Additional recharge was applied to Iron County and the remainder of Michigan, by using trial and error to create an input recharge grid without visually apparent state- and county-line artifacts (fig. 12). An additional 0.0008 ft/d (3.5 in/yr) was added to raster cells below the threshold in Iron County; 0.0004 ft/d (1.8 in/yr) was added to the remainder of cells below the threshold in Michigan.

A global recharge multiplier parameter was then applied to the adjusted potential recharge grid, similar to that used in the GFLOW models for the Washburn, Great Divide, and Medford Units. The global recharge multiplier allows the magnitude of simulated recharge to be adjusted so that the model matches the baseflow targets, while maintaining the spatial distribution of recharge simulated by the SWB model.

Surface-water features, such as streams and lakes, were simulated with analytic "linesink" elements. The linesink geometries and elevations were derived from the National Hydrography Dataset (NHDPlus version 2; McKay and others, 2012). To maintain a tractable number of linesink equations, the NHDPlus hydrography was simplified by minimizing the number of vertices, subject to a distance tolerance that limited the distance a simplified line could deviate from the original line (Gillies, 2013).

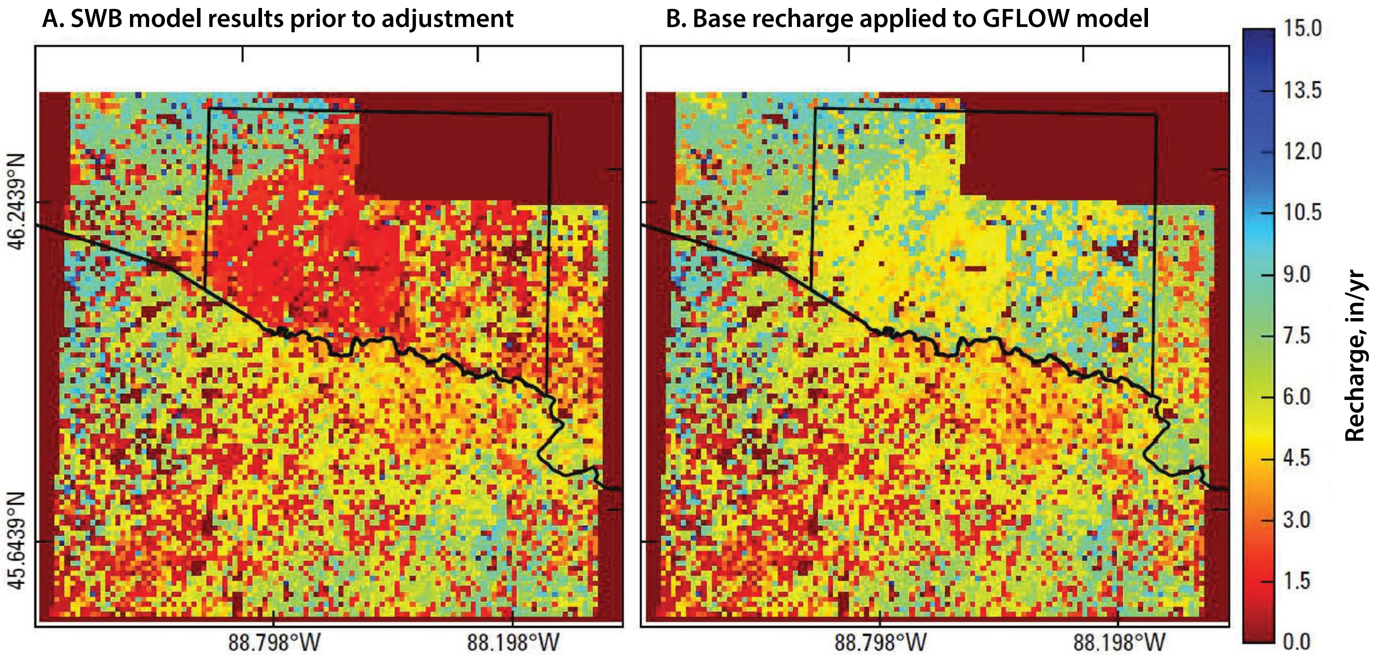
Linesinks can be modeled as "near-field" or "far-field" elements. The purpose of the far-field linesinks is to establish a hydraulic boundary condition for the groundwater flow solution in the near-field areas of the model that are of interest (the Nicolet Unit). The far-field linesinks were assigned zero values of streambed resistance, allowing them to act as infinite sources or sinks, effectively "pinning" the water-table elevation at their locations. This formulation establishes a boundary condition along the model perimeter, while allowing intervening groundwater divides surrounding the unit to be simulated in the model solution. Simulation of these divides avoids model errors that can result when the modeler specifies perimeter boundary conditions a priori (Hunt and others, 1998).

The linesinks were spatially categorized into three groups of various detail. The most detailed group, simplified to a tolerance of 200 m, included all streams within the forest unit. A second group, simplified to a 300-m tolerance, included all streams in the area between the Nicolet Unit and the model far-field. Linesinks in both of these groups were assigned values of streambed resistance and routed to simulate the accumulation of streamflow from interactions of streams and aquifers. A third group of linesinks in the area beyond the routed stream network (model far-field) was simplified to a tolerance of 500 m and contained only second- and higher-order streams.

Streams and lakes within and immediately surrounding the forest unit were simulated as routed near-field elements, or stream linesinks. Streamflow routing conserves baseflow along rivers and through lakes so that simulated baseflows can be directly compared with measured streamflows during model calibration. Near-field lakes larger than 1 square kilometer were also simulated as routed stream linesinks along the perimeter of the lake for drainage lakes (streams entering and leaving the lake), or as nonrouted linesinks with bed resistance values for seepage lakes (no inlet or outlet streams). Groundwater exchange with the streams is computed by the model as a function of the groundwater level at the stream, the resistance to exchange between groundwater and surface water, and the specified stream stage. The width of the line assigned to each stream related to its arbolate sum, following the method of Feinstein and others (2010), and it ranged from 0.4 to 34 ft. The arbolate sum is defined as the total length of stream channels, including tributaries, upstream of a given location in the stream network. It provides a measure of the size of the drainage system contributing to that location. The widths assigned to linesinks representing lakes were computed by using the methodology of Haitjema (2005, p. 5).

Groundwater withdrawal from high-capacity wells, defined in Wisconsin as wells capable of pumping at 70 gpm or more, was simulated within the model domain by using water-use data collected by the WDNR (R. Smail, written communication, 2016). Although Nicolet Unit wells are classified as high-capacity wells, the average pumping rates of most of them are far less than 70 gpm. A total of 231 wells with non-zero pumping rates are represented in the models; these wells pump at an average 24 gpm and cumulatively at about 5,500 gpm. All wells in the model are assumed to be fully penetrating from the water table to the base of the model. Pumping from private residential wells or supply wells at forest unit campsites was not simulated in the model because withdrawal rates tend to be low and much of the withdrawal is returned to the aquifer through septic infiltration. Although not a large enough hydrologic stress to be included in the regional groundwater flow model,

Figure 12. Recharge adjustment applied to areas of the recharge grid within Michigan (1.8 inches/year) and Iron County (3.5 inches/year).



these low-withdrawal wells were used for groundwater quality analysis. Chemical and isotope sampling from wells in the forest unit is described in section 3 of this report.

Model calibration and results

Model calibration is the process of adjusting model parameters until the model satisfactorily reproduces field measurements consisting of stream discharge at baseflow conditions and water levels in wells or lakes, while honoring the conceptual model. A calibration objective function (the sum of squared, weighted differences between field measurements and equivalent model outputs) was developed and minimized, subject to the constraint of the conceptual model, by coupling the GFLOW models to the parameter estimation program PEST (Doherty, 2011). Numerous publications detail the advantages of formal parameter estimation (for example, Anderson and others, 2015; Kelson and others, 2002; Poeter and Hill, 1997), which can be considered a form of automated trial-and-error calibration. The primary benefit of a properly prepared and executed parameter-estimation calibration as compared with typical manual trial-and-error calibration is the ability to systematically explore the full range of possible parameter values (for example, hydraulic conductivity and recharge) and to produce estimates that represent a quantified best fit of simulated model output to observed data (for example, groundwater levels and streamflows). In addition, the interaction between model parameters and outputs can be quantified and assessed.

Parameters that were adjusted during calibration included hydraulic conductivity for each zone and a recharge grid multiplier (table 12). Initial hydraulic conductivity values were estimated on the basis of the data inventory in section 1, and initial recharge values were imported from the SWB model results described in section 2, modified to correct for differences in state datasets (see Description of the GFLOW model). The surface-water bed resistance parameter is relatively insensitive to the calibration data, so it was fixed at a value of 10 d, similar to that parameter in the Park Falls Unit model (Bradbury and others, 2018) as well as other studies (for example, Juckem and others, 2014; Kelson and others, 2002). The overall calibration methodology and approach are outlined by Doherty and Hunt (2010).

A calibration dataset was developed to compare steady-state model outputs with field measurements of the system. Historical water-level measurements were obtained from Wisconsin Department of Natural Resources well construction reports and the National Water Information System. Where present, multiple measurements of head were averaged to develop a single, steady-state value. Stream baseflows were also obtained from the National Water Information

System and from annual baseflow estimates published in Gebert and others (2011). At sites with continuous measurements, average annual baseflow estimates were computed by using the modified Base Flow Index method described by the Institute of Hydrology (1980) and by Wahl and Wahl (1988). At all other National Water Information System sites not listed in Gebert and others (2011), average annual baseflow values were estimated from miscellaneous measurements by using the statewide regression equation described in Gebert and others (2011), which relates measured flow to basin area and to flow at an index station. The water level and baseflow measurements were categorized into groups on the basis of the data source and estimated quality (uncertainty) (table 13). The targets used in calibration are included as part of the electronic database.

Relative importance in the calibration is expressed by weights assigned to each target. Weights were initially assigned to targets individually to reflect the inverse of the estimated target uncertainty. During calibration, the weighting was further adjusted at the group level by using multipliers to maintain a desired balance in the calibration objective function. The head observations were grouped by quality into several classes by using the estimated locational accuracy or data quality (or both) of each well. The location accuracy is important because the head targets are based on a wellhead elevation assigned from a DEM. Other data quality metrics were the number of measurements being averaged at a site, the timeliness of the measurements, and the presence of accompanying water quality data (implying a higher quality of water-level measurement). Head targets more than 5 km outside of the Nicolet Unit were assigned very low weights, to focus the parameter estimation on water levels in and adjacent to the unit. Weighting for the head targets is shown in table 13. A weight of 0.1 can be thought of as a 95 percent confidence interval of plus or minus (±)20 ft around the observed head. Similarly, weights of 0.25 and 0.05 can be expressed as 95 percent confidence intervals of ±8 ft and ±40 ft around the observed head, respectively. The lowest quality head and baseflow targets were assigned weights of zero, meaning they did not play a role in the nonlinear regression used to estimate the model parameters. Zero-weighted targets were retained in the calibration dataset to allow for qualitative comparison with model results.

Similar to head targets, baseflow targets were arranged into three groups on the basis of measurement source and quality. Baseflow target weights were assigned as the inverse of the target uncertainty, estimated as target flow rate multiplied by a coefficient of variation, which represents an estimate of the ratio of the standard deviation of the error divided by the mean value (table 13). USGS gaging stations with recent, long-term records were initially given the highest weight (coefficient of variation of 0.01, which represents a 95 percent confidence interval of ±2 percent around the observed flow). The annual baseflows estimated from miscellaneous measurements were assigned coefficients of variation based on the reported quality of the measurement (see U.S. Geological Survey, 2011b) and a standard error of 14 percent reported by Gebert and others (2011). Measurements without a quality designator were given a coefficient of 0.64 (50 percent error plus 14 percent for the statewide relation). Baseflow estimates obtained from Gebert and others (2011) were subjectively given coefficients of 0.25 (95 percent confidence interval of ±50 percent), as the underlying measurements for these values are commonly several decades old and of unknown quality. Although the above estimates if coefficient of variation represent an attempt to prioritize measurements of lower uncertainty, they are approximate at best and are mostly intended to reflect a larger uncertainty in miscellaneous measurements as compared to the gages. The overall goal of the observation weighting for both heads and baseflows was to achieve a balanced objective function that allowed all important observation groups to be "seen" by the calibration process, thereby maximizing the information transfer from the observations to the model input parameters (see Doherty and Hunt, 2010, for more explanation). In the calibration of both the North and South models, the observation group weight multipliers were adjusted in favor of the head measurement groups, to direct the parameter estimation algorithm to minimize negative bias in the head measurements (see table 13 and discussion below).

Final parameter values calibrated to measured water levels and stream baseflow (table 12) are within expected ranges on the basis of field data and previous studies. The resulting average recharge values for the forest unit in the north (7.1 in/yr) and south (7.5 in/yr) models are consistent with other reported values (Fienen and others, 2013; Gebert and others, 2011; Pint and others, 2003). Although the simplifying assumptions of GFLOW and TGUESS limit direct comparisons of hydraulic properties, the approximate simulated regional transmissivity (430–4,300 ft^2/d) is similar to the mean transmissivity value obtained from TGUESS (1,738 ft^2/d for unlithified materials). Because the uniform model aquifer base is not necessarily equal to the true aquifer base, the modeled hydraulic conductivity parameter does not represent the true aquifer. Table 12 shows the approximate effective hydraulic conductivity representative of the aquifer for each zone. The approximate effective hydraulic conductivity values range from 28 to 62 ft/d for outwash and from 4 to 50 ft/d for till or mixed sediments. Other regional studies suggest similar hydraulic conductivity values ranging from about 1 to 80 ft/d for outwash and from 0.2 to 2 ft/d for till (Batten, 1987; Krohelski and Carlson, 2005; Patterson, 1989). The effective hydraulic conductivity values for shallow bedrock zones may be somewhat overestimated; these values are calculated on the basis of the estimated actual saturated thickness of unlithified sediments only, which does not include potential transmissivity of surficial fractured bedrock. Most zones that span both models have two reported parameter values, one for each model. These values may differ because, although the zone boundaries are the same for both models, different areas of the zone are represented in each model. The actual zone being simulated (and therefore calibrated) is effectively the intersection of the model near-field and the zone polygon. Additionally, all zones contain some glacial outwash deposits that are too dispersed to be represented discretely in GFLOW. Many wells (head targets) are completed in this outwash, resulting in higher modeled hydraulic conductivities for these "mixed-sediment" zones than if the outwash were not present.

The head and baseflow targets are mostly well matched by the calibrated model, as shown in figures 13–16. Calibration statistics for the head groups are shown in table 14 and summarized in figure 13. Mean errors of approximately −11 to −12 ft indicate a bias in both models towards simulated heads that are greater than the observations. Inspection of figures 13 and 15 shows this bias to be uniformly distributed across the model domain (and simulated range of head elevations). Because one of the primary outputs of the flow model is a water-table map, during calibration we attempted to reduce the negative bias in the head targets by weighting the head observation groups more heavily than the baseflows (table 13). The height of the simulated water table is proportional to the ratio of recharge (R) to transmissivity (T), (R/T). However, both the baseflow targets (which require a minimum volume of recharge to be matched) and the conceptual model (the reasonable range of transmissivities, based on TGUESS results, previous studies, and "soft" geological knowledge) place a lower limit on R/T ratios used in the models. For both models, appreciable reduction of the head bias required either lowering the recharge multiplier such that baseflow targets were all undersimulated or the use of transmissivity values greater than 10,000 ft^2/d in some units. The chosen parameter set is therefore a trade-off between fitting the observation data and honoring the conceptual model. As a result of this tradeoff, model baseflows are on average simulated lower than observed (fig. 16). The largest high-quality baseflow target for the North and South models were simulated 13 percent and 5 percent low, respectively. The calibrated recharge of 7.1 and 7.5 in/yr could be biased low by a similar magnitude. The bias in heads and baseflows might be the result of real-world processes and features, such as evapotranspiration, vertical hydraulic gradients near surface-water bodies and wetlands and fine-scale variability in hydraulic conductivity that are not adequately represented in these two-dimensional regional models.

Although groundwater discharging to wetlands was not explicitly included in the model, it is implied in the model output in areas where simulated heads rise above the land surface. Such areas of "flooding" or "overpressurization" were used as a qualitative calibration metric, by spatial comparison to marshes on USGS 1:100,000-scale topographic maps. Simulated flooding in the calibrated model shows good agreement with the mapped wetlands (fig. 15).

Application of the models

The GFLOW groundwater flow models are useful decision-support tools for groundwater management in the Nicolet Unit. Hydraulic heads simulated by the two models were merged into one raster to evaluate the water table continuously across the entire unit (plate 10). Where the models overlap, water table elevations from each model were averaged and the resulting contours manually edited for consistency. Model-generated water-table maps are advantageous compared to water-table maps constructed by interpolation between point measurements, in that they provide a physically based depiction of the groundwater system that accounts for mass and energy conservation. Representation of the physical process of groundwater flow can help constrain water table elevations in areas of sparse water-level data, such as the national forest units.

The model solutions can be used to compute flowpaths through the groundwater system from discrete starting locations to discharge points (such as streams or wells). Starting locations are specified in the GFLOW graphical user interface as hypothetical particles; the paths of the particles are then traced through the groundwater flow system and included in the model output. Computation of particle travel times requires specifica-

Table 13. Calibration targets and associated weights used for calibration with the parameter estimation program PEST, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Type	Group name[1]	Data source	Description	Number of targets	Group weight multiplier	Calibration weight	Estimated uncertainty
North model							
Base flows	nwis_dv	NWIS	Baseflow separation of daily values	6	0.50	1/(CV x flow)	0.01–0.1 (CV)
	nwis_fm	NWIS	Field measurements	25	1.50	1/(CV x flow)	0.13–0.64 (CV)
	misc	Gebert and others (2011)	Miscellaneous and partial records measurements	51	3.00	1/(CV x flow)	0.5 (CV)
Heads	heads_best	NWIS, WDNR and WGNHS	NWIS wells with high altitude accuracy and many recent measurements; wells located by WCRs to within 50 ft	17	0.20	0.1	2 ft
	heads_good	NWIS, WDNR and WGNHS	NWIS wells with moderate altitude accuracy and many recent measurements or high altitude accuracy with only a single recent measurement, accompanied by water quality measurements; wells located by WCRs to within 100 ft	53	0.80	0.2	4 ft
	heads_fair	NWIS, WDNR and WGNHS	Single measurements in NWIS older with an altitude accuracy of 10 ft; wells located by WCRs to within 200 ft	1,941	0.70	0.035	20 ft
	farfield	NWIS, WDNR and WGNHS	Head measurements more than 7 km from Nicolet Unit	794	0.10	0–0.05	2–20+ ft
	heads_poor	NWIS, WDNR and WGNHS	Poorly located or other low quality well construction reports	56	—	0	—
South model							
Base flows	nwis_dv	NWIS	Baseflow separation of daily values	2	0.2–0.44	1/(CV x flow)	0.01–0.1 (CV)
	nwis_fm	NWIS	Field measurements	12	4.00	1/(CV x flow)	0.13–0.64 (CV)
	misc	Gebert and others (2011)	Miscellaneous and partial records measurements	29	5.00	1/(CV x flow)	0.5 (CV)
Heads	heads_best	NWIS, WDNR and WGNHS	NWIS wells with high altitude accuracy and many recent measurements; wells located by WCRs to within 50 ft	5	0.30	0.15	2 ft
	heads_good	NWIS, WDNR and WGNHS	NWIS wells with moderate altitude accuracy and many recent measurements or high altitude accuracy with only a single recent measurement, accompanied by water quality measurements; wells located by WCRs to within 100 ft	809	0.20	0.05	4 ft
	heads_fair	NWIS, WDNR and WGNHS	Single measurements in NWIS older with an altitude accuracy of 10 ft; wells located by WCRs to within 200 ft	2,401	0.60	0.03	20 ft
	farfield	NWIS, WDNR and WGNHS	Head measurements more than 7 km from forest unit	452	0.10	0–0.05	2–20+ ft
	heads_poor	NWIS, WDNR and WGNHS	Poorly located or other low quality well construction reports	28	—	0	—

Abbreviations: CV = coefficient of variation; NWIS = National Water Information System; WDNR = Wisconsin Department of Natural Resources; WGNHS = Wisconsin Geological and Natural History Survey; WCR = well construction report

[1]*Group name attribute in GFLOW targets data file (see table 15)*

tion of effective porosity. In addition, the deep base elevations employed in these models require that the effective porosity values be adjusted to correct for the additional simulated aquifer thickness (see Juckem and Dunning, 2015). Particle travel times were not considered in this study.

Plates 9 and 10 show pathline output from the models indicating general directions of groundwater flow. The individual pathlines were created by initiating particles at the water table at various locations throughout the groundwater system, and then tracking those particles forward for an arbitrary time period or until the particles discharged to a surface-water feature or well. The water-table contours and pathlines show general directions of groundwater flow and can be used to delineate divides between groundwater basins. The regional groundwater divide is similar to the surface-water divide, and thus most groundwater in the unit flows southeast; the far western part of the unit drains south to the Wolf and Wisconsin River basins.

The GFLOW models can also be used to evaluate groundwater discharge to surface water features (plate 9). This plate shows modeled baseflow, colored to indicate water exchange with the aquifer. Most streams in the unit gain water from the aquifer although a few lose water to it. The plate also shows saturated aquifer thickness and water sample alkalinity and electrical conductivity. Groundwater-dominated samples such as those from site N11 (fig. 8a) and from sites N28, N31, and N36 (fig. 8b), which have higher values of alkalinity and electrical conductivity, correspond to areas modeled by GFLOW as groundwater discharge points, whereas surface-runoff-dominated samples such as those from sites N2 (fig. 8a) and N40 (fig. 8b) are typically located in upland recharge areas. Any features that do not follow this pattern could indicate local hydrogeologic conditions that are not well represented by the regional GFLOW model or a blend of groundwater- and runoff-dominated conditions. This combination of flow modeling and geochemistry can be used as a guide for future modeling and site-specific investigations.

The GFLOW model has many other potential uses, such as the following.

- Delineating areas contributing groundwater to specific springs, lakes, wells, and streams;
- Evaluating where streams are modeled as gaining or losing groundwater;
- Determining the expected drawdown and zone of influence of any proposed new high-capacity wells in or near the forest;
- Quantifying the impact of any proposed high-capacity wells on water levels or flows in nearby surface-water features;
- Identifying potential migration directions of contaminant releases to groundwater and potentially affected groundwater receptors;
- Evaluating the potential effects of climate change on groundwater resources; and
- As a foundation for more detailed studies of specific sites.

The GFLOW model can easily be focused on specific features or areas by incrementally adding detail as needed.

Assumptions and limitations

One of the main objectives in constructing regional groundwater flow models of the Nicolet Unit was to develop an overall picture of the regional water table and groundwater flow directions, and the models achieve this objective. Owing to difficulties in calibrating the model to observed baseflows and a systematic low bias in calibrated recharge and baseflows, particularly in the South model, the models should be used with caution to quantify groundwater discharge to surface-water features. The Nicolet Unit groundwater and surface-water systems are assumed to be in close hydraulic connection in the modeled area; this assumption is consistent with the relatively transmissive nature of the glacial sediments, high net annual precipitation, the presence of springs and perennial headwater streams, and previous modeling in nearby areas. The models, then, assume that elevations of surface-water features represent the groundwater system; perched systems (areas where an upper water table is "perched" on an unsaturated zone) are not well represented. Areal two-dimensional assumptions were appropriate for the model because the groundwater flow system is thin and areally extensive; however, because areal two-dimensional assumptions may not be representative within two to three aquifer thicknesses of a surface-water feature (Haitjema, 1995; Hunt and others, 2003), simulated groundwater levels near surface-water features can be considered approximate only. These approximations may explain some of the negative bias (oversimulation) of heads near lakes (for example, Haitjema, 1995, p. 259). All pumping wells represented in the model are assumed to penetrate the full aquifer thickness. This assumption may

Figure 13a. Simulated vs. measured heads for weighted head targets, showing 1:1 line, for North model.

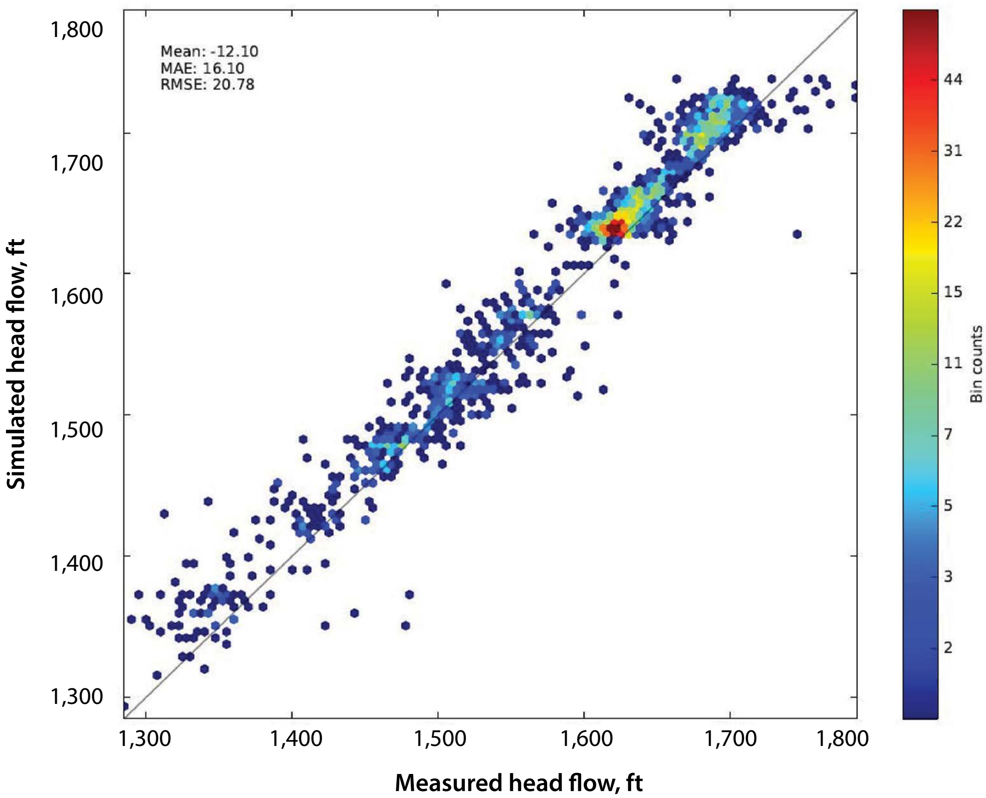


Figure 13b. Simulated vs. measured heads for weighted head targets, showing 1:1 line, for South model.

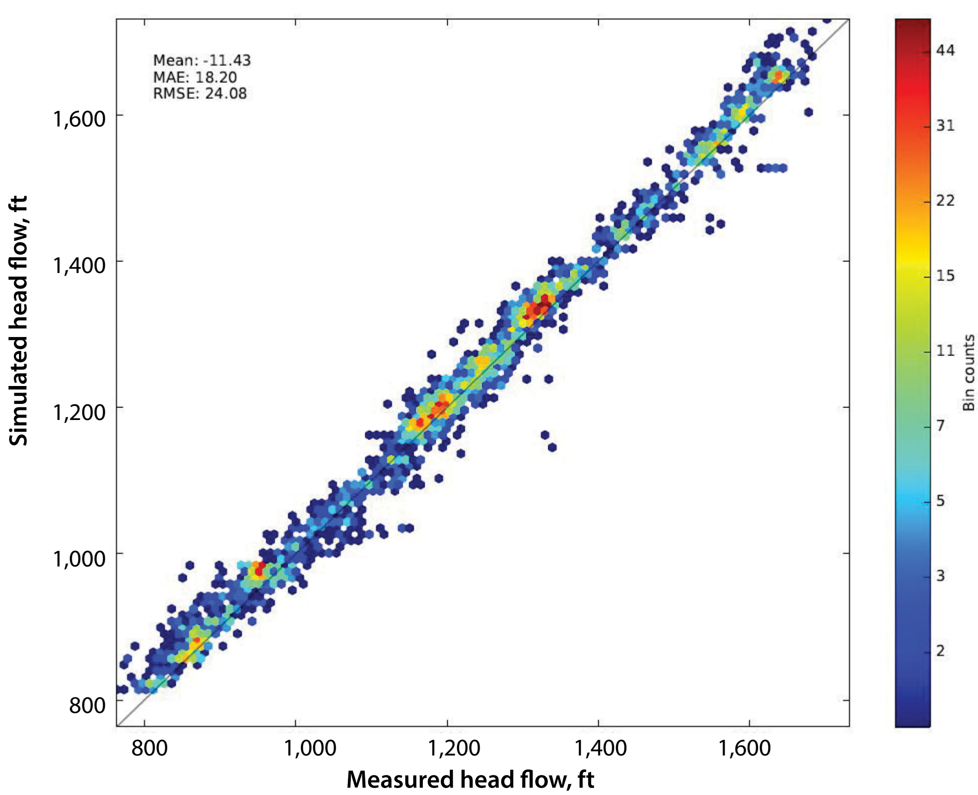


Figure 14a. Simulated vs. measured flows for flow targets, showing 1:1 line, for North model.

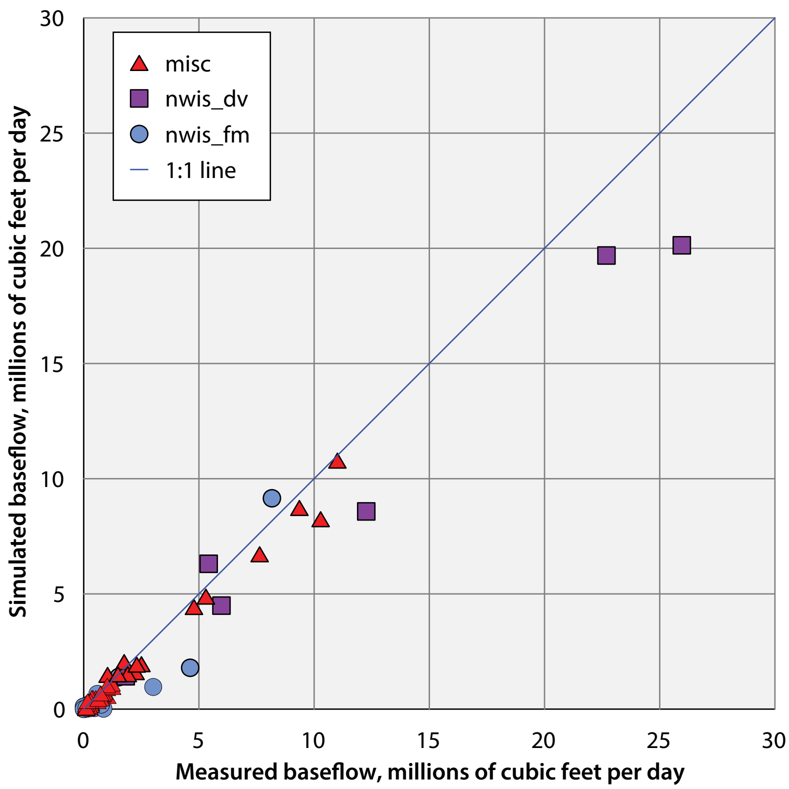
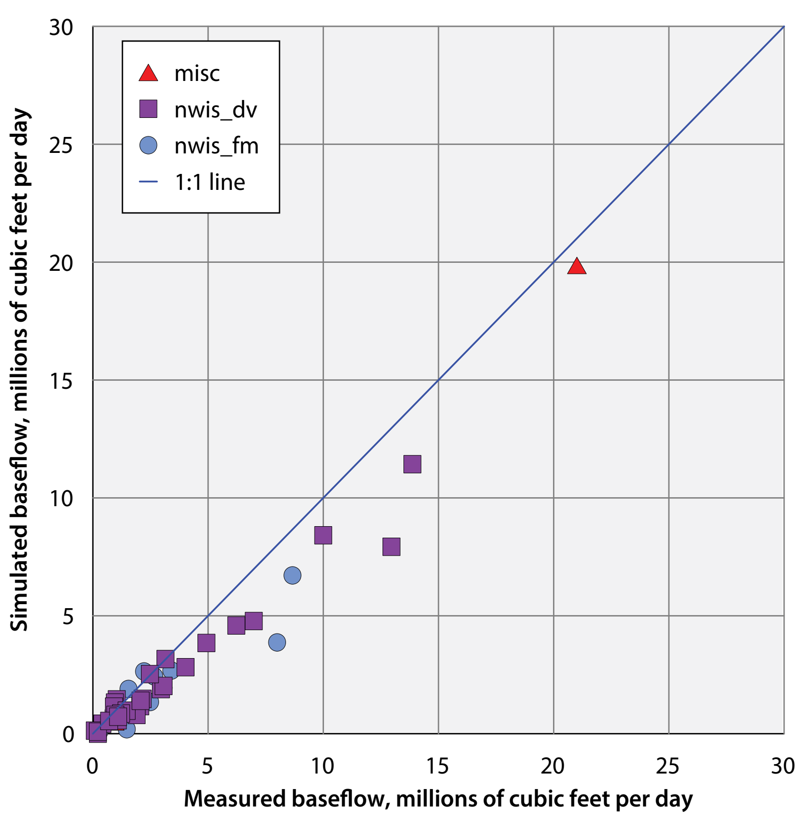


Figure 14a. Simulated vs. measured flows for flow targets, showing 1:1 line, for South model.



produce a positive bias in simulated heads near pumping wells, especially where the wells in reality penetrate only part of the aquifer.

The model described here is a regional-scale model that represents the groundwater system with laterally extensive, piecewise-constant zones. Local subsurface variability that is known to exist (for example, variability in aquifer thickness and hydraulic conductivity due to glacial erosional and depositional processes) cannot be represented in the model at scales smaller than the model zones, which simulate average regional conditions. Possibly as a result of this heterogeneity, the model-simulated heads are biased high and the baseflows (and therefore recharge) biased low in order to maintain reasonable values of transmissivity. In addition, the model is designed and calibrated for groundwater flow in a single aquifer layer composed of unconsolidated sediments sometimes combined with a thin fractured upper-bedrock zone. In areas of near-surface fractured rock, such as the southeastern corner of the Nicolet Unit in Oconto County, the model may be unreliable. Additional field investigations, analyses and model refinement are needed for accurate simulation of processes that are sensitive to local aquifer heterogeneity in this and similar areas.

Simulated heads and baseflows matched in the calibration process were relatively insensitive to the streambed resistance parameter; therefore, this parameter is not well constrained. The value used of 10.0 d is similar to values for streambed resistance in other national forest unit models created for this project, as well as in other studies in northern Wisconsin (for example, Juckem and others, 2014; Kelson and others, 2002). Steady-state simulations were assumed appropriate for this study given the large lateral extent and dense surface-water network (for example, Haitjema, 1995, p. 293).

Recommendations for future modeling

Additional data collection and advances in modeling techniques will improve our ability to incorporate more detail into future models. The wide range of heterogeneity in almost all hydrogeologic parameters (aquifer thickness, glacial material, bedrock type, recharge, precipitation, streamflow) across the large Nicolet Unit proved difficult to capture in the two GFLOW models prepared for this unit. Local areas of interest should be simulated in greater detail by using the GFLOW models developed here as starting points for creating and calibrating more detailed finite difference inset models (Hunt and others, 1998). Calibration targets in the forest unit are sparse; additional measurements of groundwater levels and baseflow would help refine model results. Additional subsurface data in the Nicolet Unit may reveal more detailed patterns in hydraulic conductivity that are not currently visible. While transmissivity and hydraulic conductivity in the unit do vary spatially (plates 1, 2, 3), data are limited in less-populated areas and in more fine-grained deposits where well records are sparse. Although the analytic element modeling technique is limited to representing variations in hydraulic conductivity with piecewise-constant zones, greater levels of detail in hydraulic conductivity could be readily incorporated into finite difference inset models.

Table 14. Calibration results for groundwater head targets and associated weights used for calibration with the parameter estimation program PEST, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Group name[1]	Number of targets	Mean error (ft)	Mean absolute difference (ft)	Root mean square error (ft)	Calibration weight (1/std)
North model					
farfield	794	–13.01	25.15	34.29	0–0.05
heads_best	17	–9.29	12.67	17.09	0.1
heads_fair	1,941	–12.21	16.21	20.87	0.035
heads_good	53	–9.21	13.26	18.39	0.2
heads_poor	56	–10.51	17.10	22.92	0
South model					
farfield	452	–17.16	20.29	26.28	0–0.05
heads_best	5	–6.79	16.95	17.72	0.15
heads_fair	2,401	–9.85	17.99	24.14	0.03
heads_good	809	–12.90	17.70	22.59	0.05
heads_poor	28	25.06	37.81	68.76	0

Abbreviations: ft = feet; std = standard deviation

[1]*Group name attribute in GFLOW targets data file (see table 15)*

Figure 15a. GFLOW results for Nicolet Unit's North model: weighted head target residuals and simulated heads above land surface (flooding) compared to WDNR Wisconsin Wetlands Inventory.

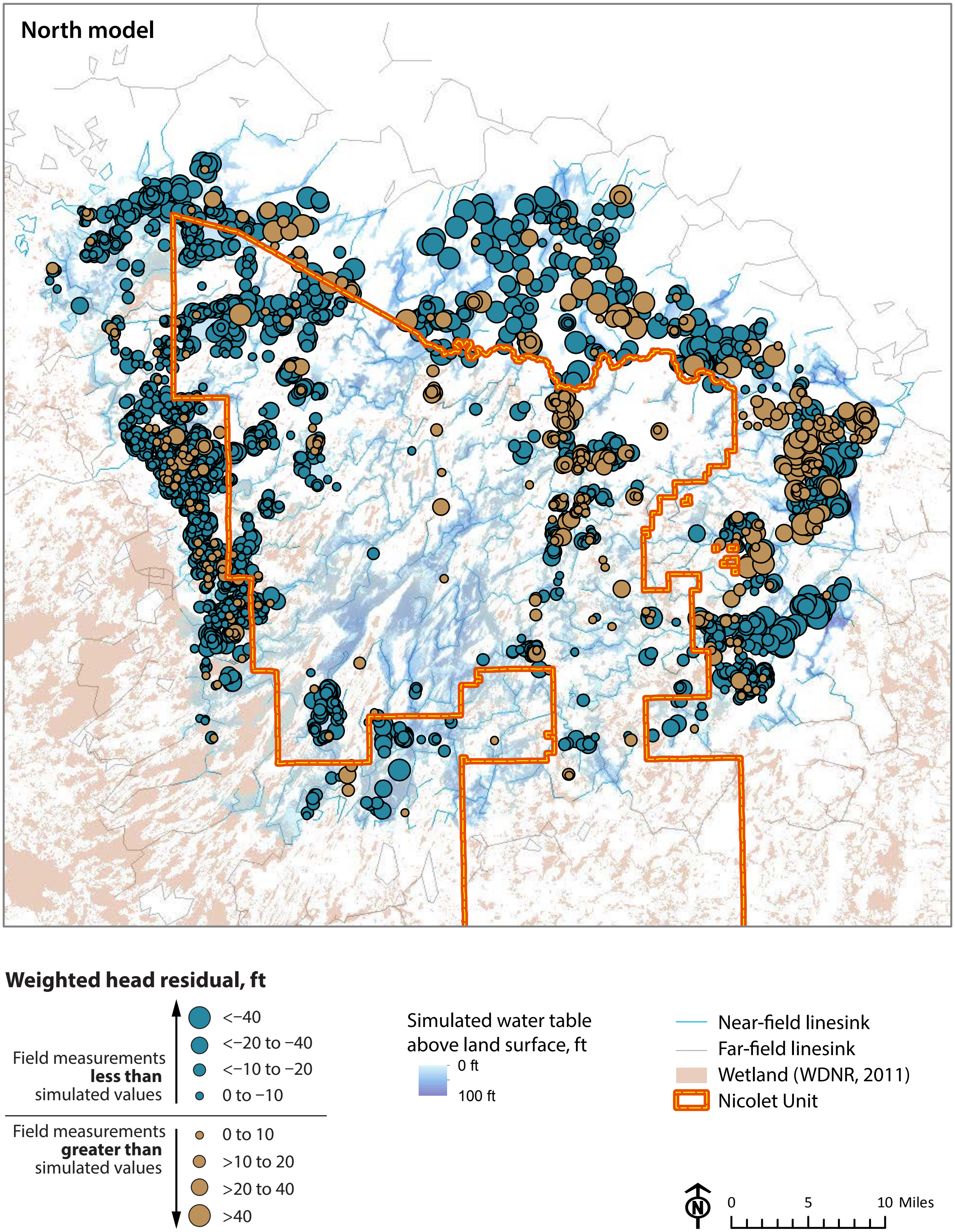


Figure 15b. GFLOW results for Nicolet Unit's South model: weighted head target residuals and simulated heads above land surface (flooding) compared to WDNR Wisconsin Wetlands Inventory.

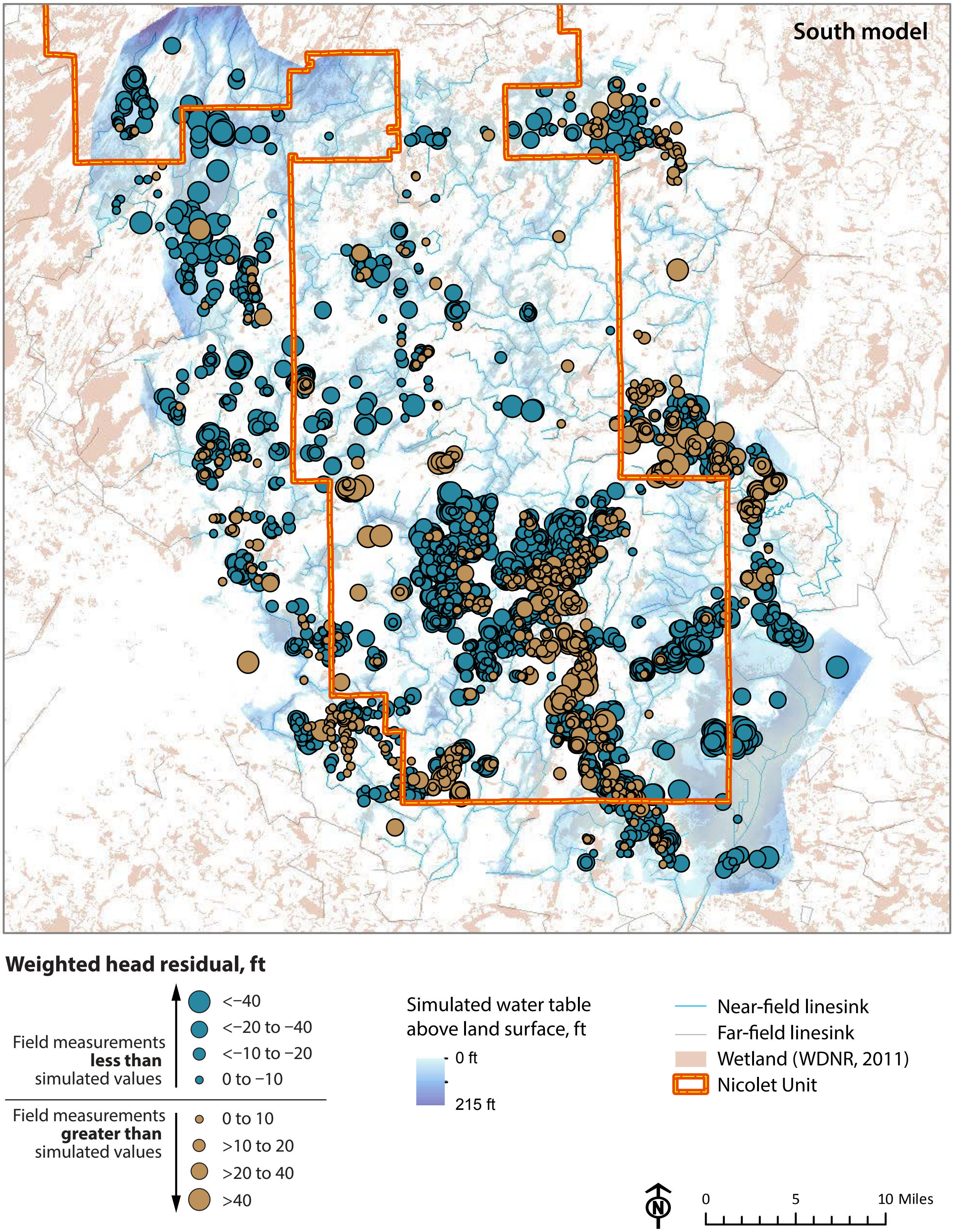


Figure 16a. GFLOW results for Nicolet Unit's North model: weighted flow target residuals.

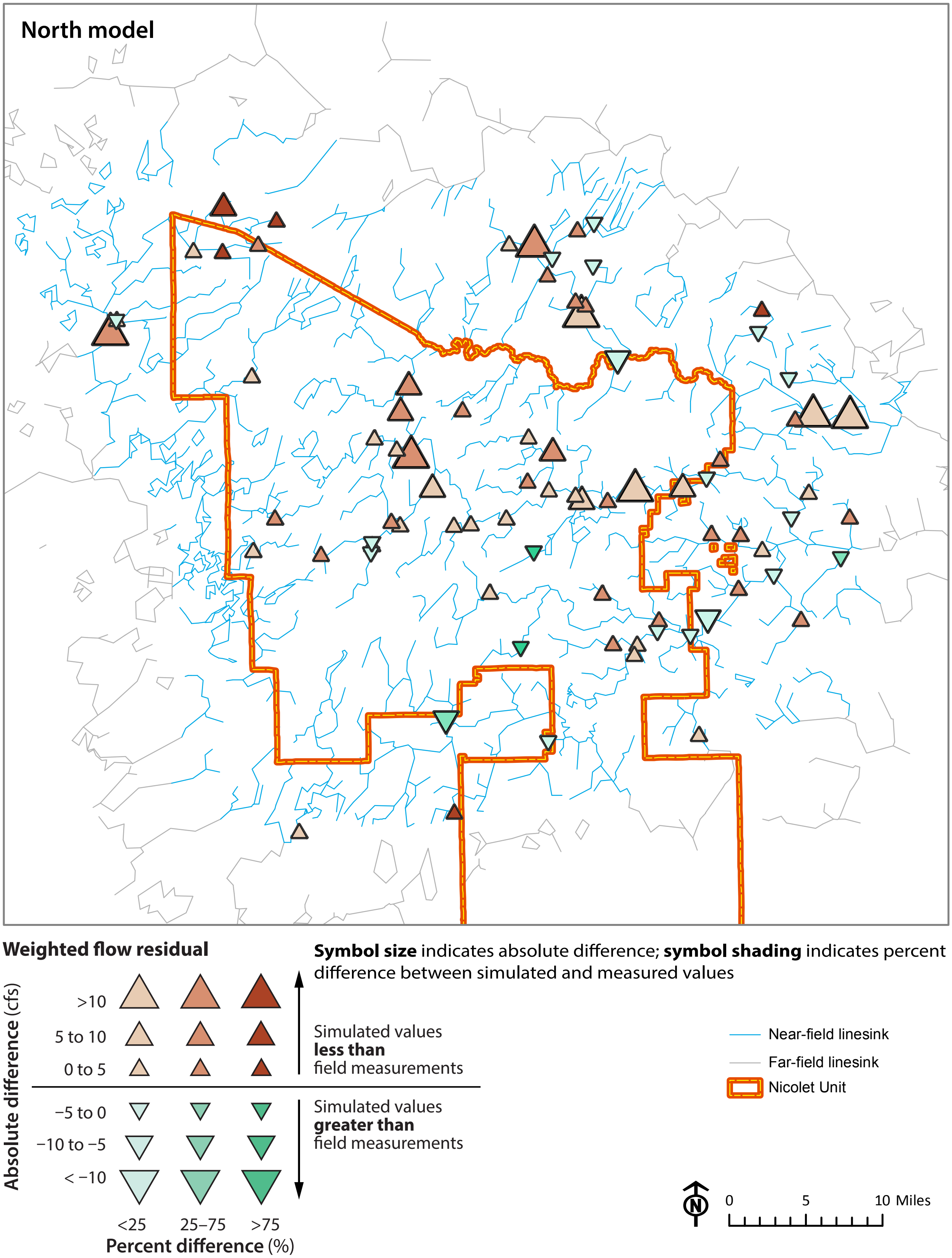
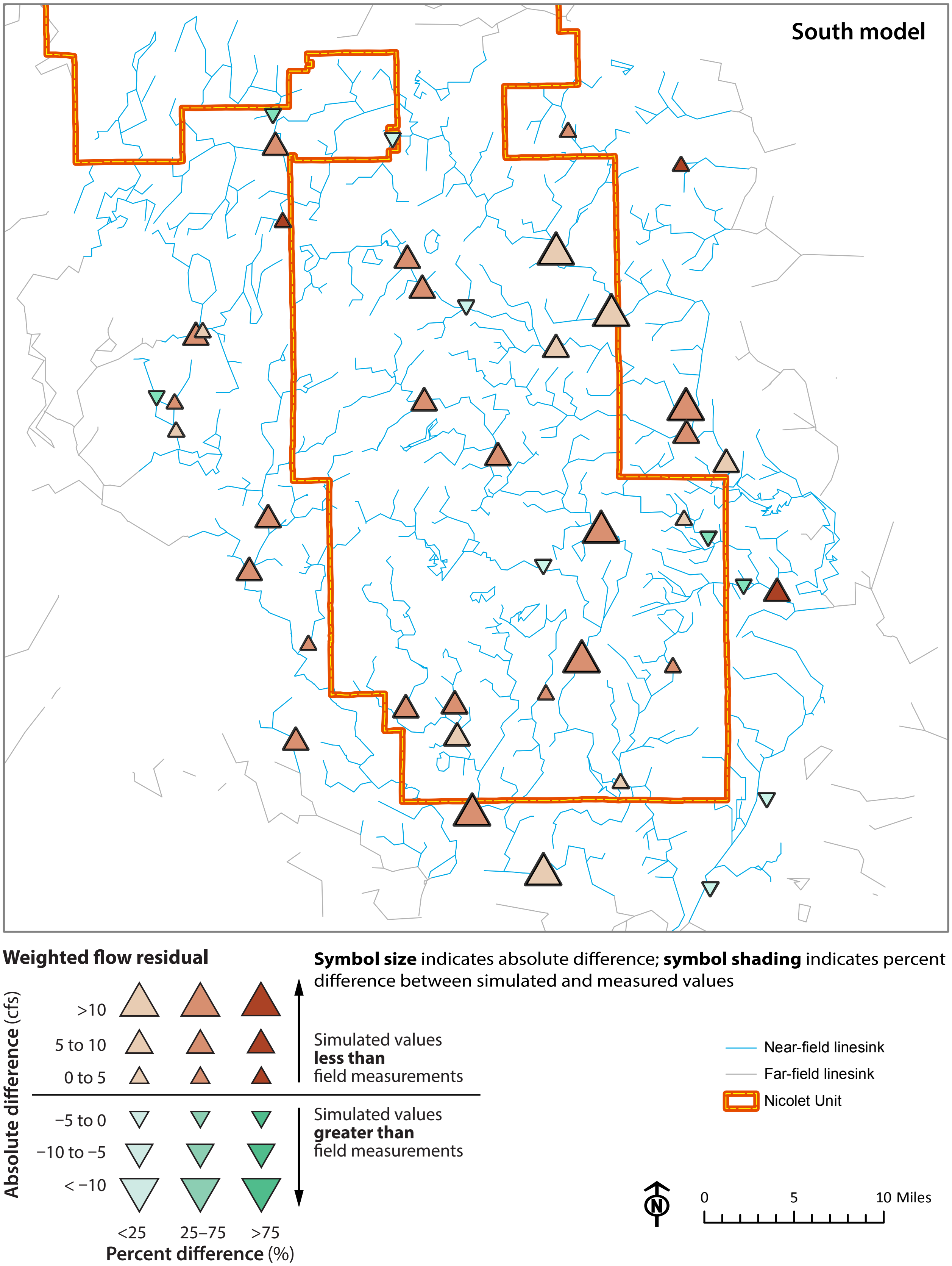


Figure 16b. GFLOW results for Nicolet Unit's South model: weighted flow target residuals.



Summary

The primary aquifer in the Nicolet Unit consists of shallow glacial outwash and till. This aquifer is thin, ranging from zero to 200 ft thick, and it is absent in local areas where the bedrock is near the surface, particularly in the southeastern part of the unit. The aquifer is sufficient to supply water to low-capacity domestic wells; its mean estimated hydraulic conductivity is 27 ft/d and its range is 0.2 to 1,200 ft/d. The glacial aquifer has the potential to support high-capacity wells in some areas; the approximate average potential yield is 100–200 gpm. Additional analyses would be necessary to determine the site-specific potential for such wells and how they might affect nearby groundwater levels and surface-water flows.

Crystalline bedrock beneath the glacial materials can supply adequate water to low-capacity wells in areas where the glacial deposits are too thin or too fine grained. In general, the bedrock aquifer has estimated hydraulic conductivities about an order of magnitude lower than the overlying glacial deposits. The bedrock aquifer, which has a low likelihood of supporting high-capacity wells, has an approximate average potential yield of about 20 gpm.

Few high-capacity wells are present in this region. Of the 26 active high-capacity wells in the unit, most obtain their water from the glacial aquifer. Although these wells are permitted to pump more than 70 gpm, the majority pump at far lower rates (average of 24 gpm for wells in the groundwater flow model). The total withdrawal in the unit is 240 gpm and 5,500 gpm in the broader region represented in the regional groundwater model.

About 80 percent of the domestic wells within the Nicolet Unit are screened in the sand and gravel aquifer at an average depth of 80 ft. Of the bedrock wells, most pump from the top 140 ft of bedrock, although some pump from as deep as 300 ft.

Groundwater levels measured in 2016 in a long-term monitoring well are similar to those measured in 1967. More recent water levels in three wells have risen since a regional drought in about 2010. These wells provide important baseline data that can be used in future studies.

The SWB-modeled mean potential recharge is fairly low (4.6 in/yr) compared to other reported values. Although the magnitude appears low, the results are spatially consistent with surficial geology through soil characteristics. The SWB model results were calibrated to measured baseflow by using the groundwater flow model. During calibration, a regional multiplier that was applied to the SWB grid produced in an overall mean recharge value of 7.1 in/yr for the northern part of the unit and 7.5 for the southern part.

Water quality within the unit is generally unaltered by human activity. Moderately elevated chloride concentrations were observed at certain sample locations, likely as a result of local activities such as road salting. Water from several wells failed to meet the Wisconsin preventive action limit for arsenic, and water from one well failed to meet the preventive action limit for lead. None of water samples from these wells had concentrations in excess of the safe drinking water standard for these constituents. We recommend that additional water samples from these wells be analyzed for lead and arsenic to confirm these results.

Groundwater in the Nicolet Unit is distinguished from surface water by higher electrical conductivity, alkalinity, and concentrations of dissolved ions such as calcium and magnesium. Groundwater well samples have an average conductivity of 249 µS/cm and alkalinity of 108 mg/L. A single lake sample has values of 31 µsS/cm and 8 mg/L, respectively. Isotopes of hydrogen and oxygen can also be used to distinguish groundwater, which is isotopically lighter, or more negative, than surface water. No unit-wide spatial patterns in groundwater chemistry were identified in this study; identification of such trends would require a more extensive groundwater sampling program.

The regional groundwater divide is similar to the surface-water divide, and most groundwater in the unit flows southeast; the far western part of the unit drains south to the Wolf and Wisconsin River basins.

The GFLOW groundwater flow model is a useful decision-support tool that can be used to evaluate many aspects of the flow regime, such as regional flow patterns, groundwater discharge to streams, and interactions of groundwater with surface water. The model may also be used to simulate potential effects of land use, pumping, or climate change.

Hydrogeologic data are sparse within the Nicolet Unit. The data and models presented in this report can help guide future data collection to improve the understanding of groundwater resources within the Chequamegon-Nicolet National Forest. Data collection should focus on areas of interest, areas with no nearby wells, or areas that are poorly simulated by the groundwater flow model. Recommended future activities include the following.

- Continue studies of groundwater recharge in the Nicolet unit. As discussed above, recharge estimates developed for this report are apparently biased low compared to earlier estimates, and the reasons for this bias are currently unclear.
- Focus studies on the hydrogeology of shallow-bedrock areas in the southeast part of the Nicolet unit in Oconto County. In the area northeast and south of the Village of Mountain, numerous wells obtain water from shallow and fractured bedrock, but the groundwater system there is poorly understood and poorly simulated by the regional model developed for this report.
- Maintain at least two long-term monitoring wells, one in the northern and one in the southern portion of the Nicolet Unit to provide baseline groundwater-level data.
- Continue to measure baseflow and groundwater levels to improve calibration of future groundwater flow models.
- Develop three-dimensional finite difference inset models for areas of interest to improve simulation of groundwater flow. One area of great uncertainty is the shallow bedrock area in the southeastern part of Oconto County. Numerous wells in this area draw small amounts of water from the upper, fractured bedrock zone but the hydrogeology of this area has never been well characterized.

Brule Springs

Anna Fehling

Data availability

The results of the inventory, modeling, and analysis described in this report are available in an electronic database for public use (table 15). These data can be downloaded from the Wisconsin Geological and Natural History Survey website at https://wgnhs.uwex.edu/.

Table 15. Summary of available electronic data, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin.

Data	Name	Format	Description/source
Wells			
Located wells	Nic_LocWCRs_WGNHS_2016	Point features	Data points from WCRs located to within the quarter-quarter section and from geologic records
Monitoring wells	Nic_MWLocs_WGNHS_2016	Point features	Location of monitoring wells FR-908, FR-656, and FR-087
Monitoring well drilling summary	Monitoring well drilling summary—Nicolet Unit.pdf	PDF	Geologic and well construction information for well FR-908
Geology			
Bedrock elevation contours	Nic_BedElev_WGNHS_2016	Polyline features	Interpolated from WCRs and other data
Depth to bedrock contours	Nic_BedDep_WGNHS_2016	Polyline features	Interpolated from WCRs and other data
Saturated thickness contours of glacial materials	Nic_GlacSatThickness_WGNHS_2016	Polyline features	Interpolated from WCRs and other data
Hydraulic properties			
Bedrock hydraulic properties	Nic_BedTGUESS_WGNHS_2016	Point features	Hydraulic conductivity and transmissivity results from TGUESS
Glacial hydraulic properties	Nic_GlacTGUESS_WGNHS_2016	Point features	Hydraulic conductivity and transmissivity results from TGUESS
Recharge			
Mean annual potential recharge	Nic_PoRec_WGNHS_2016	Raster data	Annual recharge mean of all modeled years from SWB model output
Annual potential recharge, individual years	Nic_PoRec[yyyy]_WGNHS_2016, e.g. Nic_PoRec2000_WGNHS_2016	Raster data	Annual potential recharge for years 2000–2010 (11 files) from SWB model output
Calibrated recharge grids	Nic_RechGFLOW_N_WGNHS_2016 Nic_RechGFLOW_S_WGNHS_2016	Raster data	Annual recharge applied to GFLOW model, calibrated from SWB results
Groundwater			
Simulated water table contours	Nic_WatTabGFLOW_WGNHS_2016	Polyline features	GFLOW model output, merged into one coverage
Gaining and losing streams	Nic_BaseflowGFLOW_N_WGNHS_2016 Nic_BaseflowGFLOW_S_WGNHS_2016	Polyline features	GFLOW model output
Simulated groundwater flow paths	Nic_GWFlowpathGFLOW_N_WGNHS_2016 Nic_GWFlowpathGFLOW_S_WGNHS_2016	Polyline features	GFLOW model output

(continued)

Table 15. Summary of available electronic data, Nicolet Unit of Chequamegon-Nicolet National Forest, Wisconsin *(cont.)*.

Data	Name	Format	Description/source
Geochemistry			
Geochemistry sampling locations	Nic_GeochemSites_WGNHS_2016	Point features	WGNHS water sampling locations
Geochemistry results	Nic_Geochemistry_WGNHS_2016	Excel	Field and laboratory water sample results
Model			
GFLOW targets	Nic_TargetsGFLOW_N_WGNHS_2016 Nic_TargetsGFLOW_S_WGNHS_2016	Point features	Simulated and observed values for GFLOW flow and head targets
USGS data archive for GFLOW models	https://dx.doi.org/10.5066/F7QR4W2W	Model files	GFLOW groundwater models for north and south sections of Nicolet Unit

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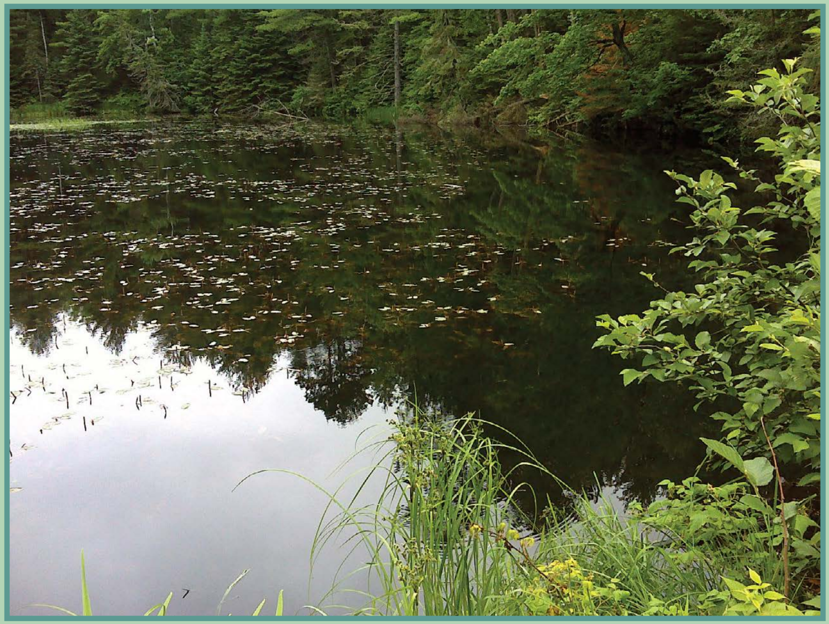
Trilliums, near Saul's Spring

Anna Fehling



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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.

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