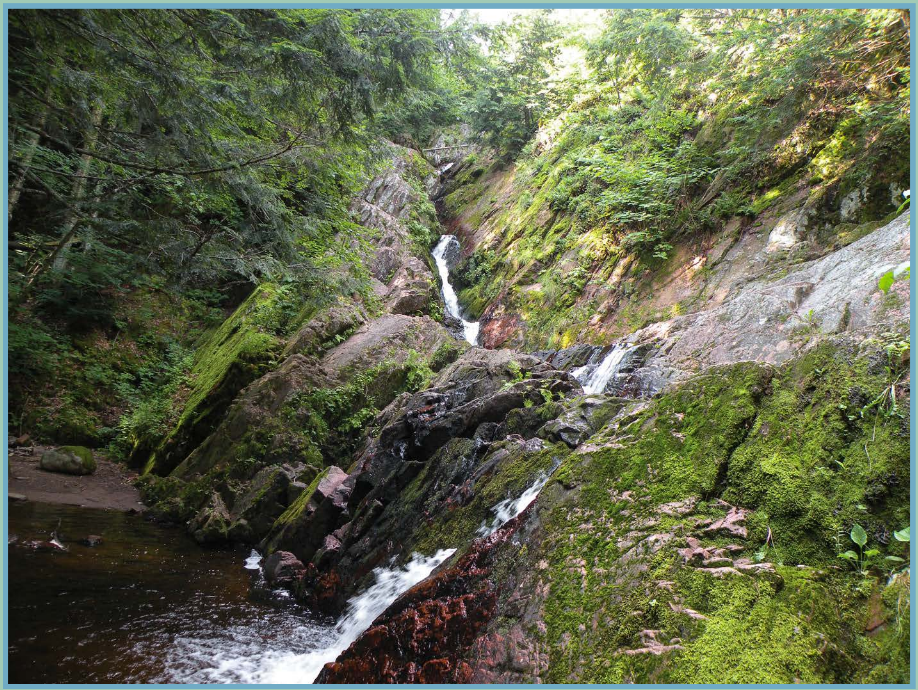
WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

# Characterization of groundwater resources in the Chequamegon-Nicolet National Forest, Wisconsin: Washburn/Great Divide Unit



Technical Report 004-4 • 2018

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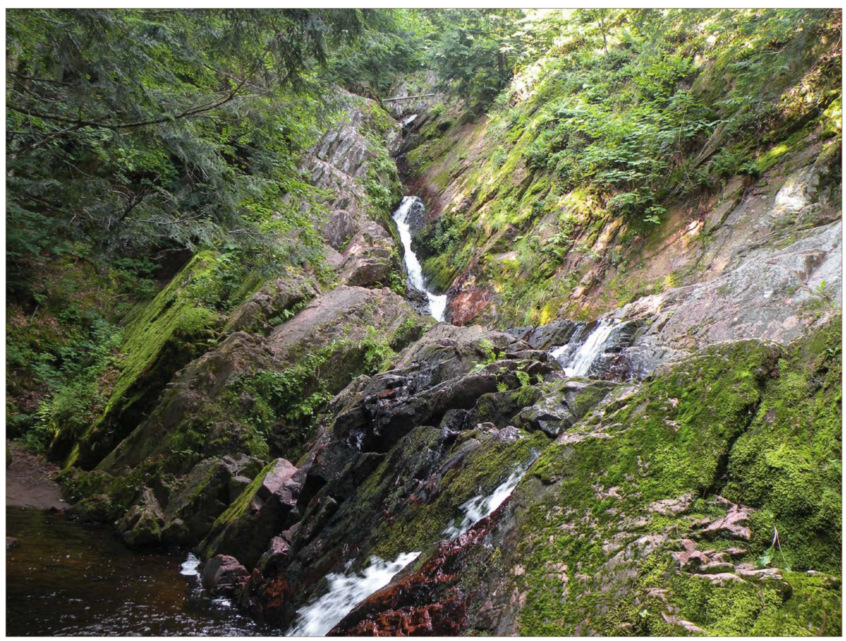
Summary report prepared for the U.S. Forest Service
Prepared in cooperation with the U.S. Geological Survey

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## PLATES

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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 this national forest are sparse and to date there has been no comprehensive analysis of its groundwater system. Additionally, concern is growing 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 development of tools to evaluate the sensitivity of hydrologic flows and temperature to future climate and land-use changes. The potential for future hardrock prospecting and iron ore mining in the Penokee Range and volcanic rocks of Proterozoic age within or near the Washburn/Great Divide Unit is an additional motivation for improving the understanding of local hydrogeology and baseline water quality in the CNNF.

To address these issues, in 2010 the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS), acting cooperatively with the U.S. Forest Service (USFS), began to review and analyze groundwater resources in the CNNF. The study was divided into four reports corresponding to the national forest's four main contiguous land units: Medford, Nicolet, Park Falls, and Washburn/Great Divide. This report documents the study results within the Washburn/Great Divide Unit in Ashland, Bayfield, and Sawyer Counties, Wisconsin. The Washburn/Great Divide Unit is composed of two adjacent ranger districts, Washburn District in the north and Great Divide District in the south.

The project inventoried available data and development of tools to improve the understanding of aquifer characteristics and the groundwater flow regime, defining more clearly the interactions of groundwater with surface water, evaluating the vulnerability of aquatic resources to climate change, and providing a basis to support future studies in this national forest.

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

1. **Hydrogeologic data.** Inventory and interpret existing geologic and hydrogeologic data in the unit, such as the physical and hydraulic properties of aquifers and water use, assembled into a spatial database.
2. **Groundwater potential recharge.** Construct a soil-water balance model for predicting spatial and temporal distribution of potential recharge.
3. **Geochemistry of groundwater and surface water.** Geochemical sampling and analysis to obtain a representative characterization of current water chemistry in the forest.
4. **Groundwater flow model.** Construct a groundwater flow model, which can be used to develop a water-table map and to evaluate future water-management scenarios.

The initial portion of the study inventoried and analyzed available hydrogeologic data, which were then 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 combined with previous studies of the regional geology indicate that subsurface materials in the unit consist of glacial sediments overlying crystalline and sandstone bedrock. The spatial analysis suggests that surficial glacial deposits consisting of stream sediment or sandy till form an aquifer with low to moderate average productivity. This aquifer ranges from zero to more than 600 feet (ft) thick and is generally thicker in the Washburn District than in the Great Divide District. The horizontal hydraulic conductivity estimates for this aquifer ranged from 0.02 to 1,900 feet per day (ft/d), with a mean of 32 ft/d. About 85 percent of wells in the unit obtain 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 200 gallons per minute (gpm). Bedrock beneath the glacial materials, generally consisting of sandstone in the north and crystalline rock in the south, can supply adequate water to low-capacity wells in areas where the glacial deposits are too thin or too fine grained. The mean horizontal hydraulic conductivity in bedrock is estimated to be about an order of magnitude lower than that in overlying glacial deposits. The crystalline bedrock aquifer has little likelihood of supporting high-capacity wells, with an approximate average potential yield of about 20 gpm. Most bedrock wells pump from the top 120 ft of bedrock, although some pump from as deep as 400 ft. Specific capacities (discharge divided by drawdown) are generally low in both the glacial materials and bedrock throughout the Washburn/Great Divide 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.

Fourteen high-capacity wells are active in the unit, all of which obtain their water from the glacial aquifer. Although these wells are permitted to pump more than 70 gpm, the majority pump at much lower rates (average of 25 gpm for wells used in the groundwater flow model).

In the second part of this study, potential recharge was estimated by using a soil-water balance (SWB) model. This model produced temporally and spatially variable estimates of potential recharge in the Washburn/Great Divide Unit for years 2000 through 2010. The mean overall potential recharge throughout the model domain for this time period was 10.4 inches per year (in/yr), with means of 12.4 in the Washburn District and 9.3 in the Great Divide District. The general trend in the distribution of recharge in the units correlates primarily with surficial geology through soil characteristics; potential recharge is high on the outwash barrens (Copper Falls Formation stream sediment) of the northern part of the Washburn District, moderate on the Copper Falls till in the southern part, and lower over the Miller Creek Formation clay till plains both east and west of the unit. Overall potential recharge in the Great Divide District is more moderate, but common patterns in the district are of higher recharge in sandy soils and forest cover and lower recharge in finer soils and wetland cover. SWB models may overestimate recharge in wetlands, which cover about 18 percent of the unit. If we assume zero recharge in wetlands, then an average unit-wide potential recharge is 9.5 in/yr. However, it is likely that recharge in wetlands is actually greater than zero, and so the SWB-simulated unit-wide average potential recharge is between 9.5 and 10.4 in/yr. During calibration of the groundwater flow model, a regional multiplier applied to the SWB grid produced an overall mean recharge value of 11.1 in/yr for the Washburn District and 8.8 for Great Divide District.

In the third part of this study, we inventoried surface-water and groundwater geochemistry, in order to characterize current water quality in the Washburn/Great Divide Unit. Water samples from groundwater wells, spring ponds, streams, and lakes were analyzed for major ion chemistry, basic nutrients, and the stable isotopes oxygen-18 ($^{18}O$) and deuterium ($^{2}H$). Analyses show that water in the Washburn/Great Divide Unit contains low concentrations of most dissolved constituents and thus is interpreted to be relatively unaffected by human activities. Groundwater is distinguished from surface water by higher electrical conductivity along with greater alkalinity and concentrations of dissolved ions such as calcium and magnesium. Groundwater well samples have an average conductivity of 183 microsiemens per centimeter (µS/cm) and alkalinity of 83 milligrams per liter (mg/L), whereas lake (surface water) samples have averages of 58 µS/cm and 28 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. This information can be used to evaluate where wells may be drawing from surface water or, conversely, where surface water features may be predominantly groundwater fed. Concentrations of dissolved iron and manganese in, respectively, 5 and 9 groundwater samples in the Washburn and Great Divide Districts were in excess of the Wisconsin NR140 preventive action limit (PAL), and in some cases failed the enforcement standard (ES), for manganese or iron. Both these metals are often natural constituents of groundwater and are generally considered aesthetic contaminants based on taste and appearance.

For the fourth part of the study, regional groundwater flow models were constructed for the Washburn and Great Divide Districts by using the analytic element model code GFLOW. The flow models provide a framework with which to estimate key aquifer properties, simulated water table elevations, flow paths, flow rates, and discharge zones. The simulated groundwater divide is similar to a regional surface-water divide that splits the unit roughly in two across the Great Divide District; most of the Washburn District drains north to Lake Superior whereas the Great Divide District drains south to the Mississippi River. The flow 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 the effects of changes in pumping or land use on 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 (Leaf and others, 2019a, 2019b).

# Introduction

## Background

The Chequamegon-Nicolet National Forest (CNNF) in northern Wisconsin is home to an abundance of water resources such as 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 this national forest is also important for assessing the feasibility and potential effects of multi-use projects such as mines, timber harvest, and agriculture. Traditional groundwater studies rely on data from groundwater wells, which are sparse in the undeveloped forest, and prior to this study there was no comprehensive data inventory or analysis of the groundwater system in the CNNF. An improved understanding of forest hydrology would help managers to protect and use these resources wisely.

In addition, concern is growing about the hydrologic effects 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 and metallic mineral extraction. The potential effect of these changes on water resources has not been documented. Managers 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 these national forest resources, in 2010 the U.S. Forest Service (USFS) began a cooperative study with the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS), acting collaboratively, to review and analyze groundwater resources in the CNNF. This multiyear hydrogeological study presents an innovative approach to studying hydrogeology in an undeveloped area 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 Washburn/Great Divide Unit (fig. 1), which comprises more than 1,000 square miles ($mi^2$) in Ashland, Bayfield, and Sawyer 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 groundwater system works under current land-use and climatic conditions. The project inventoried available data and developed tools with the following goals:

- Improve the understanding of aquifer characteristics and the groundwater flow regime;
- More clearly define interactions of groundwater with surface water;
- Better identify 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 this national forest.

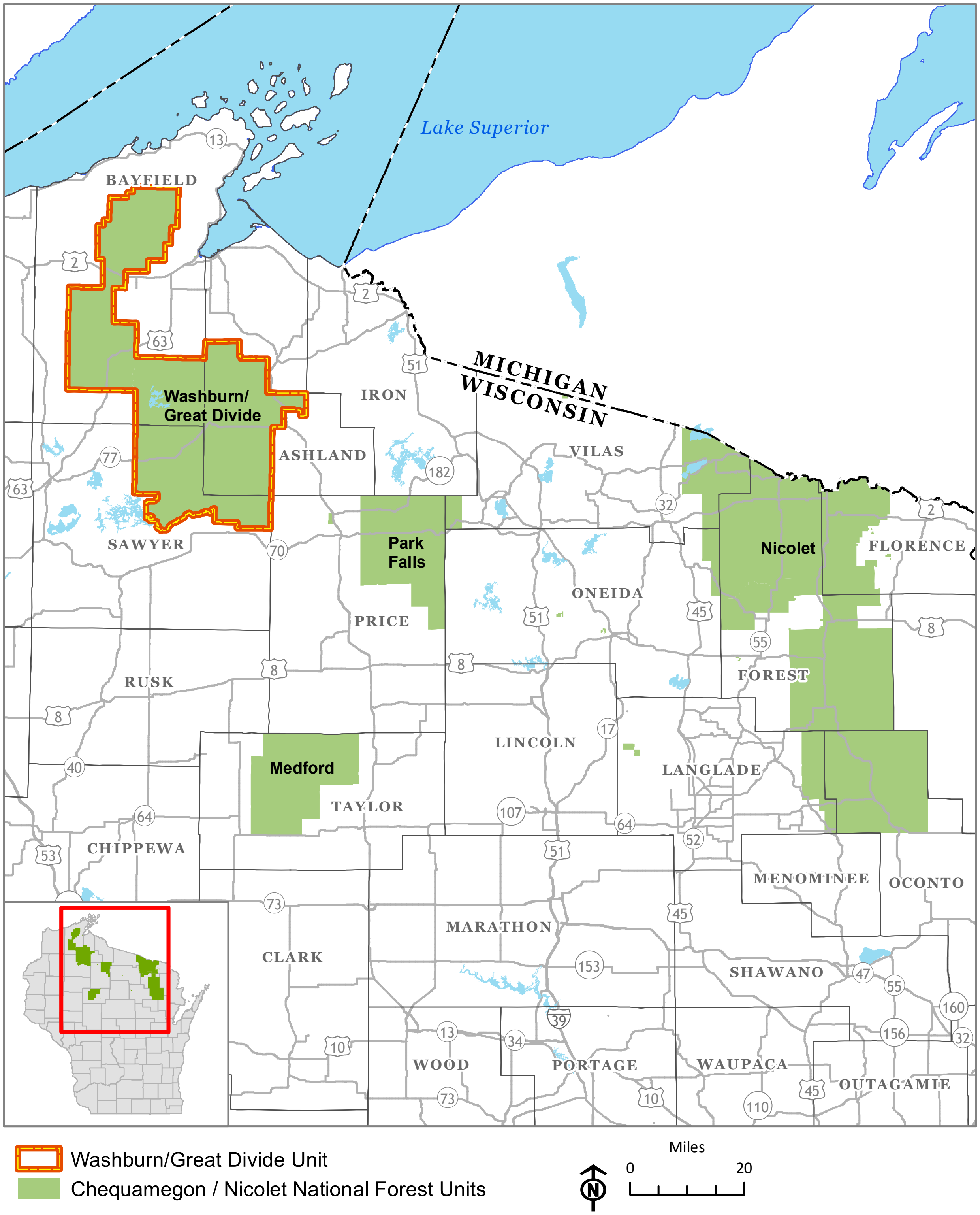
## Study approach

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

1. **Hydrogeologic data.** Inventory and interpret existing geologic and hydrogeologic data in the Washburn/Great Divide Unit, assembled into a spatial database. Results include the distribution of physical and hydraulic aquifer properties and water-use data.
2. **Groundwater potential recharge.** Construct a soil-water balance model for predicting spatial and temporal distribution of potential recharge.
3. **Geochemistry of water.** Geochemical sampling and analysis to characterize current water chemistry in the unit.
4. **Groundwater flow model.** Construction of a groundwater flow model, which can be used as a tool to develop a water-table map of current conditions and evaluate future hydrologic scenarios.

These components meet the goals of the project by summarizing key elements of the existing hydrologic system in the CNNF, which are aquifer characteristics, the distribution of potential recharge, and surface-water–groundwater interactions. The flow model provided a quantitative framework for simulating heads, flows, flow paths, and responses to potential stress. The model can be used to show general directions of groundwater flow, identify areas

**Figure 1.** Location of Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.




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.

that contribute to high-priority surface-water reaches, and evaluate baseflow contribution distributed throughout CNNF sub-basins. This study also highlights areas where more data or other types of data are needed to contribute to the understanding of the system. The analyses and models presented here are broad in scope but provide an important base from which to develop future site-specific analyses.

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

## Previous work

Regionally, a number of water-related topics have been studied in and around the CNNF, although none of these pursued a comprehensive analysis of the entire national forest. Juckem and Hunt (2007, 2008) and Lenz and others (2003) describe groundwater flow models in regions 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 national forest. 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 available for Vilas County as part of the National Science Foundation–funded Long-Term Ecological Research and the U.S. Geological Survey's Water Energy Biogeochemical Budgets site at Trout Lake, as well as models constructed in nearby Forest and Langlade Counties in support of permitting a proposed mine (the Crandon mine). WGNHS staff has mapped at 1:100,000 scale the Quaternary geology of portions of the CNNF in Florence, Forest, Langlade, Oconto, Oneida, Taylor, and Vilas Counties. These county maps contain geological unit descriptions and cross sections. Modern Quaternary mapping is available from the WGNHS at the more generalized 1:250,000 scale for Ashland, Bayfield, and limited parts of Rusk and Sawyer Counties.

Before this study, little comprehensive information was available on groundwater conditions in the Washburn/Great Divide Unit. Neither bedrock geology nor glacial geology has been mapped prior to this study in the county. A regional bedrock map of northwestern Wisconsin intersects the southern portion of the Washburn/Great Divide Unit (Mudrey and others, 1987); a statewide bedrock map covers the remainder of the unit (Mudrey and others, 1982). Cannon and others (2007) studied the iron ore deposits and associated geology of the Gogebic iron range, and Clayton (1985) mapped surficial geology in the Superior region, which contains most of the Washburn/Great Divide Unit. A portion of the unit in Sawyer County is not covered by the Clayton (1985) map; for this area glacial and surficial geology was evaluated by using larger-scale quadrangle maps from USGS (Richmond and Fullerton, 2001; 2007) or by using land type association maps available from the Wisconsin Department of Natural Resources (1999). These maps associate materials and landscapes having similar ecological characteristics.

Few regional studies of groundwater and surface water have been conducted within the unit. The USFS has actively collected ecological and surface-water data in the Washburn/Great Divide Unit, including water temperature, streamflow, and basic water quality of selected streams and lakes. Locations of springs and spring-fed surface water features, here called spring ponds, in the Washburn/Great Divide Unit were compiled as part of a statewide springs inventory (Macholl, 2007).

## Setting

The Washburn/Great Divide Unit (fig. 1) comprises nearly 1,100 square miles (mi$^2$) in Ashland, Bayfield, and Sawyer Counties, Wisconsin. Of this, approximately 900 square miles are managed by USFS. The unit is composed of two adjacent ranger districts, Washburn District in the north and Great Divide District in the south. This report refers to the whole as a unit, and to the separate areas as districts. The Washburn/Great Divide Unit is mostly forested and is characterized by numerous wetlands, springs, lakes, and streams; approximately 25 percent of the unit is covered by wetlands (Wisconsin Department of Natural Resources, 2011). The surface-water drainage divide between the Mississippi and Lake Superior basins runs roughly northwest-southeast across the center of the unit; surface water in the north drains to Lake Superior and in the south to the Mississippi River. Several regional rivers originate in the unit—the White River, Namekagon River, Marengo River, Bad River, and the East and West Forks of the Chippewa River. Surface-water streams and lakes are much more common in the Great Divide District. In this district, low-relief uplands greater than 1,500 ft in elevation transition to steeply north-sloping topography at the northern boundary. Northern Washburn District, located along the Bayfield Peninsula, is characterized by hummocky topography around 1,300 ft in elevation that drains to Lake Superior to the east and west. The climate is humid and temperate; the northwestern and north-central regions of Wisconsin that include the Washburn and Great Divide Districts receive average precipitation of 32.0 and 32.4 inches per year (in/yr), respectively (Wisconsin State Climatology Office, 2017).

## Geology

Glacial geology in the Washburn/Great Divide Unit as mapped by Clayton (1985) is shown on plates 1 and 2 and summarized in table 1. Surficial materials, which differ markedly within the unit, consist of unlithified till and outwash deposited during several glaciations between about 16,000 and 9,500 years ago. The northern Washburn District is characterized by thick sandy stream sediment of the Copper Falls Formation (units su, sc, sg; table 1, plates 1, 2). Surrounding the Washburn District, clayey till of the Miller Creek Formation (units gl, gw) dominate the lowlands near Lake Superior. The contact between these distinct deposits is marked by stream generation where the soil transitions from sand to finer-grained material. Deposits in the flatter uplands of southern Washburn District and Great Divide District primarily consist of thin (less than 100 ft thick) till and outwash deposits of the Copper Falls Formation (units sg, gg, gm). Glacial sediments range from less than 50 to hundreds of feet thick; sediments are thickest in the northern and eastern Washburn District and are thin or absent in several areas, notably in the northern Great Divide District (Clayton, 1985).

Glacial sediments overlie Precambrian igneous and metamorphic bedrock in the south and sandstones in the north (plate 3, table 2) (Mudrey and others, 1982). The oldest rock in the unit is Archean crystalline rock, located in the southern Great Divide District (plate 3, units Agr, Avo, Agn). North of the Archean bedrock, a belt of younger Proterozoic metamorphic and volcanic rocks trends east-west across the middle of the Washburn/Great Divide Unit, corresponding to high-relief topography and thin glacial deposits. This belt includes iron ore deposits associated with metasedimentary and metavolcanic rocks in northeast Great Divide (plate 3b, units Pms, Pif) as well as younger igneous rock of the Midcontinent Rift System (plate 3, units Pku, Pkl, Pkg) deposited about 1.1 Ga (Cannon and others, 2007). To the north of this belt, bedrock consists of thick sandstones associated with the Midcontinent Rift System (plate 3a, units Pbg, Pko). These sandstones, although not extensively studied, are thought to have low primary and secondary porosities and not be valuable as aquifers. The belt of igneous and metamorphic rocks

**Table 1.** Postglacial, glacial, and bedrock units that crop out in Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| | |
|---|---|
| **Postglacial deposits** | |
| sm | Stream sediment |
| p | Organic sediment |
| **Glacial deposits** | |
| **Miller Creek Formation** | |
| sp | Spillway sediment |
| b | Shoreline sediment |
| **Offshore sediment (red laminated silt and clay)** | |
| oc | Collapsed offshore sediment |
| **Till (reddish unsorted sandy silt and clay)** | |
| gl | Lake-modified glacial topography |
| gw | Wave-planed topography |
| gh | Valley sides |
| **Copper Falls Formation** | |
| **Proglacial stream sediment** | |
| su | Uncollapsed proglacial stream sediment; includes sub-units su(a-h) |
| sc | Collapsed proglacial stream sediment |
| sg | Hummocky stream sediment overlain by silty material |
| **Till (reddish brown, gravelly, clayey, silty sand)** | |
| gg | Thin mass-movement till |
| gm | Subglacially molded topography |
| gt | Glacial thrust masses |
| **Pre-Pleistocene rock (bedrock)** | |
| r | Cambrian or Precambrian bedrock |

*Modified from Clayton, 1985*

effectively divides the unit into three geologic zones: crystalline basement rock crops out to the south and sandstone to the north. This belt is referred to as a transition zone following the nomenclature of Leaf and others (2015). The potential for future hardrock prospecting and iron ore mining in the Penokee Range and volcanic rocks of Proterozoic age within or near the Washburn/Great Divide unit is one of the motivations for improving the understanding of local hydrogeology and baseline water quality in the CNNF.

**Table 2.** Subsurface bedrock units, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| Era | Unit | Description |
|---|---|---|
| Neoproterozoic or Cambrian | Pbg | Bayfield Group—Feldspathic quartzose sandstone with some orthoquartzitic sandstone |
| Mesoproterozoic | Pko | Oronto Group—feldspathic sandstone, siltstone, shale, and conglomerate |
| | Pku | Upper volcanic sequence—basalt flows and minor interbedded sedimentary rocks |
| | Pkl | Lower volcanic sequence—mafic volcanic rocks and underlying quartzite |
| | Pkg | Intrusive mafic and associated rock—gabbro, troctolite, ferrogranodiorite, granophyre, and anorthosite |
| Paleoproterozoic | Pqz | Quartzite and associated slate, dolomite, ferruginous slate, conglomerate, and chert |
| | Prg | Post-tectonic granite |
| | Pgr | Intermediate to granitic intrusive rocks |
| | Pms | Meta-argillite, meta-siltstone, quartzite, meta-graywacke, meta-conglomerate, meta-iron-formation, and marble |
| | Pif | Magnetic iron-formation |
| | Pvn | Dominantly mafic metavolcanic rocks with subordinate felsic metavolcanic rocks |
| Neoarchean | Agr | Granite and associated rocks |
| | Avo | Mafic to intermediate metavolcanic rocks and associated metasedimentary rocks |
| | Agn | Quartzofeldspathic gneiss, migmatite, and amphibolite |

*Modified from Mudrey and others, 1982*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This report is divided into chapters according 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 Kenneth R. Bradbury; Section 2, Peter R. Schoephoester; Section 3, Aaron Pruitt; Section 4, Andrew T. Leaf, Paul F. Juckem, and Randall J. Hunt; project coordination and synthesis, Anna Fehling and Kenneth R. Bradbury.

# Section 1: Hydrogeologic data

## Objectives

Initially, the WGNHS 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 (GIS) database, which contains 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), which form the primary database for the hydrogeologic study of the Washburn/Great Divide Unit, are one-page reports prepared by drillers upon the completion of any new water well in Wisconsin (plate 4, Located wells). These reports specify the well location, date drilled, owner's name, well depth, subsurface materials, and groundwater levels. They can be used to interpret spatial hydrogeologic information such as regional water levels and bedrock depth. Although the quality of different records may differ greatly, the WCRs as a group provide insight into the hydrogeology of a region. The plate also shows the locations of mapped springs and spring-fed surface water features, here called spring ponds (Macholl, 2007) and other relevant data points.

About 80 percent of the WCRs used in this study were obtained from a digital database maintained by the Wisconsin Department of Natural Resources (2016). This database, which extends back to about 1988, typically identifies wells using a Wisconsin Unique Well Number. Most WCRs filed prior to 1988 are not in the Wisconsin database but instead are stored as scanned images on file at the WGNHS. These wells generally do not have Wisconsin Unique Well Numbers but instead are identified by WGNHS image numbers, keyed to Wisconsin counties.

Using WCRs and Esri ArcGIS software, WGNHS staff prepared a GIS database for the Washburn/Great Divide Unit. Because the WCR records generally locate wells to only the nearest quarter-quarter section or to a lot number, records were manually moved to the correct location in a process called geolocation. WGNHS staff examined individual wells on aerial photographs and land ownership records, and staff digitized the most likely location of the wells in relation to visible buildings, roads, and other landscape features on the NAD 83 Wisconsin Transverse Mercator projection. The location of each well was also assigned a confidence rating. The study area extended outside the Washburn/Great Divide Unit boundary into parts of Ashland, Bayfield, Douglas, Iron, and Sawyer Counties. In all, this process located 4,698 wells in the project area to within an estimated 750 ft of their true location, the majority of which are located outside the Washburn/Great Divide Unit. Physical data associated with each of these wells were assembled in the database.

Of the 4,698 located wells within the Washburn/Great Divide Unit, about 85 percent are screened in the glacial aquifer; these wells have an average bottom depth of about 70 ft, although some are more than 300 ft deep. Of the remaining 15 percent that are screened in bedrock, the average well pumps from the top 120 ft of bedrock, although some pump from as deep as 400 ft. In the bedrock WCRs, depth to bedrock averages about 60 ft and ranges from 4 to 170 ft; the total well depth averages 170 ft and may be as deep 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, which contains detailed descriptions of lithology and stratigraphy compiled from more than 45,000 paper records of well or exploratory drilling, can also provide a valuable source of information on bedrock depth to supplement the WCRs. The data have not been peer reviewed, but they are given a higher level of confidence in rock description than WCRs and are sometimes 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. Previously published geologic maps were also used to interpret bedrock surface, such as bedrock elevation maps in the Bad River Indian Reservation east of the Washburn District (Batten and Lidwin, 1995) and geologic records of shallow bedrock published as part of glacial mapping by Clayton (1985).

### 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 Wisconsin Department of Natural Resources since 2011. As of 2014, this database contains records of 14 high-capacity wells within the Washburn/Great Divide Unit (table 3, plate 4 (note that several symbols for high-capacity wells plot on top of each other) (R. Smail, written communication, 2016). Although many high-capacity wells in Wisconsin pump at rates in the hundreds of gallons per minute, wells in this unit pump at much lower rates. Combined, these 14 wells withdraw approximately 12 million gallons of groundwater per year (equivalent to about 23 gpm, if a constant pumping rate is assumed), less than 1 percent of the approximate average unit-wide recharge rate. Most water was withdrawn from four wells, of which the most-used well pumped at an average rate of 11 gpm. All wells with available construction records are reported to be screened in the glacial aquifer and are 95 ft deep on average. Outside of the unit, high-capacity wells are slightly more common but still pump at relatively low rates. The 87 active high-capacity wells represented in the regional groundwater model (section 4) pump at an average 25 gpm and have a combined average discharge of about 2,200 gpm.

## Methods

### Interpolation of hydrostratigraphic layers

Information in the WCR database was interpolated to produce three map layers:

- Bedrock surface elevation
- Depth to bedrock
- Saturated thickness of unlithified materials

The GIS layer representing the bedrock surface was created by interpolating depth to bedrock values from WCRs and geologic records. Elevations of wells and surfaces were taken from the 10-meter (m) digital elevation model (DEM). The DEM is a raster representation of land elevation

**Table 3.** High-capacity well withdrawals in the Washburn/Great Divide Unit, 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** | | | | | | | | |
| 2117 | MJ060 | 101 | Gravel | 347,760 | 419,892 | — | — | 191,913 |
| 72198 | YG956 | 159 | Sand and gravel | — | — | 180,000 | 3,253,000 | 858,250 |
| 75454 | BF165 | 97 | Sand and gravel | 6,266,600 | 8,603,000 | 4,775,720 | 2,591,100 | 5,559,105 |
| **Private domestic supply** | | | | | | | | |
| 68575 | | 45 | Sand | 15,500 | 18,000 | 20,000 | 11,500 | 16,250 |
| 68581 | QX297 | 92 | Sand | 19,800 | 36,000 | 11,400 | 12,300 | 19,875 |
| 68577 | | No record located | | 40,000 | 32,000 | 44,000 | 40,000 | 39,000 |
| 68580 | | No record located | | 20,500 | 22,000 | 30,000 | 22,000 | 23,625 |
| 68582 | | No record located | | 16,500 | 14,000 | 26,000 | 21,000 | 19,375 |
| 68578 | QX296 | 90 | Sand | 16,000 | 28,000 | 22,000 | 18,000 | 21,000 |
| 68579 | | No record located | | 24,500 | 24,000 | 28,000 | 19,500 | 24,000 |
| 68576 | | No record located | | 32,500 | 32,000 | 34,000 | 23,000 | 30,375 |
| 68583 | | No record located | | 29,000 | 30,000 | 28,000 | 25,000 | 28,000 |
| **Golf course irrigation** | | | | | | | | |
| 68585 | TZ227 | 74 | Sand and gravel | 1,885,180 | 2,082,470 | 2,280,190 | 1,360,780 | 1,902,155 |
| 68584 | | No record located | | 4,072,670 | 5,136,640 | — | 3,189,020 | 3,099,583 |

of Wisconsin, derived from the U.S. Geological Survey's 10-m National Elevation Dataset (U.S. Geological Survey, 2013). The 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 assigned land surface elevation, wells with higher confidence in spatial location also have a higher confidence in bedrock elevation.

The bedrock surface was interpolated by 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 surface was then manually edited and refined to be consistent with local topography and landforms. This step eliminated problems such as the bedrock surface interpolated above the known land surface in areas where data points were sparse. Following this correction, the TIN surface was converted to a smooth raster grid and imported into Esri ArcMap software for contouring and plotting.

The DEM resolution, WCR location confidence, and spatial distribution of WCRs are all sources of uncertainty in developing the bedrock surface-elevation map layer. The scarcity of wells inside the Washburn/Great Divide Unit leads to large areas of little or no data. The accuracy of the map layer is unknown in these areas, whereas the accuracy increases with increasing density of data points. The bedrock-surface depiction was created to honor available data points as closely as possible. However, spatial interpolation of poorly distributed point data can lead to artificial closed contours ("bullseyes") that are purely an artifact of the process used to create the contours. These artifacts have been manually edited where the data allows but represent an uncertainty in the dataset. Subsurface exploration or more geophysical data would increase the accuracy of bedrock surface elevation in areas with few data points.

The depth-to-bedrock raster surface was calculated by subtracting the bedrock surface raster from the land surface elevation. Saturated thickness coverage was calculated by subtracting bedrock surface elevation from the water table surface obtained from groundwater flow models (section 4). Owing to the size of the unit, two groundwater flow models were developed. The output of these models was 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 include 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 be an indicator of aquifer productivity. For the Washburn/Great Divide Unit, specific capacity values were used to estimate transmissivity and horizontal hydraulic conductivity according to 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 for regional applications reasonable estimates of transmissivity and horizontal hydraulic conductivity. The TGUESS program uses parameters obtained from WCRs and aquifer thickness. Aquifer thickness for wells finished in unconsolidated materials was estimated from the saturated thickness reported for each well, calculated as the difference between the water level and the bottom of the well. For wells completed in bedrock, the aquifer thickness was set to the length of open-borehole penetration below the bedrock surface.

Wells with specific capacity measurements were sorted into two groups: wells screened in glacial (unlithified) deposits and wells screened in bedrock. Wells with missing or obviously incorrect data were removed from the analysis, as were wells with test results that appeared to be influenced by casing storage effects. The final data set contained 3,969 wells finished in unlithified materials and 646 wells finished in bedrock.

## Water-level measurements

A monitoring well in each unit measured continuous groundwater levels. Water levels for the Washburn/Great Divide Unit were obtained at monitoring wells BA-241 and BA-242 located just north of Pigeon Lake, a 200-acre seepage lake in the southern Washburn District (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 the National Water Information System (NWIS) website under site numbers 462050091202901 (BA-241) and 462047091202901 (BA-242). Records for these wells are available online at http://waterdata.

usgs.gov/wi/nwis/inventory/?site_no=462050091202901. The wells are both approximately 50 ft deep and screened in unlithified sand and gravel. Well construction information and a site sketch are in the supplemental digital data associated with this report.

Groundwater levels are also available between 1967 and 2015 for a public supply well (AS-54) located near the Village of Glidden, in Ashland County just east of the unit (plate 4b). Records for this well are available on the NWIS website: http://nwis.waterdata.usgs.gov/nwis/gwlevels/?site_no=461109090373001. The well is 73 ft deep and is screened in sand and gravel.

# Results

## Hydrostratigraphic layers

The bedrock surface in the Washburn/Great Divide Unit (plate 5) is generally about 800 ft above sea level in the north, corresponding to mapped sandstone bedrock (units Pbg, Pko; plate 3, table 2), and rises steeply to about 1,400 ft near the contact with intrusive and volcanic rocks to the south (units Pku, Pkg; plate 3, table 2). Local buried bedrock valleys eroded in sandstone may be as low as 400 ft above mean sea level. Owing to limited subsurface data, the extent of these valleys is not known.

Depth to bedrock ranges from greater than 700 ft in the western Washburn District (plate 6a) to less than 100 ft in the Great Divide District (plate 6b). Areas of deeper bedrock correspond primarily to areas of low bedrock elevation.

The saturated thickness of unlithified materials in the unit ranges from less than 50 ft to more than 600 ft. It is about 200–300 ft in the northern Washburn District, and thicker zones lie near deep bedrock valleys (plate 7a). Saturated thickness is less than 50 ft along the transition zone that commonly exposes igneous and volcanic rocks, and it is generally less than 100 ft in the southern Great Divide District (plate 7b).

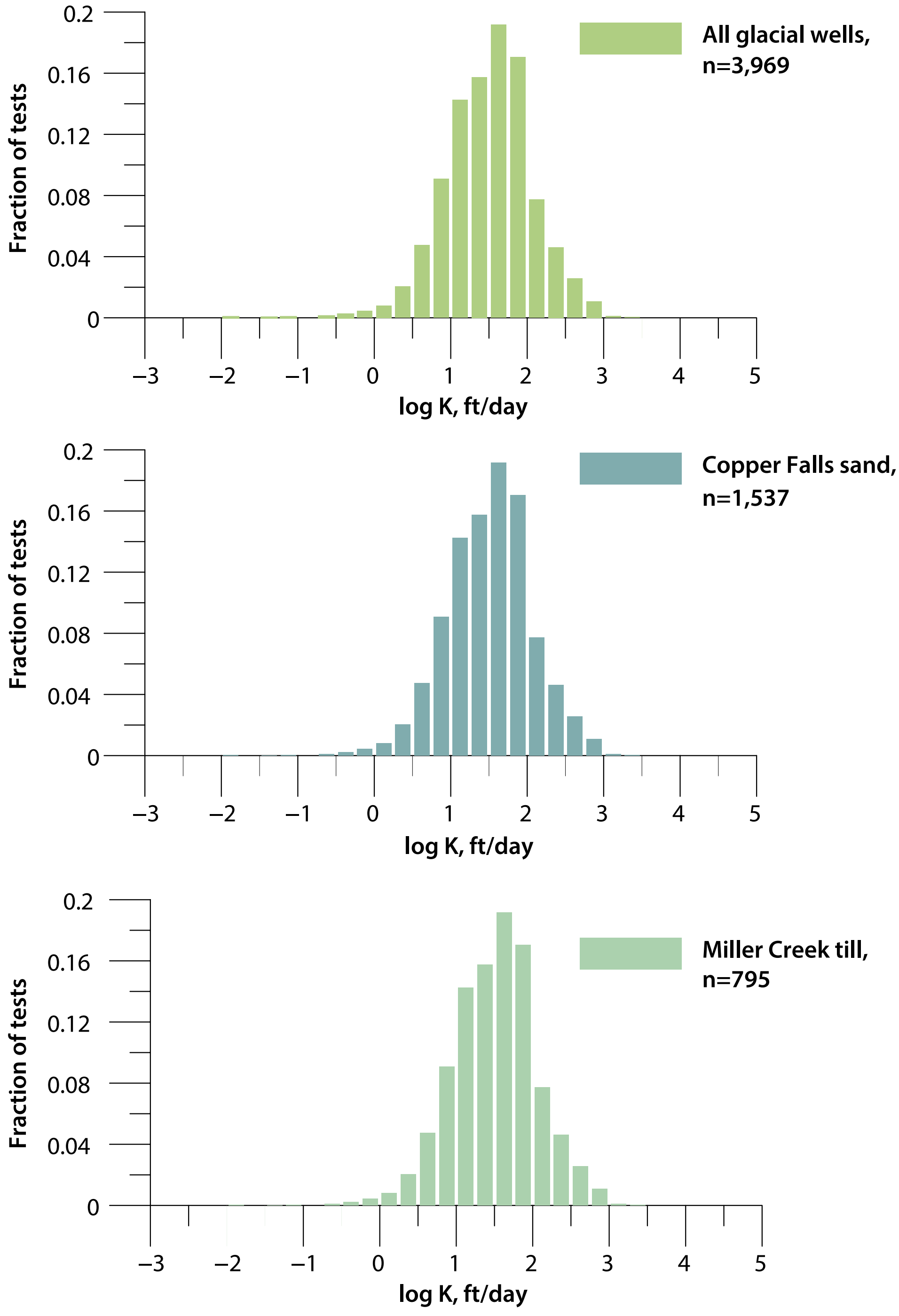
## Hydraulic properties

Plates 1–3, figure 2, and table 4 illustrate horizontal hydraulic conductivity estimates. About 85 percent of the 4,615 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 too fine (such as the Miller Creek Formation silt and clay near the Lake Superior shore), or where glacial deposits are thin or absent. More than half of the 646 analyzed bedrock wells were completed in sandstone. Because the hydraulic conductivity estimates are log-normally distributed, the geometric mean was used to evaluate the central tendency of the data. Estimated hydraulic conductivities in the glacial materials had a mean of 32 ft/d and a range of 0.02 to 1,900 ft/d (plate 3a). In general, transmissivities and hydraulic conductivities in bedrock are about an order of magnitude lower than in glacial materials; mean hydraulic conductivity is 3.0 ft/d and range is 0.003 to 9,100 ft/d (plate 3b).

On the basis of the TGUESS analysis of specific capacity reported in WCRs, the horizontal hydraulic conductivity varies between mapped glacial units (table 4, fig. 2). Wells completed in the Miller Creek Formation clay till have mean hydraulic conductivities somewhat lower than conductivities in the Copper Falls stream sediments (17 vs. 41 ft/d). The hydraulic conductivities in unlithified materials may be skewed toward higher values owing to the lack of wells completed in less permeable, finer-grained deposits. Wells completed in bedrock also show some difference in hydraulic conductivity between mapped units, especially between sandstone and crystalline rock. The sandstone in the region has not been extensively studied but appears to have very low primary or matrix porosity. Crystalline rock has a slightly higher mean hydraulic conductivity than sandstone (3.9–7.5 vs. 2.5–3 ft/d) and more clearly shows a bimodal distribution. The bimodal distribution in the volcanic and metavolcanic units is probably due to differences between matrix and fracture hydraulic conductivity in these units. Bedrock wells with very high hydraulic conductivity are probably getting substantial yield from fractures.

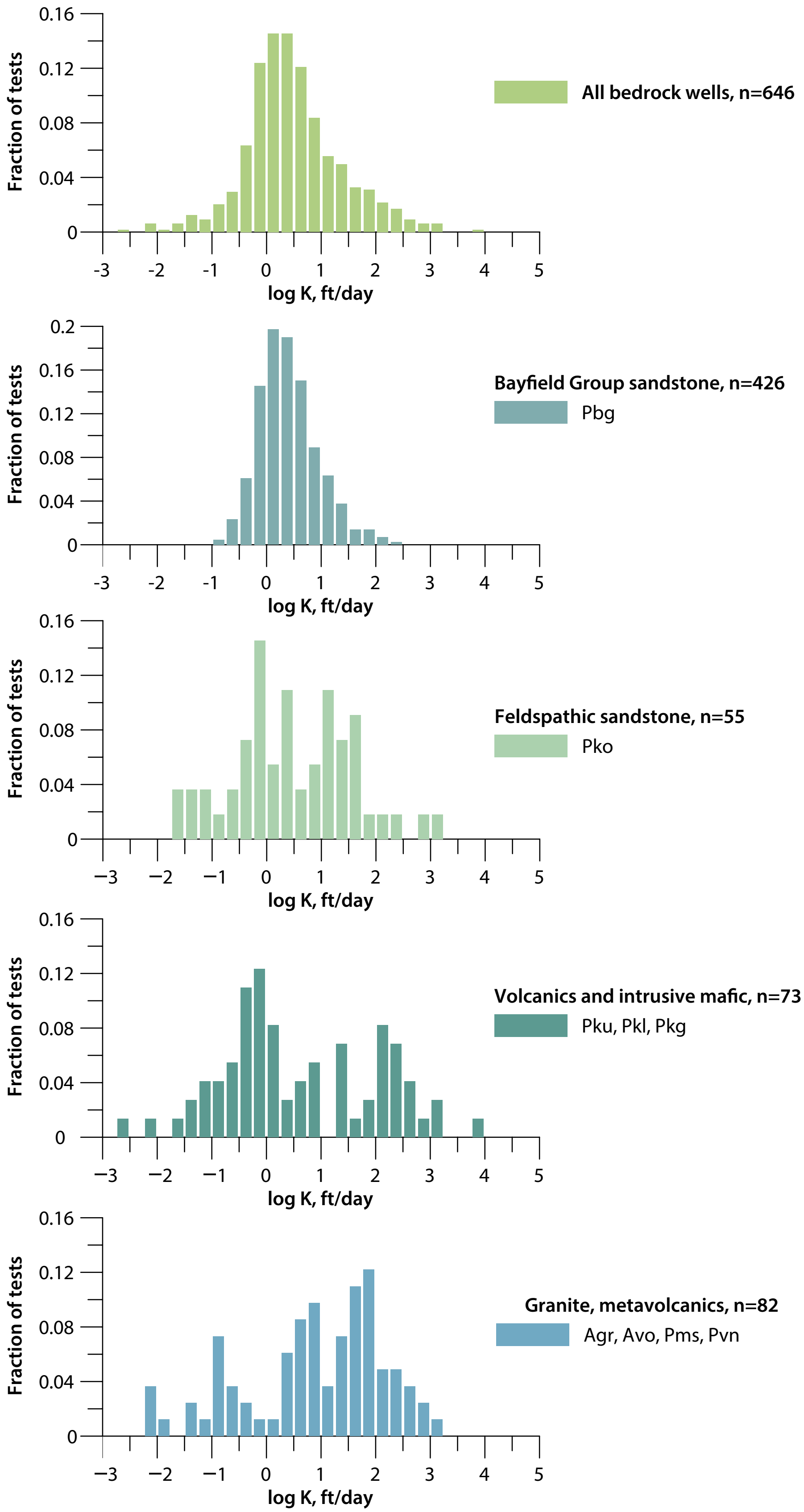
Aquifer yield depends on hydraulic conductivity and aquifer thickness. Transmissivity (plate 1), the product of the two, was therefore used to evaluate potential aquifer yield. Mean transmissivity was 1,400 $ft^2$/d in the glacial materials and 100 $ft^2$/d in the bedrock. If we assume mean transmissivity and a drawdown of 40 ft (on the basis of average aquifer thickness penetrated by analyzed wells in glacial materials), then in many places the glacial aquifer could support a typical yield of 200 gpm, above the 70 gpm minimum for high-capacity wells. Most evaluated wells in the Washburn/Great Divide Unit are in crystalline rock; a similar analysis for the crystalline bedrock aquifer using 40 ft of drawdown suggests it could support about 20 gpm. Yields of several hundreds of gallons per minute are possible in either aquifer where transmissivity is greater than about 1,000 $ft^2$/d. This analysis suggests that the glacial aquifer has the potential to support high-capacity wells in areas of higher transmissivity, but that in general those wells could not produce much more than several hundred gallons per minute. Similarly, a statewide map of probable sand and

**Figure 2a.** Hydraulic conductivity estimated from specific capacity tests of wells in unlithified materials[1], Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.




[1] *Wells in glacial materials were evaluated for two units, those mapped as clayey till and lake sand on the 1:1,000,000-scale map that covers the entire unit (Richmond and Fullerton (2001, 2007). Unit names shown on this figure indicate the correlative glacial deposit, Miller Creek till (units gu, gl, gw, gh) and Copper Falls sand (units su, sc, sg), respectively, shown on the more detailed Pleistocene map by Clayton (1985) and on plates 1 and 2 of this report.*

**Figure 2b.** Hydraulic conductivity estimated from specific capacity tests of wells grouped by bedrock type, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin. See table 2 for descriptions of bedrock units.



gravel well yields shows that in this region yields are unlikely to exceed 100 gpm, except in the Copper Falls Formation sand of northern Washburn District (Devaul, 1975). The bedrock aquifer is unlikely to support high-capacity wells unless extensive bedrock fractures are present.

Specific capacities are generally low throughout the Washburn/Great Divide Unit, suggesting 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). If we use 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 35 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 but require larger diameter wells.

### Water levels

A hydrograph of the Pigeon Lake wells BA-241 and BA-242 (plate 4a; fig. 3) from 2011 to 2015 shows the 30-day moving average of groundwater elevation and precipitation measured at the Brule climate station about 17 miles to the west (National Centers for Environmental Information (previously National Climatic Data Center), 2016). Pigeon Lake surface-water elevations were reportedly low when the wells were installed in 2011 but have begun to recover since 2013. A similar trend is visible in the groundwater levels, which rose more than 5 ft between January 2013 and January 2015. For comparison, water levels at Shell Lake, a 2,500-acre seepage lake about 50 miles to the southwest (outside this forest unit), rose about 2 ft during the same time period (City of Shell Lake, 2016).

The long-term observation well AS-54 (plate 4b; fig. 4) shows limited change during the monitored time frame between 1967 and 2012. Groundwater levels varied from about 1,510.7 to 1,511.4 ft with no overall trend. 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 leads to the following general observations.

- The glacial outwash and till deposits form a shallow aquifer with low to moderate productivity. The aquifer is relatively thin (less than 100 ft thick) in Great Divide District, thin to absent along the high-relief belt of igneous rock trending through the center of the unit, and 200 to more than 600 ft thick in northern Washburn District. The hydraulic conductivity estimated by the TGUESS method ranged from 0.02 to 1,900 ft/d; the mean was 32 ft/d.
- Bedrock beneath the glacial materials, generally consisting of sandstone in the north and crystalline rock in the south, can supply adequate water to low-capacity wells in areas where the glacial deposits are too thin or too fine grained. In general, hydraulic conductivities in the bedrock aquifer are about an order of magnitude lower than in the overlying glacial deposits. Wells with very high hydraulic conductivity in bedrock are likely getting yield from fractures.
- The glacial aquifer has the potential to support high-capacity wells with an approximate average potential yield of 200 gpm. The crystalline bedrock aquifer, which has an approximate average potential yield of 20 gpm, is unlikely to support high-capacity wells.
- About 85 percent of the 4,615 evaluated wells within the Washburn/Great Divide Unit are screened in the glacial aquifer; these wells have an average depth of about 70 ft. The average bedrock well pumps from the top 120 ft of bedrock, although some pump from nearly 400 ft deep.
- Only 14 high-capacity wells are active within the Washburn/Great Divide Unit, and few are in the region generally. High-capacity wells in the unit with available construction records are screened in the glacial aquifer and are 95 ft deep on average; although these wells are permitted to pump at rates greater than 70 gpm, the total combined pumping in the unit is only 23 gpm. In the broader region represented in the regional groundwater model (section 4), high-capacity wells pump at an average 25 gpm.
- Subsurface data within the Washburn/Great Divide Unit are sparse, and additional data collection would improve the understanding of these groundwater resources. Large areas of the Washburn/Great Divide unit are nearly devoid of subsurface hydrogeologic data—in particular, the higher elevation sand barrens west of the Village of Washburn in the Washburn District or throughout much of the eastern Great Divide District north and south of the Village of Clam Lake (plates 4a, 5a). As a result, bedrock elevations and aquifer thicknesses are poorly known in these areas (see plates 5, 7). Additionally, modern Pleistocene geologic mapping may reveal spatial patterns in hydraulic properties that are not currently clear.

**Table 4.** Summary of hydraulic estimates in unlithified materials and bedrock, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin

| | Hydraulic estimates | | |
|---|---|---|---|
| | Minimum | Maximum | Geometric mean |
| **Wells in unlithified deposits** | | | |
| **All wells (n = 3,969)** | | | |
| Transmissivity ($ft^2/d$) | 3 | 180,000 | 1,400 |
| Conductivity (ft/d) | 0.02 | 1,900 | 32 |
| Specific capacity (gpm/ft) | 0.01 | 60 | 0.8 |
| **Miller Creek till (n = 795)** | | | |
| Transmissivity ($ft^2/d$) | 3 | 49,000 | 890 |
| Conductivity (ft/d) | 0.02 | 470 | 17 |
| **Copper Falls sand (n = 1,537)** | | | |
| Transmissivity ($ft^2/d$) | 48 | 110,000 | 1,700 |
| Conductivity (ft/d) | 0.4 | 1,100 | 41 |
| **Wells in bedrock** | | | |
| **All wells (n = 646)** | | | |
| Transmissivity ($ft^2/d$) | 0.8 | 11,000 | 100 |
| Conductivity (ft/d) | 0.003 | 9,100 | 3 |
| Specific capacity (gpm/ft) | 0.004 | 40 | 0.5 |
| **Bayfield Group sandstone (n = 426)** | | | |
| Transmissivity ($ft^2/d$) | 10 | 3,200 | 120 |
| Conductivity (ft/d) | 0.1 | 220 | 2 |
| **Feldspathic sandstone (n = 55)** | | | |
| Transmissivity ($ft^2/d$) | 0.8 | 4,000 | 50 |
| Conductivity (ft/d) | 0.03 | 1,300 | 3 |
| **Volcanic and intrusive mafic rock (n = 73)** | | | |
| Transmissivity ($ft^2/d$) | 1 | 11,000 | 98 |
| Conductivity (ft/d) | 0.003 | 9,100 | 4 |
| **Granite and metavolcanic rock (n = 82)** | | | |
| Transmissivity ($ft^2/d$) | 2 | 3,600 | 77 |
| Conductivity (ft/d) | 0.007 | 1,200 | 8 |

**Figure 3.** Hydrograph of monitoring wells BA-241 and BA-242 near Pigeon Lake showing 30-day running average water-table elevation, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin; bar graph records monthly precipitation at Brule climate station (location on fig. 5).

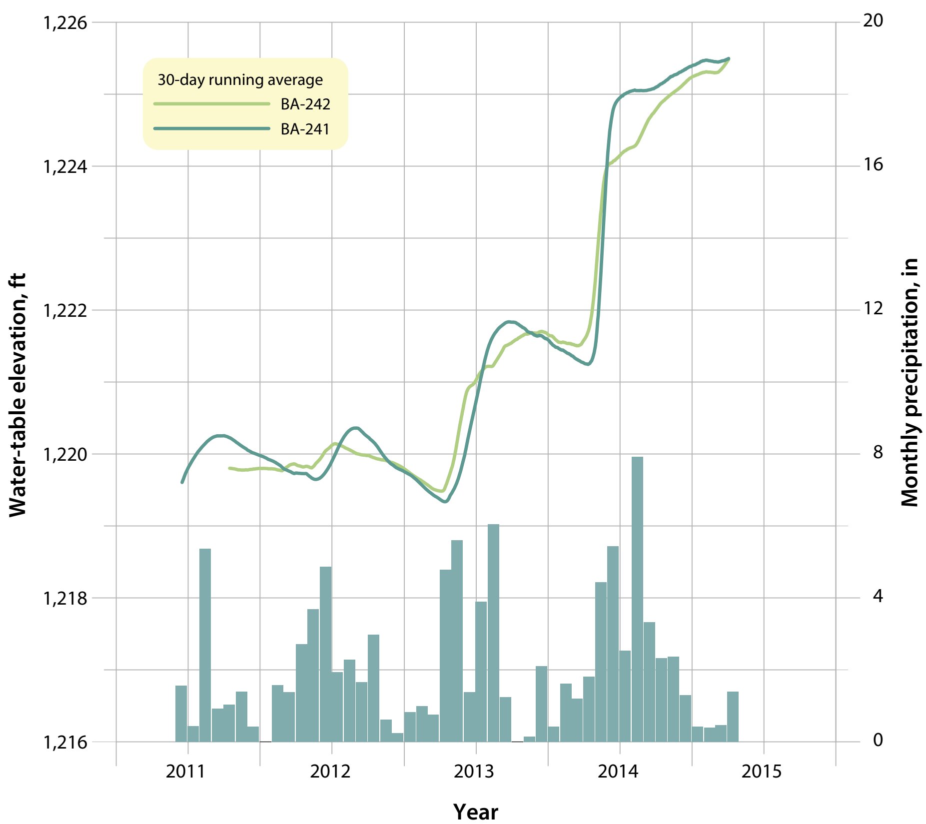
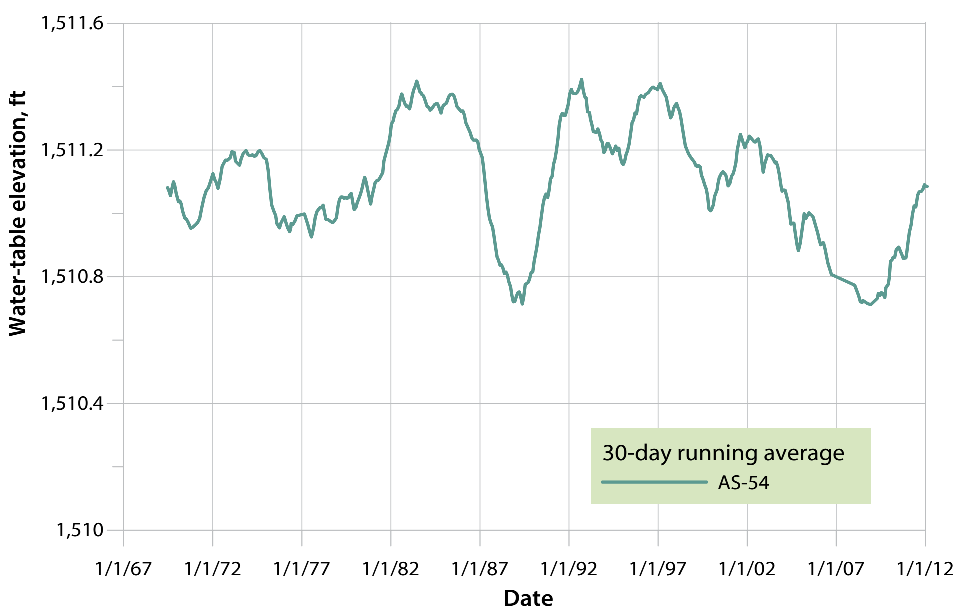



**Figure 4.** Hydrograph of monitoring well AS-54, near Glidden, Wisconsin, showing 30-day running average water-table elevation, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.



# Section 2: Potential recharge to groundwater

## Objectives

As part of this study, the WGNHS used a soil-water balance (SWB) model to model the hydrology of 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 in the Washburn/Great Divide Unit of deep drainage, here called potential recharge. The primary output is a summary map showing the general distribution of potential recharge in the Washburn/Great Divide Unit. The electronic files produced by this analysis are included in the file geodatabase discussed in section 1 (see Data availability).

Results of the SWB model also provided an input for the groundwater flow model (section 4). During flow model calibration the potential recharge grid was modified using a multiplier. This direct recharge input 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 an SWB model (Westenbroek and others, 2010) to an area encompassing the Washburn/Great Divide Unit. Figure 5 shows the model extent: an area of some 3,000 mi$^2$ covering the unit and all intersecting watersheds of the 12-Digit Watershed Boundary Dataset (Natural Resources Conservation Service, 2011a).

The model estimates the distribution of potential groundwater recharge through time by using a modified Thornthwaite-Mather method to track soil moisture storage and flux 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 according to 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, based on 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; and

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

The model calculates runoff from each cell (outflow) and routes it to adjacent cells (inflow) in 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), is removed from the model. Runoff is also removed when it reaches a surface water body; cells with 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 each time step, the SWB code does not allow ponding. Water in closed depressions in the flow-direction grid is removed primarily by recharge, and small areas of unrealistically high recharge may result. However, all closed depressions were removed from this model (see Data sources – Flow direction, below). To account for model assumptions that may result in local instances of unrealistically high recharge values, infiltration rates were limited to 100 in/day.

### 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 on a 30-m DEM from the USGS 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 most appropriate for 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 30-m DEM before the final calculation of the flow-direction input grid.

Following construction of the model, it became apparent that the DEMs available at the time of modeling have processing artifacts in the outwash deposits of northern Washburn District that display as a somewhat linear, hummocky fabric superimposed on the landscape. The affected area does in reality have hummocky topography and contains many true closed depressions. On the basis of an updated review of the corrected 2012 10-m DEM, these depressions account for approximately 22 percent of the model area. Areas of the model not on collapsed proglacial stream sediment and hummocky stream sediment have closed depressions accounting for approximately 7 percent of the area. Removing true closed depressions can result in lower modeled values of potential recharge, but the true closed depressions are located in sandy soils and the removal of these depressions did not appear to reduce potential recharge results.

### 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 datasets input into the SWB model—hydrologic group and available water storage (Natural Resources Conservation Service, 2011b). The hydrologic group, which is a classification of the infiltration potential of a soil map unit, is used in the SWB model runoff calculations. The primary categories range from A to D, representing low runoff potential 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. Because any infiltration in this situation would ultimately be available downslope as runoff through artificial drainage, 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

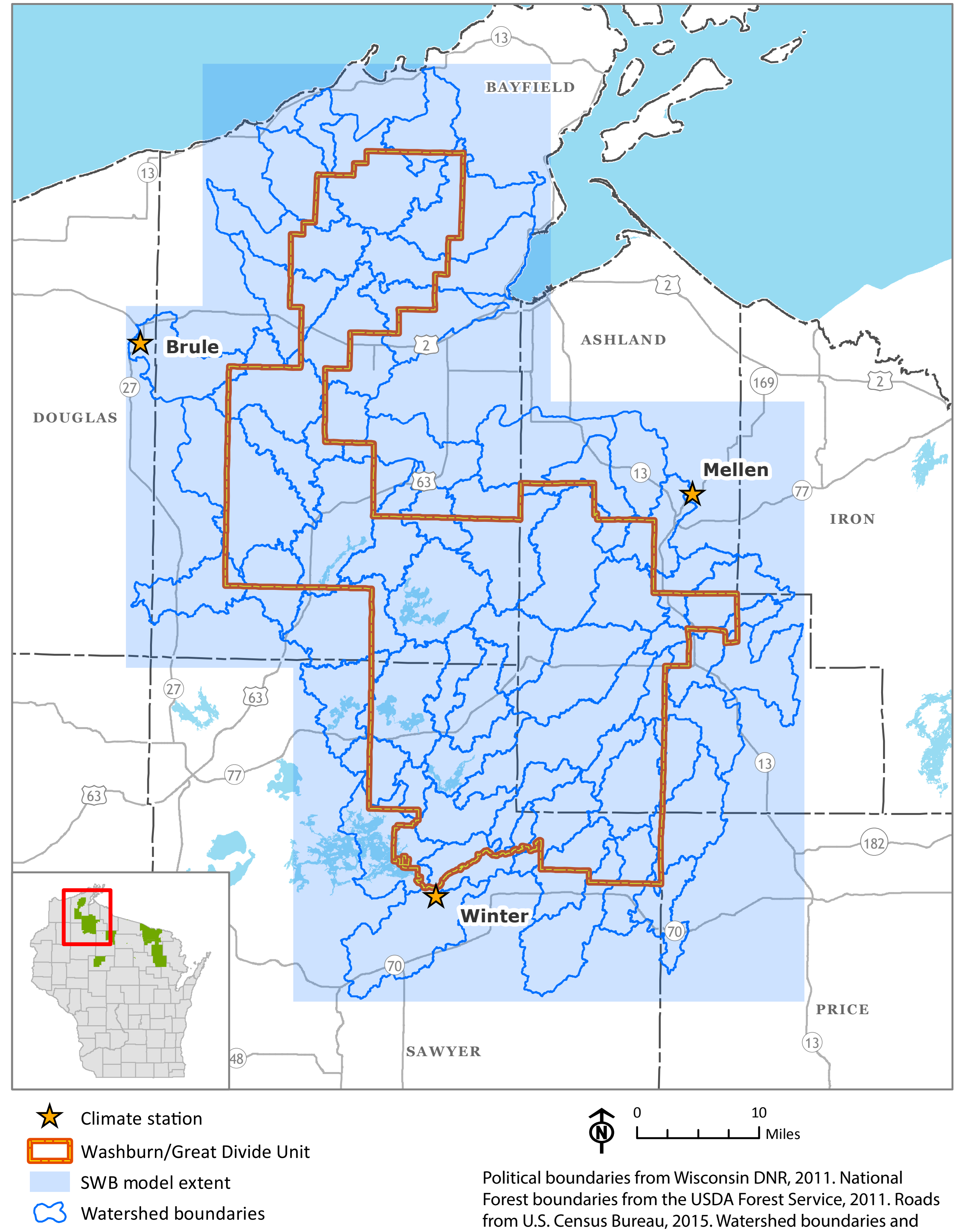
The WISCLAND dataset (Wisconsin Department of Natural Resources, 1998) provides land cover data for the model area. These data are used in calculations of interception, runoff, and evapotranspiration, and to estimate the depth of vegetation root zones. Although more recent land cover datasets are available, WISCLAND categories have already been parameterized for use in the SWB model (Westenbroek and others, 2010). Moreover, land-use patterns in the model area have changed little since the WISCLAND dataset was collected.

### 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, several stations provided climate inputs. A review of climate records from the National Centers for Environmental Information (2016) found that three stations in or near the model domain provided relatively complete records and a spatial distribution that encompassed much of the Washburn/Great Divide Unit. The model's extent was subdivided on the basis of proximity to the three stations, and each subdivision received climate data from the nearest station, Brule, Mellen, or Winter (station 0471131, 0475286, or 0479304, respectively) (fig. 5). Gaps in the records of these three primary stations were supplemented with data from other nearby stations.

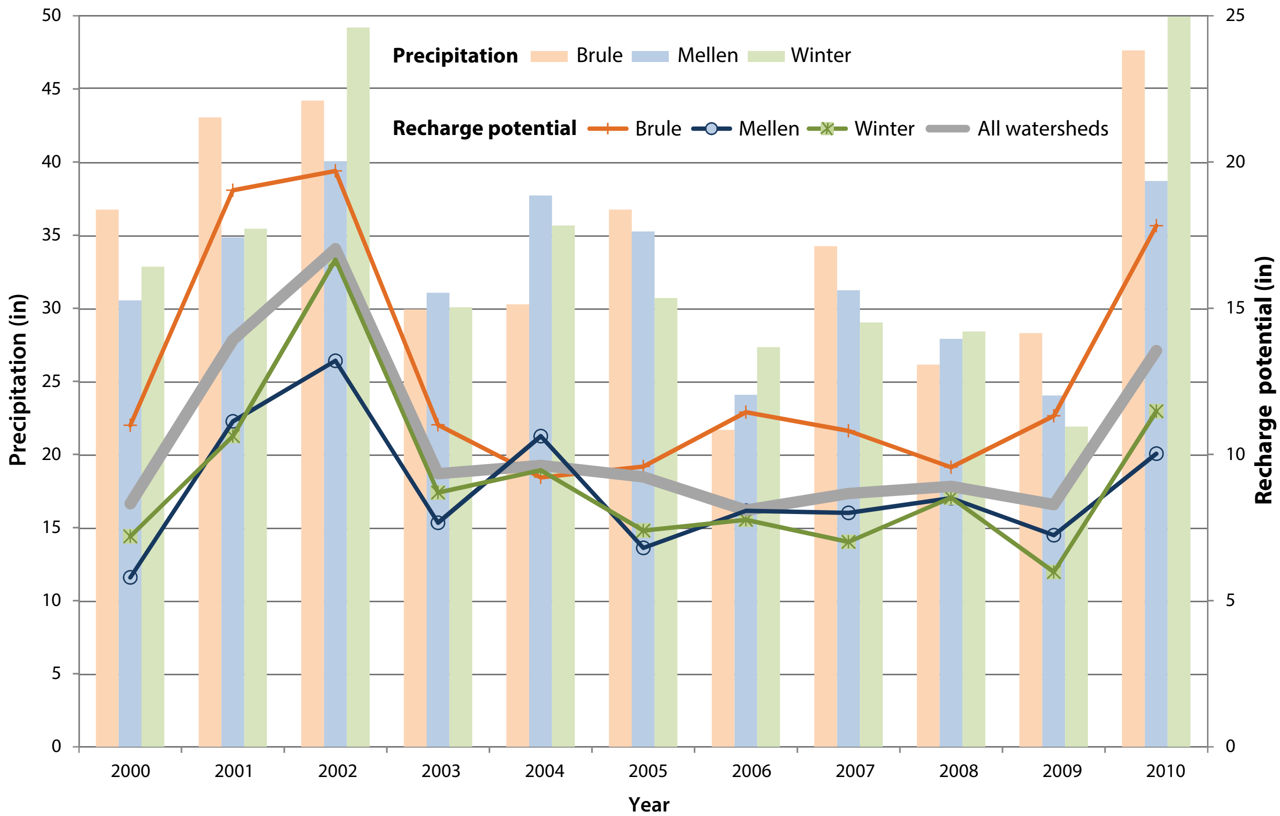
The simulation period of the model, years 2000–2010, represents recent climate conditions while also showing variability in total annual precipitation (fig. 6). Variable precipitation leads to variable recharge to the groundwater system; selecting a model period with higher variability in precipitation can give an indication of the long-term variability in potential recharge. The same time period was used for all four CNNF units after we compared the four units' precipitation statistics. The goal was a single, recent, and relatively short time period that represented the average and extremes of a longer time period. The record at the Winter station was most complete; its average precipitation was 32 in/yr and its range was 18 to 50 in/yr during the period 1950–2010. Moreover, the recent period of 2000 to 2010 showed a similar average (33 in/yr) and some of the same variability (22–50 in/yr). These annual averages compare favorably with the 30-year average precipitation (32.0 and 32.4 in/yr) in the northwestern and north-central regions of Wisconsin (Wisconsin State Climatology Office, 2017).

**Figure 5.** Map showing boundary of soil-water balance model covering Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.




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.

**Figure 6.** Graph of total annual precipitation and mean potential recharge at three climate stations near Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.




## Running the soil-water balance 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 tabulated for the three climate stations. The full model extent was subdivided, and three 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 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 model's full 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 in the Washburn/Great Divide Unit.

The mean potential recharge simulated within the model domain for the period 2000 through 2010 was 10.4 in/yr (mean, 12.4 in the Washburn District and 9.3 in the Great Divide District). See table 5 for average simulated values of each parameter in the water balance equation. The average values (table 5) are consistent with other reported recharge values for these and nearby areas (for example, fig. 2 in Gebert and others, 2011; table 3 in Juckem and Robertson, 2013; fig. 12 in Leaf and others, 2015; Lenz and others, 2003; and reported modeled values from Hunt and others, 2010). The SWB results were adjusted during groundwater flow modeling to produce a calibrated recharge map (plate 8).

As the groundwater model was developed (section 4), the SWB model grid was adjusted to calibrate to groundwater flow model targets (water levels and stream baseflows). This adjustment changes the magnitude of recharge while maintaining the spatial distribution of SWB results. The SWB grid was down-sampled, or generalized, for import into the groundwater flow model. As described in section 4 of this report, two groundwater flow models were created, one each for the Washburn District and Great Divide District. The recharge multipliers were 0.97 and 0.90, respectively, resulting in modeled mean recharge values of 11.1 in/yr and 8.8 in/yr (table 6). Plates 8a and 8b depict the calibrated mean annual groundwater recharge for the Washburn and Great Divide Districts, respectively. Groundwater flow model calibration is discussed in more detail in section 4.

The general trend in the distribution of recharge throughout the units seems to correlate with surficial geology through soil characteristics and, to a lesser extent, land cover. Plate 8a (Washburn District) shows broad variability in recharge: very high on the outwash barrens of the northern part of the unit (Copper Falls Formation stream sediment), more moderate on the Copper Falls till in the southern part, and lower over the Miller Creek Formation clay till plains both east and west of the unit. Plate 8b (Great Divide District) overall shows more moderate recharge marked by local areas of higher recharge over sandy soils and forest cover and lower recharge over finer soils and wetland cover. This pattern is consistent with what is known about 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. It is a common misconception that wetlands are always groundwater recharge areas, when in fact they are commonly areas of discharge or low recharge.

Although some local recharge rates are higher than is typically considered appropriate for large-scale areal groundwater recharge, these rates may be reasonable for the high-elevation sand barrens in the north-central part of the Washburn District, which lacks an integrated surface-water runoff system; plate 8a displays these values as greater than 15 in/yr.

The SWB 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 results contain more detail in spatial resolution than the calibrated recharge. They also include yearly grids of potential recharge and its variability from 2000 to 2010 (fig. 6). This graph shows total annual precipitation for the three principal stations used in this study, along with average potential recharge throughout each of the model subdivisions.

**Table 5.** Approximate average water balance values for years 2000–2010[1] used in soil-water balance model, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| Water balance parameter | Average value (in/yr) | | |
|---|---|---|---|
| | Unit-wide | Washburn | Great Divide |
| Precipitation | 33 | 33 | 33 |
| Interception | 1 | 1 | 1 |
| Runoff from grid | 2 | 3 | 2 |
| Evapotranspiration | 15 | 14 | 16 |
| Recharge | 10 | 11 | 9 |
| Runoff to surface water[2] | 5 | 4 | 5 |

*[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.*

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

| Scenario | Recharge (in/yr) | | |
|---|---|---|---|
| | Entire unit | Washburn | Great Divide |
| Original model (includes wetland recharge) | 10.4 | 12.4 | 9.3 |
| Assuming zero wetland recharge | 9.5 | — | — |
| Calibrated to GFLOW model (by using multiplier of 0.9 and 0.97)[1] | N/A | 11.1 | 8.8 |

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.*

Annual potential recharge, which is correlated with precipitation, varied from 5.8 to 19.7 in/yr during the 11 years 2000 to 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 SWB 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 and stores or redistributes large volumes of groundwater.

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. The Washburn/Great Divide Unit contains about 18 percent wetlands (by land use), mostly in Great Divide; but determining which of these wetlands contribute to recharge was outside the scope of this study. We therefore assumed that, in the Washburn/Great Divide Unit, zero recharge in wetlands produces an average potential recharge of 9.5 in/yr. However, it is likely that recharge in wetlands is actually greater than zero. Including simulated wetland, recharge produces a unit-wide average of 10.4 in/yr, and so the SWB-simulated unit-wide average potential recharge is likely between 9.5 and 10.4 in/yr (table 6). The lower value, which was calculated on the assumption of no recharge in wetlands, is nearer to the GFLOW-adjusted mean recharge of 8.8 and 11.1 in/yr for Great Divide and Washburn Districts, respectively.

Although true closed depressions exist in the model domain, all of these depressions were filled to improve the functionality of the flow-direction grid, which can lead to underestimates of potential recharge. However, even with removal of closed depressions, SWB still reported high values of potential recharge due to the sandy terrain in areas of hummocky topography. Additionally, the SWB model does not account for dewatering in pits and quarries, which affects recharge in these areas. The few gravel pits present 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

In the third part of this study of Washburn/Great Divide Unit hydrogeology we inventoried surface water and groundwater quality. WGNHS staff conducted a water sampling program in the Washburn/Great Divide Unit during 2012 in order to characterize current water chemistry in the unit. Water samples were collected from groundwater wells, spring ponds, streams, and lakes. They were analyzed for major ions, 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; it is not intended to be a comprehensive record of the geochemistry of the Washburn/Great Divide Unit. The sample site locations and laboratory results are included in the file geodatabase (see Data availability).

## Methods

### Selection of sampling sites

Sampling sites were selected after an initial field reconnaissance in April 2012. During this reconnaissance we scouted for access to sites and measured pH and electrical conductivity in the field at 30 sites (table 7). Later, in September 2012, we collected samples at 40 well, spring pond, stream, and lake sites in the unit, including some of the sites sampled earlier for field parameters (table 8). Figure 7 shows the location of all these sites. The final sample selection contained 16 wells, 1 spring pond, 9 groundwater-dominated streams, 5 surface-water-dominated streams, and 9 lakes. The wells selected for groundwater sampling are operated by the USFS at campgrounds and picnic areas. The sample from the spring pond was obtained as near to the spring discharge point as possible. Samples from streams were usually obtained at or just upstream of road crossings. Streams that were selected for sampling had been classified by the USFS according to its dominant water source, groundwater or runoff, on mean annual maximum water temperature and mean alkalinity at baseflow (D. Higgins, written communication, 2011). Samples from lakes were obtained at or near boat ramps or footpath access points. Figure 7 shows all sampling points in the Washburn/Great Divide Unit, and table 9 contains information about the specific wells sampled. On the basis of available records, the wells range from about 80 to more than 300 ft deep and are open to the glacial aquifer.

### Sampling procedures

Samples were collected in September 2012. Groundwater samples were collected directly from hand pumps permanently installed on USFS wells or by bailers in wells without hand pumps. One well volume was purged prior to sampling. Samples from streams, lakes, and the spring pond were collected by dipping a sampling bottle directly into the water. Samples were collected in prepared bottles provided by the laboratory. For ion samples, three containers were used. For major cations and anions, including Ca, Mg, Na, and Cl, the water was passed through a membrane filter with 0.45-micron (µm) pore size and stored in 15 milliliter (ml) vials pre-acidified with nitric acid. A second, filtered sample for nutrients was placed into 125-ml polyethylene bottles pre-acidified with HCl. A third, unfiltered, sample for alkalinity was placed in a non-acidified 125-ml polyethylene bottle. At each site, an unfiltered sample for isotopic analysis was placed in a separate 250-ml polyethylene bottle. All samples were immediately placed on ice in coolers in the field. Geochemical samples were transported to the laboratory within 48 hours of sampling. Isotopic samples were refrigerated at the WGNHS prior to shipment to the laboratory.

### Analytical procedures

For all samples, temperature, pH, electrical conductivity, and dissolved oxygen were measured in the field immediately after sampling using electronic field meters.

Major ions, nutrients, and laboratory alkalinity were analyzed at 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

Groundwater and surface water in the Washburn/Great Divide Unit are dominantly of the Ca-Mg-$HCO_3$ type. Concentrations of most dissolved ions are relatively low, as is common in a crystalline bedrock terrane beneath a cover of unlithified noncarbonate sediment. Electrical conductivity is commonly used to estimate total dissolved solids and, on the basis of electrical conductivity values generally 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 distributions of relative ion concentrations (fig. 8). Groundwater is distin-

**Table 7.** Water chemistry field analyses, April 2012, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| Site name | Site number | Date sampled | pH | Conductivity (µS/cm) |
|---|---|---|---|---|
| **Groundwater-dominated stream[1]** | | | | |
| Shunenberg Creek | 27 | 4/12/12 | 7.8 | 155 |
| Twentymile Creek at FR 377 | 31 | 4/11/12 | 7.4 | 123 |
| Venison Creek at FR 177 | 37 | 4/11/12 | 7.0 | 105 |
| Venison Creek at FR 174 | 38 | 4/11/12 | 6.6 | 59 |
| Johnson Springs Culvert | 106 | 4/12/12 | 7.7 | 302 |
| Eighteenmile Creek at FR 213 | 107 | 4/12/12 | 7.5 | 110 |
| East Branch Eighteenmile Creek at FR 213 | 108 | 4/12/12 | 7.6 | 102 |
| Morgan Creek | 110 | 4/12/12 | 7.6 | 104 |
| Morgan Falls, base | 111 | 4/12/12 | 7.4 | 85 |
| Upper Marengo River at FR 194 | 116 | 4/11/12 | 7.0 | 93 |
| Marengo River near FR 617 | 117 | 4/11/12 | 7.2 | 109 |
| **Lake** | | | | |
| Horseshoe Lake | 46 | 4/12/12 | 6.9 | 18 |
| Black Lake outlet | 49 | 4/11/12 | 6.6 | 58 |
| Hoist Lake | 101 | 4/12/12 | 7.2 | 16 |
| Unnamed seepage at Hwy E | 102 | 4/12/12 | 6.8 | 56 |
| Unnamed seepage at Star Lake Rd | 103 | 4/12/12 | 5.9 | 51 |
| Anodonta Lake | 104 | 4/12/12 | 6.9 | 177 |
| Anodonta Lake outlet | 105 | 4/12/12 | 7.3 | 200 |
| Perch Lake | 11 | 4/12/12 | 6.8 | 25 |
| **Spring pond** | | | | |
| Johnson Springs | 26 | 4/12/12 | 7.7 | 286 |
| Venison Springs | 119 | 4/11/12 | 7.4 | 182 |
| **Surface-water dominated stream[1]** | | | | |
| Fishtrap Creek at Hwy GG | 29 | 4/11/12 | 5.7 | 31 |
| Log Creek at FR 161 | 39 | 4/11/12 | 4.6 | 42 |
| Tributary to Whiskey Creek at FR 198 | 109 | 4/12/12 | 7.5 | 107 |
| Chippewa River at FR 162 | 113 | 4/11/12 | 6.4 | 103 |
| Chippewa River at Hwy GG | 114 | 4/11/12 | 6.7 | 87 |
| Unnamed Stream at FR 164 | 115 | 4/11/12 | 5.7 | 30 |
| Whiskey Creek at FR 194 | 118 | 4/11/12 | 7.7 | 64 |
| **Well** | | | | |
| Dug well at St Peter's Dome | 112 | 4/12/12 | 7.1 | 59 |

Abbreviation: µS/cm = microsiemens per centimeter

[1] *Streams classified by the U.S. Forest Service.*

**Figure 7a.** Water sampling sites in Washburn District of Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin

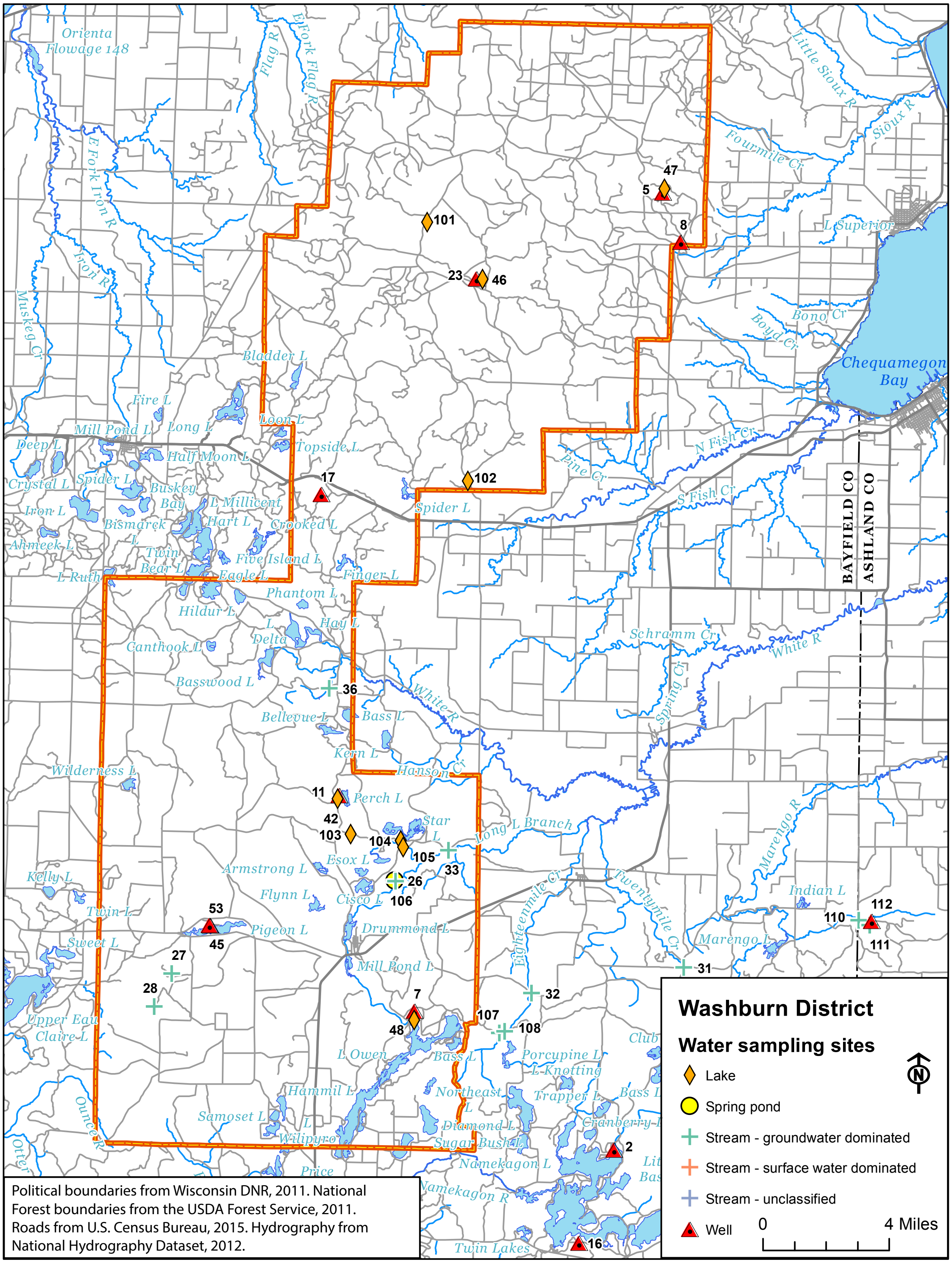


**Figure 7b.** Water sampling sites in the Great Divide District of Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

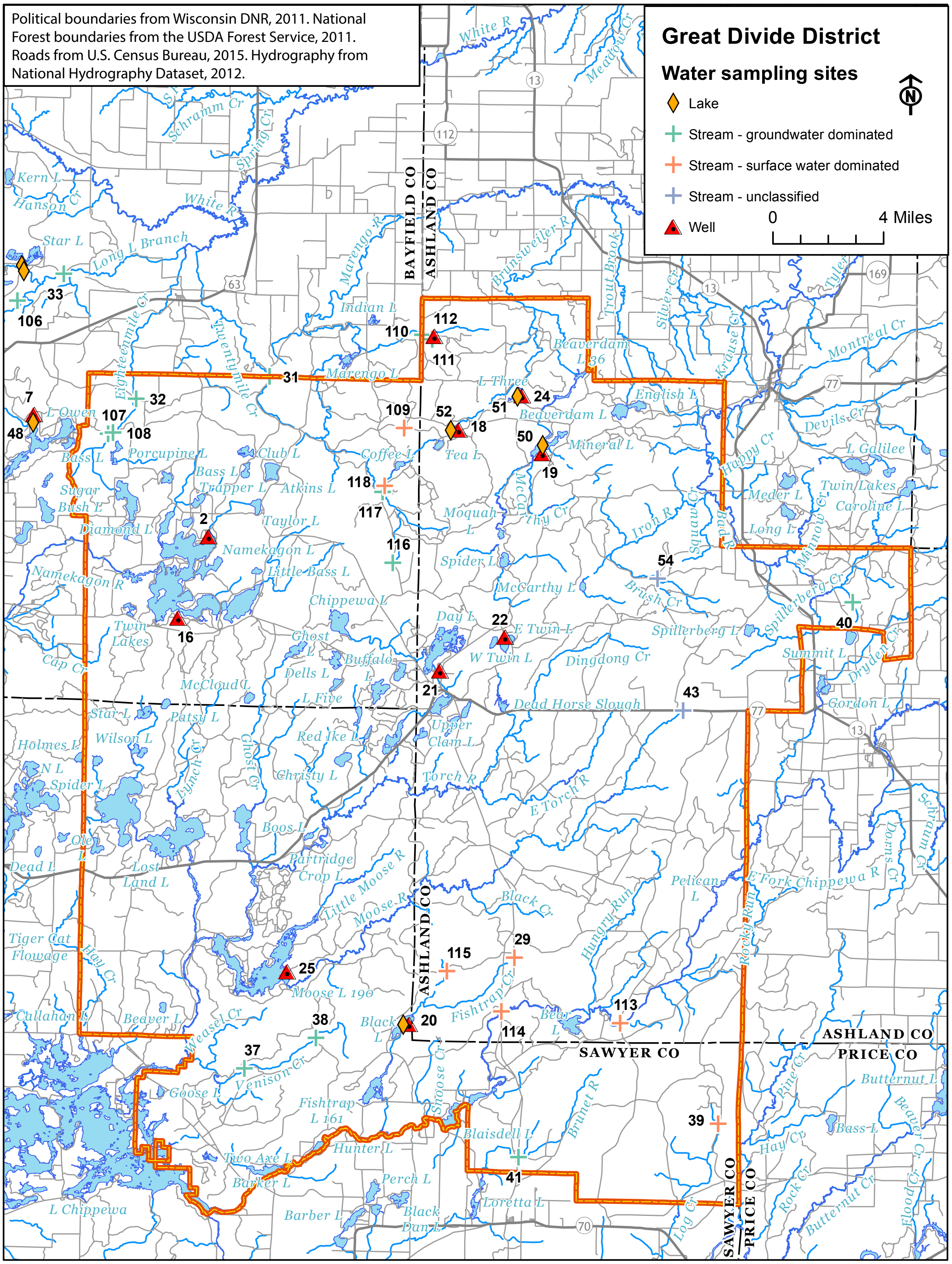


**Table 8.** Water chemistry field analyses, September 2012, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| Site name | Site number | Date sampled | Temp. (°C) | Conductivity (µS/cm) | Alkalinity mg/l $CaCO_3$ | Dissolved oxygen (mg/L) | pH |
|---|---|---|---|---|---|---|---|
| **Groundwater-dominated stream[1]** | | | | | | | |
| Shunenberg Creek | 27 | 9/15/2012 | 17.8 | 150 | 68 | 10.0 | 7.7 |
| Bearsdale Creek | 28 | 9/15/2012 | 16.3 | 152 | 68 | 11.5 | 8.3 |
| Twentymile Creek at FR 377 | 31 | 9/16/2012 | 15.4 | 160 | 56 | 10.5 | 7.5 |
| Eighteenmile Creek | 32 | 9/15/2012 | 14.7 | 174 | 80 | 9.4 | 8.1 |
| Long Lake Branch | 33 | 9/15/2012 | 13.1 | 261 | 128 | 9.6 | 8.3 |
| South Fork White River | 36 | 9/14/2012 | 12.9 | 194 | 88 | 9.2 | 8.2 |
| Venison Creek at FR 177 | 37 | 9/16/2012 | 12.9 | 195 | 104 | 8.5 | 7.7 |
| Venison Creek at FR 174 | 38 | 9/16/2012 | 10.4 | 38 | 100 | 5.9 | 7.6 |
| Knab Creek | 40 | 9/17/2012 | 12.2 | 190 | 100 | 8.3 | 7.5 |
| Brunet River | 41 | 9/16/2012 | 16.3 | 188 | 84 | 6.4 | 7.2 |
| **Lake** | | | | | | | |
| U.S. Forest Service head-quarters, Wanoka Lake | 17 | 9/14/2012 | 8.5 | 168 | 36 | 7.7 | 8.0 |
| Perch Lake | 42 | 9/14/2012 | 21.3 | 67 | 12 | 1.9 | 7.4 |
| Horseshoe Lake | 46 | 9/14/2012 | 19.8 | 26 | 8 | 8.1 | 8.1 |
| Twin Lakes | 47 | 9/14/2012 | 14 | 21 | 12 | 8.1 | 7.2 |
| Lake Owen | 48 | 9/15/2012 | 17.7 | 22 | 64 | 9.7 | 8.1 |
| Black Lake | 49 | 9/16/2012 | 18.3 | 152 | 40 | 6.4 | 7.4 |
| Mineral Lake | 50 | 9/17/2012 | 16.9 | 73 | 32 | 7.1 | 7.2 |
| Lake Three | 51 | 9/16/2012 | 19.7 | 72 | 28 | 8.6 | 7.3 |
| Beaver Lake | 52 | 9/16/2012 | 19 | 56 | 20 | 8.9 | 7.4 |
| **Spring pond** | | | | | | | |
| Johnson Springs | 26 | 9/15/2012 | 20 | 30 | 152 | 9.6 | 8.1 |
| **Surface-water dominated stream[1]** | | | | | | | |
| Fishtrap Creek at Hwy GG | 29 | 9/16/2012 | 13.7 | 310 | 12 | 10.8 | 6.6 |
| Log Creek at FR 161 | 39 | 9/16/2012 | 15.3 | 37 | 12 | 6.4 | 5.8 |
| **Well** | | | | | | | |
| Namakagon Lake Well | 2 | 9/15/2012 | 8.4 | 180 | 80 | 4.6 | 8.4 |
| Birch Grove Well | 5 | 9/14/2012 | 8.4 | 149 | 72 | 1.1 | 6.9 |
| Lake Owen Well | 7 | 9/14/2012 | 10.6 | 191 | 96 | 0.6 | 7.6 |
| Long Lake Well | 8 | 9/14/2012 | 9.3 | 143 | 64 | 1.8 | 6.9 |
| Perch Lake Well | 11 | 9/14/2012 | 9 | 245 | 120 | 7.8 | 8.5 |
| Namakagon Lodge Well 2 | 16 | 9/15/2012 | 9.8 | 94 | 40 | 2.6 | 7.4 |
| Beaver Lake Well | 18 | 9/16/2012 | 9.4 | 158 | 56 | 9.4 | 7.3 |
| Mineral Lake Well | 19 | 9/16/2012 | 8.5 | 221 | 80 | 2.5 | 7.1 |
| Black Lake Well | 20 | 9/16/2012 | 8.8 | 253 | 132 | 1.4 | 8.0 |
| Day Lake Well | 21 | 9/15/2012 | 8.9 | 151 | 68 | 5.1 | 8.8 |

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

*(continued)*

[1] *Streams classified as groundwater dominated or surface water dominated by the U.S. Forest Service.*

**Table 8.** Water chemistry field analyses, September 2012, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin, *(cont.)*

| Site name | Site number | Date sampled | Temp. (°C) | Conductivity (µS/cm) | Alkalinity mg/l $CaCO_3$ | Dissolved oxygen (mg/L) | pH |
|---|---|---|---|---|---|---|---|
| **Well** | | | | | | | |
| E. Twin Lakes Well | 22 | 9/17/2012 | 9 | 243 | 120 | 3.1 | 8.3 |
| Horseshoe Lake Camp Well | 23 | 9/14/2012 | 14.2 | 79 | 36 | 6.0 | 8.7 |
| Lake Three Well | 24 | 9/16/2012 | 12 | 114 | 56 | 7.7 | 7.2 |
| Moose Lake Well | 25 | 9/16/2012 | 9.7 | 258 | 140 | 9.1 | 7.2 |
| Pigeon Lake Well 1 | 45 | 9/15/2012 | 9.8 | 194 | 76 | 10.0 | 7.7 |
| Pigeon Lake Well 2 | 53 | 9/15/2012 | 10.5 | 257 | 96 | 1.7 | 7.2 |
| **Unclassified stream** | | | | | | | |
| Moose River | 43 | 9/17/2012 | 13.5 | 186 | 76 | 1.6 | 7.4 |
| Brush Creek | 54 | 9/17/2012 | 14 | 170 | 80 | 6.7 | 7.3 |

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

[1] *Streams classified as groundwater dominated or surface water dominated by the U.S. Forest Service.*

**Table 9.** Wells sampled in the Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| Well sampled | Site number[1] | WI unique well no.[2] | Total depth (feet) | Material, reported by driller |
|---|---|---|---|---|
| Namakagon Lake | 2 | FD137 | — | — |
| Birch Grove | 5 | FD073 | 175 | Sand |
| Lake Owen | 7 | GV519 | 89 | Clay and sand |
| Long Lake | 8 | GV517 | 189 | Sand and gravel |
| Perch Lake | 11 | FD076 | 124 | Sand |
| Namakagon Lodge | 16 | GV516 | 86 | Sand |
| Beaver Lake | 18 | No WCR identified | — | — |
| Mineral Lake | 19 | JB982 | 77 | Clay, sand and gravel |
| Black Lake | 20 | JB389, PT941 | — | — |
| Day Lake | 21 | FD101, FD079 | — | — |
| East Twin Lakes | 22 | FF647, DL039 | — | — |
| Horseshoe Lake Camp | 23 | KN002 | 329 | Sand, some silt, clay, and gravel |
| Lake Three | 24 | FF648 | — | — |
| Moose Lake | 25 | No WCR identified | — | — |
| Pigeon Lake 1 | 45 | BA-0241[3] | — | Sand and gravel |
| Pigeon Lake 2 | 53 | BA-0242[3] | — | Sand and gravel |

Abbreviation: WCR = well construction report

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

[2] *Wisconsin Unique Well Number.*

[3] *Monitoring wells installed for this project. Number indicates WGNHS geologic log number. Well construction information included as electronic data (see Data availability).*

guished from surface water by higher alkalinity, conductivity, pH, and magnitude of ion concentrations such as calcium and magnesium. Table 10 contains the major ion analyses, and table 11 shows average values for each source type. To calculate sample averages, samples with non-detect results were assumed to have a concentration of half the detection limit. Charge balance calculations showed that although most samples satisfy standard criteria for acceptable lab analyses, 17 samples had unacceptable charge balance errors (table 10). 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 milliequivalents per liter (meq/L) for anion sums 0–3 meq/L, (2) the charge balance is within 2 percent for anion sums 3–10 meq/L, (3) the charge balance within 5 percent for anion sums 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, groundwater is much more alkaline than surface water and has higher pH and electrical conductivity. Groundwater well samples have an average alkalinity of 83 mg/L (range 36–140 mg/L) and conductivity of 183 (range 79–258) µS/cm. Wells with lower conductivity and alkalinity, such as Horseshoe Lake Camp well (fig. 7a, site 23), produced water with lower electrical conductivity and alkalinity. Water from this well, located in the sand barrens in the central part of the Washburn District (fig. 7a) likely reflects low-conductivity precipitation rapidly recharging through the sand.

Sample results from two surface-water sites, Moose River and Brush Creek (fig. 7b, sites 43, 54), differed from results obtained by the USFS at the same sites in the early 1990s (D. Higgins, written communication, 2013). At these sites earlier measures of electrical conductivity were below 50 µS/cm, and the streams were classified as surface-water dominated. In contrast, conductivities measured in the present study were more than 170 µS/cm at both sites, suggesting groundwater dominance. The cause of these differences is unclear at this time, but it might result from differing sampling protocols, a change in the flow regime of groundwater and surface water at these sites, or temporal variability. Owing to this uncertainty, this report refers to these two streams as "unclassified."

Surface waters such as lakes and streams mix groundwater inflow and surface water runoff. Streams classified by the USFS as runoff dominated have average conductivity and alkalinity values of 87 µS/cm and 33 mg/L, respectively (table 11). Lake samples have similar values—average conductivity of 58 µS/cm and alkalinity of 28 mg/L. Groundwater-dominated streams have higher average values of 183 µS/cm and 88 mg/L; and Johnson Springs has even higher values (310 µS/cm and 152 mg/L). Plate 9 shows the spatial distribution of alkalinity and electric conductivity as measured in sampled streams and lakes. In general, groundwater-dominated features have higher alkalinity and conductivity than surface-water dominated features. Blue symbols indicate water features that are more likely fed by groundwater, such as Long Lake Branch (plate 9a, site 33), whereas red symbols indicate surface-runoff–dominated features, such as Horseshoe Lake (plate 9a, site 46). Geochemistry results agree well with modeled groundwater flow paths and stream discharge (plate 9a; section 4). Samples from groundwater-dominated features (higher conductivity and alkalinity) frequently align with discharge areas (near ends of groundwater flow arrows), whereas precipitation and runoff-dominated features are more often in upland recharge areas.

The relative concentration of various ions in each water source is shown graphically on Stiff diagrams (fig. 8). 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 prevalence of the individual ions. The plots illustrate that groundwater wells and groundwater-dominated streams typically contain a higher concentration of dissolved ions, but the ratio of constituent ions is about the same for all water sources.

## Water quality indicators

The geologic setting of the Washburn/Great Divide Unit, noncarbonate 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 values of Cl, $NO_3$, or P likely represent places where land use or cultural activities are degrading water quality. Chloride, nitrate, and phosphorus levels were typically near or below detection limits in all samples (table 10). Chloride concentrations were less than 4 mg/L in most samples. The two sites with the highest chloride concentrations were Moose River (fig. 7b, site 43; 11.5 mg/L) and Johnson Springs (fig. 7a, site 26; 6.4 mg/l).

**Table 10.** Water chemistry laboratory results for the Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| Site number[1,2] | Nitrate (mg/L) | Cl (mg/L) | As (mg/L) | Ca (mg/L) | Cu (mg/L) | Fe[3] (mg/L) | K (mg/L) | Mg (mg/L) | Mn[3] (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| **Groundwater stream** | | | | | | | | | |
| 27 | < 0.1 | < 0.5 | < 0.005 | 17.1 | < 0.001 | 0.09 | 0.5 | 4.5 | 0.002 |
| 28 | < 0.1 | < 0.5 | < 0.005 | 17.0 | 0.003 | 0.3 | 0.6 | 4.5 | 0.025 |
| 31 | < 0.1 | < 0.5 | < 0.005 | 15.6 | < 0.001 | 0.091 | 0.6 | 5.5 | 0.003 |
| 32 | < 0.1 | < 0.5 | < 0.005 | 19.4 | 0.001 | 0.14 | 0.5 | 5.1 | 0.026 |
| 33 | < 0.1 | 3.6 | < 0.005 | 33.7 | 0.002 | 0.016 | 0.7 | 8.5 | 0.004 |
| 36 | < 0.1 | < 0.5 | < 0.005 | 21.6 | < 0.001 | 0.018 | 0.8 | 5.7 | 0.002 |
| 37 | < 0.1 | < 0.5 | < 0.005 | 22.1 | < 0.001 | 0.294 | 0.8 | 7.8 | 0.144 |
| 38 | < 0.1 | < 0.5 | < 0.005 | 21.5 | 0.001 | 0.357 | 0.8 | 7.0 | 0.111 |
| 40 | < 0.1 | < 0.5 | < 0.005 | 22.5 | 0.003 | 0.246 | 0.8 | 5.7 | 0.150 |
| 41 | < 0.1 | < 0.5 | < 0.005 | 16.8 | 0.001 | 0.291 | 0.7 | 5.5 | 0.080 |
| **Lake** | | | | | | | | | |
| 17 | < 0.1 | < 0.5 | < 0.005 | 6.2 | 0.002 | 0.08 | 0.6 | 1.9 | 0.057 |
| 42 | < 0.1 | < 0.5 | < 0.005 | 1.7 | 0.002 | 0.087 | 0.7 | 0.7 | 0.012 |
| 46 | < 0.1 | < 0.5 | < 0.005 | 1.3 | < 0.001 | 0.008 | 0.4 | 0.4 | 0.004 |
| 47 | < 0.1 | < 0.5 | < 0.005 | 0.9 | 0.002 | 0.049 | 0.5 | 0.4 | 0.012 |
| 48 | < 0.1 | 1.3 | < 0.005 | 16.0 | 0.002 | 0.017 | 0.5 | 4.2 | 0.003 |
| 49 | < 0.1 | 1.0 | < 0.005 | 8.9 | 0.001 | 0.991 | 0.4 | 2.8 | 0.047 |
| 50 | < 0.1 | 1.0 | < 0.005 | 7.6 | 0.002 | 0.662 | 0.3 | 2.3 | 0.072 |
| 51 | < 0.1 | < 0.5 | < 0.005 | 5.4 | 0.011 | 0.143 | 0.4 | 1.9 | 0.005 |
| 52 | < 0.1 | < 0.5 | < 0.005 | 2.7 | 0.008 | 0.032 | 0.6 | 0.9 | 0.006 |
| **Spring pond** | | | | | | | | | |
| 26 | < 0.1 | 6.4 | < 0.005 | 39.0 | 0.002 | 0.01 | 0.8 | 11.1 | 0.003 |
| **Surface-water stream** | | | | | | | | | |
| 29 | < 0.1 | 0.8 | < 0.005 | 3.2 | 0.004 | 1.121 | 0.6 | 1.2 | 0.122 |
| 39 | < 0.1 | 1.7 | < 0.005 | 3.2 | 0.005 | 1.407 | 0.6 | 1.3 | 0.111 |
| **Well** | | | | | | | | | |
| 2 | < 0.1 | 1.6 | < 0.005 | 20.0 | 0.001 | 0.12 | 0.6 | 4.2 | 0.076 |
| 5 | < 0.1 | 0.6 | < 0.005 | 17.4 | < 0.001 | 0.864 | 0.8 | 3.3 | 0.394 |
| 7 | < 0.1 | 0.9 | < 0.005 | 21.3 | 0.002 | 0.126 | 0.7 | 5.9 | 0.065 |
| 8 | < 0.1 | < 0.5 | < 0.005 | 13.7 | 0.001 | 0.078 | 0.6 | 5.6 | 0.061 |
| 11 | < 0.1 | < 0.5 | < 0.005 | 29.6 | 0.003 | 0.019 | 0.7 | 8.6 | 0.003 |
| 16 | < 0.1 | < 0.5 | < 0.005 | 7.9 | < 0.001 | 2.146 | 0.5 | 2.4 | 0.359 |
| 18 | < 0.1 | < 0.5 | < 0.005 | 13.4 | 0.013 | 0.064 | 0.4 | 6.7 | 0.004 |
| 19 | < 0.1 | 3.3 | < 0.005 | 17.0 | 0.004 | 10.47 | 0.8 | 6.2 | 0.334 |
| 20 | < 0.1 | < 0.5 | < 0.005 | 30.7 | 0.001 | 0.033 | 0.9 | 8.8 | 0.033 |
| 21 | < 0.1 | < 0.5 | < 0.005 | 15.4 | < 0.001 | 0.003 | 1.2 | 5.4 | 0.036 |
| 22 | < 0.1 | < 0.5 | < 0.005 | 25.7 | 0.002 | 0.056 | 1.4 | 9.7 | 0.080 |
| 23 | < 0.1 | < 0.5 | < 0.005 | 8.0 | < 0.001 | 0.003 | 0.4 | 2.0 | 0.008 |
| 24 | < 0.1 | < 0.5 | < 0.005 | 10.6 | 0.088 | 0.073 | 0.6 | 3.6 | 0.049 |
| 25 | < 0.1 | < 0.5 | < 0.005 | 31.5 | 0.002 | 2.502 | 1.0 | 9.4 | 0.623 |
| 45 | 0.2 | < 0.5 | < 0.005 | 19.0 | 0.004 | 0.004 | 0.6 | 4.4 | 0.003 |
| 53 | < 0.1 | 3.6 | < 0.005 | 27.2 | < 0.001 | 3.364 | 1.0 | 6.8 | 0.120 |
| **Unclassified stream** | | | | | | | | | |
| 43 | < 0.1 | 11.5 | < 0.005 | 19.4 | 0.001 | 0.374 | 2.1 | 6.0 | 0.130 |
| 54 | < 0.1 | < 0.5 | < 0.005 | 17.7 | 0.002 | 0.488 | 0.7 | 5.8 | 0.074 |

*Table 10 reads across two pages.*

| Site number[1,2] | Na (mg/L) | P (mg/L) | Pb (mg/L) | Sulfate (mg/L) | Zn (mg/L) | Ammonia (mg/L) | Charge balance[4] (%) |
|---|---|---|---|---|---|---|---|
| **Groundwater stream** | | | | | | | |
| 27 | 2 | < 0.02 | < 0.002 | .41 | 0.001 | < 0.1 | 4 |
| 28 | 2 | 0.02 | < 0.002 | 4.1 | < 0.002 | < 0.1 | 4 |
| 31 | 2 | <0.02 | < 0.002 | 3.6 | < 0.002 | < 0.01 | 6 |
| 32 | 2 | < 0.02 | < 0.002 | 3.0 | 0.003 | < 0.1 | 5 |
| 33 | 2 | < 0.02 | < 0.002 | 4.4 | < 0.002 | < 0.1 | 5 |
| 36 | 2 | < 0.02 | < 0.002 | 4.1 | 0.004 | < 0.1 | 5 |
| 37 | 3 | 0.03 | < 0.002 | 4.2 | < 0.002 | < 0.01 | 6 |
| 38 | 3 | 0.02 | < 0.002 | 2.2 | 0.003 | 0.02 | 6 |
| 40 | 3 | < 0.02 | < 0.002 | 1.8 | 0.011 | 0.03 | 7 |
| 41 | 3 | 0.03 | < 0.002 | 2.7 | < 0.002 | < 0.01 | 9 |
| **Lake** | | | | | | | |
| 17 | < 1 | < 0.02 | < 0.002 | 1.6 | 0.144 | < 0.1 | 21 |
| 42 | < 1 | < 0.02 | < 0.002 | 2.0 | 0.026 | 0.01 | 26 |
| 46 | < 1 | < 0.02 | < 0.002 | 4.1 | 0.02 | < 0.1 | 39 |
| 47 | < 1 | < 0.02 | < 0.002 | 2.6 | 0.042 | < 0.1 | 51 |
| 48 | 2 | < 0.02 | < 0.002 | 2.9 | 0.006 | < 0.1 | 5 |
| 49 | < 1 | 0.02 | < 0.002 | 1.6 | 0.007 | 0.11 | 9 |
| 50 | 1 | < 0.02 | < 0.002 | 2.1 | 0.002 | 0.02 | 5 |
| 51 | < 1 | < 0.02 | < 0.002 | 2.4 | 0.003 | < 0.01 | 16 |
| 52 | < 1 | < 0.02 | < 0.002 | 1.7 | 0.017 | 0.06 | 32 |
| **Spring pond** | | | | | | | |
| 26 | 3 | < 0.02 | < 0.002 | 4.2 | < 0.002 | < 0.1 | 5 |
| **Surface-water stream** | | | | | | | |
| 29 | < 1 | < 0.02 | < 0.002 | 0.9 | 0.015 | 0.11 | 6 |
| 39 | < 1 | 0.03 | < 0.002 | 1.4 | 0.021 | 0.07 | 4 |
| **Well** | | | | | | | |
| 2 | 3 | 0.05 | < 0.002 | 3.0 | 0.018 | 0.07 | 6 |
| 5 | 1 | < 0.02 | < 0.002 | 0.2 | 0.279 | 0.48 | 7 |
| 7 | 2 | < 0.02 | < 0.002 | 1.7 | 1.134 | < 0.1 | 8 |
| 8 | 2 | < 0.02 | < 0.002 | 3.9 | 0.358 | < 0.1 | 4 |
| 11 | 2 | < 0.02 | < 0.002 | 5.2 | 0.098 | < 0.1 | 4 |
| 16 | 1 | < 0.02 | < 0.002 | 0.7 | 0.273 | < 0.1 | 4 |
| 18 | 2 | < 0.02 | < 0.002 | 4.2 | 0.073 | < 0.01 | 5 |
| 19 | 6 | < 0.02 | < 0.002 | 11 | 0.172 | 0.06 | 3 |
| 20 | 3 | 0.04 | < 0.002 | 4.0 | 0.086 | < 0.01 | 6 |
| 21 | 2 | < 0.02 | < 0.002 | 4.1 | < 0.002 | 0.02 | 4 |
| 22 | 4 | 0.03 | < 0.002 | 10.8 | 0.033 | 0.03 | 7 |
| 23 | < 1 | < 0.02 | < 0.002 | 3.7 | 0.046 | 0.03 | 16 |
| 24 | 2 | < 0.02 | < 0.002 | 4.2 | 0.126 | < 0.01 | 12 |
| 25 | 3 | 0.02 | < 0.002 | 1.2 | 0.028 | < 0.01 | 4 |
| 45 | 3 | 0.03 | < 0.002 | 4.4 | 0.009 | < 0.1 | 5 |
| 53 | 3 | < 0.02 | < 0.002 | 14.2 | < 0.002 | 1.11 | 3 |
| **Unclassified stream** | | | | | | | |
| 43 | 4 | 0.03 | < 0.002 | 0.7 | 0.002 | < 0.01 | 4 |
| 54 | 3 | 0.08 | < 0.002 | 4.1 | 0.004 | < 0.01 | 4 |

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

[1]*See table 8 for site locations.*

[2]*Streams classified by the U.S. Forest Service.*

[3]*Analyses exceeding the enforcement standard or preventive action limits (or both) for manganese (0.3 mg/L; 0.06 mg/L) or iron (0.3 mg/L; 0.15 mg/L) are highlighted.*

[4]*Unacceptable charge balance errors are highlighted. 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 is within 0.2 meq/L for anion sums 0–3 meq/L, (2) the charge balance is within 2 percent for anion sums 3–10 meq/L, (3) the charge balance within 5 percent for anion sums 10–800 meq/L.*

**Table 11.** Average[1] water quality, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| Site type[2] | 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) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groundwater stream | 10 | 183 | 9.1 | 7.8 | 88 | 20.7 | 6.0 | 2.4 | 0.7 | 0.2 | 0.1 | 3.6 | 3.4 |
| Lake | 9 | 58 | 7.6 | 7.6 | 28 | 5.6 | 1.7 | 1.5 | 0.5 | 0.2 | 0.0 | 1.1 | 2.3 |
| Spring pond | 1 | 310 | 10.8 | 8.1 | 152 | 39.0 | 11.1 | 3.0 | 0.8 | 0.0 | 0.0 | 6.4 | 4.2 |
| Surface-water stream | 2 | 37 | 6.13 | 6.1 | 12 | 3.2 | 1.3 | <1 | 0.6 | 1.3 | 0.1 | 1.3 | 1.2 |
| Well | 16 | 183 | 4.6 | 7.7 | 83 | 19.3 | 5.8 | 2.6 | 0.8 | 1.2 | 0.1 | 2.0 | 4.8 |
| Unclassified stream | 2 | 178 | 4.15 | 7.3 | 78 | 18.6 | 5.9 | 3.5 | 1.4 | 0.4 | 5.9 | 5.9 | 2.4 |

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

[1] *To calculate sample averages, samples with nondetect results were assumed to have a concentration of half the detection limit.*

[2] *Streams classified by the U.S. Forest Service.*

**Figure 8.** Stiff plots of average major ion constituents in four types of water source, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

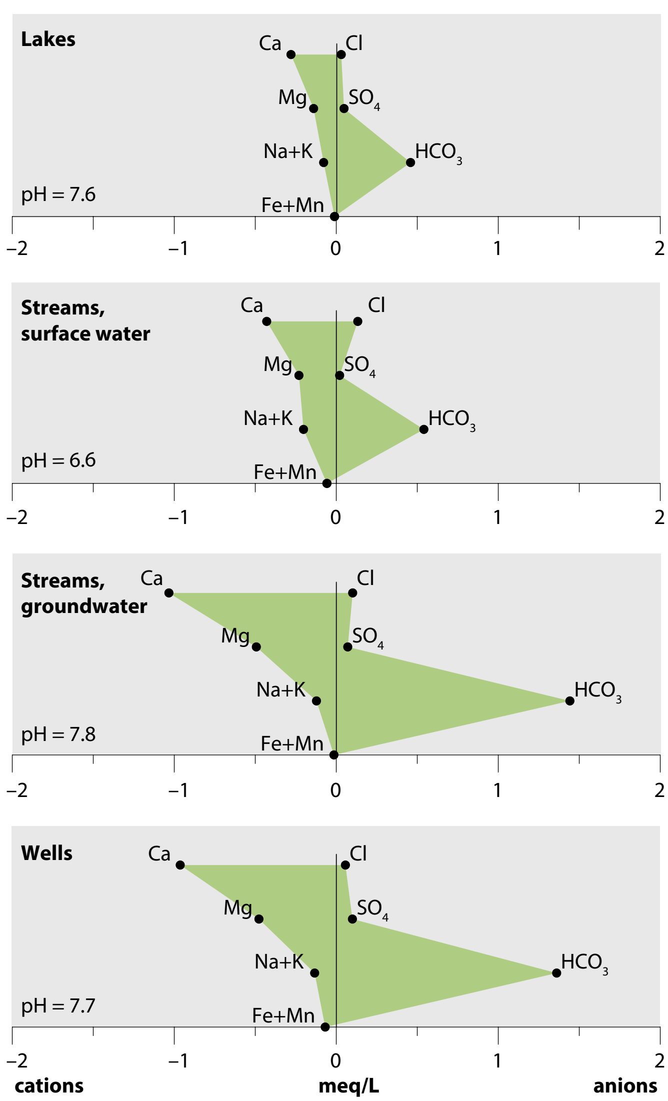
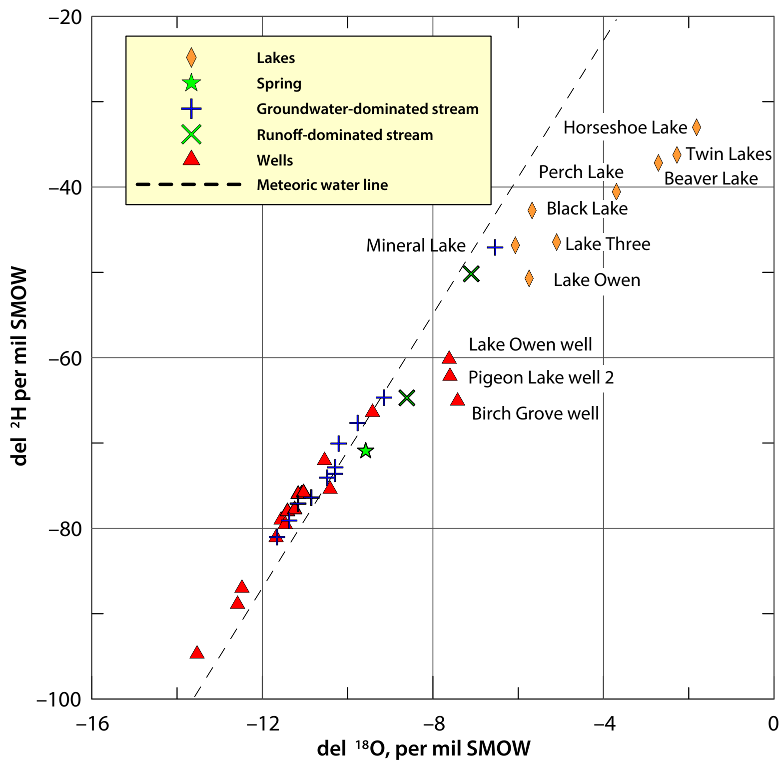


**Figure 9.** Oxygen-18 vs. deuterium in water samples, plotted against the meteoric water line, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.




Concentrations of dissolved iron and manganese in some groundwater samples in the districts were in excess of the Wis. Admin. Code § NR 140 (February 2017) preventive action limit, and in some cases failed the enforcement standard, for manganese or iron (table 10). The manganese enforcement standard of 0.3 mg/L was not met in the Birch Grove well (fig. 7a, site 5; 0.39 mg/L), the Namakagon Lodge well (fig. 7b, site 16; 0.36 mg/L), the Mineral Lake well (fig. 7b, site 19; 0.33 mg/L), and the Moose Lake well (fig. 7b, site 25; 0.62 mg/L); concentrations were in excess of the preventive action limit of 0.06 mg/L in six additional wells. Manganese, which is commonly a natural constituent of groundwater, is generally considered an aesthetic contaminant based on taste and appearance. However, according to the Wisconsin Division of Public Health (see https://www.dhs.wisconsin.gov/water/manganese.htm), infants should not drink water containing a manganese concentration that is above the health advisory level of 0.3 mg/L. Also, people who drink more than 8 cups of water a day and have a liver disease should avoid drinking water that is above the health advisory level. Concentrations in samples from five wells were in excess of the iron enforcement standard of 0.3 mg/L; the highest iron concentration was found in the Mineral Lake well (10.4 mg/L). Iron is considered a secondary or aesthetic contaminant based on taste and appearance rather than on any detrimental health effect.

## Isotopes of hydrogen and oxygen

The relative abundance of the stable isotopes deuterium ($^2H$) and oxygen-18 ($^{18}O$) in groundwater and surface water can provide information on the mixing of groundwater and surface water, 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 part per thousand notation, symbolized by δ (delta) SMOW (Standard Mean Ocean Water). Typically, inland waters have negative δ values because they are isotopically lighter than ocean water. The covariance between δ $^2H$ and δ $^{18}O$ in precipitation is called the meteoric water line (MWL), a formulation of the ratio of $^2H$ to $^{18}O$ found in unevaporated precipitation. Isotopic 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 (lighter precipitation) are typically a result of precipitation during colder months. Water samples plotting off the MWL are interpreted as having been exposed to surface water evaporation or other physical processes. In groundwater studies, deuterium and oxygen-18 concentrations are commonly used to identify groundwater that was recharged by a surface-water feature exposed to evaporation before the water entered the aquifer.

Figure 9 and table 12 show the isotope results from water samples collected in the Washburn/Great Divide Unit. The meteoric water line is based on samples from north-

**Table 12.** Isotopic content of water samples collected in the Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| Sample location[1] | Site number | $\delta^{18}O$ (per mil SMOW) | $\delta^2H$ (per mil SMOW) |
|---|---|---|---|
| **Well** | | | |
| Beaver Lake Well | 18 | −11.03 | −75.81 |
| Birch Grove Well | 5 | −7.42 | −65.08 |
| Black Lake Well | 20 | −10.54 | −72.04 |
| Day Lake Well | 21 | −11.46 | −79.53 |
| EastTwin Lakes Well | 22 | −11.41 | −78.03 |
| FS HQ at Wanoka Lake | 17 | −11.16 | −76.00 |
| Horseshoe Lake Camp Well | 23 | −13.53 | −94.72 |
| Lake Owen Well | 7 | −7.62 | −60.17 |
| Lake Three Well | 24 | −12.48 | −87.01 |
| Long Lake Well | 8 | −12.58 | −88.89 |
| Mineral Lake Well | 19 | −11.56 | −79.01 |
| Moose Lake Well | 25 | −9.42 | −66.40 |
| Namakagon Lake Well | 2 | −11.68 | −81.09 |
| Namakagon Lodge Well | 16 | −11.08 | −75.96 |
| Perch Lake Well | 11 | −10.41 | −75.41 |
| Pigeon Lake Well 1 | 45 | −11.24 | −77.80 |
| Pigeon Lake Well 2 | 53 | −7.60 | −62.17 |
| **Spring pond** | | | |
| Johnson Springs | 26 | −9.58 | −70.93 |
| **Groundwater-dominated stream** | | | |
| Eighteenmile Creek | 32 | −10.48 | −74.07 |
| Twentymile Creek | 31 | −11.16 | −77.11 |
| Bearsdale Creek | 28 | −10.85 | −76.39 |
| Brunet River | 41 | −9.15 | −64.68 |
| Downstream Venison Creek | 37 | −10.21 | −70.07 |
| Fishtrap Creek | 29 | −6.54 | −47.08 |
| Knab Creek | 40 | −10.29 | −72.86 |
| Log Creek | 39 | −7.10 | −50.18 |
| Long Lake Branch | 33 | −10.30 | −73.62 |
| Moose River | 43 | −8.61 | −64.70 |
| Shunenberg Creek | 27 | −11.37 | −79.09 |
| South Fork White River | 36 | −11.66 | −81.02 |
| Upstream Venison Creek | 38 | −9.76 | −67.65 |
| **Unclassified stream** | | | |
| Brush Creek | 54 | −10.05 | −72.49 |
| **Lake** | | | |
| Beaver Lake | 52 | −2.71 | −37.17 |
| Black Lake | 49 | −5.67 | −42.75 |
| Horseshoe Lake | 46 | −1.82 | −33.00 |
| Lake Owen | 48 | −5.74 | −50.71 |
| Lake Three | 51 | −5.10 | −46.45 |
| Mineral Lake | 50 | −6.07 | −46.82 |
| Perch Lake | 42 | −3.70 | −40.56 |
| Twin Lakes | 47 | −2.28 | −36.24 |

Abbreviations: $\delta^{18}O$ = ratio of oxygen-18 to oxygen-16; $\delta^2H$ = ratio of deuterium; per mil SMOW = parts per thousand, Standard Mean Ocean Water

[1]*Streams classified by the U.S. Forest Service.*

ern Vilas County (Krabbenhoft and others, 1990). Most groundwater and groundwater-dominated surface-water samples cluster along the lower-left side of the plot; well-water samples are generally more negative than water from spring ponds and creeks, indicative of groundwater recharge predominantly during colder months. The meteoric water line established by Krabbenhoft is taken from precipitation samples collected approximately 80 miles east of the Washburn/Great Divide Unit, so it is not surprising that groundwater samples collected in the Washburn/Great Divide Unit do not fall exactly on this line.

Consistent with the electrical conductivity and alkalinity data above, several groundwater-dominated streams and Johnson Springs have a similar isotopic signature as groundwater samples and plot in the same region of figure 9. Lakes and runoff-dominated streams plot to the right of the MWL, characteristic of water that has undergone open-water evaporation. Three wells in the unit (Lake Owen well, Pigeon Lake well 2, and Birch Grove well) have samples that also plot to the right of the MWL, between lake samples and other well samples. These isotopic signatures suggest mixing of groundwater and surface water, and these three wells likely produce some water originating in nearby lakes.

## Discussion

The results show that water in the Washburn/Great Divide Unit contains low concentrations of most dissolved ions and thus that it is relatively unaltered by human activities. Groundwater is distinguished from surface water by higher electrical conductivity (average 183 µS/cm for wells vs. 58 for lakes), alkalinity (83 vs. 28 mg/L), pH, and concentrations of dissolved ions such as calcium and magnesium. Overall water quality is very good. Concentrations of nitrate-nitrogen and phosphorus were below detection levels and concentrations of chloride were also very low. Several wells produced water with elevated levels of dissolved iron or manganese. Isotopes of hydrogen and oxygen can show whether features have undergone open-water evaporation as well as distinguish surface water (isotopically heavier, less negative) from groundwater (isotopically lighter, more negative). The isotopic data suggest that several lakeshore wells at picnic or campground areas produce a mixture of groundwater and water originating as surface water. Geochemistry results agree well with simulated groundwater flow paths and stream discharge (see section 4). This overview also provides a basis for future geochemical investigations of specific areas in the Washburn/Great Divide Unit.

# Section 4: Groundwater flow model

## Objectives

The data inventory and analysis described in the previous sections were incorporated into groundwater flow models of the Washburn and Great Divide Districts. Two models were constructed because of the large area spanned by the two districts, the density of surface water features, and limitations of the analytic element modeling technique. The models were constructed using the analytic element groundwater modeling program GFLOW (Haitjema, 1995). The flow models support the goals of this project by providing estimates of key aquifer properties and 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 using the analytic element groundwater-flow modeling program GFLOW (Haitjema, 1995). Hunt (2006) reviews applications of the analytic element method, and Haitjema (1995) discusses the underlying concepts and mathematics of the method. A complete description of analytic elements is beyond the scope of this report, but a brief description follows.

An aquifer of infinite lateral extent 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. The solution is not confined to a grid, so 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 do not vary with time but typify long-term representative conditions. The analytic element method and comparisons of analytic element to finite-difference numerical model techniques have been discussed by others (Haitjema, 1995; Hunt and others 1998; and Hunt and others, 2003).

### Conceptual model

In humid climates, groundwater flow patterns are influenced by topography, the pattern of surface-water features (such as rivers and lakes that intersect the water table), the aquifer transmissivity, recharge to the aquifer, and pumping. Conceptualization of the hydrologic system forms the framework for development of the mathematical model by simplifying the groundwater system into important component parts. Three steps are required to develop the conceptual model: (1) characterize the aquifer or aquifers; (2) identify sources and sinks of water; and (3) identify and delineate hydrologic boundaries in the area of interest.

The shallow regional groundwater system surrounding the Washburn/Great Divide Unit is characterized by three main regions: a relatively thin (less than 200 ft thick) glacial aquifer overlying less-permeable crystalline rocks in the Great Divide District; thicker outwash deposits overlying sandstone in the northern Washburn District, and fine-grained till overlying sandstone, outwash, and sandy till along the Lake Superior shoreline (see Clayton, 1985; plates 2, 3, 7). For the purposes of the regional groundwater flow models described here, we simplify this complex system into a conceptual model that treats the aquifer as a single layer. The hydrogeologic properties of this single layer vary spatially according to the dominant materials described above. This simplification is justified because at the regional scale discussed here the aquifer is very thin (hundreds of feet or less) compared to its lateral extent (many miles). Under these conditions, three-dimensional flow effects become negligible, and horizontal groundwater flow dominates. The limitations section below discusses the effects of these assumptions. 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, 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

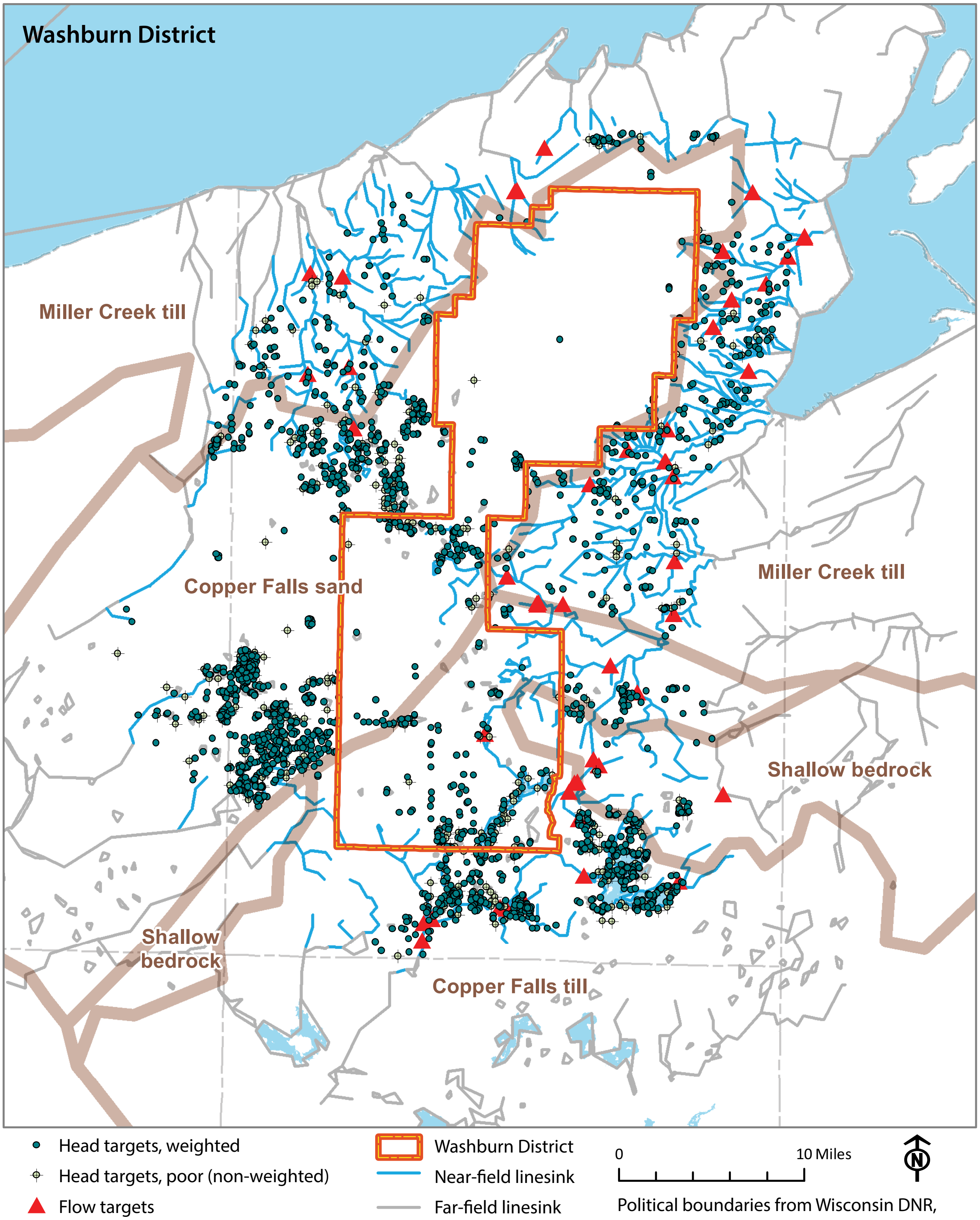
Owing to the large size of the Washburn/Great Divide Unit, two separate GFLOW models, one for each district, were developed; they are referred to here as the Washburn model (north) and the Great Divide model (south) (fig. 10). Each model contains both a near-field and a far-field region. The near-field region is the area where the model is most detailed and calibrated. Model results are considered valid in the near field. The far-field region is used to establish distant boundary conditions and to connect the model to major regional groundwater and surface-water features. Model results are not considered valid for the far-field region. The initial model delineated hydraulic conductivity zones and estimated starting parameter values, such as hydraulic conductivity values for the zones, a base elevation for the simulated groundwater system, a global resistance value for linesink elements representing streams and lakes, and a resistance value for linesinks representing Lake Superior (Washburn model). Resistance is defined as the stream or lakebed thickness divided by the vertical hydraulic conductivity of the sediment and has units of days (d). A value of 10.0 d corresponds to a 1-foot (ft) sediment thickness and a vertical hydraulic conductivity of 0.1 ft/d. Gridded potential recharge results were imported from the SWB model (see section 2) and given a global recharge multiplier that was adjusted during model calibration as described below. In two-dimensional areal models groundwater flow is simulated by the aquifer transmissivity of a single layer, where transmissivity represents hydraulic conductivity multiplied by saturated thickness. Hydraulic conductivity is set at regional values, 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, our calibration focused on horizontal hydraulic conductivity rather than base elevation because that focus produced a model that was more stable and robust during parameter estimation (see Feinstein and others, 2006).

A base elevation of 500 ft above sea level (NAVD 88) was assigned to each model because so doing promotes a more stable solution, allows parameters of the two models to be more easily compared, and reduces the overall variation in model transmissivity caused by differences in water table elevation within the domain (see discussion below). The Washburn model base of 500 ft is approximately 100 ft below Lake Superior and approximately 400–600 ft below the water table in the interior of the Bayfield Peninsula, where unconsolidated outwash deposits are at least several hundred feet thick. The Great Divide model base of 500 ft is approximately 900–1,000 ft below stream elevation in much of the Great Divide District, with the exception of the northern edge, where the water table slopes towards Lake Superior.

A sloping water-table surface and uniform model base elevation produce a simulated transmissivity gradient that is purely an artifact of the model structure. Saturated thickness, and therefore transmissivity, varies as a function of the height of the water table above the uniform base. In the Washburn model, this simulated transmissivity gradient may align with a real gradient in transmissivity, caused by both a thickening of the aquifer and greater amounts of coarse-grained sediments towards the interior of the Bayfield Peninsula. Throughout much of the Great Divide model area, the water table is relatively flat, and heads are well simulated by the model. The largest residuals in heads were found outside of the Great Divide District near the northern edge of the model, where the aquifer is shallow and likely has a base that slopes with the water table—a condition that is difficult or impossible to properly simulate in a regional two-dimensional analytic element model. Juckem and Dunning (2015, p. 12) contains a more detailed discussion of base elevation and its implications.

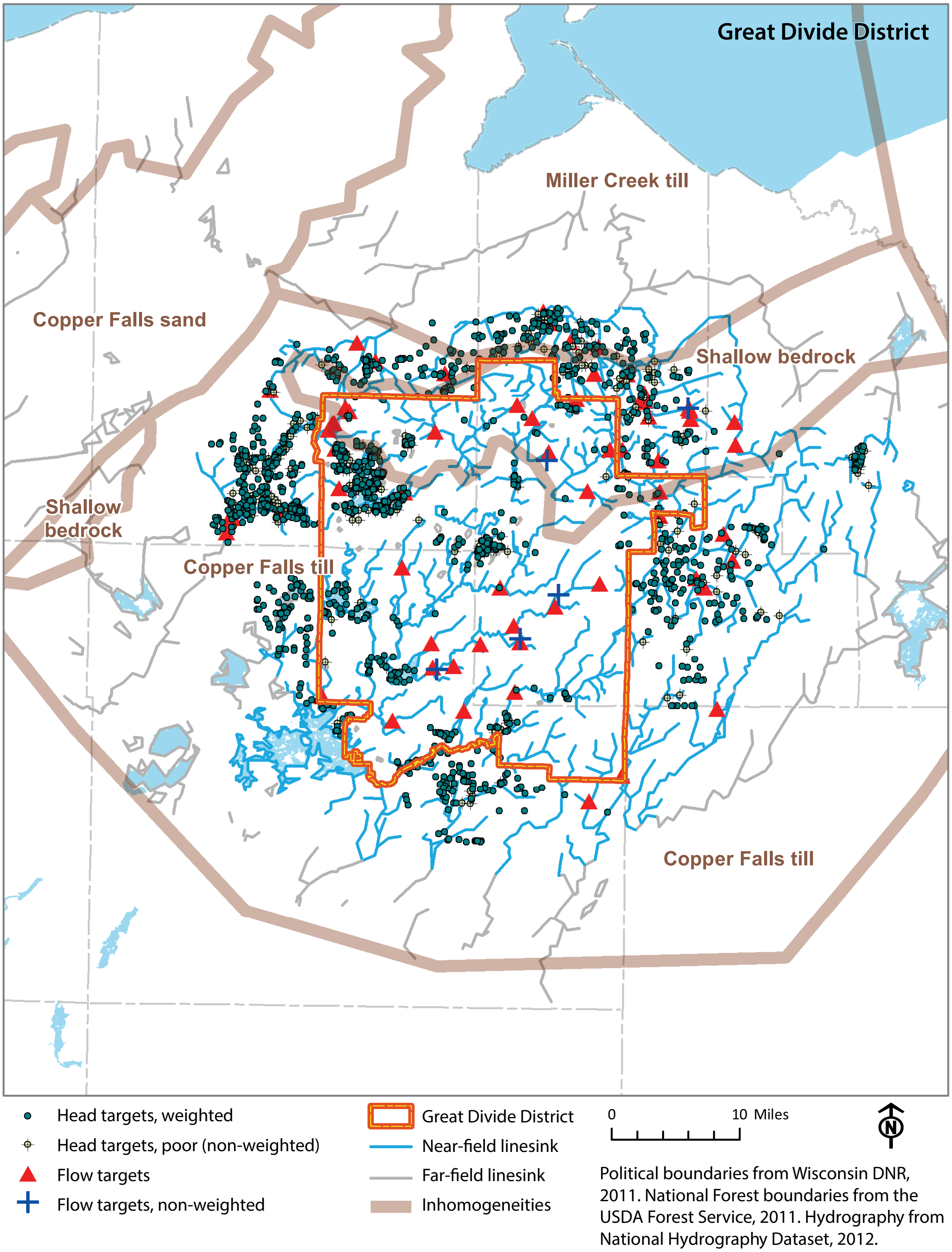
The model domain was divided into five zones of differing aquifer hydraulic conductivity values on the basis of variations in the hydrogeologic regime as described above (fig. 10). These zones are called inhomogeneities in GFLOW terminology and are labeled on figures 10a and 10b. The northernmost zone (Copper Falls sand) corresponds mostly to sandy sediments of the Copper Falls Formation. The hydrologic region to the east of this zone (Miller Creek till) corresponds to the clay-rich till of the Miller Creek Formation along the Lake Superior shoreline; it is almost entirely outside the national forest boundary. The hydrologic region to the south of the models (Copper Falls till) corresponds mostly to sandy till of the Copper Falls Formation. Two additional zones represent areas of shallow bedrock, where the surficial aquifer likely occupies a mix of shallow bedrock fracture systems and surficial deposits of variable thickness. The default hydraulic conductivity value is applied only to areas in the far-field that are not described by one of these inhomogeneities.

**Figure 10a.** Regions of differing glacial deposits and of shallow bedrock in the Washburn District GFLOW model, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.




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

**Figure 10b.** Regions of differing glacial deposits and of shallow bedrock in the Great Divide District GFLOW model, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.



Recharge was applied to the model by down-sampling the SWB model results to a 1 km resolution and then importing them into the GFLOW graphical user interface through the Hybrid GFLOW–MODFLOW sequential-coupling feature (Haitjema, 2015). Sequential coupling refers to linking models in a sequence such that the output of one model (in this case the SWB model simulation) is input into another. Sequential coupling in this case 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. The name "MODFLOW" refers to the USGS modular groundwater flow modeling code (Harbaugh, 2005; although this project did not use the MODFLOW code, it did utilize an interface developed to work with that code). Aquifer hydraulic conductivity and groundwater recharge were included as calibration parameters. Calibration (see model calibration section below) of the potential recharge was accomplished by applying a multiplier to the SWB grid, which maintains the spatial distribution of the SWB model results while calibrating the magnitude (total volume of recharge) to measured values of annual baseflow.

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 limit on the distance that a simplified line could deviate from the original line (Gillies, 2013).

The linesinks were spatially categorized into three groups of various detail. The most detailed group, simplified to a tolerance of 200 m, contained all streams within the Washburn/Great Divide Unit. In the Great Divide model, a second group, simplified to a 300 m tolerance, contained all streams in the area between the unit and the model far-field. Both of these groups were assigned values of streambed resistance and placed in the routed stream network. A third group of linesinks in the area beyond the routed stream network (model far-field) were simplified to a tolerance of 500 m and contained only second-order and higher streams. 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).

Streams and lakes within and immediately surrounding the Washburn/Great Divide Unit were simulated as routed near-field elements, or stream linesinks. Streamflow routing conserves baseflow along rivers and through lakes so that during model calibration simulated baseflows can be directly compared with measured streamflows. Near-field lakes 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 resistance linesinks 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. Surface-water bed resistance is defined as the streambed thickness divided by the vertical hydraulic conductivity of the sediment; it has units of days (d). Therefore, a model resistance value of 10.0 d corresponds to a 1-ft sediment thickness and a vertical hydraulic conductivity of 0.1 ft/d. The width of each stream was assigned according to its arbolate sum, following the method of Feinstein and others (2010). The arbolate sum is defined as the total length of stream channels, including tributaries, upstream of a given location in a stream network. It provides a measure of the size of the drainage system contributing to that location. Linesinks representing lakes were computed using the methodology of Haitjema (2005, p. 5).

Groundwater withdrawal from high-capacity wells, defined in Wisconsin as wells permitted to pump at 70 gallons per minute or more, was simulated within the model domain by using water-use data collected by the Wisconsin Department of Natural Resources (R. Smail, written communication, 2016). Although classified as high-capacity wells, most wells in the Washburn/Great Divide unit pump at average rates far less than 70 gallons per minute. A total of 87 wells with non-zero pumping rates are represented in the models; these wells pump at an average of 25 gpm and in total about 2,200 gpm. All wells are assumed in the model to be fully penetrating from the water table to the base of the model. Pumping from private residential wells or supply wells at Washburn/Great Divide 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. Though not a large enough hydrologic stress to be included in the regional groundwater flow model, these wells were used for groundwater quality analysis. Chemical and isotope sampling from wells in the Washburn/Great Divide 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 and water levels in wells, 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 manual trial-and-error calibration is the ability to systematically explore a fuller range of possible parameter values (for example, hydraulic conductivity and recharge) and produce estimates that represent a quantified best fit between simulated model output and observed data (for example, groundwater levels and streamflows). In addition, the interaction between model parameters and outputs can be quantified and assessed.

During calibration, the hydraulic conductivity parameter was adjusted for each zone as was a recharge grid multiplier (table 13) applied uniformly to all recharge values in the model. Initial hydraulic conductivity values were estimated on the basis of the data inventory in section 1, and initial recharge values were imported from SWB model results described in section 2. An additional piecewise-constant recharge inhomogeneity covering areas of the model outside of the SWB grid was adjusted in tandem with the recharge multiplier to match the areal average of the SWB grid. The resistance parameter is relatively insensitive to the calibration data, so it was fixed at a value of 0.3 d, similar to values used in other studies (Juckem and others, 2014; Kelson and others, 2002). Initial calibration of the Lake Superior resistance parameter resulted in it being estimated at a supplied upper bound of 10,000 d. The value for Lake Superior resistance was ultimately scaled back to 100 d (the same value used by Lenz and others, 2003), with minimal effect on the calibration residuals. In general, a higher base elevation and higher resistance value for Lake Superior were favorable for matching baseflows in Whittlesey Creek near Ashland (plate 4a), as these parameters control the portioning of discharge between the creek and Lake Superior. 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 WCRs and the NWIS. Where present, multiple measurements of head were averaged to develop a single, steady-state value. Stream baseflows were obtained from NWIS, annual baseflow estimates published by Gebert and others (2011) and Leaf and others (2015), USGS field measurements on the Bayfield Peninsula (Fienen and others, 2016), and streamflow measurements collected within the Washburn/Great Divide Unit by USFS staff (Higgins, written communication, 2/20/2013). At sites with continuous measurements, average annual baseflow estimates were computed using the modified Base Flow Index method described by Wahl and Wahl (1988) and Institute of Hydrology (1980). Miscellaneous low-flow measurements from NWIS, USGS, and USFS were converted to annual baseflow estimates through use of the statewide regression equation described by Gebert and others (2011), which relates measured flow to basin area and flow at an index station. The water level and annual baseflow targets were assigned groups based on the data source and estimated quality (uncertainty) (table 14). The targets used for calibration are entered into the electronic database associated with this report.

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 multipliers, to maintain a desired balance in the calibration objective function. The head observations were grouped by measurement source and quality into several classes according to 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 included 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 water-level measurement). Weighting for the head targets is shown in table 14, as are equivalent uncertainty values

**Table 13.** Calibrated parameter values for groundwater flow models, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest.

**Recharge**

| Parameter name | Model | Grid file name | Optimized parameter value | Average simulated recharge (in/yr) | Description |
|---|---|---|---|---|---|
| Recharge multiplier | Washburn | GD.rta | 0.97 | 11.1 | Multiplier for soil-water balance grid and resulting mean simulated recharge |
| Recharge multiplier | Great Divide | Washburn.rta | 0.90 | 8.8 | Multiplier for soil-water balance grid and resulting mean simulated recharge |

**Hydraulic conductivity**

| Representative zone[1] | Calibration status | GFLOW identifier | Average simulated saturated thickness[1] (ft) | Optimized parameter value[2] (ft/d) | Approx. simulated trans-missivity ($ft^2/d$) | Representative actual saturated thickness[3] (ft) | Effective average hydraulic conductivity (ft/d) | Description of zone |
|---|---|---|---|---|---|---|---|---|
| **Washburn District model** | | | | | | | | |
| Copper Falls sand | Adjustable | CopperFalls_sand | 620 | 15.3 | 9,500 | 300 | 30 | Sandy Copper Falls stream sediments |
| Copper Falls till | Adjustable | CopperFalls2 | 830 | 4.8 | 4,000 | 40 | 100 | Copper Falls till |
| Miller Creek Formation | Adjustable | Miller creek | 360 | 17.1 | 6,100 | 120 | 50 | Clay-rich till of Miller Creek Formation |
| Shallow bedrock—west | Fixed | shallow BR | — | 0.5 | — | — | — | Shallow bedrock zone west of unit. This zone was set to equal the calibrated value from "shallow bedrock—east" |
| Shallow bedrock—east | Fixed | ShbedrockE | 850 | 0.5 | 420 | 7 | 60 | Shallow bedrock zone in southeast part of Washburn District |
| **Great Divide District model** | | | | | | | | |
| Copper Falls sand | Fixed | CopperFalls_sand | — | 15.3 | — | — | — | Sandy Copper Falls stream sediments |
| Copper Falls till | Adjustable | CopperFalls2 | 890 | 2.7 | 2,400 | 60 | 40 | Copper Falls till |
| Miller Creek Formation | Adjustable | Miller creek | 370 | 2.8 | 1,000 | 60 | 20 | Clay-rich till of Miller Creek Formation |
| Shallow bedrock—west | Tied to shallow bedrock–east | shallow BR | — | 0.5 | — | — | — | Shallow bedrock zone west of unit. This zone was set to equal the calibrated value from "shallow bedrock—east" |
| Shallow bedrock—east | Adjustable | ShbedrockE | 810 | 0.5 | 400 | 10 | 40 | Shallow bedrock zone in northern portion of Great Divide District |
| **Washburn/Great Divide Unit** | | | | | | | | |
| Default hydraulic conductivity | — | conductivity | — | 3.0 | — | — | — | Required GFLOW input representing areas outside of model |

Abbreviations: in/yr = inches per year; ft = feet; ft/d = feet per day, $ft^2/d$ = square feet per day

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

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

[3]*Mean modeled water table elevation minus actual bedrock surface elevation*

**Table 14.** Calibration targets and associated weights used for calibration with the parameter-estimation program PEST, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin.

| Group name[1] | Data source | Description | Number of targets: Washburn | Number of targets: Great Divide | Calibration weight | Estimated uncertainty |
|---|---|---|---|---|---|---|
| **Baseflow** | | | | | | |
| nwis_dv | NWIS | Continuous measurements (daily values) | 5 | 3 | 1 / (CV x flow) | 0.01–0.05 (CV) |
| nwis_fm | NWIS | Miscellaneous measurements | 13 | 8 | 1 / (CV x flow) | 0.08–0.64 (CV) |
| sir20155162 | Leaf and others (2015) | Annual baseflow estimates from Bad River model | 1 | 22 | 1 / (CV x flow) | 0.04–0.5 (CV) |
| sm_streams | NWIS | Miscellaneous measurements <1 cfs | 5 | 12 | 1.00E–05 | — |
| usfs | USFS | USFS field measurements | 5 | 14 | 1 / (CV x flow) | 0.5 (CV) |
| redcliff | Unpublished | USGS field measurements | 10 | 0 | 1 / (CV x flow) | 0.2 (CV) |
| misc | Gebert and others (2011) | Annual baseflow estimates | 10 | 13 | 1 / (CV x flow) | 0.5 (CV) |
| **Head** | | | | | | |
| head_good | WDNR, WGNHS | WCRs located to within 50 ft | 56 | 157 | 0.07 | 29 ft |
| head_fair | WDNR, WGNHS | WCRs located to within 100 ft | 1,874 | 1,313 | 0.03 | 67 ft |
| head_lgtrm | NWIS | Wells with water level time series | 4 | 3 | 0.2 | 10 ft |
| head_misc | NWIS | Artesian wells and wells with water quality measurements | 17 | 21 | 0.05 | 40 ft |
| head_poor | WDNR, WGNHS | Poorly located (>100 ft) or other low-quality WCRs | 323 | 241 | 0 | — |

Abbreviations: CV = coefficient of variation; cfs = cubic feet per second; NWIS = National Water Information System

[1]*Group name attribute in GFLOW targets data file (see table 16)*

**Table 15.** Washburn model—Calibration results for groundwater head targets and associated weights used for calibration with the parameter estimation program PEST; Washburn/Great Divide Unit, 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) |
|---|---|---|---|---|---|
| **Washburn model** | | | | | |
| head_good | 56 | 21.65 | 32.64 | 53.47 | 0.07 |
| head_fair | 1874 | −4.63 | 15.02 | 23.02 | 0.03 |
| head_lgtrm | 4 | −9.40 | 12.70 | 13.35 | 0.2 |
| head_misc | 17 | −5.50 | 15.35 | 19.58 | 0.05 |
| head_poor | 323 | −4.09 | 22.44 | 30.10 | 0 |
| **Great Divide model** | | | | | |
| head_good | 157 | −3.02 | 10.39 | 14.57 | 0.07 |
| head_fair | 1313 | −5.73 | 18.14 | 28.00 | 0.03 |
| head_lgtrm | 3 | 1.58 | 2.96 | 3.04 | 0.2 |
| head_misc | 21 | −3.18 | 16.31 | 23.76 | 0.05 |
| head_poor | 241 | −5.17 | 25.03 | 36.78 | 0 |

Abbreviation: 1/std = reciprocal of standard deviation

[1]*Group name attribute in GFLOW targets data file (see table 16)*

that reflect both the original uncertainty estimate for the target and subsequent adjustment of the group weight multipliers to balance the objective function.

Similar to head targets, baseflow targets were arranged into groups based on measurement source and quality. Baseflow target weights were assigned to approximate the inverse of target uncertainty, estimated as target flow rate multiplied by a coefficient of variation (CV); this coefficient represents an estimate of the ratio of the standard deviation of the error divided by the mean value (table 14). Weights were assigned as described below.

USGS gaging stations with continuous records were given the highest weights (coefficient of variation (CV) of 0.01–0.05, which can be conceptualized as a 95-percent confidence interval of ±2–10 percent around the observed flow).

The annual baseflows estimated from miscellaneous measurements greater than 1 cubic foot per second (cfs) were assigned CVs based on the reported quality of the measurement (see U.S. Geological Survey, 2011) and a standard error for the state-wide equation of 14 percent reported by Gebert and others (2011). For targets represented by the average of several miscellaneous measurements, the above CV was divided by the square root of the number of measurements averaged, to reflect a lower uncertainty about the population mean. Measurements without a quality designator were assumed to have a measurement error of 50 percent (CV of 0.64: 50 percent error + 14 percent for the state-wide relation for a single measurement).

Miscellaneous measurements of less than 1 cfs were given a uniform weight of $1 \times 10^{-5}$, to restrict them to only a small influence on the objective function relative to other baseflow targets that were of higher quality or representative of larger drainage areas commensurate with the scale of the regional model.

Baseflow estimates obtained from Gebert and others (2011) were subjectively given CVs of 0.5 (95-percent confidence interval of ±100 percent), because the underlying measurements for these values are often several decades old and of unknown quality.

Likewise, annual baseflow estimates from low-flow measurements collected on the Bayfield Peninsula in 2002 as part of a study with the Red Cliff Band of Lake Superior Chippewa (Fienen and others, 2016) were assigned a subjective CV of 0.2 (95-percent confidence interval of ±40 percent).

Annual baseflow estimates from the Bad River MODFLOW model (Leaf and others 2015) were given the original weights used in the calibration of the groundwater flow model described in that study, to preserve differences within that group.

While the above CV estimates 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 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).

On the basis of field data and previous studies, final parameter values calibrated to measured water levels and stream baseflows (table 13) are within expected ranges. The recharge multipliers of 0.97 for Washburn and 0.90 for Great Divide produce mean areal recharge values of 11.1 and 8.8 in/yr, respectively, which are consistent with other reported values (Gebert and others, 2011; Leaf and others, 2015; Lenz and others, 2003; Pint and others, 2003; Robertson and others, 2012). The simplifying assumptions of GFLOW and TGUESS limit direct comparisons of hydraulic properties; to better compare results, the average simulated saturated thickness for each inhomogeneity was used to produce estimates of approximate transmissivity for the zones present in each model nearfield (table 13). 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 13 also shows the approximate effective hydraulic conductivity representative of the aquifer for each zone. The approximate effective hydraulic conductivity for the Copper Falls Formation sand is about 30 ft/d, consistent with TGUESS and other reported model values (Leaf and others, 2015; Lenz and others, 2003). The Copper Falls sand and Miller Creek Formation clay till zones (fig. 10) were modeled with higher transmissivity than the mean TGUESS value but are generally within the same magnitude. The Copper Falls till unit and shallow bedrock zones have similar transmissivity to TGUESS (2,300 $ft^2$/d vs. 1,400 $ft^2$/d for glacial wells; 400 $ft^2$/d vs. 100 $ft^2$/d for bedrock).

The head and baseflow targets are well matched by the calibrated model (figs. 11–14). Results by head group are shown in table 15. Simulated water levels generally matched weighted head targets throughout the entire range in measured water levels (fig. 11). Head targets in the high-relief bedrock ridges north of the Great Divide District are poorly simulated. These local areas may have various aquifer base elevations or thickness, vertical gradients, or perched conditions, which cannot be represented in the regional model with a single base elevation and large, piecewise-constant parameter zones. Additional refinement of the model would be necessary for this area to be studied in detail. Baseflow targets (fig. 12) also matched well.

Although groundwater discharge 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 areas in the unit mapped as wetland (Wisconsin Department of Natural Resources, 2011). Simulated flooding in the calibrated model shows good agreement with the mapped wetlands (fig. 13).

## Application of the model

The GFLOW groundwater flow model is a useful decision-support tool for groundwater management in the Washburn/Great Divide Unit. Hydraulic heads simulated by the two models were merged into one raster to evaluate the water table continuously in 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 CNNF units.

The GFLOW model can 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, while many small tributaries surrounding the Washburn District are modeled as dry (no baseflow component); a few streams are modeled as losing to the aquifer. The plate also shows thickness of the saturated aquifer and alkalinity and electric conductivity of surface-water samples. Groundwater-dominated samples (higher values of alkalinity and electric conductivity) correspond to areas modeled by GFLOW as groundwater discharge points, whereas surface-runoff–dominated samples are typically located in upland recharge areas. Features that do not follow this pattern could indicate local hydrogeologic conditions that are not well represented by the regional GFLOW model. This combination of flow modeling and geochemistry can be used as a guide for future modeling and site-specific investigations.

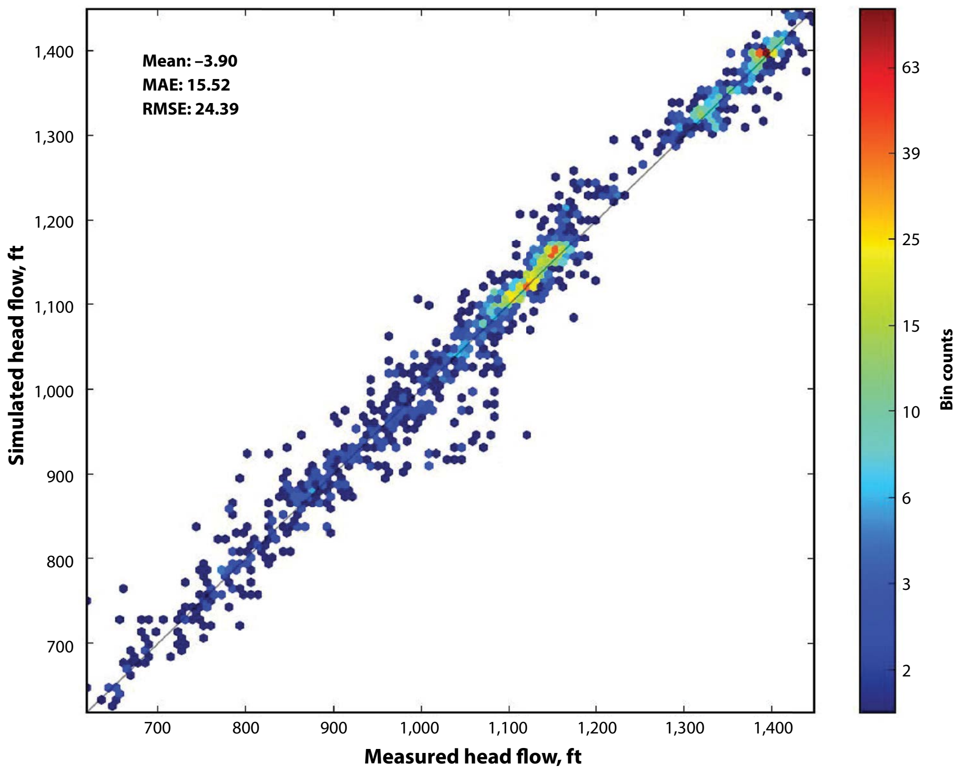
The model can also be used to compute flow paths through the groundwater system from discrete starting locations to discharge points (such as streams or wells). Starting locations are specified in the GFLOW graphical user interface as hypothetical particles; the paths of the particles are then traced through the groundwater flow system and shown in the model output. Computation of particle travel times requires specification 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 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 water-table map, along with pathlines generated from each model (plates 10a,b), shows general directions of groundwater flow and can be used to delineate divides between groundwater basins. The water table generally follows the land surface, sloping gently south in the southern Great Divide District and steeply north near the northern edge of the Washburn/Great Divide Unit. In Washburn District, the water table is high in the outwash barrens and slopes downward towards Lake Superior. Groundwater flow paths are short in Great Divide where the glacial aquifer is thin and discharges to local streams soon after recharging; flow paths are much longer in the interior of the Bayfield Peninsula, an area largely devoid of streams. In this area, containing mostly higher-elevation sand barrens, the water table is relatively deep (50–100 feet below the surface) and the unsaturated zone is thick and permeable. Groundwater recharge is rapid in this area and flow paths are longer because few surface-water features intersect the water table.

**Figure 11.** Simulated vs. observed heads for weighted head targets plotted against 1:1 line (a) Washburn District model and (b) Great Divide District model, Chequamegon-Nicolet National Forest, Wisconsin. Dot color denotes density of data points.

**A. Washburn District**




**B. Great Divide District**

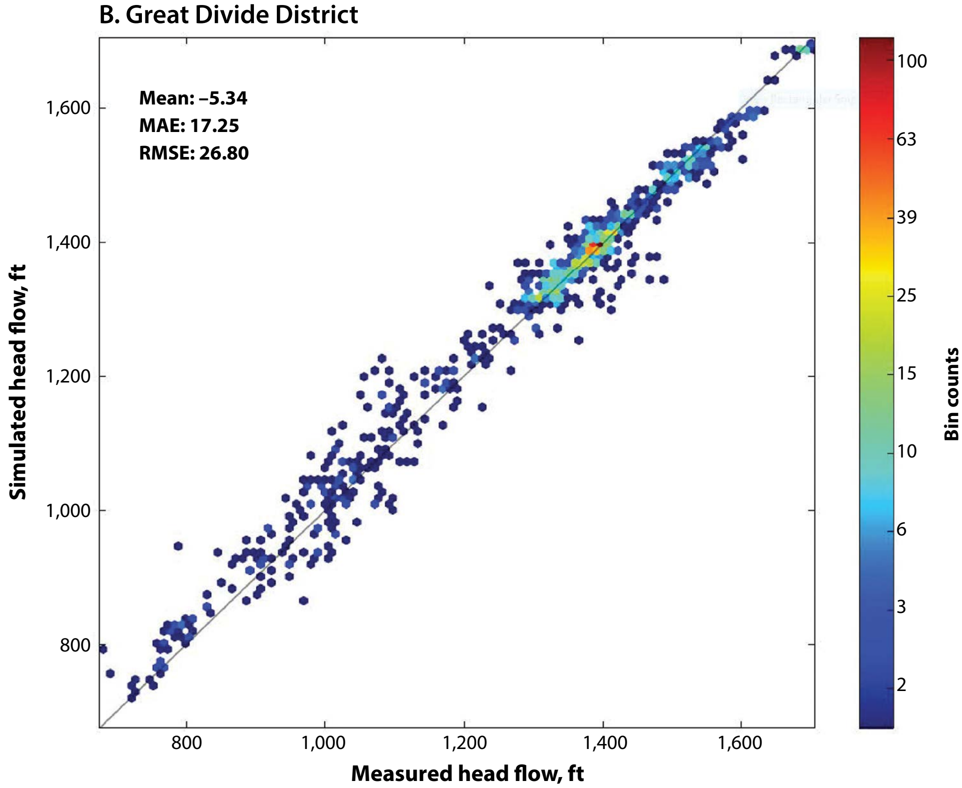
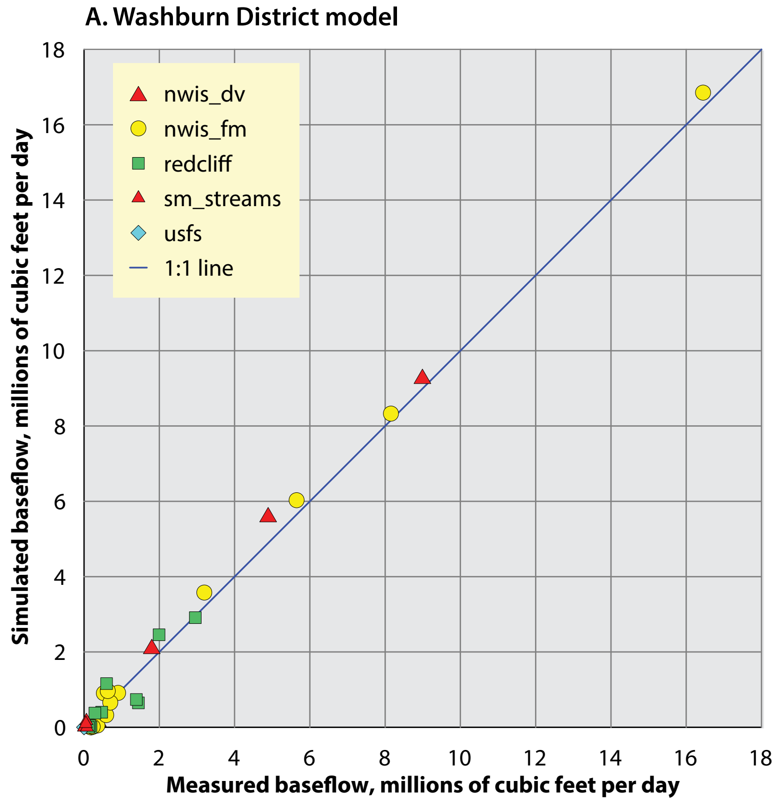


**Figure 12.** Simulated vs. observed flows plotted against 1:1 line for (a) Washburn District model and (b) Great Divide District model, Chequamegon-Nicolet National Forest, Wisconsin. See table 14 for definitions and additional descriptions of target groups (indicated by different scatter point symbols).



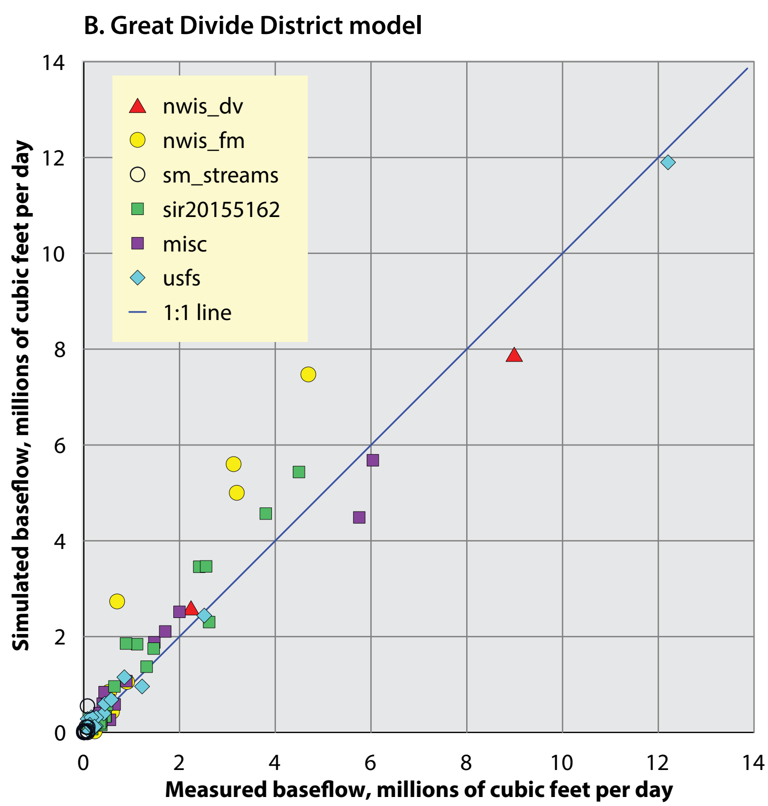



**Figure 13a.** GFLOW results for Washburn District model: weighted head target residuals and simulated heads above land surface (flooding) compared to wetlands listed in inventory of Wisconsin wetlands.

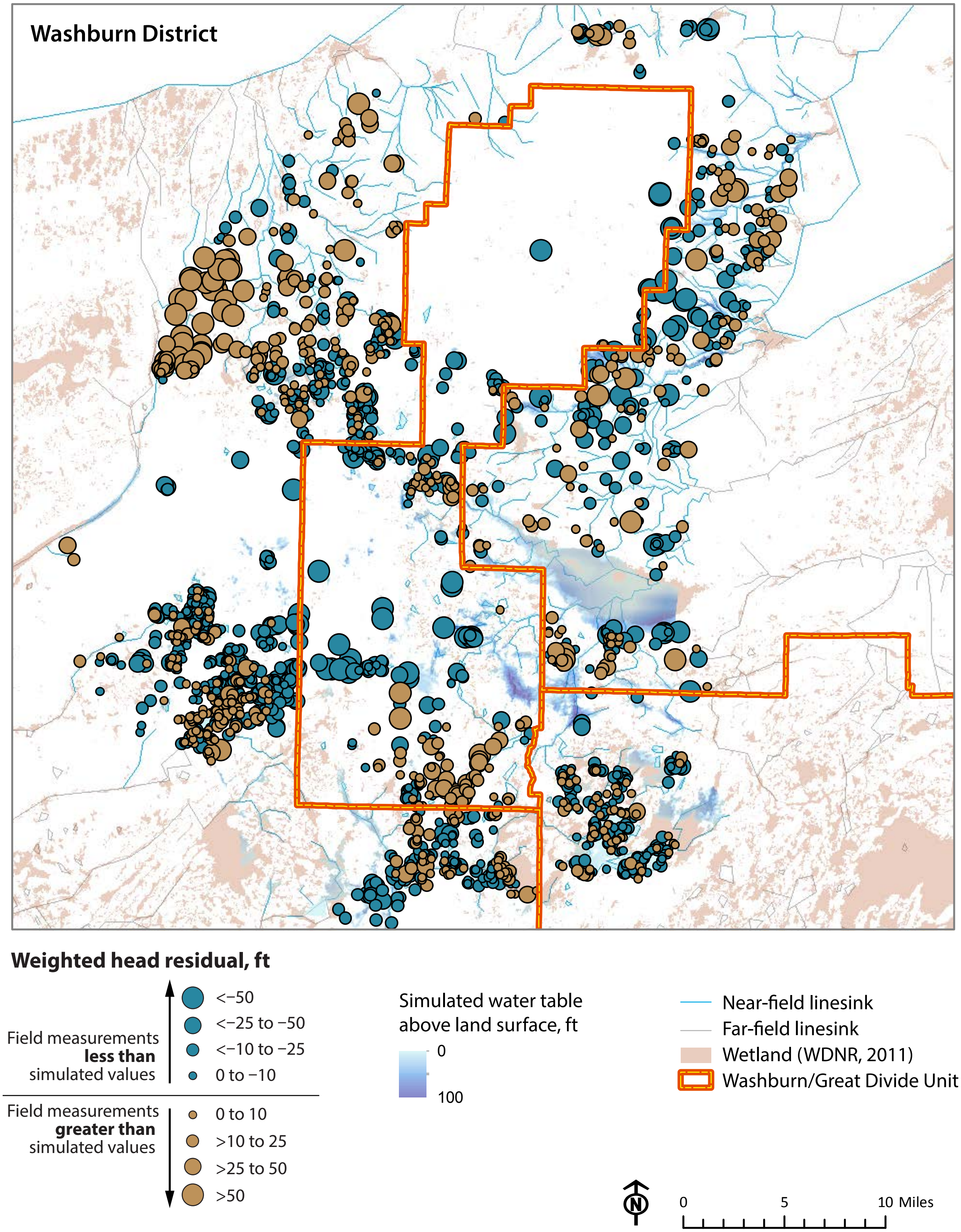


**Figure 13b.** GFLOW results for Great Divide District model: weighted head target residuals and simulated heads above land surface (flooding) compared to wetlands listed in inventory of Wisconsin wetlands.

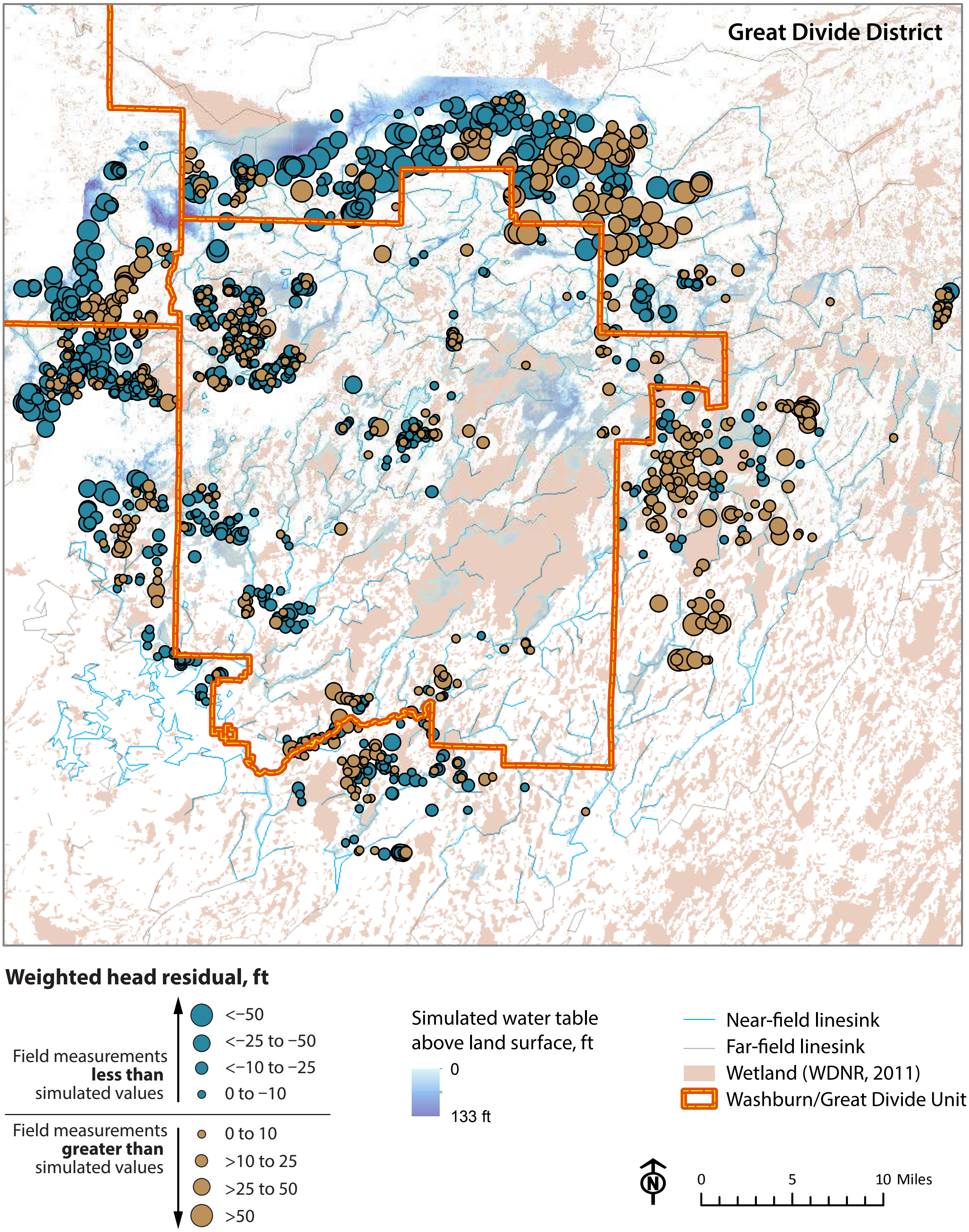


**Figure 14a.** GFLOW results for Washburn District model: weighted flow target residuals.

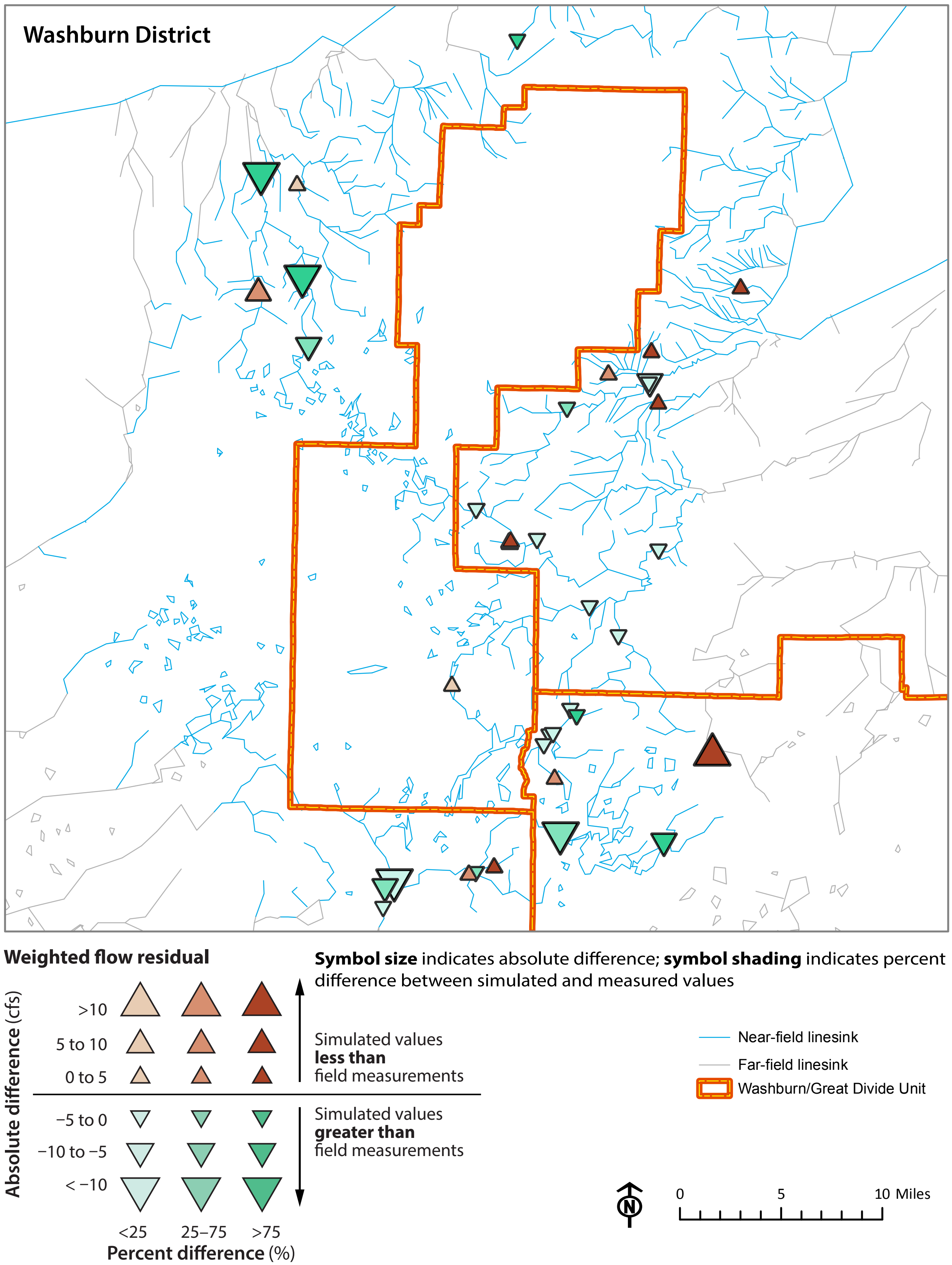
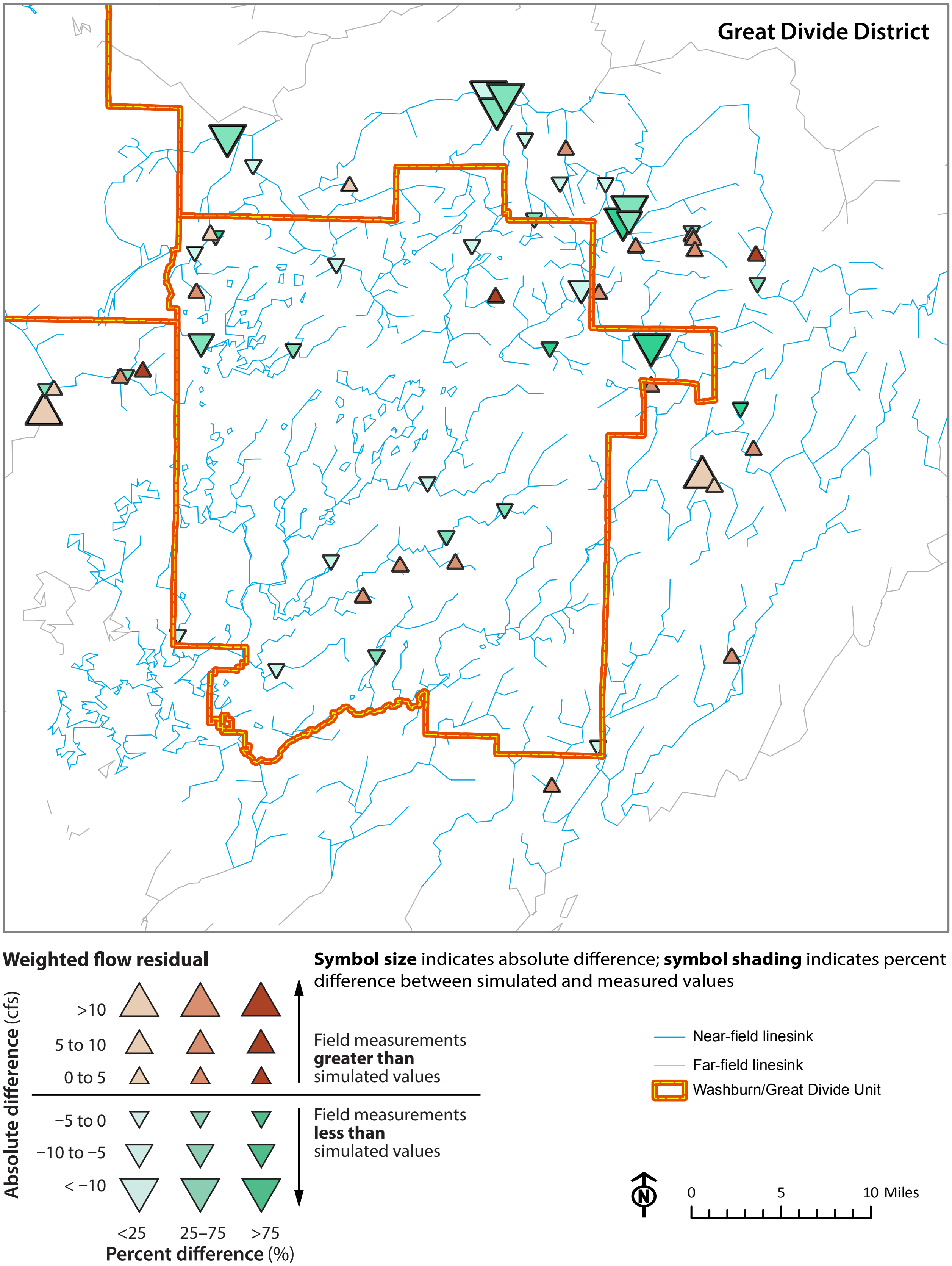


**Figure 14b.** GFLOW results for Great Divide District model: weighted flow target residuals.



The GFLOW model has many other potential uses:

- Delineating areas contributing groundwater to specific springs, lakes, wells, and streams;
- Identifying areas where groundwater divides may differ from surface-water divides;
- Evaluating where streams are simulated as gaining or losing groundwater under different climatic or land-use conditions;
- Determining the expected drawdown and zone of influence of any proposed high-capacity well in or near the Washburn/Great Divide Unit;
- Quantifying the effect of any proposed high-capacity well on water levels and flows in nearby surface-water features;
- Identifying potential migration direction of contaminants released 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.

## Assumptions and limitations

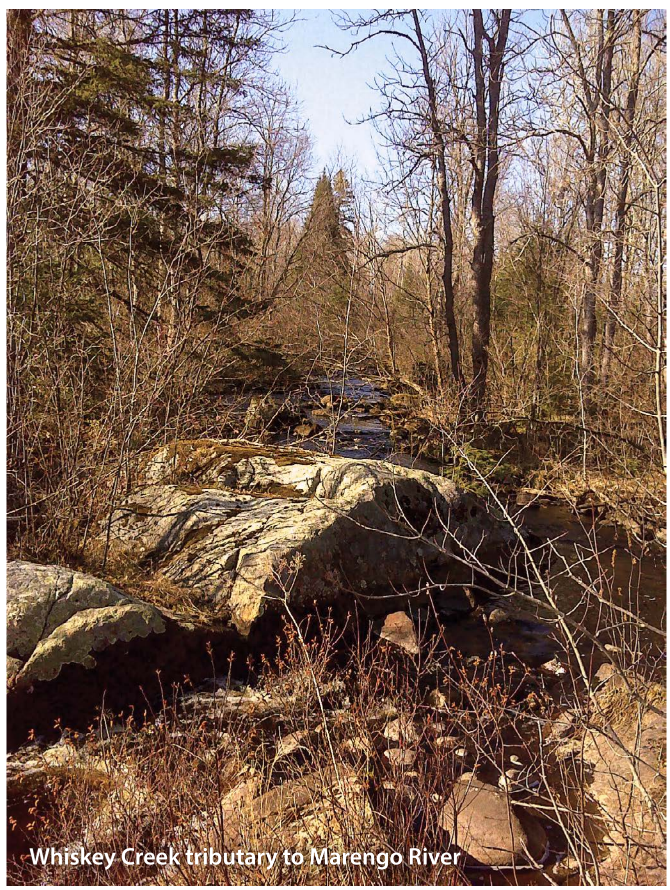
We assumed that the Washburn/Great Divide Unit groundwater and surface-water systems are in close hydraulic connection in the modeled area; this assumption is consistent with the relatively transmissive nature of the unlithified sediments, high net-annual precipitation, the presence of springs and perennial headwater streams, and previous modeling in nearby areas. It follows then that modeling assumes that the elevations of surface-water features in fact represent the groundwater system; but perched systems (areas where an unsaturated zone lies beneath an upper water table) are not well represented. Model calibration could be in error if the model was calibrated to water levels representing shallow wetlands or perched systems rather than the true water table; determining areas that might have been miscalibrated would require additional field study beyond the scope of this project. 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 a distance equivalent to two to three aquifer thicknesses from a surface-water feature (Haitjema, 1995; Hunt and others, 2003), simulated groundwater levels near surface-water features can be considered approximate only. We assumed that all pumping wells represented in the model penetrate the full aquifer thickness. This assumption may produce a positive bias in simulated heads near pumping wells, especially where the wells 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 of hydrogeologic properties. 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. Also, it must be kept in mind that the model is designed and calibrated for groundwater flow in a single aquifer consisting of unconsolidated sediments above shallow fractured bedrock; it should not be used to estimate groundwater flow in deeper bedrock systems. Additional field investigation and model refinement are needed to accurately simulate processes that are sensitive to local aquifer heterogeneity.

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 0.3 d is similar to values in other Washburn/Great Divide Unit models created for this project, as well as 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 (see Haitjema, 1995, p. 293).

## Recommendations for future modeling

Additional data collection and advances in modeling techniques will improve the ability to incorporate more detail into future models. Local areas of interest could be studied in greater detail by refining the linesink strings within the analytic element model or by creating a finite difference inset model (Hunt and others, 1998). Calibration targets in the Washburn/Great Divide Unit are sparse; additional measurements of baseflow and groundwater levels along with additional characterization of water chemistry would help refine model results. Additional subsurface data in the unit as well as modern maps of glacial deposits may reveal more detailed patterns in hydraulic conductivity that are not currently visible. While transmissivity and hydraulic conductivity in the unit vary spatially (plates 1–3), data is 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 detail in hydraulic conductivity could be readily incorporated into finite difference inset models.



Whiskey Creek tributary to Marengo River

Ken Bradbury

# Summary

The primary aquifer in the Washburn/Great Divide Unit consists of glacial outwash and till. This aquifer ranges from zero to more than 600 ft thick and is absent in local areas; generally, the aquifer is thicker in the Washburn District. The aquifer is sufficient to supply water to low-capacity domestic wells, with a mean estimated hydraulic conductivity of 32 ft/d and a range of 0.02 to 1,900 ft/d. The glacial aquifer has the potential to support high-capacity wells in some areas; the approximate average potential yield is 200 gpm.

Bedrock beneath the glacial materials, generally consisting of sandstone in the north and crystalline rock in the south, can supply adequate water to low-capacity wells in areas where the glacial deposits are too thin or too fine grained. The bedrock aquifer has mean estimated hydraulic conductivities about an order of magnitude lower than that of the overlying glacial deposits. Wells with very high hydraulic conductivity in bedrock are likely drawing water from large fractures or fracture zones. The crystalline bedrock aquifer has little likelihood of supporting high-capacity wells; its approximate average potential yield is about 20 gpm.

Few high-capacity wells are present in this region. The 14 active high-capacity wells in the unit all obtain their water from the glacial aquifer. Although each well is permitted to pump more than 70 gpm, the majority pump at much lower rates (the combined average 2011–2014 pumping rate in the unit was 23 gpm).

About 85 percent of the domestic wells within the Washburn/Great Divide Unit are screened in the glacial aquifer at an average depth of 70 ft. Of the bedrock wells, most pump from the top 120 ft of bedrock, although some pump from as deep as 400 ft.

The SWB-modeled mean potential recharge is moderately high (10.4 in/yr), with means of 12.4 in the Washburn District and 9.3 in the Great Divide District. Recharge varies spatially, primarily correlating with surficial geology through soil characteristics. The SWB model may overestimate recharge in wetlands; the assumption of zero recharge in wetlands produces an average unit-wide potential recharge of 9.5 in/yr. During calibration of the groundwater flow model, a regional multiplier that was applied to the SWB grid produced an overall mean recharge value of 11.1 in/yr for Washburn District and 8.8 in/yr for Great Divide District.

Water quality within the unit is generally unaltered by human activity. Slightly elevated nutrient concentrations were observed at certain sample locations, likely as a result of local land-use activities.

Groundwater in the Washburn/Great Divide 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 183 µS/cm and alkalinity of 83 mg/L, whereas lake samples have averages of 58 µS/cm and 28 mg/L, respectively. Among the lakes, the chemistry suggests that some lakes having very low conductivity and alkalinity (such as Horseshoe Lake, Twin Lakes, Perch Lake) are dominated by precipitation and runoff and receive little or no groundwater, whereas lakes having higher values of these parameters (such as Lake Owen, Black Lake) have a considerable groundwater component. Isotopes of hydrogen and oxygen can also be used to distinguish groundwater, which is isotopically lighter, or more negative, than surface water.

A regional surface-water divide splits the unit roughly in two across the Great Divide District; most of Washburn District drains north to Lake Superior and Great Divide District drains south to the Mississippi River. Although groundwater divides in general follow topography and are similar to surface-water divides, they are not necessarily identical in this unit. One important use of the GFLOW model is to delineate groundwater basins appropriate for specific hydrologic features such as individual lakes, streams, or springs.

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 between groundwater and 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 Washburn/Great Divide Unit. The data and models presented in this report can help guide future data collection to improve the understanding of groundwater resources within the CNNF. Data collection should focus on areas of interest, areas with no nearby wells, or areas that are poorly simulated by the groundwater flow model. Key areas lacking adequate information are as follows:

In the Washburn District the higher-elevation sand barrens west of the Village of Washburn are nearly devoid of hydrogeologic data yet represent an important recharge area for the surrounding forest and for streams flowing into Lake Superior. Water sample analyses show that groundwater in this area is nearly pristine, and it is important to maintain this excellent groundwater quality in such an important recharge area where many groundwater flow paths originate (see plates 9a,10a). In much of this area, depth to bedrock and aquifer thickness are uncertain (see plates 5a, 6a). In order to improve the understanding of this important resource, future studies of the area should determine depth to bedrock, install monitoring wells to measure groundwater elevations and vertical hydraulic gradients, and prepare one or more hydrogeologic cross sections across the Bayfield Peninsula.

Little hydrogeologic data is available in an area of very shallow crystalline bedrock along the Penokee Range in the northern portion of the Great Divide Unit District. Bedrock fractures likely dominate groundwater flow in this region, but detailed evaluation of fractured-rock hydrogeology in this area was beyond the scope of this project, and the modeling techniques described in this report have only limited applicability in this terrane. An improved understanding the hydrogeology of these materials will be increasingly important if the area remains a potential candidate for hardrock mineral exploration.

Likewise, hydrogeologic data are extremely sparse in the eastern half of the Great Divide District (see plates 4b, 5b), and aquifer properties and aquifer thicknesses are very uncertain there.

Recommended future activities include the following.

- Develop modern maps of the Quaternary geology of the Washburn/Great Divide Unit at a scale of 1:100,000. Good Quaternary maps are essential for evaluating and delineating hydrogeologic characteristics at larger scales. In 2016, the most recent Quaternary map of the unit is that by Clayton (1985) of the Superior region. Although this map covers most of the Bayfield Peninsula, its scale (1:250,000) is too generalized for detailed hydrogeologic study. Areas of the unit outside of this map lie in Rusk and Sawyer Counties; in these areas the only available Quaternary maps are land type association maps that are based on ecological characteristics.
- Conduct focused studies on the hydrology of the higher-elevation sand barrens west of the Village of Washburn. The barrens are a unique hydrologic environment that provides recharge to the surrounding Bayfield Peninsula. The limited groundwater samples available for this area suggest that groundwater there is essentially pristine, but it is vulnerable to contamination because of rapid flow paths and potentially little contaminant attenuation in the unsaturated sand. Construction of a detailed hydrogeologic cross section across the Bayfield Peninsula, based on new data from monitoring wells and geophysical surveys, would greatly increase the hydrogeologic understanding of this important and unique area.
- Likewise, we recommend focused hydrogeologic studies in areas of near-surface bedrock in portions of the Penokee Range in the northern portion of the Great Divide District. This is an area of potential interest for future hardrock mining; characterizing the resource now will provide a far improved basis for decision making and an understanding of the resource as future management challenges arise.
- Maintain at least one monitoring well in each unit to provide baseline groundwater-level data.
- Measure baseflow and groundwater levels to improve groundwater flow model calibration.
- Obtain additional subsurface data, including subsurface drilling or geophysics, to constrain bedrock surface and hydraulic conductivity estimates as suggested above.
- In constructing groundwater models for smaller areas, use water chemistry to help identify surface waters that are clearly fed by groundwater.

# Data availability

The results of the inventory, modeling, and analysis described in this report are available in an electronic database (table 16). These data can be downloaded from the WGNHS web site at https://wgnhs.uwex.edu/.

**Table 16.** Summary of available electronic data, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin

| Data | Name | Format | Description/source |
|---|---|---|---|
| **Wells** | | | |
| Located wells | WGD_LocWCRs_WGNHS_2016 | Point features | Data points from WCRs located to within the quarter–quarter section and from geologic records |
| Monitoring well construction | Well construction information–Washburn–Great Divide.pdf | PDF | Location, geologic records and well construction for monitoring wells BA-241, BA-242, and AS-54 |
| Monitoring wells BA–241, BA–242 | WGD_PigeonLakeWells_WGNHS_2016 | Point features | Location of monitoring wells BA–241 and BA–242 at Pigeon Lake |
| Monitoring well AS–54 | WGD_AS54_WGNHS_2016 | Point features | Location of monitoring well AS–54 in Ashland County |
| **Geology** | | | |
| Bedrock elevation contours | WGD_BedElev_WGNHS_2016 | Polyline features | Interpolated from WCRs and other data |
| Depth to bedrock contours | WGD_BedDep_WGNHS_2016 | Polyline features | Interpolated from WCRs and other data |
| Saturated thickness contours of glacial materials | WGD_GlacSatThickness_WGNHS_2016 | Polyline features | Interpolated from WCRs and other data |
| **Hydraulic properties** | | | |
| Bedrock hydraulic properties | WGD_BedTGUESS_WGNHS_2016 | Point features | Hydraulic conductivity and transmissivity results from TGUESS |
| Glacial hydraulic properties | WGD_GlacTGUESS_WGNHS_2016 | Point features | Hydraulic conductivity and transmissivity results from TGUESS |
| **Recharge** | | | |
| Mean annual potential recharge | WGD_PoRec_WGNHS_2016 | Raster data | Annual recharge mean of all modeled years from SWB model output |
| Annual potential recharge, individual years | WGD_PoRec[yyyy]_WGNHS_2016, e.g. WGD_PoRec2000_WGNHS_2016 | Raster data | Annual potential recharge for years 2000–2010 (11 files) from SWB model output |
| Calibrated recharge grids | WGD_RechGFLOW_Wash_WGNHS_2016 WGD_RechGFLOW_GD_WGNHS_2016 | Raster data | Annual recharge applied to GFLOW model, calibrated from SWB results |
| **Groundwater** | | | |
| Simulated water table contours | WGD_WatTabGFLOW_WGNHS_2016 | Polyline features | GFLOW model output, merged into one coverage |
| Gaining and losing streams | WGD_BaseflowGFLOW_Wash_WGNHS_2016, WGD_BaseflowGFLOW_GD_WGNHS_2016 | Polyline features | GFLOW model output |
| Simulated groundwater flow paths | WGD_GWFlowpathGFLOW_Wash_WGNHS_2016, WGD_GWFlowpathGFLOW_GD_WGNHS_2016 | Polyline features | GFLOW model output |

*(continued)*

**Table 16.** Summary of available electronic data, Washburn/Great Divide Unit, Chequamegon-Nicolet National Forest, Wisconsin *(cont.)*

| Data | Name | Format | Description/source |
|---|---|---|---|
| **Geochemistry** | | | |
| Geochemistry sampling locations | WGD_GeochemSites_WGNHS_2016 | Point features | WGNHS water sampling locations |
| Geochemistry results | WGD_Geochemistry_WGNHS_2016 | Excel | Field and laboratory water sample results |
| **Model** | | | |
| GFLOW targets | WGD_TargetsGFLOW_Wash_WGNHS_2016, WGD_TargetsGFLOW_GD_WGNHS_2016 | Point features | Simulated and measured values for GFLOW baseflow and head targets |
| USGS model data archive | https://dx.doi.org/10.5066/F708648W | Model files | Groundwater flow models and associated files |


Old dug well at St. Peter's Dome State Natural Area

Ken Bradbury

# References


Anderson, M.P., Woessner, W.W., and Hunt, R.J., 2015, Applied groundwater modeling—Simulation of flow and advective transport (2nd ed.): Academic Press, Inc., 564 p.

Batten, W.G., and Lidwin, R.A., 1995, Water resources of the Bad River Indian Reservation, northern Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 95-4207, 45 p.

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

Cannon, W.F., LaBerge, G.L., Klasner, J.S., and Schulz, K.J., 2007, The Gogebic iron range—A sample of the northern margin of the Penokean fold and thrust belt: U.S. Geological Survey Professional Paper 1730, 44 p.

City of Shell Lake, 2016, Shell Lake water levels: City of Shell Lake, http://www.shelllake.org/find-your-fun/the-lake/lake-levels/, accessed June 17, 2016.

Clayton, L., 1985, Pleistocene geology of the Superior region, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 46, 40 p., 1 pl, scale 1:250,000.

Devaul, R.W., 1975, Probable yields of wells in the sand-and-gravel aquifer, Wisconsin: Wisconsin Geological and Natural History Survey Map M054, scale 1:1,000,000.

Doherty, J., 2011, PEST, Model-independent parameter estimation user manual (5th ed.), and addendum: Brisbane, Queensland, Australia, Watermark Numerical Computing, 217 p.

Doherty, J., and Hunt, R.J., 2009, Two statistics for evaluating parameter identifiability and error reduction: Journal of Hydrology, v. 366, no. 1-4, p. 119–127., doi:10.1016/j.jhydrol.2008.12.018.

Doherty, J.E., and Hunt, R.J., 2010, Approaches to highly parameterized inversion—A guide to using PEST for groundwater-model calibration: U.S. Geological Survey Scientific Investigations Report 2010–5169, 60 p.

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

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

Fienen, M.N., Feinstein, D.T., Dunning, C.P., Leaf, A.T., and Buchwald, C.A., 2016, Simulation of the ground-water-flow system of the Bayfield Peninsula focusing on the Red Cliff Reservation, Bayfield County, Wisconsin: U.S. Geological Survey Administrative Report, 63 p.

Fitzpatrick, F.A., Peppler, M.C., Schwar, H.E., Hoopes, J.A., and Diebel, M.W., 2005, Monitoring channel morphology and bluff erosion at two installations of flow-deflecting vanes, North Fish Creek, Wisconsin, 2000–03: U.S. Geological Survey Scientific Investigations Report 2004–5272, 34 p.

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

Gillies, S., 2013, The Shapely user manual, http://toblerity.org/shapely/manual.html, accessed June 9, 2016.

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

Haitjema, H.M., 2005, Dealing with resistance to flow in surface waters, Haitjema Software, http://www.haitjema.com/documents/Dealingwithresistancetoflowintosurfacewaters.pdf, 9 p., accessed June 13, 2016.

Haitjema, H.M., 2015, Hybrid GFLOW-MODFLOW modeling sequential coupling only, Haitjema Software, http://www.haitjema.com/documents/ Hybrid_GFLOW MODFLOW_Modeling.pdf, 17 p., accessed October 5, 2016.

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

Hart, D.J., Schoephoester, P.R., and Bradbury, K.R., 2012, Groundwater recharge in Dane County, Wisconsin—Estimating recharge using a GIS-based water-balance model: Wisconsin Geological and Natural History Survey Bulletin 107, 11 p., https://wgnhs.uwex.edu/pubs/000130/.

Hunt, R.J., 2006, Ground water modeling applications using the analytic element method: Ground Water, v. 44, no. 1, p. 5–14.

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

Hunt, R.J., Haitjema, H.M., Krohelski, J.T., and Feinstein, D.T., 2003, Simulating ground water-lake interactions—Approaches and insights: Ground Water, v. 41, no. 2, p. 227–237, doi:10.1111/j.1745-6584.2003.tb02586.x.

Hunt, R.J., Juckem, P.F., and Dunning, C.P., 2010, Simulation of the shallow groundwater-flow system near the Hayward Airport, Sawyer County, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2010–5049, 14 p., http://pubs.usgs.gov/sir/2010/5049/.

Institute of Hydrology, 1980, Low flow studies report no. 3—Research report: Wallingford, Oxon, United Kingdom, Institute of Hydrology Report no. 3, p. 12–19.

Juckem, P.F., and Dunning, C.P., 2015, Simulation of the regional groundwater-flow system of the Menominee Indian Reservation, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2014–5237, 40 p., doi:10.3133/sir2014523777.

Juckem, P.F., and Hunt, R.J., 2007, Simulation of the shallow ground-water-flow system near Grindstone Creek and the Community of New Post, Sawyer County, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2007–5014, 29 p.

Juckem, P.F., and Hunt, R.J., 2008, Simulation of contributing areas and surface-water leakage to potential replacement wells near the community of New Post, Sawyer County, Wisconsin, by means of a two-dimensional ground-water-flow model: U.S. Geological Survey Open-File Report 2008–1133, 12 p.

Juckem, P.F., and Robertson, D.M., 2013, Hydrology and water quality of Shell Lake, Washburn County, Wisconsin, with special emphasis on the effects of diversion and changes in water level on the water quality of a shallow terminal lake: U.S. Geological Survey Scientific Investigations Report 2013–5181, 77 p., doi:10.3133/sir20135181.

Juckem, P.F., Fienen, M.N., and Hunt, R.J., 2014, Simulation of groundwater flow and interaction with surface water on the Lac du Flambeau Reservation, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2014–502, 34 p., doi:10.3133/sir20145020.0.

Kelson, V.A., Hunt, R.J., and Haitjema, H.M., 2002, Improving a regional model using reduced complexity and parameter estimation: Ground Water, v. 40, no. 2, p. 132–143.

Krabbenhoft, D.P., Anderson, M.P., Bowser, C.J., and Valley, J.W., 1990, Estimating groundwater exchange with lakes—1. The stable isotope mass balance method: Water Resources Research, v. 26, no. 10, p. 2445–2453.

Krohelski, J.T., Rose, W.J., and Hunt, R.J., 2002, Hydrologic investigation of Powell Marsh and its relationship to Dead Pike Lake Vilas County, Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 02–4034, 21 p.

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

Leaf, A.T., Fehling, A., Bradbury, K.R., Hunt, R.J., and Juckem, P.F., 2019a, GFLOW groundwater flow model for the Great Divide Unit of the Chequamegon-Nicolet National Forest, WI: U.S. Geological Survey data release, doi:10.5066/F708648W.

Leaf, A.T., Fehling, A., Bradbury, K.R., Hunt, R.J., and Juckem, P.F., 2019b, GFLOW groundwater flow model for the Washburn Unit of the Chequamegon-Nicolet National Forest, WI: U.S. Geological Survey data release, doi:10.5066/F7VH5MS6.

Lenz, B.N., Saad, D.A., and Fitzpatrick, F.A., 2003, Simulation of ground-water flow and rainfall runoff with emphasis on the effects of land cover, Whittlesey Creek, Bayfield County, Wisconsin, 1999–2001: U.S. Geological Survey Water-Resources Investigations Report 03–4130, 47 p.

Macholl, J.A., 2007, Inventory of Wisconsin's springs: Wisconsin Geological and Natural History Survey Open-File Report 2007-03, 1 CD-ROM.

McKay, L., Bondelid, T., Dewald, T., Johnston, J., Moore, R., and Rea, A., 2012, NHDPlusVersion2—User guide: Horizon Systems, http://www.horizon-systems.com/nhdplus/NHDPlusV2_documentation.php, accessed November 15, 2014.

Mudrey, M.G. Jr., Brown, B.A., and Greenberg, J.K., 1982, Bedrock geology of Wisconsin: Wisconsin

Geological and Natural History Survey Regional Map M078, 1 sheet, scale 1:1,000,000.

Mudrey, M.G. Jr., LaBerge, G.L., Myers, P.E., and Cordua, W.S., 1987, Bedrock geology of Wisconsin, Northwest sheet: Wisconsin Geological and Natural History Survey Regional Map M094, 2 sheets, scale 1:250,000.

National Centers for Environmental Information, 2016, U.S. daily surface data: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, http://www.ncdc.noaa.gov, accessed October 2011 and June 2016.

Natural Resources Conservation Service, 2011a, Watershed boundary dataset for Wisconsin: U.S. Department of Agriculture, Natural Resources Conservation Service, http://datagateway.nrcs.usda.gov, accessed 2011.

Natural Resources Conservation Service, 2011b, Soil Survey Geographic (SSURGO) database for Ashland, Bayfield, Douglas, Iron, Price, Sawyer, and Washburn Counties, Wisconsin: U.S. Department of Agriculture, Natural Resources Conservation Service, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053627, accessed October 2011.

Pint, C.D., Hunt, R.J., and Anderson, M.P., 2003, Flow path delineation and ground water age, Allequash Basin, Wisconsin: Ground Water, v. 41, no. 7, p. 895–902, doi:10.1111/j.1745-6584.2003.tb02432.x.

Poeter, E.P., and Hill, M.C., 1997, Inverse models—A necessary next step in ground-water modeling: Ground Water, v. 35, no. 2, p. 250–260.

Richmond, G.M., and Fullerton, D.S., eds., 2001, Quaternary geologic map of the Lake Superior 4° × 6° quadrangle, United States and Canada: U.S. Geological Survey Miscellaneous Investigations Series I–1420 (NL–16), scale 1:1,000,000.

Richmond, G.M., and Fullerton, D.S., eds., 2007, Quaternary geologic map of the Minneapolis 4° × 6° quadrangle, United States and Canada: U.S. Geological Survey Miscellaneous Investigations Series I–1420 (NL–15), scale 1:1,000,000.

Robertson, D.M., Garn, H.S., Rose, W.J., Juckem, P.F., and Reneau, P.C., 2012, Hydrology, water quality, and response to simulated changes in phosphorus loading of Mercer Lake, Iron County, Wisconsin, with emphasis on effects of wastewater discharges on water quality: U.S. Geological Survey Scientific Investigations Report 2012–5134, 58 p.

U.S. Geological Survey, 2011, USGS water data for the Nation—Help: Discharge measurement quality code, accessed October 7, 2016, at https://help.waterdata.usgs.gov/codes-and-parameters/discharge-measurement-quality-code.

U.S. Geological Survey, 2013, National elevation dataset—Digital elevation data for Wisconsin: U.S. Geological Survey, http://ned.usgs.gov. Wisconsin 10-m data received from USGS in 2003, 30-m data accessed May 2013.

Wahl, K.L., and Wahl, T.L., 1988, Effects of regional ground-water level declines on streamflow in the Oklahoma Panhandle, *in* Proceedings of the Symposium on Water-Use Data for Water Resources Management, American Water Resources Association, Bethesda, Maryland, p. 239–249.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB—A modified Thornthwaite-Mather soil-water-balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods 6–A31, 60 p.

Wisconsin Department of Natural Resources, 1998, WISCLAND 1.0 Wisconsin Land Cover Data: Wisconsin Department of Natural Resources, http://dnr.wi.gov/maps/gis/datalandcover.html, accessed 2011.

Wisconsin Department of Natural Resources, 1999, Wisconsin Land Type Associations: Wisconsin Department of Natural Resources, http://dnr.wi.gov/maps/gis/documents/land_type_associations.pdf, accessed 2007.

Wisconsin Department of Natural Resources, 2011, Wisconsin wetland inventory: Wisconsin Department of Natural Resources, http://dnr.wi.gov/topic/wetlands/inventory.html, accessed 2011.

Wisconsin Department of Natural Resources, 2016, Water well data disk: Wisconsin Department of Natural Resources, Public Water Supply Section, CD-ROM.

Wisconsin Geological and Natural History Survey, 2012, wiscLITH—A digital lithologic and stratigraphic database of Wisconsin geology (vers. 3): Wisconsin Geological and Natural History Survey Open-File Report, CD-ROM, accessed 2012.

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

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