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

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Prepared in cooperation with the U.S. Geological Survey

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List of abbreviations

CNNF	**Chequamegon-Nicolet National Forest**
DEM	**digital elevation model**
SWB	**soil-water balance**
USFS	**U.S. Forest Service**
USGS	**U.S. Geological Survey**
WCR	**well construction report**
WDNR	**Wisconsin Department of Natural Resources**
WGNHS	**Wisconsin Geological and Natural History Survey**

Executive summary

The Chequamegon-Nicolet National Forest (CNNF) in northern Wisconsin contains many groundwater-dependent water resources such as streams, lakes, springs, and wetlands. However, hydrogeologic data in this national forest are sparse, and to date there has been no comprehensive analysis of the 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 groundwater–surface-water system and the development of tools to evaluate the sensitivity of hydrologic flows and temperature to future climate and land-use changes. To address these issues, in 2010 the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS), cooperatively with the U.S. Forest Service (USFS), began to review and analyze groundwater resources in the CNNF. The study was divided by location 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 Park Falls Unit in Price and Vilas Counties, Wisconsin.

The project inventoried available data and developed tools to improve the understanding of aquifer characteristics and the groundwater flow regime, more clearly define groundwater–surface-water interactions, evaluate the vulnerability of aquatic resources to climate change, and provide a basis to support future studies in this national forest.

The four primary objectives 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 aquifer hydraulic properties 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.
4. **Groundwater flow model**. Construct a groundwater flow model, which can be used to develop a water-table map and to evaluate future water-use and land-management scenarios.

In the initial portion of the study, we inventoried and analyzed available hydrogeologic data, which were then assembled into a spatial database. Data sources included well construction reports, published locations of bedrock outcrops, published water-table maps, groundwater-level measurements, high-capacity well pumping rates, and a geophysical survey. These data were analyzed to produce maps of bedrock elevation, depth to bedrock, and aquifer saturated 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 unlithified glacial till and outwash deposits overlying Precambrian crystalline bedrock. The spatial analysis suggests that the surficial glacial sand and gravel deposits form a shallow, thin aquifer (less than 10 feet (ft) to 250 ft thick) with low to moderate average productivity, referred to as the "glacial aquifer" in this report. The hydraulic conductivity estimates for this aquifer ranged from 0.9 to 1,700 ft/day (ft/d); the mean is 39 ft/d. About 80 percent of wells in the Park Falls Unit obtain water from this aquifer.

The glacial aquifer has the potential to support high-capacity wells, but in general those wells could not produce much more than 100–200 gallons per minute (gpm). Precambrian rock beneath the glacial sands and gravels transmits water through fractures, but in general it is less productive than the glacial aquifer, and bedrock wells are commonly drilled in areas where the upper aquifer is thin or absent. Hydraulic conductivities in bedrock are about an order of magnitude lower than conductivities in the overlying sand and gravel. The bedrock aquifer has little likelihood of supporting high-capacity wells; the approximate average potential yield is 10 gpm. Of the bedrock wells, most pump from the top 100 ft of bedrock, although some pump from as deep as 300 ft. Specific capacities are generally low throughout the Park Falls Unit, although some wells have high yields with specific capacities (discharge divided by drawdown) greater than 10 gallons per minute per foot (gpm/ft). Few high-capacity wells are located in this area (only about 25 wells within 10 miles (mi) of the unit), and most of these wells pump from the sand and gravel aquifer. Although these wells are permitted to pump greater than 70 gpm, the majority pump at much lower rates (average 40 gpm). Water level data from two monitoring wells suggest that groundwater elevations not directly affected by human use have remained stable during the past few decades.

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 Park Falls Unit for the years 2000 through 2010. The mean overall potential recharge for this time period was 8.5 inches per year (in/yr) and ranged from 6.5 to 14 in/yr, largely owing to variable precipitation. The SWB model may overestimate recharge in wetlands, which cover about 30 percent of the unit. If zero recharge is assumed in wetlands, then an average forest-wide potential recharge of 6.8 in/yr is produced. However, it is likely that recharge in wetlands is actually greater than zero, and so the SWB-model–simulated average potential recharge in this unit is between 6.8 and 8.5 in/yr. The spatial distribution throughout the unit correlates with surficial geology through soil characteristics and, to a lesser extent, land cover. Local patterns of higher recharge are present over sandy soils and forest cover, with lower recharge over finer soils and wetland cover.

In the third part of this study, we inventoried surface-water and groundwater geochemistry, in order to obtain a representative picture of current groundwater and surface-water quality in the Park Falls 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). The results show that water in the Park Falls Unit contains low concentrations of most of these constituents and thus is relatively unaffected by human activities. Groundwater is distinguished from surface water by higher electrical conductivity and alkalinity; groundwater well samples have an average conductivity of 161 micro-Siemens per centimeter (µs/cm) and alkalinity of 83 mg/L, whereas samples interpreted as surface-water dominated have averages of 33 µs/cm and 13 mg/L, respectively. Concentrations of dissolved ions such as calcium and magnesium are also higher in groundwater. 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. Some samples contained elevated chloride, nitrate, or phosphorus, suggesting the local influence of land-use activities such as road salting.

A regional groundwater flow model was constructed for the Park Falls Unit by using the analytic element model code GFLOW. The flow model provides key aquifer properties, simulated water table elevations, flow paths, flow rates and discharge zones. Groundwater flows primarily to the west with the exception of the southeast corner of the unit, similar to the regional flow of surface water. The model can be a powerful decision-support tool for water-resource management. Potential uses for the model include delineating areas contributing groundwater to surface-water features, determining the expected drawdown from a new well, and evaluating the effects of changes in pumping or land use on streamflow and water levels.

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

Introduction

Background

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

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 groundwater–surface-water system 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) requested that the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS), cooperatively, review and analyze groundwater resources in the CNNF. This multi-year hydrogeological study presents an innovative approach to studying hydrogeology in undeveloped areas with sparse datasets. The study is divided by location into four reports corresponding to the four main CNNF contiguous land units: Medford, Nicolet, Park Falls, and Washburn/Great Divide. This report documents the results of this study within the Park Falls Unit (fig. 1), which comprises more than 280 square miles (mi^2) in Price and Vilas Counties, Wisconsin.

Purpose and goals

The purpose of this study is to integrate existing hydrologic knowledge of the entire CNNF system and to provide a comprehensive quantitative framework for describing how the 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 groundwater–surface-water interactions;
- 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.

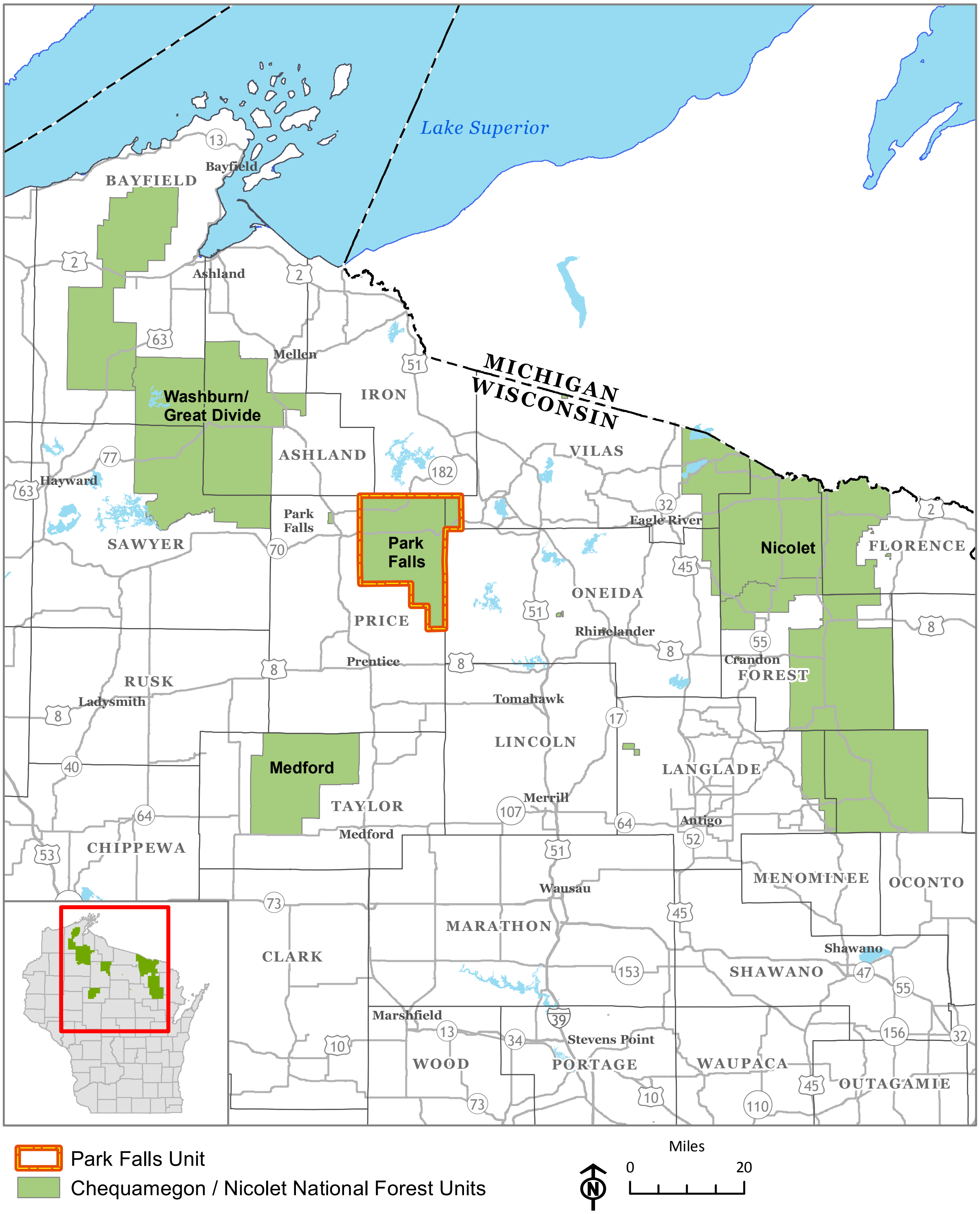
Study approach

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

1. **Hydrogeologic data**. Inventory and interpret existing hydrogeologic data in the Park Falls 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 obtain a representative picture 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 under current conditions and evaluate future hydrologic scenarios.

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

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



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

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 contributing areas to high priority surface-water reaches, and evaluate baseflow contribution distributed through the CNNF sub-basins. This study also highlights areas where more data or other types of data are needed to contribute to our understanding of the system. The analysis 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 includes a comprehensive analysis of the entire national forest. Lenz and others (2003) and Juckem and Hunt (2007, 2008) describe groundwater flow models that include the western and southwestern portion of the CNNF, respectively. Fitzpatrick and others (2005) characterized the Fish Creek watershed north of the CNNF, and Krohelski and others (2002) describe a groundwater flow model in eastern areas of the national forest. 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 the proposed Crandon Mine. WGNHS staff have mapped the Quaternary geology of portions of the CNNF, including Florence, Forest, Langlade, Oconto, Oneida, Taylor, and Vilas Counties, at the 1:100 000 scale. These county maps contain geological unit descriptions and cross sections. Modern Quaternary mapping is available at the more generalized 1:250,000 scale for Ashland, Bayfield, and limited parts of Rusk and Sawyer Counties.

Before this study, little comprehensive information was available on the geology or groundwater conditions in the Park Falls Unit. No county-scale (1:100 000) bedrock mapping is available for either Price or Vilas Counties, and no county-scale glacial map is available for Price County. The map of Mudrey and others (1987) of the bedrock geology of the northwest region of Wisconsin includes most of the Park Falls Unit. Unlike some of the other units of the CNNF, the Park Falls Unit lacks a modern map of its Pleistocene geology. The best current mapping of glacial and surficial geology of the region is contained in Land Type Associations maps available from the Wisconsin Department of Natural Resources (1999). These maps associate geologic materials and landscapes having similar ecological characteristics.

During the late 1990s, the WGNHS surveyed groundwater quality throughout Price County (Roffers and Cates, 2000) and produced a regional water-table map based on interpolation of well records (Cates and Batten, 1999). In both of these projects, data inside the Park Falls Unit were sparse. Patterson (1989) developed a county-scale groundwater report and water-table map for Vilas County, which contains the eastern part of the Park Falls Unit.

For many years (1937–1994) the USGS and WGNHS jointly collected water-level data from an observation well (PR-006) (USGS ID 455448090263401) located in Park Falls, Wisconsin, as part of a statewide groundwater monitoring network. Although it lies outside the Park Falls Unit, this well has the longest groundwater-level record in the area. Collection of water-level data from this well was discontinued in 1994. The U.S. Forest Service has actively collected ecological and surface-water data in the Park Falls Unit, such as 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 Park Falls Unit were compiled as part of a statewide springs inventory (Macholl, 2007).

Setting

The Park Falls Unit (fig. 1) spans more than 280 mi^2 in Price and Vilas Counties. Of this, approximately 240 mi^2 are owned by USFS. The unit is mostly forested and is characterized by numerous wetlands, springs, lakes, and streams; approximately 40 percent of the unit is covered by wetlands (Wisconsin Department of Natural Resources, 2011). A regional surface-water divide runs roughly northeast-southwest near the eastern boundary of the Park Falls Unit, with most surface water flowing west to the South Fork Flambeau River and only the southeast corner of the unit flowing southeast to the Wisconsin River. This divide is similar to the regional groundwater divide mapped by Cates and Batten (1999). Elevation ranges from about 1,480 ft at the eastern boundary to more than 1,700 ft in the south along the surface-water divide. The climate is humid and temperate, and it has an average precipitation of 31 inches per year (in/yr) based on the Park Falls climate station record from 1960 to 2010 (National Climate Data Center, 2011).

Geology

Geological surficial materials consist of unlithified till and outwash deposited during the most recent glaciation of the area between about 25,000 and 12,000 years ago (Cates and Batten, 1999). The Land Type Associations (Wisconsin Department of Natural Resources, 1999) that show glacial geology landforms are shown on plates 1 and 2. Generally, outwash is present in the north of the unit and drumlins in the south. Glaciers also shaped the regional topography; the melting of buried blocks of glacial ice created numerous closed-depression surface-water features in the area (Cates and Batten, 1999). Glacial sediment overlies Precambrian igneous and metamorphic bedrock, as shown on plate 3 and in table 1 (Mudrey and others, 1982; Mudrey and others, 1987).

Table 1. Bedrock geology units in the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin. (See plate 3 for locations.)

Era	Unit	Description
Paleo-proterozoic	Pgr	Intermediate to granitic intrusive rocks
	Pmg	Metamorphosed ultramafic to mafic intrusive rocks
	Pms	Meta-argillite, meta-siltstone, quartzite, meta-graywacke, meta-conglomerate, meta-iron-formation, and marble
	Pvn	Dominantly mafic meta-volcanic rocks; subordinate felsic meta-volcanic rocks
	Pvu	Dominantly mafic, intermediate, and felsic meta-volcanic rocks; subordinate meta-sedimentary rocks
Neo-archean	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, Randall J. Hunt and Paul F. Juckem; Project coordination and editing, Kenneth R. Bradbury and Anna Fehling. We sincerely thank the U.S. Forest Service for its support of this project and thank the U.S. Forest Service personnel and two anonymous reviewers whose comments helped improve and clarify this manuscript.

Section 1: Hydrogeologic data

Objectives

Initially, the WGNHS inventoried and analyzed available hydrogeologic data, in order to characterize key aquifer properties. Data for the Park Falls Unit were inventoried in 2010 and 2011, and spatial data were compiled in a Geographic Information System (GIS) database. This database of water levels, hydraulic properties, and hydrostratigraphy supported a subsequent groundwater flow model (section 4).

Data sources

Data sources that were used for this project were publicly available well construction reports, published locations of bedrock outcrops, and results of a geophysical survey conducted by WGNHS. These sources are described below.

Well construction reports

Well construction reports (WCRs), which form the primary database for the hydrogeologic study of the Park Falls 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 individual records may differ greatly, the WCRs as a group provide insight into the hydrogeology of a region. Plate 4 also locates mapped springs and spring ponds (Macholl, 2007) and shows the elevation of the water table.

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

Using the WCRs, WGNHS staff prepared a GIS database for the Park Falls Unit, the fundamental tool used for storing spatial data for the project. Because the WCR records generally locate wells only to the nearest quarter-quarter section or to a lot number, records were manually moved to the correct location in a process called geolocation. WGNHS staff examined the site of each well 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 included parts of Price, Ashland, Iron, Oneida, and Vilas Counties outside the Park Falls Unit boundary. In all, this process located 1,656 wells in the project area, the majority of which are located outside the Park Falls Unit. Of the located wells, 1,535 were within an estimated 750 ft of their true location. Physical data associated with each of these wells were assembled in the database.

Of wells in the WCR database, about 80 percent are screened in the sand and gravel aquifer at an average depth of less than 100 ft. Of the remaining 20 percent that are screened in bedrock, the average well pumps from the top 100 ft of bedrock, although some pump from as deep as 300 ft. In WCRs for bedrock wells, depth to bedrock averages about 60 ft and ranges from 0 to 230 ft; the total well depth averages 125 ft and may be as deep as 400 ft.

Water-table maps

A water-table map of Price County (Cates and Batten, 1999) shows most of the Park Falls Unit; the water table map of Vilas County (Patterson, 1989) shows the eastern portion of the unit. These maps were constructed by interpolating point measurements of water levels recorded in WCRs. Because neither map covers the entire unit, they were combined to produce a single map of the Park Falls Unit (plate 4). In addition, a separate water-table map was produced that was based on our groundwater flow model. This map is discussed in further detail in section 4.

Outcrops

Records of bedrock outcrops are used to interpret the bedrock elevation surface and to evaluate areas where the glacial aquifer is thin. Bedrock outcrops are rare in the Park Falls Unit, but some have been recorded along the South Fork Flambeau River. Bedrock outcrops were located on early maps (King, 1882) and then integrated with other available data to interpolate a bedrock elevation map (plate 5).

Geophysical survey of shallow bedrock

Earth conductivity, a measure of how well the earth conducts electricity, is generally lower in solid rock than in saturated sediment and therefore may be used to evaluate differences in subsurface materials. A geophysical survey of electrical conductivity in the Park Falls Unit confirmed an area of shallow bedrock near the center of the unit and subsequently was used to interpret bedrock elevation (plate 5).

It was initially unclear whether large granitic knobs and boulders northeast of the intersection of Gates Lake Road and Forest Road 137 (fig. 2) represented in-place bedrock or were large glacial erratics. In June 2011, WGNHS and USGS personnel used two different earth conductivity instruments, the EM-31 and the GEM-2, to measure conductivity near this intersection.

Near the exposed rock, the two earth conductivity instruments produced consistent low conductivity readings (3.20 and 3.02 micro-siemens per meter (µs/m), respectively) (fig. 2), respectively. Readings gradually increased as distance from the exposed rock increased. These results confirm that the exposed boulders are true parts of the bedrock surface rather than glacial erratics.

Water use

Records of monthly water use for high-capacity wells (wells capable of pumping at least 70 gpm or more) have been maintained by the WDNR since 2011. As of 2014, the WDNR database contained no records of high-capacity wells pumping within the Park Falls Unit and few records in this region generally (R. Smail, written communication, 2016). Twenty-five active high-capacity wells are located within 10 miles of the unit (table 2, plate 4). Although many high-capacity wells in Wisconsin pump at rates in the hundreds of gallons per minute, about 70 percent of the local wells pump at an average rate well below 70 gpm. All except four of these wells obtain their water from the sand and gravel aquifer rather than from bedrock.

Methods

Interpolation of hydrostratigraphic layers

Information in the WCR database, as well as geophysical survey results and located outcrops, were interpolated to produce three map layers:

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

The surface common to all three map layers, the bedrock surface, was interpolated on the basis of mapped outcrops, the geophysical survey, and WCR depth-to-bedrock values. Elevations of wells and surfaces were taken from the 10-meter (m) digital elevation model (DEM). This model is a raster representation of land elevation of Wisconsin, derived from the USGS 10-m National Elevation Dataset (U.S. Geological Survey, 2003). This elevation dataset contains a seamless mosaic of best-available elevation data. Interpolation tools available in Esri ArcMap software allowed elevations to be assigned to wells. Because the bedrock elevation at each well depends on the assigned land-surface elevation, wells whose spatial location merits higher confidence also merit higher confidence in bedrock elevation. The resolution of the DEM, the degree of confidence in WCR location, and the spatial distribution of WCRs are all sources of uncertainty in the interpolated bedrock surface.

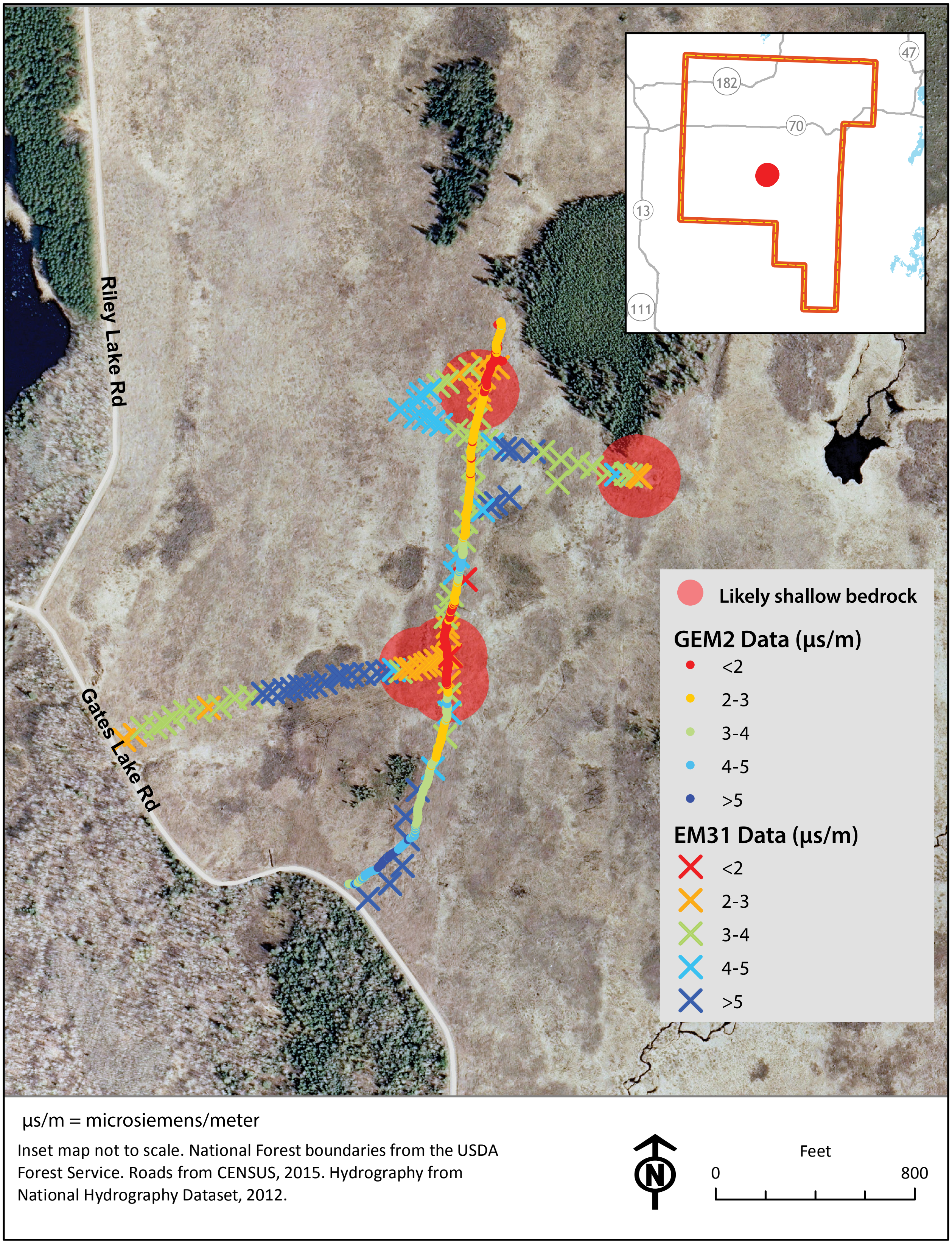
The bedrock surface was interpolated by using a triangular irregular network (TIN) algorithm in Groundwater Modeling System (GMS) software. This triangular network algorithm connects the data points (in wells or on outcrops) with triangles and interpolates elevations along the triangle surfaces. This method has the advantage of exactly honoring the data points. The resulting surface was then manually edited and refined so that it was consistent with local topography and landforms. This step eliminated problems such as a 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 previously published water table contours (Cates and Batten, 1999; Patterson, 1989) were combined to create one contoured surface representing the Park Falls Unit water table (plate 4).

The depth-to-bedrock raster surface was calculated by subtracting the bedrock surface raster from the land surface elevation. The saturated thickness coverage was calculated by subtracting bedrock surface elevation from the water-table surface compiled from Cates and Batten (1999) and Patterson (1989). These surfaces were also imported into Esri ArcMap software for contouring and plotting.

A map of the water-table surface in the Park Falls Unit was created by combining previously published water table contours (Cates and Batten, 1999; Patterson, 1989) (plate 4). The depth-to-bedrock raster surface was calculated by subtracting the bedrock surface raster from the land surface elevation. The region of saturated thickness was calculated by subtracting bedrock surface elevation

Figure 2. Earth conductivity measurements near north Gates Lake Road in Park Falls Unit. Varicolored line trending slightly northeast is composed of overlapping color dots.



µs/m = microsiemens/meter

Inset map not to scale. National Forest boundaries from the USDA Forest Service. Roads from CENSUS, 2015. Hydrography from National Hydrography Dataset, 2012.

Table 2. High-capacity well withdrawals within 10 miles of Park Falls 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
Domestic supply								
72069	KA943	58	Sand	—[1]	53,000	53,000	53,000	53,000
Industrial								
2723	NC063	205	Granite	26,580,000	24,738,000	27,533,000	30,225,000	27,269,000
2724	MV943	293	Granite	33,530,000	36,148,000	43,632,000	45,325,000	39,660,000
Irrigation								
2649	ME941	65	Gravel	0[1]	166,320,000	0	0	41,580,000
69029	—	—	No record located	2,160,000	10,800,000	24,000,000	2,000,000	9,740,000
Livestock								
72066	TO463	38.5	Sand and gravel	—	1,438,000	1,438,000	1,438,000	1,438,000
72070	VG926	76.5	Sand and gravel	—	18,072,000	18,072,000	18,072,000	18,072,000
72071	UT163	75	Gravel	—	1,438,000	1,438,000	1,438,000	1,438,000
Public supply								
1073	EJ757	140	Sand and gravel	3,740,000	2,210,000	3,440,000	5,881,000	3,819,000
1074	EJ758	115	Sand and gravel	3,430,000	2,559,000	3,507,000	5,938,000	3,858,000
1108	AR340	100	Sand and gravel	32,010,000	27,600,000	26,270,000	25,860,000	27,935,000
1795	AR313	80	Sand	75,080,000	66,750,000	63,800,000	60,800,000	66,608,000
69537	WJ900	100	Sand and gravel	32,200,000	26,720,000	25,250,000	24,320,000	27,123,000
69888	GS662	—	No record located	—	5,000	5,000	5,000	5,000
69889	EP590	77	Gravel, granite	—	5,000	5,000	5,000	5,000
69890	GS661	—	No record located	—	5,000	5,000	5,000	5,000
70089	WL775	170	Sand and gravel	66,990,000	63,610,000	61,590,000	59,530,000	62,930,000
72670	YI504	77	Sand and gravel	—	—	0	281,000	141,000
73667	YJ233	111	Sand and gravel	—	—	—	9,664,000	9,664,000
75241	BF117	151	Granite, broken	12,000	12,000	0	8,000	8,000
75242	BF118	53.5	Sand and gravel	7,700,000	7,330,000	8,690,000	11,798,000	8,882,000
84643	BG719	76	Gravel	43,960,000	63,380,000	55,230,000	52,810,000	53,845,000
84644	BG720	41	Drift	41,240,000	44,790,000	32,970,000	38,864,000	39,467,000
84645	BG721	49	Sand	33,460,000	34,260,000	24,660,000	7,460,000	24,959,000
84646	BG722	70	Gravel	40,870,000	42,650,000	30,400,000	52,393,000	41,578,000

Abbreviations: ft = feet; gpm = gallons per minute; no. = number

[1] — = no data (well did not exist or no record); 0 = well existed but wasn't pumped

from the water-table surface compiled as described earlier. These surfaces were also imported into Esri ArcMap software for contouring and plotting.

Estimation of hydraulic properties

Many WCRs report the results of specific capacity testing, which can be used to estimate hydraulic properties of subsurface materials. Specific capacity is defined as well yield divided by drawdown, and it can be an indicator of aquifer productivity. For the Park Falls Unit, specific capacity results reported on WCRs were used to estimate transmissivity and hydraulic conductivity according to the TGUESS method (Bradbury and Rothschild, 1985). This method treats the specific capacity information reported by well drillers as a short-duration pumping test, corrected as needed 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 based on many well tests, provide reasonable estimates of transmissivity and hydraulic conductivity for regional applications.

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 apparently influenced by casing storage effects. The final data set contained 699 wells finished in unlithified materials and 82 wells finished in bedrock.

Water-level measurements

A monitoring well was selected in each unit to measure continuous groundwater elevation. In the northwest quadrant of the Park Falls Unit, measurements were obtained during the summer of 2011 at the USFS Wintergreen Trail well (plate 4; fig. 7, site 8; Wintergreen Trail parking area off Highway 70 about 4.5 miles east of Fifield). This well is fairly isolated from streams, pumping wells, and the effects of development and thus provides information about natural fluctuations in the local water table. The well is 74 ft deep and is screened in unlithified sand and gravel. The well, which lies just south of a local groundwater divide, is located at a high point in the landscape, about 1,547 ft above mean sea level. Groundwater near the well flows generally southwest towards Sailor Creek (plate 4) to the north, groundwater flows northwest to discharge to the South Fork Flambeau River. Additional information on the well is included in the digital supplemental material (see table 13) and the “located wells” geodatabase under Object ID #1017.

The long-term monitoring well PR-006, part of a statewide groundwater monitoring network operational between 1937 and 1994, was also evaluated for trends in groundwater level. This well is located in Park Falls, Wisconsin, west of the northwest corner of the unit. The well is 12.5 ft deep and is screened in glacial sand and gravel. Water levels are publicly available from the USGS National Water Information System. website under site number 455448090263401. Records for this well are available online at http://waterdata.usgs.gov/wi/nwis/inventory/?site_no=455448090263401. Annual water levels in this well usually fluctuated no more than 4.5 feet between 1937 and 1994, with no discernable long-term trend.

Beginning in May, 2017, water levels have been measured in PR-0087, a bedrock well in the south-central area of the unit near the Wilson Flowage (plate 4, “+” symbol). A 1,000-ft-deep borehole, which was drilled in 2013 as part of a WGNHS geothermal study, was converted to nested piezometers in late 2014. The nested wells are screened at the top of the bedrock at about 60 ft below ground surface and at a large fracture in the bedrock at 330 ft depth, which was found to provide the bulk of groundwater flow into the borehole. Static water levels were obtained after continuous water level recorders were installed in the well. These continuous water levels are publicly available as part of the statewide monitoring network (USGS site numbers 454856090104601 and 454856090104602). Fehling and Hart (2017) describe this site and borehole in more detail.

Results

Hydrostratigraphic layers

Elevation of the interpolated bedrock surface in the Park Falls Unit (plate 5) ranges from about 1,560 ft above sea level in the central part of the forest to about 1,440 ft in the northwest part of the unit. Bedrock elevation within the unit, although it follows no obvious pattern, is generally lower to the west.

Depth to bedrock in the unit ranges from zero to more than 200 ft (plate 6). In several areas near the center of the unit, bedrock is less than 10 ft deep. Bedrock is deepest in areas of higher land elevation in the southern part of the unit, especially in the uplands adjacent to the Elk River.

The saturated thickness of unlithified materials (plate 7) ranges from less than 10 ft in the center of the unit to nearly 250 ft beneath the southern uplands near the Elk River.

Hydraulic properties

Plates 1–3, figure 3, and table 3 illustrate estimates of hydraulic conductivity and transmissivity. The majority of wells draw their groundwater from unlithified materials; bedrock wells commonly correspond with areas of thin glacial sediments. Because the results are log-normally distributed, the geometric mean was used to evaluate the central tendency of the data. Hydraulic conductivities were moderate in the unlithified materials (mean, 39 ft/d; range, 0.9 to 1,700 ft/d). In general, the hydraulic conductivities are about an order of magnitude lower in bedrock than in the glacial aquifer (mean, 2.7 ft/d; range, 0.14 to 2,400 ft/d). The histogram of bedrock hydraulic conductivity (fig. 3) is weakly bimodal, a distribution that usually indicates both fracture and matrix conductivity. Fractures generally account for about an order of magnitude more conductivity than matrix. 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 1,500 ft^2/d in glacial materials and 44 ft^2/d in bedrock. If we assume mean transmissivity and a drawdown of 30 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 about 150 gpm, well above the 70 gpm minimum for high-capacity wells. A similar analysis for the bedrock aquifer that uses 50 ft of drawdown suggests it could support about 10 gpm. Yields of several hundred

Figure 3a. Hydraulic conductivity estimated from specific-capacity tests in the Park Falls Unit.

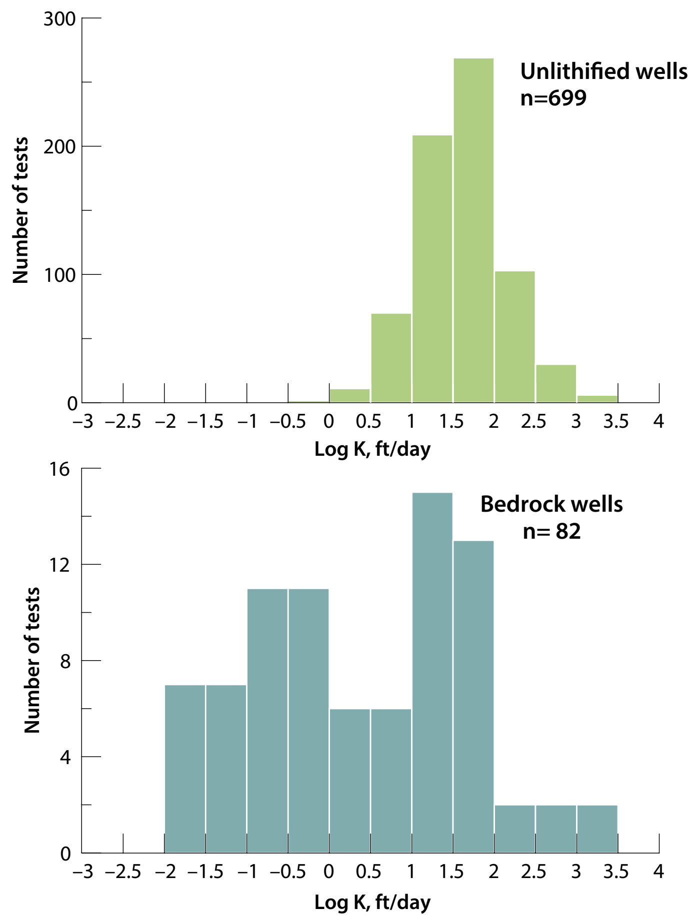


Table 3. Summary of hydraulic estimates for the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin

Wells studied and hydraulic estimates	Specific capacity (gpm/ft)	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)
Wells in unlithified materials (n = 699)			
Minimum	0.029	47	0.9
Maximum	20	120,000	1,700
Geometric mean	0.8	1,500	39
Wells in bedrock (n = 82)			
Minimum	0.014	2.5	0.014
Maximum	10	2,400	2,400
Geometric mean	0.2	44	2.7

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

Figure 3b. Transmissivity estimated from specific-capacity tests in the Park Falls Unit.

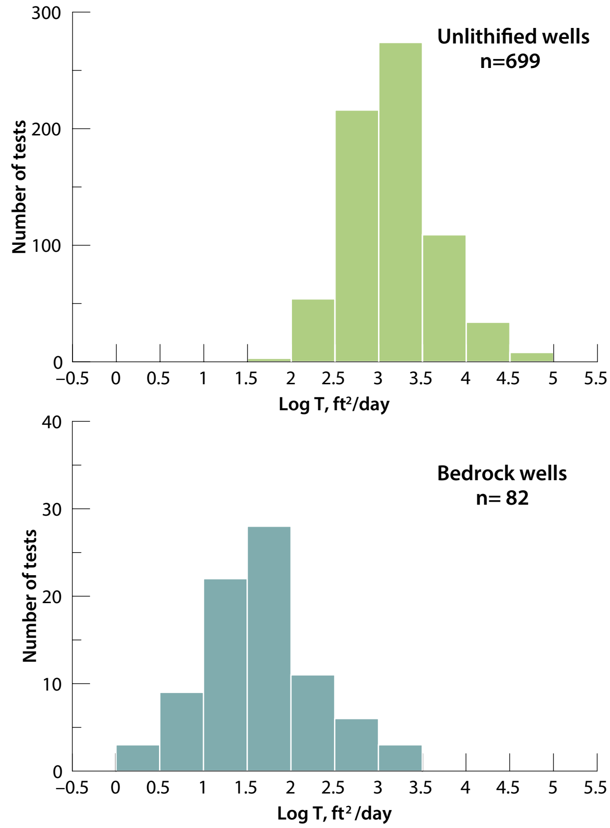
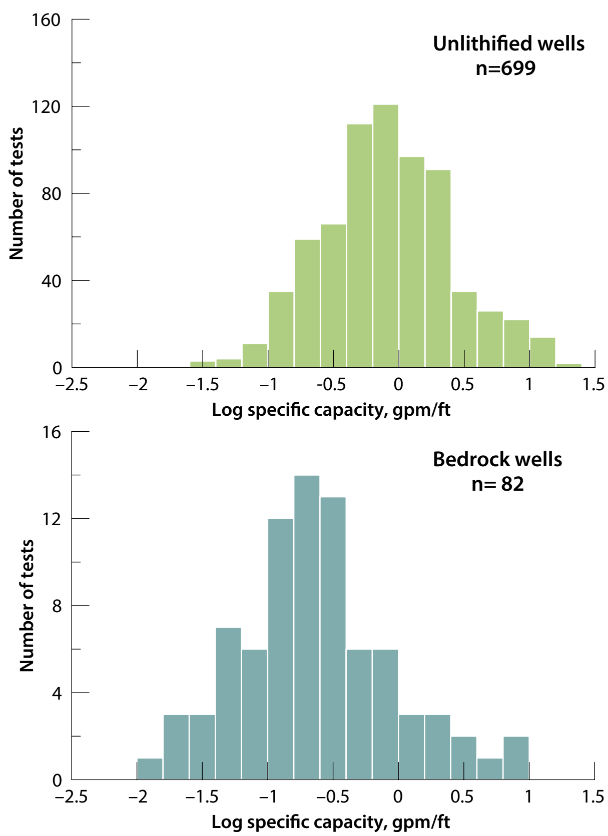


Figure 3c. Specific-capacity test results in the Park Falls Unit.



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 does have the potential to support high-capacity wells in areas of higher transmissivity, but that in general those wells could not produce much more than 100–200 gpm. This conclusion is consistent with a statewide map of probable yields of sand and gravel wells; yields in the Park Falls Unit are mostly less than 100 gpm but may be as much as 500 gpm (Devaul, 1975).

Specific capacities (discharge divided by drawdown during a well completion test) are generally low for all wells in the forest unit, which suggests low to moderate aquifer productivity, although a few wells have specific capacities greater than 10 gallons per minute per foot (gpm/ft). Again, if we assume a drawdown of 30 ft, a typically constructed well in this area could support a yield of as much as about 10 gpm in the bedrock aquifer and 25 gpm in the glacial aquifer. Because specific capacity depends on well construction and most wells in the Park Falls Unit are designed for low use, higher yields are possible but require larger diameter wells.

The hydraulic data (plates 1,2, and 3) show no spatial patterns, possibly because the data are sparse in the interior of the Park Falls Unit. Likewise, the data from the wells finished in unlithified materials show no consistent correlation to glacial geology.

Water levels

A hydrograph of the Wintergreen Trail well (plate 4, fig. 4) during the summer of 2011 shows groundwater elevation along with precipitation measured at the Park Falls National Climate Data Center station (2011). Between early June and late August, the water table, which was about 39 ft below ground surface, declined from about 1,508.25 to 1,507.5 ft above mean sea level. These elevations are within about 5 ft of the mapped water table (plate 4). Total precipitation during this time period measured 2 in. The well responds to rainfall after a time lag of 2 to 3 days. It is interesting to note that the depth to water measured in early June was within 1 ft of the depth measured at the time of drilling in 1979, indicating that groundwater levels may not have changed much in this vicinity during the 32 years measured. This well's hydraulic properties, which were analyzed by the TGUESS method, are lower than the mean in the Park Falls Unit. The well has a specific capacity of 0.3 gpm/ft, hydraulic conductivity of 7.3 ft/d, and a transmissivity of 263 ft^2/d.

The long-term observation well PR-006 near Park Falls, Wisconsin, (plate 4) also changed little during the monitored time frame between 1937 and 1994 (fig. 5). The water table elevation ranged from 1,504.3 to 1,510.4 ft with no discernable overall trend. Water levels in the glacial aquifer are shallow in this location, generally less than 5 ft below the ground surface. Static water levels in PR-0087, the deep bedrock well, were measured on 6/14/2016. Water levels in the deep piezometer were about 1 ft above ground surface, and in the shallow (60 ft) piezometer they were about 6 ft below ground surface. Fehling and Hart (2017) illustrate how a shallow network of bedrock fractures might explain the vertical distribution of hydraulic head at this site.

Figure 4. Hydrograph of Wintergreen Trail well during the summer of 2011, also showing precipitation measured at Park Falls climate station.

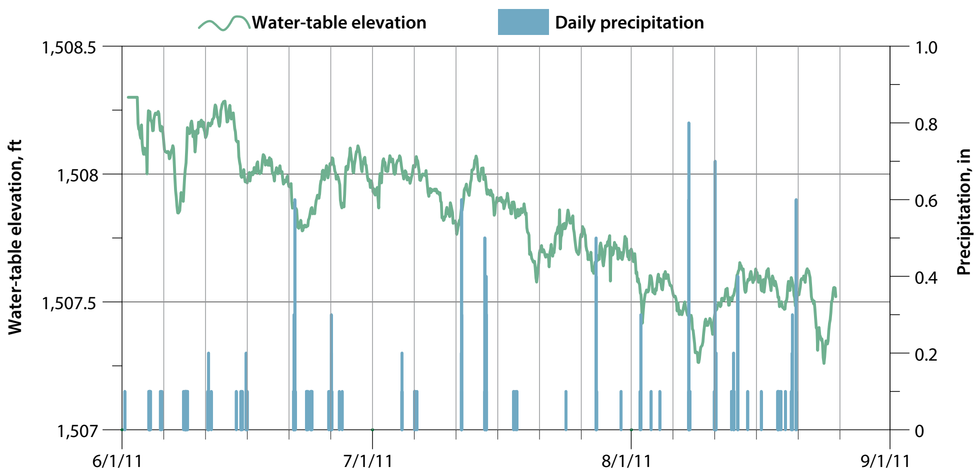
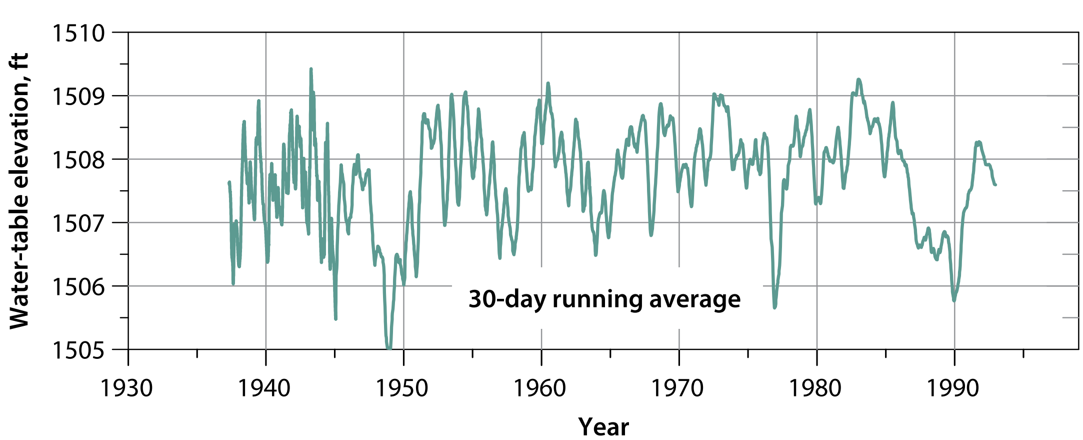


Figure 5. Hydrograph of monitoring well PR-006 in Park Falls, Wisconsin, plotted as 30-day running average.



Discussion

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

1. Glacial sand and gravel deposits form a shallow aquifer with low to moderate productivity. This aquifer is thin, ranging from less than 10 to as much as 250 ft thick, and is locally absent. The hydraulic conductivity estimated by use of the TGUESS method ranged from 0.9 to 1,700 ft/d; the mean was 39 ft/d.
2. Precambrian rock beneath the glacial sands and gravels, which transmits water through fractures, can supply adequate water to low-capacity wells. In general, hydraulic conductivities in this bedrock unit are about an order of magnitude lower than in the overlying sand and gravel.
3. The glacial aquifer has the potential to support high-capacity wells, but in general those wells could not produce much more than 100–200 gpm. The bedrock aquifer, which has an approximate average potential yield of 10 gpm, is unlikely to support high-capacity wells.
4. About 80 percent of wells in the Park Falls Unit obtain their water from the sand and gravel aquifer. Of the remaining 20 percent of wells, most pump from the top 100 ft of bedrock, although some pump from as deep as 300 ft.
5. No high-capacity wells are present in the Park Falls Unit, and few are in the region generally. Most of the active pumping wells within 10 miles of the unit obtain their water from the glacial aquifer. Although these wells are permitted to pump at rates greater than 70 gpm, the majority pump at lower rates (average 40 gpm).
6. Water-level data from two monitoring wells, located near the city of Park Falls (well PR-006) and near the Wintergreen Trail (the Wintergreen Trail well), suggest that groundwater levels not directly affected by human use have remained stable during the past few decades. These wells provide important baseline data representative of the general study area.
7. Subsurface data within the Park Falls Unit are sparse, and additional data collection could improve our understanding of these groundwater resources. Additionally, modern mapping of hydraulic properties within Pleistocene geologic units may reveal spatial patterns that are not currently clear.


Emily Lake

Linda Deith

Section 2: Potential recharge to groundwater

Objectives

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

As part of this same study, areal average recharge values were also estimated during groundwater flow model development (section 4). SWB results were used to guide initial flow model estimates and to corroborate these calibrated recharge values. However, it is important to distinguish between the two models, which provide different but equally valuable information. The SWB model calculates the spatial distribution of deep drainage, here called potential recharge. It is not calibrated to observed groundwater recharge, but it can be used to identify areas of relatively higher or lower potential infiltration and provide numerical estimates of these differences. The groundwater flow model provides an additional estimate of regional recharge that is not spatially variable but that has been calibrated to observed groundwater data.

Methods

Overview

Groundwater potential recharge was estimated through application of a soil-water balance (SWB) model (Westenbroek and others, 2010) to an area encompassing the Park Falls Unit. Figure 6 shows the model extent: an area exceeding 1,000 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 flow on a spatially referenced grid at daily time increments. Inputs to the SWB model include map data layers for land surface topography and soil and land cover characteristics, as well as tabular climate records. Model outputs (pdatasets 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

The model calculates runoff from each cell (outflow) and routes it to adjacent cells (inflow) by using a flow-direction grid. Runoff is used up in each daily time step; it either becomes infiltration in a downslope grid cell through runoff routing or 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.

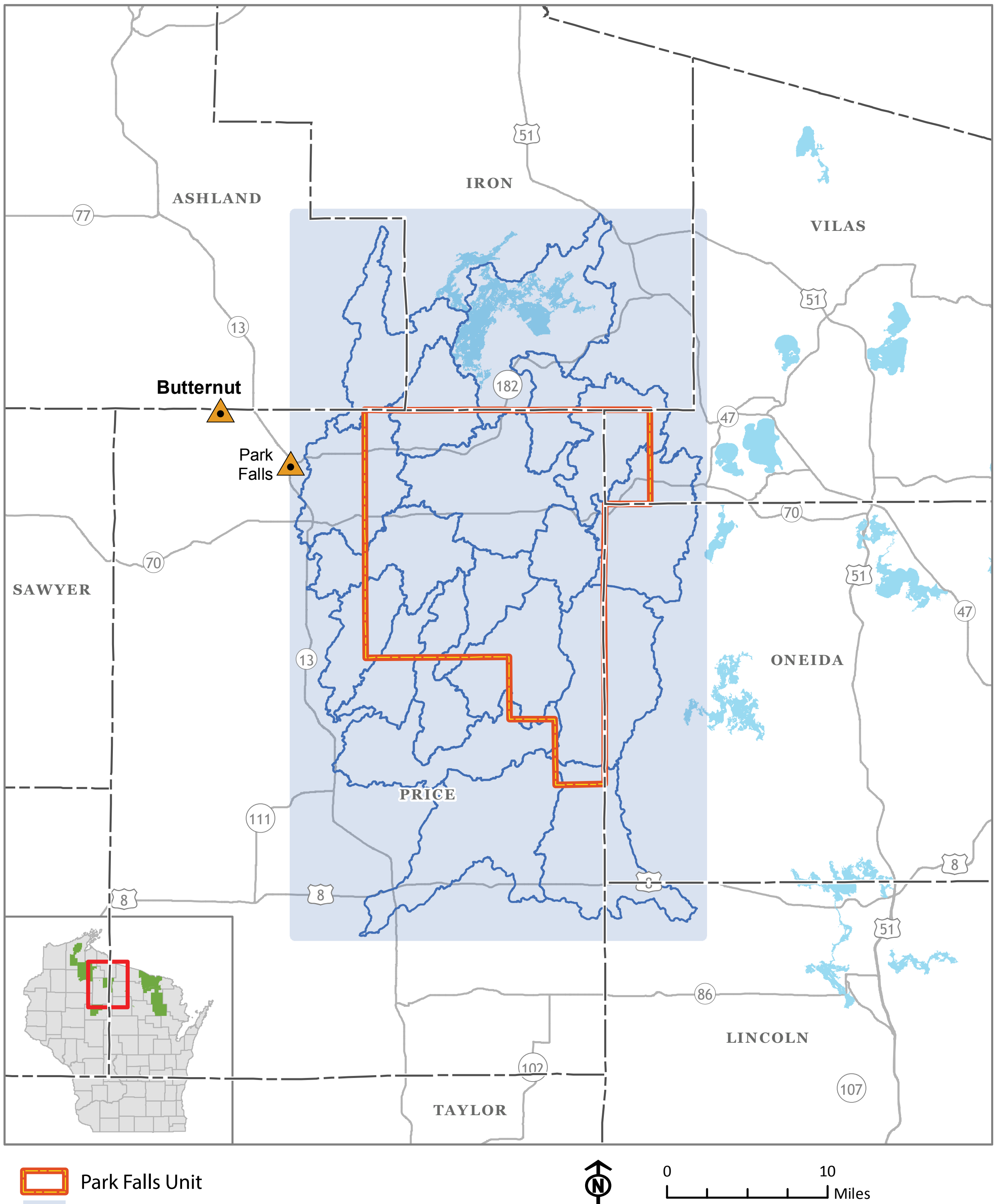
Because all runoff is used up each time step, the SWB code does not allow ponding. Water in closed depressions in the flow-direction grid is removed primarily by recharge, and focused areas of unrealistically high recharge may result over closed depressions. However, all closed depressions were removed 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/d.

Data sources

Flow direction

The SWB model uses digital topographic data to determine surface-water flow direction and to properly route runoff. Flow direction was calculated by using a 30-m DEM from the USGS National Elevation Dataset (U.S. Geological Survey, 2003) 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 DEM before the final calculation of the flow-direction input grid. Several fill thresholds were tested, and a complete fill was determined to be the most appropriate. Closed depressions account for less than 5 percent of the model area and are mostly located in the northern part

Figure 6. Extent of Park Falls soil-water balance model.



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

of the unit in the Northern Highland Outwash Plains (plate 1). Although true closed depressions are present in the model area, the identification, verification, and incorporation of these data were beyond the scope of this study but could be incorporated into future site-specific studies.

Hydrologic soil group and available water storage

Digital soil map data from the Natural Resources Conservation Service Soil Survey Geographic Database were used for two 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 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, 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 for root-zone moisture accounting.

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

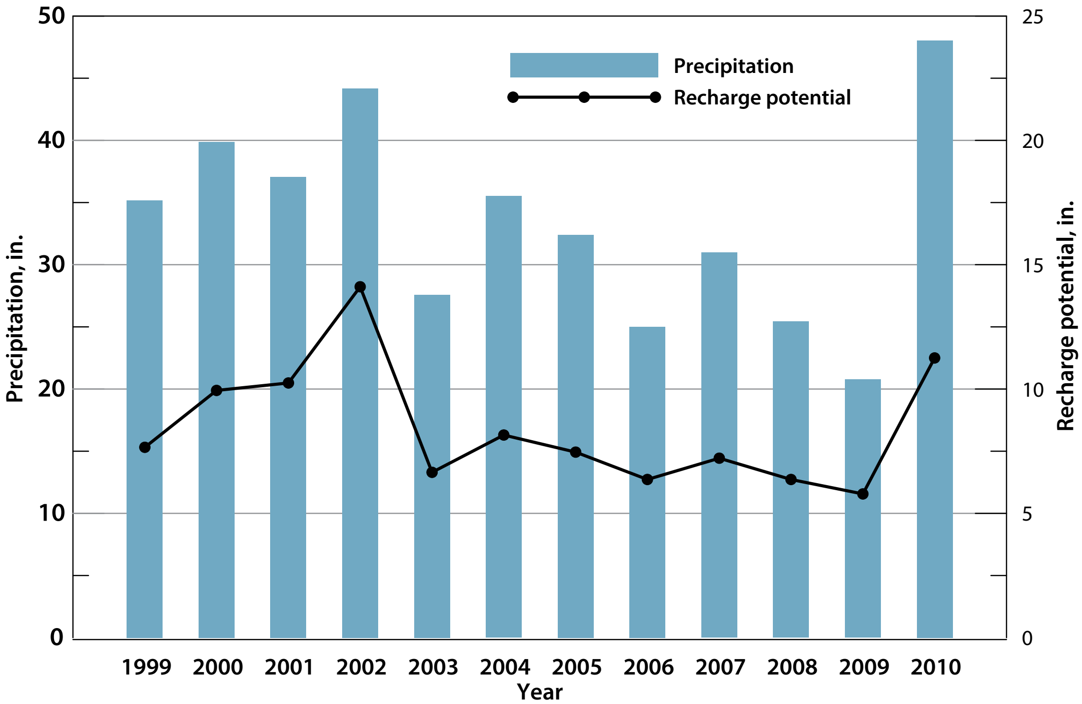
The SWB model uses tabulated daily temperature and precipitation observations as inputs to specify precipitation, track snow cover and melt, determine frozen-ground conditions, and estimate potential evapotranspiration. These data were based on the National Climate Data Center, 2011) climate record at Park Falls station (fig. 6) (National Climate Data Center ID: 476398), which is located near the Park Falls Unit and contains a relatively complete record for the period of interest. Where the Park Falls station record was incomplete, data were supplemented by using a nearby record at Butternut station (fig. 6) (National Climate Data Center ID: USC00471249).

The simulation period of the model, 2000–2010, represents recent climate conditions while also showing variability in total annual precipitation. 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 changes in potential recharge. The the same time period was used for the simulation period in all four Chequamegon-Nicolet National Forest units studied (Medford, Nicolet, Park Falls, and Washburn/Great Divide) after we compared 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 average precipitation during the Park Falls period of record, 1960 to 2010, is recorded as 31 in/yr, with a range of 18 to 49 in/yr. The selected simulation period of 2000 to 2010 showed a similar average of 33 in/yr and nearly the same variability (21 to 48 in/yr) (fig. 7).

Running the SWB model

Data grids for the four map inputs (flow direction, hydrologic group, available water storage, and land cover) were generated from the source datasets for input to the model. Daily climate data for minimum, maximum, and average temperature and for total precipitation were tabulated for the Park Falls climate station. The model was then run for the period 1999 through 2010; the year 1999 was used to develop antecedent moisture conditions for 2000.

Figure 7. Total annual precipitation at Park Falls climate station paired with annual mean recharge potential.



Results

Discussion

The SWB model simulated the daily soil-water budget for the model period and was configured to output grids of annual potential recharge and summary tables of the water balance. The grids were converted to raster format for further aggregation and analysis. In addition, to better understand average conditions, the 11 grids (one for each of the 11 years simulated) were averaged to produce a grid of mean annual potential groundwater recharge during the model period in the Park Falls Unit (plate 8).

The mean potential recharge within the model domain for the period 2000 through 2010 was 8.5 in/yr. The average values for each parameter in the water balance equation are included in table 4. The distribution in the unit seems to correlate with surficial geology through soil characteristics and, to a lesser extent,

Table 4. Soil-water balance approximate average water balance parameters for years 2000–20101 in the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin.

Water balance parameter	Average value (in/yr)
Precipitation	33
Interception	1
Runoff from grid	2
Evapotranspiration	15
Recharge	8
Runoff to surface water[2]	7

Abbreviation: in/yr = inches per year

[1]Based on daily water balance statistics output for the full model grid, including areas outside the Park Falls Unit.

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

land cover. Overall potential recharge in the Park Falls Unit is moderate, characterized by locally 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 recharge areas, when in fact they commonly areas of discharge or low recharge.

The average values reported above are consistent with the reported recharge in nearby areas (for example, Gebert and others, 2011, fig. 2; and reported modeled values from Hunt and others, 2010; Lenz and others, 2003), but they are somewhat higher than the areal averaged recharge of 7.0 in/yr derived by the groundwater flow model (section 4). Additionally, some local potential recharge rates in the SWB grid are higher than is typically considered appropriate for large-scale areal groundwater recharge. Plate 8 displays these values as greater than 15 in/yr.

Recharge variability with time is summarized in figure 7. This graph shows total annual precipitation and average potential recharge over each of the modeled years. Annual potential recharge, which is correlated with precipitation, varied from 6.5 to 14 in/yr in the 11 years between 2000 and 2010.

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 considerable redistribution and storage of groundwater occurs.

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 recognize this perpetual source of water and applies evapotranspiration only after precipitation or snowmelt. The Park Falls Unit contains about 34 percent wetlands (by land use); however, investigation of which of these wetlands contributes to recharge was outside the scope of this study. We therefore assumed that, in the Park Falls Unit, zero recharge in wetlands produces an average potential recharge of 6.8 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 8.5 in/yr, and so the SWB-model-simulated unit-wide average potential recharge is 6.8–8.5 in/yr.

Although true closed depressions likely exist in the model domain, all of these depressions were filled to improve the functionality of the flow-direction grid. Recharge is potentially underestimated for some of these true closed depressions. 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 Park Falls Unit hydrogeology, we inventoried basic surface water and groundwater geochemistry. WGNHS sampled various waters in the Park Falls Unit during 2011, in order to obtain a representative picture of current water chemistry there. Water samples were taken from groundwater wells, spring ponds, streams, and lakes. They were analyzed for major ion chemistry, basic nutrients (nitrate and phosphorus), and the stable isotopes oxygen-18 (^{18}O) and deuterium (^{2}H). This report summarizes the data collected; however, it is not intended to be a comprehensive analysis of the geochemistry of this unit. The location of geochemistry sampling sites and the subsequent laboratory results are included in the file geodatabase (see Data availability).

Methods

Selection of sampling sites

Water at 40 sites in or near the Park Falls Unit were sampled (fig. 8; tables 5, 6), and analyses were completed on-site or later at a laboratory. Sample sites, which were distributed among four site types and spatially across the unit, and were accessible for sampling, were 11 wells, 8 spring ponds, 18 streams, and 3 lakes. Most of the wells selected for groundwater sampling are operated by the USFS at campgrounds and picnic areas. Spring pond sites contained springs with discrete flow and ponds fed by groundwater (Macholl, 2007). Samples from these sites were obtained as near to known spring discharge points as possible. Stream samples were usually obtained at or near road crossings, on the upstream side. Samples from lakes were obtained at or near boat ramps or footpath access points.

Sampling procedures

Most samples were collected during June and July 2011 and a few were collected in August 2011. Groundwater samples were collected directly from hand pumps permanently installed on the Forest Service wells; one private well was sampled by using the homeowner's permanent pump, and one shallow piezometer was sampled using a peristaltic pump. Wells were purged of approximately one well volume prior to sampling. Samples from spring ponds, streams, and lakes were collected by dipping a sampling bottle directly into the water. Samples were placed in prepared bottles provided by the laboratory (see below). For ion samples, three containers were used. For major cations and anions, including Ca, Mg, Na, and Cl, the sample was filtered by using a syringe to push the sample through a membrane with 0.45- micron (µm) pore size into a 15-milliliter (ml) vial pre-acidified with nitric acid. A second, filtered sample for nutrients was placed into 125-ml polyethylene bottles pre-acidified by HCl. A third, non-filtered, sample for alkalinity was placed in a non-acidified 125-ml polyethylene bottle. Unfiltered samples for isotopes were placed into separate 250-ml polyethylene bottles. All samples were immediately placed on ice in coolers in the field. Geochemical samples were transported to the laboratory (see below) within 48 hours after sampling. Isotope samples were refrigerated at the WGNHS prior to shipment to the laboratory.

Analytical procedures

Temperature, pH, and electrical conductivity of all samples were measured with electronic field meters in the field immediately after sampling. Field alkalinity and dissolved oxygen were measured by a colorimetric field kit.

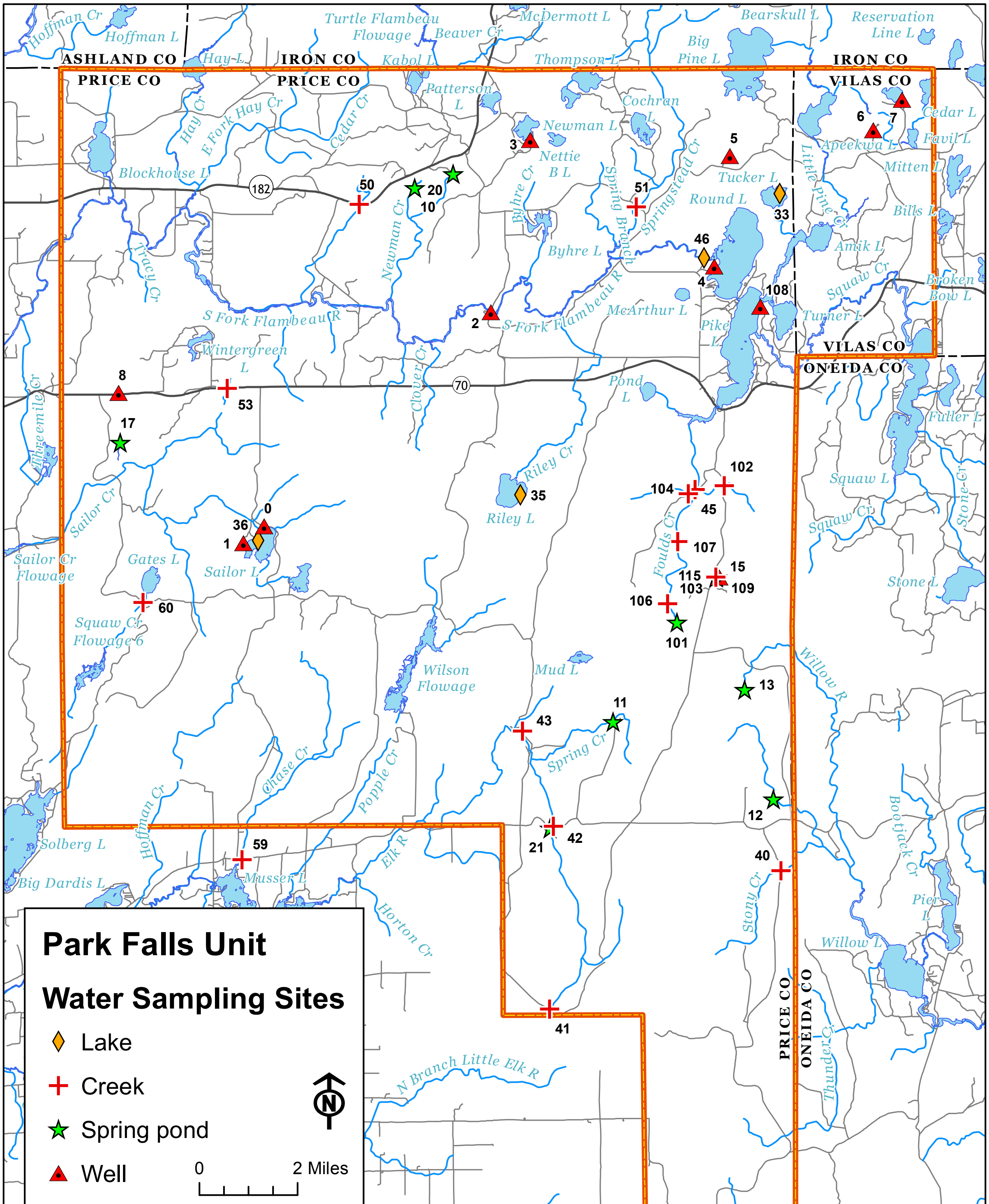
Major ions, nutrients, and laboratory alkalinity were analyzed at the Water and Environmental Analysis Laboratory at the University of Wisconsin–Stevens Point (https://www.uwsp.edu/cnr-ap/weal). Oxygen-18 and deuterium were analyzed at the University of Waterloo Environmental Isotope Laboratory in Waterloo, Ontario, Canada (http://www.uweilab.ca/).

Results

Major ion chemistry

Groundwater and surface water in the Park Falls Unit are dominantly a Ca-Mg-HCO_3 type. Concentrations of most ions are relatively low, as is common in a crystalline bedrock terrain beneath a cover of unlithified non-carbonate sediment (tables 6, 7, 8). Both groundwater and surface water contain low total dissolved solids and have a similar relative concentration of various ions. Groundwater is distinguished from surface water by higher pH, electrical conductivity, alkalinity, and concentrations of dissolved ions such as calcium and magnesium. Tables 6 and 7 contain the major ion results, and table 8 shows average results for each source type. Charge balance calculations showed that although most samples satisfy standard criteria for acceptable lab analyses, seven samples had unacceptable charge balance errors (table 7). The criteria for determining acceptable charge balances depends on the

Figure 8. Water sampling sites showing site number and type, Park Falls Unit.



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

Table 5. Wells sampled in the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin.

Well sampled	Sample site number[1]	Project ID[2]	WI unique well no.[2]	WGNHS image number[3]	Total depth (feet)	Material, reported by driller
Sailor Lake Picnic Well	0	—	—	PR1208	242	Hard, black granite
Sailor Lake Campground	1	971	—	PR1209	176	Red and black granite
Smith Rapids Well	2	No WCR found			—	—
Newman Lake Well	3	No WCR found			—	—
Round Lake Well	4	467	SH884		150	Gray granite
Twin Lakes Well	5	1037	—	PR1394	44	Coarse gravel
Emily Lake Well	6	1578	GP576	—	101	Sand and gravel
Wabasso Lake Well	7	1576	GP577	—	81	Sand and gravel
Wintergreen Trail Well[4]	8	1017	—	PR1131	74	Sand and gravel
Tabbert's Well	108	Private well; no WCR found			66	Precambrian volcanic rock[5]
Sieverson Pond Well	109	Shallow monitoring well			3.7	Muck and peat

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

[2] *Project ID in Located WCR geodatabase.*

[3] *Identifier for scanned image on file at the Wisconsin Geological and Natural History Survey.*

[4] *Used as monitoring well for this project. Well construction information included in Appendix 1.*

[5] *Homeowner identification of substrate.*

sum of the anions. The balance was considered acceptable if (1) the cation-anion difference was within 0.2 milliequivalents per liter (meq/L) for anion sums 0–3 meq/L, (2) the charge balance was within 2 percent for anion sums 3–10 meq/L, and (3) the charge balance was 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 average pH and electrical conductivity. Groundwater well samples have an average alkalinity of 83 mg/L and conductivity of 161 µs/cm. Groundwater samples vary considerably within these categories; alkalinity ranges from 24 to 116 mg/L and conductivity ranges from 62 to 234 µs/cm. Some wells may be drawing water from nearby surface water, although no such samples were clearly identified. Round Lake well (fig. 8, site 4) has the lowest conductivity, but other parameters are typical for groundwater; Wintergreen Trail well (fig. 8, site 8) has the lowest alkalinity and is dilute, but neither its conductivity nor isotopic signature are characteristic of groundwater. Wintergreen Trail well is near a surface-water divide and the sample may reflect young groundwater. Spring pond samples, which have slightly lower average alkalinity and conductivity, are interpreted to be moderately influenced by surface-water inputs.

Surface waters such as lakes and creeks contain a mix of groundwater inflow and surface water runoff. Water samples with low conductivity and alkalinity were interpreted as "surface-water dominated" (table 8); those collection sites are West-flowing Foulds Creek, Sailor Creek, East-flowing Foulds Creek tributary, Riley Lake, Squaw Creek, and Stony Creek (fig. 8; sites 102, 36, 104, 35, 60, and 40). These samples have an average alkalinity of 12 mg/L (range 8–16) and electric conductivity of 33 µs/cm (range 29–37). Conversely, surface water samples with high conductivity and alkalinity, such as Foulds Creek downstream of Foulds spring pond (fig. 8, site 106), are likely fed by groundwater. Plate 9 shows the spatial distribution of alkalinity and electrical conductivity in creeks and lakes. In general, higher alkalinity and conductivity correspond to surface-water features fed predominately by groundwater (spring ponds and headwater streams), and these are consistent with the groundwater flow paths derived from the groundwater flow model described in the next section of this report. Blue symbols indicate water features that are more likely fed by groundwater, whereas red symbols indicate surface-water–dominated features. Plate 9 also shows results of groundwater flow modeling, showing groundwater

Table 6. Water chemistry (field results) of the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin.

Location sampled	Site number	Date sampled	Time sampled	Temp. (°C)	Conductivity (µs/cm)	Alkalinity mg/l $CaCO_3$	Dissolved oxygen (mg/L)	pH
Wells								
Sailor Lake Picnic Area	0	6/26/11	—	7.5	172	100	1	—
Sailor Lake Campground Well	1	6/3/11	9:00	14.4	181	65	0.3	7.4
Smith Rapids Well	2	6/2/11	9:30	8.1	233.6	95	3.5	7.7
Newman Lake Well	3	6/2/11	14:20	9.5	130.7	55	2	7.1
Round Lake Well	4	7/29/11	—	15.6	61.8	85	2–3	7.8
Twin Lakes Well	5	6/2/11	11:00	8.4	138.8	55	0.4	8.6
Emily Lake Well	6	6/2/11	11:52	8.4	222.2	105	1	7.9
Wabasso Lake Well	7	6/2/11	11:30	8.2	198.2	95	1.5	7.9
Wintergreen Trail Well	8	7/29/11	—	11.2	—	20	3–4	—
Tabbert's Well	108	7/28/11	—	12.3	133.6	60	2–3	7.0
Sieverson Pond Well	109	7/28/11	—	9.9	149	70	3	—
Spring ponds								
Newman Spring	10	6/2/11	16:00	18.9	178.1	65	7	7.6
Grant Spring	11	8/26/11	11:00	17.4	37.8	5	3	5.5
Willow Spring at FR130	13	6/2/11	16:50	19.2	139.6	65	8	7.7
Hogsback Spring	17	8/25/11	17:00	21.5	161.3	45	8	6.6
Camp Four Springs	20	6/2/11	14:53	18.3	181.6	65	7	7.7
Unnamed Elk River spring	21	6/3/11	8:32	6.7	198.7	90	2–3	7.0
Foulds spring pond	101	6/2/11	14:50	13.5	151.6	60	10	8.4
Sieverson Spring at Sheep Ranch Rd	115	6/1/11	16:20	16.8	107.5	50	—	6.8
Creeks								
Little Willow Creek at FR 130	12	6/2/11	17:10	19.6	68.5	30	7	6.6
Sieverson Creek at Sieverson Crk Rd	15	7/27/11	—	12.4	119.7	50	4–5	6.8
Sailor Creek	36	6/3/11	9:15	16.8	31.8	15	5	6.3
Stony Creek	40	6/2/11	17:25	18.6	35.4	15	6	5.6
Elk River at FR 503	41	6/3/11	9:02	13	51	25	6–8	6.2
Elk River at Sheep Ranch Road	42	6/3/11	8:20	13.1	103.9	50	5–6	6.7
Elk River at FR 136	43	6/3/11	8:55	13.4	116.3	50	6–8	6.9
Foulds Creek at Foulds Creek Road	45	5/31/11	17:35	19.9	67.7	25	4.5	6.7
Camp C Creek at FR 182	50	6/2/11	15:30	18.2	150.4	50	6	7.0
Springstead Creek at FR 144	51	6/2/11	13:50	17.7	79.4	40	5.5	6.9
Dalrymple Creek	53	6/2/11	9:14	10.9	82.4	30	7	6.3
Chase Creek at County Road H	59	6/3/11	10:10	17.2	53.5	20	5	6.4
Squaw Creek	60	6/3/11	8:15	15.8	36.6	15	4	6.1
Foulds Creek tributary at FR 132—west-flowing	102	6/3/11	10:25	14.2	28.7	10	6–8	4.8
Sieverson Creek at FR 124	103	6/2/11	10:09	11.4	59.2	20	5	6.0
Foulds Creek tributary—east-flowing	104	6/24/11	—	14.8	32.3	15	8	5.8
Foulds Creek—downstream of Foulds spring pond	106	6/25/11	—	16.4	152.2	—	—	—
Foulds Creek—main branch	107	7/29/11	—	—	—	65	5–6	7.1
Lakes								
Tucker Lake	33	6/2/11	13:00	19.3	111.6	35	7	7.3
Riley Lake	35	6/26/11	—	19.9	35.3	10	10	6.6
Round Lake Dam	46	6/2/11	10:10	16	61.8	25	7	7.0

Abbreviations: °C = degrees Celsius; µs/cm = microsiemens per centimeter; ppm = parts per million; mg/L = milligrams per liter flow vectors and the general increase in baseflow downstream in groundwater-fed streams. The modeling is discussed in more detail in section 4.

The relative concentrations of various ions in each water source are shown on Stiff diagrams (fig. 9). In these diagrams, average ion concentrations are converted to electron milliequivalents. Cations plot on the left side of the diagrams, and anions plot on the right. The width of the resulting polygon indicates the concentration of dissolved constituents, and the shape indicates the relative importance of the individual ions. The plots illustrate that groundwater (wells and spring ponds) differs from surface water (lakes and streams) in overall concentrations, but the relative concentrations of the constituent ions are about the same for all groups.

Water quality indicators

The geologic setting of the Park Falls Unit, non-carbonate 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 affecting water quality. The majority of water samples collected during 2011 contained non-detectable concentrations of chloride and nitrate, and total phosphorus was on the order of 0.02 mg/L (table 7). However, several samples were elevated in one or more of these constituents. At the Wintergreen Trail well (fig. 8, site 8), Cl was elevated, possibly as a result of road salting on nearby Highway 70. Chloride was also slightly elevated (greater than 2 mg/L) at Newman Spring, Grant Spring, Hogback Spring, Camp Four Springs, and Camp C Creek (fig. 8;

Figure 9. Stiff plots of average concentrations of major ion constituents from the Park Falls Unit, categorized by water source. (meq/L, milliequivalents per liter)

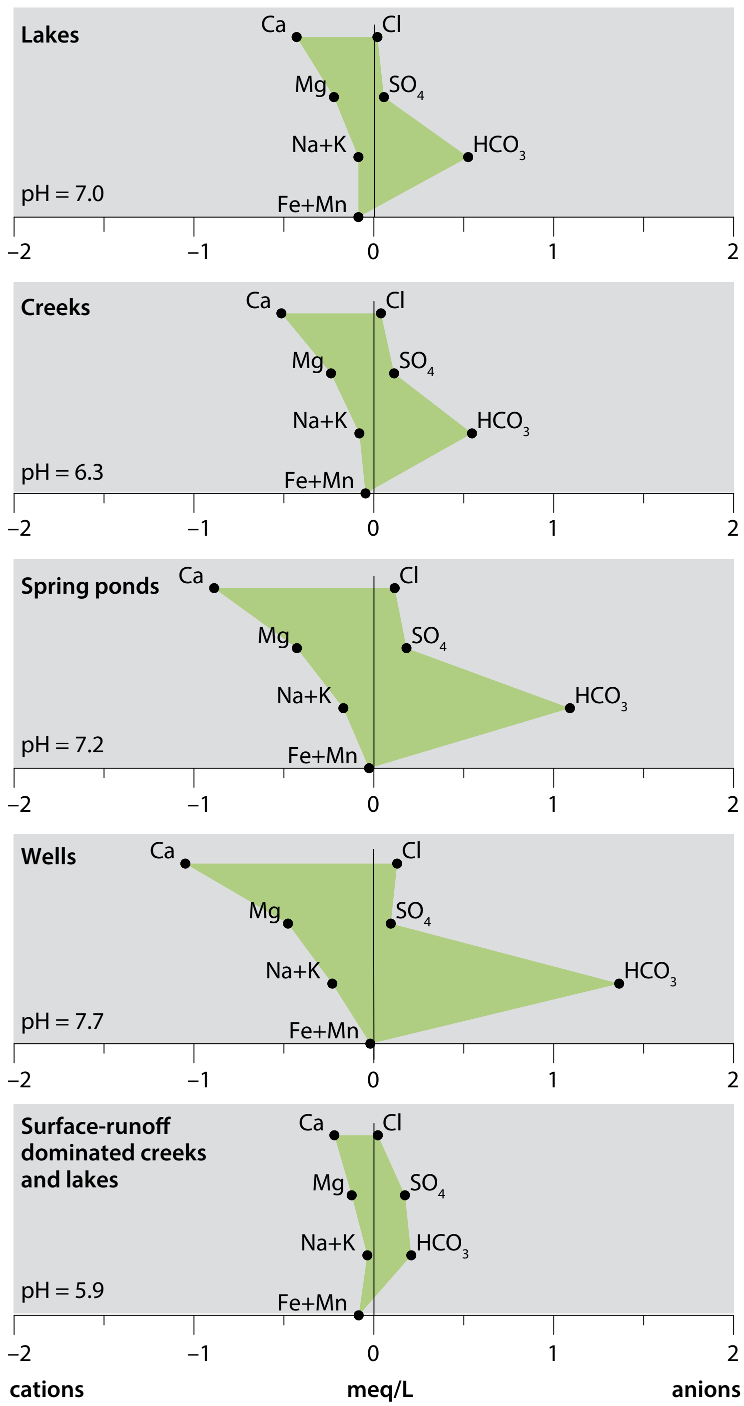


Table 7. Water chemistry (laboratory results) of the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin.

Site number[1]	$NO_2 + NO_3$ (N) (mg/L)	Cl (mg/L)	Alkalinity (mg/L)	As (mg/L)	Ca (mg/L)	Cu (mg/L)	Fe[2] (mg/L)	K (mg/L)	Mg (mg/L)
Wells									
1	<0.1	<0.5	88	<0.005	21.8	0.013	0.11	1.6	6.5
2	<0.1	<0.5	108	<0.005	29.3	0.003	0.03	1.2	10.0
3	<0.1	<0.5	64	<0.005	12.0	0.003	0.06	0.9	4.3
4	<0.1	<0.5	116	<0.005	16.7	0.003	0.15	1.1	6.4
5	1	<0.5	64	<0.005	16.6	0.006	0.08	1.1	5.1
6	<0.1	<0.5	116	<0.005	32.0	0.002	0.89	1.4	6.7
7	<0.1	<0.5	104	<0.005	30.1	0.001	0.12	1.1	4.9
8	<0.1	43.4	24	<0.006	9.3	0.002	0.01	1.6	6.4
108	<0.1	<0.5	60	<0.009	25.7	0.005	1.01	0.8	4.4
109	0.2	<0.5	88	<0.010	16.4	0.004	0.29	1.1	3.1
Spring ponds									
10	<0.1	9	72	<0.005	21.0	0.001	0.23	1.5	6.7
11	<0.1	4.5	24	<0.005	4.7	0.017	2.89	4.1	1
13	0.4	<0.5	68	<0.005	19.2	0.001	0.23	0.8	4.6
17	<0.1	8.2	64	<0.005	15.8	0.003	0.07	4	6.8
20	<0.1	10.3	72	<0.005	19.3	0.001	0.04	1.4	7.0
21	<0.1	<0.5	100	<0.005	24.9	0.001	0.00	0.8	7.8
101	<0.1	<0.5	76	<0.005	21.4	0.001	0.03	0.8	4.0
115	<0.1	<0.5	56	<0.005	15.9	0.003	0.15	0.4	3.3
Creeks									
12	<0.1	<0.5	32	<0.005	9.4	0.001	0.57	0.5	2.7
15	<0.1	<0.5	52	<0.007	16.8	0.001	0.18	0.6	3.5
36	<0.1	<0.5	12	<0.005	3.7	0.001	0.81	0.5	1.4
40	<0.1	0.7	16	<0.005	5.2	0.001	0.53	0.2	1.6
41	1.3	0.8	28	<0.005	6.2	0.002	1.48	1.0	1.9
42	<0.1	0.7	52	<0.005	14.1	0.001	0.69	0.9	4.2
43	<0.1	0.8	56	<0.005	16.0	0.002	0.67	1.0	4.7
45	0.2	<0.5	28	<0.005	10.6	0.001	0.78	0.4	2.6
50	<0.1	9.4	52	<0.005	15.5	0.001	0.37	1.1	5.7
51	<0.1	1.9	36	<0.005	10.9	0.003	1.13	1.4	3.1
53	<0.1	2.2	24	<0.005	9.3	0.001	0.65	0.8	3.5
59	0.2	0.7	24	<0.005	6.8	0.001	0.93	0.4	2.5
60	<0.1	0.7	12	<0.005	4.4	0.002	1.43	0.8	1.6
102	<0.1	1.6	8	<0.005	3.7	0.001	1.77	0.2	1.3
103	<0.1	0.6	24	<0.005	9.9	0.002	0.65	0.4	2.0
104	<0.1	1.1	12	<0.005	5.1	0.003	0.88	0.2	1.7
106	<0.1	<0.5	76	<0.005	22.9	0.001	0.14	0.4	4.2
107	0.2	<0.5	72	<0.008	20.5	0.001	0.30	0.5	4.2
Lakes									
33	<0.1	<0.5	56	<0.005	14.1	0.001	0.17	1.0	4.5
35	<0.1	<0.5	16	<0.005	4.2	0.003	3.64	0.6	1.3
46	<0.1	1.5	24	<0.005	7.5	0.001	1.06	0.8	2.3

Table 7 reads across two pages.

Site number[1]	Mn[2] (mg/L)	Na (mg/L)	P (mg/L)	Pb (mg/L)	Sulfate (mg/L)	Zn (mg/L)	Anions (mg/L)	Cations (mg/L)	Charge balance[3] (%)
Wells									
1	0.16	4	0.09	<0.002	8.5	0.061	1.9	1.9	1.9
2	0.01	3	0.02	<0.002	12.4	0.364	2.4	2.5	0.9
3	0.49	2	0.02	<0.002	4.9	5.217	1.4	1.2	5.2
4	0.04	14	0.02	0.004	1.3	0.012	2.4	2.0	7.8
5	0.02	2	0.01	<0.002	5.2	0.004	1.4	1.4	1.3
6	0.18	3	0.11	<0.002	0.1	0.077	2.3	2.4	1.1
7	0.24	2	0.01	<0.002	1.3	0.191	2.1	2.0	1.6
8	0.02	12	<0.012	0.004	0.5	<0.002	1.7	1.6	4.9
108	0.10	1	0.05	0.004	5.8	0.039	1.3	1.8	14.2
109	0.00	<1	0.03	0.003	5.1	0.015	1.9	1.1	25.1
Spring ponds									
10	0.01	4	0.01	<0.002	4.1	0.010	1.8	1.8	1.2
11	0.10	1	0.44	0.002	2.2	0.264	0.7	0.7	0.2
13	0.02	2	0.03	<0.002	5.8	0.018	1.5	1.5	1.0
17	0.02	4	0.27	<0.002	6.2	0.024	1.6	1.7	1.0
20	0.00	4	0.02	<0.002	4.6	0.014	1.8	1.8	2.0
21	0.01	4	0.05	<0.002	6.3	0.014	2.1	2.1	1.0
101	0.00	2	0.02	<0.002	6.8	0.007	1.7	1.5	4.8
115	0.00	2	0.02	<0.002	33.4	0.032	1.8	1.2	21.5
Creeks									
12	0.03	1	0.02	<0.002	2.6	0.018	0.7	0.8	5.4
15	0.01	1	0.02	0.004	4.3	0.018	1.1	1.2	2.9
36	0.09	1	0.02	<0.002	1.3	0.008	0.3	0.4	19.1
40	0.04	1	0.03	<0.002	1.1	0.023	0.4	0.5	12.8
41	0.29	1	0.05	<0.002	1.5	0.029	0.6	0.6	2.1
42	0.13	2	0.05	<0.002	2.6	0.013	1.1	1.2	3.7
43	0.17	2	0.05	<0.002	3.0	0.036	1.2	1.3	5.2
45	0.05	1	0.02	<0.002	3.1	0.005	0.6	0.8	13.9
50	0.03	4	0.02	<0.002	4.1	0.019	1.4	1.5	2.6
51	0.17	2	0.03	<0.002	1.9	0.013	0.8	1.0	9.1
53	0.06	2	0.02	<0.002	3.2	0.011	0.6	0.9	18.7
59	0.20	1	0.03	<0.002	2.4	0.008	0.6	0.6	7.7
60	0.18	1	0.04	<0.002	41.1	0.010	1.1	0.5	39.7
102	0.08	1	0.02	<0.002	1.7	0.018	0.2	0.4	27.9
103	0.06	1	0.04	0.002	6.2	0.048	0.6	0.7	8.8
104	0.05	1	—	<0.002	3.5	0.027	0.3	0.5	16.4
106	0.00	2	—	<0.002	5.8	0.003	1.6	1.6	1.5
107	0.03	1	<0.012	0.003	4.8	0.01	1.5	1.4	3.5
Lakes									
33	0.01	2	0.03	<0.002	4.5	0.007	1.2	1.2	0.6
35	0.03	<1	—	<0.002	1.4	0.015	0.3	0.5	14.1
46	0.06	1	0.03	<0.002	2.3	0.006	0.6	0.7	8.3

Abbreviations: no. = number; mg/L = milligrams per liter; meq/L = milliequivalents per liter

[1]*See table 6 for site locations.*

[2]*Well analyses exceeding the enforcement standard or preventative action limit (or both) for manganese (0.3 mg/L; 0.06 mg/L) or iron (0.3 mg/L; 0.15 mg/L) are highlighted.*

[3]*Unacceptable charge balance errors are highlighted. The criteria for determining acceptable charge balances depends on the sum of the anions. The balance was considered acceptable if (1) the cation-anion difference is within 0.2 meq/L for anion sums 0–3 meq/L, (2) the charge balance is within 2% for anion sums >3–10 meq/L, (3) the charge balance within 5% for anion sums >10–800 meq/L. Results from samples having unacceptable charge balance errors should be used with caution.*

Table 8. Average water quality in the Park Falls 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)
Wells	10	161	1.7	7.7	83.2	21.0	5.8	4.6	1.2	0.3	0.1	4.6	4.5
Spring ponds	8	145	7.2	7.2	66.5	17.8	5.2	2.9	1.7	0.5	0.0	4.1	8.7
Creeks	18	72	5.6	6.3	33.3	10.3	2.9	1.5	0.6	0.8	0.1	1.4	5.4
Lakes	3	70	8.0	7.0	32.0	8.6	2.7	1.5	0.8	1.6	0.0	0.7	2.7
Surface-water-dominated creeks and lakes	6	33	6.7	5.9	12.7	4.4	1.5	0.6	0.4	1.5	0.1	0.8	8.3

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

sites 10, 11, 17, 20, 50). Nitrate is somewhat elevated at the Elk River crossing of Forest Road 503 (fig. 8; site 41). Phosphorus is slightly elevated at Hogback Spring, Grant Spring, and the Emily Lake well (fig. 8; sites 17, 11, 6). The specific causes of elevated constituents at each of these sites are not known.

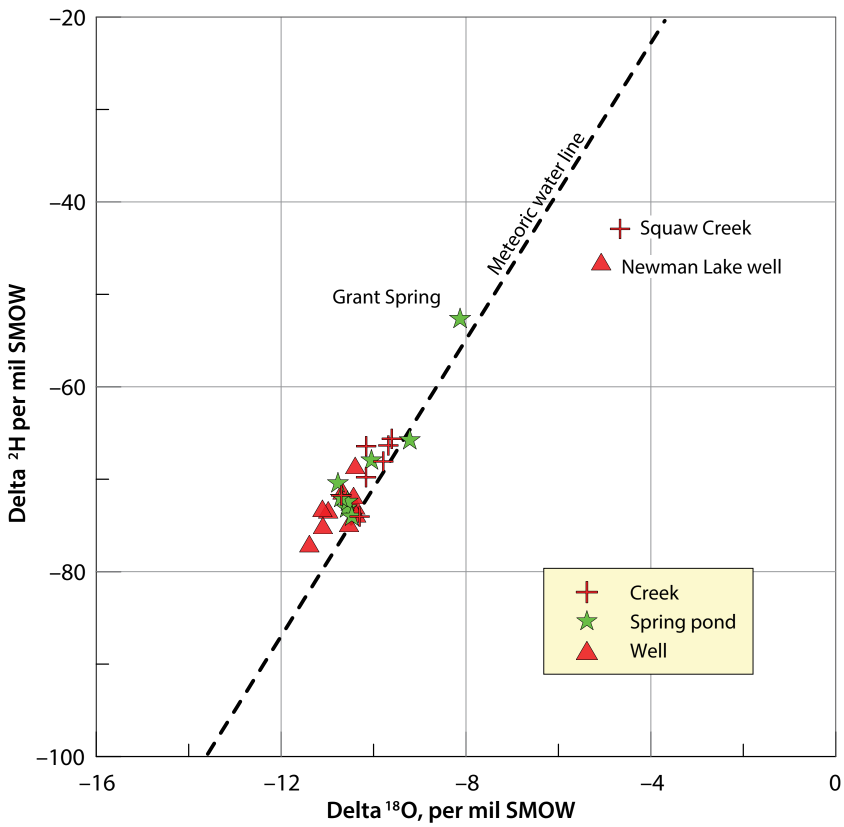
Several groundwater samples in the Park Falls Unit slightly exceeded the Wisconsin NR140 enforcement standard (ES) or preventative action limits (PAL) for dissolved iron or manganese (table 7). Iron is not considered hazardous to health at these concentrations, and the iron standards are based on aesthetic factors such as taste and appearance. A sample from a well at Newman Lake (site 3) exceeded the manganese enforcement standard of 0.3 mg/l. The source of both the iron and manganese is likely from natural minerals in the region, but might also be from plumbing and pipe fixtures, or other anthropogenic sources. It is recommended that these wells be re-tested periodically to ensure that these constituent concentrations meet standards for drinking water quality.

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

Figure 10 and table 9 show the isotope results from water samples collected in the Park Falls Unit in the summer and fall of 2011. The MWL (fig. 10) is based on samples from northern Vilas County (Krabbenhoft and others, 1990). Most groundwater and surface water samples cluster along the lower-left side of the plot, and groundwater-dominated samples from wells are generally more negative than water from spring ponds and creeks. Few groundwater or surface water samples fall precisely on the local meteoric water line, possibly because the line established by Krabbenhoft and others (1990) is taken from precipitation samples collected approximately 20 miles northeast of the Park Falls Unit. Additionally, the Krabbenhoft MWL is based on samples from November 1985 to August 1987 whereas the Park Falls samples were obtained in a short time period and may not reflect seasonal variation. The currently available data do not allow for an

Figure 10. Oxygen-18 vs. deuterium in water samples plotted against meteoric water line; samples from the Park Falls Unit.



interpretation of the minor deviation to the left of the meteoric water line, but this deviation is minimal and does not affect the interpretations and discussion below.

Though still plotting along the MWL, thus indicating unevaporated water, creek water is slightly heavier, or less negative, than groundwater. This phenomenon is consistent with the hypothesis that these creeks receive a high percentage of heavier summer precipitation. Most groundwater has a light signature (plots along the lower left MWL) because groundwater is recharged from lighter winter precipitation. In the summer, precipitation is subject to evapotranspiration and therefore less is available for groundwater recharge. However, some of this isotopically heavy summer precipitation may flow through shallow wetlands and discharge to a nearby creek. The isotopic signature of the creek—heavier than groundwater but unevaporated—could be reflecting flow through these shallow wetlands (Hunt and others, 1996; Zimmerman and others, 1967).

Grant Spring (fig. 8, site 11; fig. 10) although it plots along the MWL, has a heavier isotope signature than other spring ponds and creeks. The low pH, alkalinity, and conductivity also suggest that this sample is dominated by surface water. Samples obtained by USFS in a similar location indicate that the sample is likely influenced by upstream acid bog runoff and does not represent true spring discharge.

Two samples (Squaw Creek and Newman Lake well (fig. 8, sites 60 and 3, respectively; fig. 10)) plot much farther to the right of the MWL, indicating water that has undergone open-water evaporation. This plotted position suggests that the Newman Lake picnic area well draws water from nearby Newman Lake. The Squaw Creek sample was collected downstream from a lake (Gates Lake, fig. 8) and it also reflects surface-water evaporation.

Discussion

The results show that water in the Park Falls Unit is relatively pristine, with low concentrations of constituents, such as nitrate and chloride, often associated with human activities. Groundwater is distinguished from surface water by higher electrical conductivity (average 161 vs. 33 µs/cm) and higher alkalinity (83 vs. 13 mg/L). Concentrations of dissolved ions such as calcium and magnesium are also higher in groundwater. These relations can be used to evaluate where wells may be drawing from surface water, such as the Newman Lake well (fig. 8, site 3), or conversely where surface-water features may be predominantly groundwater fed. Several samples contained elevated chloride, nitrate, or phosphorus, suggesting the local influence of activities such as road salting.

Table 9. Oxygen and hydrogen isotope data from water samples collected in the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin.

Sample location	Site number	Sample date	$\delta^{18}O$ (per mil SMOW)	$\delta^{2}H$ (per mil SMOW)	Land type assoc.[1]
Well					
Sailor Lake Picnic Well	0	6/26/2011	−10.67	−71.25	1
Sailor Lake Campground Well	1	6/26/2011	−10.40	−68.50	1
Smith Rapids Well	2	6/26/2011	−10.39	−72.90	2
Newman Lake Well	3	6/26/2011	−5.07	−46.46	2
Round Lake Well	4	6/26/2011	−10.43	−71.77	3
Twin Lakes Well	5	6/26/2011	−10.98	−73.31	3
Emily Lake Well	6	6/26/2011	−10.38	−73.73	2
Wabasso Lake Well	7	6/26/2011	−10.53	−74.78	2
Wintergreen Trail Well	8	7/29/2011	−11.11	−73.15	3
Tabbert's Well	108	7/28/2011	−11.39	−76.97	3
Sieverson Pond Well	109	7/28/2011	−11.10	−75.01	1
Spring pond					
Newman Springs	10	6/26/2011	−10.05	−67.97	1
Grant Spring	11	8/26/2011	−8.13	−52.67	1
Little Willow Spring	12	6/26/2011	−9.22	−65.79	4
Willow Spring	13	6/26/2011	−10.58	−73.17	1
Hogsback Springs	17	8/25/2011	−10.56	−72.44	4
Camp Four Springs	20	6/27/2011	−10.47	−74.06	4
Unnamed Elk River springs	21	6/26/2011	−10.77	−70.45	4
Foulds Spring Pond	101	6/25/2011	−10.71	−72.03	1
Creek					
Sieverson Creek at Sheep Ranch Road (FR 132)	15	6/25/2011	−10.30	−74.04	4
Foulds Creek at Foulds Creek Road	45	6/24/2011	−10.16	−66.43	1
Squaw Creek	60	7/29/2011	−4.67	−42.92	1
Foulds Creek tributary—west-flowing	102	6/24/2011	−9.79	−68.09	1
Sieverson Creek at FR 124	103	6/25/2011	−9.68	−66.35	4
Foulds Creek tributary—east-flowing	104	6/24/2011	−9.61	−65.62	1
Foulds Creek—downstream of dam	106	6/25/2011	−10.70	−71.77	1
Foulds Creek—main branch	107	7/29/2011	−10.16	−69.79	1

Abbreviations: per mil SMOW = per thousand Standard Mean Ocean Water

[1]*Land type association: 1=Chequamegon washed till and outwash, 2=Glidden drumlins, 3=Flambeau silt-capped drumlins, 4=Northern Highland and Vilas–Oneida outwash plains.*

Section 4: Groundwater flow model

Objectives

The data inventory and analyses described in previous sections were incorporated into a groundwater flow model of the Park Falls Unit that was constructed by using the analytic element model code GFLOW. Construction of the flow model supports the goals of this project by providing key aquifer properties, simulated water table elevations, flow paths, flow rates, and discharge zones. The primary output is a calibrated regional model that can be refined to analyze site-specific concerns as they arise. The model is also useful for evaluating data needs to guide future monitoring programs.

Model construction

Overview

The two-dimensional groundwater flow model used for this study was developed by using the analytic element groundwater flow modeling code 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 infinite horizontal aquifer is assumed in analytic element modeling. Features important for controlling groundwater flow (for example, wells and surface-water features) are entered as mathematical elements or strings of elements. The amount of detail specified for the features depends on distance from the area of interest and the purpose of the model. Each element is represented by an analytic solution to the groundwater flow equation. The effects of these individual solutions are superposed to form a solution for any location in the simulated groundwater flow system. Because the solution is not confined to a grid, heads and flows can be computed anywhere in the model domain without interpolating between grid cells. In the GFLOW model used here, the analytic elements are two-dimensional and are used only to simulate steady-state conditions—that is, simulated water levels do not vary with time. 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 the pattern of surface-water features, such as rivers and lakes that intersect the water table, and by transmissivity of the aquifer, recharge to the aquifer, and pumping. Conceptualization of the hydrologic system forms the framework for development of the mathematical model and simplifies 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 in the Park Falls Unit is a relatively thin glacial aquifer (it ranges from about 50 to 250 ft thick but locally can be thinner or absent). Because the underlying crystalline bedrock has comparatively low permeability (hydraulic conductivities are an order of magnitude smaller than those of the glacial deposits; see section 1), we assumed that the glacial aquifer constituted the bulk of the modeled shallow groundwater system. 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 (although no high-capacity wells are present in the Park Falls Unit). Therefore, accurate locations and elevations of surface-water features and pumping wells along with accurate estimates of average baseflow are essential for correctly simulating the groundwater system.

Description of the GFLOW model

In order to develop the model, we estimated the elevation of the base of the groundwater system, the regional horizontal hydraulic conductivity, and the areally averaged recharge rate. In two-dimensional areal models, groundwater flow is simulated by using the aquifer transmissivity of a single layer, where transmissivity represents hydraulic conductivity multiplied by saturated thickness. Hydraulic conductivity is set at a regional value, and saturated thickness is calculated from the height of the simulated water table above the model's base elevation. As such, transmissivity varies throughout the model domain. Although both base elevation and hydraulic conductivity affect transmissivity, our calibration efforts focused on horizontal hydraulic conductivity rather than base elevation because so doing produced a model that was more stable and robust during parameter estimation (for example, Feinstein and others, 2006). Testing of the GFLOW solution showed that a base elevation equal to 1,350 ft above NAVD 88 provided a stable solution. This modified elevation is approximately 50 ft below the elevation of the lowest, most downstream segment of the South Fork Flambeau River; for comparison, 1,350 ft is 100 ft to 200 ft lower than the top of the crystalline bedrock in the Park Falls Unit. In addition to aquifer hydraulic conductivity, groundwater recharge also was considered a calibration parameter. Although recharge is known to vary spatially (section 2), a single value of areally averaged recharge was found to produce realistic model results. Modeling recharge according to piecewise-constant average recharge values is commonly considered appropriate for regional applications, and no alternative was available at the time of modeling. Although the GFLOW recharge does not vary spatially, it is calibrated to observed groundwater data and thus provides an important parameter to compare with SWB results.

Hydraulic conductivity was also tested during calibration. Initially, a horizontal hydraulic-conductivity zone was used to represent the entire model domain. During the calibration process, however; it became apparent that the shallow groundwater system is better represented by two hydraulic-conductivity values: one global value and one value representing areas of shallow bedrock. This shallow bedrock zone, or inhomogeneity, was assigned a lower hydraulic conductivity and shallower base elevation to simulate the transmissivity of glacial deposits where the aquifer's saturated thickness is small (plate 6). The area of shallow bedrock is simulated as a shallow base inhomogeneity, and it is shown conceptually as the area labeled "shallow bedrock" on figure 11.

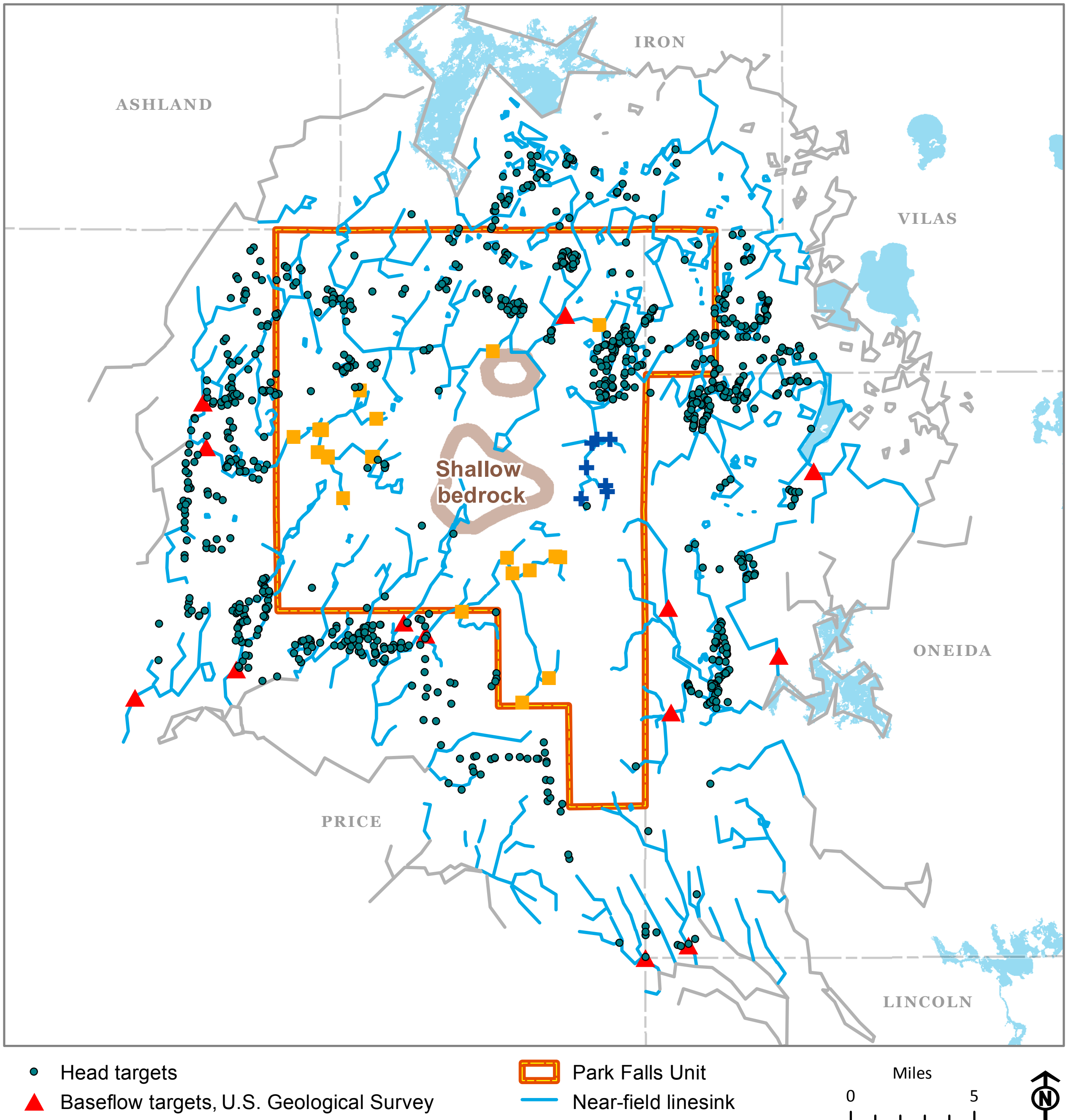
Surface-water features, such as streams and lakes, were simulated with various analytic elements in the model called linesinks. Linesinks can either be modeled as "near-field" or "far-field" elements. The analytic element streams outside of the Park Falls Unit were simulated as far-field linesinks for which the stream stage is fixed and there is no resistance between the groundwater and surface-water systems. Because this formulation "pins" the water table to surface-water stages, locations and elevations of far-field surface-water features control water levels at the model boundary. As a result, the model simulates the groundwater divides separating the unit's area of interest (the "near-field") from the more regional flow system (the "far-field). Simulation of the 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 Park Falls 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 could be compared with measured streamflows. Near-field linesinks have finer discretization than far-field linesinks, and baseflow in the streams is computed by the model as a function of the groundwater level at the stream and the resistance to groundwater–surface-water exchange. Streambed 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. Streambed resistance was estimated during calibration, and the width of each stream, which was assigned according to stream order and field observations, ranged from 5 to 50 ft. In general, the model is not very sensitive to stream width.

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 non-routed resistance linesinks for seepage lakes (no inlet or outlet streams). The value of lakebed resistance was initially estimated during calibration but was fixed for final calibration at 10 d at all lakes owing to low parameter identifiability (Doherty and Hunt, 2009). The width assigned to linesinks representing lakes was approximately the length of the shortest axis of the lake represented by the linesink (Haitjema, 2005).

Groundwater withdrawal by wells was not simulated because no high-capacity pumping wells were present in the Park Falls Unit. Pumping from private residential wells or supply wells at campgrounds in the unit 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 accounted for in the regional groundwater flow model, water from these wells was used for groundwater quality analysis. Chemical and isotope sampling from wells in the Park Fall Unit is described in section 3.

Figure 11. Hydrologic features of the GFLOW model of the Park Falls Unit.



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

Model calibration and results

Model calibration is the process of adjusting model parameters until the model satisfactorily reproduces field measurements consisting of water levels in wells and stream discharge. Numerous publications detail the advantages of formal parameter estimation (for example, Kelson and others, 2002; Poeter and Hill, 1997), which can be considered a form of automated trial-and-error calibration. The primary benefit of a properly prepared and executed parameter-estimation calibration as compared with typical manual trial-and-error calibration is the ability to estimate parameter values (for example, hydraulic conductivity and recharge) that are 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. In this study, the GFLOW model was coupled with the parameter estimation code PEST (Doherty, 2011).

Parameters that were adjusted during calibration included hydraulic conductivity, groundwater recharge, and stream sediment resistance (table 10). Initial hydraulic conductivity and recharge values were estimated on the basis of the data inventory and SWB analysis in sections 1 and 2, as well as from prior studies in the area (Pint and others, 2003; Robertson and others, 2012). Surface-water sediment resistance of lakes was initially estimated but was ultimately given a fixed value. The overall calibration methodology and approach are outlined by Doherty and Hunt (2010).

Groundwater elevation targets for the model (table 11) consisted of historical measurements from 972 private wells within and surrounding the forest unit (Wisconsin Department of Natural Resources, 2010). Relative importance in the calibration is expressed by weights assigned to each target. The quality of the head observations was grouped into the three classes "best," "fair," and "poor" determined by the estimated accuracy of each well's location. The location accuracy is important because the well measuring-point elevation is assigned from a DEM of the land surface. Location accuracy affects the utility of the target groundwater elevation, because the reported depth to water is measured from the estimated top of the well. Wells that could be geolocated on aerial photographs were estimated to be located within 100 ft of their true location and were assigned a higher relative weight (0.5) for calibration than wells that were located from plat maps (estimated accuracy of 100 to 900 ft and a weight of 0.2) or were estimated to the nearest quarter-quarter of a section (assigned a weight of 0.05). The relatively high calibration weight of 0.5 can be thought of as a 95-percent confidence interval of ±4 ft around the observed head. Similarly, weights of 0.2 and 0.05 can be expressed as 95-percent confidence intervals of ±10 ft and ±40 ft around the observed head, respectively.

Historical and contemporary streamflows also were used to calibrate the model (table 11). Baseflow, or flow, targets (fig. 11) included miscellaneous measurements by USGS personnel (Gebert and others, 2011), flows measured as part of a University of

Table 10. Calibrated parameter values for the groundwater flow model of the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin.

Parameter name	Optimized parameter value	Approx. transmissivity	Description
Average areal recharge	7.0 in/yr		Uniform areally averaged recharge to the entire model area
Regional hydraulic conductivity	19.3 ft/d	3,700 ft^2/d	Hydraulic conductivity/transmissivity of the forest unit representing glacial deposits above crystalline bedrock. Base elevation was set at 1,350 ft above NAVD88.
Shallow bedrock hydraulic conductivity	7.0 ft/d	370 ft^2/d	Hydraulic conductivity/transmissivity of the local shallow bedrock areas of the Park Fall Unit. Base elevation was set at 1,490 ft above NAVD88.
Resistance—Drainage and seepage lakes	10 d		Resistance is the quotient of the bed thickness divided by the vertical hydraulic conductivity of the lakebed sediments. Value was fixed owing to low parameter identifiability.
Resistance—streams	10 d		Resistance is the quotient of the bed thickness divided by the vertical hydraulic conductivity of the streambed sediments.

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

Table 11. Calibration targets and associated weights used for calibration with the parameter estimation program PEST in the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin.

Head targets—ranked by accuracy of WCR location	Number of targets	Calibration weight (1/std)
Best: <100 ft	399	0.5
Fair: 100–900 ft	512	0.2
Poor: >900 ft (within a quarter–quarter section)	61	0.05
Flow targets—observed (cfs)	**Number of targets**	**Estimated 95% confidence interval around target (%)**
>20	4	±1
5–20	9	±4
2–5	9	±20
<2	21	NA (zero weight)

Abbreviations: std = standard deviation; cfs = cubic feet per second; ± = plus or minus; NA = not applicable; WCR = well construction report

Wisconsin-Madison Master's thesis project along Foulds Creek (Pruitt, 2013), and numerous streamflow measurements collected within the Park Falls Unit by USFS staff (Dale Higgins, written communication, 1/24/2012). For the purpose of calibrating the model, measurements from each site were adjusted to long-term average baseflow conditions. Streamflows measured by USFS staff in 1994 and 2002 and Pruitt (2013) were adjusted on the basis of geochemical analyses of the water for a simple end-member mixing analysis (targets from the USFS (Dale Higgins, written communication, 1/24/2012), and from Pruitt (2013)). The groundwater end-member is based upon samples from known groundwater discharge points, and the surface-water end-member is based on samples from streams which the USFS classified as "surface-water dominated." The groundwater end-member, Foulds Spring Pond (fig. 8, site 101), has an alkalinity of 60 mg/L and electrical conductivity of 151.6 µs/cm, whereas the surface water end-member, West Flowing Foulds Creek tributary (fig. 8, site 102) has an alkalinity of 10 mg/L and conductivity of 28.7 µs/cm. Hardness, conductivity, and alkalinity of stream samples near the end-member sites were used to estimate the percent of total measured streamflow that was derived from groundwater discharge as opposed to surface flow from runoff or released from surface-water–dominated wetlands. Streamflow measurements by USGS personnel were adjusted by using a state-wide regression equation for computing baseflow (Gebert and others, 2011). Baseflow targets are included as part of the electronic database.

Similar to head targets, flow targets were grouped into four classes based on the expected ability of the regional groundwater model to simulate the magnitude of the streamflow. Four observed adjusted streamflows greater than 20 cubic feet per second (cfs) were given the highest weight (coefficient of variation = 0.005, which represents a 95-percent confidence interval of ±1 percent around the observed flow), as they reflect a regional watershed streamflow which is commensurate with the regional focus of the groundwater model. Flows less than 20 and greater than 5 cfs were given the next highest weight (coefficient of variation = 0.02, or 95-percent confidence interval of ±4 percent around the observed flow), flows between 2 and 5 cfs were given low weights (coefficient of variation= 0.1, or 95-percent confidence interval of ±20 percent around the observed flow), and flows less than 2 cfs were reported but given zero weight in the calibration (because regional models are not expected to simulate low flows accurately and high weights would degrade the ability of the model to simulate other calibration targets).

During the calibration, hydraulic conductivity, groundwater recharge, and streambed sediment resistance were adjusted by the parameter estimation code PEST (Doherty, 2011) in order to match simulated and observed water level and streamflow targets. Hydraulic conductivity was separated into two zones for calibration of the model (fig. 11)—a regional average hydraulic conductivity area that represents the larger Park Falls Unit and one local discontinuous zone near the center of the model where Precambrian bedrock is shallow and glacial deposits thin. The base elevation of the local zone also was elevated above the regional base to simulate the very thin glacial aquifer. A higher base elevation (1,490 ft) was assigned to the local zone as compared with 1,350 ft for the regional base. An areal uniform recharge rate was specified for the entire model domain. Seepage-lake and drainage-lake sediment resistance (table 10) were initially estimated; however, during calibration it became evident that the calibration dataset did not contain sufficient information to identify the seepage and drainage lake resistance parameters. Therefore, the final calibration fixed lake resistance parameters at 10 d and estimated the remaining streambed resistance parameter.

Final parameter values calibrated to observed water levels and stream baseflow (table 10) are within expected ranges on the basis of field data and previous studies. GFLOW calibrated annual recharge at 7.0 in/yr, which falls between the SWB mean deep drainage value of 8.5 in/yr (including wetland recharge) and 6.8 in/yr (if zero recharge in wetlands is assumed; see section 2). Similarly, though the simplifying assumptions of GFLOW and TGUESS limit direct comparisons of hydraulic properties, mean transmissivity values from TGUESS (1,500 ft^2/d for unlithified materials) fall within the same order of magnitude as the approximate regional transmissivity (3,700 ft2/d).

Simulated results from the final calibrated model closely fit observed value (figs. 12–15). Figures 12 and 13 show simulated versus observed head and flow targets, respectively, and results of weighted head and flow targets are shown graphically in figures 14 and 15. Unweighted statistics that compared all target water levels to all 972 simulated levels showed a mean difference of –0.34 ft (a negative difference indicates that target values are, on average, less than simulated values), a mean absolute difference of 7.3 ft, and a root mean squared difference of 11.0 ft. Results by head group are shown in table 12. Simulated water levels generally matched measured water levels throughout the entire 283-ft range in measured water levels (fig. 12). Three head targets (figs. 12, 14) with the weakest correlation to simulated values suggest that water levels are locally simulated too low near wetlands in the Elk River headwaters just south of the Park Falls Unit boundary. However, other targets in the Elk River watershed match simulated water levels well, and refinement on this small scale was outside the scope of the regional model. Simulated streamflow values were also well simulated for both the large (fig. 13a) and the smaller flows (fig. 13b). The gage with the largest volume of flow (fig. 13a) deviates slightly from the 1:1 line. This gage receives water from an area larger than the Park Falls Unit, which is the intended focus of calibration. The gage was given a lower weight to improve model fit within the unit, as can be seen by the good fit to other large flow targets (fig. 15).

Although groundwater-fed wetlands were not explicitly included in the model, they are implied in the model output in areas where simulated heads rise above the land surface. Such areas of "flooding" or "over-pressurization" were used as a qualitative calibration metric, by spatial comparison to the Wisconsin wetland inventory (Wisconsin Department of Natural Resources, 2011). Simulated flooding in the calibrated model shows good agreement with the mapped wetlands (fig. 14).

Figure 12. Simulated vs. observed heads for weighted head targets plotted against 1:1 line, Park Falls Unit.

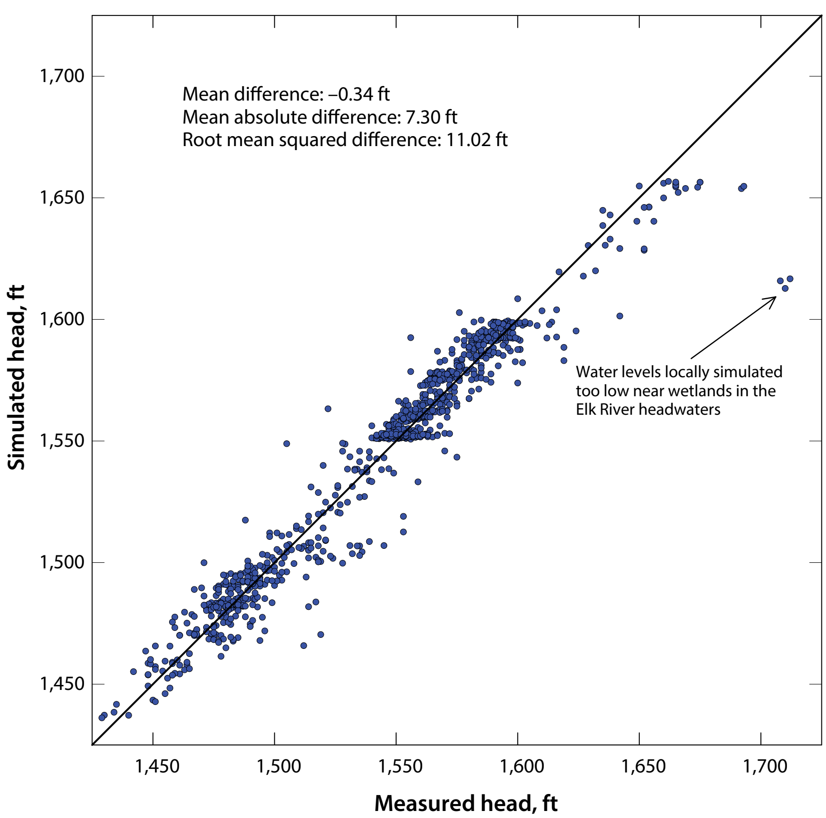


Figure 13a. Simulated vs. observed flows for all flow targets, plotted against 1:1 line.

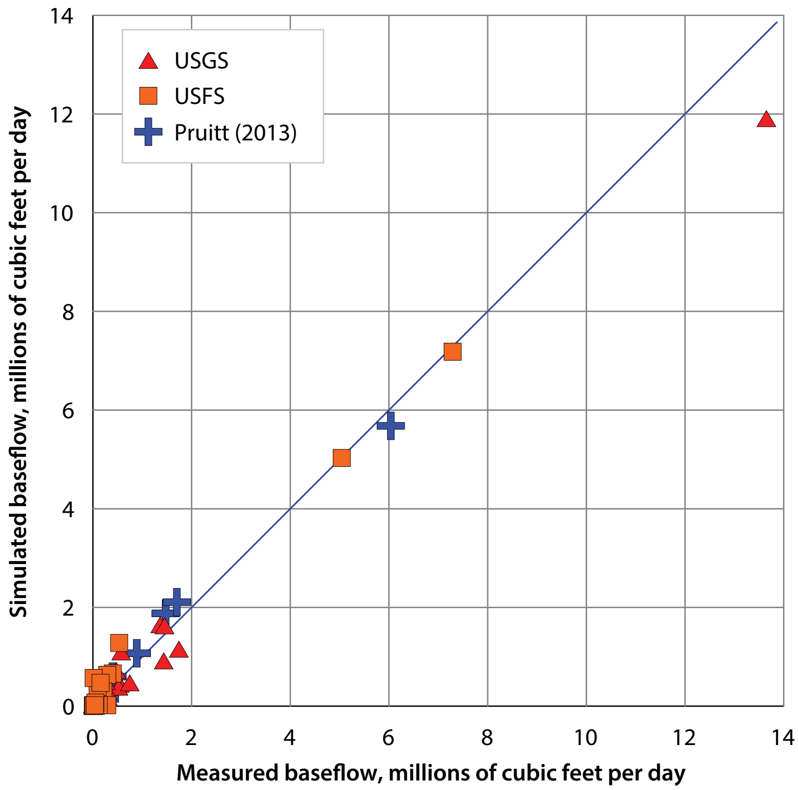
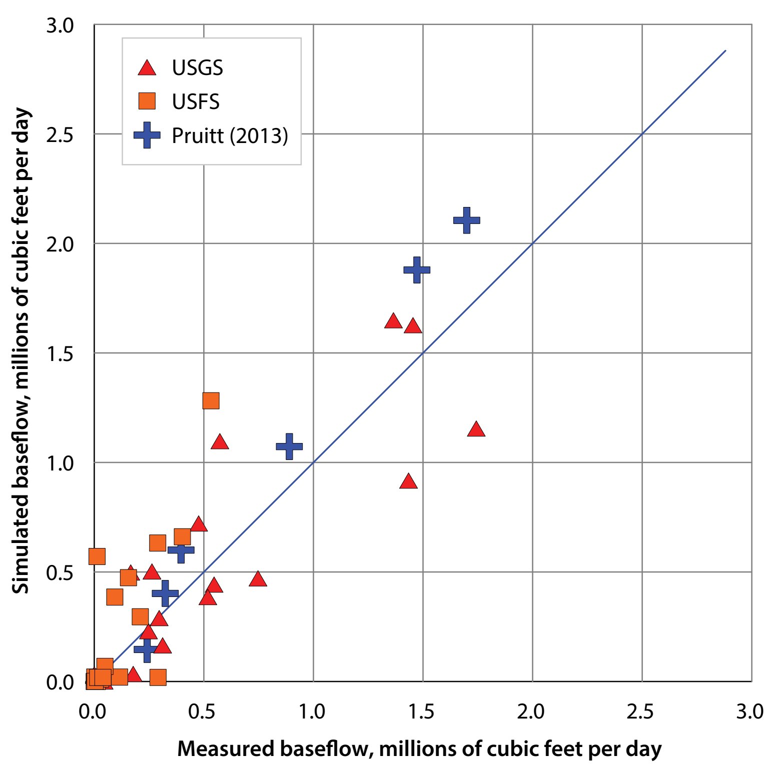


Figure 13b. Simulated vs. observed flows for lower-flow targets, plotted against 1:1 line.



Application of the model

The GFLOW groundwater flow model is a useful decision-support tool for groundwater management in the Park Falls Unit. Hydraulic heads simulated by the model compose a unit-wide water-table map (plate 10). The construction of this map differs from traditional water-table maps constructed by interpolation between point measurements (plate 1), and the resulting contours may be different in particular where data points are sparse. Model-generated water-table maps are very useful in areas of sparse data and abundant surface water, such as the Chequamegon-Nicolet National Forest. Because the model enforces mass balance, the water-table surface produced by the calibrated model is mathematically exact within the constraints and assumptions of the model. Such a map, along with model-generated pathlines (plate 10), shows general directions of groundwater flow and can be used to delineate divides between groundwater basins. As seen on plate 10 (as well as plate 1), groundwater flows primarily to the west with the exception of the southeast corner of the unit where it flows to the east and south, similar to the flow of surface water on the regional divide.

The GFLOW model can also be used to evaluate groundwater discharge to surface-water features (plate 9). This plate shows modeled baseflow, colored to indicate water exchange with the aquifer. Few streams in the unit lose water to the aquifer. The plate also shows saturated aquifer thickness and water sample alkalinity and electrical conductivity. Higher values of alkalinity and electrical conductivity (likely groundwater-dominated water samples) correspond to areas modeled by GFLOW as groundwater discharge points. Some surface-water-dominated samples are also located in areas of groundwater discharge; these locations are interpreted to have additional surface water inflows that are not illustrated by the groundwater flow model.

The GFLOW model has many other potential uses.

- Delineating areas contributing groundwater to specific springs, lakes, wells, and streams;
- Evaluating where streams are modeled as gaining or losing groundwater in response to different conditions;
- Determining the expected drawdown and zone of influence of any proposed new high-capacity wells in or near the Park Falls Unit;
- Quantifying the effect of any proposed high-capacity wells on nearby surface-water features;
- Evaluating the potential effects of climate change on groundwater resources; and
- As a foundation for more detailed studies of specific sites.

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

Assumptions and limitations

We assumed that the Park Falls Unit groundwater and surface-water systems were in close hydraulic connection in the modeled area; this assumption is consistent with the relatively transmissive nature of unlithified sediments, high net-annual precipitation, presence of springs and perennial headwater streams, and previous modeling in nearby areas. It follows then that the model assumed that elevations of surface-water features in fact represent the groundwater system; perched systems are not well represented. Areal two-dimensional assumptions were appropriate for the model because the groundwater flow system is thin and areally extensive; however, because areal two-dimensional assumptions may not be representative within two to three aquifer thicknesses of a surface-water feature (Haitjema, 1995; Hunt and others, 2003), simulated groundwater levels near surface-water features can be considered approximate only. As a result, the streambed-resistance parameter values used to match measured streamflows also can be considered only approximate, because simulated streamflow depends upon approximate simulated heads near the stream in addition to streambed resistance. Therefore, calibrated values of streambed resistance will include artifacts that result from the effects of the areal two-dimensional assumption on heads near surface-water features. The calibration dataset did not contain sufficient information to constrain estimates of seepage and drainage lakebed resistance; therefore, the 10 d values are derived from professional judgment rather than calibration and should be revisited if future modeling objectives include lake-groundwater interaction. Steady-state simulations were assumed appropriate for this study given the large lateral extent and dense surface-water network (for example, Haitjema, 1995, p. 293). The model described here is a regional-scale model; therefore, small-scale properties of the groundwater system (for example, local variations in hydraulic conductivity and recharge) can be represented only approximately by the average regional condition.

Table 12. Calibration results for groundwater head targets and associated weights used for calibration with the parameter estimation program PEST in the Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin.

Head targets—ranked by accuracy of WCR location	Number of targets	Mean error (ft)	Mean absolute difference (ft)	Root mean square error (ft)	Weight (1/std)
Best: <100 ft	399	0.5	8.2	12.7	0.5
Fair: 100–900 ft	512	–1.6	6.2	8.2	0.2
Poor: >900 ft (within a quarter–quarter section)	61	4.5	10.7	17.9	0.05

Abbreviations: ft = feet; std = standard deviation

Figure 14. GFLOW results for Park Falls model: weighted head target residuals and simulated heads above land surface (flooding) compared to wetlands listed in inventory of Wisconsin wetlands.

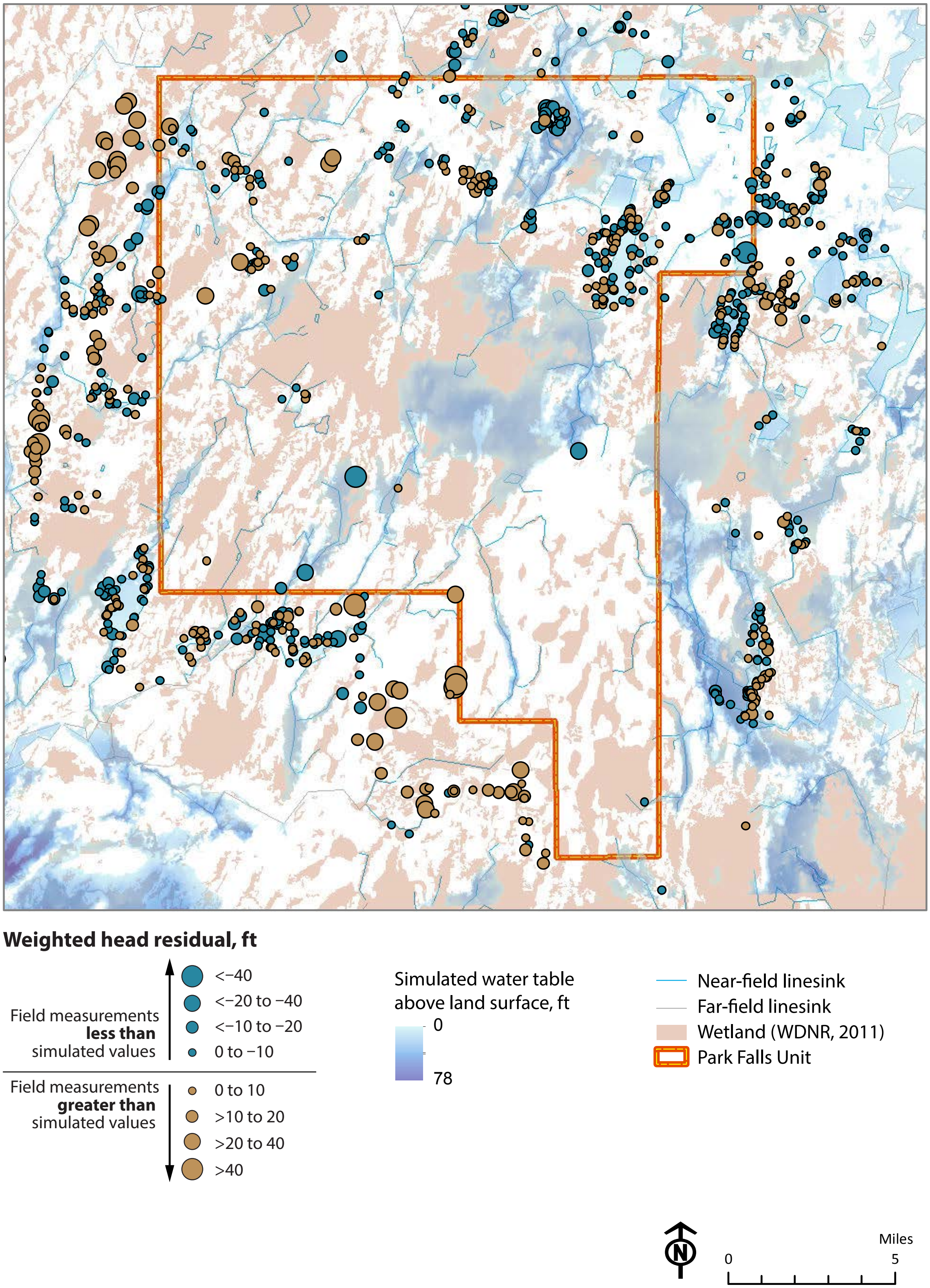
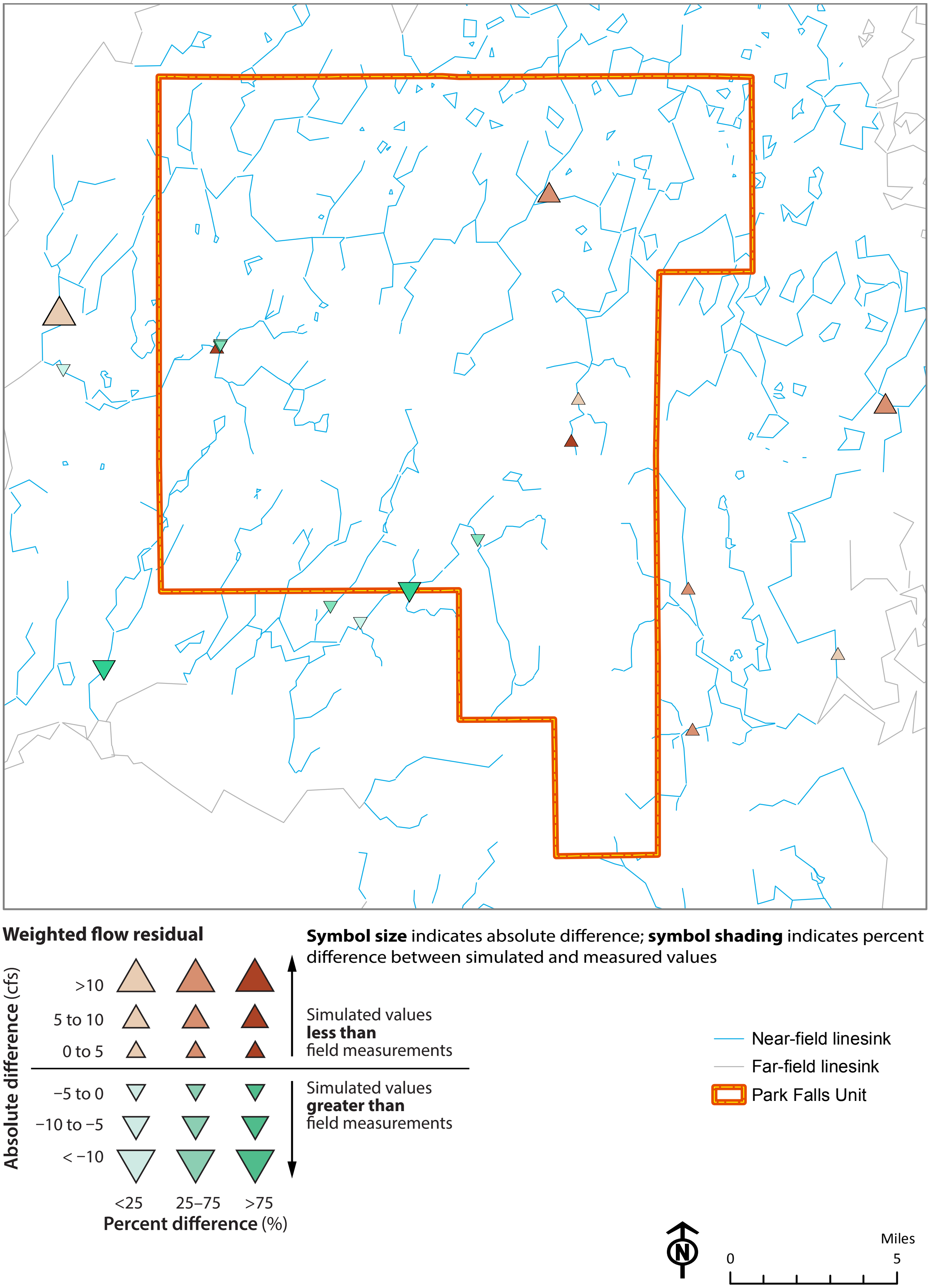


Figure 15. GFLOW results for Park Falls model: weighted flow target residuals.



Recommendations for future modeling

Additional data collection and advances in modeling techniques will improve the ability to incorporate more detail into future models. Calibration targets in the Park Falls Unit are sparse; additional measurements of groundwater levels and baseflow would help refine model results. Future modeling could also be improved by including the SWB results as a recharge input, a feature that was not available when this flow model was developed. This feature allows the user to import a grid of spatially variable recharge and calibrate to regional groundwater conditions by applying a multiplier to the grid. Lastly, additional subsurface data in the unit as well as modern maps of glacial deposits may reveal patterns in hydraulic conductivity not currently visible. Although transmissivity and hydraulic conductivity in the Park Falls Unit do vary spatially (plates 1–3), the current data do not reveal obvious spatial patterns, particularly where well records are sparse.


Twin Lake

Linda Deith

Summary

1. The primary aquifer in the Park Falls Unit consists of shallow glacial sand and gravel deposits. This fairly thin (less than 250 ft thick) aquifer has low to moderate productivity; its mean estimated hydraulic conductivity is 39 ft/d and its range is 0.9 to 1,700 ft/d. The glacial aquifer has the potential to support local high-capacity wells whose approximate average potential yield is 150 gpm.

2. Precambrian rock beneath the glacial sands and gravels also transmits water through fractures and can supply adequate water to low-capacity wells as needed in areas where the upper aquifer is thin or absent. The bedrock unit has an estimated mean hydraulic conductivity about an order of magnitude lower than conductivity in the overlying sand and gravel. The bedrock aquifer, with an approximate average potential yield of 10 gpm, has little likelihood of supporting high-capacity wells.

3. Few high-capacity wells are present in this region. Most of the active high-capacity wells within 10 miles of the unit obtain their water from the glacial aquifer. Although these wells are permitted to pump greater than 70 gpm, the majority pump at much lower rates (average 40 gpm).

4. About 80 percent of the domestic wells in the Park Falls Unit obtain their water from the sand and gravel aquifer. Of the bedrock wells, most pump from the top 100 ft of bedrock, although some pump from as deep as 300 ft.

5. Two monitoring wells located far from human effects provide important baseline data representative of the general study area. Groundwater elevations in these wells have remained stable during the past few decades.

6. The SWB-modeled mean potential recharge is moderate (8.5 in/yr), and local patterns indicate higher recharge over sandy soils and forest cover and lower recharge over finer soils and wetland cover. The SWB model may overestimate recharge in wetlands. If we assume that zero recharge in wetlands produces an average potential recharge of 6.8 in/yr in the Park Falls Unit, then the SWB-model simulated unit-wide average potential recharge is likely between 6.8 and 8.5 in/yr.

7. Water quality within the unit is generally unaltered by human activity. Elevated nutrient concentrations were observed at a few sample locations, likely as a result of local land-use activities such as road salting. Slightly elevated concentrations of iron and manganese occurred in several wells sampled; these likely originate from local minerals in the aquifer or from plumbing systems.

8. Groundwater is distinguished from surface water by higher pH, electrical conductivity, alkalinity, and concentrations of dissolved ions such as calcium and magnesium. Groundwater well samples have an average conductivity of 161 µs/cm and alkalinity of 83 mg/L, whereas samples interpreted as surface-water dominated have averages of 33 µs/cm and 13 mg/L, respectively.

9. The regional surface-water and groundwater divides are similar; water in the unit generally flows to the west with the exception of the southeast corner of the unit where it flows to the southeast. 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 groundwater-surface water interactions. The model may also be used to simulate potential effects of land use, pumping, or climate change.

10. Hydrogeologic data are sparse within the Park Falls 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. Recommended future activities include the following:

    a. Maintain at least one monitoring well in each unit to provide baseline groundwater-level data.

    b. Measure baseflow and groundwater elevations to improve groundwater flow model calibration.

    c. Investigate the extent and magnitude of recharge in wetland areas.

    d. Obtain additional subsurface data to constrain hydraulic conductivity estimates.

Data availability

The results of the inventory, modeling, and analysis described in this report are available in an electronic database for public use (table 13). These data can be downloaded from the WGNHS web site at https://wgnhs.uwex.edu/.

Table 13. Summary of available electronic data, Park Falls Unit, Chequamegon-Nicolet National Forest, Wisconsin.

Data	Name	Format	Description/source
Wells			
Located wells	PF_LocWCRs_WGNHS_2016	Point features	WCRs located to within the quarter-quarter section
Monitoring well construction	Monitoring well information-Park Falls Unit.pdf	PDF file	Geologic and construction data for Wintergreen Trail well
PR-0087 well	PF_PR0087WellSite_WGNHS_2016	Point features	Location of monitoring well PR-0087 near Wilson Lake
Wintergreen Trail well	PF_WintergreenWellSite_ WGNHS_2016	Point features	Location of monitoring well at Wintergreen Trail
Geology			
Bedrock elevation contours	PF_BedElev_WGNHS_2016	Polyline features	Interpolated from WCRs and other data
Depth to bedrock contours	PF_BedDep_WGNHS_2016	Polyline features	Interpolated from WCRs and other data
Outcrops	PF_HistOutcrop_WGNHS_2016	Point features	Bedrock outcrop locations interpreted by WGNHS from King (1882)
Saturated thickness contours of glacial materials	PF_GlacSatThickness_WGNHS_2016	Polyline features	Interpolated from WCRs and other data
Geophysics			
Geophysics survey: EM-31	PF_GeophysEM31_WGNHS_2016	Point features	EM-31 ground conductivity survey results
Geophysics survey: GEM-2	PF_GeophysGEM2_WGNHS_2016	Point features	GEM-2 ground conductivity survey results
Areas of high bedrock	PF_GeophysBedHigh_WGNHS_2016	Point features	Likely areas of shallow bedrock estimated from geophysical survey results
Hydraulic properties			
Bedrock hydraulic properties	PF_BedTGUESS_WGNHS_2016	Point features	Hydraulic conductivity and transmissivity results from TGUESS
Glacial hydraulic properties	PF_GlacTGUESS_WGNHS_2016	Point features	Hydraulic conductivity and transmissivity results from TGUESS
Wintergreen Trail well hydrograph	PF_WintergreenWell_WGNHS_2016	Excel	Continuous water-level measurements by WGNHS
Recharge			
Mean annual potential recharge	PF_PoRec_WGNHS_2016	Raster data	Annual recharge mean of all modeled years from SWB model output
Annual potential recharge, individual years	PF_PoRec[yyyy]_WGNHS_2016, for example, PF_PoRec2000_ WGNHS_2016	Raster data	Annual potential recharge for years 2000–2010 (11 files) from SWB model output

Abbreviations: SWB = soil-water balance; WCR = well construction report

Data	Name	Format	Description/source
Groundwater			
Regional water table contours	PF_RegWatTab_WGNHS_2016	Polyline features	Regional water table compiled from Cates and Batten (1999) and Patterson (1989)
Simulated water table contours	PF_WatTabGFLOW_WGNHS_2016	Polyline features	GFLOW model output
Simulated groundwater flow paths	PF_GWFlowpathGFLOW_ WGNHS_2016	Polyline features	GFLOW model output
Modeled baseflow	PF_BaseflowGFLOW_WGNHS_2016	Polyline features	GFLOW model output
Geochemistry			
Geochemistry sampling locations	PF_GeochemSites_WGNHS_2016	Point features	WGNHS water sampling locations
Geochemistry results	PF_Geochemistry_WGNHS_2016	Excel	Field and laboratory water sample results
Model			
GFLOW targets	PF_ TargetsGFLOW_WGNHS_2016	Point features	Modeled and measured values for GFLOW flow and head targets
USGS data archive for GFLOW model	http://dx.doi.org/10.5066/F7RV0KTV	Model files	Groundwater flow model and associated files

Abbreviations: SWB = soil-water balance; WCR = well construction report


Sundews

Linda Deith

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