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

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

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

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List of abbreviations

CNNF	Chequamegon-Nicolet National Forest
DEM	digital elevation model
MWL	meteoric water line
NRCS	Natural Resources Conservation Service
PAL	preventive action limit
SWB	soil-water balance
TIN	triangular irregular network
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
WCR	well construction report
WDNR	Wisconsin Department of Natural Resources
WGNHS	Wisconsin Geological and Natural History Survey

Executive summary

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

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

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

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

The initial portion of the study inventoried and analyzed available hydrogeologic data, which was assembled into a spatial database. Data sources included well construction reports, high-capacity-well pumping rates, and groundwater-level measurements. These data were analyzed to produce maps of bedrock elevation, depth to bedrock, and saturated aquifer thickness, and to produce estimates of hydraulic conductivity. The assembled data as well as previous studies of the regional geology show that subsurface materials in the unit consist of unlithified glacial sediments over Precambrian crystalline bedrock. The spatial analysis suggests that the surficial glacial sand and gravel deposits form a shallow aquifer (20–200 feet (ft) thick) with low to moderate productivity. This shallow aquifer, composed mostly of glacially derived sand and gravel, is referred to as the glacial aquifer in the remainder of this report. The horizontal hydraulic conductivity estimates for this aquifer ranged from 0.06 to 3,000 feet per day (ft/d), and have a mean of 46 ft/d. About 65 percent of wells in the Medford Unit obtain their water from this aquifer. The sand and gravel aquifer has the potential to support high-capacity wells in some areas; the approximate average potential yield is 200–300 gallons per minute (gpm). Crystalline bedrock beneath the glacial deposits also transmits water through fractures, but in general it is less productive than the glacial aquifer, and bedrock wells are commonly located in areas where the glacial aquifer is thin. In general, this bedrock unit has horizontal hydraulic conductivities about an order of magnitude lower than those of the overlying sand and gravel. The bedrock aquifer has a low likelihood of supporting high-capacity wells; its approximate average potential yield is 5–10 gpm. Of the bedrock wells, most pump from the top 60 ft of bedrock, although some wells are as much as 500 ft deep. Regardless of the aquifer in which the wells are completed, specific capacities (discharge divided by drawdown) of wells are generally low (less than 1 gallon per minute per foot (gpm/ft)) throughout the Medford Unit, although some wells have high yields with specific capacities greater than 10 gpm/ft.

Currently, no high-capacity wells are located in the Medford Unit, although 15 high-capacity wells are located within 10 miles of the unit, and all of these wells pump from the glacial aquifer. Although such high-capacity wells are permitted to pump more than 70 gpm, the majority pump at lower rates. On average, each of these wells uses 12 million gallons of groundwater per year (equivalent to about 23 gpm, if a constant pumping rate is assumed). Groundwater levels in a monitoring well not directly affected by human use provide important baseline data for the general study area. The measured groundwater level fluctuated with precipitation but generally remained stable during the past five years.

For 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 deep drainage in the Medford Unit for the years 2000 through 2010. The mean overall potential recharge for this time period was 5.8 inches per year (in/yr), and it ranged from 4.3 to 8.9 in/yr, largely owing to changes in precipitation. The general trend in the distribution of recharge within the model area correlates with surficial geology through soil characteristics, and higher potential in the southern half of the unit corresponds with hilly topography of the Copper Falls Formation. The SWB model may overestimate recharge in wetlands, which cover about 18 percent of the unit. Assuming zero recharge in wetlands produces an average forest-wide potential recharge of 5.0 in/yr. However, it is likely that recharge in wetlands is greater than zero, and so the SWB-simulated forest-wide average potential recharge is between 5.0 and 5.8 in/yr. During calibration of the groundwater flow model a regional multiplier of 0.77 was applied to the SWB grid that resulted in an overall mean recharge value of 4.4 in/yr.

The third part of this study was a basic inventory of surface-water and groundwater geochemistry, in order to better characterize current water quality in the forest. Water samples from wells, springs, 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 Medford Unit has low concentrations of most dissolved constituents and thus has been relatively unaffected by human activities. Groundwater in the Medford Unit is distinguished from surface water by higher electrical conductivity and by greater alkalinity and greater concentrations of dissolved ions such as calcium and magnesium. Groundwater well samples have an average conductivity of 313 microsiemens per centimeter (µS/cm) and alkalinity of 132 milligrams per liter (mg/L), whereas samples interpreted as surface-runoff dominated have averages of 63 µS/cm and 20 mg/L, respectively. Isotopes of hydrogen and oxygen can also be used to distinguish groundwater, which is isotopically lighter, or more negative, than surface water. This relation can be used to evaluate which wells may be drawing from surface water or, conversely, which surface-water features may be predominantly groundwater fed. Some samples contained slightly elevated levels of chloride, suggesting the possible influence of local land-use activities such as road salting.

Concentrations of three metals in groundwater samples in the Medford Unit were higher than recommended limits established to protect health. Four well samples slightly exceeded the Wisconsin NR140 preventive action limit (PAL) for arsenic, and two samples slightly exceeded the PAL for lead. In addition, two groundwater samples in the Medford Unit slightly exceeded the enforcement standard for manganese, and samples from four other wells exceeded the PAL. In all of these samples the concentrations of these metals are still very low, near the level of detection by the analytical methods used. The source of the metals is unknown and might come from natural minerals in the region or from plumbing and pipe fixtures or other anthropogenic sources. We recommend that these wells be retested periodically to ensure that these constituent concentrations meet standards for drinking water quality.

In the fourth part of the study, a regional groundwater flow model was constructed for the Medford Unit by using the analytic element model code GFLOW. The flow model provides a framework with which to estimate key aquifer properties, simulated water-table elevations, flow paths, flow rates, and discharge zones. In this unit, groundwater flows primarily to the southwest except in the northern and southern areas of the unit, similar to regional surface-water flow. The flow model can be a powerful decision-support tool for water resource management. Potential uses for the model include delineating areas that contribute groundwater to surface-water features, determining the expected drawdown from a new well, and evaluating how changes in pumping or land use change streamflow and water levels.

The 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. In particular, very little hydrogeologic information was available in the Kidrick Swamp and Steve Creek watershed areas in the northwest part of the unit. The GFLOW model suggests that numerous groundwater flow paths originate in this area that terminate in the Yellow River, Jump River, or their tributaries. Additional hydrogeologic data collection in this area is necessary to confirm the simulated flow paths. In areas of sparse data, particularly the northwest, north-central, and southwest parts of the Medford Unit, additional subsurface data is needed to constrain aquifer thickness and hydraulic conductivity estimates. Passive seismic and electromagnetic surveys along existing forest roads might prove to be a cost-effective way of developing improved bedrock elevation and aquifer thickness maps.

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

Introduction

Background

The Chequamegon-Nicolet National Forest (CNNF) in northern Wisconsin is home to an abundance of water resources—streams, lakes, springs, and wetlands—that depend on the recharge and discharge of groundwater. Groundwater discharge is a primary factor in the establishment, persistence, and survival of groundwater-dependent ecosystems. In addition, groundwater-derived baseflow is the limiting factor for many recreational uses such as fishing and canoeing. Understanding groundwater in the Medford Unit is also important for assessing the feasibility and potential effects of multi-use projects such as mines, timber extraction, and agriculture. 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 forest managers better protect and allocate these resources.

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

To improve the baseline understanding of forest-wide resources, in 2010 the U.S. Forest Service (USFS) requested that the Wisconsin Geological and Natural History Survey (WGNHS) and U.S. Geological Survey (USGS), acting jointly, review and analyze groundwater resources in the CNNF. This multi-year hydrogeological study presents an innovative approach to studying hydrogeology in undeveloped areas with sparse datasets. The study is divided by location into four reports corresponding to the four main CNNF contiguous land units: Medford, Nicolet, Park Falls, and Washburn/Great Divide. This report documents the results of this study within the Medford Unit (fig. 1), which comprises more than 250 square miles in Taylor County.

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 consists of an inventory of available data and development of tools with the following goals:

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

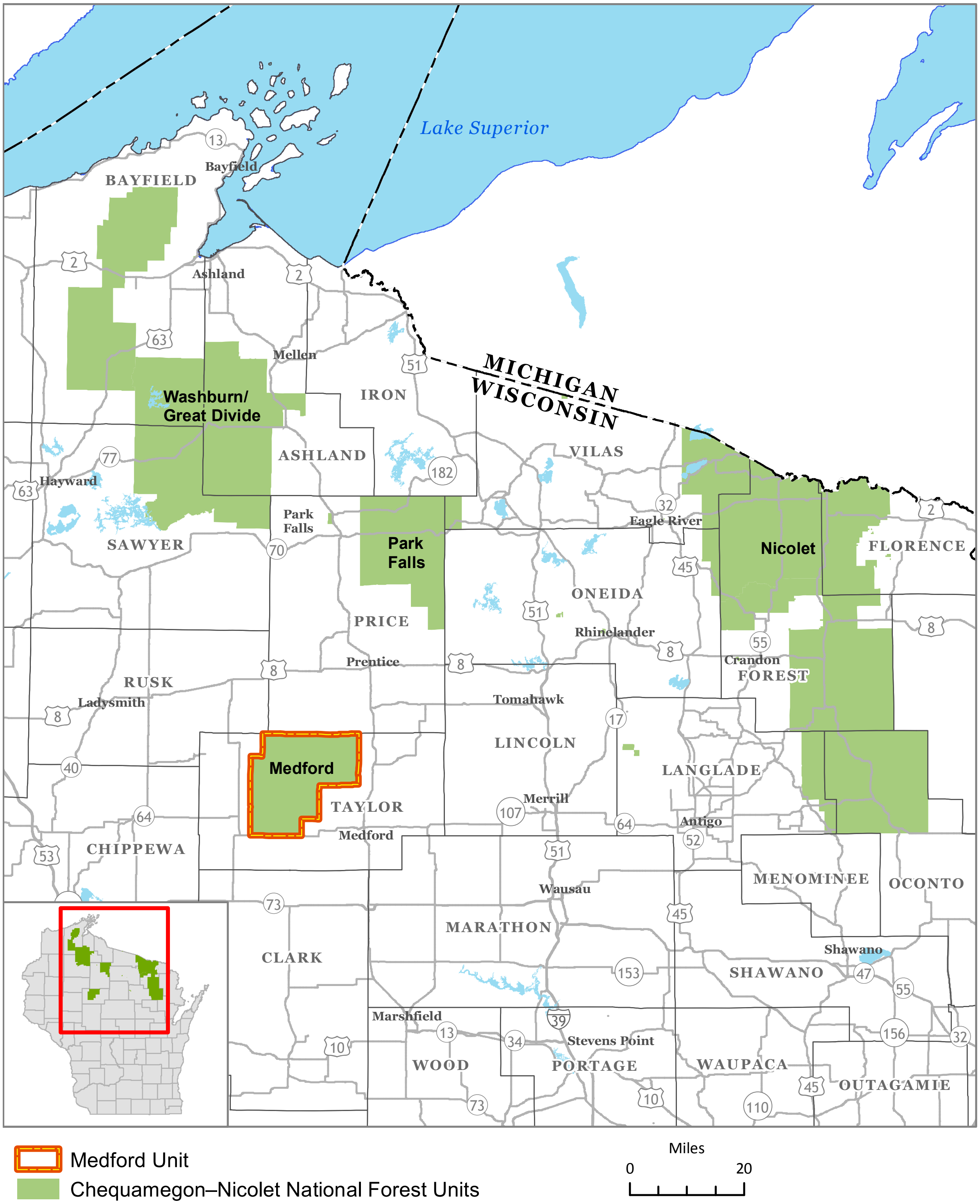
Study approach

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

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

These components meet the goals of the project by summarizing key elements of the existing hydrologic system throughout the CNNF, such as aquifer characteristics, potential recharge distribution, and surface-water–groundwater interactions, which are relevant to groundwater-dependent ecosystems. The flow model was needed to provide a quantitative framework for simulating heads, flows, flow paths, and responses to potential stress. The model can be used to show general directions of groundwater

Figure 1. Medford Unit location.



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.

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

The products of this 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 Medford Unit. Juckem and Hunt (2007, 2008) and Lenz and others (2003) describe groundwater flow models that include the western and southwestern portion of the CNNF, respectively. Fitzpatrick and others (2005) characterized the Fish Creek watershed north of the CNNF, and Krohelski and others (2002) describe a groundwater flow model in eastern areas of the CNNF. In addition, a long history of groundwater modeling is present for Vilas County as part of the National Science Foundation–funded Long-Term Ecological Research and the USGS'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. The WGNHS mapped the Quaternary geology of portions of the CNNF (Florence, Forest, Langlade, Oconto, Oneida, Taylor, and Vilas Counties) at the 1:100,000 scale. These county maps are supported by unit descriptions and cross sections. Modern Quaternary mapping is available at the more generalized 1:250,000 scale for Ashland, Bayfield, and limited parts of Rusk and Sawyer Counties.

Within the Medford Unit, little comprehensive information existed on the geology or groundwater conditions prior to this study. No modern county-scale mapping of bedrock geology is available for Taylor County. Mudrey and others (1987) mapped the bedrock geology of the northwest region of Wisconsin, and their map includes the Medford Unit. Attig (1993) mapped the Pleistocene geology in Taylor County. Several studies have documented the geology, economic viability, and geochemistry of a massive sulfide deposit located near the center of the unit (DeMatties and Rowell, 1996; Woodruff and others, 2003, 2004).

Regional studies of groundwater and surface water have also been conducted within the unit. The USFS has actively collected ecological and surface-water data in the Medford Unit, including water temperature, streamflow, and basic water quality, for selected streams and lakes. Taylor County published a report on the state of groundwater quality and quantity in the county in 2012 (Oberle, 2012). Locations of springs and spring-fed surface-water features, here called spring ponds, in the Medford Unit were compiled as part of a statewide springs inventory (Macholl, 2007).

Setting

The Medford Unit (fig. 1) spans more than 250 square miles in Taylor County. Of this area, approximately 200 square miles are managed by the USFS. The unit is mostly forested and is characterized by numerous wetlands, springs, lakes, and streams. Surface water regionally drains in several directions; most of the unit drains southwest to the Yellow River and ultimately the Chippewa River, whereas surface water in the northern part of the unit flows north and west to the Jump River, and in the southern part it flows south to the Black River. The unit is home to two large (more than 400 acres) flowages, the Chequamegon Waters Flowage and Mondeaux Flowage, as well as numerous wetland complexes such as Kidrick Swamp. About 25 percent of the unit is mapped as wetland (Wisconsin Department of Natural Resources, 2011). Elevation ranges from about 1,230 ft in the southwest to more than 1,600 ft at the northeastern boundary. The climate is humid and temperate; the north-central region of Wisconsin that includes the Medford Unit receives an average precipitation of 32.4 in/yr (Wisconsin State Climatology Office, 2017).

Geology

Glacial geology in the Medford Unit as mapped by Attig (1993) is shown on plates 1 and 2 and summarized in table 1. Geological surficial materials consist of unlithified till, outwash, and lake sediment deposited during several glaciations culminating between about 25,000 and 15,000 years ago. Thickness ranges from tens of feet to more than 200 feet; few bedrock outcrops are present. In the north of the unit, deposits consist of sandy till and till of the Copper Falls Formation. To the south, a zone of collapsed supraglacial sediments of the Copper Falls Formation trends southwest–northeast. This zone is characterized by hilly topography and thick, poorly sorted sediments. Thinner till deposits of the Merrill Member of the Lincoln Formation (later redefined as part of the Copper Falls Formation by Syverson and others, 2011) and the Edgar Member of the Marathon Formation are present south of the unit (Attig, 1993).

The glacial sediments overlie Precambrian igneous and metamorphic bedrock, as shown on plate 3 and in table 2 (Mudrey and others, 1987). Bedrock in the north is composed of felsic metavolcanic rock and the Flambeau granite; bedrock in the south is predominantly volcanic metasedimentary rock. A region of mafic intrusive rock is present in the center of the unit (Mudrey and others, 1987).

A massive sulfide deposit, usually referred to as the Bend deposit, is located in the Medford Unit approximately 19 miles north-northwest of the city of Medford (DeMatties and Rowell, 1996). This deposit is part of a larger belt of Precambrian metavolcanic rocks with potential for mining economically important minerals such as copper, gold, silver, and zinc; the Bend site has been explored within the past 30 years (DeMatties and Rowell, 1996; Woodruff and others, 2003). Prospecting for similar deposits has also been approved in other areas including the Mondeaux Dam in the northeast part of the unit (U.S. Forest Service, 2013). The potential for future hard-rock prospecting and mining is one reason for improving our understanding of local hydrogeology and baseline water quality in the Medford Unit.

Table 1. Glacial geology unit descriptions.

Postglacial sediment	
p	Sediment of low, typically wet areas
sp	Postglacial stream sediment
Copper Falls Formation	
Meltwater-stream sediment	
sc	Gravelly sand or gravelly sand with some sandy gravel; includes Attig (1993) unit scc
Lake sediment	
lc	Sandy and silty offshore sediment
Glacial sediment	
Gently rolling topography	
gc	Sandy till of the Chippewa Lobe
gu	Till, undifferentiated
Hilly topography of collapsed supraglacial sediment	
bgh	Gravelly, sandy sediments; includes Attig (1993) units gch, gbh, gwh, guh
Till of the Merrill Member[1]	
gm	Gently rolling topography; includes Attig (1993) unit gmh
Marathon Formation	
Glacial sediment	
ge	Gently rolling topography

Modified from Attig, 1993

[1]The Merrill Member was originally classified as part of the Lincoln Formation by Attig (1993); it was reclassified as part of the Copper Falls Formation by Syverson and others (2011).

Table 2. Bedrock geology unit descriptions.

Era	Period	Unit	Description
Paleozoic	Cambrian	Cu	Cambrian sandstone, undifferentiated
		Cm	Mount Simon Formation sandstone
Paleoproterozoic		Pfg	Flambeau granite
		Pfv	Felsic metavolcanic rock
		Pvs	Volcanic metasedimentary rock
		Pmv	Mafic metavolcanic rock
		Pmg	Mafic intrusive rock
		Pam	Amphibolite
		Pgn	Granodiorite gneiss

Modified from Mudrey and others, 1987

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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, Paul F. Juckem, Randall J. Hunt, and Andrew T. Leaf; project coordination and editing, Kenneth R. Bradbury and Anna C. Fehling.

Section 1: Hydrogeologic data

Objectives

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

Data sources

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

Well construction reports

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

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

Using the WCRs and Esri ArcGIS software, WGNHS staff prepared a geographic information system database for the Medford Unit. This database was the fundamental tool used for storing spatial data for the project. Because the WCR records generally locate wells only to the nearest quarter-quarter section or to a lot number, it was necessary to manually move records to the correct location in a process called geolocation. Using aerial photography and land ownership, WGNHS staff examined individual well records and digitized the most likely location of wells in relation to visible buildings, roads, and other landscape features identified on the NAD 83 Wisconsin Transverse Mercator projection. Each well was also evaluated for the confidence in the selected location. The study area extended outside the Medford Unit boundary and included parts of Rusk, Price, and Taylor Counties. In all, this process located 5,377 wells in the project area to within an estimated 750 ft of their true location; the majority of the wells are located outside the Medford Unit. Physical data associated with each of these wells were assembled in the database.

About 65 percent of the 5,377 wells in the WCR database for the Medford Unit are screened in the glacial aquifer; these wells have an average bottom depth of about 80 ft, although some are more than 300 ft deep. The average bedrock well pumps from the top 60 ft of bedrock, although some pump from as deep as 500 ft. Of the bedrock WCRs, depth to bedrock averages about 70 ft and ranges from 0 to 270 ft; the total well depth averages 130 ft and ranges up to 550 ft.

Geologic records

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

Water use

Records of monthly water use for high-capacity wells (wells capable of pumping at 70 gpm or more) have been maintained by the WDNR since 2011. As of 2014, the WDNR database contains no records of high-capacity wells within the Medford Unit and few in this region generally (R. Smail, written communication, 2016). There are records of 15 active high-capacity wells within 10 miles of the unit as shown in table 3 and plate 4 (several of these wells are so close together that the symbols on the plate plot on top of each other). On average, each of these wells uses 12 million gallons of groundwater per year (equivalent to about 23 gpm, if a constant pumping rate is assumed), although many high-capacity wells in Wisconsin pump at rates in the hundreds or thousands of gallons per minute. All of these wells obtain their water from the glacial aquifer and are 70 ft deep on average.

Methods

Interpolation of hydrostratigraphic layers

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

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

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

Table 3. High-capacity well withdrawals within 10 miles of the Medford Unit.

WI unique well no.	High-capacity well no.	Depth (feet)	Material reported by driller	Total annual water use (gallons)				
				2011	2012	2013	2014	Average 2011-14
Public supply								
BG824	85444	117	Gravel with clay	8,804,300	8,913,900	4,422,800	5,397,000	6,884,500
BG825	85445	90	Gravel with clay	6,913,700	4,737,800	3,664,600	4,918,700	5,058,700
BH042	86641	36	Gravel	3,218,000	3,768,000	3,326,000	5,648,000	3,990,000
BH043	86642	50	Gravel	37,930,000	37,870,000	39,489,000	43,074	28,833,019
BH044	86643	46	Gravel	35,171,000	37,070,000	37,533,000	44,510	27,454,628
BH045	86644	87	Sand and gravel	47,540,000	48,291,000	48,096,000	57,812	35,996,203
BH046	86645	52	Gravel	8,473,200	9,653,900	7,112,500	17,614,400	10,713,500
BH047	86646	45	Sand	8,574,400	9,719,300	11,609,450	10,825,400	10,182,138
BH048	86647	84	Sand and gravel	1,999,073	2,059,774	4,442,713	2,962,774	2,866,084
BH049	86648	73	Sand and gravel	745,300	248,780	46,460	87,800	282,085
BH050	86649	47	Gravel	5,059,000	6,247,000	7,696,000	10,392,000	7,348,500
FJ643	1085	86	Sand and gravel	35,440,000	35,660,000	36,777,000	43,687	26,980,172
NJ070	2324	60	Sand and gravel	17,360,000	18,420,000	14,414,000	13,609	12,551,902
Irrigation								
BE932	62801	No record located		6,883,800	6,111,600	4,365,120	816,000	4,544,130
BE933	62802	No record located		2,137,500	0	150,000	2,733,000	1,255,125

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

The saturated thickness coverage was calculated by subtracting bedrock surface elevation from the water-table surface exported from the groundwater flow model (section 4). The depth-to-bedrock raster surface was calculated by subtracting the bedrock surface raster from the land surface elevation. These surfaces were also imported into Esri ArcMap or Surfer software for contouring and plotting.

Estimation of hydraulic properties

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

Wells with specific-capacity measurements were sorted into two groups: glacial (unlithified) wells and bedrock wells. The data were reviewed for errors, and wells with missing or obviously incorrect data were removed from the analysis. Wells were also removed if the tests were apparently influenced by casing storage effects. The final data set included 3,043 wells in unlithified materials and 723 wells finished in bedrock.

Water-level measurements

As part of this study, a monitoring well was selected in each unit to measure continuous water levels. Water levels for the Medford Unit were obtained at well TA-217, located on Yellow River Road in the northwest quadrant of the unit (plate 4). This monitoring well is close to the Bend massive sulfide deposit, a potential mining location (see Geology section). The well was installed as part of this project and became part of the Wisconsin groundwater monitoring network in November 2011.

The USGS maintains daily water-level records that are publicly available from its National Water Information System website under site number 451836090354801. Records for this well are available online at http://waterdata.usgs.gov/wi/nwis/inventory/?site_no=451836090354801. The well is 30 ft deep and screened in unlithified sand and gravel. Well construction information is included in the supplemental digital data (see table 15). This well is fairly isolated from water-table influences such as streams, pumping wells, or the human-caused effects of development and thus provides information about natural fluctuations in the local water table.

Results

Hydrostratigraphic layers

The regional bedrock surface in the Medford Unit (plate 5) slopes downward gently to the west, from about 1,360 ft above sea level at the eastern boundary to 1,200 ft in the southwest. Local areas of higher or lower bedrock are likely present but may not be captured owing to the lack of data points within the Medford Unit.

Depth to bedrock within the unit ranges from less than 20 ft in the north-central part of the unit to as deep as 300 ft along the northeast boundary (plate 6). The bedrock is generally deepest in a southwest–northeast zone trending across the southern portion of the Medford unit, which corresponds to hilly glacial-collapse deposits of the Copper Falls Formation (Attig, 1993). Similarly, the saturated thickness of unlithified materials ranges from about 20 ft in lowlands and stream valleys to nearly 200 ft in areas of higher elevation (plate 7).

Hydraulic properties

Plates 1–3, figure 2, and table 4 illustrate the results of our horizontal hydraulic conductivity and transmissivity estimates. The analyzed wells included 3,043 wells completed in unlithified materials and 723 wells in bedrock. Because the estimates of hydraulic conductivity are log-normally distributed, the geometric mean was used to evaluate the central tendency of the data. Hydraulic conductivity estimates in the unlithified glacial materials had a mean of 46 ft/d and a range of 0.06 to 3,000 ft/d. In general, the hydraulic conductivities in bedrock are about an order of magnitude lower than conductivities in glacial materials; the hydraulic conductivity has a mean of 2 ft/d and a range of 0.02 to 3,700 ft/d.

Table 4. Summary of hydraulic estimates for the Medford Unit.

Well performance in two substrates	Specific capacity (gpm/ft)	Trans-missivity (ft^2/day)	Hydraulic conductivity (ft/day)
Unlithified materials (n = 3,043)			
Minimum	0.01	13	0.06
Maximum	130	130,000	3,000
Geometric mean	0.8	2,000	46
Bedrock (n = 723)			
Minimum	0.009	2	0.02
Maximum	30	9,200	3,700
Geometric mean	0.3	57	2

Abbreviations: ft = feet; gpm = gallons per minute

Aquifer yield depends on hydraulic conductivity as well as aquifer thickness. Transmissivity (plate 1; see also fig. 2 and table 4), the product of aquifer thickness and hydraulic conductivity, was therefore used to evaluate potential aquifer yield. Mean transmissivity was 2,000 square feet per day (ft^2/d) in the glacial materials and 57 ft^2/d in the bedrock. If we assume mean transmissivity and a drawdown of 40 ft (on the basis of average aquifer thickness of analyzed glacial wells), in many places the glacial aquifer could support a typical yield of 200–300 gpm, higher than the 70 gpm minimum of high-capacity wells. A similar analysis for the bedrock aquifer that used 30 ft of drawdown suggests it could support about 5–10 gpm. Yields of several hundreds of gallons per minute are possible in either aquifer where transmissivity is greater than about 1,000 ft^2/d. This analysis suggests that the glacial aquifer has the potential to support high-capacity wells in areas of higher transmissivity, but in general those wells could not produce much more than several hundred gallons per minute. Similarly, a statewide map of probable sand-and-gravel well yields shows that yields in Taylor County are unlikely to exceed 100 gpm (Devaul, 1975). The bedrock aquifer is unlikely to support high-capacity wells.

Specific capacities (discharge divided by drawdown during a well completion test) are generally low throughout the Medford Unit, suggesting low to moderate aquifer productivity, although some wells in both glacial materials and bedrock do have maximum specific capacities greater than 10 gpm/ft (see fig. 2 and table 4). If we use the same assumptions for drawdown, a typically constructed well in this area could support a yield of about 5–10 gpm in the bedrock aquifer and 30 gpm in the glacial aquifer. Specific capacity depends on well construction and most wells in the forest are designed for low use; higher yields are possible with larger-diameter wells.

There is little variability in hydraulic properties between mapped glacial and bedrock units, possibly because the data are sparse in the interior of the Medford Unit. The unlithified hydraulic conductivities may be skewed toward higher values owing to the lack of wells completed in less permeable, finer-grained deposits.

Water levels

A hydrograph of well TA-217 from 2011 through 2016 (fig. 3) shows the 30-day moving average of water-level elevation and precipitation measured at the Medford climate station (NOAA, 2016). Groundwater levels ranged from a low of 1,339.1 ft in March 2013 to a high of 1,345.4 ft in July 2015. Water levels in this well appear to fluctuate in response to seasonal variations in and timing of precipitation and are typically 15–20 ft below ground surface. Groundwater in this area flows south and west, likely discharging to the South Fork Yellow River. This well provides important baseline data representative of the general study area that can be used for future analyses.

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

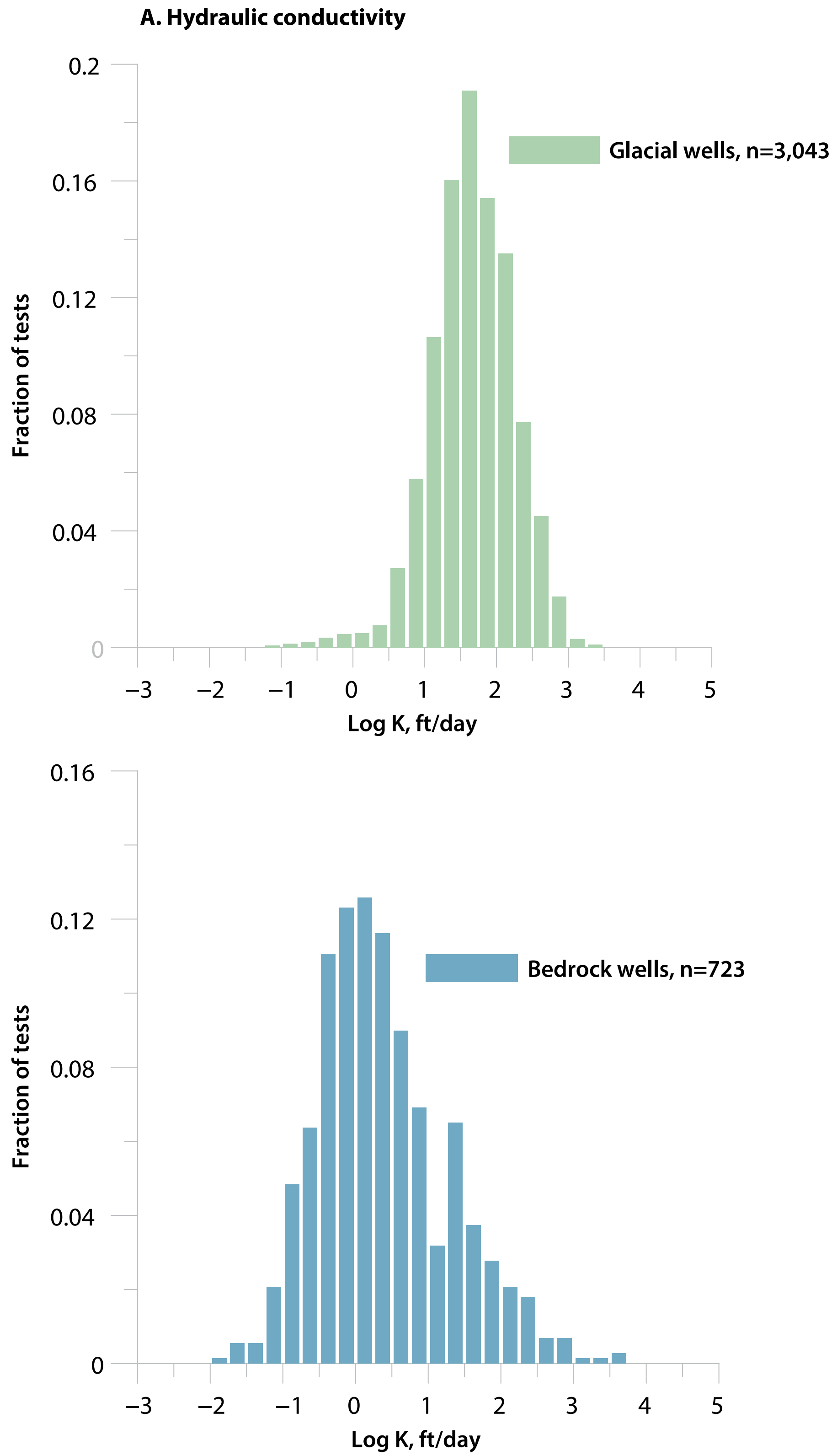


Figure 2b. Transmissivity estimated from specific-capacity tests in the Medford Unit.

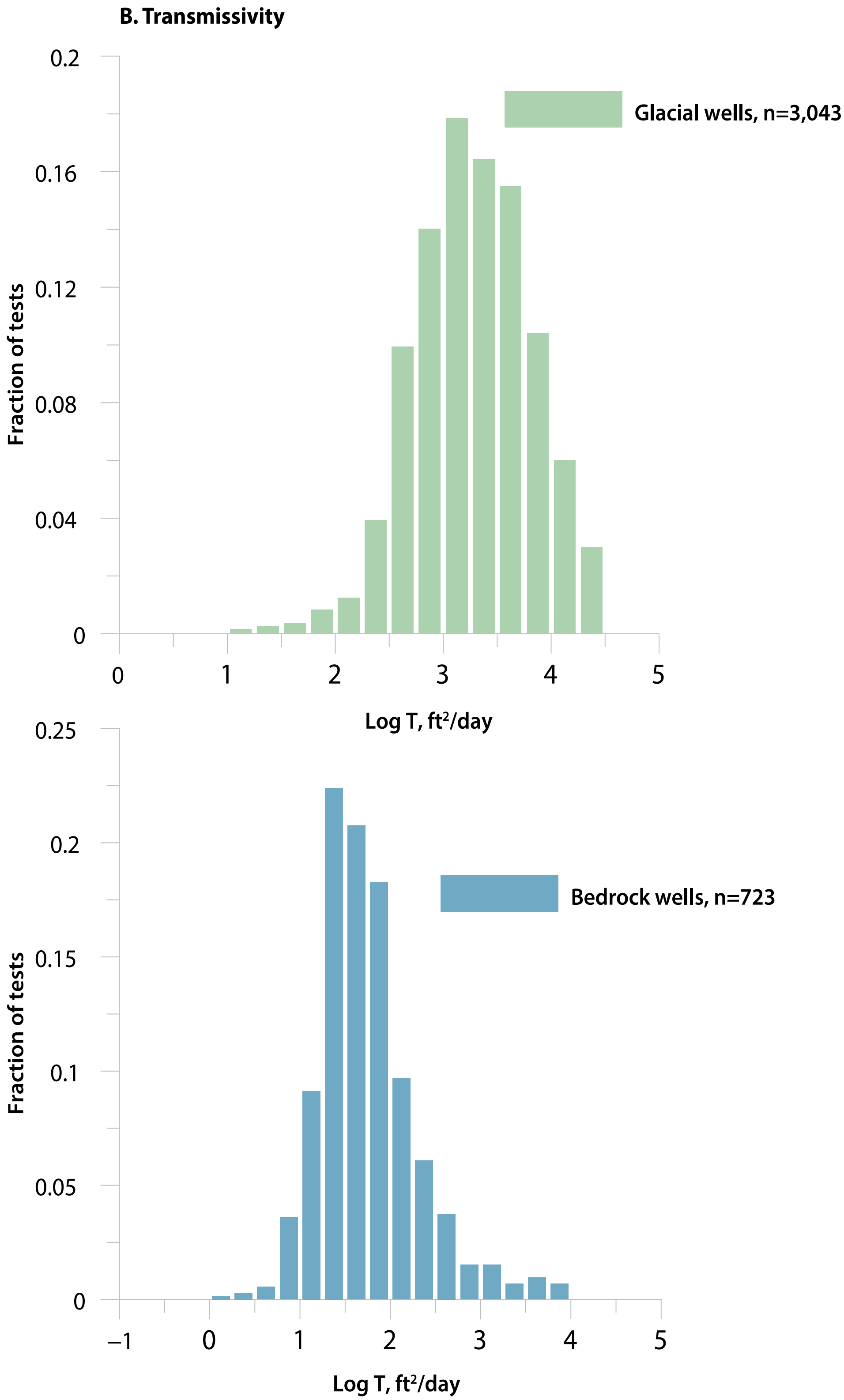


Figure 2c. Specific capacity estimated from specific-capacity tests in the Medford Unit.

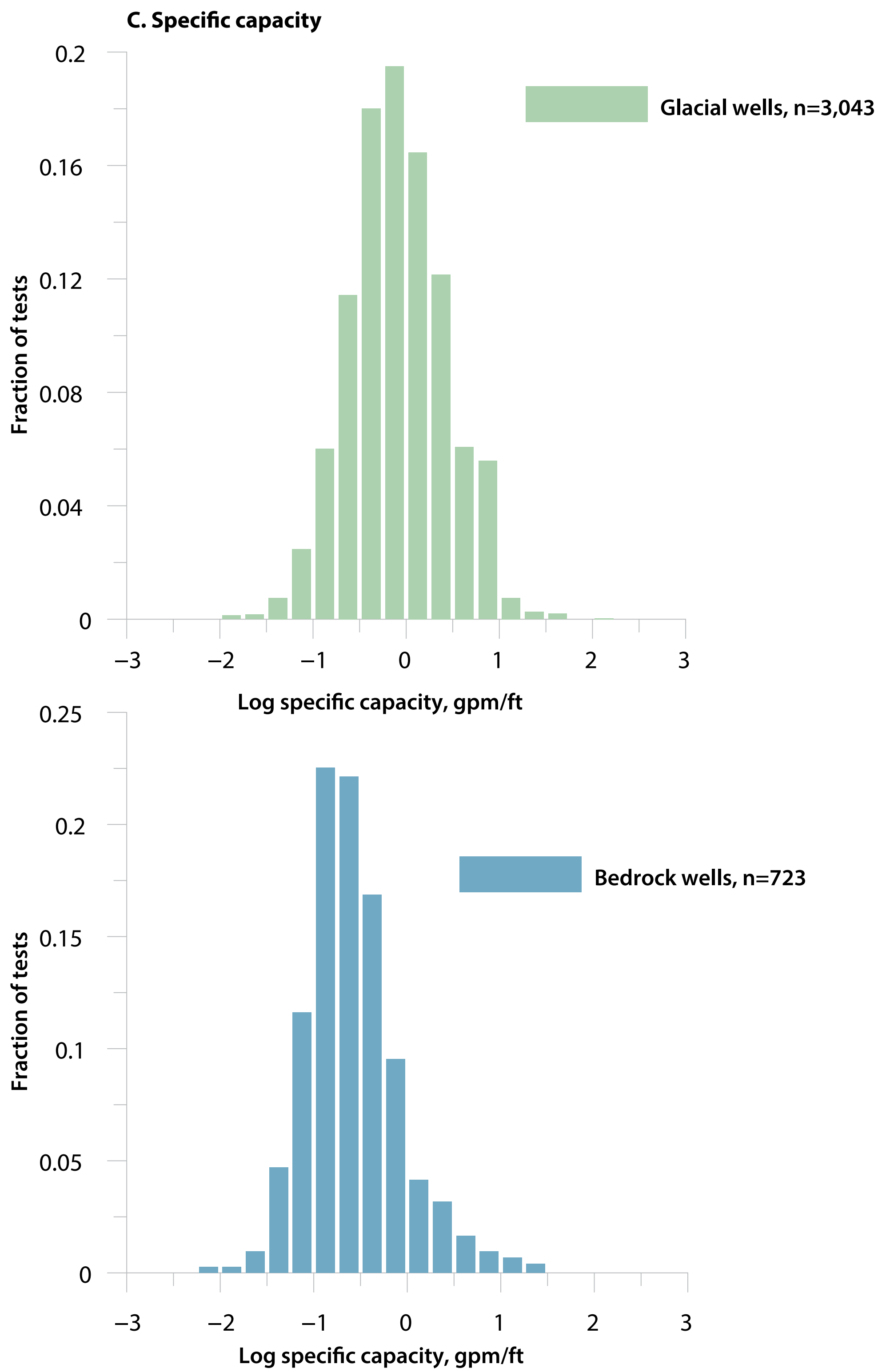
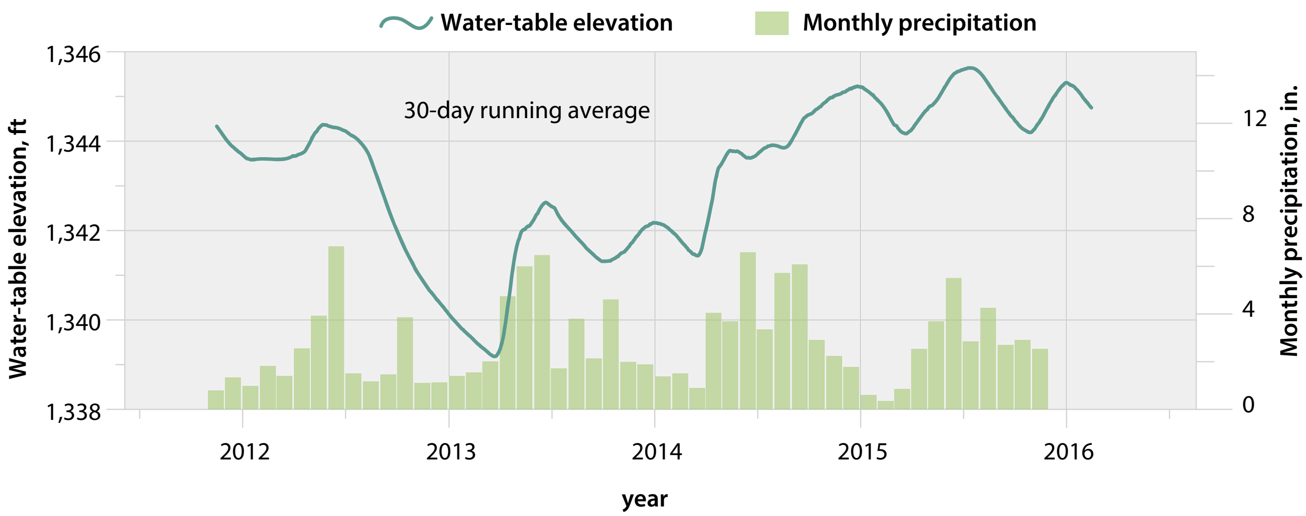


Figure 3. Hydrograph of monitoring well TA-217 showing 30-day running average and precipitation at Medford.



Discussion

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

- The glacial sand and gravel deposits form a shallow aquifer with low to moderate productivity. This aquifer is thin, ranging from 20 to 200 ft thick. The hydraulic conductivity estimated by using TGUESS ranged from 0.06 to 3,000 ft/d, with a mean of 46 ft/d.
- Crystalline bedrock beneath the glacial sands and gravels transmits water through fractures; it can supply adequate water to low-capacity wells in areas where the upper aquifer is thin or absent. In general, this bedrock unit has hydraulic conductivities about an order of magnitude lower than the overlying sand and gravel.
- The glacial aquifer has the potential to support high-capacity wells, but in general those wells could not produce much more than 200–300 gpm. The bedrock aquifer has a low likelihood of supporting high-capacity wells; its approximate average potential yield is 5–10 gpm.
- About 65 percent of the 5,377 evaluated wells obtain water from the glacial aquifer. Of the bedrock wells, most pump from the top 60 ft of bedrock, although some pump from as deep as 500 ft.
- No high-capacity wells are present in the Medford Unit and few are in the region generally. All active pumping 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 lower rates (average water use is 12 million gallons per year, equivalent to about 23 gpm).
- Water-level data from a monitoring well (TA-217, near the Bend mineral exploration site described above) in the northwest of the unit suggest that groundwater levels not directly affected by human use have remained relatively stable during the past five years, fluctuating on the order of 6 ft. The well provides important baseline data representative of regional conditions.
- Subsurface data within the Medford Unit are sparse, and additional data collection would improve the understanding of these groundwater resources.

Section 2: Potential recharge to groundwater

Objectives

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

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

Methods

Overview

Groundwater potential recharge was estimated through application of a SWB model (Westenbroek and others, 2010) to an area encompassing the Medford Unit. Figure 4 shows the model extent: an area of more than 630 square miles covering the unit and all intersecting watersheds of the 12-Digit Watershed Boundary Dataset (Natural Resources Conservation Service, 2011).

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

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

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

where (see Westenbroek and others, 2010),

Recharge = deep drainage below the root zone that we assume becomes groundwater;

Precipitation = atmospheric rainfall (not including snowmelt);

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

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

Interception = water trapped and used by vegetation;

Evapotranspiration = water evaporated or transpired from plant surfaces ; and

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

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

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

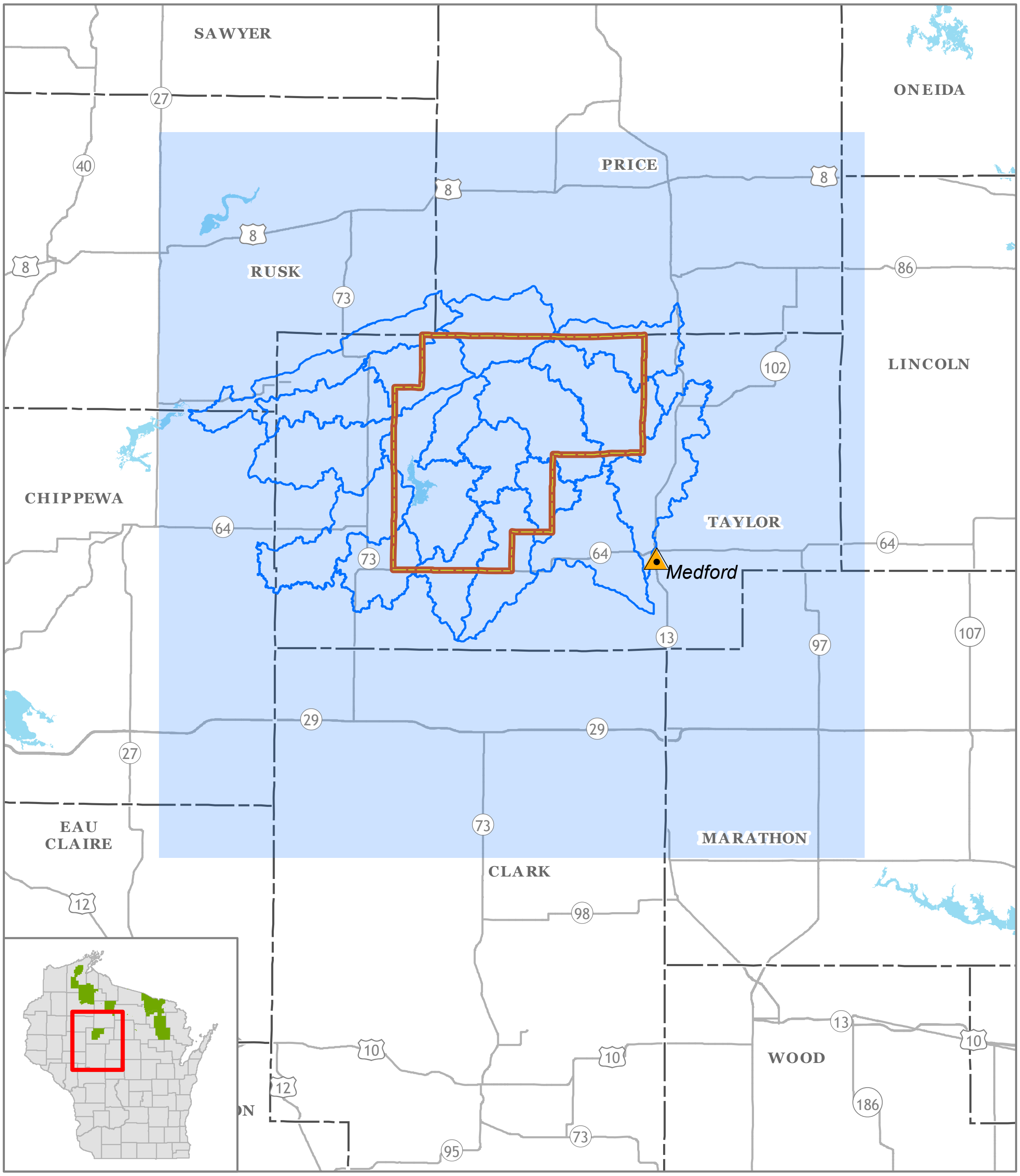
Because all runoff is used up during each time step, the SWB model code does not allow ponding. For closed depressions in the flow-direction grid, recharge is the primary mechanism for removing water from the cell, and focused areas of unrealistically high recharge values may result. However, all closed depressions were removed from this model (see Data sources—Flow direction below). To account for model assumptions that may produce 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 properly route runoff. Flow direction was calculated by using a 30-m DEM from the U.S. Geological Survey's National Elevation Dataset (U.S. Geological Survey, 2013) and a standard flow direction routine. Although more-de-

Figure 4. Extent of Medford Unit soil-water balance model.



Medford Unit
SWB model extent
Watershed boundary
Climate station

0 10 Miles

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.

tailed elevation data are available for the area, the 30-m resolution was selected as most appropriate given the scale of this study. Because DEMs typically include closed depressions that confound simple flow-planes used for surface routing of flow, a standard closed-depression fill routine was applied to the DEM before the final calculation of the flow-direction input grid. Several different fill thresholds were tested, and a complete fill was determined to be the most appropriate. Closed depressions account for less than 3 percent of the model area. Although true closed depressions are present in the model area, the identification, verification, and incorporation of these data were beyond the scope of this effort, but they could be incorporated into future site-specific studies.

Hydrologic soil group and available water storage

Digital soil map data from the Natural Resources Conservation Service Soil Survey Geographic Database were used for two input datasets to the SWB model, hydrologic group and available water storage (Natural Resources Conservation Service, 2013). The hydrologic group is a classification of the infiltration potential of a soil map unit and is used in the SWB model runoff calculations. The primary categories range from A to D, representing low to high runoff potential. Several map units in the model domain were classified with dual designations, such as "A/D", where the lower runoff designation typically indicates artificially drained land. Since 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 to account for root zone moisture.

Land cover

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

Daily temperature and precipitation

The SWB model uses tabulated daily temperature and precipitation observations as inputs to specify precipitation, track snow cover and melt, determine frozen-ground conditions, and estimate potential evapotranspiration. National Centers for Environmental Information (previously National Climatic Data Center; NOAA, 2016) data from station 475255 in the city of Medford were acquired and reviewed for completeness (fig. 4). Gaps in the records were supplemented with data from nearby stations.

The simulation period of the model, 2000–2010, represents recent climate conditions while also showing variability in total annual precipitation. Variability in precipitation results in changes in recharge to the groundwater system; selecting a model period with higher variability in precipitation can give an indication of the long-term variability in potential recharge. The same time interval was selected for all four units (Medford, Nicolet, Park Falls, and Washburn/Great Divide) after we compared precipitation statistics, in order to select a single, recent, and relatively short time period that represented the average and extremes of a longer time period. The Medford station showed an average precipitation of 33 in/yr from 2000 to 2010, ranging from a low of 26 in/yr in 2008 to a high of 43 in/yr in 2010. The annual average precipitation is similar to the 30-year average precipitation for north-central Wisconsin (32.4 in/yr; Wisconsin State Climatology Office, 2017). A graph of annual precipitation at the Medford climate station from 2000 through 2010 is shown in figure 5.

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 climate station. The model was then run for the period 1999–2010; the year 1999 was used to develop antecedent moisture conditions for year 2000.

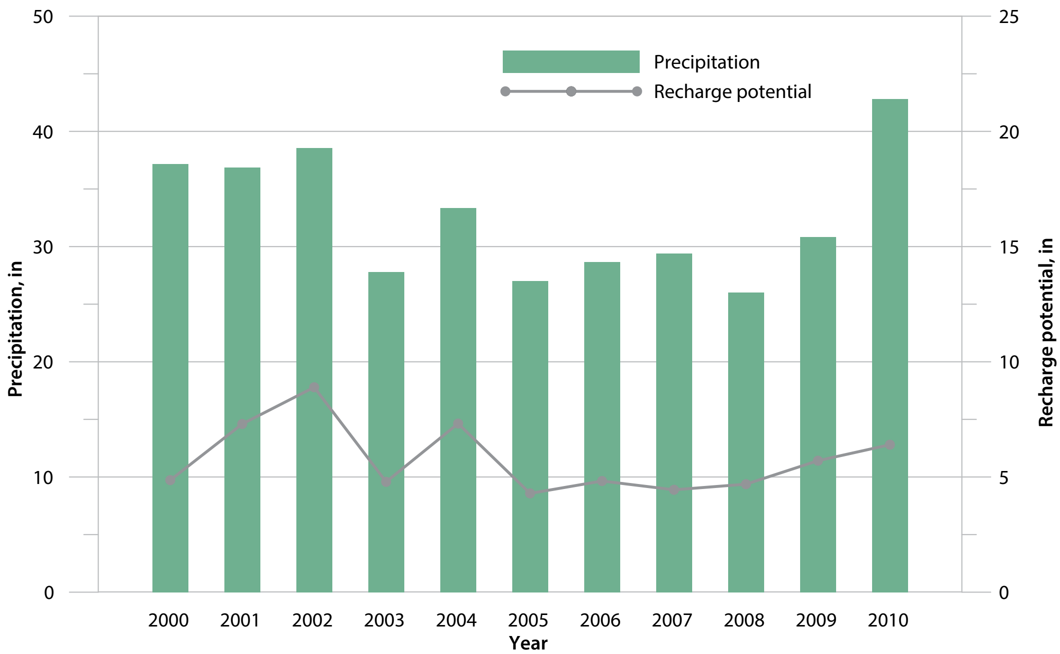
Results

Discussion

The SWB model simulated the daily soil-water budget during 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 groundwater potential recharge of the model period.

The mean potential recharge in the model domain for the period 2000–2010 was 5.8 in/yr. The average values for each component of the water balance equation are shown in table 5. The average values reported above

Figure 5. Total annual precipitation at the Medford climate station and mean recharge potential, 2000–2010.



are consistent with the reported recharge in nearby areas (for example, fig. 2 in Gebert and others, 2011; Lenz and others, 2003; and reported modeled values from Hunt and others, 2010). The SWB model results were adjusted during groundwater flow modeling to produce a calibrated recharge map (plate 8).

During groundwater-model development (section 4), the SWB model grid was adjusted to calibrate to groundwater-flow model targets (water levels and stream baseflows). This adjustment changes the magnitude of recharge while maintaining the spatial distribution of SWB model results. The SWB grid was downsampled, or generalized, for import into the groundwater flow model. During groundwater flow model calibration, the SWB model grid was adjusted by using a multiplier of 0.77, resulting in a modeled mean recharge value of 4.4 in/yr (table 6). Plate 8 depicts the calibrated mean annual recharge to groundwater for the Medford Unit. Groundwater flow model calibration is discussed in more detail in section 4.

Table 5. SWB approximate average water-balance components, Medford Unit, for 2000–2010.

Water balance component	Average value (in/yr)
Precipitation	33
Interception	3
Runoff from grid	1
Evapotranspiration	18
Recharge	6
Runoff to surface water[2]	5

Abbreviations: in/yr = inches per year

[1] *Based on daily water balance statistics output for the full model grid, including areas outside the forest unit.*

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

Table 6. SWB mean annual recharge results.

Scenario	Recharge (in/yr)
Original model (includes wetland recharge)	5.8
Assumed zero wetland recharge	5.0
Calibrated to GFLOW model (adjusted using multiplier of 0.77)[1]	4.4

Abbreviations: in/yr = inches per year

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

The general trend in the distribution of recharge in the model area correlates with surficial geology through soil characteristics. The overall potential recharge is low to moderate, with higher potential in the southern half of the Medford Unit. This southern region coincides with the hilly, collapsed material of the Copper Falls Formation, which consists of gravelly and sandy supraglacial sediments (Attig, 1993). The flatter-lying Copper Falls in the northern part of the unit along with the Edgar Member of the Marathon Formation south of the unit have been interpreted to have lower infiltration potential (Natural Resources Conservation Service, 2013).

The distribution of recharge is consistent with what is known about the groundwater system; precipitation enters the groundwater system as recharge at high points in the landscape and exits, or discharges, at low points such as wetlands. It is a common misconception that wetlands are always groundwater recharge areas, when in fact they are commonly areas of discharge or low recharge. Some local potential recharge rates in the SWB model 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.

Results of the SWB model provide detail in spatial and temporal variation that is not captured in the calibrated recharge grid shown on plate 8. Because the grid was generalized for import into the flow model, the SWB results include more detail in spatial resolution than the calibrated recharge. They also include yearly grids of potential recharge from years 2000 through 2010. Recharge variability for this time period is summarized in figure 5. This graph shows total annual precipitation and average potential recharge over each of the modeled years. Annual potential recharge is correlated with precipitation and varied from 4.3 to 8.9 in/yr for the 11 years of 2000 through 2010. The raster grids for each modeled year are included in the electronic database for public use.

Assumptions and limitations

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

Recharge in wetlands and other areas where the water table is shallow may be overestimated by the SWB model. When the water table is near the root zone, water continually leaves the system through evapotranspiration. However, the SWB model does not simulate the nearly saturated conditions in wetland areas and thus doesn't simulate the high evapotranspiration from these areas. As a result, the SWB model may overestimate recharge in these areas. About 18 percent of the Medford Unit is covered by wetlands; however, investigation of which of these wetlands contribute to recharge was outside the scope of this study. Assuming zero recharge in wetlands produces an average forest-wide potential recharge of 5.0 in/yr. However, it is likely that recharge in wetlands is actually greater than zero. Including simulated wetland recharge produces a forest-wide average of 5.8 in/yr (as discussed earlier), and so the SWB-simulated forest-wide average potential recharge is between 5.0 and 5.8 in/yr (table 6). The lower value based on no recharge in wetlands is nearer the GFLOW-adjusted mean recharge of 4.4 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 in the project area are not anticipated to change the overall results. Additional details on model limitations are outlined in Hart and others (2012).

Section 3: Baseline water chemistry

Objectives

The third part of this study was a basic inventory of surface-water and groundwater chemistry in the unit. WGNHS systematically sampled water in the Medford Unit during 2012 and 2013, in order to obtain a representative picture of its current water chemistry. The samples were distributed among groundwater wells, a spring, streams, wetlands, and lakes. Water samples were analyzed for major ion chemistry, basic nutrients (nitrate and phosphorus), and the stable isotopes oxygen-18 (^{18}O) and deuterium (^{2}H). This report contains a summary of the data collected; however, it is not intended to be a comprehensive analysis of the geochemistry within the Medford Unit. The sample site locations and laboratory results are included in the file geodatabase (see "Data availability").

Methods

Selection of sampling sites

We sampled and analyzed water in the unit from 29 sites of five site types: wells, a spring, streams, wetlands, and lakes. The sites (11 wells, 1 spring, 10 streams, 2 wetlands, and 5 lakes) were distributed both spatially and by type of water source, and they were accessible for sampling. Most of the wells selected for groundwater sampling are operated by the USFS at campgrounds and picnic areas.

Figure 6 shows all water chemistry sampling points in the Medford Unit, and table 7 contains information about the wells sampled. Spring (Glacial Spring) samples were obtained on two separate dates at a discharge point where the spring is piped to a roadside spout. Stream samples were usually obtained at or near road crossings. Lake samples were obtained at or near boat ramps or footpath access points. Most of the wells sampled are 50–100 ft deep and are screened in the glacial aquifer; three of the wells are screened in the bedrock aquifer.

Sampling procedures

Samples were collected in October 2012, July 2013, and August 2013. Groundwater samples were collected directly from hand pumps permanently installed on the USFS wells. One well volume was purged from wells prior to sampling. Samples from springs, streams, and lakes were collected by dipping a sampling bottle directly into the water. Samples were collected in prepared bottles provided by the laboratory. For major cations and anions, such as Ca, Mg, Na, and Cl, the sample was filtered by using a syringe to push the sample through a membrane with 0.45 micron pore size into a 15-milliliter (ml) vial with nitric acid preservative. The nutrients sample was filtered into a 125-ml polyethylene bottle with hydrochloric acid preservative. An unfiltered alkalinity sample was collected in a nonacidified 125-ml polyethylene bottle. Unfiltered samples for isotopic analyses were collected in separate 250-ml polyethylene bottles. All samples were immediately placed on ice in coolers in the field. Cation, anion, and nutrient samples were transported to the laboratory within 48 hours of sampling. Isotopic samples were refrigerated at the WGNHS office in Madison, Wisc., until shipped to the laboratory.

Analytical procedures

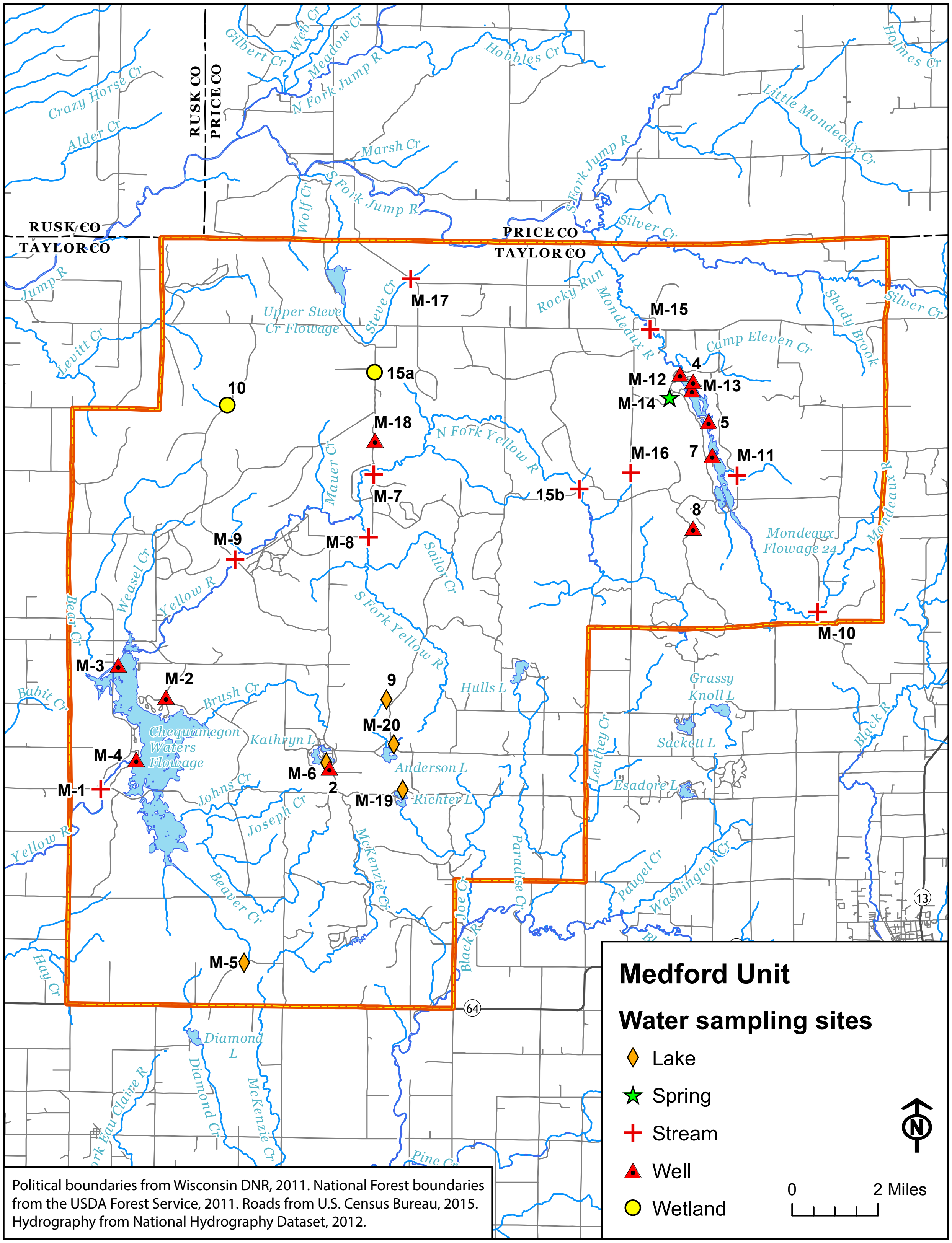
For all samples, electronic field meters measured temperature, pH, and electrical conductivity in the field during sample collection. Dissolved oxygen was measured by either an electronic field meter or colorimetric field kit. Major ions, nutrients, and laboratory alkalinity were analyzed at the Water 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 Iowa State University Stable Isotope Lab (https://www.ge-at.iastate.edu/research/climate-quaternary/siperg/).

Results

Major ion chemistry

Groundwater and surface water in the Medford Unit are dominantly a Ca-Mg-HCO_3 type, meaning that the dominant dissolved ions are calcium, magnesium, and bicarbonate (see fig. 7). Concentrations of most ions are relatively low, as is common in a crystalline bedrock terrane beneath a cover of unlithified noncarbonate sediment. Electrical conductivity is commonly used to estimate total dissolved solids content. On the basis of values less than 400 microsiemens per centimeter (µS/cm), groundwater and surface-water samples had low total dissolved solids, a nearly neutral average pH, and similar distribution of relative ion concentrations. Groundwater is distinguished from surface water by higher electrical conductivity, alkalinity, and concentrations of ions such as calcium and magnesium. Tables 8 and 9 contain the major ion results, and table 10 shows average results for each source type. To calculate sample averages, samples with nondetect results were assumed to have a concentration of half the detection limit. Charge balance calculations showed that although most samples satisfy standard criteria for acceptable lab analyses, 16 samples had unacceptable charge balance errors (table 9). The criteria for determining acceptable

Figure 6. Water sampling locations in the Medford Unit.



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

As expected, groundwater is much more alkaline than surface water and has higher electrical conductivity. Groundwater well samples have an average alkalinity of 132 milligrams per liter (mg/L) (range 68–207) and conductivity of 313 µS/cm (range 188–465). Wells with lower conductivity and alkalinity, such as the North Twin Lake well (site 8; fig. 6 and table 7), may be influenced by nearby surface waters.

Surface waters such as lakes and streams are a mix of groundwater inflow and surface water runoff. A subset of stream, lake, and wetland samples with low alkalinity and conductivity were interpreted as receiving water primarily from surface runoff; they are presented in table 10 as "surface-runoff dominated." These samples, which have low conductivity (average of 63 µS/cm and range of 29–92 µS/cm) and alkalinity (average of 20 mg/L and range of less than 4 to 44 mg/L), were obtained from the following sites: Spruce Lake, Mondeaux River at Highway (Hwy) D, Jerry Lake, Kidrick Swamp, Mauer Wetland, and

Table 7. Information about wells sampled in the Medford Unit.

Well sampled	Site number[1]	Project ID[2]	WI unique well no.[3]	WGNHS image number[4]	Total depth (feet)	Material, reported by driller
Chippewa Campground well at trailer fill station	M-2	129	BQ502	—	84	Sand and gravel
County picnic area, well at	M-3	No WCR identified	—	—	—	—
Eastwood Camp well	4	5571	—	TA2701	63	Sand and gravel
Kathryn Lake well	2	5325	—	TA1984	123	Sand and gravel
Miller Dam County park, well at	M-4	1116	EP729	—	70	Granite
Mondeaux Dam concession well	M-12	169	GU347	—	64	Granite
Monitoring well TA-217 (Bend well)[5]	M-18	Shallow monitoring well	—	—	30	Sand and gravel
North Twin Lake well	8	No WCR identified	—	—	—	—
Picnic Point Campground well	7	5199	—	TA2705	51	Sand and gravel
Spearpoint Campground well	M-13	3068	—	TA767	54	Sand
West Point Campground well	5	4603	—	TA770	80	Granite

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

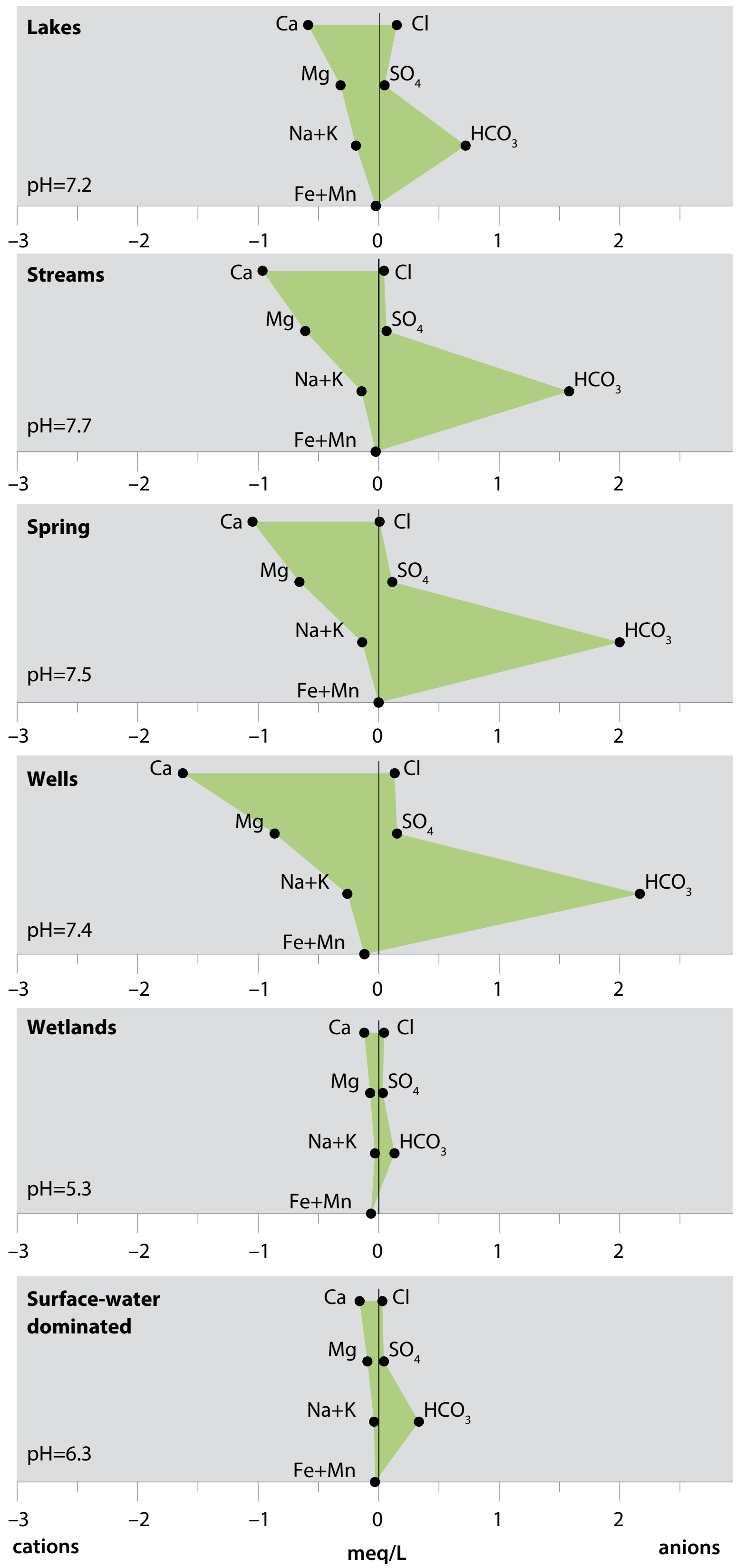
[2]Object ID in Located WCR geodatabase.

[3]Wisconsin Unique Well Number.

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

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

Figure 7. Stiff plots of average major ion constituents from the Medford Unit, categorized by water source.



Richter Lake (sites M-5, M-15, 9, 10, 15a, and M-19, respectively; fig. 6). The Mondeaux River sample likely reflects water from the upstream Mondeaux Flowage, which was being drained for the winter during sample collection. Jerry Lake, Kidrick Swamp, and Mauer Wetland all have much lower pH values (5.1–5.5), typical of wetlands fed predominately by precipitation (Kratz and Medland, 1989). In contrast, surface-water samples with high conductivity and alkalinity, such as Steve Creek at Hwy N and a small tributary to the North Fork Yellow River at the Ice Age trailhead (sites M-16 and M-17; fig. 6), are likely fed by groundwater. These groundwater-dominated streams flowed when other streams in the area were stagnant or dry.

Plate 9 shows the spatial distribution of alkalinity and electrical conductivity in sampled streams, wetlands, and lakes. Blue symbols indicate water features that are more likely fed by groundwater, whereas red symbols indicate surface-runoff dominated features. Water chemistry results agree well with simulated groundwater flow paths and stream discharge (section 4 of this report; plate 9). Samples from groundwater-dominated features (for example, M-16, M-17, fig. 6; higher conductivity and alkalinity) commonly are located in discharge areas (near ends of groundwater flow paths), and surface-runoff-dominated locations (for example M-5, M-9, M-10, M-15a; fig. 6) are more common in upland recharge areas.

The relative concentrations of various ions at each water source are shown in Stiff diagrams (fig. 7). In these diagrams, average ion concentrations are converted to electron milliequivalents. Cations plot on the left side of the diagrams, and anions plot on the right. The width of the resulting polygon indicates the concentration of dissolved constituents, whereas the

Table 8. Water chemistry at sampling sites in the Medford Unit.

Type and location of sample site	Site number	Date	Temp. (°C)	Conductivity (µS/cm)	Dissolved oxygen (ppm, mg/L)	pH
Well						
Chippewa Campground well at trailer fill station, sample #1	M-2	10/3/2012	14.0	382	5.5	7.7
Chippewa Campground well at trailer fill station, sample #2	M-2	6/15/2013	14.4	381	6	7.6
Eastwood Camp well	4	6/15/2013	9.6	261	4	7.8
Kathryn Lake well	2	6/15/2013	8.6	289	3	6.7
Mondeaux Dam concession well	M-12	10/4/2012	11.6	251	2.8	7.6
Monitoring well TA-217 (Bend well), sample #1	M-18	10/5/2012	10.0	465	5.3	6.6
Monitoring well TA-217 (Bend well), sample #2	M-18	6/15/2013	10.2	424	8	6.8
North Twin Lake well	8	6/15/2013	10.0	188	5	7.6
Picnic Point Campground well	7	9/6/2013	8.8	257	1.8	7.4
Spearpoint Campground well	M-13	10/4/2012	8.6	224	5.2	8.1
Well at County picnic area	M-3	10/3/2012	10.7	380	3.8	7.5
Well at Miller Dam County park	M-4	10/3/2012	11.6	313	2.7	7.9
West Point Campground well	5	9/6/2013	8.5	251	2.1	7.3
Spring						
Glacial Spring, sample #1	M-14	10/4/2012	9.0	248	3.1	7.5
Glacial Spring, sample #2	M-14	6/15/2013	9.6	265	3	7.6
Stream						
Mink Creek at FR 104	M-11	10/4/2012	9.1	223	6.6	7.7
Mondeaux River at FR 103	M-10	10/4/2012	11.0	148	4.7	9.0
Mondeaux River at HWY D	M-15	10/4/2012	14.3	88	6.9	7.5
North Branch Yellow River at FR 112	M-7	10/3/2012	12.7	174	4.4	7.4
South Fork Yellow River at FR 112	M-8	10/3/2012	16.8	154	6.8	8.1
Small tributary to North Fork Yellow River at Ice Age trailhead	M-16	10/4/2012	11.9	292	5.8	7.6
Steve Creek at HWY N	M-17	10/4/2012	11.7	290	1.7	7.3
Yellow River at FR 102 bridge	15b	9/6/2013	17.7	151	5.9	7.3
Yellow River at FR 121	M-1	10/3/2012	11.0	272	3.8	7.3
Yellow River at FR 575	M-9	10/3/2012	16.0	214	5.0	7.9
Lake						
Anderson Lake, outlet at HWY M	M-20	10/5/2012	5.3	205	7.3	8.1
Jerry Lake	9	6/15/2013	21.3	92	6	5.4
Kathryn Lake, off fishing float	M-6	10/3/2012	17.0	187	6.7	8.1
Richter Lake, at boat landing	M-19	10/5/2012	13.2	89	7.2	7.6
Spruce Lake, at boat landing	M-5	10/3/2012	19.2	29	5.3	7.0
Swamp						
Kidrick Swamp	10	6/15/2013	16.5	42	5	5.1
Mauer Wetland	15a	6/15/2013	17.5	37	4	5.5

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

Table 9. Water chemistry laboratory results for the Medford Unit.

Site number[1]	NO_2 + NO_3 (N)	Chloride	Alkalinity	As[2]	Ca	Cu	Fe	K	Mg
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Groundwater (wells)									
2	<0.1	10.3	68	<0.003	20.857	0.0221	0.111	1.93	10.790
4	<0.1	<0.5	116	0.005	26.863	0.0042	0.037	0.75	10.866
5	0.5	7.6	96	<0.004	25.236	<0.002	8.022	0.89	7.807
7	<0.1	<0.5	108	<0.004	24.377	<0.002	12.334	0.81	7.524
8	<0.1	0.9	76	0.009	17.183	0.0029	5.174	1.01	6.395
M-2, sample #1	<0.1	4.9	168	0.005	48.239	0.0081	0.096	1.42	9.032
M-2, sample #2	<0.1	8.3	184	<0.003	49.980	0.0020	0.029	1.33	9.064
M-3	1.5	8.2	168	<0.003	42.926	0.0038	0.037	1.43	14.979
M-4	<0.1	0.8	156	<0.003	35.846	<0.0004	0.279	1.28	12.391
M-12	<0.1	1.9	116	<0.003	29.337	0.0012	0.592	1.21	8.941
M-13	<0.1	3.4	100	<0.003	23.945	0.0008	0.026	0.81	9.130
M-18, sample #1	3.0	<0.5	207	<0.003	36.811	0.0015	0.001	0.41	14.077
M-18, sample #2	3.2	0.7	156	0.005	41.940	0.0077	0.923	1.10	15.531
Surface water (springs, streams, lakes, swamps)									
9	<0.1	1.4	12	0.008	5.240	0.0247	0.491	0.70	1.877
10	<0.1	1.1	<4	0.006	1.807	0.0148	1.052	0.34	0.631
15a	<0.1	2.0	8	0.006	3.001	0.0052	1.201	0.15	1.097
15b	0.3	0.7	68	<0.004	16.909	0.003	0.952	0.46	6.341
M-1	<0.1	3.8	120	<0.003	29.651	<0.0004	0.095	0.90	10.782
M-5	<0.1	0.5	12	<0.003	2.201	0.0004	0.328	1.01	0.759
M-6	<0.1	8.5	72	<0.003	17.651	0.0012	0.014	1.27	6.209
M-7	<0.1	0.4	76	<0.003	28.054	0.0012	1.378	0.78	11.536
M-8	<0.1	1.0	72	<0.003	8.832	<0.0004	0.168	0.50	3.541
M-9	<0.1	1.0	108	<0.003	41.083	0.0008	0.322	0.98	16.254
M-10	<0.1	1.8	68	<0.003	6.734	<0.0004	0.209	0.33	2.814
M-11	<0.1	<0.5	112	<0.003	12.115	<0.0004	0.055	0.35	4.641
M-14, sample #1	<0.1	<0.5	128	<0.003	14.396	<0.0004	0.001	0.27	5.395
M-14, sample #2	<0.1	<0.5	116	<0.003	27.584	0.0024	0.028	0.70	10.594
M-15	<0.1	<0.5	44	<0.003	2.606	<0.0004	0.175	0.08	1.025
M-16	<0.1	1.3	152	<0.003	23.587	<0.0004	0.049	0.80	8.933
M-17	<0.1	2.5	144	<0.003	23.663	<0.0004	0.280	0.80	8.210
M-19	<0.1	1.2	44	<0.003	4.214	<0.0004	0.013	0.28	1.463
M-20	<0.1	15.0	80	<0.003	29.343	0.0006	1.225	1.88	8.929

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

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

[2] *Highlighting indicates analyses that exceed the enforcement standard or preventive action limits (PAL) for arsenic (0.01 mg/L; 0.001 mg/L), manganese (0.3 mg/L; 0.06 mg/L), or lead (0.015 mg/L; 0.0015 mg/L). For arsenic and lead, laboratory detection limits were greater than the PAL; only analyses exceeding the detection limits 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 the cation-anion difference is within 0.2 meq/L for anion sums of 0–3 meq/L or if the charge balance is within 2% for anion sums of >3–10 meq/L.*

Table 9 reads across two pages.

Site number[1]	Mn[2]	Na	P	Pb[2]	SO_4	Zn	Anions	Cations	Charge balance error[3]
	mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(meq/L)	(meq/L)	(%)
Groundwater (wells)									
2	0.0278	6.30	0.015	<0.002	12.63	0.084	1.9	2.3	8.4
4	0.0511	2.71	0.021	<0.002	6.90	0.260	2.5	2.4	1.6
5	0.3640	3.80	0.093	<0.004	0.6	0.359	2.2	2.4	5.8
7	0.3474	2.70	0.017	<0.004	<0.4	0.516	2.2	2.5	6.3
8	0.1056	2.43	<0.005	0.003	3.96	0.178	1.6	1.7	2.5
M-2, sample #1	0.0167	11.18	0.115	0.003	5.71	0.070	3.6	3.7	1.2
M-2, sample #2	0.0041	12.93	0.098	<0.002	5.02	0.088	4.0	3.9	2.0
M-3	0.0036	7.06	0.043	<0.002	10.45	0.130	3.8	3.7	1.3
M-4	0.1397	5.25	0.127	<0.002	3.81	0.175	3.2	3.1	1.7
M-12	0.2320	4.20	0.059	<0.002	10.94	0.015	2.6	2.5	2.9
M-13	0.0601	3.48	0.013	<0.002	11.55	0.360	2.3	2.1	4.5
M-18, sample #1	0.0463	3.27	0.023	<0.002	7.12	0.002	4.3	3.2	15.8
M-18, sample #2	0.0595	3.91	0.084	<0.002	9.11	0.010	3.4	3.6	3.4
Surface water (springs, streams, lakes, swamps									
9	0.0492	0.94	0.075	0.004	4.39	0.070	0.4	0.5	16.2
10	0.0842	0.44	0.039	0.005	1.77	0.112	0.1	0.2	54.3
15a	0.1009	0.71	0.022	0.003	1.55	0.036	0.2	0.3	14.1
15b	0.2129	2.50	0.120	<0.004	4.9	0.007	1.5	1.6	2.1
M-1	0.1415	4.25	0.033	<0.002	6.16	<0.002	2.6	2.6	0.9
M-5	0.0438	0.56	0.015	<0.002	3.83	<0.002	0.3	0.2	16.7
M-6	0.0035	5.39	0.014	<0.002	1.47	0.003	1.7	1.7	1.4
M-7	0.2767	4.47	0.068	<0.002	3.54	<0.002	1.6	2.6	24.3
M-8	0.0401	1.53	0.022	<0.002	1.67	<0.002	1.5	0.8	29.2
M-9	0.1570	5.68	0.045	<0.002	3.87	<0.002	2.3	3.7	23.8
M-10	0.0422	1.16	0.016	<0.002	1.29	<0.002	1.4	0.6	38.6
M-11	0.0205	2.18	0.039	<0.002	1.27	<0.002	2.3	1.1	34.6
M-14, sample #1	0.0021	1.73	0.028	<0.002	3.38	<0.002	2.5	2.5	0.5
M-14, sample #2	0.0079	3.99	0.056	<0.002	7.45	0.011	2.6	1.3	35.6
M-15	0.0105	0.36	0.009	<0.002	0.36	<0.002	0.9	0.2	57.4
M-16	0.0130	3.57	0.078	<0.002	3.25	<0.002	3.1	2.1	19.8
M-17	0.4159	3.56	0.085	<0.002	5.14	<0.002	3.1	2.1	19.2
M-19	0.0029	0.76	<0.005	<0.002	0.54	<0.002	0.9	0.4	42.7
M-20	0.1108	10.99	0.056	<0.002	1.45	<0.002	2.1	2.8	15.1

Table 10. Average water quality results[1] from the Medford Unit.

Site type	Samples (no.)	Conductivity (µs/cm)	Dissolved oxygen (mg/L)	pH	Alkalinity (mg/L $CaCO_3$)	Ca (mg/L)	Mg (mg/L)	N (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	Cl (mg/L)	SO_4 (mg/L)
Well	13	313	4.2	7.4	132	32.6	10.5	5.3	1.1	2.1	0.11	4.7	7.3
Spring	1	257	3.1	7.5	122	21.0	8.0	2.9	0.5	0.0	0.00	<0.5	5.4
Stream	10	201	5.2	7.7	96	19.3	7.4	2.9	0.6	0.4	0.13	1.6	3.1
Lake	5	120	6.5	7.2	44	11.7	3.8	3.7	1.0	0.4	0.04	5.3	2.3
Well	13	313	4.2	7.4	132	32.6	10.5	5.3	1.1	2.1	0.11	4.7	7.3
Spring	1	257	3.1	7.5	122	21.0	8.0	2.9	0.5	0.0	0.00	<0.5	5.4
Stream	10	201	5.2	7.7	96	19.3	7.4	2.9	0.6	0.4	0.13	1.6	3.1
Wetland	2	40	4.5	5.3	8	2.4	0.9	0.6	0.2	1.1	0.09	1.6	1.7
Surface-runoff-dominated streams, lakes, and wetlands[2]	6	63	5.7	6.3	20	3.2	1.1	0.6	0.4	0.5	0.05	1.1	2.1

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

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

[2]*This group is a subset of surface water samples interpreted to receive water primarily from surface runoff precipitation. It includes the following sites: Spruce Lake, Mondeaux River at Hwy D, Jerry Lake, Kidrick Swamp, Mauer Wetland, and Richter Lake (M-5, M-15, 9, 10, 15a, and M-19).*

shape indicates the relative importance of the individual ions. The plots illustrate that groundwater (wells and springs) typically contains a higher concentration of dissolved ions, whereas wetlands and features interpreted as surface-runoff dominated have much lower concentrations of ions. Despite differences in concentrations, the ratio between constituent ions are about the same for all water sources, as indicated by the similar plot shapes.

Water quality indicators

The geologic setting of the Medford Unit, noncarbonate glacial deposits over crystalline bedrock, contains few natural sources of dissolved nutrients such as chloride, nitrate, and phosphorus. For this reason, water samples with elevated values of Cl, NO_3, or P likely represent places where land-use or cultural activities are changing water quality. The majority of water samples collected contained low (less than 5 mg/L) levels of chloride, and low or nondetectable levels of nitrate and phosphorus (table 9). However, some samples were elevated in one or more of these parameters. Nitrate is slightly elevated (greater than 3 mg/L) at monitoring well TA-217 (site M-18, fig. 6; near the Bend mineral exploration site). Although there is little development in the vicinity of TA-217, a nearby parcel with a rustic campsite could be changing the water quality. Chloride was the most commonly elevated water quality parameter, possibly as a result of road salting. At Anderson Lake and the Kathryn Lake well (sites M-20 and 2; fig. 6) chloride concentrations were higher than 10 mg/L but were still far lower than the Wisconsin NR140 secondary drinking water standard of 250 mg/L. Elevated chloride at these sites may be due to proximity to highways where deicing salt is applied. Chloride concentrations were higher than 5 mg/L in samples from the West Point Campground well, Chippewa Campground well, County picnic well, Miller Dam County Park well, and Kathryn Lake (sites 5, M-2, M-3, M-4, M-6; fig. 6). Phosphorus was less than 0.15 mg/L at all sites.

Concentrations of three metals in groundwater samples in the Medford Unit were higher than recommended limits established to protect health. Four well samples slightly exceeded the Wisconsin NR140 preventive action limit (PAL) for arsenic, and two samples slightly exceeded the PAL for lead (table 9). In Wisconsin, the PAL for these elements is set at 10 percent of the drinking water standard; it is intended as an early warning that the constituents' concentrations are elevated. The arsenic PAL of 0.001 mg/L was exceeded in wells at Eastwood Campground (0.005 mg/L), North Twin Lake (0.009 mg/L), Chippewa Campground (0.005 mg/L), and monitoring well TA-217 (0.005 mg/L; fig. 6, site M-18). The lead PAL of 0.0015 mg/L was exceeded at the North Twin Lake well (0.003 mg/L) and the Chippewa campground well (0.003 mg/L). In all of these samples the concentrations of arsenic or lead are still very low, and they are near the level of detection of the analytical methods used. The source of the arsenic and lead is unknown, and it might come

Table 11. Isotopic data collected in the Medford Unit.

Sample location	Site number	Sample date	$\delta^{18}O$ (per mil SMOW)	$\delta^{2}H$ (per mil SMOW)
Wells				
Chippewa Campground well at trailer fill station, sample #1	M2	10/3/2012	−9.20	−60.17
Chippewa Campground well at trailer fill station, sample #2	M2	6/15/2013	−9.19	−60.98
Eastwood Camp well	4	6/15/2013	−10.16	−68.32
Kathryn Lake well	2	6/15/2013	−10.91	−73.66
Mondeaux Dam concession well	M12	10/4/2012	−10.15	−68.83
Monitoring well TA-217 (Bend well), sample #1	M18	10/5/2012	−11.47	−78.71
Monitoring well TA-217 (Bend well), sample #2	M18	6/15/2013	−11.88	−81.18
N. Twin Lake well	8	6/15/2013	−9.54	−66.44
Spearpoint Campground well	M13	10/4/2012	−10.67	−72.20
Well at County picnic area	M3	10/3/2012	−9.54	−62.93
Well at Miller Dam County park	M4	10/3/2012	−9.59	−63.71
Springs				
Glacial Spring, sample #1	M14	6/15/2013	−9.99	−65.74
Glacial Spring, sample #2	M14	10/4/2012	−10.03	-66.59
Streams				
Mink Creek at FR 104	M11	10/4/2012	−9.53	-65.56
Mondeaux River at FR 103	M10	10/4/2012	−5.05	−49.08
Mondeaux River at HWY D	M15	10/4/2012	−4.34	−37.95
Steve Creek at HWY N	M17	10/4/2012	−9.57	−64.94
Yellow River at FR 121	M1	10/3/2012	−7.84	−58.76
Yellow River at FR 575	M9	10/3/2012	−5.78	−51.74
Yellow River—North Branch, at FR 112	M7	10/3/2012	−6.44	−53.34
Yellow River—small tributary to North Fork, at Ice Age trailhead	M16	10/4/2012	−9.59	−63.81
Yellow River—South Fork, at FR 112	M8	10/3/2012	−8.75	−64.17
Lakes				
Anderson Lake outlet at HWY M	M20	10/5/2012	−4.69	−47.00
Jerry Lake	9	6/15/2013	−8.41	−61.23
Kathryn Lake, off fishing float	M6	10/3/2012	−4.39	−41.92
Richter Lake, at boat landing	M19	10/5/2012	−5.24	−46.61
Spruce Lake, at boat landing	M5	10/3/2012	−2.80	−34.90
Wetlands				
Kidrick Swamp	10	6/15/2013	−9.18	−60.61
Mauer Wetland	15a	6/15/2013	−9.17	−59.90

Abbreviations: $\delta^{18}O$, ratio of oxygen-18 to oxygen-16; $\delta^{2}H$, ratio of deuterium; in units of "per mil" or ‰ relative to Standard Mean Ocean Water (SMOW) standard from natural minerals in the region, plumbing and pipe fixtures, or other anthropogenic sources. We recommend that these wells be retested periodically to ensure that these constituent concentrations meet standards for drinking water quality.

Two groundwater samples in the Medford Unit slightly exceeded the Wisconsin NR140 enforcement standard of 0.3 mg/L for manganese, and four other wells exceeded the PAL of 0.06 mg/L (table 9). The manganese enforcement standard was exceeded in wells at West Point Campground (0.36 mg/L) and Picnic Point Campground (0.35 mg/L). The PAL for manganese was equaled or exceeded in wells at North Twin Lake (0.106 mg/L), Miller Dam County Park (0.140 mg/L), Mondeaux Dam concession area (0.232 mg/L), and Spearpoint Campground (0.060 mg/L. The manganese likely derives from natural minerals in the region, but it might also be from plumbing and pipe fixtures or other anthropogenic sources. We recommend that these wells be retested periodically to ensure that these constituent concentrations meet standards for drinking water quality. Concentrations of iron were in excess of the public welfare enforcement standard of 0.3 mg/L for dissolved iron; the maximum concentration of 12.3 mg/L was found at Picnic Point Campground well. Iron is not considered hazardous to health at these concentrations, and this standard is based on aesthetic factors such as taste and appearance. The iron also likely derives from natural minerals present in the region.

Isotopes of hydrogen and oxygen

The concentration of stable isotopes deuterium (^{2}H) and oxygen-18 (^{18}O) in groundwater and surface water can provide information on mixing (groundwater or surface water), age, and source areas. These heavier isotopes are less common in water molecules than the lighter hydrogen (^{1}H) and oxygen (^{16}O) isotopes. Isotopes of hydrogen and oxygen are fractionated through evaporation and condensation. Evaporation preferentially removes a greater fraction of lighter isotopes and condensation preferentially adds water molecules with heaver isotopes as air masses move from moisture source to moisture sink areas. Consequently, inland waters are isotopically lighter than ocean water.

Isotopic concentrations in analyzed water are reported relative to isotopic concentrations in ocean water in 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 relationship between $\delta\ ^{2}H$ and $\delta\ ^{18}O$ in precipitation is linear and is known as the meteoric water line (MWL), a formulation of the ratio of ^{2}H to ^{18}O found in unevaporated precipitation. Isotopic concentrations in precipitation locally differ from the MWL; it is, therefore, important to evaluate samples against a locally derived MWL. Samples that plot along the lower left part of the line (lighter precipitation) are typically derived from precipitation during colder months. Water samples plotting off the MWL are interpreted as having been exposed to surface-water evaporation or other physical processes. In groundwater studies, deuterium and oxygen-18 concentrations are commonly evaluated to distinguish groundwater from surface waters.

Figure 8 and table 11 show the isotopic results from water samples collected in the Medford Unit. The local MWL is based on precipitation samples from northern Vilas County, approximately 70 miles northeast of the Medford Unit (Krabbenhoft and others, 1990). The linear plot of well water samples and the spring samples along the lower left of figure 8 is a typical signature for groundwater samples originating as recharge from terrestrial precipitation. Samples from surface-water sources, in which evaporation has preferentially removed lighter isotopes, are expected to plot to the right of the MWL. However, several streams (South Fork Yellow River, Mink Creek, Steve Creek, an unnamed tributary to the North Fork Yellow River at Ice Age trailhead) plot with the heaviest groundwater samples and along the MWL. These streams may receive a higher percentage of groundwater inflow than streams that plot to the right of the MWL.

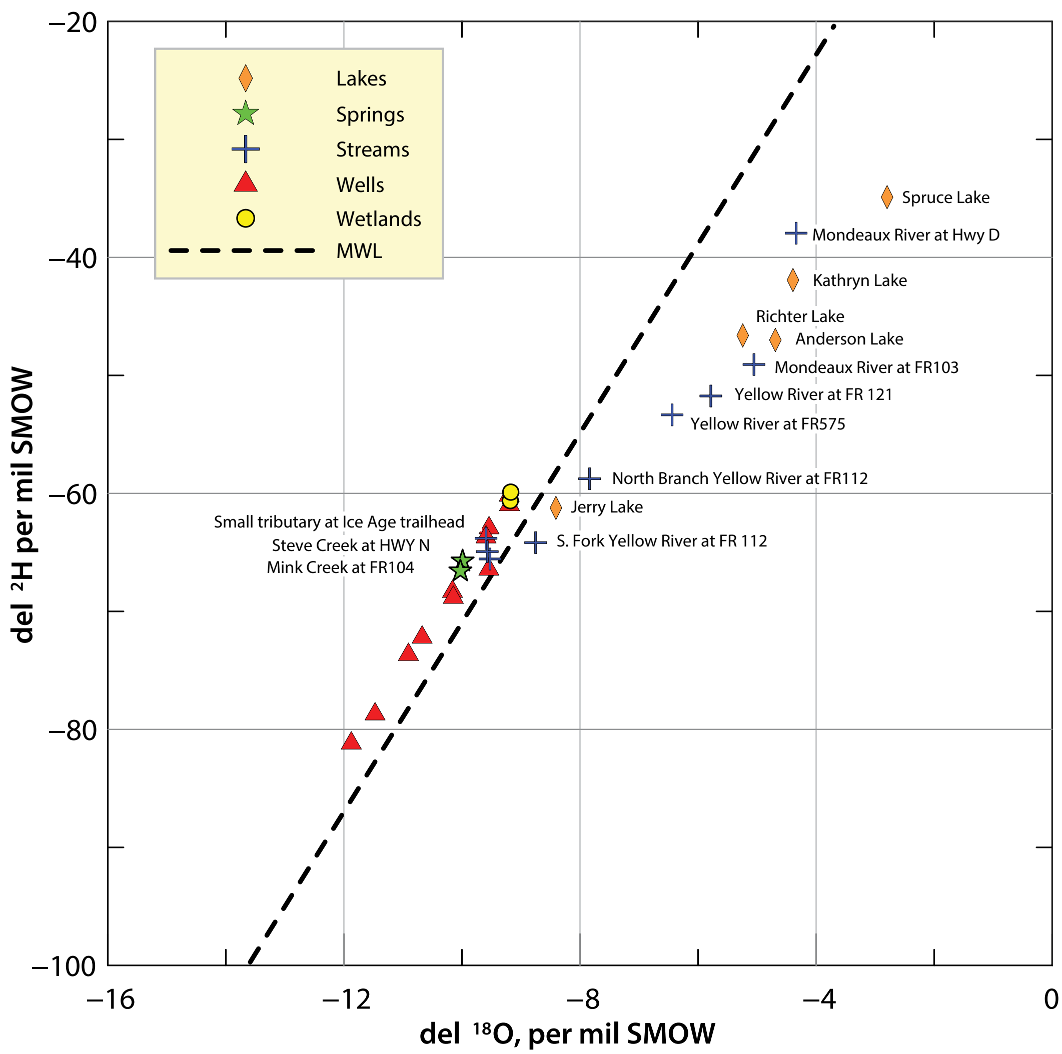
The two wetland samples have an isotopic signature similar to that of the groundwater-dominated streams and spring. Unlike the streams, however, the markedly lower conductivity, pH, and alkalinity of the wetlands suggest that they are primarily fed by precipitation. Although Jerry Lake is similar to the wetlands, it has an isotopic signature slightly to the right of the MWL and has likely undergone some evaporation.

Most lakes and streams have heavier signatures that deviate from the MWL, indicating water that has undergone open-water evaporation. These features plot to the right of the MWL on figure 8. Spruce Lake and the Mondeaux River at Hwy D have the heaviest signatures, consistent with the assumption that runoff dominates these features.

Discussion

The chemical analyses show that water in the Medford Unit is relatively unaltered by human activities and has low concentrations of most naturally occurring constituents. Groundwater is distinguished from surface water by higher electrical conductivity (average of 313 vs. 63 µS/cm) and alkalinity (average of 132 vs. 20 mg/L). Concentrations of dissolved ions, such as calcium and magnesium, are also higher in groundwater. Isotopes of hydrogen and oxygen can show whether features have undergone open-water evaporation as well as distinguish surface water (isotopically heavier, less negative) from groundwater (isotopically lighter, more negative). These results can be used to evaluate where surface-water features are more likely to be fed by runoff, such as Spruce Lake and Mondeaux River at Hwy D, or by groundwater, such as Steve Creek at Hwy N and a small tributary at the Ice Age trailhead. Chemistry results agree well with modeled groundwater flow paths and stream discharge (see section 4). Several samples contained slightly elevated chloride, suggesting the possible influence of land-use activities such as road salting. This overview also provides a basis for future geochemical investigations of specific areas in the Medford Unit.

Figure 8. Oxygen-18 (^{18}O) vs. deuterium (^{2}H) in water samples from the Medford Unit, and meteoric water line.



Section 4: Groundwater flow model

Objectives

The data inventory and analysis described in the previous sections were incorporated into a groundwater flow model of the Medford Unit 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 in detail. 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, 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, the aquifer transmissivity, recharge to the aquifer, and pumping. Conceptualization of the hydrologic system forms the framework for mathematical model development and simplifies the groundwater system into important component parts. To develop the conceptual model, we first characterized the aquifer (or aquifers), then identified sources and sinks of water, and finally identified and delineated hydrologic boundaries in the area of interest.

The shallow regional groundwater system in the Medford Unit occurs in a relatively thin aquifer (about 50 to 250 ft thick) composed mostly of glacially deposited materials but in places also including a fractured and weathered bedrock zone overlying comparatively impermeable Precambrian igneous and metamorphic rocks (Attig, 1993). The underlying crystalline bedrock has comparatively low permeability, and its transmissivities are more than an order of magnitude smaller than those of the glacial deposits (see section 1). Aquifer transmissivity varies within the glacial deposits, according to saturated thickness and lithology type. Lateral variability in aquifer transmissivity is incorporated into the model in piecewise-constant zones that represent areas where one or more features—glacial till, outwash, shallow fractured bedrock, or anomalies in saturated thickness—predominate. 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 Medford Unit itself). Therefore, accurate locations and elevations of surface-water features and pumping wells along with accurate estimates of average baseflow are critical to simulating the groundwater system.

Description of the GFLOW model

Initial model development included estimating the elevation of the base of the groundwater system and regional horizontal hydraulic conductivity, importing a grid of recharge rate from the SWB model (see section 2), and estimating a global resistance value for linesink elements representing streams and lakes. Surface-water bed resistance is defined as the streambed or lakebed thickness divided by the vertical hydraulic conductivity of the sediment and has units of days (d). A value of 0.3 d corresponds to a 1-ft sediment thickness and a vertical hydraulic conductivity of 3.3 ft/d. 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 regional values, and saturated thickness is calculated from the height of the simulated water table above the model base elevation, which is assumed to be horizontal (a sloping base elevation is not supported in GFLOW). As such, transmissivity varies throughout the model domain. Although both base elevation and hydraulic conductivity affect transmissivity, parameter calibration efforts focused on horizontal hydraulic conductivity rather than on base elevation because parameter estimates then produced a more stable model (for example, Feinstein and others, 2006).

Testing of the GFLOW solution showed that a base elevation equal to 750 ft above NAVD 88 provided a stable solution. For comparison, this modified elevation is approximately 475 ft below the elevation of the lowest, most downstream, segment of the Yellow River at the southwest corner of the unit, and it is about 250 ft lower than the deepest crystalline bedrock in the model domain. The deep base elevation was selected to minimize the model's artificial differences in transmissivity resulting from an assumed uniform aquifer base (the base in reality likely varies with topography) and a nonuniform water table, and to facilitate stability in the model solution. See Juckem and Dunning (2015, p. 12) for a more thorough discussion of base elevation and its implications.

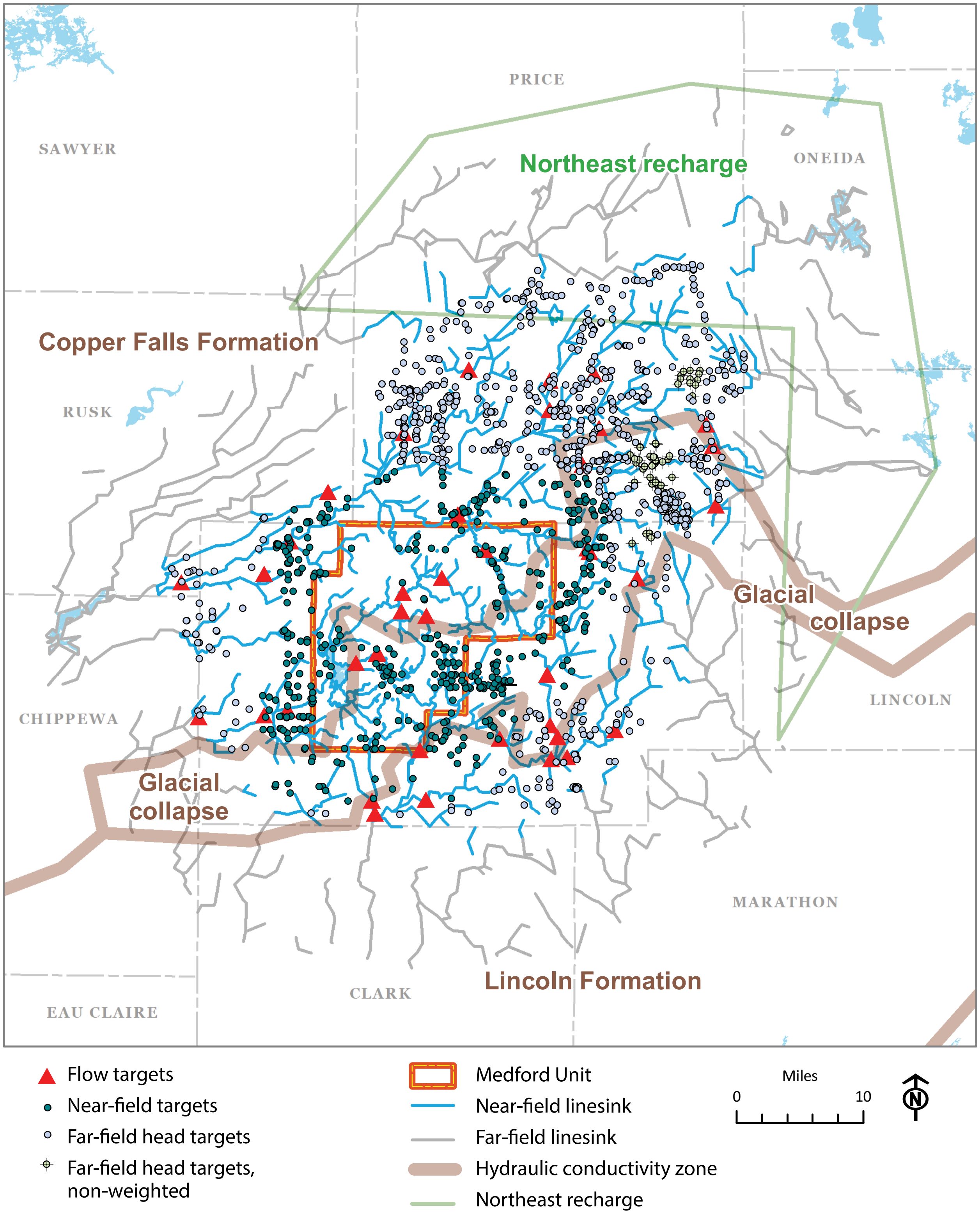
The model domain was divided into three zones of differing aquifer hydraulic conductivity on the basis of variations in the glacial deposits (fig. 9; see plate 1 for a map of glacial deposits). In the north part of the model, the hydraulic conductivity value represents the sandy till and till of the Copper Falls Formation. A central zone, or inhomogeneity, represents the hilly, collapsed material of the Copper Falls Formation; a southern zone represents tills of the Merrill Member of the Lincoln Formation (later reclassified as Copper Falls Formation by Syverson and others, 2011) and the Edgar Member of the Marathon Formation. We began to develop the model before the Lincoln Formation was reclassified; the Lincoln Formation naming convention is used here to maintain consistency with the original flow model.

Recharge was applied to the model by downsampling the SWB model results to a 1 km resolution, and then importing them into the GFLOW graphical user interface by means of the Hybrid GFLOW-MODFLOW sequential coupling feature (Haitjema, 2015). Sequential coupling refers to linking models in a sequence, such that the output of one model (in this case the SWB simulation) is input into another. Sequential coupling in this case allows for a more realistic representation of groundwater recharge, by incorporating the physical processes represented in the SWB model and climatic inputs that are more easily measured. MODFLOW refers to the USGS modular groundwater flow modeling code (Harbaugh, 2005); although this project did not use the MODFLOW code it did utilize an interface developed to work with that code. Because the GFLOW model domain is larger than the SWB domain, a zone of areally averaged recharge equal to the mean value of the SWB grid was added in the northeast. Aquifer hydraulic conductivity, groundwater recharge, and streambed resistance were included as calibration parameters. Calibration of the potential recharge was accomplished by applying a multiplier to the SWB grid, which maintains the spatial distribution of the SWB model results while calibrating the magnitude (total volume of recharge) to measured values of annual baseflow.

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

The linesinks were spatially categorized into three groups of differing detail. The most detailed group, simplified to a tolerance of 100 m, contained all streams within the Medford Unit. A second group, simplified to a 300 m tolerance, contained all streams coded in NHDPlus as Perennial, in the area between the boundaries of the Medford Unit and the model far-field. Both of these groups were assigned values of streambed resistance and were included in the routed-stream network. A third group of linesinks in the area beyond the routed-stream network (model far-field) were simplified to a tolerance of 500 m; this group contained only perennial, second-order, and higher-order streams. The far-field linesinks were assigned zero values of streambed resistance, allowing them to act as infinite sources or sinks, effectively "pinning" the water-table elevation at their locations. This formulation establishes a boundary condition along the model perimeter, while allowing intervening groundwater divides surrounding the Medford Unit to be simulated in the model solution.

Figure 9. Features of the GFLOW model of the Medford Unit.



Political boundaries from Wisconsin DNR, 2011. National Forest boundaries from the USDA Forest Service, 2011. Hydrography from National Hydrography Dataset, 2012. Lincoln Formation later redefined as part of Copper Falls Formation (Syverson and others, 2011).

Streams and lakes within and immediately surrounding the Medford Unit were simulated as routed near-field elements, or stream linesinks. Streamflow routing conserves baseflow along rivers and through lakes so that simulated baseflows can be directly compared with measured streamflows during model calibration. Near-field lakes were also simulated as routed-stream linesinks along the perimeter of the lake for drainage lakes (streams enter and leave the lake), or as nonrouted resistance linesinks for seepage lakes (no inlet or outlet streams). Groundwater exchange with the streams is computed by the model as a function of the groundwater level at the stream, the resistance to exchange between groundwater and surface water, and the specified stream stage. The arbolate sum is defined as the total length of stream channels, including tributaries, upstream of a given location in the stream network. It provides a measure of the size of the drainage system contributing to that location. In general, the model is not very sensitive to stream width. The widths assigned to linesinks representing lakes were computed by the methodology of Haitjema (2005, p. 5).

Groundwater withdrawal from high-capacity wells, those capable of pumping at 70 gpm or more, was simulated within the model domain by using water-use data collected by the WDNR (R. Smail, written communication, 2016). All wells are assumed in the model to be fully penetrating from the water table to the base of the model. No high-capacity wells are present within the Medford Unit itself. Pumping from private residential wells or supply wells at campsites 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 included in the regional groundwater flow model, these wells were used for groundwater quality analysis. Chemical and isotopic sampling from wells in the Medford Unit is described in section 3.

Model calibration and results

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

Parameters that were adjusted during calibration were hydraulic conductivity, a recharge grid multiplier, and surface-water bed resistance (table 12). Initial hydraulic conductivity values were estimated on the basis of the data inventory in section 1, and initial recharge values were imported from SWB model results described in section 2. The resistance parameter is usually insensitive to model calibration and is difficult to measure in the field, so it was initially assigned a value of 0.3 d, which is similar to values used in other studies (see Juckem and others, 2014; Kelson and others, 2002). The overall calibration methodology and approach are outlined by Doherty and Hunt (2010).

Groundwater-level targets for the model (table 13) consisted of historical measurements from private wells (recorded in WCRs) reviewed as part of this project (section 1), records from the USGS National Water Information System, and interpreted lake levels. Relative importance in the calibration is expressed by weights assigned to each target. The quality of the head observations was grouped into several classes on the basis of the estimated locational accuracy or data quality (or both) of each well. 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 water level elevation because the reported depth to water is measured from the estimated top of the well. Wells that were visible on digital orthophotography were estimated to be located within 50 ft of their true location and were assigned a higher weight (0.25) for calibration than wells that were more approximately located on the basis of parcel data or aerial photography (estimated accuracy of 100 ft and a weight of 0.05). Wells with multiple measurements, reliable metadata, and accurate locations were assigned a relatively high calibration weight of 0.5. In addition to well targets, lake elevations were interpreted from the National Elevation Dataset and were assigned a weight of 0.1. A weight of 0.1 can be thought of as a 95-percent confidence interval of ±20 ft around the observed head. Similarly, weights of 0.25 and 0.05 can be expressed as

Table 12. Calibrated parameter values for the groundwater flow model of the Medford Unit.

Parameter	GFLOW identifier	Optimized parameter value	Average simulated saturated thickness[1] (ft)	Approx. simulated transmissivity (ft^2/d)	Representative actual saturated thickness[2] (ft)	Effective average hydraulic conductivity (ft/d)	Description
SWB recharge grid multiplier	rgrid_mult	0.77	—	—	—	—	Multiplier for soil-water balance (SWB) model potential recharge grid
Mean recharge	N/A	4.4 in/yr	—	—	—	—	Mean value of SWB gridded recharge after multiplier was applied
Northeast recharge	routside	4.4 in/yr	—	—	—	—	Areally averaged recharge for northeast portion of the model domain not covered by SWB grid, set to equal mean value of grid
Hydraulic conductivity of Copper Falls Formation	k	3.5 ft/d	670	2,300	70	40	Hydraulic conductivity/ Transmissivity representing Copper Falls glacial deposits above crystalline bedrock; base elevation was set at 750 ft above NAVD88 for entire model domain
Hydraulic conductivity of collapsed glacial sediments	kcollapse	1.4 ft/d	780	1,100	130	10	Hydraulic conductivity/ Transmissivity representing hilly, collapsed Copper Falls glacial deposits
Hydraulic conductivity of Lincoln Formation[3,4]	klincoln	1.9 ft/d	670	1,300	40	30	Hydraulic conductivity/ Transmissivity of Merrill Member of the Lincoln Formation[4] and the Edgar Member of the Marathon Formation
Resistance	rlinesink	2.1 d	—	—	—	—	Resistance is the quotient of the bed thickness divided by the vertical hydraulic conductivity of the lakebed or streambed sediments

Abbreviations: ft = feet; d = day; yr = year; in = inches

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

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

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

[4]*The Lincoln Formation was discontinued and the Merrill Member was redefined as part of the Copper Falls Formation by Syverson and others (2011).*

Table 13. Calibration targets and associated weights used for calibration with the parameter estimation program PEST.

Group name[1]	Data source	Description	Number of targets	Calibration weight	Estimated uncertainty
Baseflow					
flux_usfs	USFS field measurements	Field measurements	5	1/(0.3 x flow)	0.3 (CV[2])
flux_usgsgag	Gebert and others (2011)	Streamflow gaging stations	2	1/(0.01 x flow)	0.01 (CV)
flux_usgsmis	Gebert and others (2011)	Miscellaneous measurements	9	1/(0.25 x flow)	0.25 (CV)
flux_usgspar	Gebert and others (2011)	Partial record sites	24	1/(0.25 x flow)	0.25 (CV)
Heads					
head_good	NWIS, WDNR, and WGNHS	NWIS wells with multiple measurements and/or reliable metadata; WCRs located to within 50 ft	7	0.25–0.5	2–4 ft
head_fair	WDNR and WGNHS	WCRs located to within 100 ft	195	0.05	20 ft
head_lake[3]	National Elevation Dataset (NED)	DEM elevations for lakes	35	0.1	10 ft
head_longtrm	NWIS	Wells with water level time series	2	0.5	2 ft
head_poor	WDNR and WGNHS	Poorly located (>100 ft) or other low-quality WCRs	240	0	—
head_gt1680	Varies	Head targets outside the forest unit with elevations above 1,680 ft, where thicker glacial materials are poorly represented by the regional model	57	0	—
farfield	Varies	Head targets from all groups (good, fair, lake, etc.) located more than 7 km outside of forest unit; calibration weights were reduced by 80%	781	0–0.1	>10 ft

Abbreviations: ft = feet; m = meters

[1]*Group name in targets shapefile (Med_TargetsGFLOW_WGNHS_2016).*

[2]*Coefficient of variation.*

[3]*Near-field lakes with an apparent large vertical gradient or perched condition were given a weight of zero.*

95-percent confidence intervals of ±8 ft and ±40 ft around the observed head, respectively.

During calibration, weights were adjusted to reduce focus on head targets outside of the Medford Unit and on heads that differ from regional conditions. Targets located in areas high in the landscape with thick glacial sediment (see plate 7) likely have aquifer base elevations and thicknesses that differ from those of the regional system; they could not be reproduced by the model without degrading the model's ability to simulate heads within and near this unit. To increase model accuracy within the area of interest, targets more than 7 km outside the unit boundaries were reduced in weight by 80 percent (group "farfield" in table 13), and targets outside the unit with measured heads greater than 1,680 ft were given zero weight ("head_gt1680" in table 13). These two groups are shown as "far-field head targets" and "far-field nonweighted head targets" on figure 9. Additionally, some lake targets that were considerably higher than nearby well water levels were given a weight of zero to account for potential perched conditions or high vertical gradients not simulated by the two-dimensional model.

Historical and contemporary streamflow targets also were used to calibrate the model (table 13). Baseflow targets (fig. 9) included annual baseflow estimates published by Gebert and others (2011) and streamflow measurements collected within the Medford Unit by USFS staff (Higgins, written communication, 2/20/2013). For the purpose of calibrating the model, measurements from each site were adjusted to the long-term average baseflow conditions. Streamflow measurements collected by the USFS were adjusted by using a state-wide regression equation for estimating annual baseflows from low-flow measurements obtained from index gages (Gebert and others, 2011). Baseflow targets are included as part of the electronic database.

Similar to head targets, baseflow targets were grouped into four classes based on measurement uncertainty and the expected ability of the regional groundwater model to simulate the magnitude of the baseflow. Baseflow target weights were assigned as the inverse of the target uncertainty, estimated as target flow rate multiplied by a coefficient of variation (table 13). Two USGS gaging stations (USGS site numbers 05361500 and 05362000), where annual baseflows were estimated from continuous time series of streamflow (Gebert and others, 2011), were given the highest weight (coefficient of variation of 0.01, which represents a 95-percent confidence interval of ±2 percent around the observed flow). These larger baseflow values measured at the gages also integrate discharge at the watershed scale, which is commensurate with the regional focus of the groundwater model. The annual baseflow estimates obtained from Gebert and others (2011) and those estimated from USFS measurements were given coefficient of variation estimates of 0.25 and 0.3, respectively (95-percent confidence intervals of ±50 and ±60 percent). The estimates for these groups are approximate and are intended only to reflect a larger uncertainty in miscellaneous measurements compared to the gages. The overall goal of the observation weighting for both heads and baseflows was to achieve a balanced objective function that allowed all important observation groups to be "seen" by the calibration process, thereby maximizing the information transfer from the observations to the model input parameters (see Doherty and Hunt, 2010, for more explanation).

Two large baseflow targets on the Yellow River (USGS site numbers 05363765 and 05363810) were zero-weighted, owing to presumed influence from the nearby Chequamegon Waters reservoir. The measured values at these sites were consistently oversimulated by the model during the calibration process, and they may be artificially low owing to control of reservoir outflows during low-flow periods. Other measurements in the Yellow River basin are well simulated by the model.

During calibration, the hydraulic conductivity, groundwater recharge, and surface-water sediment resistance were adjusted by the parameter estimation code PEST (Doherty, 2011) in order to match simulated and observed water level and baseflow targets. Hydraulic conductivity was separated into three zones for calibration of the model (fig. 9; see Description of the GFLOW model). Groundwater recharge was calibrated by varying a multiplier of the SWB model potential-recharge grid. The SWB grid was initially too detailed for the GFLOW graphical user interface, and the resolution was downsampled to 1 km. An additional areally averaged recharge inhomogeneity in the northwest provided recharge to part of the model domain not covered by the SWB grid. This recharge value was set equal to the mean value of the calibrated SWB grid and was adjusted in tandem during calibration. Surface-water bed resistance was calibrated by using a single value applied to all surface-water features, including seepage lakes, drainage lakes, and streams.

Final parameter values calibrated to measured water levels and stream baseflow (table 12) are within expected ranges on the basis of field data and previous studies. The recharge multiplier of 0.77 results in a mean areal recharge of 4.4 in/yr, consistent with other reported values (Gebert and others, 2011; Pint and others, 2003; Robertson and others, 2012). Though the simplifying assumptions of GFLOW and TGUESS limit direct comparisons of hydraulic properties, the approximate simulated regional transmissivity (1,100–2,300 ft^2/d) falls within the same order of magnitude as mean transmissivity values from TGUESS (2,000 ft^2/d for unlithified materials). Because the uniform model base is not necessarily equal to the true aquifer base, the modeled hydraulic conductivity parameter does not represent the true aquifer. Table 12 shows the approximate effective hydraulic conductivity representative of the aquifer for each zone.

The head and baseflow targets are well matched by the calibrated model, as shown in figures 10–12. Comparison of the 620 weighted target water levels to simulated heads showed a mean difference of 6.5 ft (positive indicates that target values are, on average, greater than simulated values), a mean absolute difference of 13.3 ft, and a root

Figure 10. Simulated vs. observed head targets, showing 1:1 line.

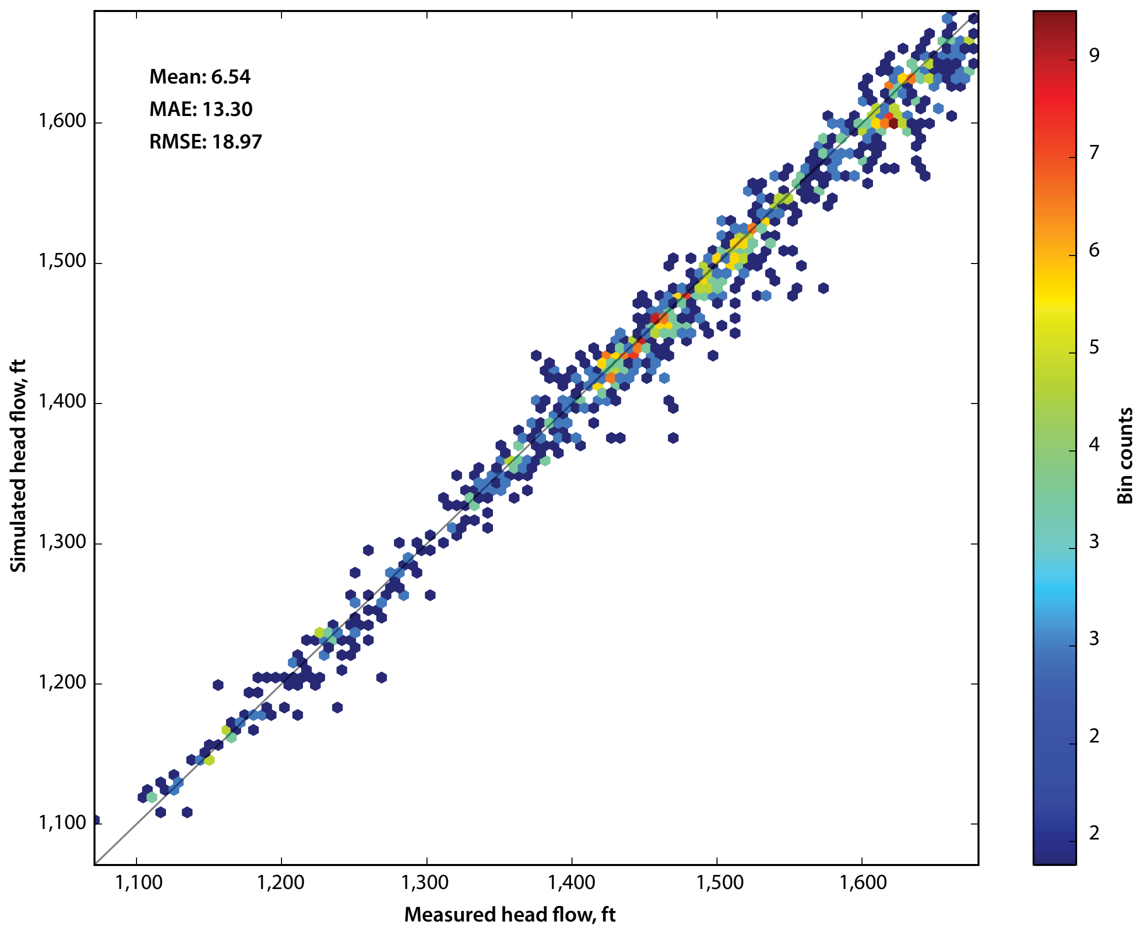


Figure 11. Simulated vs. observed flows for baseflow targets, showing 1:1 line.

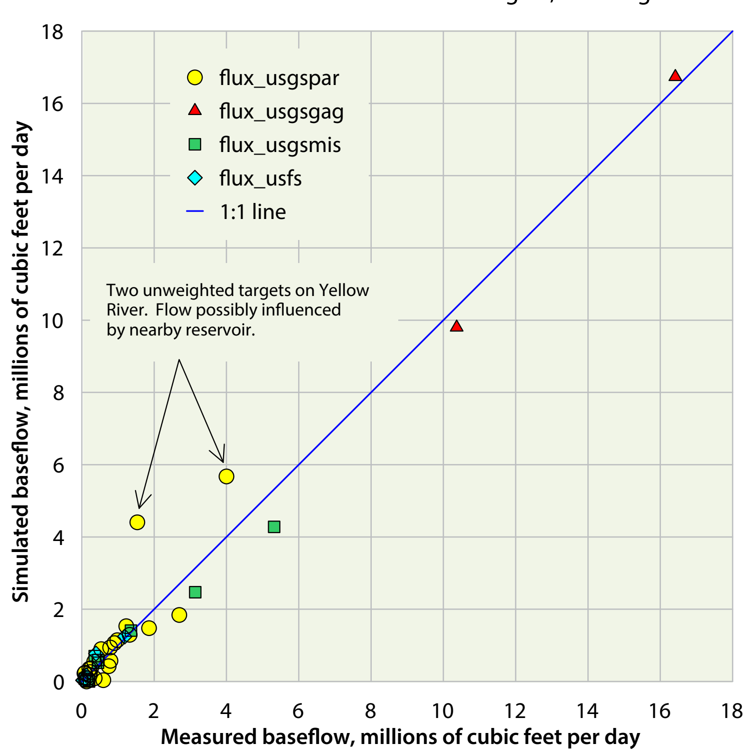


Figure 12. GFLOW results for Medford model: weighted head target residuals and simulated heads above land surface (flooding) compared to WDNR Wisconsin Wetlands Inventory.

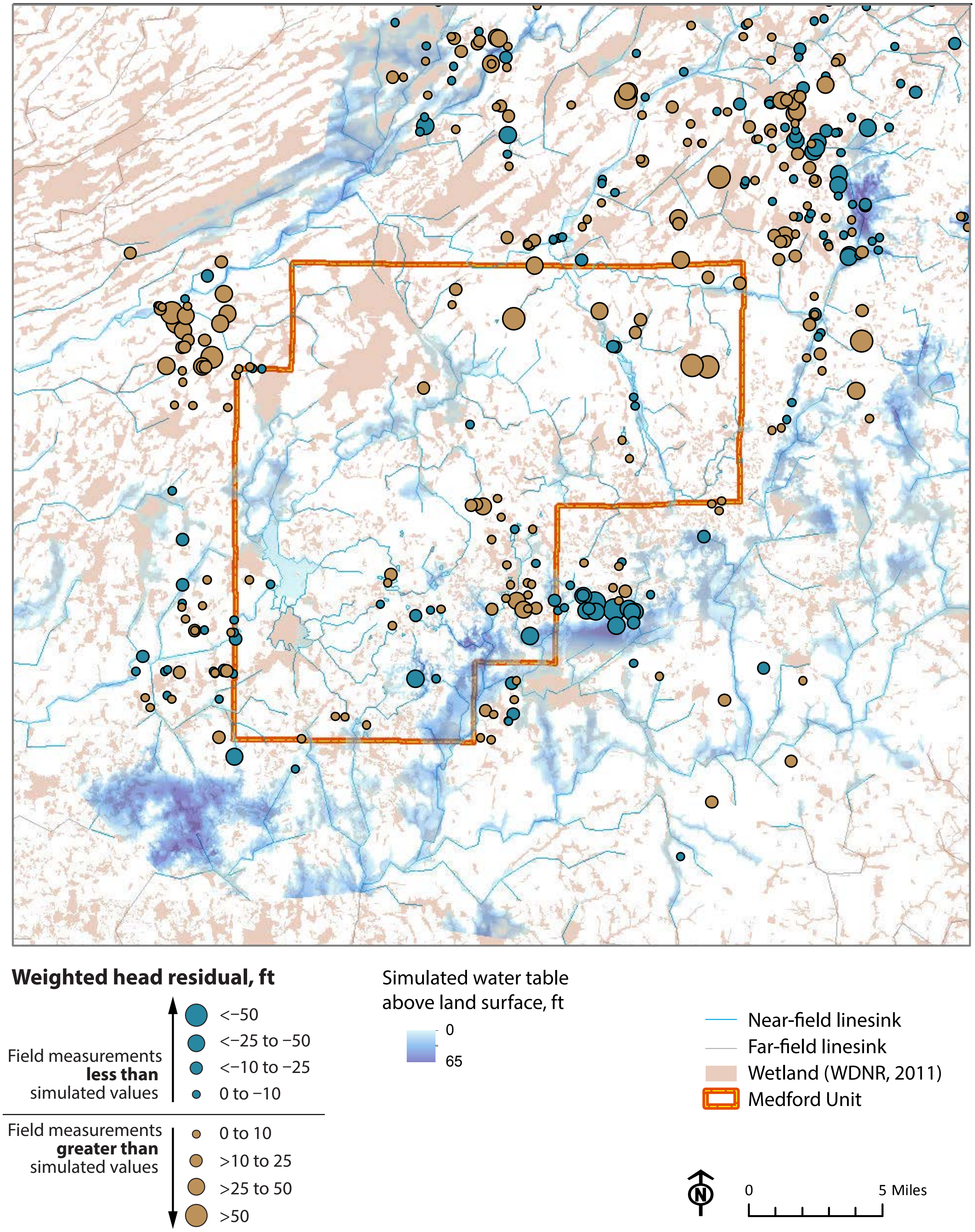
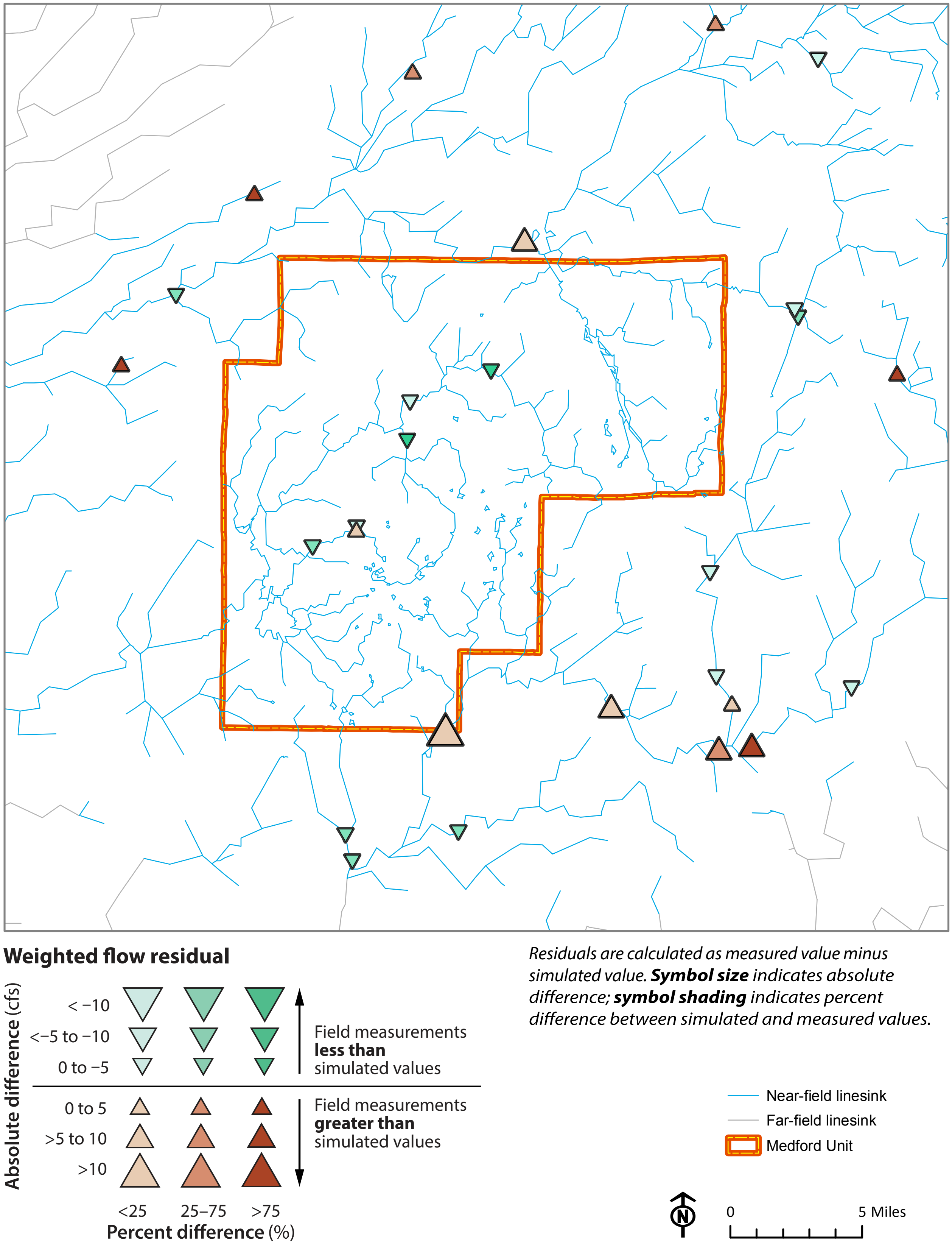


Figure 13. GFLOW results for Medford model: weighted flow target residuals.



mean squared difference of 19.0 ft. Results by head group are shown in table 14. Simulated water levels generally matched weighted head targets throughout the entire range in measured water levels (fig. 10). Unweighted targets in areas of thick glacial sediments consistently have simulated heads lower than measured ones (group head_gt1680 in table 14). These local areas may have high aquifer base elevations, high vertical gradients, or perched conditions, which cannot be represented in the regional model with a single base elevation and large, piecewise-constant parameter zones. Additional refinement of the model would be necessary for these areas to be studied in detail. Simulated baseflow values generally matched measured conditions well (fig. 11). Results of weighted head and baseflow targets are shown graphically in figure 12.

Although groundwater discharging to wetlands was not explicitly included in the model, it is implied in the model output in areas where simulated heads rise above the land surface. Such areas of "flooding" or "overpressurization" were used as a qualitative calibration metric, by spatial comparison to the Wisconsin Wetlands coverage (Wisconsin Department of Natural Resources, 2011). Simulated areas of flooding in the calibrated model agree well with the mapped wetlands (fig. 12).

Application of the model

The GFLOW groundwater flow model is a useful decision-support tool for groundwater management in the Medford Unit. Hydraulic heads simulated by the model provide a forest-wide water-table map (plate 10). Model-generated water-table maps are advantageous compared to water-table maps constructed by interpolation between point measurements, in that they provide a physically based depiction of the groundwater system that accounts for mass and energy conservation. Representation of the physical process of groundwater flow can help constrain water-table elevations in areas of sparse water-level data, as is typical in large forest regions.

The model solution can also be used to compute flowpaths through the groundwater system from discrete starting locations to discharge points (such as streams or wells). Starting locations are specified in the GFLOW graphical user interface as hypothetical particles; the paths of the particles are then traced through the groundwater flow system and included in the model output. Computation of particle travel times requires specification of effective porosity. In addition, the deep base elevation employed in this model requires that the effective porosity values be adjusted to correct for the additional simulated aquifer thickness (see Juckem and Dunning, 2015). Particle travel times were not considered in this study.

Plates 9 and 10 show pathline output from the model indicating general directions of groundwater flow. The individual pathlines were created by initiating particles at the water table at various locations throughout the groundwater system, and then by tracking those particles forward for an arbitrary time period or until the particles discharged to a surface-water feature or well. The water-table contours and pathlines show general directions of groundwater flow and can be used to delineate divides between groundwater basins. Groundwater flows primarily to the southwest; the northern part of the unit flows northwest and the southern part flows south, similar to surface flow on the regional topographic water divide.

Table 14. Calibration results for groundwater head targets and associated weights used for calibration with the parameter estimation program PEST.

Group name[1]	Number of targets	Mean error (ft)	Mean absolute difference (ft)	RMSE (ft)	Calibration weight (1/std)
head_good	7	4.38	8.69	10.86	0.25–0.5
head_fair	195	3.32	13.05	19.24	0.05
head_lake	35	6.00	7.71	12.81	0.1
head_longtrm	2	–5.06	8.25	9.68	0.5
head_poor	240	1.19	13.10	18.99	0
head_gt1680	57	54.37	54.47	60.14	0
farfield	781	6.84	13.24	18.30	0–0.1

Abbreviations: ft = feet; RMSE = root-mean-square error; std = standard deviation

[1]*Group name in targets shapefile (Med_TargetsGFLOW_WGNHS_2016).*

The GFLOW model can also be used to evaluate groundwater discharge to surface-water features (plate 9). This plate shows modeled baseflow, ranging up to nearly 200 cubic feet per second, colored to indicate water exchange with the aquifer. Most streams in the unit gain water from the aquifer. The plate also shows saturated thickness of the aquifer and alkalinity and electrical conductivity of the water samples. Groundwater-dominated samples (higher values of alkalinity and electrical conductivity) correspond to areas modeled by GFLOW as groundwater discharge points whereas surface-runoff-dominated samples are typically located in upland recharge areas. Features that do not follow this pattern could indicate local hydrogeologic conditions that are not well represented by the regional GFLOW model. For example, Steve Creek appears to be in a modeled recharge area but geochemistry and visual observation suggest it receives surface water. This combination of flow modeling and geochemistry can be used as a guide for future modeling and site-specific investigations.

The GFLOW model has many other potential uses:

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

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

Assumptions and limitations

The Medford Unit groundwater and surface-water systems are assumed to be in close hydraulic connection in the modeled area; this assumption is consistent with the relatively transmissive nature of the glacial sediments, high net-annual precipitation, the presence of springs and perennial headwater streams, and previous modeling in nearby areas. It follows then that modeling assumes that elevations of surface-water features represent the groundwater system; perched systems are not well depicted. 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. All pumping wells represented in the model are assumed to penetrate the full aquifer thickness. This assumption may produce a positive bias in simulated heads near pumping wells, especially where the wells penetrate only part of the aquifer.

The model described here is a regional-scale model that represents the groundwater system with laterally extensive, piecewise-constant zones. Local subsurface variability that is known to exist (for example, variability in aquifer thickness and hydraulic conductivity due to glacial erosional and depositional processes) cannot be represented in the model at scales smaller than the model zones, which simulate average regional conditions. Also, the model is designed and calibrated for groundwater flow in a single aquifer composed of unconsolidated sediments combined with a zone of shallow bedrock directly connected to the glacial materials. The model is not calibrated for flow in deeper fractured bedrock, and it should not be used to estimate groundwater flow in bedrock. Additional field investigations are needed to refine the model so that it accurately simulates processes that are sensitive to local heterogeneity in the aquifer.

Simulated heads and baseflows matched in the calibration process were relatively insensitive to the streambed-resistance parameter; therefore, this parameter is not well constrained. The calibrated value of 2.1 d is similar to values in other forest unit models created for this project, as well as in other studies in northern Wisconsin (see Juckem and others, 2014; Kelson and others, 2002). Steady-state simulations were assumed appropriate for this study given the large lateral extent and dense surface-water network (for example, p. 293 of Haitjema, 1995).

Recommendations for future modeling

The model developed for this study is intended to simulate groundwater flow throughout a large regional area and therefore greatly simplifies the hydrogeologic system. It is an appropriate model for the amount of data available regionally and should be a starting point for the construction of more detailed models of specific areas of interest. Additional data collection and advances in modeling techniques will improve the ability to incorporate more detail into future models. Local areas of interest could be studied in greater detail by refining the linesink strings within the analytic element model, or by creating finite difference inset models of areas of interest (Hunt and others, 1998). Calibration targets in the Medford Unit are sparse; additional measurements of groundwater levels and baseflow would help refine model results. Additional subsurface data in this unit may reveal more-detailed patterns in hydraulic conductivity that are not currently visible. Transmissivity and hydraulic conductivity in the unit do vary spatially (plates 1–3); data is limited in less-populated areas and in more fine-grained deposits where well records are sparse. Although the analytic element modeling technique is limited to representing variations in hydraulic conductivity with piecewise-constant zones, greater detail in hydraulic conductivity could be readily incorporated into finite difference inset models.


Mondeaux Flowage

Linda Deith

Data availability

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

Table 15. Summary of available electronic data.

Data	Name	Format	Description or source
Wells			
Located wells	Med_LocWCRs_WGNHS_2016	Point features	Data points from WCRs located to within the quarter-quarter section and from geologic records
Monitoring well TA-217	Med_WellTA217_ WGNHS_2016	Point features	Location of monitoring well TA-217/ Bend well
Monitoring well construction	Monitoring well construction-Medford Unit.pdf	PDF file	Geologic and construction data for well TA-217
Geology			
Bedrock elevation contours	Med_BedElev_WGNHS_2016	Polyline features	Interpolated from WCRs and other data
Depth to bedrock contours	Med_BedDep_WGNHS_2016	Polyline features	Interpolated from WCRs and other data
Saturated thickness contours of glacial materials	Med_GlacSatThickness_ WGNHS_2016	Polyline features	Interpolated from WCRs and other data
Hydraulic properties			
Bedrock hydraulic properties	Med_BedTGUESS_ WGNHS_2016	Point features	Hydraulic conductivity and transmissivity results from TGUESS
Glacial hydraulic properties	Med_GlacTGUESS_ WGNHS_2016	Point features	Hydraulic conductivity and transmissivity results from TGUESS
Recharge			
Mean annual potential recharge	Med_PoRec_WGNHS_2016	Raster data	Annual recharge mean of all modeled years from SWB model output
Annual potential recharge, individual years	Med_PoRec[yyyy]_ WGNHS_2016 (e.g., Med_ PoRec2000_WGNHS_2016)	Raster data	Annual potential recharge for years 2000–2010 (11 files) from SWB model output
Calibrated recharge grid	Med_RechGFLOW_ WGNHS_2016	Raster data	Annual recharge applied to GFLOW model, calibrated from SWB results
Groundwater			
Simulated water table contours	Med_WatTabGFLOW_ WGNHS_2016	Polyline features	GFLOW model output
Simulated groundwater flow paths	Med_GWFlowpathGFLOW_ WGNHS_2016	Polyline features	GFLOW model output
Modeled baseflow	Med_BaseflowGFLOW_ WGNHS_2016	Polyline features	GFLOW model output
Geochemistry			
Geochemistry sampling locations	Med_GeochemSites_ WGNHS_2016	Point features	WGNHS water sampling locations
Geochemistry results	Med_Geochemistry_ WGNHS_2016	Excel	Field and laboratory water sample results
Model			
GFLOW targets	Med_TargetsGFLOW_ WGNHS_2016	Point features	Simulated and observed values for GFLOW baseflow and head targets
USGS data archive for GFLOW model	https://dx.doi.org/10.5066/ F7416W1P	Model files	Groundwater flow model and associated files

Summary

- The primary aquifer in the Medford Unit consists of shallow glacial sand and gravel deposits. This relatively thin (20–200 ft) aquifer has low to moderate productivity; its mean estimated hydraulic conductivity is 46 ft/d and its range is 0.06–3,000 ft/d. The glacial aquifer in some areas has the potential to support high-capacity wells, whose approximate average potential yield is 200–300 gpm.
- Crystalline bedrock beneath the glacial sands and gravels also transmits water through fractures, particularly in its upper weathered zone, and can supply adequate water to low-capacity wells in areas where the upper aquifer is thin. This bedrock unit has a mean estimated hydraulic conductivity about an order of magnitude lower than that of the overlying sand and gravel. The bedrock aquifer has a low likelihood of supporting high-capacity wells; its approximate average potential yield is about 5–10 gpm.
- Few high-capacity wells are present in this region; only 15 are active within 10 miles of the unit and all obtain their water from the glacial aquifer. Although they are permitted to pump more than 70 gpm, the majority pump at lower rates (average water use is 12 million gallons per year, equivalent to about 23 gpm). Additional analyses would be necessary to determine the site-specific potential for future high-capacity wells and to evaluate the effect they might have on nearby groundwater levels and surface-water flows.
- About 65 percent of the wells in the Medford Unit obtain their water from the glacial aquifer. Of the bedrock wells, most pump from the top 60 ft of bedrock, although some pump from as deep as 500 ft.
- Monitoring well TA-217, located near the Bend mineral exploration site, is isolated from human activity and provides important baseline data for the general study area. The measured groundwater level has fluctuated with precipitation but generally remained stable for the past five years. Dissolved nitrate concentrations were slightly elevated in water samples from this well but met drinking water standards. The cause of the elevated nitrate at this site is unclear.
- The SWB-modeled mean potential recharge is low to moderate (5.8 in/yr), with higher potential in the southern half of the Medford Unit. The SWB model may overestimate recharge in wetlands; the assumption of zero recharge in wetlands produces an average forest-wide potential recharge of 5.0 in/yr. During calibration of the groundwater flow model a regional multiplier of 0.77 was applied to the SWB grid, which resulted in an overall mean recharge value of 4.4 in/yr.
- Water quality within the unit is generally unaltered by human activity. Slightly elevated nutrient concentrations were observed at a few sample locations, possibly as a result of local land-use activities such as road salting. Concentrations of arsenic and lead in groundwater samples from six wells in the Medford Unit were slightly higher than recommended limits established to protect health but met enforcement standards. The arsenic and lead likely originate in natural local sources. In addition, elevated levels of dissolved iron and manganese were measured in several wells, also likely originating in natural deposits of these metals. Dissolved nitrate was slightly elevated in one well; the source of the nitrate in this well is unclear.
- Groundwater in the Medford Unit is distinguished from surface water by higher electrical conductivity, alkalinity, and concentrations of dissolved ions such as calcium and magnesium. Groundwater well samples have an average conductivity of 313 µS/cm and alkalinity of 132 mg/L, whereas samples interpreted as surface-runoff dominated have averages of 63 µS/cm and 20 mg/L, respectively. Isotopes of hydrogen and oxygen can also be used to distinguish groundwater, which is isotopically lighter, or more negative, than surface water.
- 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 can also be used to simulate potential effects of land use, pumping, or climate change.

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

  a. Collect additional hydrogeologic data in this area to see if it confirms the simulated flow paths. Very little hydrogeologic information was available in the Kidrick Swamp and Steve Creek watershed areas in the northwest part of the Medford Unit. The GFLOW model suggests that numerous groundwater flow paths originate in this area that terminate in the Yellow River, Jump River, or their tributaries.

  b. Maintain at least one monitoring well in the Medford Unit to provide baseline groundwater-level data.

  c. Continue to measure baseflow and groundwater levels to improve calibration of the groundwater flow model.

  d. Obtain additional subsurface data to constrain aquifer thickness and hydraulic conductivity estimates, particularly in areas of sparse data such as the northwest, north-central, and southwest parts of the Medford Unit. Passive-seismic and electromagnetic surveys along existing forest roads might prove to be a cost-effective way of improving maps of bedrock elevation and aquifer thickness.

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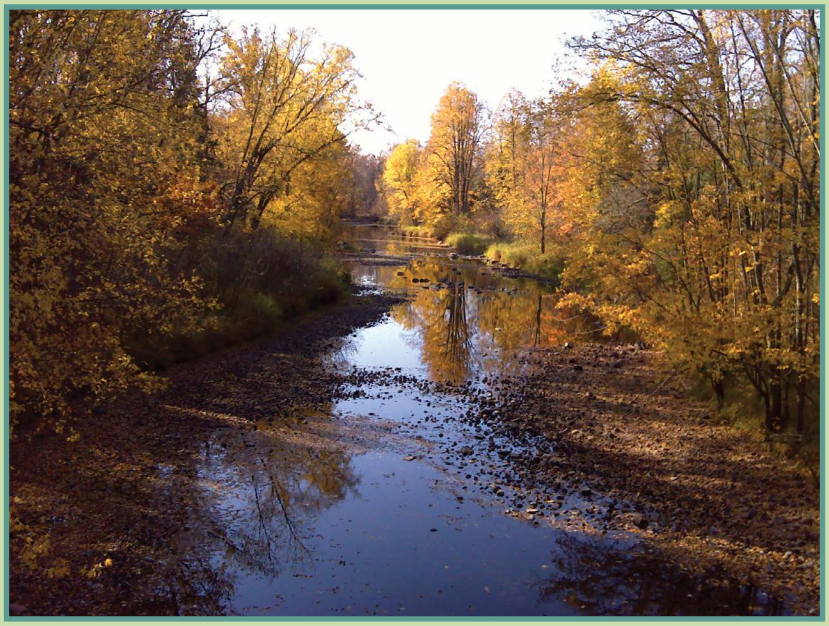

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The Survey conducts earth-science surveys, field studies, and research. We provide objective scientific information about the geology, mineral resources, water resources, soil, and biology of Wisconsin. We collect, interpret, disseminate, and archive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

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