Wisconsin Geological
and Natural History Survey
DIVISION OF EXTENSION
UNIVERSITY OF WISCONSIN–MADISON

Hydrogeologic atlas of Bayfield County, Wisconsin

Technical Report 005 • 2019

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Back: Spring at tributary to the White River, © Grace Graham

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(Plates are available at https://wgnhs.org/pubs/000967*)*

Abstract

This hydrogeologic atlas provides a regional-scale interpretation and analysis of groundwater resources in Bayfield County, Wisconsin. It was developed primarily from existing data sources; field data was limited to checking locations and obtaining passive seismic measurements. The atlas includes an overview of typical well construction in Bayfield County; interpretations of the water-table elevation and groundwater flow directions (plate 1); depth to the water table (plate 2); the thickness of unconsolidated materials, or depth to bedrock (plate 3); the distribution of groundwater recharge (plate 4), and relative susceptibility of groundwater to contamination (plate 5).

The regional geology of northern Wisconsin controls the hydrogeologic setting of Bayfield County. Glacial deposits cover most of the county, and primarily consist of clayey lowlands that stretch inland for 5 to 10 miles from Lake Superior, sandy uplands that cover the center of the county, and rocky uplands that contain abundant lakes and streams to the south. Most groundwater recharge occurs in upland areas. The presence of low-permeability clays is critical to the natural protection of aquifers and wells in Bayfield County. The presence of clay at the surface ultimately limits the rate of groundwater recharge and can slow the downward migration of contaminants into shallow groundwater. Areas with coarse sands at or near the surface and areas with shallow, fractured bedrock are most vulnerable to rapid migration of contaminants originating at the surface.

The groundwater susceptibility map (plate 5) shows an estimate of the degree and distribution of areas that are naturally susceptible to contamination. Characteristics that increase susceptibility include (1) high groundwater-recharge rates, (2) high permeability of geologic materials, (3) shallow depths to bedrock, and (4) shallow depths to the water table. In Bayfield County, the areas most susceptible to groundwater contamination are characterized by sand and gravel of varying thickness at the surface. Groundwater is also highly vulnerable to contamination where shallow crystalline bedrock is present near the surface, in southwestern and southeastern Bayfield County and along the Lake Superior shoreline.

The susceptibility map provides a technical basis for determining where in the county additional preventative measures or monitoring may be warranted for groundwater protection efforts. Those interested in conservation practices to preserve or improve groundwater quality can use this information to prioritize their efforts.

Houghton Falls

Introduction

The purpose of this hydrogeologic atlas is to provide an inventory and analysis of groundwater resources in Bayfield County, Wisconsin. The atlas consists of maps and other interpretative material that deliver county-scale information on groundwater availability, the direction of groundwater flow, and the physical properties that may affect the susceptibility of Bayfield County's aquifers and water-supply wells to contamination. This atlas may serve as an educational resource for community members interested in natural resources and groundwater investigations. The atlas also may serve as a technical tool for local officials and land managers to assess potential effects of various activities on groundwater resources and protect groundwater quality.

Background

This work expands on a 2015 study that focused on agricultural areas within Bayfield County (Gotkowitz and Li, 2016). The 2015 project was prompted by the siting of the county's first proposed concentrated animal feeding operation. The study included a series of maps and cross sections illustrating groundwater resources and typical well construction in agricultural regions with the goal of helping develop sound practices for manure storage and spreading. Following recommendations for additional work described in that report, Bayfield County contracted with the Wisconsin Geological and Natural History Survey (WGNHS) to produce a countywide hydrogeologic atlas.

Scope

The WGNHS completed this work over the course of two project stages. The first portion of the atlas, a water-table map and water-well database, was completed in 2017 (Fehling and Gotkowitz, 2017). The remaining mapping and analysis were compiled during 2017 and 2018. This report summarizes all components of the completed hydrogeologic atlas:

- Water-well database appended with information on well construction and aquifer composition,
- Water-table map (plate 1),
- Depth-to-water-table map (plate 2),
- Depth-to-bedrock map (plate 3),
- Mean annual groundwater-recharge map (plate 4), and a
- Groundwater-susceptibility map (plate 5).

The maps and their associated datasets are available in digital form. The maps are intended to be used at a scale of 1:100,000 and are not considered to be accurate enough for site-specific applications. These regional interpretations may provide a useful framework for site-specific analyses.

Project area and hydrogeologic setting

The study area covers all of Bayfield County, excluding the Apostle Islands (fig. 1). Agricultural land use is concentrated in the northwestern and eastern lowland regions of the county. The Chequamegon-Nicolet National Forest covers much of the central and southeastern parts of the county, and the Red Cliff Reservation is in the northeastern part.

Surficial geology

Bayfield County contains several physiographic regions (fig. 2). Clayey lowlands stretch inland from Lake Superior's southern shore for 5 to 10 miles (mi). Sandy uplands in the center of the county are characterized by high-relief topography of around 1,300 feet (ft) in elevation with few surface-water features. In southern Bayfield County, rocky uplands over 1,500 ft in elevation contain abundant lakes and streams. Between these areas is a transition zone where the land surface dips steeply to the north.

The uppermost and youngest sedimentary geologic unit in the lowlands is the Miller Creek Formation (fig. 2), which was deposited by glaciers advancing through low-lying areas 11,000 to 9,500 years ago (Clayton, 1984). The Miller Creek Formation is composed of fine-grained, sandy silt and clay with discontinuous lenses of sand and gravel. Wetland peat deposits are located north of the steeply north-sloping topography near the southern extent of the Miller Creek deposits. Toward the inner margins of the lowlands where the elevation increases, sand and gravel deposits interpreted as ancient shorelines are present in places near the contact with the older Copper Falls Formation. The Copper Falls Formation consists of coarse-grained glacial sediment that was deposited more than 11,500 years ago. The coarsest of these deposits are found in the sandy uplands in the center of the Bayfield peninsula. Within this formation, some moderately coarse-grained sediment consisting of clayey, silty sand is present in parts of southern Bayfield County (Clayton, 1984).

Figure 1. Shaded topographic-relief map of Bayfield County showing town names; boundaries of agricultural regions, national forest, and tribal lands; and places of interest mentioned in the report.

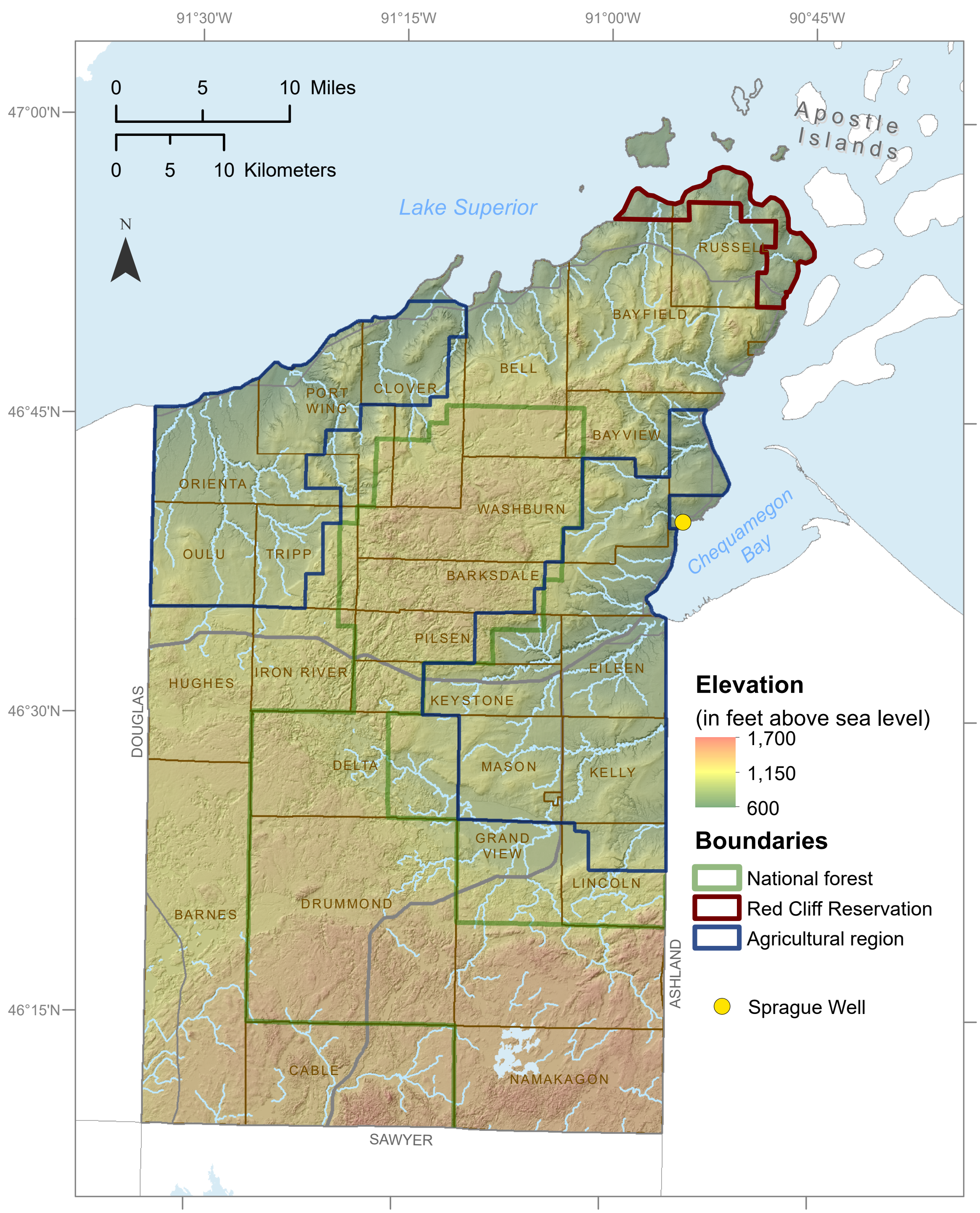
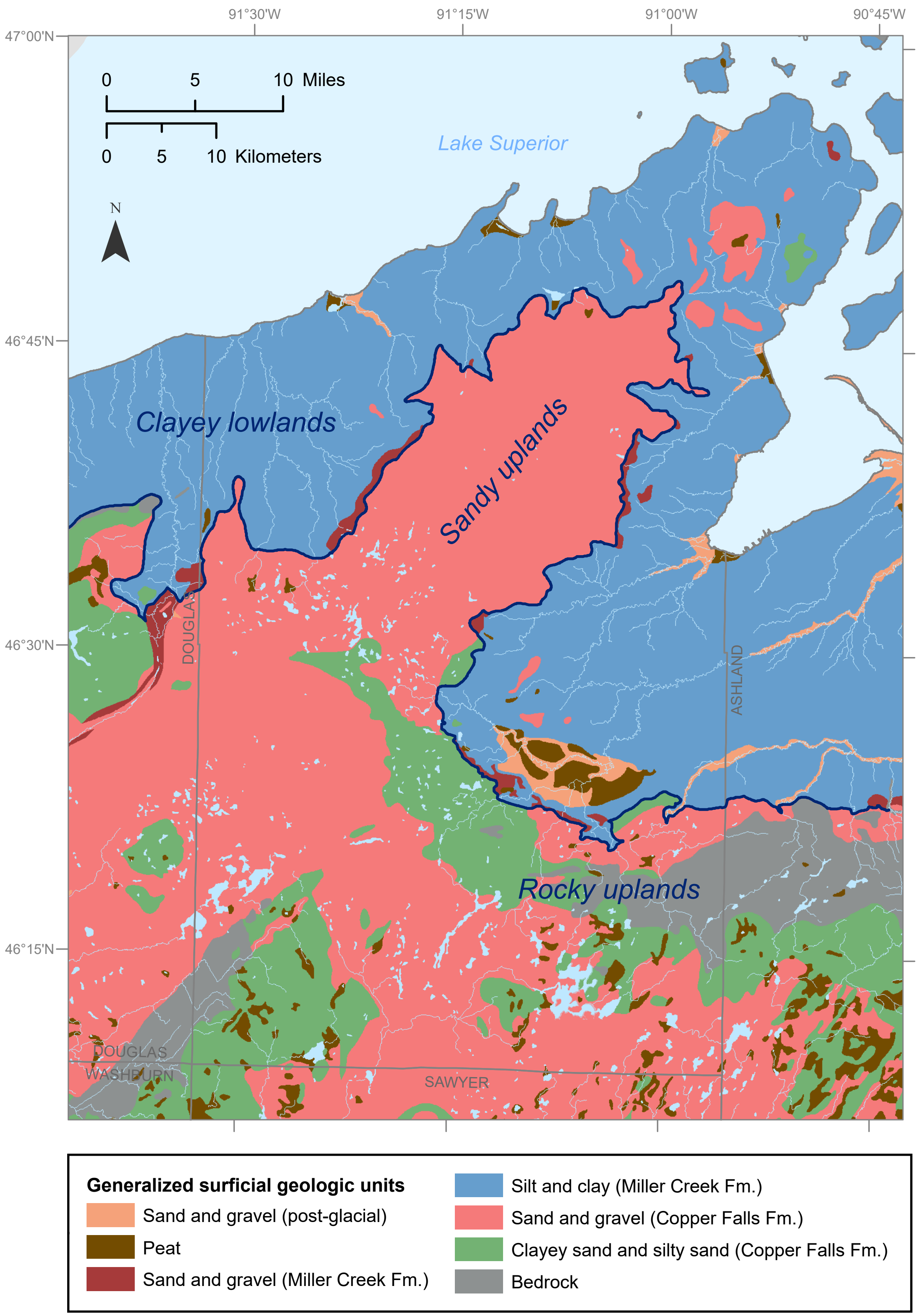


Figure 2. Generalized map showing surficial geology of Bayfield County (modified from Clayton, 1984).



Bedrock geology

Bedrock of the Bayfield Group (fig. 3) underlies most of northern Bayfield County and consists of a series of sandstone formations. Bedrock of the underlying Oronto Group occurs in the center of the county and consists of sandstone, siltstone, shale, and conglomerate. These rocks are poorly understood because they are buried by thick layers of sediment. South of these sedimentary rocks, a belt of more resistant igneous and metamorphic bedrock generally corresponds to the steeply north-dipping topography. A similar incline in the bedrock surface may be seen in northwestern Bayfield County, where a protrusion of igneous bedrock (basalt) remains at higher elevations than the surrounding sandstone and siltstone (fig. 3).

Available evidence suggests that the shape of the bedrock surface also reflects the tectonic faulting and folding that were once active in this region. The Douglas fault, for example, appears to influence bedrock elevation in the center of the county. When the fault was active hundreds of millions of years ago, bedrock from the south shifted upward and northward over rocks to the north (Cannon and others, 1999; Esther Stewart, WGNHS, personal communication, 2017). Today, buried by thick deposits of glacial sediment, the bedrock on the south side of the fault appears to be slightly higher than the bedrock to the north, probably due to the differential erosion of rock on either side of the fault (fig 4).

Aquifers and aquitards

The geologic materials present in the county form several different hydrogeologic units that store and transmit groundwater. An *aquifer* is a geologic unit that stores or transmits economically or environmentally useful quantities of groundwater. Aquifers usually consist of permeable geologic materials such as sand, gravel, or sandstone, and they typically transport groundwater rapidly enough to supply wells or springs. *Aquitards* are geologic units that contain and store groundwater, but they have low permeability; therefore, groundwater moves through them very slowly. Aquitards are usually composed of materials such as clay or shale and generally may not supply enough water to serve wells or springs. However, because of their low permeability, aquitards may act as protective layers for adjacent aquifers.

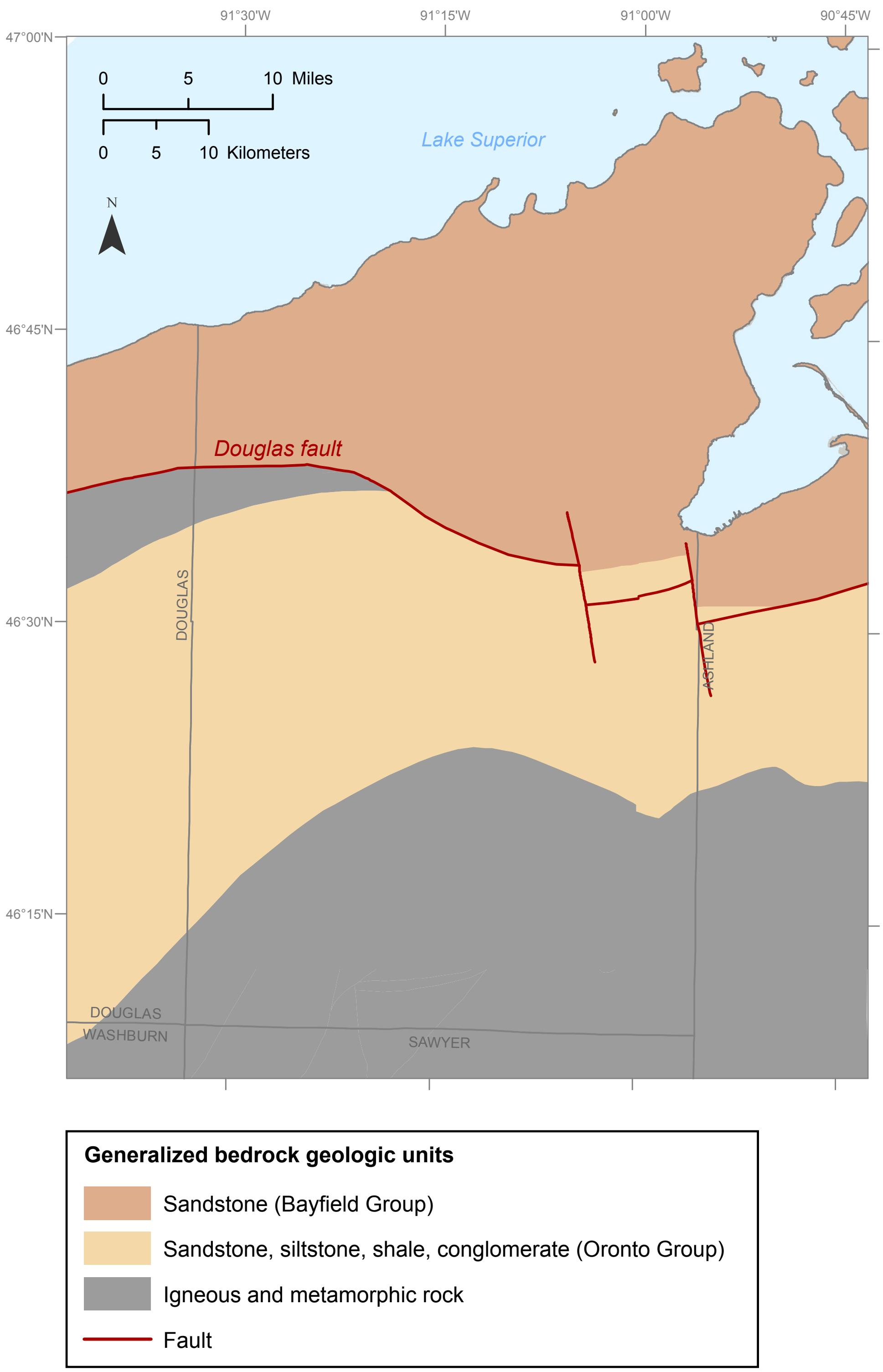
The three important aquifer units in Bayfield County consist of sand and gravel, sandstone, and fractured crystalline rock (fig. 4). The Miller Creek Formation (described above) contains discontinuous lenses of sand and gravel that form small, often disconnected aquifers surrounded by finer-grained silt and clay. The Copper Falls Formation varies in composition, but in places it consists of permeable, sandy material. Many wells in the county draw water from these sand and gravel aquifers. Sandstone and conglomerate formations of the Bayfield and Oronto Groups form a second important aquifer under much of the county and supply water to numerous wells. Fractured crystalline rocks (granite, basalt, and similar rocks) form a third aquifer that is tapped by wells in some parts of the county; however, yields from these rocks tend to be low (Fehling and others, 2018).

Water table and potentiometric surface

Below the land surface, the soil, sediment, and rock are divided into a lower saturated zone and an upper unsaturated zone. In the saturated zone, all pore spaces and fractures are completely filled with water. The water table is the top of the saturated zone. The slope or gradient of the water table influences the direction of flow of shallow groundwater; just as surface water flows downhill, groundwater flows down-gradient.

The water table is the elevation that water rises to in a shallow well. However, in deep wells—including many water-supply wells in Bayfield County—the water level in the well may not reflect the elevation of the water table. Water levels in deep wells represent the hydraulic head at the bottom of the well casing. The distribution of this pressure at depth is the *potentiometric surface* and represents the level to which water rises in deep wells. The potentiometric surface may be higher or lower than the water table. An *artesian well* is one in which the potentiometric surface is higher than the land surface; if such wells are uncapped, water flows naturally from the well under artesian pressure. Artesian wells located in lowland areas near Chequamegon Bay, such as the Sprague well at Thompson's West End Park in the city of Washburn (fig. 1), tap groundwater at pressures that exceed the elevation of the land surface. Such flowing wells are evidence that the deep potentiometric surface is higher than the land surface in these areas, creating upward hydraulic gradients and artesian conditions within the groundwater system. In contrast, deep wells in upland areas of Bayfield County with water levels lower than the local water table indicate areas of downward hydraulic gradients.

Figure 3. Generalized bedrock geologic map of Bayfield County (modified from Cannon and others, 1999; Nicholson and others, 2006).



Both the water table and potentiometric surface fluctuate seasonally and are typically highest during rainy periods and in the spring following snowmelt. In general, seasonal changes in the water table tend to be greatest at higher elevations in the landscape. The water table is less responsive to seasonal changes near large bodies of water, such as along the shore of Lake Superior. In some wells, particularly deeper wells, there can be a delay of weeks to months between recharge events and responses in the water table or potentiometric surface.

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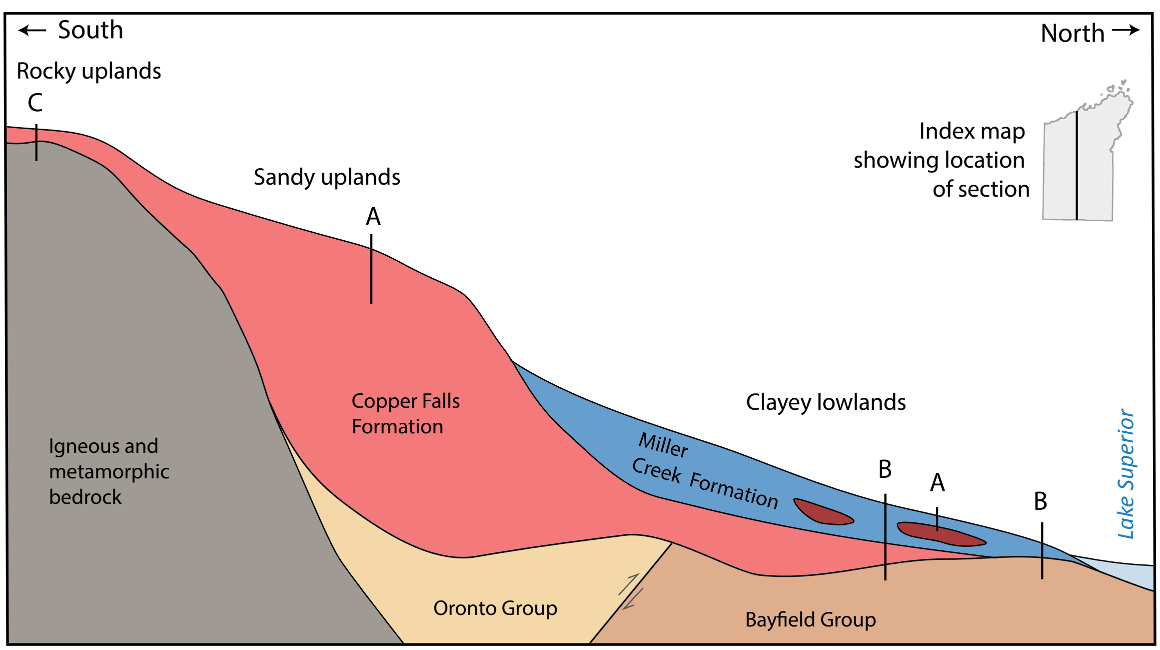
Figure 4. Generalized north-south cross section of Bayfield County, showing wells drawing water from the sand and gravel aquifer (A), the sandstone aquifer (B), and the crystalline aquifer (C). The Douglas fault is also shown at the contact between the Oronto and Bayfield Groups. Arrows indicate relative sense of movement.



Methods

This atlas was developed primarily from existing data sources, including water-well and other subsurface data, published geologic maps, outcrop descriptions, and previous reports and studies. Limited field data was collected to field-check locations and obtain passive seismic measurements (described below).

Approach

A water-well database was constructed for the county that includes information on well construction and aquifer composition. This database was used to (1) understand which aquifers are used as primary water supplies and (2) evaluate the natural protection of water quality at documented wells. The water-table map was developed to understand the direction of groundwater flow at a regional scale. The depth to the water table (or the thickness of the unsaturated zone), depth to the bedrock (or the thickness of the unconsolidated material), and the distribution of the groundwater recharge are all important factors that influence the susceptibility of groundwater to contamination. Maps of each of these factors were developed and integrated together to evaluate the susceptibility, or relative vulnerability, to groundwater contamination in different parts of the county.

Water-well database

The construction and hydrogeologic setting of a water well are important factors to consider when assessing a well's susceptibility to contamination and designing a well-monitoring or well-protection program. The purpose of the water-well database is to make such information accessible and easily interpretable for county and town officials. The water-well database for Bayfield County includes 3,360 well records from the Wisconsin Department of Natural Resources (WDNR) that were compiled as part of a separate project (S.W. Mauel, E. Pederson, and P.R. Schoephoester, WGNHS, unpublished data, 2010; also see Fehling and Gotkowitz, 2017, for more information).

For this project, additional fields based on well construction reports were added to the database to facilitate interpretation of the hydrogeologic setting and the degree of natural groundwater-quality protection at each well. Wells were categorized by the type of material recorded at the well opening (sand and gravel, sandstone, or other type of bedrock). Wells also were categorized by the presence of fine-grained sediment above the screened interval or open hole. Sediments were classified as fine grained if the well construction report described sediment as either clay, clay and gravel, mud or muck, or silt. Each well was classified by the number of fine-grained layers identified in the well construction report and by the total thickness of these layers.

Map development

Water table

Water-table elevations in Bayfield County were simulated by using an existing digital groundwater-flow model (Fehling and others, 2018) that was developed with GFLOW (Haitjema, 1995), a two-dimensional analytic-element computer code that solves for groundwater elevation. The method accounts for groundwater-recharge rates, aquifer properties, and the surface elevation of streams and lakes. The model was calibrated to achieve a good match between the simulated water table and data from the region. These data include measurements of streamflow and water levels in shallow wells.

Because the existing model (Fehling and others, 2018) focused on national forest lands in Bayfield County, details were added to the existing model to extend the water-table map to the entire county. The simulated water-table contours were then exported from the model for further editing. The simulated elevation of the water table was refined by comparing it to elevations of the land surface, streams, and lakes.

Water levels in shallow wells also were used to help interpret the water-table elevation. These wells, however, reflect the elevation of the water table with varying degrees of accuracy. Water levels in shallow wells are more likely to indicate the water table elevation than water levels in deeper wells, which may reflect upward or downward hydraulic gradients. Although the water levels in the deeper wells may not match the water-table elevations shown on the map, measurements from those wells were used to gain a better overall understanding of the aquifer system.

Depth to water table

The depth-to-water-table map was developed by subtracting the interpreted water-table elevation from the land-surface elevation (derived from 5-ft-resolution lidar data). The depth-to-water-table surface was smoothed to correct small-scale details imprinted from the lidar data.

Depth to bedrock

The depth-to-bedrock map is based on multiple sources of information, including (1) existing well construction reports, (2) geologic logs, (3) observed and previously mapped bedrock-outcrop locations (Cannon and others, 1999; Nicholson and others, 2006), and (4) geophysically determined estimates calculated by using the horizontal-to-vertical spectral ratio (HVSR) passive seismic method (Chandler and Lively, 2016). Table 1 summarizes each of the datasets. For more information on the HVSR passive seismic data collection and accuracy, see appendix 1.

Bedrock-elevation contours were constructed manually, resulting in a structure-contour map showing the elevation of the bedrock surface. The bedrock-elevation contours were converted into a continuous surface (raster) file for use by a geographic information system (GIS). Next, we subtracted the bedrock-surface elevation from the land-surface elevation (derived from 5-ft-resolution lidar data) to calculate the depth to bedrock. Finally, the raw results from this subtraction were smoothed by reassigning to every 10-meter (m) × 10-m cell the average estimated depth to bedrock within a 150-m radius of the cell. This smoothing evened out the extra detail imprinted from the high-resolution lidar data. The smoothing resulted in minimal changes to the original interpretation of the bedrock elevation and ensured that bedrock-elevation contours are legible at the selected 1:100,000 scale.

Groundwater recharge

Groundwater-recharge rates were estimated by using the Soil-Water-Balance (SWB) computer model (Westenbroek and others, 2010), which integrates the relations of multiple influences on recharge in an iterative, daily simulation. This method was developed by the U.S. Geological Survey (USGS) and WGNHS (Dripps and Bradbury, 2007; Westenbroek and others, 2010) and has been used in other locations in

Table 1. Data used to construct the depth-to-bedrock map

Data type	Description	Source
Well construction reports	Countywide well database. Includes 539 wells completed in bedrock and 2,821 that were completed above bedrock.	S.W. Mauel, E. Pederson, and P.R. Schoephoester, WGNHS, unpublished data (2010), amended for this project; and Fehling and Gotkowitz (2017).
	Additional well data; wells that reached bedrock in the Red Cliff Reservation and in Ashland, Sawyer, and Douglas Counties. Records archived at WGNHS. Wells geolocated to the parcel using plat books and online property information.	WGNHS unpublished records.
	Wells geolocated by Bayfield County in 2017 and 2018. Locations verified to the parcel level by WGNHS.	Well database provided by Bayfield County GIS office.
Geologic logs	Geologic logs archived at the WGNHS.	WGNHS unpublished records.
Outcrop locations	Outcrops observed while conducting fieldwork.	This project.
	Areas with abundant outcrops previously mapped on USGS bedrock maps.	Cannon and others (1999) and Nicholson and others (2006).
HVSR passive seismic data	115 measurements made during 2017 and 2018.	This project (appendix 2).
	17 measurements collected for an unrelated project.	WGNHS unpublished records.
	16 measurements provided by Minnesota Geological Survey.	Chandler and Lively (2016); data images provided by the authors.

Abbreviations: GIS, Geographic Information System; HVSR, horizontal-to-vertical spectral ratio; USGS, U.S. Geological Survey; WGNHS, Wisconsin Geologic and Natural History Survey

Wisconsin. The model tracks the fate of precipitation on the land surface and within the soil root zone using the following equation (from Westenbroek and others, 2010):

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

Where—

Recharge = drainage below the root zone;

Precipitation = rainfall;

Snowmelt = water derived from snowmelt, calculated by tracking snow accumulation and atmospheric temperature;

Inflow = water routed from an adjacent upslope cell as surface runoff (*outflow*);

Interception = water trapped by vegetation that is transpired or evaporated from plant surfaces;

ET = water evaporated or transpired by plants, estimated using the Thornthwaite-Mather (1957) method; and

Δ soil moisture = the amount of soil moisture held in storage; soil moisture is capped at the maximum amount of water the type of soil can hold.

Inputs to the SWB model consisted of daily climate records for the model's time period as well as map layers representing land elevation (U.S. Geological Survey, 2017), land cover (Wisconsin Department of Natural Resources, 2016), and soil properties (National Resources Conservation Service, 2017).

To run the recharge model, the county was divided into a grid of 30-m × 30-m cells, a resolution ultimately determined by the coarsest model input (land cover). All other input layers were resampled to fit this grid. Digital elevation data from the National Elevation Dataset (U.S. Geological Survey, 2017) was developed into a flow-direction grid, forming the surface over which surface-water runoff was routed. Closed depressions were filled to prevent the unrealistically high recharge estimates that result from pooling in the model; filling closed depressions has been a regular approach that the WGNHS has used in other SWB estimates in Wisconsin.

Daily precipitation and temperature data from the Brule, Wisc., weather station (Global Historical Climatology Network ID: USC00471131) were applied to the entire model area. This station was selected because (1) complete precipitation and temperature records from 2000 and 2010 were available for it, and (2) it was used for a separate SWB assessment for National Forest Service lands included in the study area (Fehling and others, 2018). The recharge model did not account for differences in weather patterns that could have led to higher or lower precipitation throughout the county or for differences in the timing of winter thaws; such detail was beyond the scope of this analysis.

Groundwater susceptibility

Groundwater susceptibility was evaluated using an overlay process that combined and weighted four physical factors known to influence the vulnerability of shallow aquifers to surface contamination. The factors evaluated were (1) the depth to the water table, (2) the depth to bedrock, (3) the groundwater-recharge rate, and (4) the surficial geologic material. The classifications within each factor were ranked 1 through 5 on the basis of whether the conditions provide aquifer protection (ranked as 1, or least susceptible) or allow for easy migration to the water table (ranked as 5, or most susceptible), following the scheme provided in table 2. The rankings were based on other maps in this atlas series and on previous mapping of the regional surficial geologic materials by Clayton (1984).

The rankings of the four factors were added together (for a maximum possible score of 20) to characterize groundwater susceptibility. Areas with the highest overall score are considered most susceptible to groundwater contamination originating at the surface. The resulting numerical values indicate only relative levels of vulnerability. The index totals were divided into four classes using natural breaks (that is, the natural clustering of susceptibility scores; see table 2).

Table 2 . Factors ranked for groundwater susceptibility model

Susceptibility factor	Attribute	Rank
Depth to water table (ft)	0–25	5
	25–50	4
	50–75	3
	75–100	2
	>100	1
Depth to bedrock (ft)	0–20	5
	20–40	4
	40–60	3
	60–80	2
	80–100	1
	>100	0
Annual groundwater recharge rate (in/year)	>15	5
	12–15	4
	9–12	3
	6–9	2
	3–6	1
	<3	1
Surficial material (units mapped by Clayton, 1984)	Post-glacial stream sediments; Miller Creek Fm. shoreline sediments; Copper Falls Fm. stream sediments	5
	Copper Falls Fm. till	4
	Shallow bedrock	3
	Miller Creek Fm. till units commonly eroded to expose Copper Falls Fm. (wave-planed topography and valley sides)	2
	Peat; Miller Creek Fm. offshore sediments; Miller Creek Fm. till (lake-modified and unmodified glacial topography)	1

Overall susceptibility	**Total score**
High	≥12
Moderate–High	9–<12
Moderate–Low	5–<9
Low	<5

Abbreviations: Fm., Formation; ft, feet; in, inches

Results and discussion

Well construction and local stratigraphy

Well construction may affect well-water quality in several ways. Important considerations include the depth of the well casing below the ground surface, the total depth of the well, and the geologic materials present above the well casing. The well casing is the lining that supports an open vertical hole between the land surface and the tapped aquifer (fig. 5). Casings usually consist of steel or plastic pipes that extend from a foot or so above the ground surface to a depth determined by state well construction codes and by the well driller. Water enters the well between the bottom of the casing and the bottom of the well (fig. 5). This interval below the casing is commonly screened where wells are completed in unconsolidated sand and gravel.

Figure 5 shows the relative levels of natural protection for wells constructed in generalized settings typical for Bayfield County. When present above the well opening, fine-grained material such as clay may act locally as an impediment to downward groundwater flow. This fine-grained material, or cap, may help protect a well from surface contamination. Wells completed in shallow, fractured bedrock and wells with thin or coarse-grained overlying material (such as sand and gravel) typically have more direct routes for groundwater to infiltrate from the surface. As described by Gotkowitz and Li (2016), wells that are drilled and cased through clay-rich deposits (such as the Miller Creek Formation) and are screened in deep sand lenses or bedrock generally pump groundwater that recharged tens to hundreds of years ago. These wells are less susceptible to anthropogenic contamination.

Of the 3,360 wells in the county database, 3,044 wells had sufficient geologic information to be cataloged in more detail. Categorizations of aquifer type, well depth, and fine-grained caps for the cataloged wells in Bayfield County are summarized in table 3 and the distribution of the different categories are shown in figure 6 through figure 8.

Most wells in Bayfield County are completed in sand and gravel where the sandy Copper Falls Formation is present. These wells are mainly relatively shallow with a thin cap of fine-grained sediments, suggesting higher vulnerability (fig. 7, fig. 8). Wells with little natural protection are also located along the Lake Superior shoreline where bedrock is near the land surface and the water table is shallow. Many of these wells are completed in fractured sandstone; the fractures provide a pathway for contamination to migrate with groundwater flow with little to no natural attenuation. For example, private water wells in the Town of Barksdale (fig. 1), where the depth to bedrock is less than 20 ft, have been affected by waste disposal practices at a former contaminated site.

In other areas of Bayfield County, sandstone wells are generally deeper and have more overlying fine-grained sediment than sand-and-gravel wells. Sandstone wells are often located in areas where the fine-grained Miller Creek Formation is present near the surface. In these areas, wells are typically drilled deeper to reach geologic materials with sufficient well yield. Wells protected by a fine-grained cap are most commonly located in lowland areas where the clay-rich Miller Creek Formation is present at the land surface. An analysis of the well construction reports, however, indicates that fine-grained deposits seem to vary significantly in depth and thickness at wells located relatively close together.

Water table

The water-table map (plate 1) shows the average elevation of the water table in Bayfield County and may be used to identify the directions of shallow groundwater flow. The map shows areas of the land surface that contribute groundwater to specific wells, streams, or lakes.

The water-table-elevation contour lines on the map represent the elevation of the water table (in feet above mean sea level). In a manner similar to contours on a topographic map, the water table is, for instance, at an elevation of 800 ft everywhere along the 800-ft contour line. The water-table elevation ranges from less than 625 ft along the Lake Superior shoreline to more than 1,400 ft in southeastern Bayfield County. Contours shown as dashed lines indicate a higher uncertainty due to a lack of data points in these areas. In particular, there are almost no data points in the central sandy uplands where the water table is very deep. The configuration of the water table (that is, its shape and the resulting groundwater flow directions) reflects the regional hydrogeologic setting and topography. The arrows on the map indicate that groundwater flows from higher to lower water-table elevations, generally perpendicular to the water-table-elevation contours.

Groundwater also flows away from groundwater divides (shown on plate 1 by thick, gray lines). A groundwater divide is analogous to a ridgetop on a topographic map: just as the land surface slopes away on either side of a ridgetop, the water table slopes away from a groundwater divide. Groundwater flows away from a

Figure 5. Typical well construction in Bayfield County and relative susceptibility of well-water quality in generalized geologic settings.

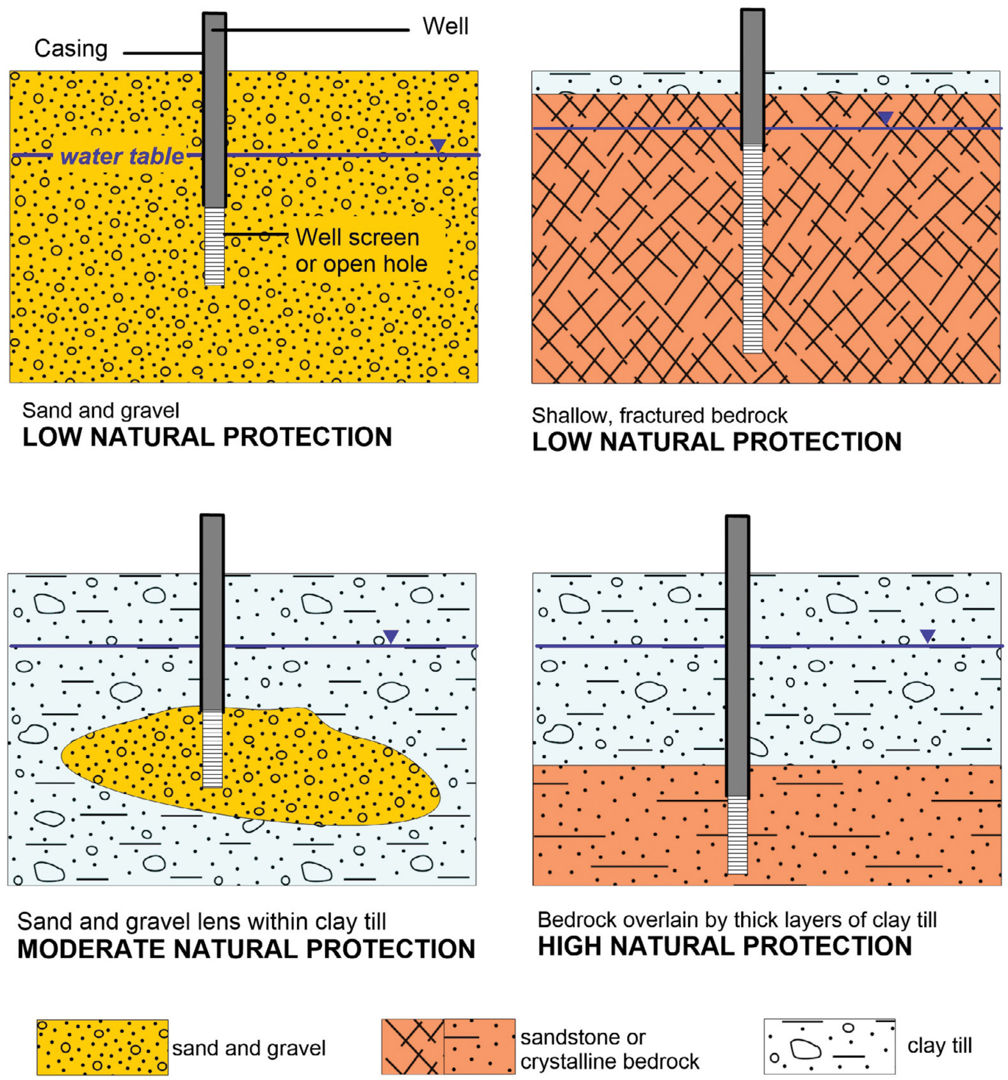


Table 3. Well characteristics in Bayfield County

Completion material	Number of wells	Average depth of well (ft)	Minimum depth (ft)	Maximum depth (ft)	Average thickness of fine-grained cap (ft)
Sand and gravel	2458	100	21	494	10
Sandstone (bedrock)	481	219	59	800	42
Bedrock other than sandstone	105	177	32	420	19

Figure 6. Locations of wells in Bayfield County, categorized by the type of geologic material recorded at the well screen or open interval.

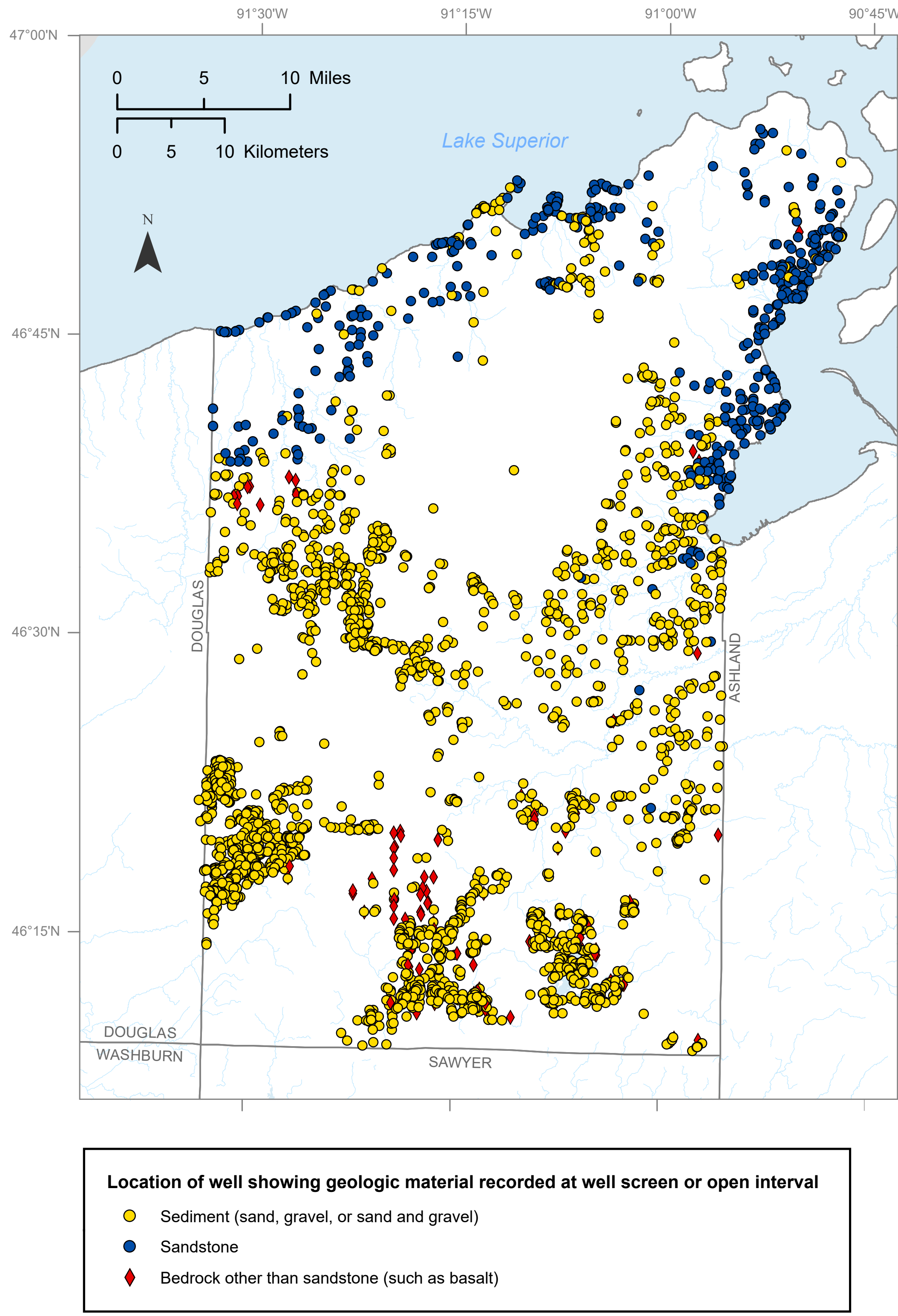


Figure 7. Locations of wells in Bayfield County, categorized by the depth to the bottom of the well.

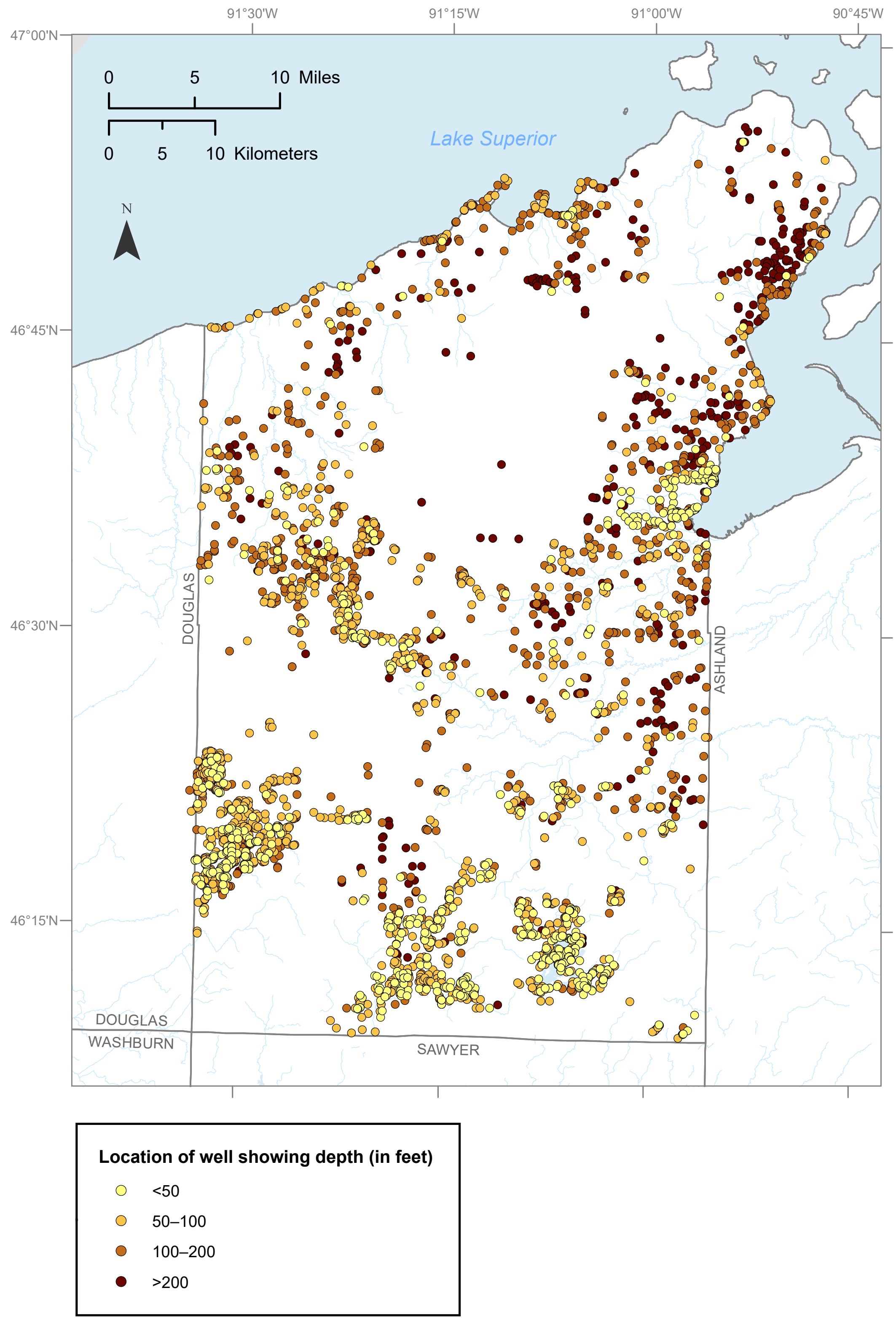
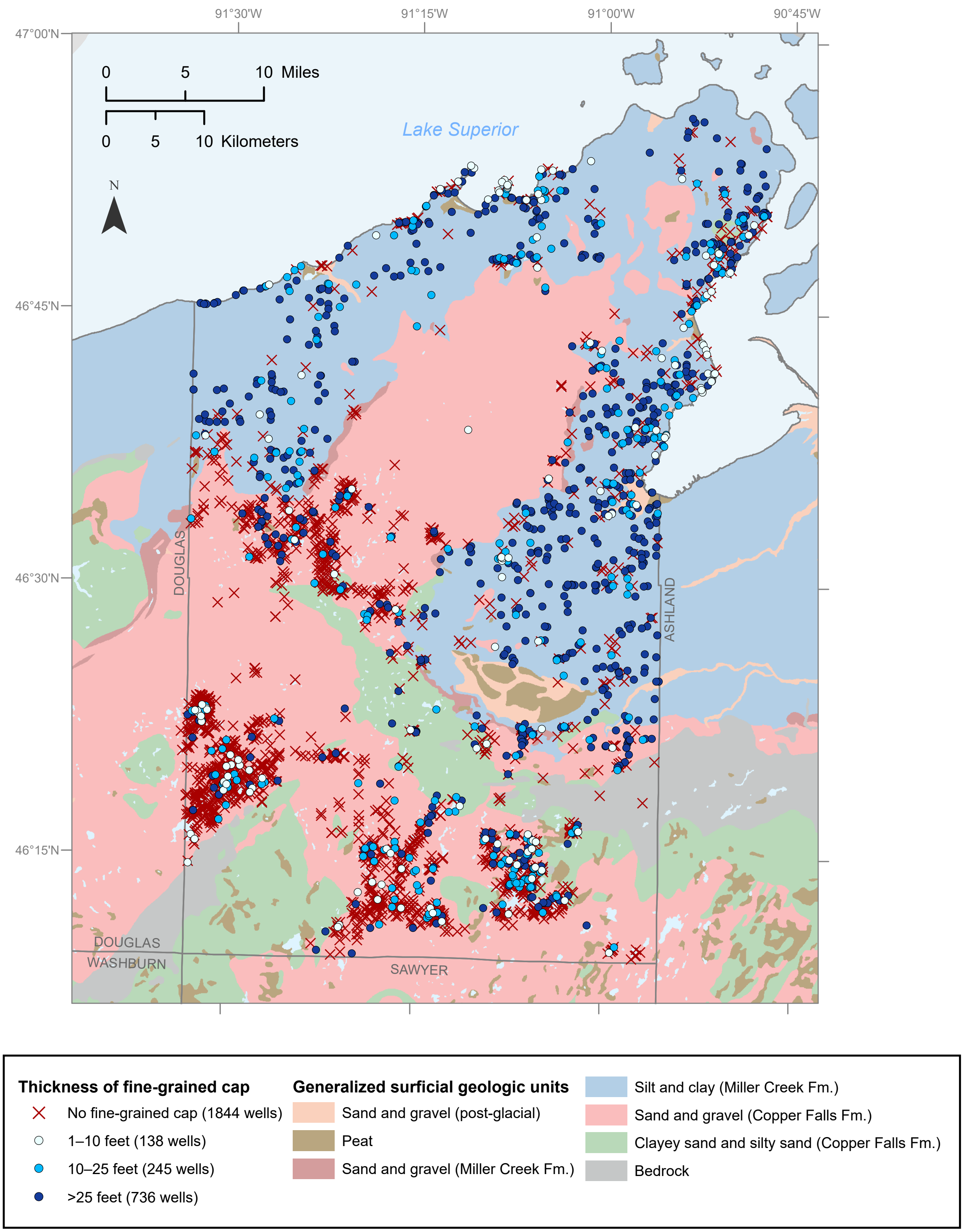


Figure 8. Locations of wells in Bayfield County, showing the degree of natural protection by overlying fine-grained sediment, as indicated by the thickness of the fine-grained cap.



divide and ultimately discharges to wells, streams, and lakes. The location of regional groundwater divides often approximately corresponds to the location of surface-water divides. For example, a major surface-water divide in southern Bayfield County marks the boundary separating water flowing northward to the Lake Superior Basin from water flowing southward to the Mississippi River Basin. Similarly, a regional groundwater divide runs roughly northwest to southeast across the southern third of the county. A smaller divide splits northern Bayfield County along the Bayfield Peninsula: groundwater to the northwest of the divide flows to towards Lake Superior; groundwater to the southeast of the divide flows generally towards Chequamegon Bay.

Although not illustrated by a water-table map, groundwater also flows vertically through the flow system. In particular, the area's clay-rich deposits create conditions that result in downward flow in upland areas and upward flow where groundwater discharges into streams and springs.

Depth to water table

Plate 2 shows the depth from the land surface to the regional water table (in feet). The depth to the water table ranges from 0 ft to more than 150 ft in Bayfield County and is greatest in the middle of the county. The map shows that that some surface-water features are located above the mapped water table, suggesting that these lakes or streams are underlain by layers of clay or other low-permeability material (aquitards). An example of a place where surface-water features are above the water table is shown in figure 9. At the map location, records of neighboring wells indicate that the regional water table is about 200 ft below Siskiwit Lake in the Town of Bell.

Depth to bedrock

Plate 3 shows the approximate depth from the land surface to the top of the bedrock surface (or the thickness of the unconsolidated aquifer materials that overlie bedrock) in Bayfield County. Overall, sediments are thickest in the middle of the county and shallowest in the southern highlands and close to the Lake Superior shore. The depth to bedrock in the county is highly variable, ranging from 0 ft (where bedrock crops out) to over 400 ft. The depth to bedrock recorded on a geologic log from west-central Bayfield County indicates about 980 ft of sediment overlying bedrock.

The extreme range of depths to bedrock in Bayfield County is unique in Wisconsin (Trotta and Cotter, 1973). These extremes are a result of a long and complicated geologic history, affected by forces as varied as continental rifting, movement and folding along tectonic faults, glaciation, and more recent erosion from surface water.

The location and density of control data shown on the map help communicate relative levels of confidence in the interpretation of bedrock depths. The areas of greatest certainty are located where there is a higher density of wells, geologic logs, or outcrop locations, which provide accurate depth to bedrock information. Wells that do not reach bedrock indicate a minimum depth to bedrock, but they do not constrain the depth to a value or a range. The passive seismic measurements are estimates of bedrock depth and are most reliable in shallow bedrock environments where bedrock depth is within 100 ft (see appendices 1 and 2).

The areas of the map with the greatest uncertainty are located within the sandy uplands, where bedrock is deeply buried by hundreds of feet of sand and there are few wells that reach bedrock. The depth to bedrock in this region is beyond the range of observed measurements. There is more certainty in the depth-to-bedrock interpretation in shallow bedrock areas, which is portrayed on the map by using a variable contour interval. Bedrock depths of less than 100 ft are mapped using a 20-ft contour interval, depths of 100 to 200 ft are shown with a 50-ft interval, and depths of more than 200 ft are shown using a 100-ft interval.

Groundwater recharge

Plate 4 shows the distribution of the estimated annual groundwater-recharge in Bayfield County for an average year. The values represent the mean annual groundwater recharge between 2000 and 2010, a timespan where annual precipitation ranged from 21.6 inches (in) to 48.2 in (fig. 10).

The distribution of groundwater recharge in Bayfield County is primarily controlled by the type of shallow geologic material that is present, which in turn determines the type of soil that develops over it. Areas capped by the sandy material of the Copper Falls Formation (fig. 2) are considered the primary areas in the county for higher groundwater recharge (Fitzpatrick and others, 2014). Here, the mean annual recharge is about 15 to 20 inches per year (in/yr). Recharge rates are lower in the clayey lowlands, averaging only 3 to 6 in/yr. This low rate is attributed to run-off of precipitation that falls on low-permeability, clayey soil of the Miller Creek Formation. Infiltration to the water table is limited by the low permeability and surface-water runoff contributes to headwater streams instead of groundwater.

Figure 11 shows annual mean groundwater-recharge rates in 2006 and 2002, the model years with the lowest and highest estimated mean recharge rates, respectively, as

Figure 9. Depth to water table near Siskiwit Lake.

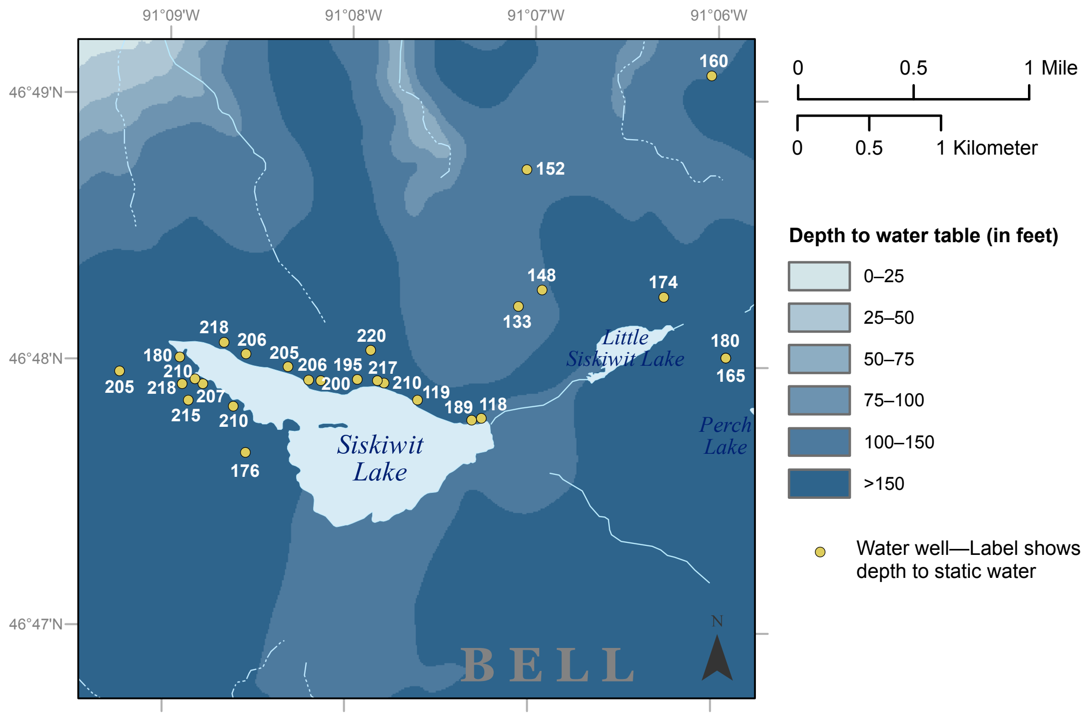


Figure 10. Annual precipitation and the mean annual groundwater-recharge rate from 2000 to 2010.

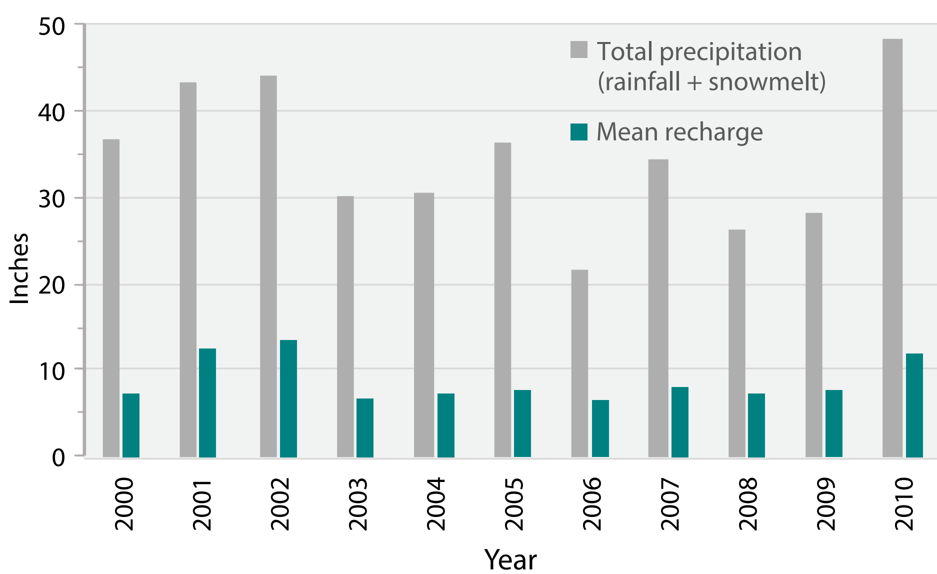
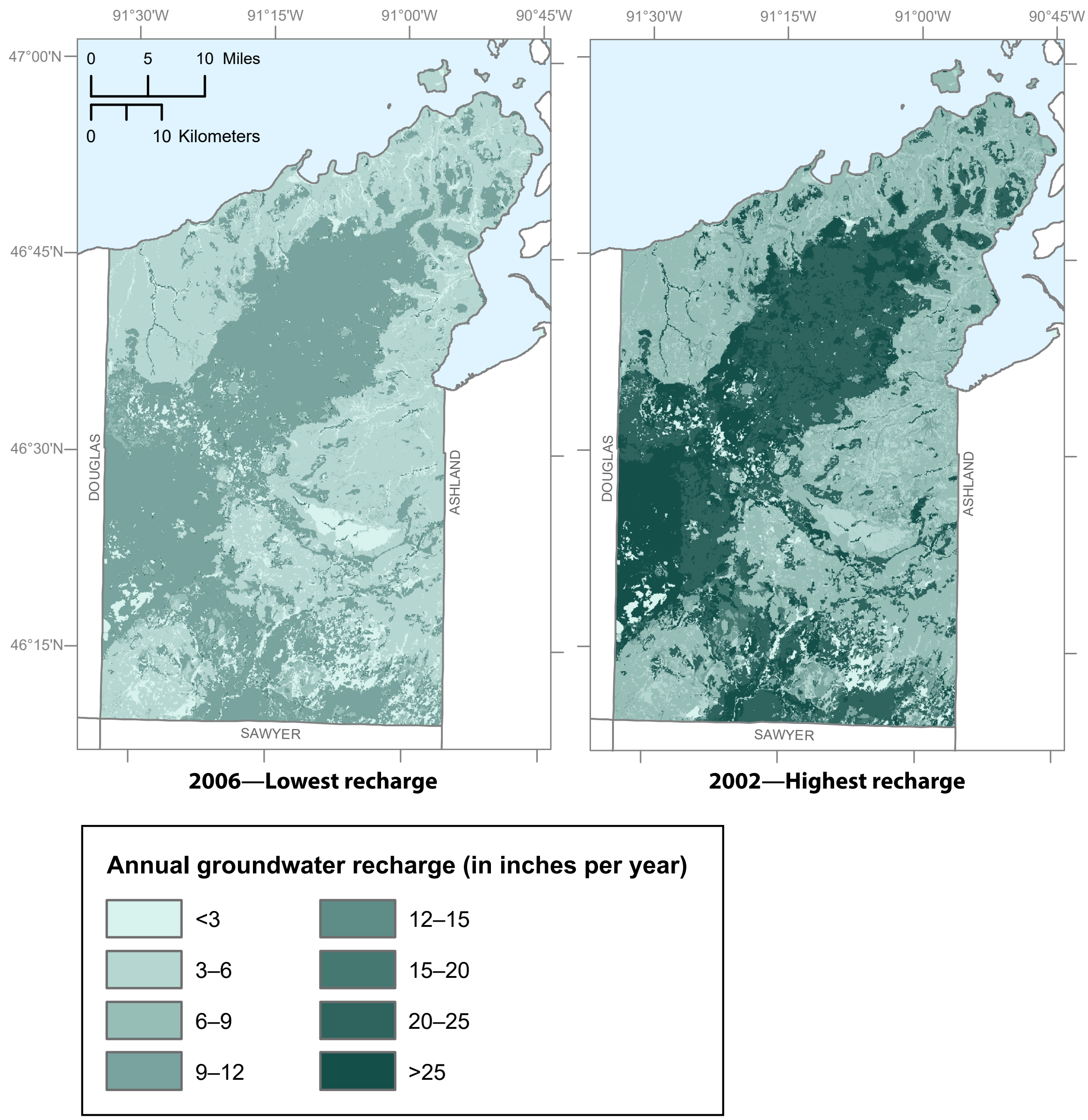


Figure 11. Estimates of mean annual groundwater-recharge rates for 2006 and 2002, the model years with the lowest and highest mean recharge rates during the model period, respectively.



shown in figure 10. Although the model results from those years indicate different rates of absolute groundwater recharge, the distribution of recharge rates across the county is similar. Simulated recharge rates in the sandy uplands are responsive to variations in precipitation, ranging from 9 to 26 in/yr over the decade-long model run. Recharge rates in the clayey lowlands vary by less than 3 in/yr over the simulation.

The SWB model does not account for the groundwater or surface-water systems. As a result, estimates of recharge rates in wetlands, lakes, and other surface waters are difficult to calculate and may be inaccurate. The model does not estimate recharge rates within mapped surface-water bodies.

Groundwater susceptibility

The groundwater-susceptibility map (plate 5) shows an estimate of the degree and distribution of areas more and less susceptible to groundwater contamination in Bayfield County. The susceptibility map does not account for or indicate the locations of existing or future contamination. Rather, the sensitivity of an aquifer to contamination is based on the ease with which contaminants at the land surface can reach the water table. This analysis is sometimes referred to as "intrinsic susceptibility" (Focazio and others, 2002) because it is an assessment of the intrinsic properties of the subsurface. Physical characteristics that increase susceptibility include (1) high groundwater-recharge rates, (2) high permeability of geologic materials, (3) shallow depths to bedrock, and (4) a thin unsaturated zone. Areas that combine these conditions are considered most susceptible to contamination and are shaded dark brown on the map.

Why do these physical characteristics matter?

Each of the four assessed physical characteristics influence the susceptibility of groundwater differently and are discussed below. Understanding how these different conditions affect the protection and vulnerability of aquifers is critical to interpreting the map.

The distribution of groundwater recharge is an important factor for groundwater susceptibility because recharge ultimately determines the ability of water-transported contaminants to reach the water table. The groundwater system is more susceptible to contamination where groundwater-recharge rates are highest (table 2).

The hydrologic properties of glacial or other shallow materials influence how quickly water and contaminants move downward into the subsurface. Fitzpatrick and others (2014) estimated the hydraulic conductivities of different materials in Bayfield County and determined that water moves downward through sand and gravel of the Copper Falls Formation at a rate that is nearly 10 times higher than through clay of the Miller Creek Formation. For this reason, areas characterized by Copper Falls sediments or other well-sorted sands near the surface are more susceptible than areas characterized by Miller Creek clays.

A shallow depth to bedrock increases the susceptibility of groundwater to contaminants. In areas where unconsolidated materials are thin, precipitation and snowmelt may rapidly infiltrate bedrock formations; groundwater may then move especially quickly through bedrock with extensive fracture networks, such as those observed in figure 12. Thicker layers of sediment may slow the downward transport of contaminants and increase the opportunity for the contaminants to either break down into less harmful components or be filtered out of the water.

The depth to the water table is equivalent to the thickness of the unsaturated zone. This thickness affects the natural protection of aquifers and the susceptibility of groundwater to contaminants originating at the surface. Depending on the composition and hydrologic properties of the materials, the thicker the unsaturated zone, the more time it takes for water and potential contaminants to migrate to the water table. During this time, microbiological and chemical reactions within the unsaturated zone may reduce concentrations of some contaminants. Areas with shallow water tables, or thinner unsaturated zones, are more susceptible to contamination.

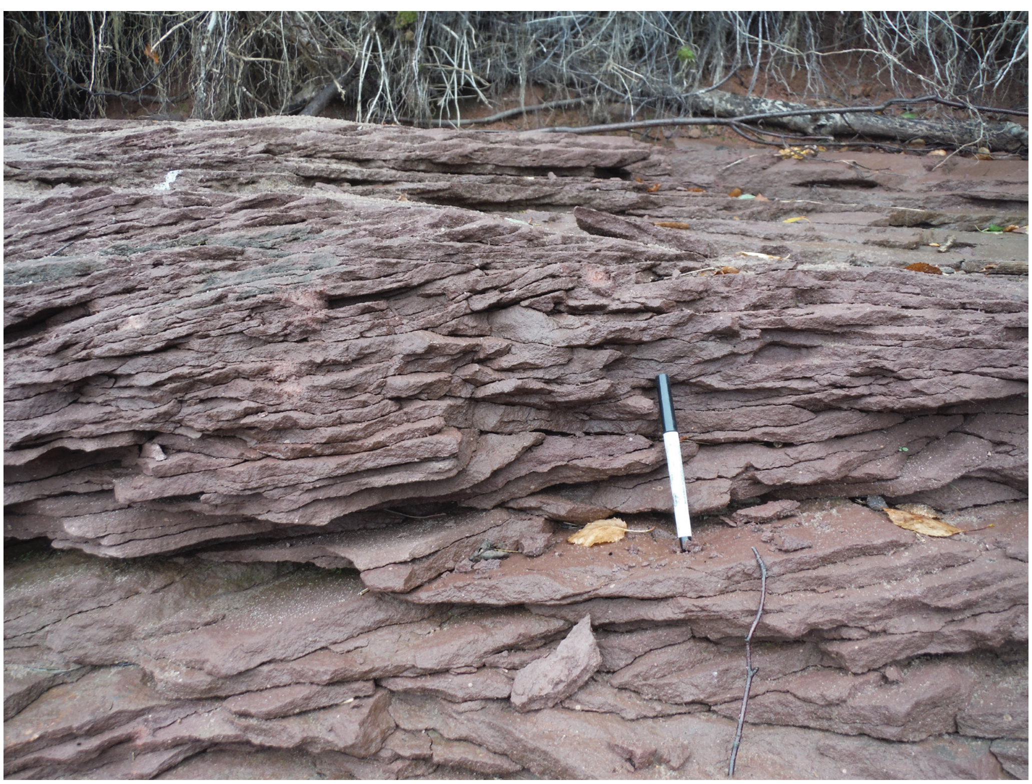
Groundwater susceptibility in Bayfield County

The areas in the county most susceptible to groundwater contamination are characterized by sand and gravel of varying thickness at the surface. In the sandy uplands, high susceptibility mapped around the towns of Iron River and Barnes is due to the combination of sandy material and a shallow water table. These towns are worth noting because the majority of water wells there lack fine-grained caps and are screened in sand and gravel at depths less than 100 ft (fig. 7, fig. 8).

In the southwestern and southeastern forested sections of Bayfield County, shallow crystalline bedrock is present near the land surface and commonly crops out (see plate 3). Groundwater in such conditions is highly vulnerable to contamination where the overlying material is coarse grained or absent, particularly where the crystalline bedrock is fractured and the water table is shallow. Similarly, shallow bedrock conditions close to the Lake Superior shore are also vulnerable to the migration of surface contaminants because the sandstone is characterized by horizontal fractures known to rapidly transport water (Gotkowitz and Li, 2016).

In Bayfield County, the presence of low-permeability clays such as those of the Miller Creek Formation is critical to the natural protection of groundwater within the glacial deposits and in the underlying bedrock aquifers. The presence of clay at the surface ultimately limits the rate of groundwater recharge and may slow the downward migration of contaminants into shallow groundwater. Areas mapped as "least susceptible" in the lowlands are characterized by thick clay layers at or near the surface that promote runoff and slow down the infiltration toward the water table.

Figure 12. Fractured sandstone outcrop at Quarry Beach in Port Wing.



Using this atlas

This hydrogeologic atlas consists of a suite of maps and a water-well database that provide basic information about the groundwater resources of Bayfield County. This information may be of use to community members, industries, and officials involved in water-quality improvement or protection efforts. Because managing and protecting water resources requires a basic understanding of regional groundwater and surface-water systems, the information in this atlas provides a reference point for these tasks.

All groundwater is susceptible to contamination. The susceptibility map (plate 5) highlights areas that are most naturally vulnerable and may be useful for identifying areas where additional monitoring may be warranted or siting locations for future land-use activities. Potential sources of contaminants in Bayfield County include manure storage and application, oil and gas pipelines, industrial facilities, landfills, and road accidents or spills. Where there are concerns about a particular activity at the surface, the water-table map (plate 1) may be used to help identify wells and surface-water features down the gradient of the activity to prioritize remediation.

As emphasized in this report, the maps and analyses presented here are based on countywide and regional data; therefore, they generally should not be used for site-specific decision making. The authors and cartographers have done their best to locate and interpret data that is accurate at a map scale of 1:100,000, which is equivalent to about 1.6 miles per inch on the map plates. However, many users may wish to answer questions or make land-use decisions at the local site scale and desire more detailed information than is available on these maps. For such users, the following approach is recommended:

- To understand the susceptibility ranking for a specific site, query the individual component maps (depth to water table, groundwater-recharge rate, and so on) to understand which factors may contribute the most to the final ranking for the site. A more complete understanding of the hydrogeologic setting may lend confidence to decision making.
- Using the accompanying database, examine individual well construction data for the area in question. Assessing data from several wells (if available) may provide insight into local geology and geologic variability. Consider the relative susceptibility of specific wells based on the conceptual diagrams in figure 5 of this report.
- Prioritize the collection of additional site-specific field data and (or) more detailed analyses, if warranted, based on the relative susceptibility shown on these maps and on the existing data availability.

Recommendations for future work

As with all mapping, interpretations presented here are subject to change and improve as new information is acquired. Two areas of study where additional data collection and mapping may advance the understanding of groundwater systems and groundwater susceptibility in Bayfield County are (1) the glacial deposits of the lowlands and (2) the groundwater divide and water table configuration in the central sandy uplands. Large-scale mapping of the glacial deposits in the lowlands would add important details to the susceptibility analysis in agricultural areas. In cross-section illustrations, Gotkowitz and Li (2016) show that lenses of sand and gravel are common throughout the Miller Creek Formation in the lowlands, but the underground connectivity of these high-conductivity lenses is not fully known. Well data also show a significant variability in thickness and presence of fine-grained material in this region (fig. 8). Smaller-scale and three-dimensional geologic mapping of the Miller Creek deposits may improve the characterization of susceptibility of specific wells in this area. For example, a well drawing water from a laterally expansive sand lens that is connected to a zone of high recharge is more vulnerable to contamination than a neighboring well completed in an isolated pocket of sand and gravel surrounded by clay.

Well installation and monitoring in the central sandy uplands may help constrain the location of the groundwater divide. In this region, the current interpretation of its location and the water table affected by it is largely inferred because there are so few wells reaching groundwater. Understanding groundwater flow directions in the uplands is important for well-head protection because the uplands are a primary groundwater recharge area and contamination there could impact groundwater sources throughout the county.

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Sand barrens

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