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

An inventory of springs in Wisconsin

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Susan K. Swanson
Grace E. Graham
David J. Hart

Wisconsin Geological and Natural History Survey

Kenneth R. Bradbury, *Director and State Geologist*

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Mark A. Borchardt, *USDA–Agricultural Research Station*
Andrew A. Breckenridge, *University of Wisconsin–Superior*
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Susan K. Swanson
BELOIT COLLEGE

Grace E. Graham
WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

David J. Hart
WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

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Kenneth R. Bradbury, Director and State Geologist

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Cover photos

Front: A fracture spring near Fennimore in Grant County, Wisconsin, © Grace Graham
Back: A seepage filtration spring near Waukesha in Waukesha County, Wisconsin, © Susan Swanson

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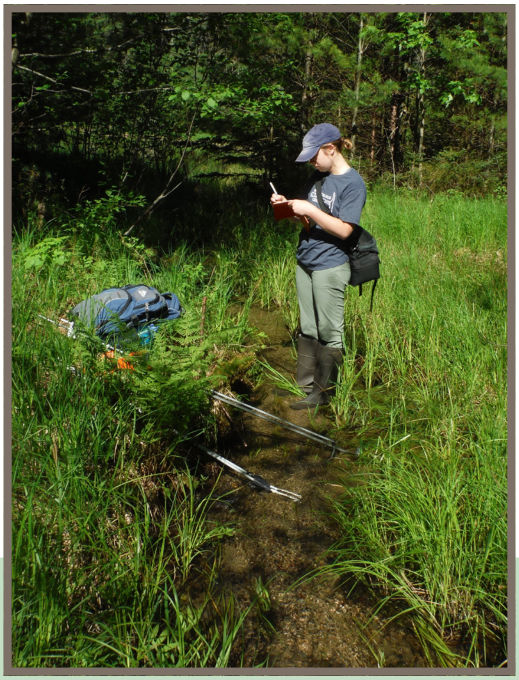

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(Appendices are available at https://wgnhs.org/pubs/000968)

Introduction

A spring is a natural point of highly focused groundwater discharge at the earth's surface. Groundwater flow converges owing to the presence of different zones of permeability in the subsurface and variations in topography. The magnitude and variability of spring flow depends not only on aquifer properties but also on the amount and timing of groundwater recharge to the flow system.

Understanding springs in Wisconsin is important because they contribute water to streams, lakes, and wetlands throughout the state. The pools and channels that form near springs also create habitat for wildlife, including endangered and threatened species. Springs in Wisconsin are not currently used for municipal drinking water supplies, but they supply fish hatcheries and some private residences, and they supplement agricultural activities by providing watering holes for livestock. While some springs that discharge from fractured or karstified rock aquifers have very small recharge areas, such springs are rare in Wisconsin. The quality of water produced by a spring can be representative of groundwater quality in an entire catchment because it is a mixture of water that recharges the aquifer at points near and far from the spring.

This report describes efforts to inventory springs in Wisconsin that discharge at rates of approximately 0.25 cubic feet per second (ft^3/s) or more at the time of the inventory. It provides comprehensive information on spring hydrology for use in determining significance of impacts due to groundwater withdrawals, which can divert groundwater away from springs, and changes in land use or climate, which can alter the amount, timing, and spatial distribution of groundwater recharge.

Objectives

This project had three major objectives.

1. **Locate springs with flow rates of 0.25 ft^3/s (112 gallons per minute (gal/min)) or more.** The flow criterion was informed by the work of the Wisconsin Groundwater Advisory Committee, a group that was established to assess the effectiveness of the main elements of the groundwater withdrawals section of the Wisconsin Statutes (Wis. Stat. § 281.34) (Wisconsin Groundwater Advisory Committee, 2007). The value is also similar to the lower threshold for a fourth-magnitude spring (100 gal/min) according to the Meinzer (1923) classification system
2. **Measure, record, and organize the salient hydrologic attributes of each spring**, including developing a field protocol for the collection of springs-related data and creating a springs database that is available to the public.
3. **Define classes of springs in Wisconsin,** including describing typical topographical, geological, hydrogeological, and geochemical characteristics and summarizing susceptibility to the effects of groundwater withdrawals and changes in land use or climate.

Background

This project marks the first comprehensive assessment of Wisconsin's spring resources in more than 60 years and the first statewide field assessment ever. Some springs were noted on Wisconsin Land Economic Inventory maps that were published between 1927 and 1947, but a much more thorough assessment of spring resources was completed by the Wisconsin Conservation Department from 1956 to 1962. This department conducted spring surveys in roughly 60 percent of the counties in the state. These surveys, accurate to about a quarter-section, included information on location, flow rate, substrate material, fish species present, and land use. They remained the most detailed and widespread information on spring resources until this project. In 2007, the Wisconsin Wildlife Federation (WWF) compiled into an electronic database the locations and attributes of more than 10,000 features from a variety of sources that identified springs, seepage lakes, wetlands, or dry depressions at some time in Wisconsin's past (Macholl, 2007). Sites described during the Wisconsin Conservation Department spring surveys account for more than 80 percent of the features in the WWF compilation, and surface water features described in Wisconsin Department of Natural Resources (WDNR) Surface Water Reports (1961–1985) account for approximately 16 percent. Other sources of information in the WWF compilation include the Wisconsin Land Economic Inventory (1927–1947) and a few more recent research efforts (Fermanich and others, 2006; Grote, 2007; Swanson and others, 2008).

Methods

Site identification

The information compiled by the WWF served as an important resource for locating possible spring sites during this project. Topographic maps, the U.S. Geological Survey Geographic Names Information System, other scientific studies, and the expertise of local land managers, fishery and wildlife biologists, foresters, county extension agents, private property owners, and others were also utilized to identify springs that might be relevant to the investigation. Site selection proceeded on a county-by-county basis. In most counties, a flow rate of 0.23 ft^3/s served as an initial minimum flow criterion for selection of features from the WWF resource. Using a somewhat lower value than 0.25 ft^3/s increased the likelihood of identifying suitably sized springs while also accounting for the high number of features with a recorded flow of 0.22 ft^3/s, which was probably originally a field estimate (100 gal/min) during the Wisconsin Conservation Department spring surveys.

About 34 percent of the features in the WWF compilation have no historical flow measurement, recorded as 0 ft^3/s. To avoid disregarding features that are suitably sized, but simply lack a historical flow measurement, all features with a recorded discharge of 0 ft^3/s were initially selected but later removed from further evaluation if historical notes suggested that the feature was dry, barely flowing, or flowing intermittently (e.g., "dry," "trickle," "seepage"), or that the flow was not highly focused (e.g., "swamp"). For the remaining 0 ft^3/s features, high-resolution aerial imagery helped identify sites worthy of additional investigation. Features were eliminated from further investigation when they appeared to be large lakes (greater than 5 acres), lakes without an outlet, or areas lacking surface water.

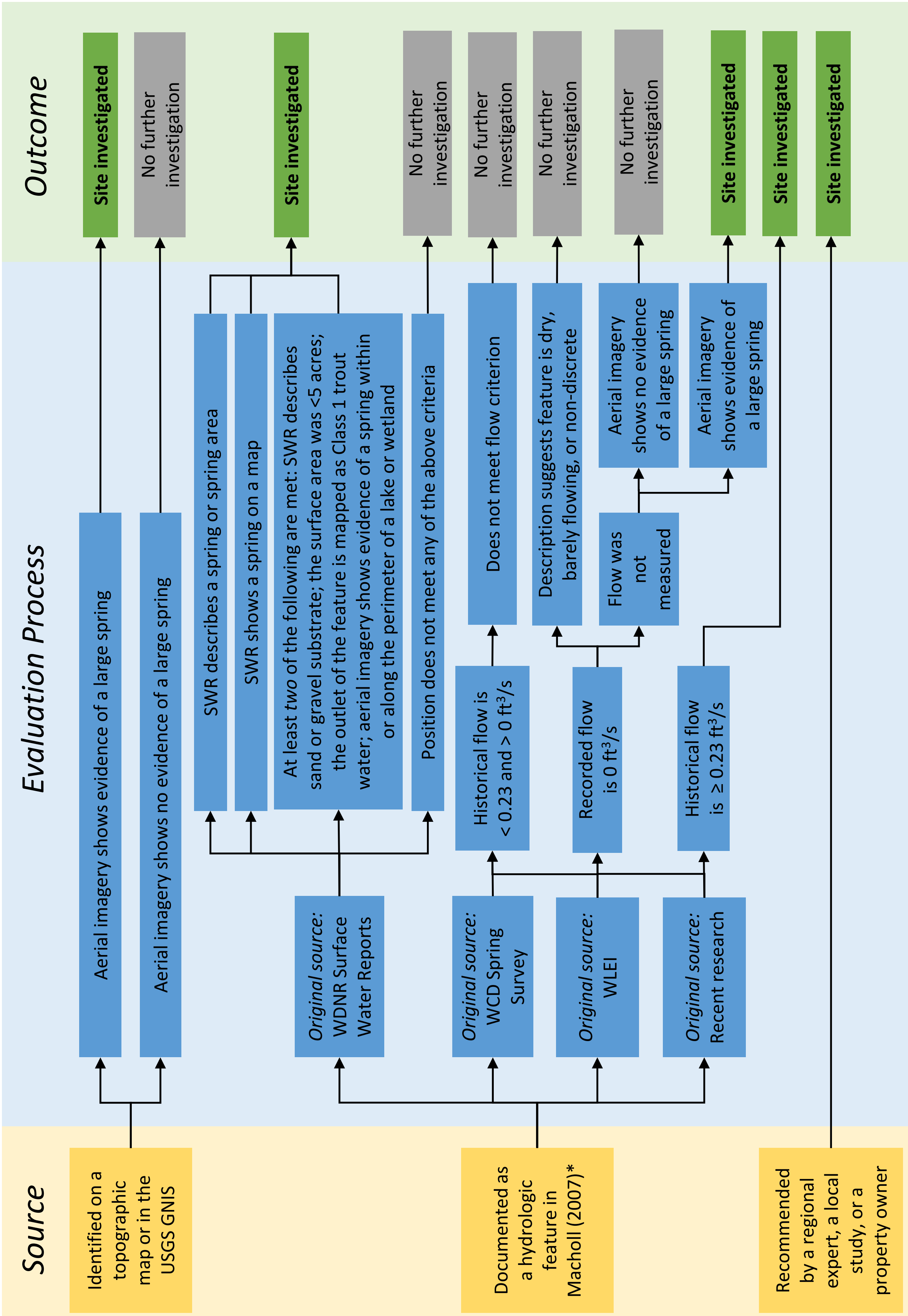
About 40 percent of the features that lack a historical flow measurement in the WWF resource were originally identified in the WDNR Surface Water Reports as seepage lakes, spring ponds, or ponds in headwater settings with much higher outflow than inflow. The majority of these features are located in northern and northeastern Wisconsin. The ponds are groundwater fed, but in most cases there is no indication that these features have highly focused groundwater discharge meeting the criteria of this project. Therefore, to prepare lists of features worthy of investigation in northern counties, project staff reviewed the original WDNR Surface Water Reports for mention of highly focused flow, examined multiple editions of aerial imagery, and checked the proximity of the features to Class 1 trout streams. Class 1 trout streams, commonly found near headwaters, are high-quality waters that support a sustainable population of naturally reproducing trout. Features were retained on the list to investigate if the reports mentioned springs or if a spring was plotted on a map. Alternatively, retained features met two or more of the following criteria:

- the report mentioned sand or gravel substrate suggesting that localized flow may be high or stable enough to displace organic material;
- the surface area of the feature was less than 5 acres;
- the outlet of the feature was mapped as Class 1 trout water; or
- aerial imagery showed evidence of highly focused flow on the perimeter of or within the feature.

Springs identified in other scientific studies, in the U.S. Geological Survey Geographic Names Information System, on 1:24,000 or 1:100,000-scale topographic maps, or through communications with local experts were added to the sites discussed above to generate a list of 1,377 features or sites deemed worthy of investigation. Figure 1 illustrates the process used to generate this list of sites, and their

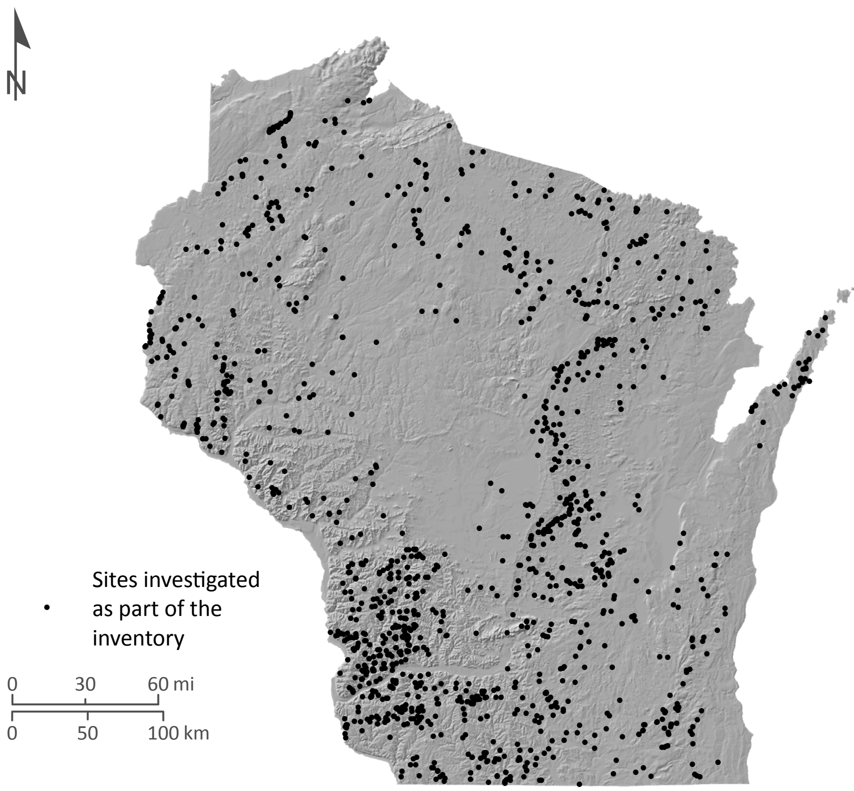
Monica Norton

Figure 1. Process used to determine potential field sites.



Abbreviations: SWR = Surface Water Reports; **USGS GNIS** = U.S. Geological Survey Geographic Names Information System; **WCD** = Wisconsin Conservation Department; **WDNR** = Wisconsin Department of Natural Resources; **WLEI** = Wisconsin Land Economic Inventory maps. Note: *Macholl (2007) includes a variety of different hydrologic features such as springs, lakes, wetlands, and dry depressions.

Figure 2: Distribution of sites investigated as part of this inventory.



statewide distribution is shown in figure 2. Property ownership for these sites was determined by using statewide layers of tax parcel and ownership data or land atlas plat books where digital data were unavailable. Many of the features under investigation were on public land, thus permission to access the features was not required. When phone numbers could be located, we attempted to call landowners of features on private land. If owners could not be reached by phone, we made door-to-door visits and distributed information letters when property owners were not at home. Project staff made contact with 71 percent of landowners (private and public). When an owner confirmed the presence of a large spring, permission to access and conduct a survey was requested. Property owners who could not be reached (29 percent) were a far greater impediment to access than property owners who refused access (2 percent). Of the 780 field visits made, 415 springs met inventory criteria and were surveyed (table 1).

Table 1. Sites investigated and springs surveyed

	Number	Percentage of total (%)
Total sites investigated	**1377**	**100**
Features		
Historically mapped features	1059	77
Newly identified features	318	23
Landowner contact		
Contacted	983	71
Not reached	394	29
Features confirmed by landowner		
Access granted (field visits)	780	57
Access not granted	25	2
Total springs surveyed	**415**	**30**

Field protocol

Field surveys proceeded on a county-by-county basis in August through November 2014, April through November 2015, March through November 2016, and March through August 2017. The field protocol is informed by existing and well-established practices for the characterization and management of spring resources (Sada and Pohlman, 2006; Florida Department of Environmental Protection, 2007; Stevens and others, 2016; U.S. Forest Service, 2012a, 2012b). It results in a comprehensive set of spring characteristics that describe spring coordinate data, access, environmental conditions on the day of the field survey, site disturbance, geology, geomorphology, spring type, flow rate, water quality (pH, specific conductance, temperature), and vegetative cover (appendices 1 and 2). Site photos and sketches (appendices 3 and 4, respectively) complement the spring characteristics. All photos have captions and sketches have labels for physical features (spring orifice, spring pool, channel), positions of water quality and discharge measurements, and locations where photos were taken. Sketches are drawn to scale and indicate cardinal direction.

The technique used to measure spring flow depended on spring channel conditions and flow rate. An 8-inch cutthroat flume was used in narrow and shallow channels composed of unlithified bed materials. The velocity-area method was implemented in wider and deeper channels by using a wading rod and an electromagnetic meter (0–20 feet per second (ft/s) ± 2–4 percent of reading) or an acoustic Doppler velocity meter (0–13 ft/s ±1 percent of reading). At locations where water discharged from a pipe or a rock outcrop, flow was sometimes measured using the timed-volume method and a 5-gallon bucket marked with ¼-gallon increments. Where these methods were not feasible, spring discharge was estimated using the float velocity method. The method used is noted in the database (appendix 2).

Attributes for springs were defined in an ArcGIS feature class within a file geodatabase and configured to be editable on a handheld GPS unit. This set-up allowed for seamless entry of attributes in the field. The mobile-friendly geodatabase displays drop-down menus for single-select attributes, which increased efficiency, reduced the possibility of variations in syntax, and ensured that attributes can be easily queried in the resulting springs database. GPS units recorded an average easting and northing within a 60-second logging interval and parameters that quantify the strength and precision of the satellite signal. The GPS units have 2- to 5-meter horizontal accuracy but have poorer vertical accuracy (greater than 5 meters). Therefore, elevation values for the spring sites were extracted from the highest-resolution digital elevation model available for each county. The model's source and resolution are included in appendix 2. Digital elevation model sources were the National Elevation Dataset and lidar datasets.

Grace Graham

Results and discussion

Spring characteristics

Spring types

The inventory provides detailed descriptions of 415 springs in 58 counties in Wisconsin (fig. 3). Richland and Grant Counties, in southwestern Wisconsin, have the highest number of springs (38 and 37, respectively), but the density of springs is higher in Richland County.

Springs are often described by their emergence setting and broad hydrogeologic properties, or sphere of discharge (Meinzer, 1923; Hynes, 1970; Springer and Stevens, 2009). Nearly all of the springs surveyed (96 percent) are rheocrene springs, springs that naturally discharge to a defined stream channel. Others (3 percent) are hillslope springs, which initially emerge from a steep (greater than 30 degrees) slope and may eventually form channelized flow, and limnocrene springs (1 percent), which discharge to a lake (fig. 4). The field protocol developed for the inventory is best suited for rheocrenes. Springs that discharge to lakes (limnocrenes) are also widespread in Wisconsin, but they are difficult to survey because they may be not visible from the shoreline and they are not easily accessible.

Figure 3: Distribution of springs flowing approximately 0.25 cubic feet per second or more at the time of the inventory.

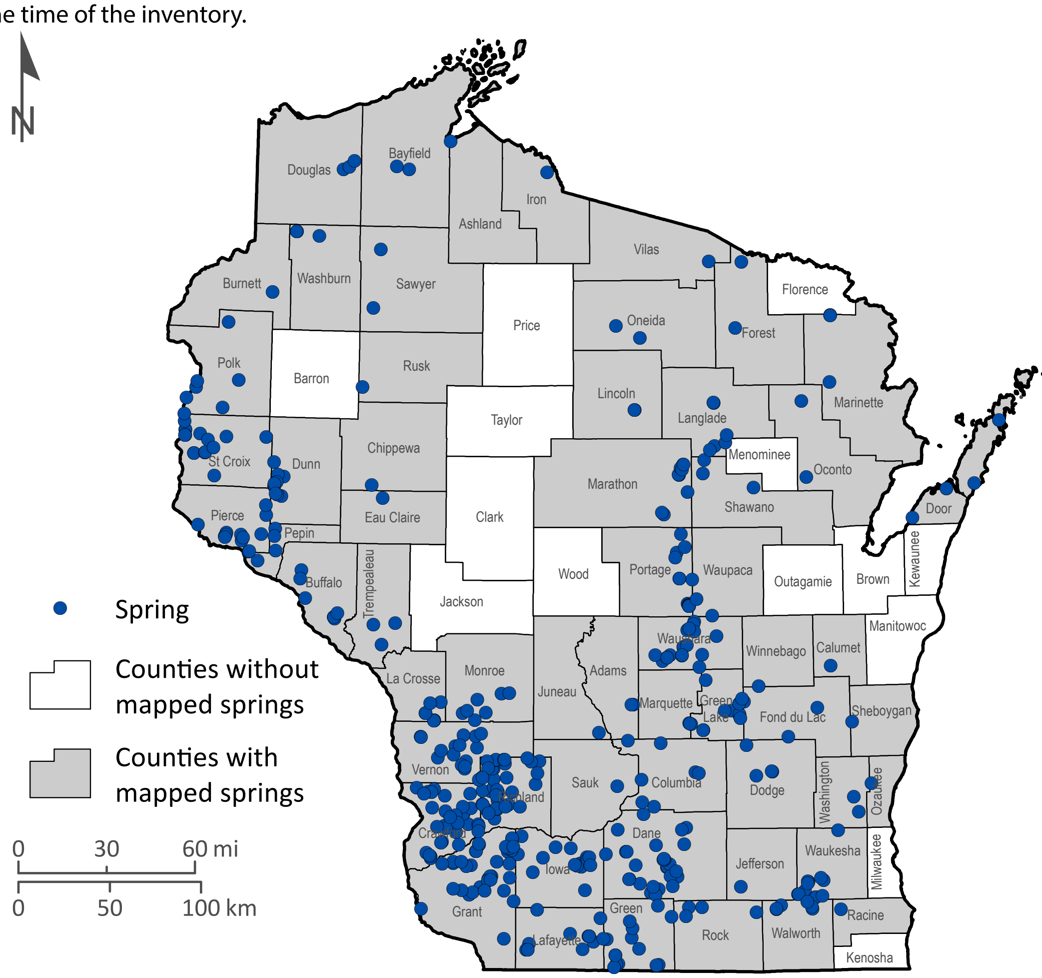


Figure 4. Types of springs.

A. RHEOCRENE SPRINGS discharge to defined stream channels.

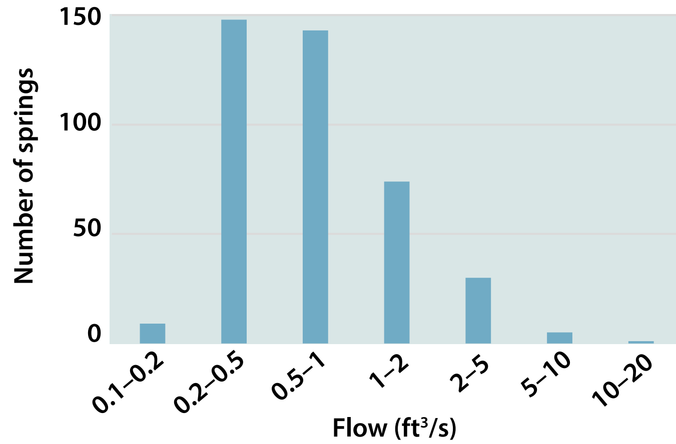
B. HILLSLOPE SPRINGS emerge from slopes of at least 30 degrees.

C. LIMNOCRENE SPRINGS discharge to lakes.

Spring flow and spring flux

The mean flow rate of the 410 springs for which flow could be measured was 0.96 ft^3/s; values ranged from 0.14 ft^3/s to 18.3 ft^3/s (fig. 5). Water depth or soft, organic substrate (or both) prevented measurement of flow for five springs. Some of the springs (37, or 9 percent) have flow rates that are less than 0.25 ft^3/s. These springs were surveyed because spring discharge was close to 0.25 ft^3/s at the time of inventory or because the spring exists in a region where there are very few larger springs. Wisconsin is also home to many other smaller springs and seeps that discharge water below 0.25 ft^3/s; however, these features are not reflected in figure 5.

Figure 5. Distribution of categories of spring flow



Spring magnitude describes the volume of flow from a spring per unit time. Since being proposed by Meinzer (1923), the designation has been applied to the average discharge of a spring or its discharge at a specified date. Table 2 summarizes the distribution of spring magnitudes using the single flow measurements made during the inventory. On the basis of spring channel conditions and interviews with property owners, the vast majority of the springs surveyed are thought to flow perennially. However, some of the springs are known to have highly variable flow, such as the only second-magnitude spring listed (table 2), which discharges from the fractured Silurian dolomite aquifer in Door County, Wisconsin. Flow at this spring varies by an order of magnitude.

Table 2. Spring magnitudes and discharge rates (Meinzer, 1923), and number of springs surveyed.

Spring magnitude	Discharge rate[a]		Number of springs surveyed
	Original units	Converted units (ft^3/s)	
1	≥100 ft^3/s	≥100	0
2	10–100 ft^3/s	10–100	1
3	1–10 ft^3/s	1–10	109
4	100 gal/min–1 ft^3/s	0.22–1	279
5	10–100 gal/min	0.022–0.22	21[b]
6	1–10 gal/min	0.0022–0.022	N/A
7	1 pint/min–1 gal/min	0.00028–0.0022	N/A
8	<1 pint/min	<0.00028	N/A

Abbreviations: ≥ = greater than; < = less than; ft^3/s = cubic feet per second; N/A = not available (range is well below flow criterion for the study)

[a]Meinzer (1923) provided discharge rates using various units. For ease of comparison, they have been converted to cubic feet per second.

[b]Very few springs were surveyed as fifth magnitude because the range is close to the flow criterion for the study.

The shape, or morphology, of the spring orifice and its immediate surroundings can provide important clues as to why water emerges at a particular location and forms a spring. About 26 percent of the springs inventoried emerge as fracture or contact springs, and 74 percent have seepage-filtration morphologies (fig. 6). At a fracture spring, groundwater discharges from joints or fractures in bedrock. Contact springs discharge water at a stratigraphic contact, along which fractures often form. Springs were classified as contact springs only if differing lithologies were observed in the field or if the spring is located in proximity to a mapped stratigraphic contact. Groundwater discharges from many small openings in permeable, unlithified material at a seepage-filtration spring.

Figure 6. Examples of spring morphologies.

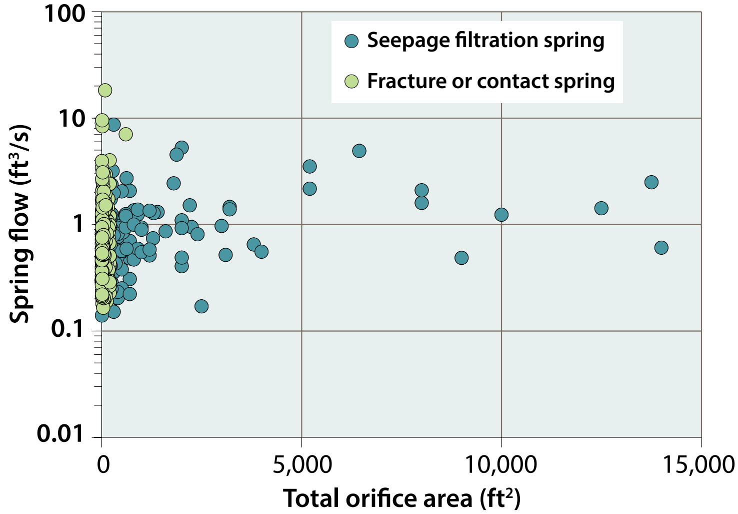
A. FRACTURE SPRINGS discharge groundwater from joints or fractures in bedrock.

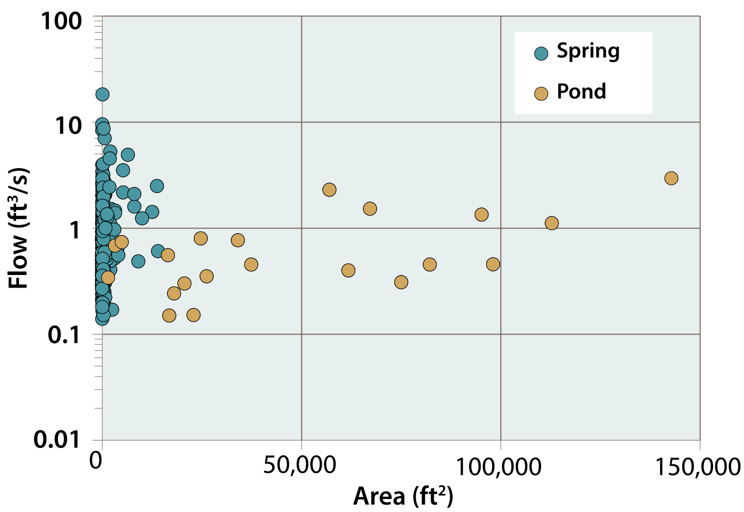
B. SEEPAGE-FILTRATION SPRINGS discharge groundwater from small openings in permeable, unlithified material.

Although the magnitude of spring discharge is commonly used to compare springs, the areal extent of the discharge should also be considered. Measurements made during the inventory show that springs with fracture or contact morphologies tend to discharge water across much smaller areas. In other words, flow is more focused, whereas in seepage-filtration springs flow is somewhat less focused (fig. 7a). For springs with similar discharges, the difference in geometry of the spring orifice results in very different spring-water velocities and physicochemical properties within the aquatic habitat created by the spring. Spring orifice area, or how focused the flow is, is also central to the difference between springs and other surface-water features. Yet, this difference is not always clearcut; even Meinzer (1927) noted that what may be considered a spring by some, may not be by others.

To better describe the nature of spring flow characteristics and distinguish springs from other surface-water features, spring flux (ft/s), defined as spring flow (ft^3/s) divided by spring orifice area (ft^2), was developed for use in this investigation. Orifice area was easily measured from site sketches, which were drawn to scale and include important physical features such as the spring orifice, spring pool, or channel. During the inventory, outflows from 21 spring ponds were also measured. For the purposes of the inventory, a spring pond was defined as a surface-water feature in a headwater setting or one that lacked channelized inflow. They also have a water depth greater than approximately 1 meter, with mostly organic substrate, and without visible discrete flow. The ponds are located at sites that were thought to show potential for springs, but upon arrival were not found to display the highly focused discharge that defines a

Figure 7. a) Spring flow vs. spring orifice area (top) and b) flow vs. area of discharge for springs and ponds (bottom).

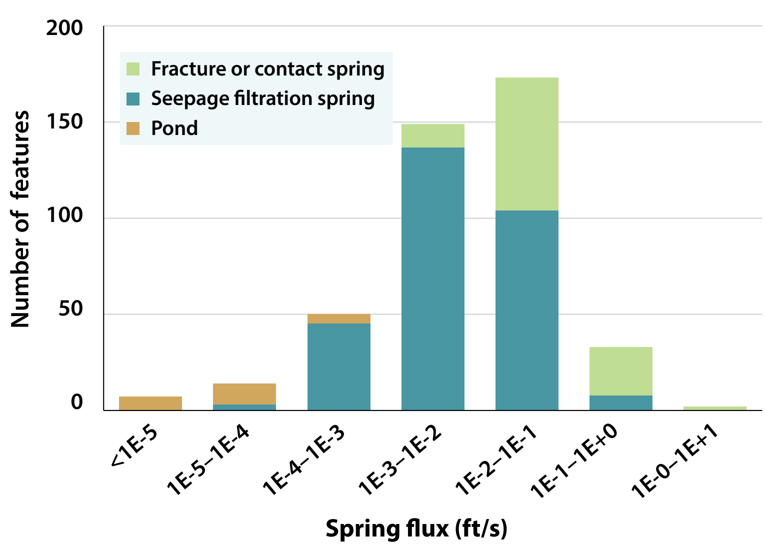




spring. Figure 7b shows that although the emergent area is much greater for most of the ponds, outflow is often less than or similar to that of spring discharge, suggesting less focused, or more diffuse, flow conditions for ponds. In the absence of detailed information on the flow distribution within each pond, the surface area, which probably underestimates the three-dimensional area of the bed of the pond, was used in spring flux calculations as an estimate of the area of water discharge.

Spring flux provides a meaningful way to distinguish between features dominated by highly focused versus diffuse groundwater flow (fig. 8). The median fluxes for the fracture or contact springs, the seepage-filtration springs, and the ponds are 4×10^{-2} ft/s, 6×10^{-3} ft/s, and 1×10^{-5} ft/s, respectively. A flux of approximately 1×10^{-4} ft/s may be an appropriate threshold for distinguishing between features that are dominated by highly focused (i.e., springs) versus diffuse (e.g., spring ponds, wetlands) groundwater flow in Wisconsin (fig. 8).

Figure 8. Distribution of categories of flux for springs and ponds (flux = spring flow ÷ spring orifice area).



Spring conditions

The conditions of the springs were categorized and recorded in the surveys. About two-thirds of the springs (68 percent) are located on privately held land. More than half of the springs display moderate to high levels of disturbance (53 percent) due to factors such as dredging or impoundment, presence of a spring house or other historic structure, proximity to roads or recreational trails, or access by livestock (table 3, fig. 9). Many display more than one type of disturbance. The majority of the highly or moderately disturbed springs (81 percent) are located on private land.

The levels and types of disturbances often illustrate the high value placed on springs and their utility in a variety of ways, today and in the past. However, these practices also compromise spring habitat by modifying channel form and substrate, increasing turbidity, changing the temperature regime of the spring through the introduction of surface flows, or promoting the introduction of non-native or invasive species that out-compete native organisms. Although not directly addressed in the inventory, figure 9c illustrates typical effects of anthropogenic disturbances on spring vegetation communities. Watercress (*Nasturtium officinale*), an introduced and non-native aquatic plant that often survives the winter, grows within the spring pool, and reed canary grass (*Phalaris arundinacea)*, also introduced and non-native, dominates the banks and area surrounding the spring channel.

Regional patterns of springs in Wisconsin

Broad patterns in the distribution of springs align with major landscape features in Wisconsin. For example, springs line the marginal ridge of the Green Bay Lobe in central Wisconsin, and they are concentrated in the Driftless Area (fig. 10). Chemical characteristics of spring waters are also similar to the general chemical characteristics of water in Wisconsin's shallow aquifer system, defined as the entire thickness of rock units above the uppermost confining unit (Kammerer, 1995). The concentration of total dissolved solids in Wisconsin's shallow groundwater is indicative of aquifer composition (Kammerer, 1995). Spring-water specific conductance (SC), which is a general measurement of total dissolved solids, reflects known distributions of dissolved solids in the state, where the lowest SC values are found in northern Wisconsin and the highest values are in the southeastern part of the state (fig. 10).

Table 3. Spring conditions

Spring condition	Number of springs
Disturbed[a] (sorted by frequency)	
Recreation or trails	214
Spring house, encased, or other manmade structure	79
Roadway	71
Impounded	69
Dredging	56
Livestock	48
Agriculture (general)	45
Residence	28
Diversion	26
Trash	11
Wildlife	6
Flooding	3
Stormwater	3
Other	2
Undisturbed	17

[a]All relevant conditions were recorded for each spring

Figure 9: Examples of disturbances near springs.

A. Spring house in Jefferson County.

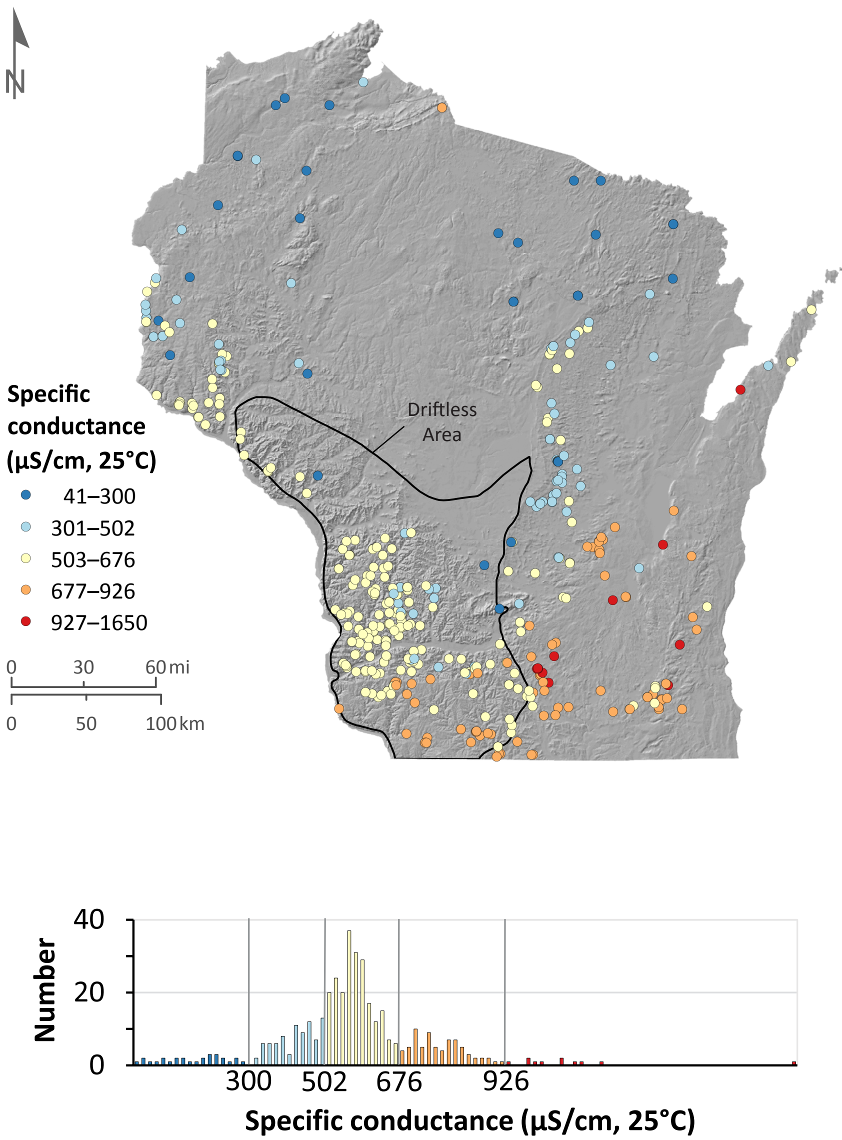
B. Structures surround a spring in Columbia County.

C. Road crosses the channel immediately downstream of springs in Green County. Watercress grows in the spring pool and reed canary grass dominates the banks and area surrounding the spring channel; both are introduced.

D. Springs near a recreational trail in Door County.

E. Spring used for watering livestock in Iowa County.

Figure 10. Map and histogram of Wisconsin's specific conductance of spring waters. Histogram shows natural breaks in distribution.



Classes of springs in Wisconsin

Subtle variations in topography, surficial geology, and bedrock geology also strongly influence the spatial distribution of springs. Patterns in spring water chemistry align with patterns in topographic position and geologic origin, thus supporting classes of spring systems and providing insight into groundwater residence times, groundwater flow paths, and the vulnerability of some spring systems. The classes identified do not encompass all of the springs inventoried. They are intended to describe the salient properties of most springs in each region and to provide a basis for site-specific investigations to better understand controls on individual springs.

Most springs in Wisconsin form as a result of preferential groundwater flow through fractures in exposed or shallowly buried Paleozoic sedimentary strata (table 4). Many of these springs, as well as nearly half of all springs surveyed, are located within or near the margins of the Driftless Area in southwestern Wisconsin. They are rheocrene, fracture, or contact springs that emerge along hillslopes or at a break in slope, primarily in valleys that have downcut into Cambrian sandstones. Others emerge near the contact of the Ordovician Prairie du Chien Group and the overlying Ordovician Ancell Group. Some also have seepage-filtration morphologies that are due to overlying, saturated, hillslope deposits (colluvium) or to fluvial deposits (alluvium) (fig. 11a). Although flow paths from ridge tops to valley walls or bottoms are relatively long, spring water SC values are moderate relative to other Wisconsin springs and reflect flow through quartz-rich sandstone aquifers (fig. 11b). Other studies with repeated water chemistry measurements for springs emerging from the

Cambrian sandstones have found low and stable nitrate, sodium, and chloride concentrations indicating relatively little impact by land-surface activities (Swanson and others, 2009; Liang, 2010). Although a nearby high-capacity pumping well could decrease groundwater flow to a spring, as a group, springs discharging from the Cambrian sandstones are probably not highly vulnerable to pumping because the greatest densities of high-capacity wells in this region are located along the floodplains of the La Crosse and Wisconsin Rivers, where few large springs exist (Wisconsin Department of Natural Resources, 2016).

Rheocrene fracture springs also commonly emerge from layered Ordovician Sinnipee Group rocks (table 4) in the southernmost, topographically higher regions of the Driftless Area of Wisconsin. Some also have seepage-filtration morphologies due to overlying, saturated, colluvium or alluvium (fig. 12a). Hillslope springs, too small to include in this inventory, commonly emerge at similar stratigraphic intervals (Swanson and others, 2014). Although groundwater flow paths to these springs are shorter, higher spring-water SC values

Table 4. Characteristics of major classes of springs in Wisconsin.

Landscape or setting	Region	Stratigraphic unit near spring orifice	Geologic material at orifice	Spring type	Morphology	Num. springs	Specific conductance (µS/cm, 25°C)		Likelihood of variable flow conditions
							Mean	Standard deviation	
Driftless Area[a]—valleys and hillslopes		Quaternary	sand, gravel	rheocrene	seepage filtration	195	564	54	moderate
		Ordovician Prairie du Chien and Ancell Groups	dolomite; some limestone and shale; sandstone	rheocrene, hillslope	fracture, contact				
		Cambrian	sandstone	rheocrene	fracture				
Driftless Area—ridges in southernmost part		Quaternary	sand, gravel	rheocrene	seepage filtration	35	742	72	high
		Ordovician Sinnipee Group	dolomite; some limestone and shale	rheocrene	fracture				
Central Wisconsin		Quaternary	sand, gravel	rheocrene	seepage filtration	11	778	38	high
		Ordovician Prairie du Chien Group	dolomite; some limestone and shale	rheocrene, hillslope	fracture				
Niagara Escarpment		Quaternary	sand, gravel	rheocrene	seepage filtration	7	716	222	high
		Silurian	dolomite	rheocrene	fracture				
Southcentral Wisconsin		Quaternary	sand, gravel	rheocrene, limnocrene	seepage filtration	15	968	243	low
		Cambrian Tunnel City Group	sandstone	rheocrene	fracture				
Marginal ridges of ice lobes		Quaternary	sand, gravel	rheocrene, limnocrene	seepage filtration	116	511	193	moderate

[a]Includes nearby springs outside the Driftless Area.

Figure 11. Springs that emerge from Cambrian sandstones within valleys in and near the Driftless Area. a) Distribution of springs and spring-water specific conductance. Bedrock geology by Mudrey and others (2007). b) An example of a rheocrene, seepage-filtration spring in this class.

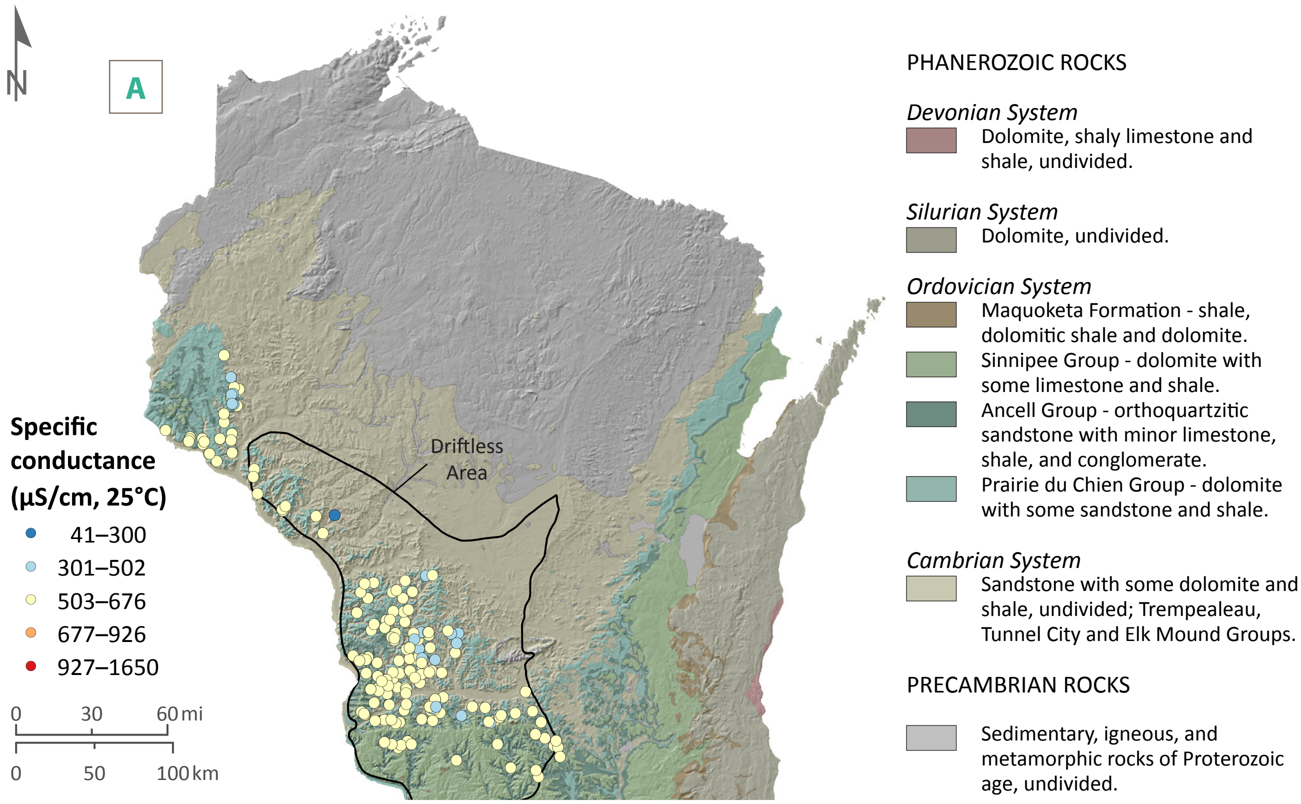
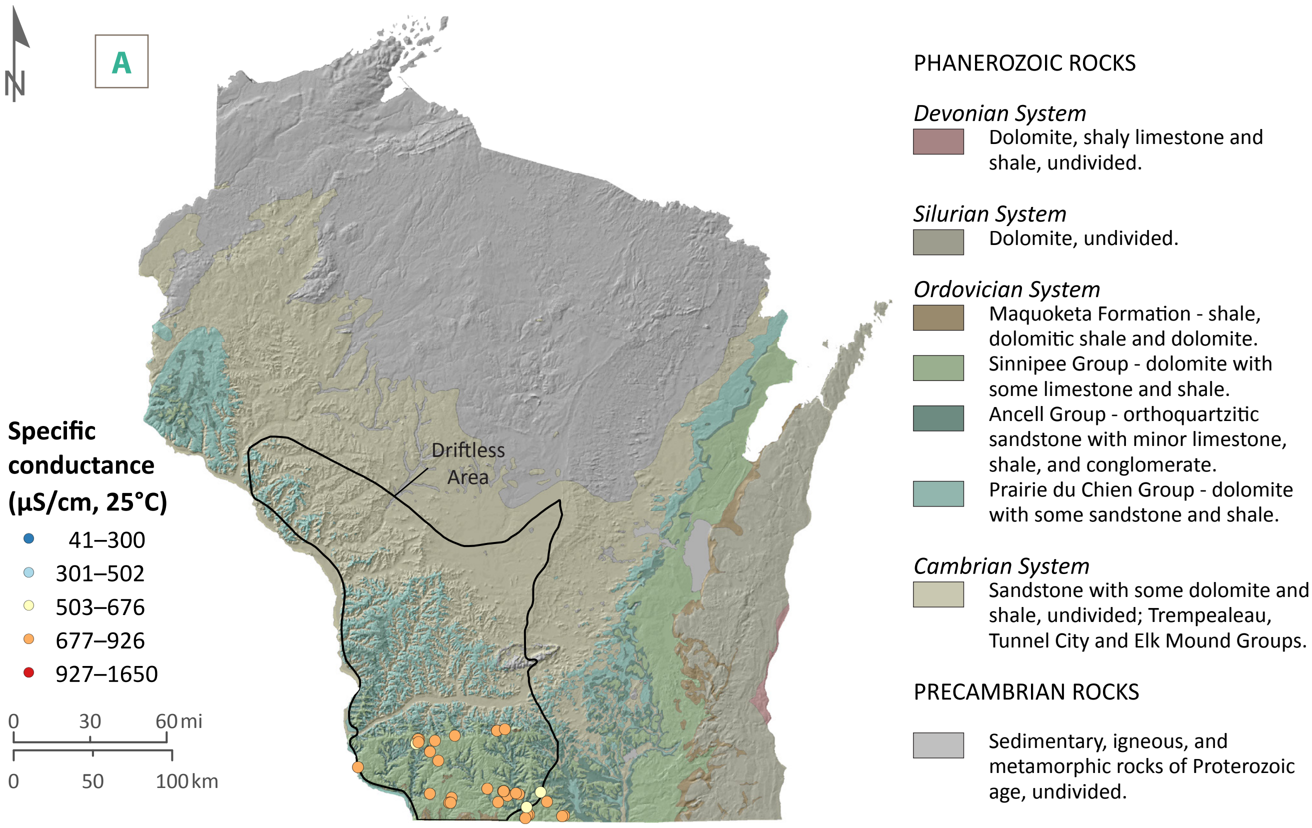


Figure 12. Springs that emerge from Sinnipee Group rocks in topographically high areas within and near the Driftless Area. a) Distribution of springs and spring water specific conductance. Bedrock geology by Mudrey and others (2007). b) An example of a rheocrene, fracture spring in this class.



reflect flow through a carbonate aquifer (fig. 12b). The Sinnipee Group's laterally extensive lithostratigraphy and the associated high- and low-permeability zones have been shown to be important to shallow groundwater flow in this region, sometimes resulting in perched groundwater (Carter and others, 2010; Swanson and others, 2014). Other studies that report repeated water chemistry measurements of springs emerging from the Sinnipee Group rocks have found elevated nitrate, sodium, and chloride concentrations indicating their sensitivity to land-surface activities (Swanson and others, 2009; Swanson and others, 2014). Springs in this setting could also be especially vulnerable to pumping where multi-aquifer wells constructed on narrow upland ridges diminish the volume of shallow or perched groundwater or divert groundwater flow away from springs.

Bedrock fracture-controlled spring systems also occur in glaciated regions where the unlithified materials are thin or absent. For example, springs emerge from the Prairie du Chien Group in central Wisconsin (Green Lake County), where streams have downcut through glacial materials and into the shallow bedrock. These rheocrene or hillslope fracture springs have high spring-water SC values for Wisconsin springs that suggest longer groundwater residence times or flow paths through a carbonate aquifer, or both (fig. 13). No repeated spring-water chemistry data are available for these springs and there are few data on spring flow. However, the springs are likely to be sensitive to land-surface activities that alter groundwater quality because they are associated with bedding-parallel fractures, and the Prairie du Chien Group is known to include karstified dolomite elsewhere in Wisconsin (Carter and others, 2010; Steelman and others, 2017). Central Wisconsin also has a very high density of high-capacity pumping wells, and the density has increased in recent years (Wisconsin Department of Natural Resources, 2016).

Springs emerge along the Niagara Escarpment where the Silurian dolomite is exposed or shallowly buried (fig. 14). These springs exhibit fracture or seepage-filtration morphologies depending on whether the fractured dolomite is exposed at the land surface or buried by unlithified materials. Spring-water SC values and flow vary widely depending on the frequency and magnitude of rainstorms. This class of springs includes the only second-magnitude spring (table 2) that was surveyed but, as noted previously, flow at this spring varies by one order of magnitude. Groundwater movement and contaminant transport in the Silurian dolomite aquifer are strongly controlled by a network of vertical and horizontal fractures. Many studies have shown that groundwater recharge can be rapid in this setting, with little attenuation of surface contaminants (e.g., Bradbury, 2003; Muldoon and Bradbury, 2005; Borchardt and others, 2011). These springs are therefore highly vulnerable to depletion by groundwater pumping and to groundwater contamination, especially where soils are thin or absent.

Springs in southern Wisconsin commonly emerge along the subcrop of the Cambrian Tunnel City Group (table 4) and its upper or lower contact, where bedding-parallel fractures promote preferential groundwater flow and are truncated by the margins of buried valleys (Swanson, 2001; Swanson and others, 2006). These rheocrene or limnocrene springs commonly form seepage-filtration morphologies with boiling sands and spring pools. Higher spring-water SC values reflect longer flow paths through the unlithified and shallow bedrock aquifer, as well as the surrounding urban environment (Swanson and others, 2001) (fig. 15). These springs are vulnerable to pumping in the city of Madison metropolitan area, especially where high-volume wells span multiple aquifers (Swanson, 2001; Parsen and others, 2016).

Other springs in glaciated regions of northern, central, and southeastern Wisconsin are controlled by variations in topography and lithology of the surficial unlithified aquifer. They commonly form at the break in slope along and between late Wisconsin end moraines and interlobate moraines or near the margins of former glacial lakebeds. These rheocrene or limnocrene seepage-filtration springs commonly have low spring-water SC values in central and northern Wisconsin, which suggest shorter groundwater residence times and short flow paths through the unlithified aquifer. Outliers that are much higher than the mean spring-water SC value, such as a spring in northern Iron County that is located near historic mine tailings, illustrate the potential vulnerability of these springs to changes in land use that may alter the quality of groundwater recharge to the shallow unlithified aquifers that support them. Near the Kettle Moraine in southeastern Wisconsin, spring-water SC values are also higher, reflecting the composition of glacial deposits and underlying carbonate bedrock or the surrounding urban environment (fig. 16).

Figure 13. Springs that emerge from Prairie du Chien Group rocks, where streams have eroded through glacial materials and into shallow bedrock. a) Distribution of springs and spring-water specific conductance. Bedrock geology by Mudrey and others (2007). b) An example of a rheocrene fracture spring in this class.

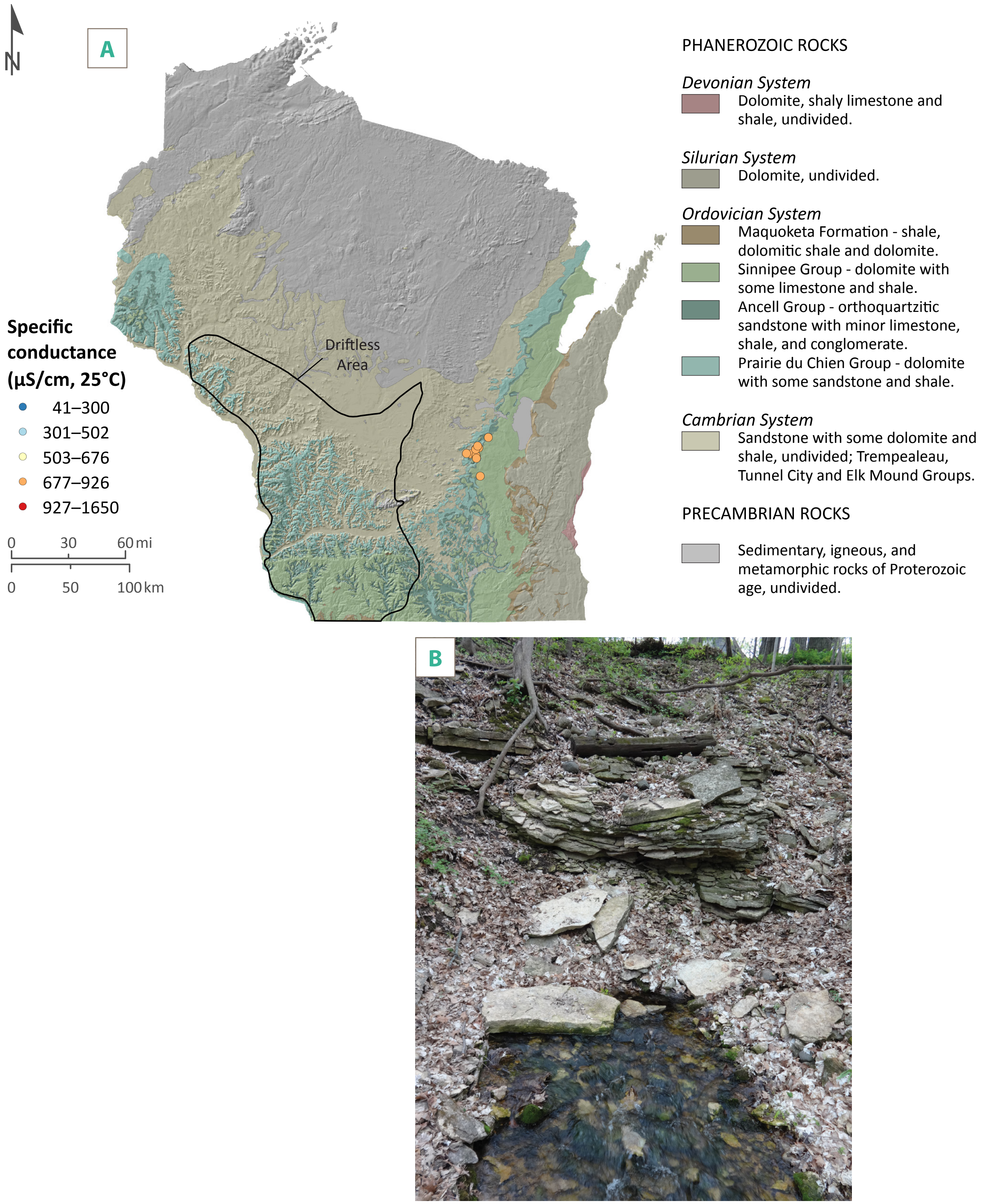


Figure 14. Springs that emerge along the Niagara Escarpment where Silurian dolomite is exposed or shallowly buried. a) Distribution of springs and spring-water specific conductance. Bedrock geology by Mudrey and others (2007). b) An example of a rheocrene fracture spring in this class.

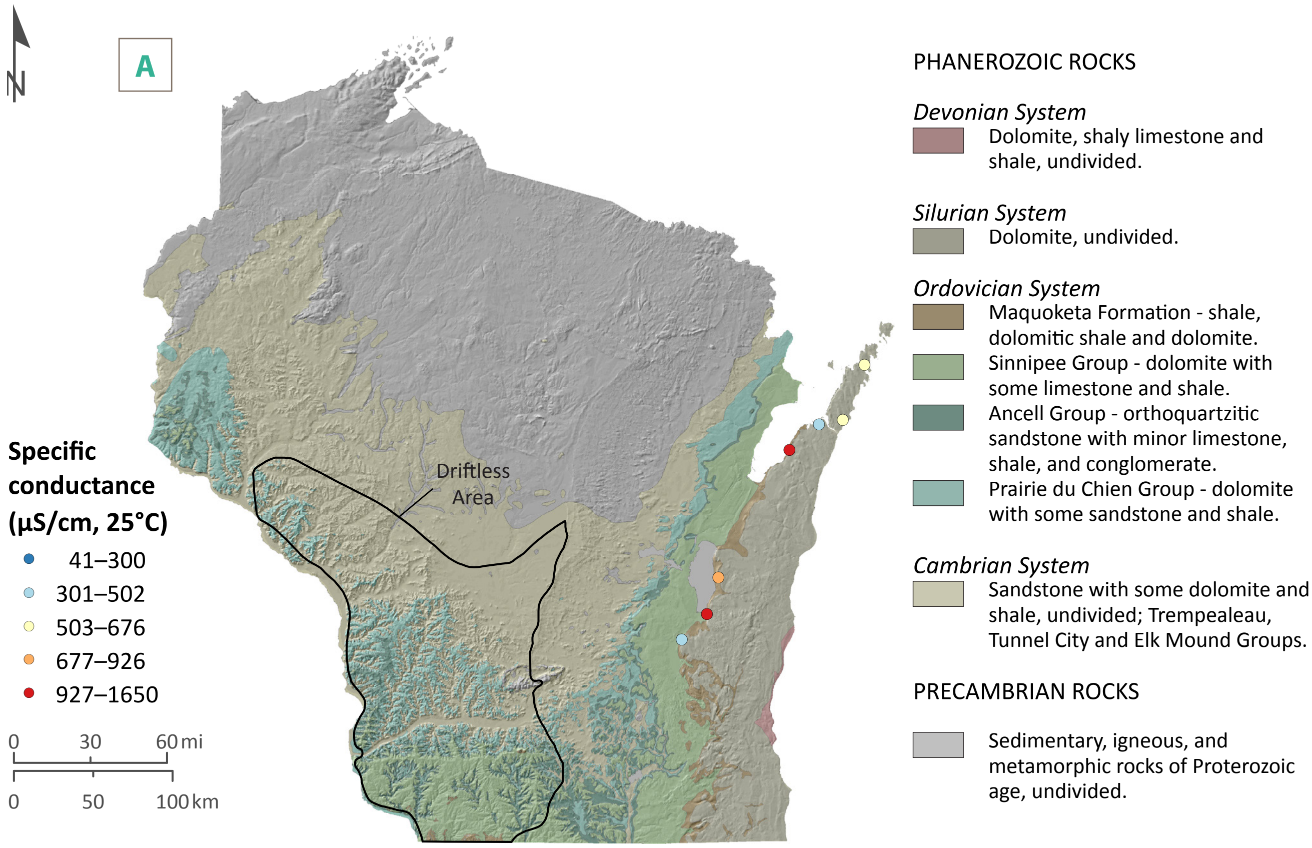


Figure 15. Springs that emerge along subcrop of the Tunnel City Group. a) Distribution of springs and spring-water specific conductance. Bedrock geology by Mudrey and others (2007). b) An example of a rheocrene, seepage-filtration spring in this class.

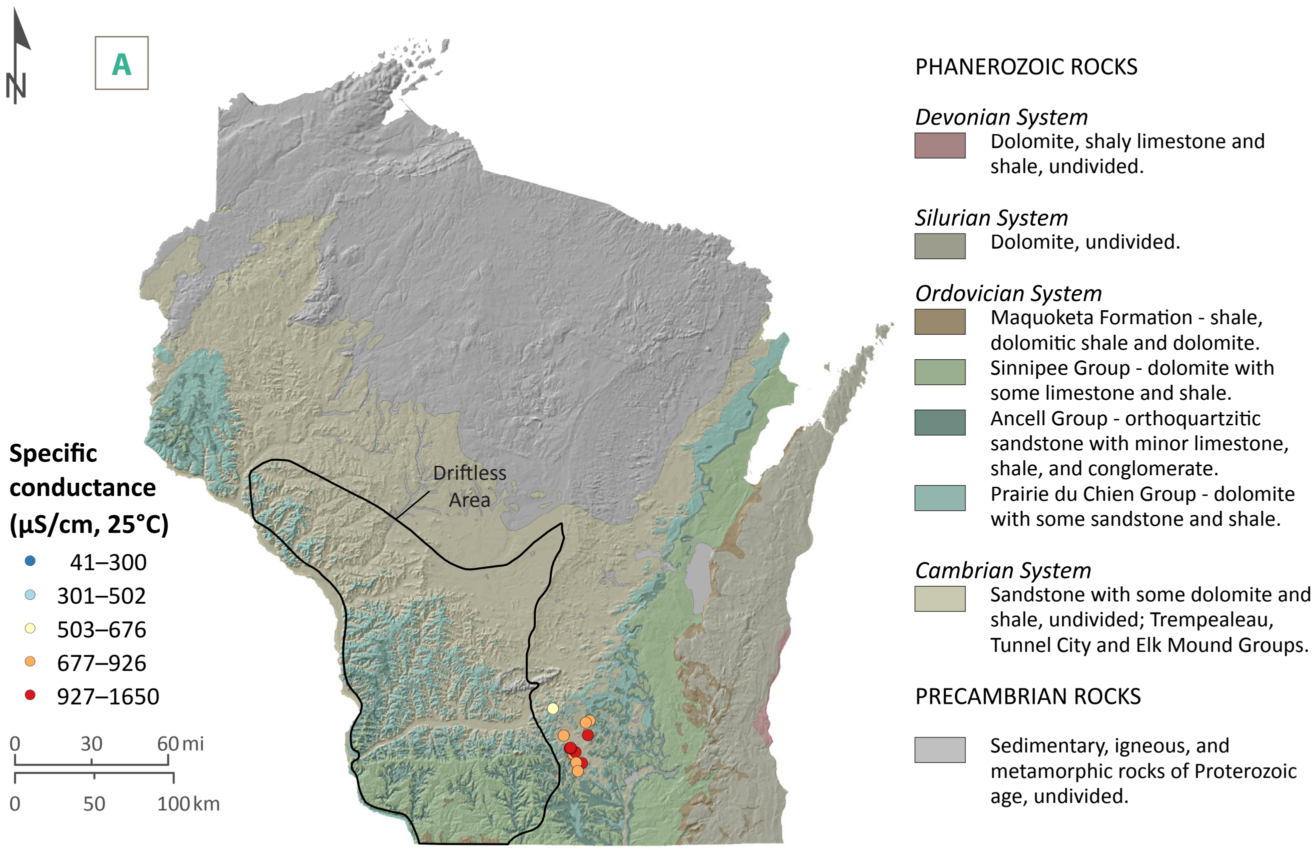
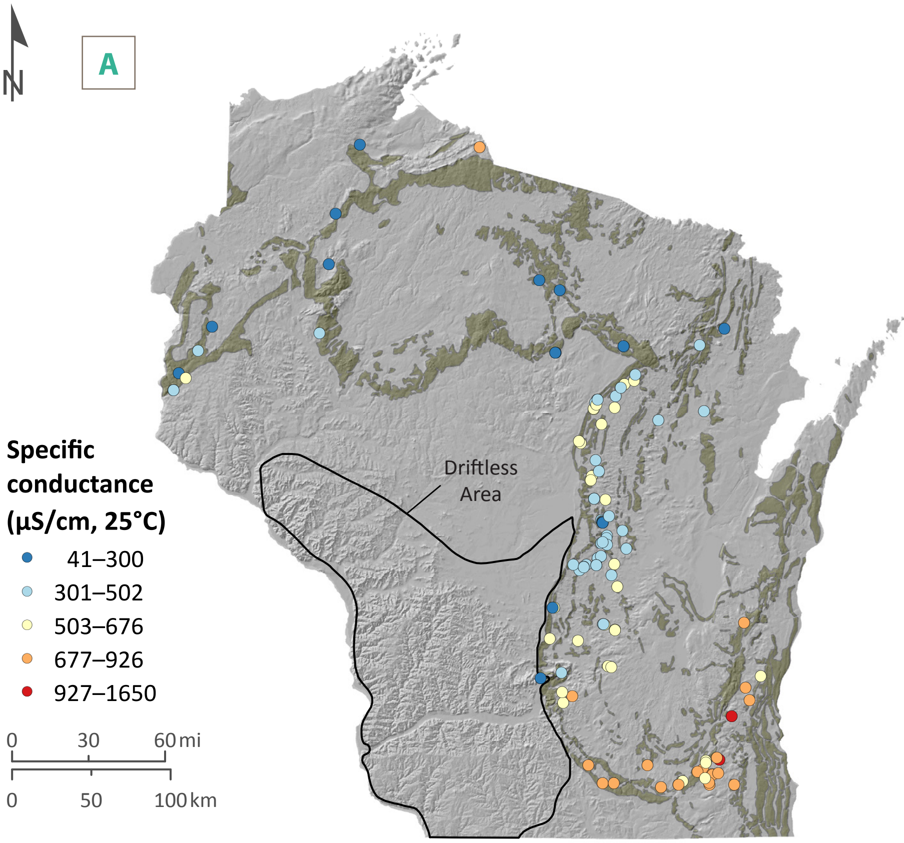


Figure 16. Springs that emerge at the break in slope along and between late Wisconsin end and interlobate moraines. a) Distribution of springs and spring-water specific conductance. Late Wisconsin end moraines by Mickelson and Knox (2013). b) An example of a rheocrene, seepage-filtration spring in this class.



Summary

Field surveys conducted between July 2014 and August 2017 produced comprehensive and widespread information on spring hydrology in Wisconsin, which should be of use to hydrogeologists, aquatic ecologists, and water resources managers who are engaged in management efforts and hydrological research across Wisconsin. Survey results show that local variations in topography, surficial geology, and bedrock geology strongly influence the spatial distribution of springs in Wisconsin. Patterns in spring water chemistry align with those in topographic position and geologic origin supporting several major classes of springs, as summarized in the previous section and in table 4.

The use of spring flux is an effort to distinguish between highly focused and diffuse groundwater discharge. This concept provides another measure to define a spring in a way not previously used. A spring flux of approximately 1×10^{-4} ft/s may be an appropriate threshold for distinguishing between features that are dominated by highly focused flow (i.e., springs) versus diffuse groundwater flow (e.g., spring ponds, wetlands) in Wisconsin.

Although great effort was made to survey all of the springs in the state with flows greater than 0.25 ft^3/s, additional springs almost certainly exist. A strength of the approach used in this inventory is that it produced a large and consistent data set of springs information, and future use of the field protocol described in this report will ensure consistency of data sets for new springs with existing inventory data. A limitation is that, although springs are dynamic features, inventory data represent conditions during a single site visit. For springs with stable flow and water chemistry conditions, the existing inventory data are likely to remain representative of spring conditions, unless groundwater withdrawals or land use have changed near the site. Repeated surveys are recommended for springs with conditions that are likely to be variable (table 4). Finally, the field protocol developed for this inventory is best suited for rheocrenes. Springs that discharge to lakes, or limnocrenes, are also widespread in Wisconsin. Future efforts to characterize springs and spring flow in Wisconsin should consider whether such features should be distinguished from the water bodies to which they discharge. This distinction is particularly important in northern Wisconsin where so-called "spring ponds" are common, but very few highly focused flow features, or springs, were observed as part of this work.

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Kenneth R. Bradbury, Director and State Geologist

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

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