AN UPDATED SPRINGS INVENTORY FOR THE STATE OF WISCONSIN

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PROJECT SUMMARY

Title: AN UPDATED SPRINGS INVENTORY FOR THE STATE OF WISCONSIN

Project I.D.: 15-HDG-01

Investigator(s):

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Period of Contract: 07/01/14 – 08/31/17

Background/Need: This project directly addressed the need for comprehensive and widespread information on spring hydrology in Wisconsin to assess impacts of high-capacity wells on spring flow rates and to characterize the susceptibility of certain spring types to impacts as a result of groundwater drawdown.

Objectives: The broad objectives of the project were (1) to create a springs database for the State of Wisconsin by conducting field surveys of springs with historical flow rates of 0.25 ft^3/s or more and (2) to establish reference springs in representative hydrogeological and ecological settings for long-term monitoring and characterization of the vulnerability of common types of springs to groundwater withdrawals or changes in recharge.

Methods: For the purposes of the inventory, a spring is defined as a discrete point of groundwater discharge flowing at approximately 0.25 ft^3/s or more at the time of the survey. The field protocol for the spring field surveys reflects the goals of the project and is informed by existing and well-established practices for the characterization and management of spring resources. 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, and vegetative cover. Site photos and sketches complement the spring characteristics. Reference springs were established at six locations that are representative of different hydrogeological and ecological settings in the state. Each reference spring discharges water at 1 ft^3/s or more, is easily accessible, and is on public land. Reference springs were initially surveyed using the protocol described above. Additionally, they were visited biannually in April and October for water quality sampling and analysis of major ions and stable isotopes of oxygen and hydrogen. Reference spring monitoring will continue through August 2019.

Results and Discussion: The inventory provides detailed descriptions of 415 springs in 58 counties in Wisconsin. Nearly all are rheocrene (96%), or springs that discharge to a defined channel. Others are hillslope springs (3%) and limnocrene (1%), or springs that discharge to lakes. About two-thirds of the springs (68%) are located on privately-held land. Over half of the springs display moderate to high levels of disturbance (53%) due to factors such as dredging or

impoundment, presence of a spring house or other structures, proximity to roads or recreational trails, or access to livestock. The majority of the highly or moderately disturbed springs (81%) are located on private land. The mean flow rate of the 410 springs for which flow could be measured is 0.96 ft^3/s; values range from 0.14 ft^3/s to 18.3 ft^3/s. About 26% of the springs emerge as fracture or contact springs, and 74% have seepage-filtration morphologies.

Conclusions/ Implications/Recommendations: On a statewide level, spring waters in Wisconsin reflect groundwater provinces that describe Wisconsin's shallow aquifer system. Local variations in topography, surficial geology, and bedrock geology, not represented in broad groundwater provinces, also strongly influence the spatial distribution of springs in Wisconsin. Patterns in spring water chemistry align with those in topographic position and geologic origin supporting categories of spring systems, including (i) rheocrene, fracture or contact springs that emerge along hillslopes or at the break in slope in the Driftless Area of Wisconsin, (ii) rheocrene, fracture or contact springs that emerge from the Sinnipee Group rocks in the southern, topographically higher regions of the Driftless Area, (iii) rheocrene, fracture springs that emerge from the Prairie du Chien Group in central Wisconsin, where streams have down-cut through glacial materials and into the shallow bedrock, (iv) rheocrene fracture or seep-filtration springs that emerge along the Niagaran Escarpment where the Silurian dolomite is exposed or shallowly buried, (v) rheocrene, seepage-filtration springs in southern Wisconsin that emerge along the subcrop of the Tunnel City Group and its upper or lower contact, where bedding-parallel fractures promote preferential groundwater flow and are truncated by the margins of buried valleys, and (vi) rheocrene and limnocrene, seepage-filtration springs that form at the break in slope along and between end and interlobate moraines or near the margins of former glacial lakebeds. To further discern seasonal variations in water chemistry and flow, the WGNHS will monitor reference springs that are representative of these spring systems quarterly for the next two years. The monitoring program will also be expanded to include ecological surveys of vegetation and invertebrates on a biannual basis.

The field protocol developed for the inventory is best suited for rheocrenes; however, 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. The spring flux metric, developed in this study and defined as spring flow/orifice area, can help distinguish between focused and diffuse discharge and may provide a useful measure to define a spring in a way not previously used.

Over the next two years, we will transition between WGNHS and WDNR acquisition and management of springs-related data. In the meantime, WGNHS has made the springs inventory data, including photos and site maps, available through geospatial web services and will host the related documents on a web-accessible server.[1] The Hydrogeological Data Viewer web application has also been updated to accommodate these services and files, enabling search and viewing of the new springs data and documents.[2]

Key Words: Springs, Wisconsin

Funding: Wisconsin Department of Natural Resources

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[1] Available at https://data.wgnhs.uwex.edu/arcgis/rest/services/springs/springs_inventory/MapServer

[2] Access to WDNR personnel is available upon request (geodata@wgnhs.uwex.edu)

1. INTRODUCTION

This project directly addressed the need for comprehensive and widespread information on spring hydrology in Wisconsin to assess impacts of high-capacity wells on spring flow rates and to characterize the susceptibility of certain spring types to impacts related to potential groundwater drawdown. The topic is relevant in Wisconsin because the Wisconsin Department of Natural Resources (WDNR) must evaluate whether groundwater pumping by new high-capacity wells (≥ 100,000 gpd) will result in significant environmental impacts to springs that result "in a current of flowing water with flows of a minimum of one cubic foot per second at least 80% of the time (2003 WI Act 310, p.2)." Prior to this work, Wisconsin's springs, irrespective of the flow criterion, were incompletely inventoried, resulting in a lack of information for use in determining significance of impacts.

The broad objectives of the project were (1) to create a springs database for the State of Wisconsin by conducting field surveys of springs with historical flow rates of 0.25 ft^3/s or more and (2) to establish reference springs in representative hydrogeological and ecological settings for long-term monitoring and characterization of the vulnerability of common types of springs to groundwater withdrawals or changes in recharge. During the first month of the project (July, 2014), these objectives were refined into the following goals in consultation with the WDNR.

1. Goals for the surveys of springs with historical flow rates of 0.25 ft^3/s or more.
    a. To locate springs with flow rates of 0.25 ft^3/s or more.
    b. To measure, record, and manage the salient hydrologic attributes of each spring.
    c. To provide initial information for the determination of whether a proposed high capacity well may have a significant environmental impact on a spring.
2. Goals for the establishment of reference springs in representative hydrogeological and ecological settings within the state.
    a. To quantify baseline conditions, including temporal variation in biological and physicochemical characteristics of representative springs.
    b. To serve as a foundation for determining principal pathways of groundwater flow to springs.
    c. To serve as a foundation for evaluating potential effects of climate change or pumping on springs in each region.

2. PROCEDURES AND METHODS

2.1 Site Identification

The initial step in this study was a review of Macholl's (2007) compilation of the locations and attributes of 10,864 hydrologic features, including springs, seepage lakes, wetlands, or dry depressions, identified from a variety of sources in the past. This database served as a primary resource for possible spring sites, but topographic maps, 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 criterion for selection of features from Macholl (2007). Using a somewhat lower value than 0.25 ft^3/s increased the likelihood of identifying suitably-sized springs. It also took into account the high number of features in Macholl (2007) with a recorded flow of 0.22 ft^3/s, which was probably converted from a field estimate (100 gpm) during surveys conducted by the Wisconsin Conservation Department (WCD) between 1956 and

1963. Sites described during the WCD surveys account for over 80% of the features in Macholl (2007).

About 34% of the features in Macholl (2007) have no historical flow measurement. To avoid disregarding features that are suitably-sized, but lack a historic flow measurement, all features with a recorded discharge of 0 ft^3/s were initially selected, and then removed from further evaluation if historic notes suggested that the feature was dry, barely flowing (e.g., “trickle,” “seepage”), flowing intermittently, or non-discrete (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 when they appeared to be a large lake (> 5 acres), a lake without an outlet, or an area lacking surface water.

About 40% of the features that lack a historical flow measurement in Macholl (2007) were originally identified in WDNR Surface Water Resources reports (SWR) as seepage lakes, spring ponds, or ponds in headwater settings with significantly higher outflow than inflow. The majority of these features are located in northern and northeastern Wisconsin. The SWRs describe the ponds as groundwater-fed, but in most cases there is no indication that these features have discrete groundwater discharge meeting the criteria of the springs inventory. Therefore, to prepare lists of features worthy of investigation in northern counties, project staff reviewed the original SWRs for mention of discrete flow, examined multiple editions of aerial imagery, and checked the proximity of the features to Class-1 trout streams. Features were retained on the list to investigate if the SWR mentioned discrete springs. Alternatively, retained features met two or more of the following criteria: i) the SWR report mentioned sand or gravel substrate suggesting that localized flow may be high or stable enough to displace organic material; ii) the surface area of the feature was less than 5 acres; iii) the outlet of the feature was mapped as Class-1 trout water; or iv) aerial imagery showed evidence of discrete flow on the perimeter of or within the feature.

Springs identified in other scientific studies, in the USGS Geographic Names Information System, on 1:100,000-scale topographic maps, or through communications with local experts were added to sites discussed above to generate a complete list of features worthy of investigation in each county. An online form (http://geodata.wgnhs.uwex.edu/springs-reporter/) developed as part of this project facilitated reporting of previously-unmapped springs by local experts. The reporter allows users to plot springs on a map and describe them using criteria that is helpful in the evaluation of whether a feature might meet the flow criterion for the inventory. Since 2015, 35 users reported 68 features using the interface.

Property ownership for the 1,377 sites deemed worthy of investigation was determined 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, attempts to call landowners of features on private land were made. If owners could not be reached by phone, door-to-door visits were made and information letters were distributed when property owners were not at home. When an owner confirmed the presence of a spring flowing at least 0.25 ft^3/s, permission to access and conduct a survey was requested. In accordance with Wisconsin law, if the spring was located within a right-of-way, or was easily accessible via navigable water, permission from owners was not always sought (Wis. Stat. § 82.50; Wis. Article IX, § 1). Project staff made contact with 71% of landowners (private and public) and 58% of landowners granted access to sites. Only 2% of landowners did not grant access to their property (**Table 1**).

Table 1. Spring sites investigated and surveyed

	Number	**Percentage of total**
Total features investigated	**1377**	
Historically mapped features	1059	77%
Newly identified features	318	23%
Property owners contacted	983	71%
Property owners who could not be reached	394	27%
Features confirmed by property owner and/or access granted (field visits)	780	58%
Property owners who did not grant access	25	2%
Total springs surveyed	**415**	**30%**

2.2 Statewide Field Surveys

Field surveys were conducted from August-November 2014, April-November 2015, March-November 2016, and March-August 2017. Surveys proceeded on a county-by-county basis, giving priority to regions experiencing the greatest demand for new high-capacity wells or rapid urban development.

2.2.1 Springs

For the purposes of the inventory, a spring is defined as a discrete point of groundwater discharge flowing at approximately 0.25 ft^3/s or more at the time of the survey. The field protocol for the statewide surveys reflects the goals of the two major components of the project and 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 et al., 2011; USDA Forest Service, 2012a, 2012b). The protocol 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, and vegetative cover (**Appendix A**). Site photos and sketches 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 cut throat flume was used in narrow and shallow channels with unlithified bed materials. The velocity-area method was implemented in wider and deeper channels using a wading rod and an electromagnetic meter (0 to 20 ft/s ± 2-4% of reading) or an acoustic Doppler velocity meter (0 to 13 ft/s ±1% of reading). At locations where water discharged from a pipe or rock outcrop, flow was sometimes measured using the timed-volume method and a five-gallon bucket marked with ¼-gallon increments. Where these methods were not feasible, spring discharge was estimated using the float velocity method.

A HACH H160 meter and an Oakton CON 400 Series Conductivity meter measured temperature, pH, and electrical conductivity, respectively. Calibration of meters took place at least once per week in the field. A Kestrel 2500 measured atmospheric temperature and wind speed, and a Nikon Forestry Pro laser rangefinder measured surface slopes and distances required for site sketches.

Protocol attributes for springs were defined in an ArcGIS feature class within a file geodatabase and configured to be editable on a Trimble Juno 3B handheld GPS using ArcPad 10.x software. This 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 springs feature class. GPS units recorded an average easting and northing over a 60-second logging interval and parameters that quantify the strength and precision of the satellite signal. The Juno 3B units have 2- to 5-meter horizontal accuracy, but have lower vertical accuracy. Therefore, elevation values for the spring sites were extracted from the highest-resolution digital elevation model (DEM) available for each county using the Extract Multi Values to Points tool in ArcGIS Spatial Analyst. The DEM source and resolution are included in the attribute table of the springs feature class. DEM sources included the National Elevation Dataset (NED) and Light Detection and Ranging (LiDAR) datasets.

2.2.2 Ponds

For the purposes of the inventory, a pond is defined as a surface water feature with a water depth greater than approximately 1 meter, with mostly organic substrate, and without visible discrete flow. If this type of feature was encountered at a site and an outlet channel was conveniently accessible, the flow rate was measured. A second feature class in the springs inventory geodatabase (in addition to the springs feature class) stores information collected at ponds. Coordinate data, land ownership, flow rate, accuracy of flow measurement, general notes describing the site, and photos comprise the attribute data for ponds (**Appendix B**).

2.2.3 Sites Investigated

A third feature class in the springs inventory geodatabase stores sites that were investigated, but not surveyed. It includes coordinate data; the Macholl (2007) spring ID, if identified using this database; the original source that suggested the occurrence of a spring at the position; and the reason why the position was not surveyed (**Appendix C**).

2.3 Reference Springs

Reference springs were established at six locations that are representative of different hydrogeological and ecological settings in the state (**Table 2**). More than 20 springs were evaluated as potential reference sites. Each reference spring discharges water at 1 ft^3/s or more, is easily accessible, and is on public land. Reference springs were initially surveyed using the protocol described in section 2.2.1. Additionally, they were visited biannually in April and October for water quality sampling. Water samples were collected at the spring orifice and filtered using a handheld vacuum pump and 0.45µm filters. Samples were analyzed for major ions and alkalinity at the Stevens Point Water & Environmental Analysis Lab and stable isotopes of Oxygen ($\delta^{18}O$) and Hydrogen ($\delta^{2}H$) at the Iowa State University Stable Isotope lab. Field measurements included pH, temperature, and electrical conductivity. Total alkalinity was also measured in the field using Chemets test kits. Site photos and spring discharge measurements at the same locations were repeated during each reference spring visit. Onset TidbiTs recorded spring water temperature near the spring orifice at one hour intervals throughout the duration of the project. WDNR biologists were contacted in 2014 to advise on strategies with respect to characterizing vegetation at the reference spring sites; however, in consultation with the WDNR, vegetation surveys were subsequently deemed to be beyond the scope of this investigation.

Table 2. Reference spring properties

Name	County	Groundwater Province	Geographic Region	Ecological Region	Uppermost Bedrock	Surficial Material
Highland Big Spring	Iowa	2	Western Uplands	Western Coulees and Ridges	Ordovician Prairie du Chien Group	Sand and gravel
Lodi Marsh	Dane	1	Eastern Ridges and Lowlands	Central Sand Hills	Cambrian sandstone	Sand and gravel
Kelly Spring	St. Croix	1	Western Uplands	Western Prairie	Ordovician Ancell Group	Sandy till
Pine River	Waushara	1	Central Plain	Central Sand Hills	Cambrian sandstone	Sandy till
Three Springs	Door	4	Eastern Ridges and Lowlands	Northern Lake Michigan Coastal	Silurian dolomite	Silt and clay
Town Line Road	Marathon	5	Northern Highland	Forest Transition	Wolf River batholith	Sand and gravel

Notes: Groundwater provinces from Kammerer, 1995; geographic regions from Martin, 1965; ecological regions from WDNR, 2015; bedrock from Mudrey et al., 2007; surficial material from Mickelson and Knox, 2013.

3. RESULTS AND DISCUSSION

3.1 Statewide Spring Surveys

3.1.1 Condition, Morphology, and Flow

The inventory provides detailed descriptions of 415 springs in 58 counties in Wisconsin. Nearly all are rheocrene (96%), or springs that discharge to a defined channel. Others are hillslope springs (3%) and limnocrene (1%), or springs that discharge to a lake. About two-thirds of the springs (68%) are located on privately-held land. Over half of the springs display moderate to high levels of disturbance (53%) due to factors such as dredging or impoundment, presence of a spring house or other structures, proximity to roads or recreational trails, or access to livestock. The majority of the highly or moderately disturbed springs (81%) are located on private land.

The mean flow rate of the 410 springs for which flow could be measured is 0.96 ft^3/s; values range from 0.14 ft^3/s to 18.3 ft^3/s (**Figure 1**). Water depth and/or soft, organic substrate prevented measurement of flow for five springs. Some of the springs (37 or 9%) 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 or because the spring exists in a region where there are very few springs.

About 26% of the springs emerge as fracture or contact springs, and 74% have seepage-filtration morphologies. At a fracture spring, groundwater discharges from joints or fractures. Contact springs discharge water at a stratigraphic contact, along which fractures often form. Groundwater discharges from many small openings in permeable material at a seepage-filtration spring. Used in association with spring morphologies, spring flux (ft/s), a metric developed for use in this investigation and defined as spring flow (ft^3/s) divided by spring orifice area (ft^2), provides a meaningful way to further distinguish between features dominated by discrete versus diffuse groundwater flow. **Figure 2** shows the distribution of spring flux for springs described in the inventory. Also included are fluxes for 21 ponds where flow measurements were made (see section 2.2.2). In the absence of detailed information on the flow distribution within each pond, the surface area of the pond was used as an estimate of the area over which water discharges. For ponds in headwater settings, the surface area probably underestimates the three-dimensional area of the lake bed. For flow-through ponds, the surface area may overestimate the actual area over which discharge occurs. However, because nearly all of the ponds visited in this investigation are in headwater settings, the former is more likely. The median fluxes for fracture or contact springs, seepage-filtration springs, and ponds are 4E-02 ft/s, 6E-03 ft/s, and 1E-05 ft/s, respectively. **Figure 2** suggests that a flux of approximately 1E-04 ft/s may be an appropriate threshold for distinguishing between features that are dominated by discrete (i.e., springs) versus diffuse (e.g., ponds, wetlands) groundwater flow in Wisconsin.

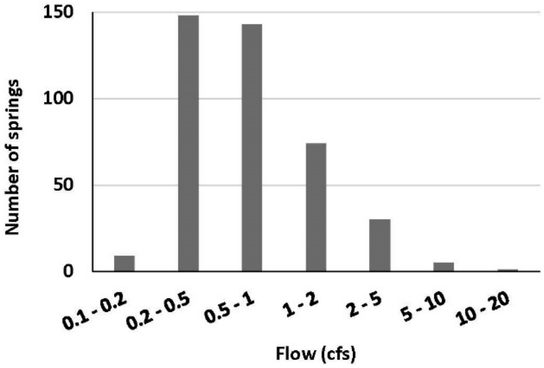

Figure 1. Distribution of spring flow

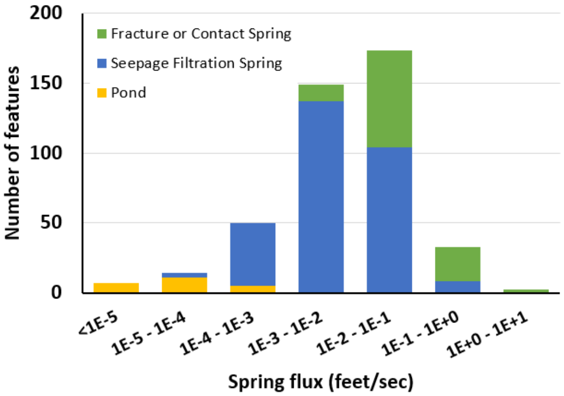

Figure 2. Distribution of flux

3.1.2 Geological Controls on Springs

On a statewide level, spring waters in Wisconsin reflect groundwater provinces that describe Wisconsin's shallow aquifer system, or the entire thickness of rock units above the uppermost confining unit (Kammerer, 1995). The concentration of total dissolved solids (TDS) in Wisconsin's shallow groundwater is indicative of aquifer composition (Kammerer, 1995). Measured spring water conductivities, which approximate TDS, generally align with known distributions of dissolved solids across the state, with the lowest conductivity values in the north-central and northwestern parts of the state and the highest values in southern and south-eastern Wisconsin (**Figure 3a, b**). Mean conductivity values for four groups of the seven groundwater provinces also differ from one another, as determined by ANOVA and Tukey-Kramer HSD tests (**Figure 3c)**. Provinces 6 and 7 were combined in this analysis due to the small number of springs and the similarity of surficial unlithified materials and bedrock units in these regions.

The results show that fluid conductivity may be a useful way to identify springs within individual provinces or groups of provinces that are influenced by factors other than the natural, near-surface aquifer composition. For example, one spring in province 6 has a fluid conductivity value of 880 µS/cm, which is much higher than all other spring conductivity values in provinces 6 and 7 (**Figure 3a**). This spring is located near the site of a former mine. In this case, spring water chemistry is probably influenced by factors other than the regional aquifer composition.

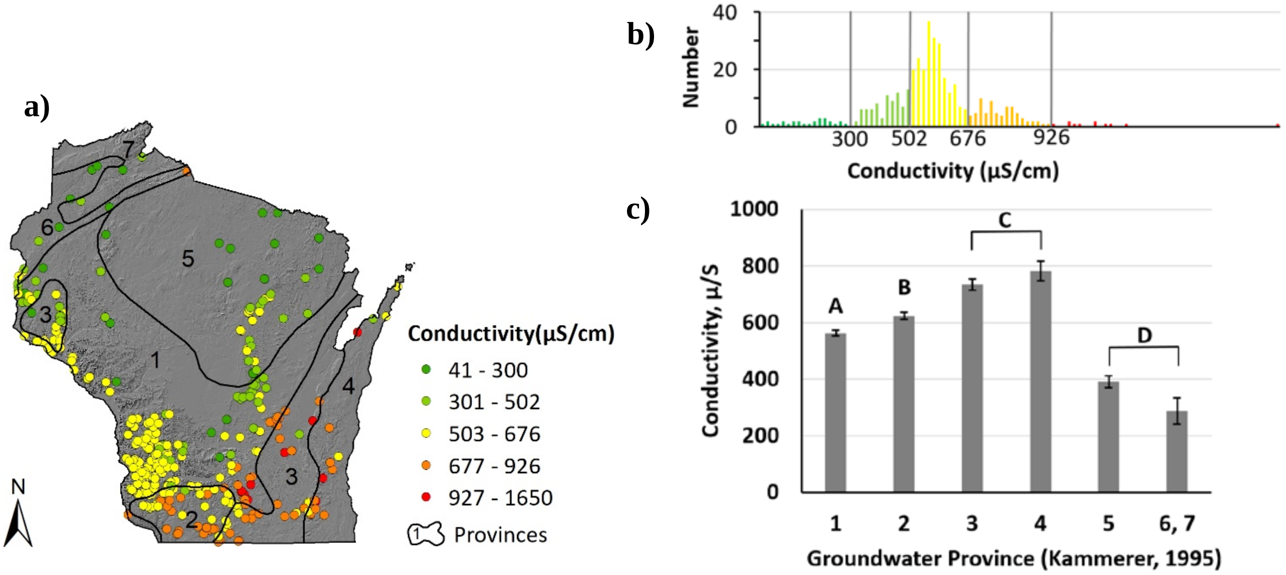

Figure 3. a) Fluid conductivity of spring waters and groundwater provinces (Kammerer, 1995), **b)** Histogram of spring conductivity values and natural breaks in the distribution, and **c)** Mean spring conductivity by groundwater province (Kammerer, 1995). Error bars are standard error in the mean. Letters indicate individual (A, B) or groups (C, D) of provinces exhibiting significant differences in mean conductivity.

Local variations in topography, surficial geology, and bedrock geology, not represented in the broad groundwater provinces, also strongly influence the spatial distribution of springs in Wisconsin. Patterns in spring water chemistry align with those in topographic position and geologic origin supporting six categories of spring systems, as discussed below, and providing further insight into groundwater residence times and flow paths.

Most springs in Wisconsin form as a result of preferential groundwater flow through fractures in exposed or shallowly buried Paleozoic sedimentary strata. Many of these springs, as well as nearly half of all springs surveyed, are located in the Driftless Area. They are rheocrene, fracture or contact springs that emerge along hillslopes or at the break in slope, primarily in valleys that have down-cut into Cambrian sandstones. Some also have seepage-filtration morphologies due to overlying, saturated, hillslope or fluvial deposits (**Figure 4a**). Although flow paths from ridge tops to valley walls or bottoms are relatively long, fluid conductivity values are moderate for Wisconsin springs (**Figure 3b**) and reflect flow through quartz-rich sandstone aquifers. Rheocrene, fracture or contact springs also emerge from the Sinnipee Group rocks in the southern, topographically higher regions of the Driftless Area (**Figure 4b**). While flow paths are shorter, the higher fluid conductivity values reflect flow through a carbonate aquifer.

Similar 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 Co.), where streams have down-cut through glacial materials and into the shallow bedrock. These rheocrene, fracture springs have high fluid conductivity values for Wisconsin springs (**Figure 3b**) that suggest longer groundwater residence times and/or flow paths through a carbonate aquifer (**Figure 5a**). Springs also emerge along the Niagaran Escarpment where the Silurian dolomite is exposed or shallowly buried.

These springs exhibit fracture or seepage-filtration morphologies depending on whether the fractured dolomite is exposed at the land surface. Fluid conductivity values and flow vary depending on the frequency and magnitude of precipitation events (**Figure 5b**).

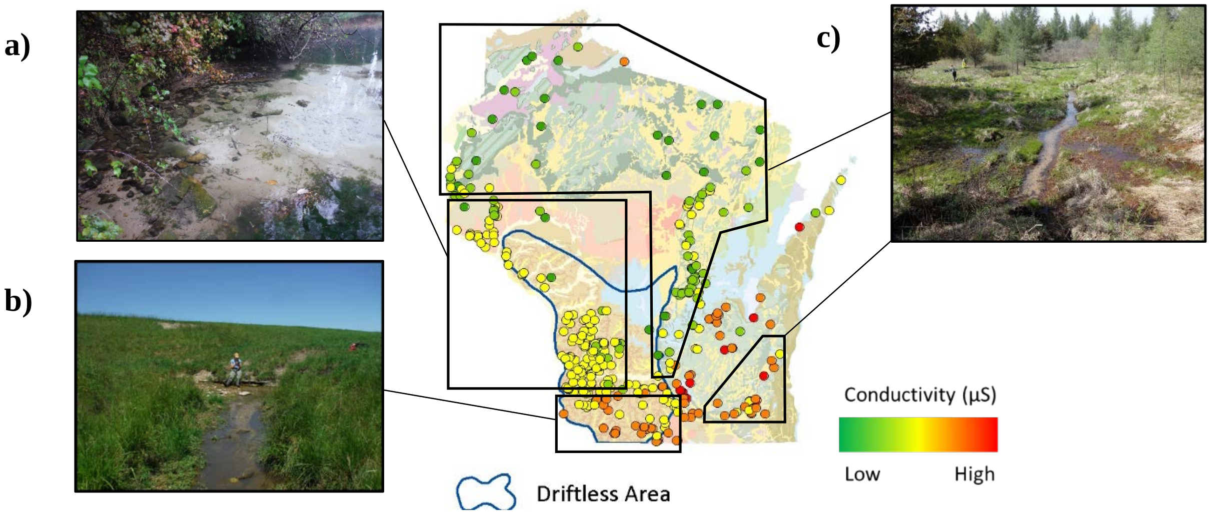

Figure 4. Examples of springs that emerge **a)** at the break in slope within valleys in the Driftless Area, **b)** near ridge-tops in the Driftless Area, and **c)** along end moraines in glaciated regions of Wisconsin. Surficial geology by Mickelson and Knox (2013).

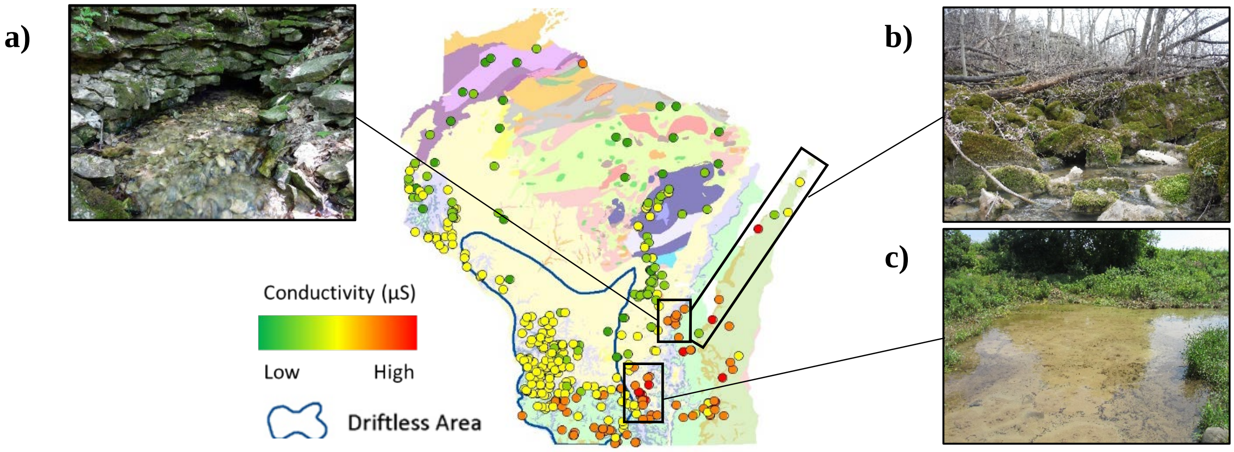

Figure 5. Examples of springs that emerge **a)** from fractured bedrock exposed in stream valleys, **b)** along the Niagaran Escarpment, and **c)** from sandstone bedrock near the margins of buried bedrock valleys. Bedrock geology by Mudrey et al. (2007).

Springs in southern Wisconsin (Dane Co.) emerge along the subcrop of the Tunnel City Group and its upper or lower contact, where bedding-parallel fractures promote preferential groundwater flow and are truncated by the margins of buried valleys. These rheocrene springs often form seepage-filtration morphologies with boiling sands and spring pools. Higher fluid conductivity values reflect longer flow paths through the unlithified and shallow bedrock aquifer, as well as the surrounding urban environment (Swanson et al., 2001) (**Figure 5c**).

Others springs in glaciated regions of northern, central, and southeastern Wisconsin are controlled by variations in topography and lithology of the surficial unlithified aquifer (**Figure 4c**). They form at the break in slope along and between end and interlobate moraines or near the margins of former glacial lakebeds. These rheocrene and limnocrene, seepage-filtration springs often have low conductivity values in central and northern Wisconsin, which suggest shorter groundwater residence times and short flow paths through the unlithified aquifer. Near the Kettle Moraine in southeastern Wisconsin, fluid conductivity values are higher, reflecting the composition of glacial deposits and underlying carbonate bedrock (**Figure 4c**).

3.2 Reference springs

Reference springs were established in representative hydrogeological and ecological settings within the state to quantify baseline conditions, including temporal variations in physicochemical characteristics. These characteristics are intended to serve as a foundation for determining principal pathways of groundwater flow to springs and for evaluating potential effects of climate change or pumping on springs in each region.

The stable isotope results for the six locations follow the general direction of storm systems across the state, from west and south to east and north (**Figure 6**). Heavier (less negative) values are expected in the south or west (e.g., Highland Big Spring in Iowa Co.) and values should become lighter (more negative) to the north and east (e.g., Town Line Road Spring in Marathon Co.; Three Springs in Door Co.). None of the springs show distinct seasonal variation in stable isotopes, presumably due to mixing along groundwater flow paths.

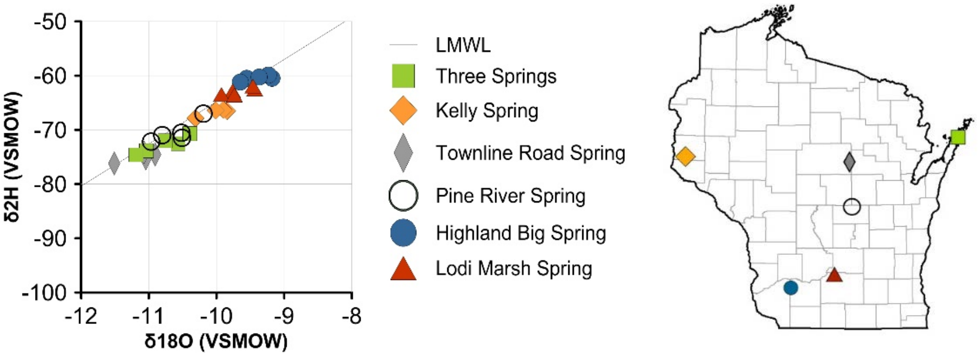

Figure 6. Stable isotope results for the six reference springs. LMWL = Local meteoric water line by Swanson et al. (2006).

Subtle differences among spring water chemistries emerged over the five sampling events from spring 2015 to spring 2017. Major ion geochemistry shows that all of the springs discharge Calcium-Magnesium-Bicarbonate type waters. Concentrations of major ions have not varied considerably over the monitoring period, so average concentrations are reported in **Table 3**. Kelly Spring (St. Croix Co.) and Pine River Spring (Waushara Co.) have lower total dissolved solids (TDS) than the four other springs, and Three Springs (Door Co.) has the highest TDS. Town Line Road Spring (Marathon Co.) has the highest concentrations of Nitrate, Sodium, and Chloride, suggesting impacts by agriculture and road salt application in the region.

Onset TidbiTs recorded spring water temperature near each spring orifice at one hour intervals throughout the duration of the project. Despite loss of dataloggers at various times, each record provides insights into the variability in temperature conditions at the reference springs (**Appendix D**). Highland Big Spring and Lodi Marsh have the most stable temperature conditions. Kelly Spring and Townline Road Spring show seasonal variation of ±1ºC that lag behind maximum and minimum air temperatures. Kelly Spring shows a greater lag than

Townline Road Spring. Three Springs and Pine River Spring show seasonal variation of ±2ºC with only a slight lag behind maximum and minimum air temperatures.

Table 3. Average Concentrations of Major Ions (mg/L) for the Six Reference Springs

Spring	Ca	Mg	K	Na	SO_4	Cl	NO_3-N	Alkalinity*	TDS
Three Springs	68.6	33.9	1.01	5.66	12.4	12.5	0.77	287	590
Town Line Road Spring	68.6	32.9	2.18	6.97	12.1	22.9	9.28	254	525
Pine River Spring	43.0	21.5	0.83	1.54	9.30	2.98	3.62	172	325
Kelly Spring	33.0	15.0	1.38	2.74	13.1	6.30	2.90	124	250
Highland Big Spring	70.3	34.0	1.61	4.94	16.1	13.2	6.34	275	544
Lodi Marsh Spring	69.5	37.3	0.87	3.62	17.5	10.3	6.20	281	547

* = mg $CaCO_3$/L; TDS = total dissolved solids.

Three Springs and Highland Big Spring exhibit the most variation in spring flow conditions over the monitoring period, while other spring flows are relatively stable (**Table 4)**. In the case of Three Springs the point of measurement drains a much larger area than the immediate spring pool. Therefore, the flow measurements for this site reflect surface runoff as well as spring flow. In all cases, more frequent flow measurements would aid in evaluating the consistency of spring flow.

Table 4. Flow Conditions at the Six Reference Springs

Spring	Flow (cfs)				
	Apr-15	***Oct-15***	***Apr-16***	***Oct-16***	***Apr-17***
Three Springs	*NA*	0.8	9.2	1.0	9.7
Town Line Road Spring	*NA*	1.7	1.4	1.2	1.9
Pine River Spring	1.4	0.8	1.4	1.4	1.4
Kelly Spring	1.1	1.2	1.3	1.1	1.2
Highland Big Spring	1.7	1.7	2.0	3.4	3.4
Lodi Marsh Spring	2.5	2.6	2.4	2.3	2.8

NA = not available; monitoring began in fall 2015

The reference springs generally reflect the variety of spring systems in Wisconsin. Highland Big Spring and Kelly Spring are both examples of the systems represented in **Figure 4a**, yet water discharging from Highland Big Spring is harder, reflecting differences in bedrock composition along groundwater flow paths. Lodi Marsh Spring and Three Springs are representative of the shallow, bedrock-controlled spring systems represented in **Figure 5b** and

5c, respectively. Townline Road Spring and Pine River Springs are representative of seepage-filtration springs in glaciated regions of Wisconsin (**Figure 4c**).

At the close of the statewide inventory in August 2017—and with insights gained from the results of this work—Townline Road Spring is thought to be a redundant monitoring point. This spring will not be included in the ongoing WGNHS monitoring and evaluation of reference springs, which was approved by the WDNR to continue through August, 2019. However, we are retaining the other five springs and adding three additional sites (for a total of eight) to adequately reflect the diversity of spring systems in the state. One spring is being added in northern Wisconsin (Bayfield Co.), one in western Wisconsin, and a third in southeastern Wisconsin (the Paradise Springs and/or Scuppernong Springs). To further discern seasonal variations in water chemistry and flow at the reference springs, the WGNHS will monitor the reference springs quarterly. We are installing benchmarks, locating each site with Real Time Kinematic (RTK) GPS, and developing rating curves for each spring site. The monitoring program for the eight reference springs will also be expanded to include ecological surveys of vegetation and invertebrates on a biannual basis.

3.3 Data Distribution

All attribute data for springs, ponds, and the sites investigated, but not surveyed are available in a file geodatabase, as described in section 2 of this report. In addition, as agreed upon by the WDNR and WGNHS, over the next two years, we will transition between WGNHS and WDNR acquisition and management of springs-related data and train WDNR on springs database management. In the meantime, WGNHS has made interim springs inventory data, including photos and site maps, available through geospatial web services and will host the related documents on a web-accessible server.[1] The Hydrogeological Data Viewer web application has also been updated to accommodate these services and files, enabling search and viewing of the new springs data and documents.[2] The WGNHS is continuing to collect field data for any new springs identified until August 2019. At the close of this period, WGNHS will deliver a protocol with flow chart, for the addition of new springs to the database including clear criteria for new spring inclusion. This protocol will also be published as a WGNHS Open File Report by August 2019.

4. CONCLUSIONS AND RECOMMENDATIONS

Field surveys conducted between July 2014 and August 2017 resulted in a comprehensive set of characteristics for 415 springs in 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 categories of spring systems. The springs-related data, as well as the spring systems described in section 3.1, should be of use to hydrogeologists, aquatic ecologists, and water resources managers who are engaged in hydrological research and management efforts across Wisconsin. While additional spring resources certainly exist in the state, future use of the field protocol described in section 2 of this report will help insure consistency of new springs data sets with existing inventory data.

The field protocol developed for the inventory is best suited for rheocrenes; however, springs that discharge to lakes, or limnocrenes, are also widespread in Wisconsin. Unfortunately,

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[1] Available at https://data.wgnhs.uwex.edu/arcgis/rest/services/springs/springs_inventory/MapServer

[2] Access to WDNR personnel is available upon request (geodata@wgnhs.uwex.edu)

limnocrenes may be not visible from the shoreline, nor are they easily accessible. 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 is a particularly important in northern Wisconsin where so-called “spring ponds” are common, but very few discrete flow features, or springs, were observed as part of this work. The use of spring flux is an effort to distinguish between focused and diffuse discharge. This concept provides another measure to define a spring in a way not previously used.

The establishment of reference springs provides information on trends in spring discharge and spring water chemistry at representative springs in Wisconsin. Continued monitoring of these systems over the next two years will improve efforts to evaluate potential effects of climate change or pumping, and to otherwise manage groundwater resources in representative hydrogeological and ecological regions of the state.

5. REFERENCES

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APPENDIX A

Spring Inventory Field Data

The following data were collected and recorded for each of the springs included in the county-level surveys and for the reference springs. Reference springs were visited twice per year.

CATEGORY	VARIABLE	WORKING FIELD NAME	DESCRIPTION	SOURCE
GENERAL SITE DESCRIPTION	Spring ID	SpringID	Unique identifier within county.	SSI
	County	County	County where spring is located.	SSI
	Surveyor(s)	Surveyor	Who conducted the survey (initials for Rick Blonn, Grace Graham, Emma Hall, Tyler Burgett, Dave Hart, Emma Koeppel, Dexter Kopas, Ava Krahn, Monica Norton, Christine Shonnard, Sue Swanson,).	SSI
	Date	Date	Date of field survey.	SSI
	Time	Time	Start time.	SSI
	Easting	Easting_WTM	Easting (WTM). As close to the spring source as possible.	SSI
	Northing	Northing_WTM	Northing (WTM). As close to the spring source as possible.	SSI
	Horizontal Precision	Horz_Precision_m	Horizontal accuracy of GPS position (meters).	SSI
	Maximum PDOP	Max_PDOP	Maximum positional dilution of precision (PDOP) during measurement.	
	Elevation	Elevation_m	From digital elevation model (DEM) (meters).	
	Elevation Source	Elevation_source	DEM source and horizontal resolution of DEM used to extract elevation.	
	Land Ownership	Land_Owner	List: state, county, city, NPS, USFS, tribal, military, private, other.	SSI
	Access	Access	Directions to springs.	SSI
	Ease of Access	Ease_Access	List: Easy access, Difficult access, Terrain prohibits access to	

			other potential spring areas.	
	Land Cover	Land_Cover	List: urban, residential, agriculture, grassland, forest, open water, wetland, barren, shrubland, other.	SSI
	Site Sketch	---	Hand drawn with scale, orientation, photo points (labeled PP), GPS point (GPS), discharge measurement point (DI), water quality measurements (WQ), orifice(s) (OR), pool (PL), channel (CH).	SSI
	Photographs	---	Photos of spring orifice, looking upstream, looking downstream, others as necessary.	SSI
ENVIRONMENTAL CONDITIONS	Air Temperature	Air_Temp_F	Air temperature on date surveyed (°F).	SSI
	Cloud Cover	Cloud_Cover_percent	Cloud cover at time of survey (%).	SSI
	Wind Speed	Wind_Speed_mph	Velocity measurement on date surveyed (mph).	SSI
	Aspect	Aspect_degrees	Direction that the spring orifice faces.	SSI
	Slope	Slope_degrees	Channel slope (°).	SSI
	Slope Variability	Slope_Variability	List: high, medium, low, none.	SSI
	Condition	Condition	List: undisturbed, light, moderate, high.	NPS
	Type of Disturbance	Type_of_Disturbance	List: wildlife, livestock, recreation, diversion, residence, impounded, dredging, flooding, trails, roadway, invasives, spring house, encased, raceways, manmade structure, trash, stormwater, drain tile, other.	SSI
GEOLOGY AND GEOMORPHOLOGY	Spring Area	Spring_Area_sqm	List: <2 m^2, 2-10 m^2, 10-100 m^2, 100-1000 m^2, 1000-10,000 m^2, 10,000-100,000 m^2	SSI

	Surface Type(s)	Surface_Types	List: backwall, colluvial slope, sloping bedrock, pool, channel, spring mound, cave, other.	SSI
	Channel or Pool Width	Width_ft	If a channel or pool exists, the mean width (feet).	NPS/SSI
	Width Location	Width_Location	List: pool, channel, pond, spring house, other.	
	Channel or Pool Depth	Depth_cm	If a channel or pool exists, the mean depth (cm).	NPS/SSI
	Depth Location	Depth_Location	List: pool, channel, pond, spring house, other.	
	Emergence Substrate Composition	Percent_organic, Percent_fines, Percent_sand, Percent_gravel, Percent_cobble, Percent_boulder, Percent_bedrock	Qualitative estimate of the % organics, fines, sand, gravel, cobble, boulder, or bedrock. Described as close to spring source as possible.	NPS/SSI
	Bedrock Composition	Bedrock_Comp	List: shale, siltstone, sandstone, conglomerate, limestone, dolomite, igneous or metamorphic, NA, other.	SSI
HYDROLOGICAL CONDITIONS	Spring Type	Spring_Type	List: helocrene, rheocrene, limnocrene, hillslope spring, cased, flowing well, other.	SSI
	Spring Source	Spring_Source	List: single orifice, multiple orifices, diffuse flow, other.	SSI
	Orifice Geomorphic Type	Orifice_Geom	List: seepage/filtration, fracture, tubular, contact.	SSI
	Discharge	Discharge_cfs	Spring flow (cfs).	SSI
	Flow Accuracy	Flow_Accuracy	Level of accuracy of flow measurement, List: low, high	
	How Measured	Discharge_Meas	List: timed volume, float velocity method, flume, AAA meter, AD meter (acoustic Doppler	SSI

			meter), EM meter (electromagnetic meter).	
	Flow Location	Flow_Location	Where flow was measured.	SSI
	Flow %	Flow_percent	Percent of flow captured (%).	NPS
WATER QUALITY	pH	pH	Measured as close to spring source as possible.	SSI
	Specific Conductance	Conductivity_uS	Measured as close to spring source as possible (µmho/cm).	SSI
	Temperature	Water_Temp_C	Measured as close to spring source as possible (°C).	SSI
	Major ions	---	*Reference springs only.* Ca, Mg, Na, K, Cl, SO_4, NO_3.	SSI
	Minor and trace ions	---	*Reference springs only.* As, Cu, Fe, Mn, Pb, and Zn	
	Alkalinity	---	*Reference springs only.* Field and laboratory analysis.	SSI
	Stable Isotopes	---	*Reference springs only.* Oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$).	SSI
BIOLOGICAL CONDITIONS	Vegetative Bed Cover	Veg_Bed_Cover_percent	The proportion of the spring pool bed or channel bed that is covered by live vegetation (%).	NPS
	Vegetative Bank Cover	Veg_Bank_Cover_percent	The proportion of the spring pool banks or channel banks that is covered by live vegetation (%).	NPS
NOTES	Notes	Notes	Other notes as necessary.	NPS
	Global ID	GlobalID	Automatically generated unique and global ID	
	GPS time and date	gps_time_date	Automatically generated GPS time and date stamp	

Number of satellites	sat_signals	Automatically generated number of satellites visible

References used in the development of the field protocols:

Florida Department of Environmental Protection, 2007. Florida Springs Initiative, program summary and recommendations, 2007, 43p.

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APPENDIX B

Pond Field Data

The following data were collected and recorded for each of the ponds surveyed during the 2014-2017 statewide springs inventory. Surveyed ponds are located in headwater settings, but discrete springs flowing close to 0.25 cfs were not observed during field visits. This pond feature class is very limited; efforts to visit or survey ponds were not exhaustive.

CATEGORY	VARIABLE	WORKING FIELD NAME	DESCRIPTION
GENERAL SITE DESCRIPTION	Pond ID	PondID	Unique identifier within county.
	County	County	County where spring is located.
	Surveyor(s)	Surveyor	Who conducted the survey (initials for Grace Graham, Emma Hall, Sue Swanson,).
	Date	Date	Date of field survey.
	Time	Time	Start time.
	Easting	Easting_WTM	Easting (WTM).
	Northing	Northing_WTM	Northing (WTM).
	Horizontal Precision	Horz_Precision_m	Horizontal accuracy of GPS position (meters).
	Maximum PDOP	Max_PDOP	Maximum positional dilution of precision (PDOP) during measurement.
	Elevation	Elevation_m	From digital elevation model (DEM) (meters).
	Elevation Source	Elevation_source	DEM source and horizontal resolution of DEM used to extract elevation.
	Land Ownership	Land_Owner	List: state, county, city, NPS, USFS, tribal, military, private, other.
	Photographs	---	Photos of pond, looking upstream and downstream from position of discharge measurement, others as necessary.
FLOW	Discharge	Discharge_cfs	Pond outflow (cfs).
	Flow Accuracy	Flow_Accuracy	Level of accuracy of flow measurement, List: low, high
	How Measured	Discharge_Meas	List: timed volume, float velocity method, flume, AAA meter, AD meter (acoustic Doppler meter), EM meter (electromagnetic meter).
NOTES	Notes	Notes	General notes as necessary.
	Global ID	GlobalID	Automatically generated unique and global ID.
	GPS time and date	gps_time_date	Automatically generated GPS time and date stamp.
	Number of satellites	sat_signals	Automatically generated number of satellites visible.

APPENDIX C

Sites investigated, but not surveyed

This feature class includes all features that were investigated, but not surveyed during the 2014-2017 Statewide Springs Inventory, conducted by staff at the Wisconsin Geological and Natural History Survey (WGNHS).

The goal of the Statewide Springs Inventory was to characterize all springs in Wisconsin that discharge about 0.25 cubic feet per second (cfs) or higher. Features with the greatest potential to meet the flow criterion were identified following selection procedures described in the Methods section of this report. This dataset provides explanations for why features that were initially identified were not surveyed.

The feature class fields are defined below.

County
County.

Easting
Easting (WTM)

Northing
Northing (WTM)

Spring_ID
The Spring IDs included in this feature class were carried from the shapefile of historical spring data compiled by Macholl (2007). Each Spring ID corresponds to the historically mapped feature that was investigated. In cases where the position of the feature was moved according to field observations, the Macholl Spring ID was still maintained. New features that were reported during this project, which were not included by Macholl, were all assigned a Spring ID of 999999.

Original_Source
Although most of the springs were identified from the shapefile of springs data compiled by Macholl, the original sources of the data are recorded in the attribute table of this feature class. Springs investigated are attributed to the following sources:

- WCD Spring Survey: Wisconsin Conservation Department (WCD) spring surveys, conducted from 1956 to 1962. Springs were surveyed for the purpose of trout management and fishery development. Surveys were conducted on a county-by-county basis, and the project covered about 2/3 of the state.

- Surface Water Inventory: WDNR Surface Water Resources publication series (1961-1985), for the Lake and Stream Classification Project. Surveys were conducted on a county-by-county basis.

- Bordner Survey: Wisconsin Land and Economic Inventory Maps (1927-1947), otherwise referred to as the "Bordner Survey". The purpose of the project was to inventory the land resources of Wisconsin. Contributors visited every quarter-quarter section of almost every county.

- Fermanich et al., 2006: Comprehensive surveys of springs in Brown and Calumet Counties. Fermanich, K., Zorn, M., Stieglitz, R., Waltman, C.S., 2006, Mapping and Characterization of Springs in Brown and Calumet Counties: UW-Green Bay, Final Report to the DNR, 56 p. plus appendices.

- Grote, 2007: Comprehensive surveys of springs in St. Croix County. Grote, K.R., 2007, Identification and Characterization of Springs in West-Central Wisconsin, University of Wisconsin, Eau Claire, 33p. plus appendices.

- Swanson et al., 2007: Comprehensive surveys of springs in Iowa and Waukesha Counties. Swanson, S.K., Bradbury, K.R., Hart, D.J., 2007, Assessing the Ecological Status and Vulnerability of Springs in Wisconsin: WGNHS Open File Report 2007-04, 15p. plus appendices.

- recent study: other miscellaneous studies not referenced in Macholl (2007)

- 1:100,000-scale topographic maps: USGS County Map Series (1986)

- local expert: including WDNR fisheries staff, WDNR wildlife biologists, county conservation offices, foresters, UW-system staff and faculty, and private land owners.

- GNIS spring: U.S. Geological Survey, Geographic Names Information System (GNIS): (https://geonames.usgs.gov/)

Reason_not_surveyed

Sites investigated, but were not surveyed for the following reasons:

- Area is inaccessible, based on field observations
- Area is inaccessible, based on aerial imagery
- Could not contact owner and could not confirm presence of spring
- Could not contact owner, pond visible on aerial imagery
- Could not contact owner, but presence of a large spring was confirmed by other recent studies
- Owner unaware of distinct spring

- Spring present, but too small to survey, based on owner description
- Spring present, but too small to survey, based on field observations*
- Confirmed presence of spring through conversation, but permission to access not granted
- Confirmed presence of spring through observation, but permission to access not granted*
- Contacted owner, but could not confirm presence of spring, and permission to access not granted
- No distinct spring observed in field
- State Fish Hatchery

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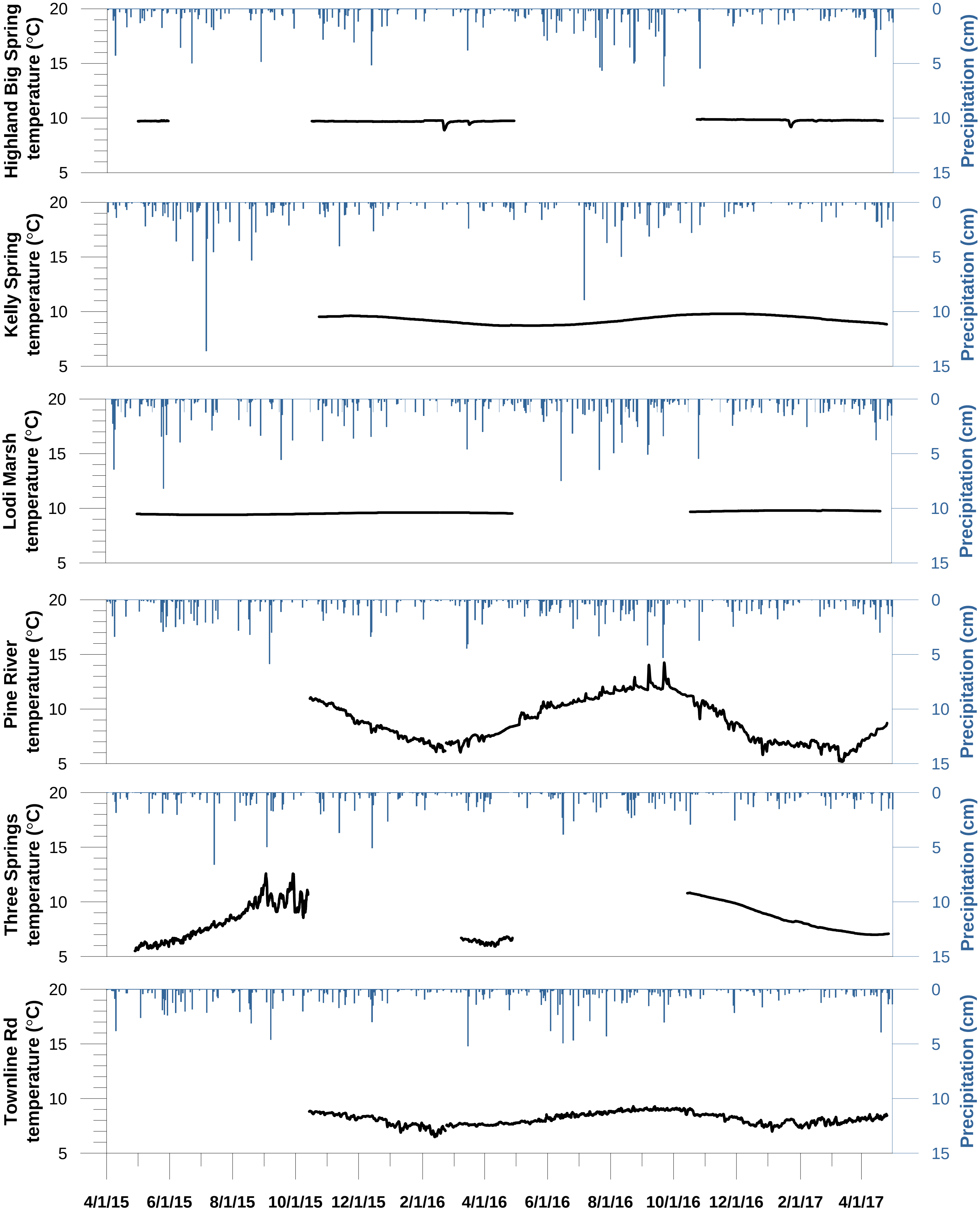
*While compiling this feature class, the positions of certain springs were moved to match where a spring was actually observed during a field visit. Locations were adjusted in the office using aerial imagery and LiDAR or NED DEMs as a guide. Positional corrections were applied to springs that were not surveyed for the following reasons:

-Confirmed presence of spring through observation, but permission to access not granted
-Spring present, but too small to survey, based on field observations

APPENDIX D



Highland Big Spring temperature (°C)
Kelly Spring temperature (°C)
Lodi Marsh temperature (°C)
Pine River temperature (°C)
Three Springs temperature (°C)
Townline Rd temperature (°C)
Precipitation (cm)
20
15
10
5
0
5
10
15
4/1/15
6/1/15
8/1/15
10/1/15
12/1/15
2/1/16
4/1/16
6/1/16
8/1/16
10/1/16
12/1/16
2/1/17
4/1/17

APPENDIX E

This work was supported by the Wisconsin Department of Natural Resources. We thank the many property owners who assisted in this effort by sharing information and allowing access to their springs. We also thank the many other local land managers, fishery and wildlife biologists, foresters, and county extension agents who contributed background information. Sincere thanks to Rick Blonn, Tyler Burgett, Emma Hall, Emma Koeppel, Dexter Kopas, Ava Krahn, Monica Norton, and Christine Shonnard, who provided valuable assistance in the field.