



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

Inventory and analysis of flowing artesian wells in Bayfield County, Wisconsin

Final report to Bayfield County

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Wisconsin Geological and Natural History Survey

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Introduction

Bayfield County initiated a county-wide inventory of flowing artesian wells in August 2022. The work was funded by the Wisconsin Department of Natural Resources (WDNR) Surface Water Grant Program and conducted with the support of the Wisconsin Geological and Natural History Survey (WGNHS) and Bayfield County departments including Health, Planning and Zoning, Land Records, Land and Water Conservation, and Administration. Flowing artesian wells can provide a reliable source of high-quality water that both community members and tourists value. The inventory is intended to support water-resource protection and management related to the Bayfield Peninsula's unique artesian aquifer.

Purpose and Scope

Building on data compiled by the WGNHS in 2019 for the Hydrogeologic Atlas of Bayfield County (Graham and others, 2019), this project was designed to map and describe flowing artesian wells, survey their water quality, and describe surrounding land uses. In support of these goals, the WGNHS was tasked with:

- Reviewing existing databases and the county atlas to identify likely flowing artesian wells in the county and developing a GIS layer of these wells.
- Working with Bayfield County to develop a survey method for identifying well owners willing to have wells visited and sampled.
- Developing a handout or information sheet that could be used during well visits to let people know about the project.
- Developing a protocol for characterizing and sampling wells and creating and defining a list of attributes for each well.
- Visiting, sampling, and describing wells.
- Conducting a literature search about historic artesian conditions in the area.
- If possible, constructing a potentiometric map of artesian head and identifying areas of artesian pressure or flow.
- Conducting a literature search on protection measures for flowing artesian wells.
- Meeting with county staff and stakeholders to discuss the projects.
- Presenting results at a public meeting.

Deliverables from the WGNHS included this report and a flowing artesian well database (see Supplemental material).

Setting

Artesian wells exist where the groundwater in a well rises to a level that is above the top of the aquifer. If the water level in a well rises above the ground surface, this is called a flowing artesian well (fig. 1). Water in an artesian well rises to a level determined by the amount of fluid pressure in the aquifer at the depth of the well opening. Flowing artesian wells tap into groundwater with high enough fluid pressure to rise above the well top and spill over.

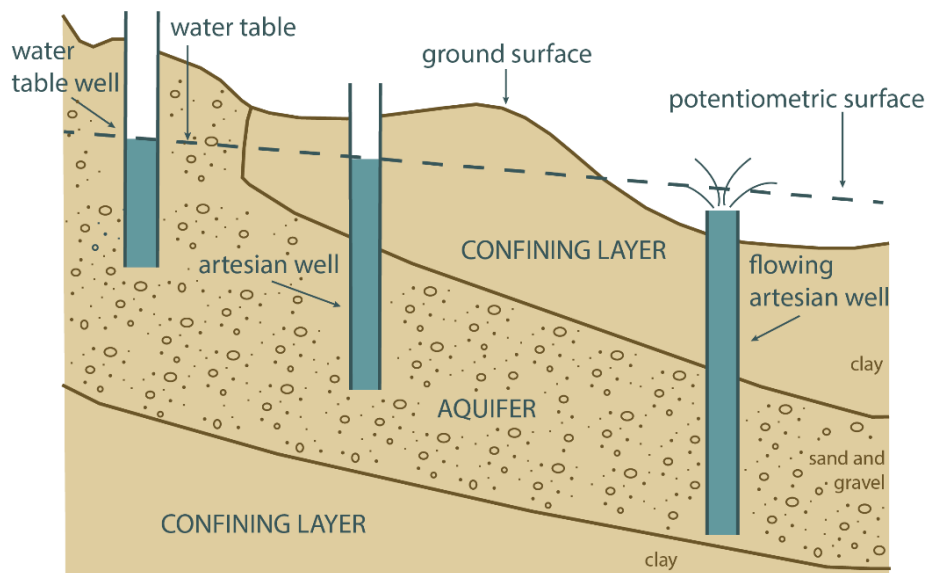


Figure 1. Generalized geology that creates artesian conditions. Modified from Ontario Ministry of the Environment, Conservation and Parks (MECP) (2015).

The geology of the Bayfield Peninsula that leads to artesian conditions is similar to what is shown in the diagram above (fig.1) and the map in figure 2. Sand and gravel (Copper Falls Formation) were deposited by meltwater streams as glaciers retreated northward before about 11,500 years ago. When glaciers readvanced into the region between about 11,500 and 9,500 years ago, the ice surrounded the sandy uplands of the Bayfield Peninsula, lakes formed in the clayey lowlands, and clay-rich material was deposited (Miller Creek Formation) (Clayton, 1984). Today the extensive layers of clay close to the Lake Superior shoreline confine the underlying sand and gravel and sandstone aquifers. In addition, the slope of the land surface is steeper than the slope of the water table. These combined conditions can result in both artesian wells and flowing artesian wells.

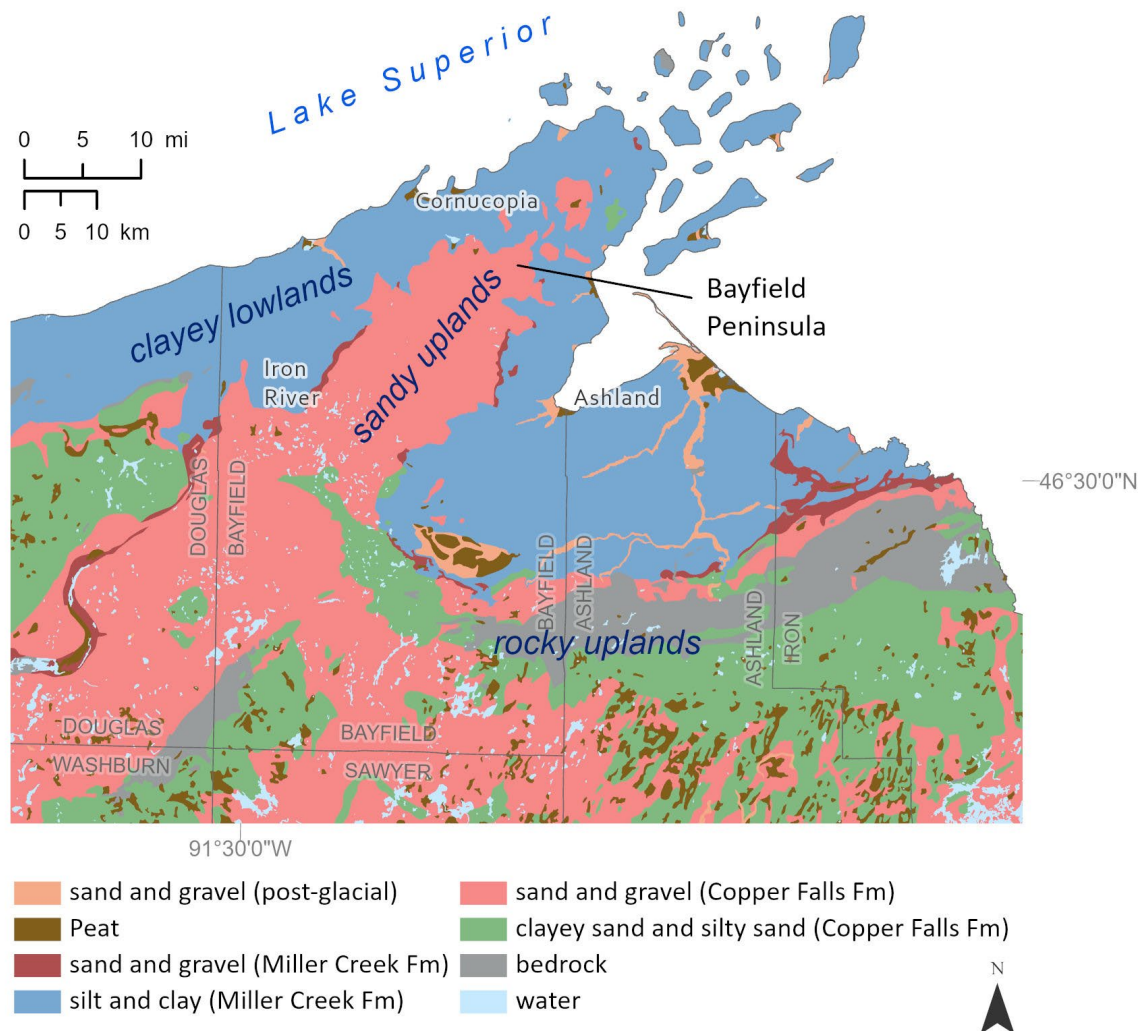


Figure 2. Generalized geology of the Bayfield Peninsula. Modified from Clayton (1984) and Graham and others (2019).

Methods

Well Identification

WGNHS staff identified flowing artesian wells from a variety of sources including well construction report (WCR) databases, WDNR maps, responses to media reports, reports by Bayfield County Board members, and reports by City of Ashland employees. These records and responses suggested the existence of up to 166 flowing wells in Bayfield County with concentrations of wells along the eastern coastline of the Bayfield Peninsula and near Ashland, Cornucopia, and Iron River. Letters and/or emails were sent to property owners seeking

permission to survey and describe wells. WGNHS staff received permission to visit 50 wells. Eight wells could not be located and were presumed abandoned, or the wells were no longer flowing. Four well locations were inaccessible due to forest road closures.

Sampling Protocol

WGNHS staff conducted well inventories in October 2022. All entries in the resulting database of flowing artesian wells include information on property ownership (e.g., private, county, etc.) and well use. While in the field, WGNHS staff recorded the position of each well and noted site conditions in the vicinity of the well including land use and the presence of nearby wells, springs, or seeps. They described well characteristics such as presence of a pump, a control valve, a screened outflow, or structures to divert water away from the well. These characteristics complement WCR information (e.g., well depth, well diameter, stickup height, casing depth, year installed), where available. Photographs were taken to document well conditions during the visit.

The technique used to measure outflow from a flowing well depended on well conditions and flow rate. Options included measuring the time it took to fill a specific volume of water or using a cutthroat flume, which is a portable device that can measure water flow in a channel with a low slope. Flow could not be measured at all locations.

Water samples were collected as close to the wellhead as possible and from well overflow rather than a tap, where feasible. An Oakton PC450 field meter measured well water pH, conductivity, and temperature. Water samples were collected, field filtered, and then analyzed for alkalinity, chloride, nitrogen, and metals at the University of Wisconsin–Stevens Point Water and Environmental Analysis Laboratory (<https://www.uwsp.edu/cnr-ap/weal/>). Water samples were analyzed for stable isotopes of oxygen and hydrogen ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) by the Iowa State University Stable Isotope Lab (<https://siperg.las.iastate.edu/stable-isotope-lab-sil/>). Samples from nine flowing wells in Bayfield County were analyzed for tritium content by the University of Waterloo Environmental Isotope Laboratory (<https://uwaterloo.ca/environmental-isotope-laboratory/analytical-services/water-samples>).

Results

Historical Artesian Conditions

Only 25% of the 166 flowing wells that were initially identified have historical flow rates, and the measurements span 85 years, which creates challenges in describing historical flow conditions. Similarly, only 57% of the historical wells have artesian head measurements (Dataset 1). The limited artesian head data precluded widespread potentiometric surface mapping, but local and general potentiometric maps of historical artesian head were drafted for areas near Cornucopia and Iron River (fig. 3). These general maps may provide the basis for future mapping efforts if artesian head measurements are made at new or existing flowing artesian wells.

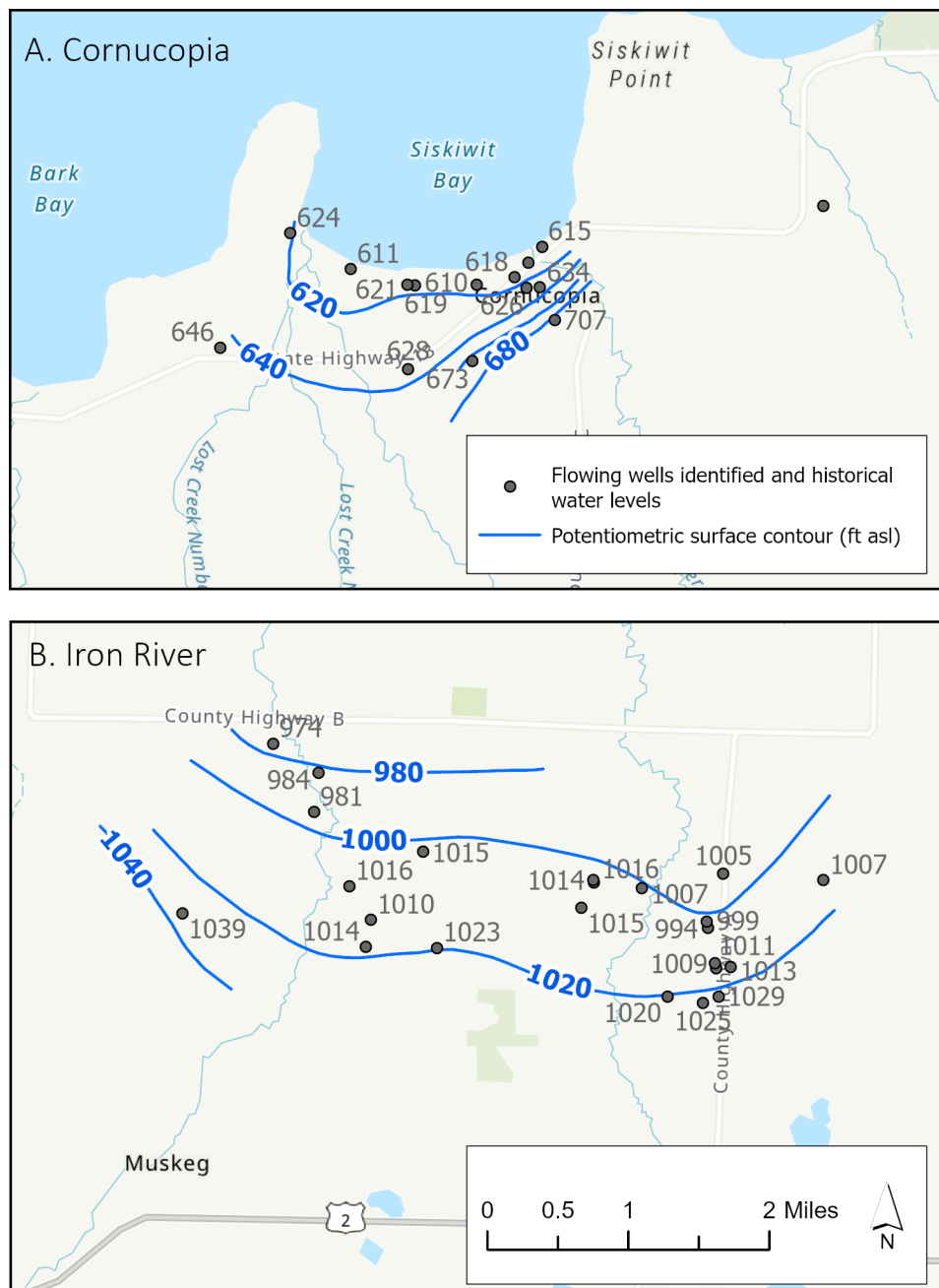


Figure 3. Generalized potentiometric surface near A) Cornucopia and B) Iron River, based on historical water levels reported on WCRs. Contours use a 20-ft interval, ft asl = feet above sea level. Basemap from Esri World Topographic Map.

Flowing Artesian Well Characteristics

A total of 50 flowing artesian wells were surveyed (Datasets 1 and 2). The wells are located in low-lying areas across Bayfield County, primarily in areas where silt and clay or peat is at the

surface (fig. 4). The majority of wells (35) were located on private property, and the most common land uses in the immediate vicinity of the wells are forested lands followed by residential or other developed lands. Pumps were installed at 29 wells, and 11 were equipped with a valve. The mean flow rate from the wells was 6.9 gallons per minute (gpm), and the median flow rate was 1.5 gpm.

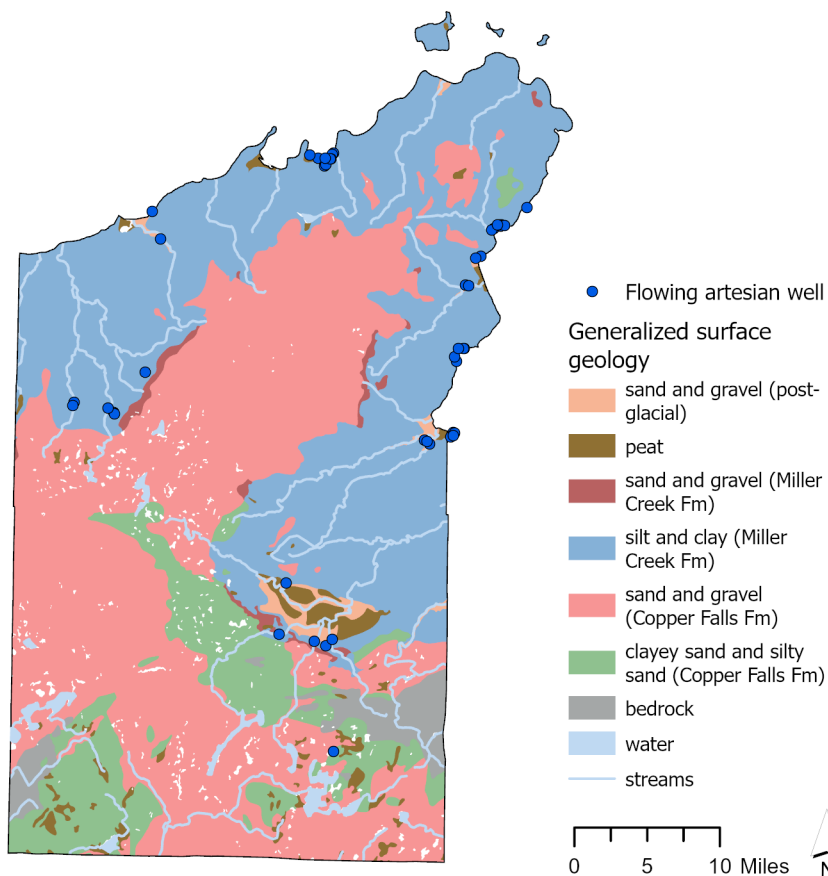


Figure 4. Positions of flowing artesian wells within Bayfield County. Generalized surface geology modified from Clayton (1984) and Graham and others (2019).

Water Quality

Dissolved Ions

A measure of the accuracy of water analysis data is called the charge-balance error. It compares the sum of the negative ionic charges in a solution to the sum of the positive ionic charges and expresses the difference from equality as a percentage. Water analysis laboratories generally consider a charge-balance error of less than about 5% to be acceptable. All samples had charge-balance errors <3%. Charge-balance errors for all samples are recorded in the flowing artesian well database (Dataset 1) along with the water analysis results.

Most of the flowing artesian wells had relatively low concentrations of dissolved ions and fairly similar water quality. Based on the single sampling event in September 2022, the majority of

wells had low specific conductance, which is a measure of the concentration of total dissolved solids (TDS) (table 1). Most of the wells also had calcium-bicarbonate groundwater, meaning calcium and bicarbonate are the dominant ions. A single well, considered an outlier, had a specific conductance of 1460 $\mu\text{S}/\text{cm}$ (at 25°C) and sodium-chloride groundwater.

Table 1. Major ion concentrations and specific conductance measurements for flowing wells in Bayfield County (samples collected in September 2022).

Analyte	Units	Mean ¹	Standard Deviation ¹	Minimum ^{1,2}	Maximum ¹	Detection Limit
Specific Conductance	$\mu\text{S}/\text{cm}$ at 25°C	230	87	110	485	1
Hardness	mg/L	95.3	33.6	47.7	202.0	0.02883
Calcium	mg/L	24.7	7.6	13.7	48.5	0.020
Magnesium	mg/L	8.2	3.9	3.3	19.7	0.007
Potassium	mg/L	1.4	0.7	0.6	3.2	0.015
Sodium	mg/L	6.4	6.2	1.3	29.6	0.234
Alkalinity	mg/L	97.7	32.4	51.0	188.0	4.0
Chloride	mg/L	8.4	14.5	ND	75.0	0.5
Nitrate + Nitrite, as N	mg/L	0.5	0.6	ND	2.2	0.1
Sulfate	mg/L	4.2	2.9	0.1	15.1	0.06

¹ Summary statistics exclude outlier with much higher conductivity and sodium-chloride groundwater.

² ND = not detected.

Although overall water quality is high, a few samples were elevated in one or more water quality parameters. Public health drinking water standards are established to protect public health by limiting the levels of contaminants in groundwater and drinking water (table 2). Public welfare standards are established for substances that affect the cosmetic or aesthetic quality of the water (table 3). Wisconsin's NR140 Public health and public welfare enforcement standards (ES) are based on federal Safe Drinking Water Act standards. Wisconsin's NR140 preventive action limits (PAL) are set at a percentage of an established ES concentration (typically 10–20%). One sample slightly exceeded the Wisconsin NR 140 public health ES for manganese. Four other samples exceeded the public health PAL, the public welfare ES, or the public welfare PAL for manganese. Several samples exceeded the public health PAL for arsenic. Manganese and arsenic are both naturally-occurring elements in minerals and rocks. Each has been previously detected at similar levels in other wells in Bayfield County (Groundwater Center, 2022). Dissolved nutrients, such as nitrate, were typically near or below detection limits except for one sample that slightly exceeded the public health PAL. Where well water with an exceedance of a Wisconsin NR 140 public health standard is used for drinking water supply, owners should be

encouraged to test their well water again to determine accuracy of the result or to see if levels have changed.

Table 2. Numbers of samples exceeding NR 140 Public Health Standards.

Public Health Standard	Analyte	Number of samples	Standard
Enforcement Standard	Manganese	1	300 µg/L
Enforcement Standard	Arsenic	0	10 µg/L
Enforcement Standard	Nitrate + Nitrite, as N	0	10 mg/L
Preventive Action Limit	Manganese	2	60 µg/L
Preventive Action Limit	Arsenic	22	1 µg/L
Preventive Action Limit	Nitrate + Nitrite, as N	1	2 mg/L

Table 3. Numbers of samples exceeding NR 140 Public Welfare Standards (aesthetic, not health-based).

Public Health Standard	Analyte	Number of samples	Standard
Enforcement Standard	Manganese	1	0.05 mg/L
Enforcement Standard	Iron	2	0.3 mg/L
Enforcement Standard	Chloride	1	250 mg/L
Preventive Action Limit	Manganese	1	0.025 mg/L
Preventive Action Limit	Iron	0	0.15 mg/L
Preventive Action Limit	Chloride	0	125 mg/L

Rain and snowmelt are very dilute, so shallow groundwater in recharge areas also tends to be dilute. As groundwater moves along its flow path in an aquifer, increases in TDS normally occurs (Freeze and Cherry, 1978). Therefore, it would be expected for water samples collected from flowing artesian wells that are closer to a groundwater divide or likely areas of groundwater recharge to be lower in TDS. Water samples collected from flowing artesian wells that are farther from a groundwater divide are likely to be higher in TDS.

Nearly all of the water samples collected from the flowing artesian wells in Bayfield County have similar and relatively low TDS. In regions with small ranges in ion concentrations, hierarchical cluster analysis has been shown to be useful in discerning subtle geochemical differences and objectively identifying meaningful patterns in sampling results (Swanson and others, 2001). Prior to applying this method to the Bayfield County samples (using Ward's linkage method), all analytical data were standardized. Standardization is necessary because some analytes have naturally higher values and vary by tens of mg/L, whereas others have lower values and vary by just a few mg/L (table 1). The analytes chosen for the cluster analysis

were hardness (as a measure of calcium and magnesium concentrations), potassium, sodium, chloride, and alkalinity, because these analytes are good indicators of aquifer materials or human influences on water quality. The dendrogram in figure 5 shows that the cluster analysis resulted in three general groups of wells: Group A contains 25 wells with higher than average levels of dissolved ions, Group B contains 22 wells with lower than average levels of dissolved ions, and Group C contains a single outlier, with very high levels of dissolved ions, as previously discussed.

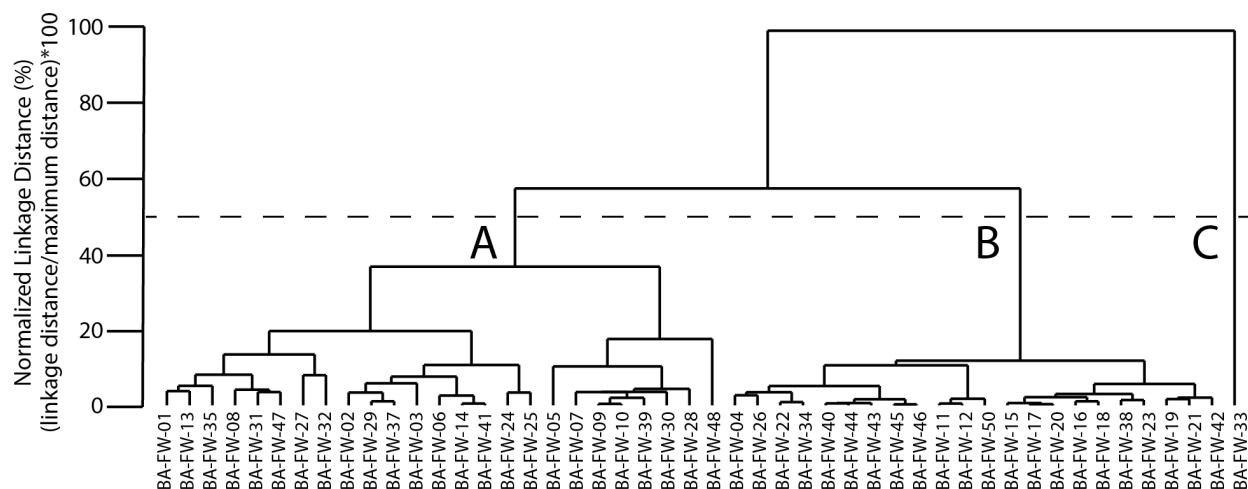


Figure 5. Dendrogram resulting from hierarchical cluster analysis. Dashed line shows a normalized linkage distance of 50%, defining three groups of flowing artesian wells lettered A, B, and C (with a single outlier).

To further illustrate the differences in average dissolved ion concentrations between the two main groups of wells (A and B), Stiff plots were created. Ionic concentrations are converted from mg/L to milliequivalence/L prior to plotting a Stiff diagram. Cations (positively charged ions) plot on the left side of the diagrams, and anions (negatively charged ions) plot on the right. The width of the resulting polygon indicates the concentration of dissolved constituents, and the shape indicates the relative prevalence of the individual ions. For comparison, we also plotted Stiff diagrams for surface and groundwater samples from a recharge area in Bayfield County (Horseshoe Lake and Sandy Uplands wells) (Fehling and others, 2022).

Figure 6 displays the Stiff plots and a conceptual model for how these groups of waters may be related to the chemical evolution of groundwater and the local geology and hydrogeology. Horseshoe Lake and the wells in the sandy uplands have very low dissolved ion concentrations. This is consistent with their positions in a groundwater recharge zone, and the sandy, silicate-rich materials in the sandy uplands (fig. 2) (Fehling and others, 2022). Dissolved ion concentrations in Group B of the flowing artesian wells are higher. This suggests that groundwater residence times (time in contact with aquifer materials) are longer, or that aquifer materials are more easily dissolved. Dissolved ion concentrations in Group A of the flowing artesian wells are higher yet, suggesting longer residence times and longer or deeper groundwater flow paths to these wells.

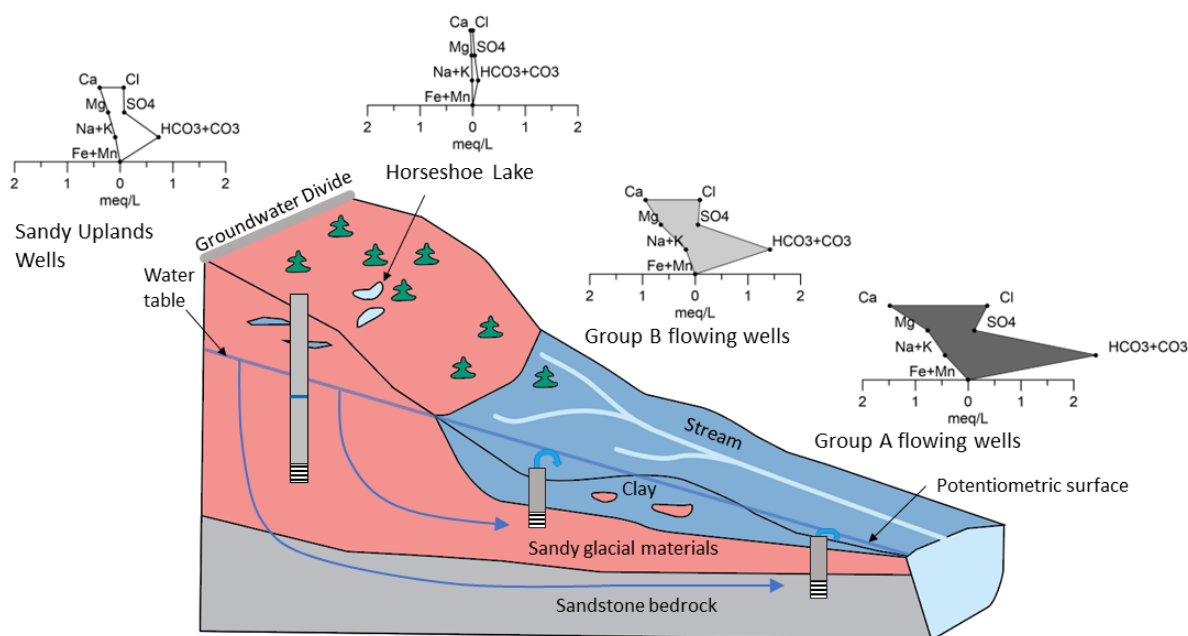


Figure 6. Conceptual model relating water chemistry to the local geology and hydrogeology in Bayfield County. The conceptual model is based on a schematic cross-section from the sandy uplands to the clayey lowlands. Units in the Stiff plots are electron milliequivalents per liter.

Most of the flowing wells in Group B are located along the Bayfield Peninsula, rather than in southern Bayfield County, and on average, these wells are located closer to a groundwater divide, where groundwater recharge is likely to occur (Graham and others, 2019). Although not exclusively, wells in Group A are located farther from a groundwater divide (Graham and others, 2019). Although the Group A well in figure 6 is shown with a well screen that is open to sandstone bedrock, this depiction is simplified. Both well groups include wells screened in sandy glacial materials as well as sandstone bedrock. Differences in distances from a major groundwater divide for the two groups of wells are statistically significant, as determined by a Student's t-test ($\alpha = 0.05$) (table 4). The actual positions of the groups of flowing artesian wells, Horseshoe Lake, and the Sandy Uplands wells within Bayfield County are shown in figure 7.

Table 4. Average distances of groups of wells from a groundwater divide.

Group	Average distance from a groundwater divide (km)	Number of wells	p value
A	13.2	25	0.04
B	10.8	22	0.04

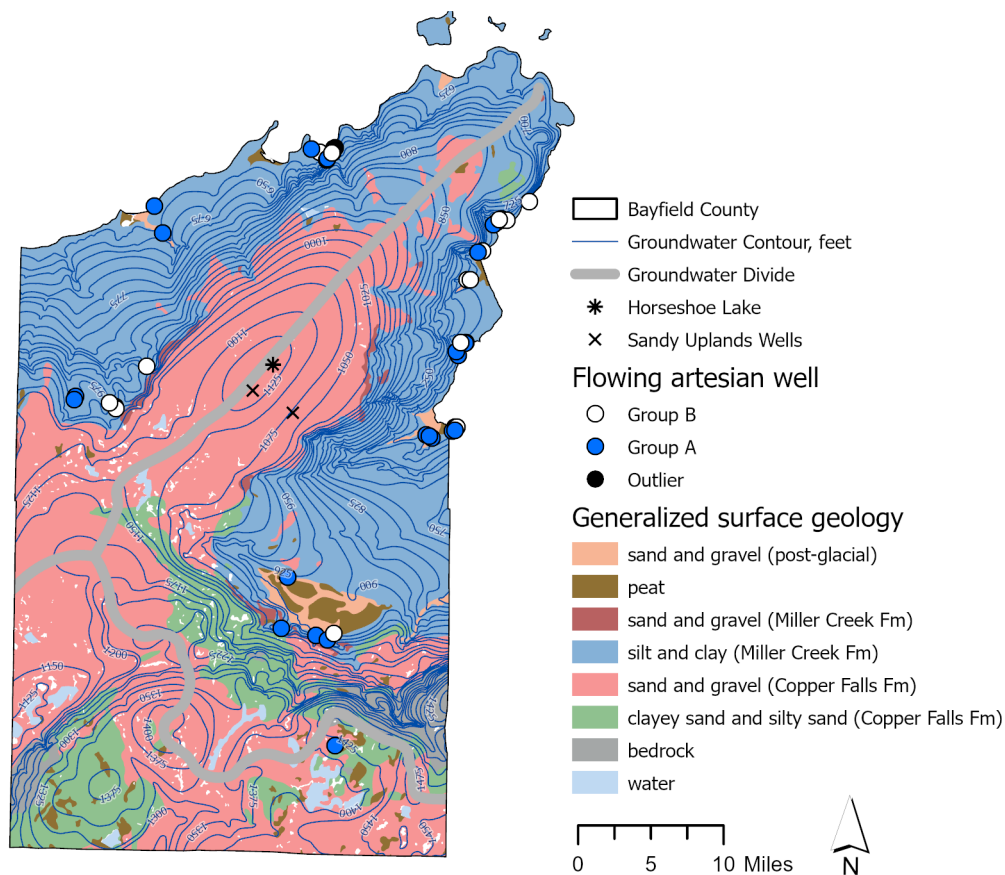


Figure 7. Positions of flowing artesian wells, Horseshoe Lake, and the Sandy Uplands wells within Bayfield County. Generalized surface geology modified from Clayton (1984) and Graham and others (2019). Groundwater contours and divides modified from Graham and others (2019).

Isotopic Analyses of Water Samples

The water samples collected from the flowing artesian wells were also analyzed for stable isotopes of oxygen and hydrogen to assist in understanding source areas and for tritium, a radioactive isotope of hydrogen, to assess groundwater ages. Stable isotopes of oxygen and hydrogen are measured as a ratio of the two most abundant isotopes of each element (^{18}O and ^{16}O or ^2H and ^1H , respectively). Isotopic concentrations are expressed as the difference between the measured ratios of a sample and a standard over the measured ratio of the standard. They are reported as parts per thousand (‰) using the delta (δ) notation. A plot of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$, as in figure 8, can provide information on sources of groundwater or to identify secondary processes such as evaporation. A local meteoric water line (LMWL) that represents the isotopic variation in precipitation for the region is included on the plot. Partitioning of groundwater and surface-water samples along the LMWL can provide information on groundwater recharge environments and seasonality. Samples that plot to the right of the LMWL are indicative of processes that fractionate oxygen and hydrogen isotopes, such as evaporation when the lighter isotopes (^{16}O and ^1H) tend toward the vapor phase while the heavier water isotopes (^{18}O and ^2H) become enriched in the liquid phase (Clark and Fritz, 1997). For example, the stable isotope

measurements for Horseshoe Lake and other lakes in the region plot to the right of the LMWL, indicating evaporative effects. In addition, the isotopic ratio of oxygen and hydrogen in precipitation for a given region changes seasonally. Winter precipitation tends to be lighter (lower left on the graph), whereas summer precipitation is heavier (upper right on the graph).

Group B flowing artesian wells have significantly lighter (more negative and plotting closer to the graph's origin) isotopic signatures than Group A wells ($\alpha = 0.05$) and their signatures are similar to the stable isotope results for the two wells in the sandy uplands (INO-1 and INO-2). This is indicative of cold source water, likely snowmelt recharge (Fehling and others, 2022). Group A wells have significantly heavier (less negative and plotting farther from the origin of the graph) isotopic signatures, which may be indicative of greater mixing along longer groundwater flow paths.

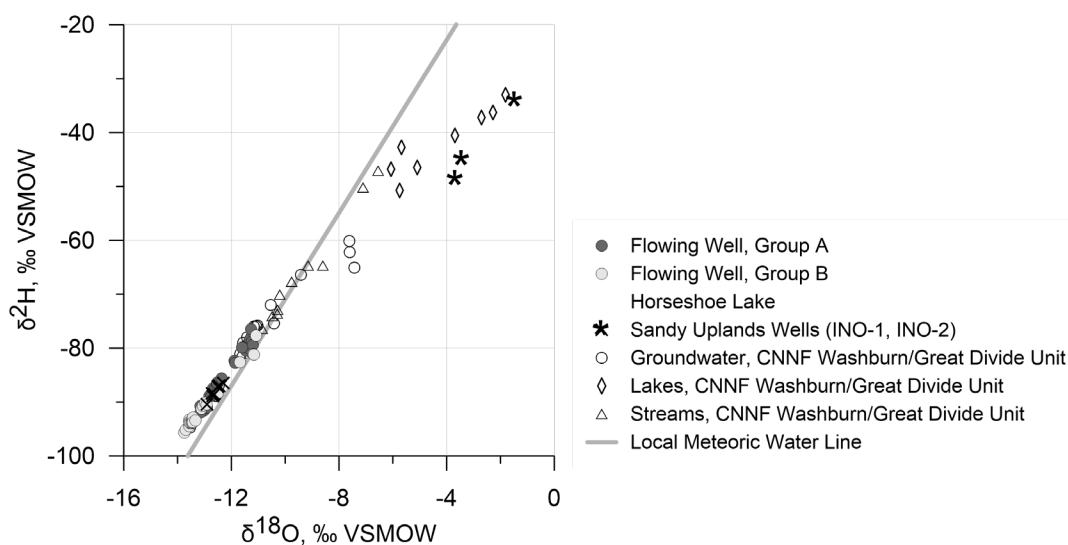


Figure 8. Plot of stable isotope analysis results for flowing artesian wells (Groups A and B), the Sandy Uplands wells and Horseshoe Lake, and other water samples from the Washburn-Great Divide Unit of the Chequamegon-Nicolet National Forest (CNNF) (Fehling and others, 2018; 2022), with the local meteoric water line (Krabbenhoft and others, 1990) plotted in gray. ‰ = parts per thousand; VSMOW: the stable isotope standard Vienna Standard Mean Ocean Water.

Tritium (^3H) is a radioactive isotope of hydrogen with a half-life (the time to decay to half of the original amount) that is equal to 12.32 years. Although it is naturally-occurring, tritium produced by atmospheric testing of nuclear weapons in the 1950s and 1960s resulted in a large increase in atmospheric tritium. Concentrations in precipitation remained elevated for several decades, and where the history of tritium in precipitation and recharge was known, this allowed it to be used to estimate the relative age of groundwater. Concentrations have since decreased to near pre-bomb concentrations. Using methods developed by Lindsey and others (2019), groundwater ages can still be classified as modern (groundwater recharged in 1953 or later), premodern (groundwater recharged prior to 1953), or mixed (a mixture of modern and premodern water).

Samples from nine wells in Bayfield County were tested for tritium content, two in the sandy uplands and seven in the clayey lowlands or in southern Bayfield County near the rocky uplands (fig. 2, table 5). Tritium contents ranged from < 0.8 TU to 5.4 TU. Based on these results and the methods developed by Lindsey and others (2019), water in the two sandy uplands wells (INO-1, INO-2) and BA-FW-4 can be classified as modern, or groundwater recharged in 1953 or later. This is consistent with our understanding of the sandy uplands as a recharge zone (Fehling and others, 2022). The rocky uplands are an area of high elevation that helps to form a major surface-water and groundwater divide, separating water flowing northward to the Lake Superior Basin from water flowing southward to the Mississippi River Basin (Graham and others, 2019). The close proximity of BA-FW-4 to the divide creates the potential for short groundwater flow paths and younger groundwater. Water flowing from clayey lowland wells can be classified as mixed, or neither entirely modern nor entirely premodern (recharged prior to 1953). This is also consistent with our understanding of longer groundwater flow paths to these flowing wells and the mixing of older and younger groundwater that likely occurs along these flow paths.

Table 5. Tritium content in water samples from nine wells in Bayfield County.

Setting	Well Name	Sample Date	Tritium Content (TU) ¹	95% Confidence Interval ($\pm 2\sigma$) ²	Groundwater Age
Sandy uplands	INO-1	04/25/22	3.9	0.7	Modern
Sandy uplands	INO-2	04/25/22	5.4	0.8	Modern
Clayey lowlands	BA-FW-08	04/26/22	0.9	0.5	Mixed
Clayey lowlands	BA-FW-46	04/26/22	< 0.8	0.6	Mixed
Clayey lowlands	BA-FW-19	10/18/22	< 0.8	0.6	Mixed
Clayey lowlands	BA-FW-24	10/19/22	< 0.8	0.6	Mixed
Clayey lowlands	BA-FW-32	10/20/22	1.3	0.7	Mixed
Near rocky uplands	BA-FW-4	10/26/22	4.1	0.7	Modern
Clayey lowlands	BA-FW-47	10/27/22	< 0.8	0.5	Mixed

¹ Tritium is reported in Tritium Units.

² σ = standard deviation.

Summary of Water Analyses

Concentrations of dissolved ions in most flowing artesian wells in Bayfield County are relatively low, which is consistent with high groundwater quality found elsewhere in the region (Fehling and others, 2018). Hierarchical cluster analysis of ion concentrations identified three groups of wells, although nearly all of the wells fell into Groups A and B (fig. 5). Figure 6 displays a

conceptual model for how these groups are related to the local geology and hydrogeology. Group B wells have somewhat lower dissolved ion concentrations and lighter isotopic signatures. On average, they are positioned closer to groundwater divides, where groundwater recharge is likely to occur. These conditions suggest somewhat shorter flow paths to the flowing artesian wells and shorter groundwater residence times (or younger water). As a result, the wells in this group may be more susceptible to contamination by activities at the land surface in the recharge zone. Group A wells have somewhat higher dissolved ion concentrations and heavier isotopic signatures. On average, they are positioned farther from groundwater divides. These conditions may suggest longer groundwater flow paths and longer residence times (or older water). Concentrations of naturally occurring ions are often higher in older groundwater because they dissolve from aquifer materials over longer time periods.

Protection Measures

Flowing wells present unique challenges to well drillers and owners. In addition to proper well construction, flowing wells require different considerations from non-flowing wells in order to maintain safe conditions. The State of Wisconsin has adopted rules pertaining to flowing wells in ch. NR 812 Wis. Adm. Code, including *General drilled type well construction requirements* (NR 812.12 (1)(c)), *Flowing wells and their construction* (NR 812.15) and *Well and drillhole filling and sealing* (NR 812.26). The Wisconsin Department of Natural Resources has also published a factsheet to assist in determining compliance with ch. NR 812 (WDNR, 2020). In addition, if flow is 70 or more gallons per minute, a high capacity well permit is required (NR 820.12(12)).

Wells in Wisconsin should be planned and constructed to conserve groundwater (NR 812.12 (1)(c)). Additional best management practices for flowing wells can be employed to prevent surface erosion in the vicinity of the well; prevent flooding conditions near the well; and prevent groundwater from the flowing well from entering a surface water body and adversely affecting aquatic habitat by changing natural flow, temperature, or chemistry conditions (Ontario MECP, 2015; Michigan EGLE, 2020).

Control of Discharge

Reduction of artesian head in the confined aquifer and loss of flow from neighboring wells can result from uncontrolled discharge of water from a flowing artesian well. To conserve groundwater, uncontrolled flow of water from a well should be avoided. Ideally, flowing wells should be constructed to be capable of controlling or stopping the discharge of water from within the well casing, and flow should be limited to the amount of water needed for an intended use. Some states have enacted laws to require well owners to comply with this best management practice unless a deviation is issued (e.g., Florida Statutes §373.209, Michigan Admin. Code R. 325.1638).

Devices that control the discharge of water should be installed on or in the well and should prevent backflow of water into the well or well casing. Figure 10 shows examples of existing flowing wells in Bayfield County where the ability to control the discharge of water could be beneficial.



Figure 10. Examples of a) uncontrolled discharge of water from within the well casing (BA-FW-49), b) uncontrolled discharge and flooding in the vicinity of a flowing well (BA-FW-06), and c) uncontrolled discharge and surface erosion in the vicinity of a flowing well (BA-FW-20).

Devices or measures to control the discharge of water from a flowing well include valved pipe connections, watertight pump connections, flowing well packer units, flowing well pitless adapters, and the extension of the casing above the static water level elevation. The Michigan Flowing Well Handbook (Michigan EGLE, 2020) and the Ontario Water Supply Wells: Requirements and Best Practices manual (Ontario MECP, 2015) are excellent resources with images and explanations of these methods. In some cases, control of discharge from a flowing well is not practical. For existing flowing wells with high hydraulic head or large flow rate, breakouts of casing seals could occur if an attempt is made to control existing flow. In all cases, well design, water pressure within the well, site environmental conditions (e.g., potential for freezing), and the advice of a licensed water well professional (ch. NR 146, Wis. Adm. Code), should be taken into account prior to installing a device to control the discharge of water.

Overflow Pipes and Erosion Control

If an existing flowing well has been constructed with an overflow pipe from the well, it should ideally direct the overflow water away from the source and away from the outside of the well casing, any soil-based wastewater systems, surface water bodies, buildings, and land not owned by the well owner (Ontario MECP, 2015). Additional protective measures that should be considered for flowing artesian wells equipped with an overflow pipe include installing a splash plate or pad at the outlet of an overflow pipe, if present, to prevent erosion near the point of discharge (Ontario MECP, 2015). Examples of flowing wells in Bayfield County with other types of erosion-control measures are shown in figure 11.



Figure 11. Examples of erosion-control measures near the point of discharge of a flowing well. a) Boulders and cobbles (BA-FW-37), b) Tree stump (BA-FW-04).

Suggested Additional Research Needs

Potentiometric Surface Mapping

Constructing a potentiometric map of artesian head for the entire county was not possible due to the limited number and distribution of flowing artesian wells and the variety of well construction conditions. Methods to measure low-pressure and high-pressure hydraulic head at flowing artesian wells exist, but care must be taken (especially for high-pressure measurements) to avoid damaging the well (Cunningham and Schalk, 2011). Obtaining well owner permissions and contracting with licensed well drillers may allow measurement of hydraulic head at some of the wells. Hydraulic heads could then be used to map the potentiometric surface in limited areas.

Additional Water Quality Sampling

A few additional flowing artesian wells were identified after fieldwork and sampling was complete in fall 2022. These wells, as well as others, could be inventoried and sampled in the future using the protocol established in this study. Water sampling results from newly identified flowing artesian wells, as well as repeated sampling of wells already in the flowing artesian well database could be used to refine geochemical groups and interpretations presented in this report.

Site-specific Assessments of Well Capture Zones

The new information compiled in this report does not allow for the delineation of capture zones for individual flowing artesian wells, but now that positions of flowing artesian wells are

documented, future efforts could identify specific areas of interest in Bayfield County for site-specific assessments of well capture zones. Smaller-scale than what is currently available and three-dimensional mapping of geologic materials in these areas would be helpful in understanding groundwater flow within the artesian aquifer. Groundwater model extent was expanded and linesink strings in an existing analytic element model (AEM) were refined as part of water table mapping for the Bayfield County Atlas. However, this model represents the hydrogeologic system as a single-layer system (Graham and others, 2019). Using the available AEM and additional geologic data would allow creation of one or more finite difference inset models in specific areas of interest, which would allow 3-D well capture zones to be simulated and mapped.

Summary

This report and the attached supplemental data describe artesian aquifer conditions and the distribution of known flowing artesian wells in Bayfield County, WI. Flowing wells are located in low-lying, clayey areas of the county, with concentrations of flowing wells along the eastern and northern coastlines of the Bayfield Peninsula and inland areas near Iron River and Bibon Marsh.

Records of 166 flowing wells were identified from WCR databases, other maps or archives, and by word-of-mouth. Historical values of artesian head were available for 57% of the records and historical flow rates were available for 25% of the records. Field surveys of 50 flowing wells were conducted in October 2022. The surveys described location, water use, well construction, flow rate, minimum potentiometric surface elevation, and water chemistry conditions as measured in 2022.

Overall, water quality in Bayfield County's artesian aquifer is high. Many parameters that indicate human influences on water quality (for example sodium, chloride, nitrate) were measured at background levels or not detected.

Hierarchical cluster analysis distinguished two general groups of wells (A and B) with minor statistical differences in water chemistry. Wells in Group A have higher amounts of dissolved ions, heavier isotopic signatures, and they tend to be located farther from mapped groundwater divides or recharge areas. These characteristics suggest longer groundwater flow paths and longer groundwater residence times. Tritium results of the Group A wells indicate that the well water is of mixed age (modern and old), a portion of the water discharging at the wells entered the groundwater system as recharge more than 70 years ago. Wells in Group B have lower TDS and are generally closer to recharge areas, suggesting shorter flow paths and residence times to these wells. Tritium was tested for one Group B well, and results indicated modern age water (recharged within the last 70 years.)

Flowing wells present unique challenges to well drillers and owners. In addition to proper well construction, flowing wells require different considerations from non-flowing wells in order to maintain safe conditions. Wells in Wisconsin should be planned and constructed to conserve groundwater (NR 812.12 (1)(c)). Additional best management practices for flowing wells can be

employed to prevent surface erosion in the vicinity of the well; prevent flooding conditions near the well; and prevent groundwater from the flowing well from entering a surface water body and adversely affecting aquatic habitat by changing natural flow, temperature, or chemistry conditions (Ontario MECP, 2015; Michigan EGLE, 2020).

Supplemental material

Supplemental material in this report includes a flowing artesian well database and corresponding photographs of the wells with descriptions of each photograph. For privacy reasons, the locations of wells have been generalized to the center of the corresponding square-mile section. A geodataset with the precise well latitudes and longitudes was provided directly to Bayfield County. See the WGNHS Publication Catalog to download these data: <https://doi.org/10.54915/lttb9848>.

Dataset 1: Flowing artesian well database

A file geodatabase (.gdb format) that includes data layers and tables of both current flowing artesian wells and historical flowing artesian wells in Bayfield County.

Dataset 2: Photos of flowing artesian wells

A photo log (.csv file) and corresponding photos (.jpg format) of flowing artesian wells.

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