ASSESSING THE VULNERABILITY OF SPRING SYSTEMS TO GROUNDWATER WITHDRAWALS IN SOUTHERN WISCONSIN

Susan K. Swanson[1]*, Kenneth R. Bradbury*[2]*, David J. Hart*[2]

ABSTRACT

This study supports the accuracy of a historical, regional spring data set in unglaciated and glaciated areas of Wisconsin. It shows that the spatial distribution of springs can be used in association with regional data sets of geochemistry, topography, and geology to reveal important controls on groundwater flow and make initial assessments of the vulnerability of spring flow to groundwater withdrawals. Contact springs emerge from every major stratigraphic unit in Iowa County, which is located in the Driftless Area, but are most commonly associated with the Sinnipee Group, near the upper contact of the St. Peter Formation, or near the upper contact of the Cambrian sandstones. Therefore, aquifer heterogeneities such as vertical and horizontal fractures or partings along major stratigraphic contacts may be particularly important in promoting discrete flow in this region. Spring waters can be distinguished on the basis of some major ion concentrations, yet stable isotope levels and concentrations of most ions are relatively constant, indicating mixing along flow paths and/or a component of flow through porous media. The stratigraphically higher springs with small and shallow recharge areas are likely to be the most vulnerable to groundwater withdrawals. In Waukesha County the spatial distribution of springs is influenced by the glacial topography and the position of the Maquoketa shale subcrop. The differences in geochemical characteristics of spring waters are more subtle, but they support the concept that groundwater flows completely within unconsolidated glacial materials before discharging to some springs, whereas it intersects shallow bedrock before discharging to others. Because regional pumping from the deep sandstone aquifer has previously been shown to influence shallow groundwater flow paths, springs in this region are likely to be vulnerable to withdrawals from both the shallow and deep parts of the groundwater system.

INTRODUCTION

Because springs are discrete points of groundwater discharge, they are often viewed as isolated features around which preservation or restoration efforts are focused. Hydrogeologic studies of springs in Wisconsin also tend to focus on specific concentrations of springs due to logistical constraints or because studies are prompted by local concerns (for example, Domber, 2000; Hunt and Steuer, 2000; Swanson, 2001). Positions of individual springs on a landscape, like those of streams and lakes, are representative of local or regional groundwater flow patterns. More often than streams and lakes, however, springs are also indicative of heterogeneity of permeability in the subsurface (Manga, 2001). Therefore, spatial analysis of springs across landscapes can reveal important aquifer properties and influences on groundwater flow. An improved understanding of aquifer properties can, in turn, be used to assess the vulnerability of individual springs or spring systems to changes in land use or groundwater withdrawals. One of the purposes of this study was to confirm the accuracy of a historical, regional spring data set for Wisconsin in two distinct geologic settings. The other purpose was to use the confirmed spring data together with regional data sets of geochemistry, topography, and geology to reveal important controls on groundwater flow and make initial assessments of the vulnerability of spring flow to groundwater withdrawals.

The overall methodology involved mapping springs in Iowa and Waukesha Counties, conducting field surveys of representative springs in each county, building a database for the spring-related information, and interpreting these data in association with existing regional information. The approach allows the formulation of hydrogeological conceptual models of springs in these settings, a critical step in assessing vulnerability of spring flow to pumping. The study also marks the first assessment of spring resources in these two regions in approximately 50 years.

[1]Department of Geology, Beloit College, 700 College Street, Beloit, Wisconsin 53511-5595

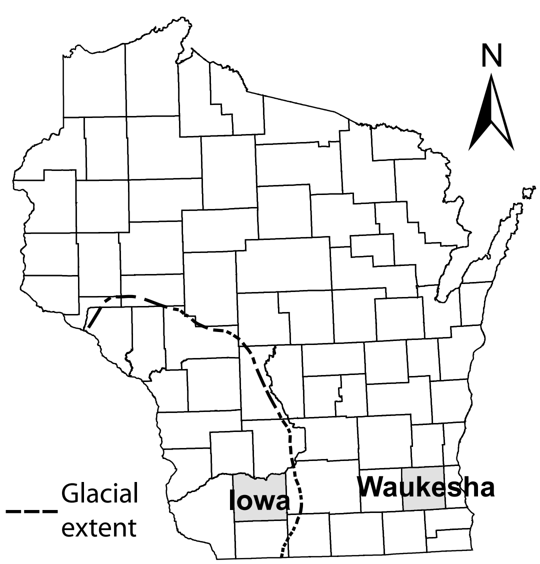
[2]Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension, Cooperative Extension, 3817 Mineral Point Road, Madison, Wisconsin 53705-5100

An understanding of ecological as well as physical characteristics of springs is important in Wisconsin because the 2003 Wisconsin Act 310 requires the Wisconsin Department of Natural Resources (WDNR) to evaluate whether groundwater pumping by new high-capacity wells (≥ 100,000 gallons per day) will result in significant environmental impacts to springs. Therefore, a comprehensive springs classification system, which includes physical, biological, and sociocultural characteristics, was used in the spring surveys (Springer and others, 2008). Data presented here will focus on physical information, but all data are available in Swanson and others (2007).

Study areas

Iowa and Waukesha Counties differ in their topography, geology, land use, and development pressures. Iowa County is located in southwestern Wisconsin in the Driftless Area (fig. 1). Land surface elevations range from 630 to 1,720 feet above mean sea level (amsl), and the region is characterized by nearly horizontal, Cambrian and Ordovician sandstone and carbonate rocks that are exposed in steep and narrow valleys. Pleistocene deposits are absent except for thin layers of loess and/or hillslope sediments on ridge tops and valley sides and stream sediment in valley bottoms (Clayton and Attig, 1997). As of 2003, the primary land uses in the county are agricultural (68%); followed by forested lands (20%); federal, state, and county lands (6%); and wetlands (5%). Urban land uses (residential, commercial, and manufacturing) account for less than 3% of the total land use. The population of Iowa County grew by 13% from 1993 to 2003, but as of 2000 the population was less that 23,000 (SWWRPC, 2005).

Figure 1. *Location of Iowa and Waukesha Counties.*



Land surface elevations in Waukesha County (fig. 1) range from 700 to 1,230 feet amsl, and the bedrock is composed of Cambrian, Ordovician, and Silurian sedimentary strata. The bedrock is overlain by thick (up to 460 feet) Pleistocene deposits throughout much of the county. One of the most prominent glacial features in the county is the Kettle Moraine, which is an irregular ridge extending from the southwest corner to the northcentral edge of the county (Clayton, 2001). Units older and deeper than the Ordovician Maquoketa Formation are lumped together and referred to as the deep sandstone aquifer for purposes of describing and modeling regional groundwater flow. Other important aquifers are the shallow bedrock aquifers, including the Silurian dolomite aquifer, and the overlying sand-and-gravel aquifer, which is composed of alluvial sediments and outwash (Feinstein and others, 2005).

Waukesha County, along with much of southeastern Wisconsin, is one of the most rapidly developing regions of the state. The rate of land conversion from rural to urban uses during the 1990s was approximately 4.7 square miles per year, and the current population of Waukesha County is over 377,000. In 2000, agricultural (30%) and natural areas (27%) remained the largest land uses; however, urban land uses rose from 29% to 37% in the preceding ten years. Much of the increase in urban land uses is attributed to the area of land used for residential purposes (Waukesha County Department of Parks and Land Use, 2006).

PROCEDURES AND METHODS

Historical information

Spring locations in Wisconsin were documented during the original Federal General Land Office Survey of Wisconsin, which began in 1833, and later during the Wisconsin Land Economic Inventory, which ran from 1927 until 1947. However, the most complete historical information on springs was collected by the Wisconsin Conservation Department (WCD) between 1956 and 1968 and covered about 60% of the counties in the state. The WCD gathered data on location, flow rate, land use, and a variety of other spring characteristics relating to their potential to support fisheries. The WCD surveys serve as the primary basis for the historical information on spring locations in Iowa and Waukesha Counties; however, they were supplemented with springs documented in the USGS Geographic Names Information System, WDNR Surface Water Resources reports, Wisconsin Geological and Natural History Survey (WGNHS) publications for southwest Wisconsin (DeGeoffroy, 1969), and publications by local experts (Schoenknecht, 2003).

All historical data were converted to an electronic format by scanning, georeferencing, digitizing, and then saving spring positions as ArcGIS shapefiles. All of the spring attribute data in the WCD surveys were also transposed to a Microsoft Access database. Six-digit unique identifiers were assigned to each spring using the Wisconsin county code and by then numbering the springs in the order they appeared in the WCD surveys. ArcGIS shapefiles and the Microsoft Access database are available in Swanson and others (2007).

Spring locations were verified by identifying the current owners of properties that, according to the historical data, contain springs. Property ownership was determined using land atlas plat books and geodatabases of tax parcels and ownership data supplied by local land information offices. Phone numbers for owners were determined using phone books and on-line resources. WDNR land managers were also identified for state lands. Contact information was found for approximately 68% of the relevant property owners in each county. Owners were contacted and asked whether a spring exists on the land today. If so, the owner was asked to describe the emergent setting, the volume of spring flow, and the persistence of spring flow.

Selection of representative springs

In Iowa County, the geographic positions of historical springs were used in association with property owners' descriptions and physical characteristics of the region to select a set of 26 representative springs to survey. The physical characteristics include elevation, slope, and aspect, as determined from a 10-meter digital elevation model, and stratigraphic position as well as position with respect to stratigraphic contacts, based on the statewide geologic map of Wisconsin (Mudrey and others, 2007). Elevation and aspect can affect the development of microclimates, and slope and aspect can be valuable in predicting the distribution of biota due to variations in solar energy (Wadsworth and Treweek, 1999). Stratigraphic position may indicate the nature of aquifer heterogeneities that are responsible for springs. Assuming that the historical spring locations are accurate, they were overlaid onto the regional datasets to determine if spatial relationships between spring position and the physical property exist. Where relationships are thought to exist, springs were selected so as to closely reproduce the distributions observed in the historical data. In Waukesha County, very few historical springs could be verified (see Results section). Therefore, 20 springs were selected primarily on the basis of property owners' descriptions, access to public or private property, and, to some degree, the geologic setting and geographic distribution of springs within the county (fig. 2).

Spring surveys

Springer and others (2008) identify the need for an integrated springs classification system to further recognition, management, and conservation of spring ecosystems. They have developed a system that builds on the historical Meinzer (1927) spring discharge classification scheme by incorporating a comprehensive set of spring characteristics including information on spring location, weather conditions, site environmental conditions and land use, habitat, vegetation, wildlife, aquatic and terrestrial invertebrates, geomorphic conditions, geologic conditions, flow characteristics, and water quality. Surveys based on this classification system were conducted at the 26 representative springs in Iowa County during June and July 2006 and the 20 representative springs in Waukesha County during July and August 2006. This allowed not only the collection of a broad set of characteristics for each spring, but also the verification of some of the information included in the historical WCD surveys. Teams of three or four researchers spent 2 to 4 hours characterizing each spring.

Standard methods were applied for all field measurements and the collection of all field samples. Spring flow was measured as close to a spring orifice as possible using a mini-current meter, a cutthroat flume, or a bucket and stop watch, depending on channel conditions. Water quality samples were collected at the orifice of each spring and analyzed for concentrations of major ions (calcium, magnesium, sodium, potassium, bicarbonate, sulfate, nitrate, and chloride), iron, phosphorous, total dissolved solids (TDS), and alkalinity. Samples were field-filtered, preserved with sulfuric (nutrients) or nitric (metals) acid, as appropriate, and processed at the Wisconsin State Laboratory of Hygiene. Dissolved oxygen, pH, conductivity, temperature, and alkalinity were also measured in the field. Geochemical results were used to calculate charge balances to ensure that errors were approximately ±5% or less.

Three of the springs in Iowa County were also monitored twice a month in 2006 for the full suite of spring characteristics, including sampling for oxygen-18 and deuterium (fig. 2). Flow was measured once a month. The three springs occur at different stratigraphic positions, elevations, and aspects. They also vary by level of disturbance. A spring near Highland is thought to discharge from the Prairie du Chien Group and occurs on a steep and wooded, south-facing slope. Another spring, near Otter Creek, is thought to discharge from the Jordan Formation. It is encased in a concrete spring pool, which occurs in an open setting, near a valley bottom. The third spring, in Governor Dodge State Park, discharges into a spring house, which is located near the upper contact of the St. Peter Formation with the Sinnipee Group. It was monitored in association with the WGNHS and the University of Wisconsin–Madison (Carter, 2008).

RESULTS

Spring locations

This investigation found approximately 407 and 282 historically documented springs in Iowa and Waukesha Counties, respectively (fig. 2). Contact information was available for 274 property owners in Iowa County, of whom 190 could be reached. Property owners confirmed the presence of 175 of these springs, and access was granted to nearly all of them. Conversations with property owners and observations in the field suggest that the positions of the springs mapped in the Iowa County WCD survey are fairly accurate (at least to the nearest quarter-section) and that many other springs that were not historically mapped also exist in Iowa County.

In Waukesha County, contact information was available for 193 property owners, of whom 138 could be reached. Property owners confirmed the presence of approximately 43 of the historical springs, but access was granted to only 25. Conversations with property owners and observations in the field suggest that the positions of the springs mapped in the Waukesha County WCD survey are also fairly accurate (at least to the nearest quarter-section). However, much of the land that historically contained springs has been developed for residential or commercial purposes. Ponds have also been created on at least six of the properties that once contained distinct springs.

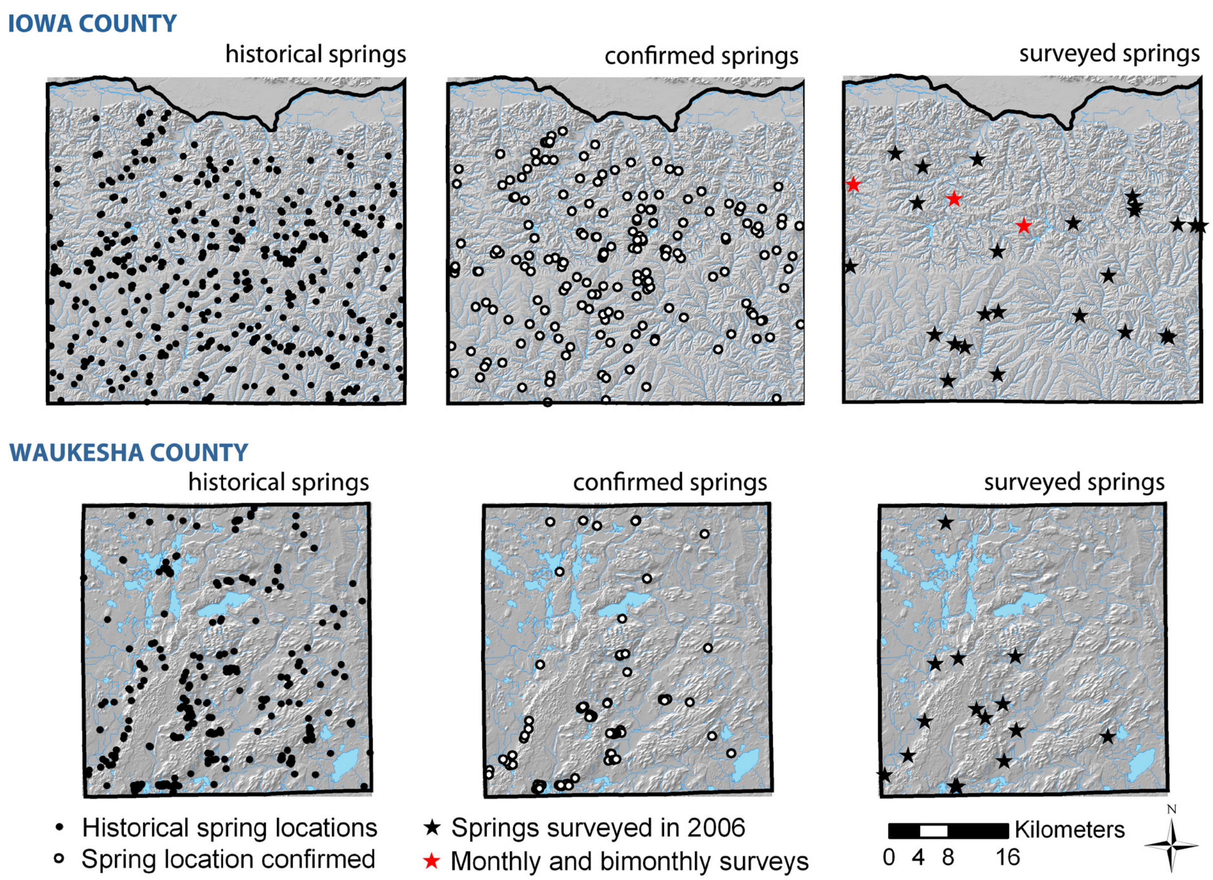


Figure 2. *Distribution of historical, confirmed, and surveyed springs in Iowa and Waukesha County.*

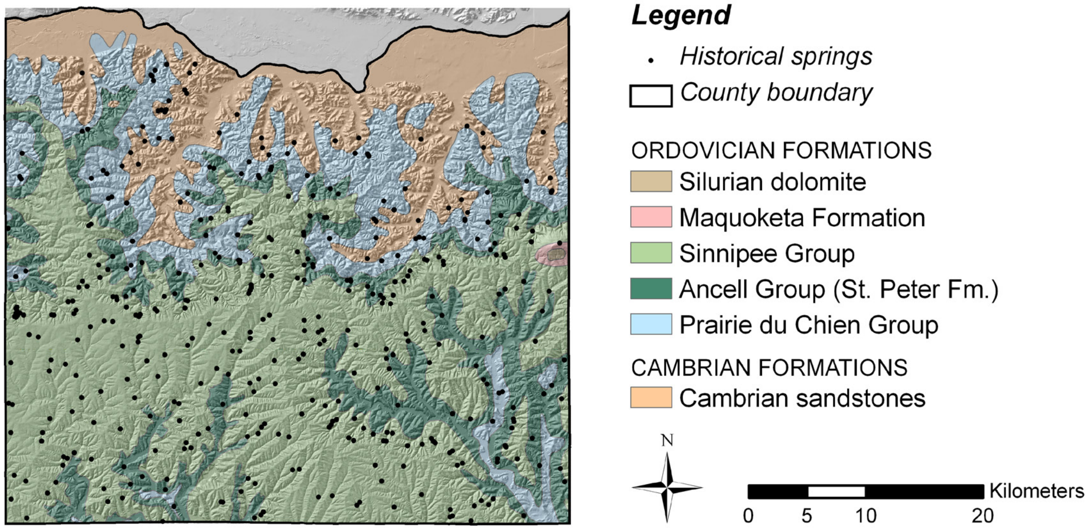


Figure 3. *Distribution of springs and bedrock geology in Iowa County, Wisconsin. Sources: Bedrock geology according to Mudrey and others, 2007; distribution of springs according to a 1958 survey by the Wisconsin Conservation Department.*

Physical characteristics

Access was granted to nearly 175 springs in Iowa County, so the distribution of springs relative to regional physical conditions could be considered in selecting springs for surveys. On the basis of the historical data, springs are associated with every major stratigraphic unit in Iowa County; however, spatial overlays of the historical springs onto the regional bedrock map show that the springs are not distributed randomly across the landscape. They are most commonly found in association with the Sinnipee Group rocks, near the upper contact of the St. Peter Formation with the Sinnipee Group rocks, or near the upper contact of the Cambrian sandstones with the Prairie du Chien Group (fig. 3). The 26 springs selected for surveying are representative of these relationships and the distribution of springs among other stratigraphic units in the county (fig. 4). Springs exist throughout the ranges of elevation, slope, and aspect in Iowa County. However, the distributions of springs relative to these properties do not differ significantly from the countywide distributions of elevation, slope, and aspect ($\alpha = 0.05$), so no distinct relationships between spring position and these three properties are thought to exist. However, in selecting representative springs, an effort was made to choose springs from a variety of elevations, slopes, and aspects, thus helping to ensure that the springs surveyed are representative of the diversity of physical and ecological conditions in the county. Because fewer springs persist in Waukesha County and access was granted to only 25, there was very little flexibility in the selection of springs for surveys in Waukesha County.

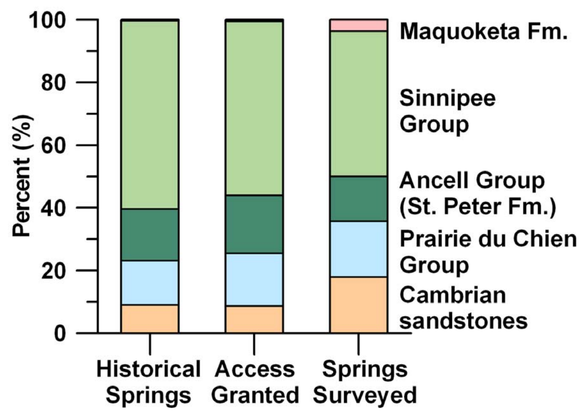


Figure 4. *Distribution of springs within major stratigraphic units, Iowa County.*

Flow was measurable at 36 of the 47 springs that were surveyed. At the remaining 11 springs, channel conditions prevented accurate measurement of flow. The mean spring discharge for the 36 springs where flow was measured in 2006 was 0.24 cubic feet per second (cfs), but the median was 0.08 cfs (fig. 5). Among the springs that were monitored, there is no clear relationship between the magnitude of flow and the major stratigraphic unit from which the spring discharges, nor is there a clear quantitative relationship between the historical flow measurements recorded in the WCD surveys and the spring flow measurements collected in this study. However, higher historical spring flows are generally associated with higher 2006 spring flows (fig. 6).

Figure 7 shows spring flow hydrographs for two of the three springs that were monitored on a monthly basis in Iowa County, the Otter Creek spring and the Highland spring. The flow record for the spring in Governor Dodge State Park is less complete and less reliable. Flow measurements were difficult at the Governor Dodge site because the water depth was too shallow for a current meter, and the bedrock channel hinders the use of a cutthroat flume. Figure 7 shows that the Otter Creek spring responded to seasonal patterns in precipitation, but the response was damped, that is, the total variation in flow was relatively low. Discharge at the spring near Highland was more variable, and may be more sensitive to storm events.

Piper diagrams show the overall similarity in geochemistry among spring waters in Iowa and Waukesha Counties; water discharging from springs in both counties is a calcium-magnesium bicarbonate type (fig. 8). To differentiate possible groundwater flow paths to springs in Iowa County, springs were grouped by the geologic unit from which the spring water is thought to emerge (table 1) and mean concentrations of analytes were then calculated. This approach assumes that the hydrogeologic properties of the geologic units differ enough to treat each unit as a separate hydrostratigraphic unit.

In Iowa County, one-way analysis of variance (ANOVA) tests were used to test for differences among the mean concentrations of major ions in spring waters grouped by geologic unit. Because only two samples are available for springs discharging near the lower contact of the Maquoketa Formation, the ANOVAs were run both with and without this group of springs. The results suggest that mean TDS, pH, and nitrate concentrations in spring waters differ significantly ($\alpha = 0.05$) among major stratigraphic units when the Maquoketa Formation springs are included. When Maquoketa Formation springs are not included, mean pH of spring waters differs at an $\alpha = 0.05$ level of significance and mean TDS and nitrate concentrations differ at an $\alpha = 0.10$ level of significance (fig. 9). Equivalent non-parametric Kruskal-Wallis tests provide similar results.

TDS concentrations in groundwater often increase along a flow path (Freeze and Cherry, 1979). Groundwater flowing along a simplified flow path

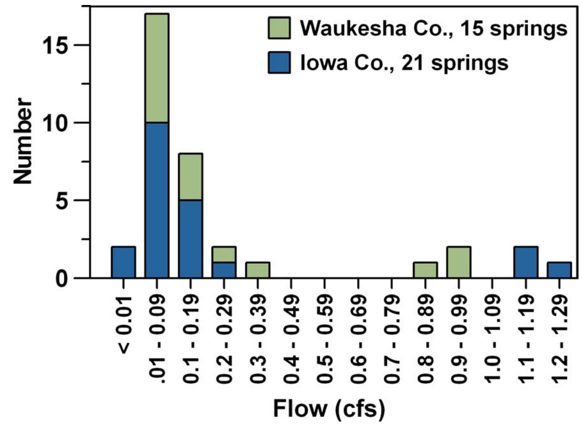


Figure 5. *Spring flow rates in Iowa and Waukesha Counties, June–August, 2006.*

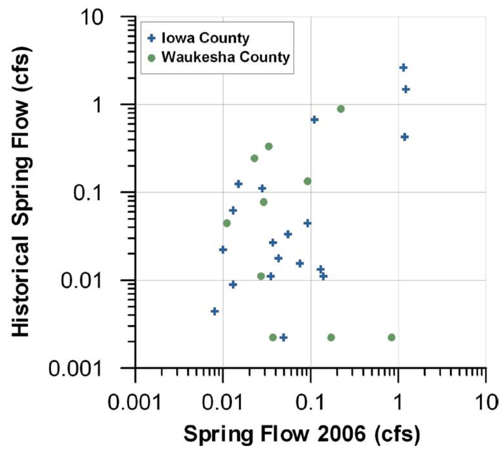


Figure 6. *Comparison of historical and 2006 spring flow rates. (Historical data gathered from Iowa County (1957) and Waukesha County (1958) WCD spring surveys.)*

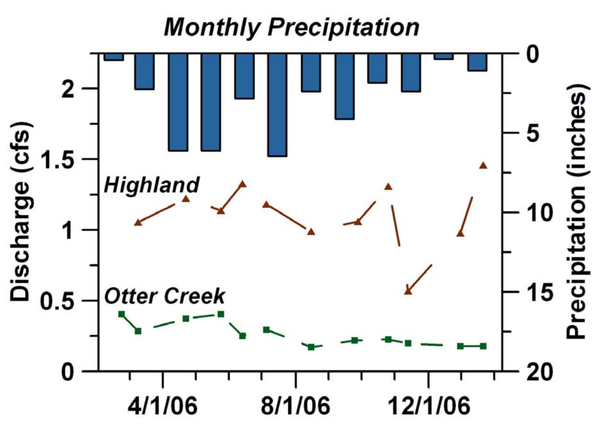


Figure 7. *Spring flow measurements for two springs in Iowa County.*

in Iowa County might be assumed to originate in a recharge area on a ridge and pass through the Sinnipee Group, the St. Peter Formation, the Prairie du Chien Group, and finally, the Cambrian sandstones. However, not all ridges in Iowa County are composed of limestone and dolomite belonging to the Sinnipee Group, and groundwater is probably recharged along some slopes as well as ridge tops. In addition, flow through fractures may dominate in some units, whereas porous media flow dominates in others, resulting in a variety of possible flow paths and residence times. The TDS results from this study support the existence of more complex, as opposed to simple, flow patterns. TDS is high in water discharging from the Sinnipee Group rocks and low in water discharging from the Cambrian sandstones (fig. 9a.). These TDS concentrations may be more representative of equilibrium conditions within particular units rather than the position along a simplified flow path.

Values of pH that are associated with the stratigraphic units in Iowa County are more indicative of a typical chemical evolution path for water dissolving calcite (Freeze and Cherry, 1979). The values increase from a mean pH of 6.9 for water discharging from the Sinnipee Group to a mean of 7.4 for water discharging from the Cambrian sandstones (fig. 9b.). Calcite saturation indexes (SI_{cal}) suggest the same chemical evolution path (fig. 9c.). Index values generally increase (become more saturated) along the simplified flow path; however, differences in the mean SI_{cal} among stratigraphic units are not significant.

Nitrate concentrations are highest and most variable in springs discharging from the Sinnipee Group (fig. 9d). Concentrations are progressively lower and less variable in water discharging from the St. Peter Fm., the Prairie du Chien Group, and the Cambrian

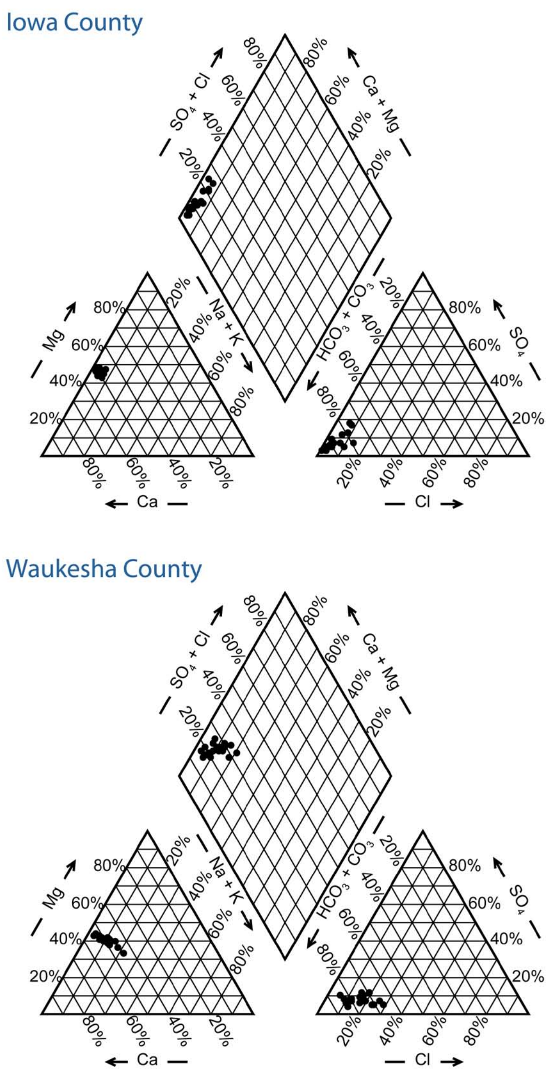


Figure 8. *Piper diagrams for spring waters in Iowa and Waukesha Counties.*

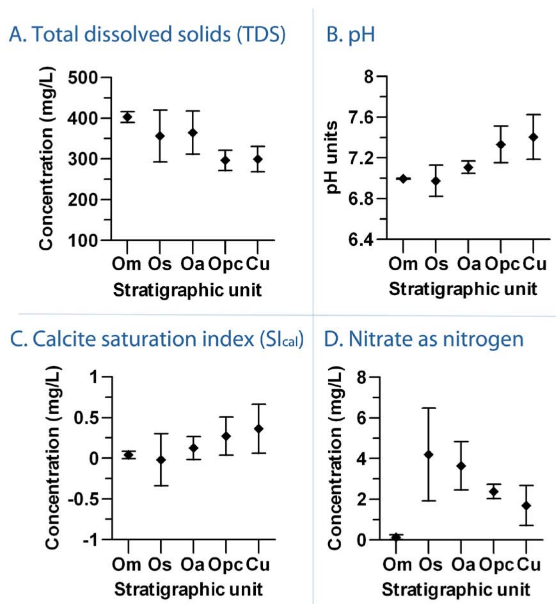


Figure 9. *Average levels of* **(A)** *total dissolved solids,* **(B)** *pH,* **(C)** *calcite saturation index, and* **(D)** *nitrate as nitrogen for spring waters discharging from major geologic units in Iowa County. Error bars represent the standard deviation of the mean. Om = Maquoketa Formation, Os = Sinnipee Group, Oa = Ancell Group (St. Peter Formation), Opc = Prairie du Chien Group, Cu = Cambrian Sandstones.*

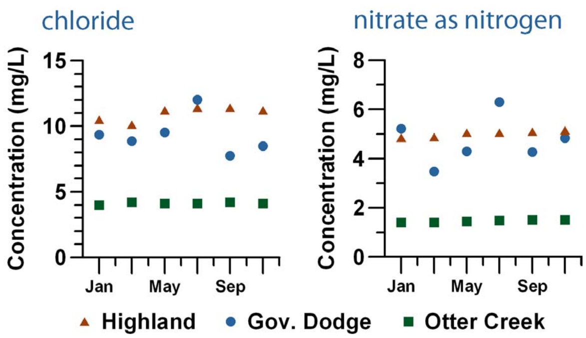


Figure 10. *Concentrations of chloride and nitrate as nitrogen at springs near Highland, Otter Creek, and Gov. Dodge State Park, Iowa County in 2006.*

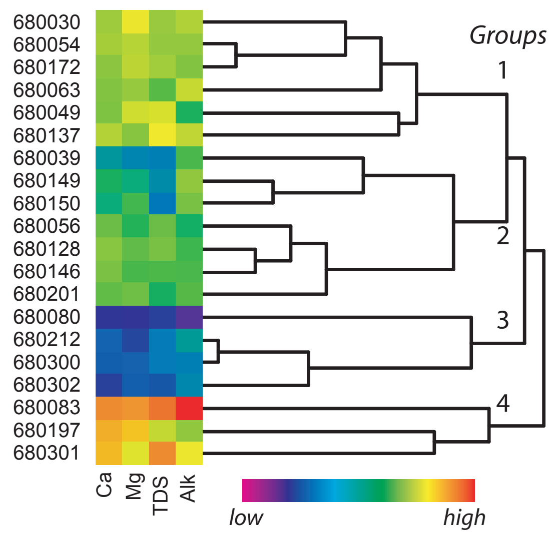


Figure 11. *Cluster analysis results, Waukesha County.*

sandstones. These relationships are not surprising because many areas that are used for row crops coincide with the areas mapped as the Sinnipee Group.

Twice monthly sampling results for the springs near Highland, Otter Creek, and Governor Dodge State Park show very little temporal variation in ion concentrations or in stable isotopes. Even nitrate and chloride concentrations, which could vary in response to seasonal inputs of fertilizers or road salts, are relatively constant (fig. 10). Concentrations of both ions do vary at the Governor Dodge spring. However, samples collected from this spring are the only ones that were not analyzed at the Wisconsin State Laboratory of Hygiene and that have charge balance errors that are consistently greater that 5% (Carter, 2008). Therefore, it is unclear if the variation in concentration is real or is a result of inaccuracies in the analyses. Concentrations of both ions, however, are consistently greater at the stratigraphically higher Highland and Governor Dodge springs.

In Waukesha County, relationships between major ion concentrations and stratigraphic units are less clear. Concentrations of some ions appear to be related to stratigraphic units; however, differences in concentrations among the units are not significant (α=0.05) (table 1). This is not surprising because water discharging to springs in the region also flows through overlying glacial deposits; some springs may exist where groundwater flows exclusively through these unconsolidated materials. Therefore, hierarchical cluster analysis of ion concentrations, which has been shown to be useful in discerning subtle geochemical differences among spring waters (Swanson and others, 2001), was used. Hierarchical clustering successively joins the most similar observations, and Ward's hierarchical clustering method was chosen for this analysis. All analytical data were standardized, by finding the difference between the data point and its mean and then dividing by the standard deviation, prior to performing the analysis. Standardization is necessary because concentrations vary over a wide range among analytes. Readers are referred to Swanson and others (2001) for further details of the approach. The analytes chosen for the cluster analysis are calcium, magnesium, TDS, and alkalinity, because these analytes were thought to be good indicators of aquifer materials. Figure 11 shows that the cluster analysis results in four groups of springs, identified by spring number.

Figure 12 shows the spatial distribution of the four groups of springs overlaid onto a map of the bedrock geology in Waukesha County. Group 1 springs are broadly associated with areas mapped as Silurian dolomite, and Group 2 springs are broadly associated with areas mapped as the Sinnipee Group. Figure 11 shows the similarity between these two groups of springs, which may help explain the position of one of the Group 2 springs (680056) in an area mapped as Silurian dolomite. Group 4 springs are broadly associated with areas mapped as Maquoketa Formation,

Table 1. *Geochemical results for springs surveyed in June, July, and August 2006.*

Spring number	Geologic unit[a]	pH	Conductivity (μS/cm)	Dissolved oxygen (mg/L)	Water temp. (°C)	Alkalinity (mg/L as $CaCO_3$)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Iron (mg/L)	Total dissolved phosphorus (mg/L)	Chloride (mg/L)	Nitrate plus nitrite as N (mg/L)	Sulfate (mg/L)	Total dissolved solids (mg/L)
Iowa County																
250009	Cu	7.2	510	8.16	9.68	260	56.4	32.4	0.7	2.1	<0.1	0.019	3.8	1.16	14.7	288
250022	Om	7.0	629	0.40	8.35	292	73.2	42.3	1.2	4.7	0.3	0.013	16.6	0.019	69.0	416
250024	Os	7.0	581	10.01	12.75	288	63.9	35.7	1.0	3.0	<0.1	0.025	6.3	3.84	16.3	344
250028	Opc	7.1	493	9.37	9.60	243	55.3	32.2	1.0	3.0	<0.1	0.032	6.6	2.73	16.0	282
250030	Cu	7.3	583	9.73	11.60	286	69.8	41.5	1.1	3.9	<0.1	0.028	7.3	2.49	16.8	338
250045	Os	7.2	680	10.90	9.40	321	73.8	42.0	0.8	7.2	<0.1	0.019	19.1	6.35	27.9	430
250101	Opc	7.6	580	11.40	9.60	284	67.4	39.2	1.8	4.6	<0.1	0.037	8.8	2.19	17.1	338
250106	Os	6.9	561	9.95	9.58	297	68.5	41.2	1.2	2.5	<0.1	0.024	7.3	3.45	18.0	356
250174	Oa	7.2	631	11.22	9.10	325	72.1	40.5	0.6	3.1	<0.1	0.018	6.5	4.53	23.6	398
250195	Cu	7.8	581	10.77	14.40	313	69.7	38.3	0.5	2.6	<0.1	0.049	1.6	0.062	10.6	334
250200	Cu	7.4	475	10.13	10.70	198	49.0	26.5	1.0	6.7	<0.1	0.061	16.4	2.79	11.8	260
250205	Cu	7.3	262	6.76	14.80	238	51.7	30.2	1.6	2.8	<0.1	0.066	4.9	1.97	8.1	276
250210[b]	Opc	7.1	536	8.83	9.58	260	57.9	29.1	1.1	3.9	<0.1	0.027	11.4	5.06	16.6	338
250215	Opc	7.3	485	10.74	8.81	241	59.7	32.2	0.9	3.4	<0.1	0.029	6.1	2.7	15.6	292
250235	Os	7.0	666	6.91	9.40	307	74.9	45.6	1.7	4.3	<0.1	0.032	15.5	7.01	44.2	430
250240	Os	7.0	562	7.10	13.10	292	62.2	36.1	0.8	2.1	<0.1	0.007	3.6	0.853	18.5	332
250248	Os	7.0	664	6.05	10.18	334	72.3	41.2	0.3	2.9	<0.1	0.015	10.9	4.73	29.4	422
250259	Opc	7.3	465	11.50	11.00	221	52.2	27.3	1.2	3.7	<0.1	0.07	3.7	1.9	23.5	274
250296	Os	6.9	378	7.71	9.49	317	65.5	38.4	0.3	1.7	<0.1	0.009	2.9	2.14	18.9	364
250309	Oa	7.1	615	6.51	9.57	268	66.4	38.7	2.4	8.6	<0.1	0.027	19.0	1.97	62.6	406
250331	Os	7.1	505	11.61	10.30	270	57.8	32.3	0.5	2.1	<0.1	0.026	3.0	1.76	13.2	306
250334	Os	6.7	339	10.04	10.09	125	35.9	19.2	1.0	4.7	<0.1	0.023	9.0	7.62	20.4	222
250380	Oa	7.1	503	9.39	9.78	240	55.8	31.6	1.0	3.9	<0.1	0.147	7.6	4.43	14.9	290
250407	Om	7.0	587	2.53	11.45	271	63.7	40.2	0.5	8.6	<0.1	0.014	33.2	0.24	26.9	390
250408[b]	Cu	7.0	424	8.44	9.65	221	47.0	26.9	0.8	2.3	<0.1	0.025	4.1	1.49	14.0	256
250409[b]	Oa	7.0	655	9.17	8.97	225	70.7	39.7	0.6	3.5	0.004	<0.05	12.0	6.3	20.4	328
Waukesha County																
680030	Om	7.1	790	5.70	9.79	319	88.4	48.0	1.9	17.9	<0.1	0.013	46.5	1.49	40.2	480
680039	Os	7.3	668	5.76	9.70	297	76.4	38.4	1.2	3.6	<0.1	0.018	13.0	0.688	40.0	400
680049	Su	7.3	820	6.79	11.15	291	85.7	46.6	2.1	31.6	<0.1	0.021	79.0	4.14	31.0	518
680054	Su	7.3	786	6.67	9.66	312	89.0	45.5	1.4	12.9	<0.1	0.013	50.0	4.02	33.6	478
680056	Su	7.2	763	6.88	9.82	290	84.1	40.7	2.5	20.8	<0.1	0.017	51.1	3.15	29.5	458
680063	Su	7.2	725	8.68	10.18	325	85.9	44.1	1.4	12.6	<0.1	0.012	33.5	4.26	28.9	450
680080	Su	7.1	594	2.46	11.46	229	63.6	32.7	1.4	18.0	<0.1	0.027	42.8	1.3	38.1	370
680083	Su	7.0	950	6.61	9.69	386	106.0	52.1	2.0	45.4	<0.1	0.016	85.7	1.68	29.3	604
680128	Os	7.1	768	6.09	10.62	295	86.4	42.2	2.3	25.1	<0.1	0.015	54.6	2.78	31.9	464
680137	Om	7.2	902	9.48	11.91	323	90.1	43.5	1.4	26.6	<0.1	0.018	75.9	2.58	27.4	536
680146	Os	7.2	741	7.72	10.80	297	85.3	41.5	2.1	15.5	<0.1	0.009	44.4	6.1	25.8	446
680149	Os	7.5	696	4.35	11.18	311	79.6	39.9	1.7	8.7	<0.1	0.013	30.8	0.156	18.5	406
680150	Os	7.4	627	2.68	9.80	306	78.5	41.3	1.7	8.8	<0.1	0.011	25.0	0.129	24.0	396
680172	Su	7.3	746	5.61	9.74	308	86.7	45.7	1.8	21.3	<0.1	0.01	50.0	1.46	43.5	486
680197	Om	7.2	810	8.09	9.66	311	103.0	50.3	2.3	12.5	<0.1	0.019	43.2	8.85	50.0	506
680201	Om	7.2	682	9.46	10.09	299	83.3	42.6	1.1	4.8	<0.1	0.009	32.7	6.6	27.4	430
680212	Om	7.3	641	10.22	9.19	283	72.3	36.2	1.5	14.0	<0.1	0.017	29.0	1.63	27.4	398
680300	Om	7.2	661	6.33	9.31	277	71.9	37.1	1.6	10.7	<0.1	0.016	28.3	1.44	31.6	398
680301	Os	6.9	1006	6.97	9.86	336	102.0	47.4	3.3	52.5	<0.1	0.016	100.0	1.49	29.0	592
680302	Om	7.3	611	10.40	9.58	279	69.7	37.0	1.3	8.0	<0.1	0.017	20.3	1.9	29.0	380

Notes: Coordinates of springs are available in Swanson and others (2007).

[a] *Om = Maquoketa Formation, Os = Sinnipee Group, Oa = Ancell Group (St. Peter Formation), Opc = Prairie du Chien Group, Cu = Cambrian Sandstones.*

[b] *July sampling event for Highland Big Spring, Otter Creek Big Spring and Governor Dodge Spring.*

but Group 3 springs do not appear to be associated with any of the mapped units. These springs have the lowest relative ion concentrations (fig. 11), and when overlaid onto a digital elevation model (fig. 13), it is clear that they align with the Kettle Moraine, as do many other historical springs (fig. 2). These observations, albeit preliminary, suggest that the Group 3 springs might be dominated by groundwater that flows primarily through unconsolidated materials, whereas groundwater discharging to Groups 1, 2, and 4 springs may flow through bedrock somewhere along the flow path.

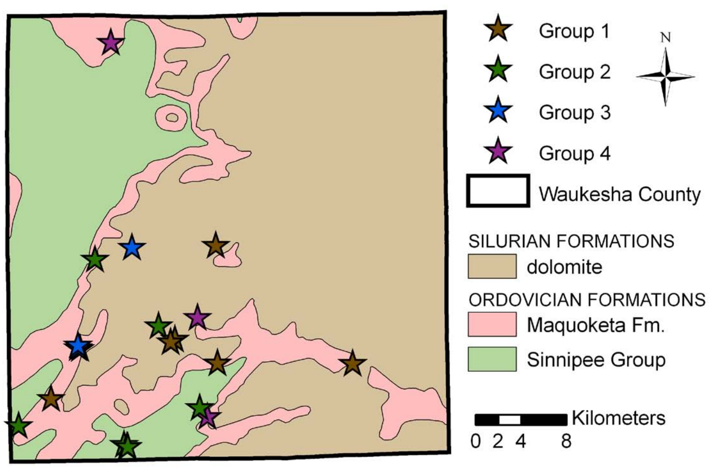


Figure 12. *Distribution of geochemical groups and bedrock geology (adapted from Mudrey and others, 2007).*

DISCUSSION

Reliability of historical spring surveys

The approach to developing conceptual models of springs and assessing their vulnerability to pumping relies on gaining confidence in the positional accuracy of historical springs mapped in the WCD surveys, as well as interpreting the site-specific geochemical and spring flow data that were collected as part of this study. In Iowa County, 92% of the property owners who were interviewed confirmed the location of one or more springs on their property. Fewer springs remain in Waukesha County, but many owners recall the existence of a spring on their property in the past. Therefore, the overall confidence in historical spring locations is high, which allows their use in association with patterns of regional geology and topography.

Although spring positions appear to be fairly accurate, overall confidence in the spring flow measurements recorded in the WCD surveys is lower. In Iowa County, the WCD survey states that flow was determined by the "floating stick" method and in Waukesha County, a V-notched aluminum weir was used to measure spring flow in most cases (WCD, 1958a, 1958b). Although both methods have the potential to accurately measure spring flow, it is clear from remarks entered in

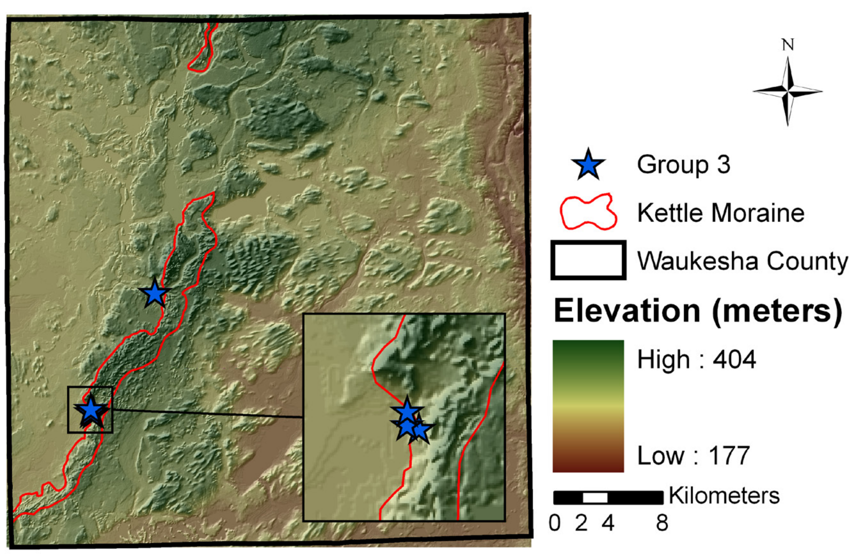


Figure 13. *Distribution of Group 3 springs relative to the Kettle Moraine in Waukesha County (adapted from Clayton, 2001).*

the surveys that the surveyors encountered a variety of conditions that might reduce the accuracy of these methods (for example, the spring is clogged with sticks and stones). Furthermore, spring flow was estimated on the basis of only one field visit, and there is no information on the variability of flow conditions for individual springs. Due to the lack of information on the range of flow conditions for each spring, it is probably unreasonable to expect a clear quantitative relationship between historical flow measurements and those made in 2006, which are also based on a single visit. However, the historical spring flow measurements can probably still be used to identify larger springs or to describe the overall range of flow conditions that might be expected in these regions. For example, two of the three springs with flow rates in excess of 1 cfs in 2006 also had flow rates in excess of 1 cfs in 1958 (fig. 6). The third spring had a flow rate of 0.4 cfs in 1958, which is still considerably higher than the mean (0.08 cfs) and median (0.03 cfs) spring flow rates of all of the springs included in the Iowa County and Waukesha County WCD surveys.

Conceptual models and vulnerability of springs to withdrawals

Field data support conceptual models for springs in Iowa County that are based on typical contact springs, where water emerges along slopes and at lithologic contacts with differences in hydraulic conductivity. However, flow paths to individual springs in this region are likely to be complex. Springs are associated with every major stratigraphic unit in Iowa County, but are most commonly found in association with the Sinnipee Group, near the upper contact of the St. Peter Formation, or near the upper contact of the Cambrian sandstones. This indicates that aquifer heterogeneities like vertical and horizontal fractures, both of which are prevalent throughout the Sinnipee Group rocks, or partings along major stratigraphic contacts may be particularly important in promoting discrete flow in the region. Perched groundwater, which Carter (2008) recently documented near the Governor Dodge Spring, could also influence the distribution of springs and complexity of spring flow paths in the region.

There is some evidence that flow is more variable in springs discharging from stratigraphically higher geologic units, which also supports a model that includes the affects of fractures. However, isotope levels and concentrations of most major ions at these springs were relatively stable throughout the monitoring period, indicating some mixing along flow paths and/or a component of flow through porous media. In regions with high topographic relief, like Iowa County, groundwatersheds are more likely to coincide with surface watersheds (Toth, 1963). Therefore, these stratigraphically higher springs may have small recharge areas that could initially be delineated by relying on topography. The wide spatial variation of nitrate concentrations in waters discharging from these springs (fig. 9d, Os and Oa springs) further supports the existence of small and shallow watersheds, where local land use influences geochemistry. There is also some evidence that flow is less variable in springs discharging from stratigraphically lower geologic units, such as the Otter Creek Spring (fig. 7). This could indicate longer or less direct flow paths. There is less spatial variability in nitrate concentrations associated with these springs, and concentrations are generally lower (fig. 9d, Opc and Cu springs). This indicates broader or deeper groundwatersheds, with a greater degree of mixing along flow paths.

The vulnerability to pumping of individual springs in Iowa County will require site-specific investigation because fractured bedrock, perched water tables, and local aquitards are common in the Driftless Area (Krohelski and others, 2000; Carter, 2008). However, some generalizations can be made on the basis of the models presented above and the distribution of high-capacity wells in the county. Springs discharging from stratigraphically higher units are likely to be vulnerable to pumping from wells along ridge tops that are installed in these aquifers or that span multiple aquifers. Because recharge areas for these springs are probably small and shallow, pumping could result in substantially reduced spring flow or complete loss of flow to small springs. Springs discharging from stratigraphically lower units are probably less vulnerable, due in part to broader contributing areas, but also because most high-capacity wells that pump water from the Cambrian sandstones are located in the floodplain of the Wisconsin River, where few springs exist (fig. 14).

The spatial distribution of springs in Waukesha County is influenced by the glacial topography and the position of the Maquoketa shale subcrop (figs. 2 and 12). Springs were historically concentrated along the western margin of the Kettle Moraine and in low-lying areas within the drumlinized zone to the east (fig. 2). Very few springs were mapped northwest of the Maquoketa shale subcrop, which is also recognized as an important recharge area for the deep sandstone aquifer (Feinstein and others, 2005).

The four geochemical groups of springs presented above require more thorough testing. However, the results suggest that while flow paths originate in surficial unconsolidated materials, groundwater may, in many cases, flow through the underlying shallow bedrock before discharging as depression springs in low-lying wetlands or near streams. Shallow bedrock is composed of Silurian dolomite east of the Maquoketa shale subcrop and weathered Ordovician Sinnipee dolomite west of the Maquoketa shale subcrop. Regional groundwater flow modeling for southeastern Wisconsin supports this conceptual model, and shows local, topographically controlled flow systems near the Kettle Moraine and other areas of relief. Numerical particle tracking analysis shows that groundwater intersects shallow bedrock before discharging to surface water bodies or at the water table (Feinstein and others, 2005). Although they are not explicitly modeled, groundwater may flow along similar paths to springs.

Feinstein and others (2005) conclude that the widespread regional pumping from the deep sandstone aquifer in southeastern Wisconsin (fig. 14) has affected some shallow flow patterns, especially those west of the Maquoketa shale subcrop, and that downward flow from the shallow (sand-and-gravel aquifer and shallow bedrock aquifers) to deep (deep sandstone aquifer) parts of the groundwater flow system occurs. Furthermore, their work shows that shallow high-capacity wells derive water primarily from diverted baseflow or from induced flow from streams. Therefore, springs in Waukesha County are likely to be vulnerable to groundwater withdrawals from both the deep and shallow parts of the groundwater flow system. The apparent loss of spring resources throughout the county complements these conclusions. Geochemical results further suggest that Group 3 springs are probably most vulnerable to withdrawals from the sand-and-gravel aquifer whereas Group 1, 2, and 4 springs are most vulnerable to withdrawals from shallow bedrock aquifers, primarily the Silurian dolomite aquifer.

This study shows that a historical, regional spring data set for Wisconsin can be used in association with regional data sets of geochemistry, topography, and geology to reveal important controls on groundwater flow and make initial assessments of the vulnerability of spring flow to groundwater withdrawals. The historical positions of springs across the landscape are complemented by more recent site-specific information at a limited number of springs. At least 20 springs were surveyed in each county. This number of springs provided sufficient data to develop conceptual models and initially assess vulnerability to pumping, suggesting that the overall approach may also be successful elsewhere in the state.

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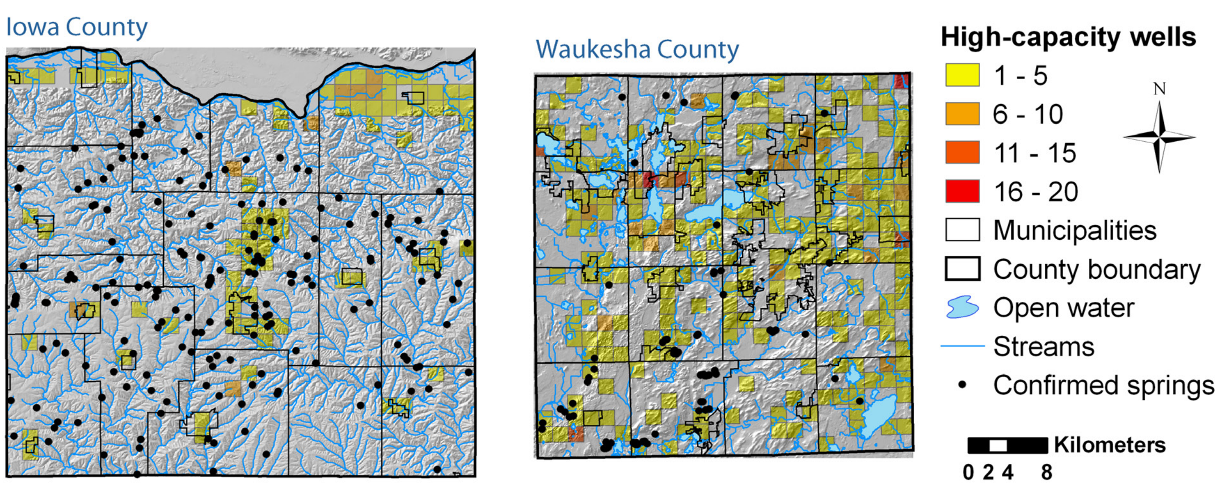

Figure 14. *Distribution of confirmed springs and current high-capacity wells in Iowa and Waukesha Counties. Distribution of high-capacity wells by section, according to the WDNR drinking water database. Wells are not differentiated by depth.*

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James M. Robertson, *Director and State Geologist*

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