Searching for the Source: The Origin of Deep Spring in the Lower Lake Waubesa Wetlands

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Abstract: Nitrate and chloride concentrations from a variety of locations were analyzed to determine the source of a high-flow spring near Lake Waubesa in southern Wisconsin. Water samples were taken from the spring, another nearby hillside spring, Lake Waubesa, and two proximate wells. The lowest chloride and nitrate average concentrations of 0.00 and 1.56 ppm, respectively, were recorded from a municipal well with a depth range of 330 to 810 feet. The highest chloride average concentration of 59 ppm was recorded from the nearby hillside spring, while the highest nitrate average concentration of 8.95 ppm was recorded from Lake Waubesa, with the second highest of 7.51 ppm coming from the hillside spring. The spring's average concentrations were 32.13 for chloride and 3.99 for nitrate. These figures indicate chloride and nitrate concentrations decrease as depth below the ground surface increases and suggest the spring's source likely originates the upper bedrock aquifer.

Keywords: Springs, purple sulfur bacteria, source analysis, chloride and nitrate in natural waters

INTRODUCTION

Madison, Wisconsin, like urban areas around the globe, has experienced significant drops in its groundwater head levels over the past century, resulting in dramatic shifts in surface-groundwater interactions such as the reverse of Lake Mendota from a discharge to recharge zone (Hunt et al. 2001). These hydrological shifts are often visible in dry stream-beds and eutrophic lakes. Local approval of new real estate development requires study and documentation of potential environmental impacts, but groundwater effects are typically not evaluated. While serious threat to municipal water supply is likely decades away, diminishing aquifers have an immediate adverse effect on many natural environments, in particular those dependent on groundwater discharge.

The location, rate, and geochemical composition of groundwater discharge is determined by the underlying hydrogeologic units. Bradbury et al. (1999) have defined three primary aquifers which underlie the Madison area. Closest to the surface is the unlithified aquifer, which is composed of sandy till, outwash, and glaciolacustrine sediments. Below the unlithified aquifer lies the upper bedrock aquifer, a solid but permeable sandstone formation. The lower bedrock aquifer, separated from the upper bedrock aquifer by a narrow confining layer called the Eau Claire Aquitard, constitutes the deepest water-bearing layer above impermeable igneous and metamorphic formations (Clayton and Attig, 1997). Water travels through and between these layers according to the distribution of hydraulic head and hydraulic conductivity. Human-induced alterations from well pumping and decreased recharge area have the potential to reduce hydraulic head in these aquifers, thereby changing flow paths and potentially disrupting surface discharge to springs.

One such threatened natural area is the pristine expanse of wetland and aquatic habitat at the southwestern end of Lake Waubesa, a member of the Yahara chain of lakes. The unique hydrology of this area includes several small streams, a large and ecologically diverse calcareous fen, and, the main focus of this paper, Bogholt Deep Spring. Discharge from these sources converges in Lake Waubesa's shallow southern boot, where their colder temperatures and low nutrient loads could play an important role in inhibiting extensive algae blooms that plague similar hydraulically isolated areas like nearby Monona Bay.

Bogholt Deep Spring, tinted bluish-purple by its resident population of purple photosynthetic bacteria, is one of the most stunning natural features in the region. Under the right conditions, it appears as a blue spot from the air, standing out from the marsh like an enormous cornflower. It is also one of the largest springs in the area and creates a pool which provides a habitat for a number of waterfowl. In order to ensure that features like Deep Spring continue to accent the landscape for generations to come, it is necessary to determine their susceptibility to development pressures like groundwater withdrawal and loss of recharge zones. As mentioned above, this susceptibility is determined in large part by the path that spring water takes within the subsurface. By defining the hydrogeologic units through which the water flows, it is then easier to predict the impact of development on discharge at the spring. The goal of this paper is to determine the units which contribute significant amounts of water to Deep Spring and make suggestions on how to structure development so as to minimize disruption to the spring.

METHODS

Field Work

Deep Spring is located in a narrow slough connected to Lake Waubesa. Discharge occurs at the center of an inverted peat cone approximately 15 feet in diameter and 24 feet deep. The center of this cone was located using a combination of depth finder measurements and soundings with a Van Dorn sampler. Once this point was located, samples were collected at specific depths in the overlying water column using the Van Dorn sampler. Approximately 250 milliliters of water from each sample were coarsely filtered to remove organic debris and then placed inside a glass collection bottle. Dissolved oxygen measurements using a Yellow Springs model 51B oxygen probe were also measured up to 10 feet below the water surface in order to verify that oxygen levels decreased with depth.

Surface water comparison samples were collected from the shore of Lake Waubesa at Goodland Park and from both Swan and Murphy Creeks at their intersections with Lalor Road. Groundwater comparison samples were chosen based on their proximity to Deep Spring and also on the depth at which the groundwater originates. One small spring, hereafter referred to as

Drinking Water Spring, emerges from the uplands to the West of Deep Spring. Although the source of Drinking Water Spring is not known conclusively, its location on the hillside suggests that it is formed by the intersection of the dipping land surface with the water table. Samples were collected from Drinking Water Spring at both the discharge point on the hillside and also at several sand boils located within the spring pool. Samples were also collected from Wisconsin Department of Natural Resources well #8 at the Nevin State Fish Hatchery. The well is open at a depth of 180 feet below the ground surface and has an artesian discharge of 400 gallons per minute. The final groundwater samples were collected from Madison Water Utility well #30 which is open at a depth of 810 feet. Collection procedures at all sites were similar except for those samples from WDNR #8 and MWU #30. These samples were not filtered because of the assumed absence of organic matter. Figure 1 shows the aerial distribution of sampling points. Once out of the field, the samples were then frozen in order to prevent further microbial activity.

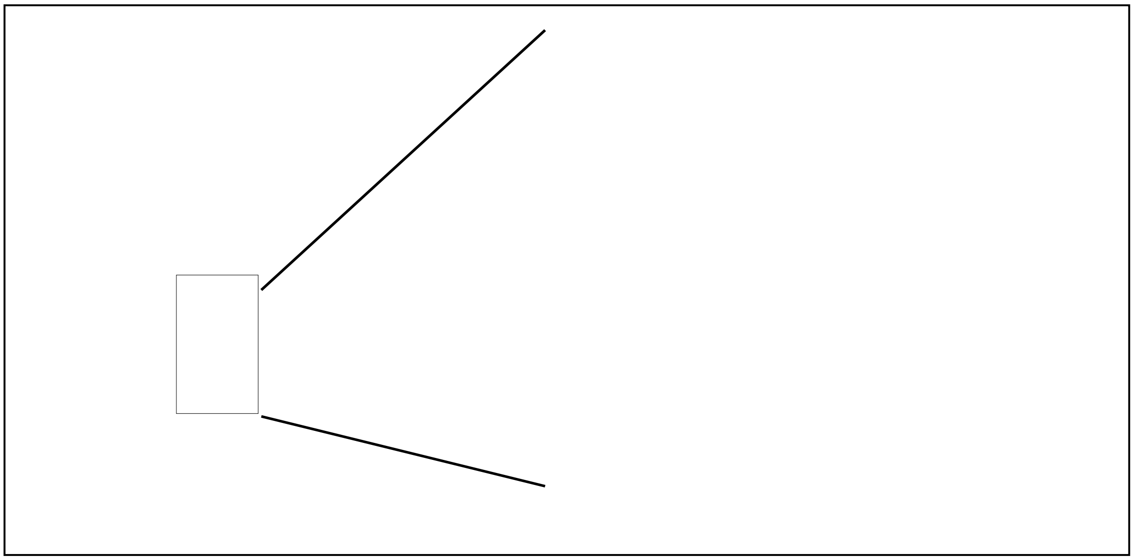

Figure 1. Arial Distribution of sampling points.

Laboratory Analyses

Samples from the bottom of Deep Spring, from the shore of Lake Waubesa, from the hillside at Drinking water spring and from MWU #30 were thawed in order to remove approximately 5 milliliters of water from each sample. These volumes were each acidified with 5 milliliters of a 1% nitric acid solution and sent to the University of Wisconsin Soil & Plant Analysis Lab to be tested for total dissolved cation concentrations.

The remaining samples were thawed shortly before analysis. Each sample was again filtered through a 0.1 micron filter to remove any iron colloids which may have precipitated during freezing. A 0.5 milliliter volume of each filtered sample was then removed for anion analyses.

Deep Spring Photographs

Upper:

Deep Spring is at the “toe” of the “stocking” that is joined by another large spring at the “heel” of the stocking. These, together with springs along “Deep Spring Whisker” which extends outward (south) of the “toe” joins with the other springs to produce Deep Spring Creek which flows as a stream of about 50-feet wide into Lake Waubesa.

Upper:

The Great Fen lies to the south of Deep Spring Creek and receives groundwater as a diffuse upward flow across its expanse toward Murphy Creek on the right and across the area to the south.

Upper:

Swan Creek is shown at the left with its wider upper branch originating upstream a few hundred feet, and its narrower lower branch being the main stream that originates in Fitchburg, enters the Town of Dunn and crosses Lalor Road on its way to Waubesa Wetlands. Its surface waters are continuous with the groundwater that underlies the wetland between Swan Creek and Deep Spring Creek. Not shown is Drinking Water Spring at the interface of the Waubesa Wetlands and the hillside west of Waubesa Wetlands whose flow enters the photograph at its right edge above the white triangle on the lower right. Its flowage begins as a surface water stream, but soon moves under the surface of the peat to flow beneath the surface toward Murphy Creek.

Lower:

Deep Spring is at the “toe” of the “stocking” and shows the presence of purple bacteria in the purple color here. The fen extends upward in the photo from shrub carr to highly stunted shrub carr whose diminutive botanical physiogomy is driven by cold uprising groundwater rich in calcium and magnesium.

Lower:

The “Heal Spring” at the “heel” of the stocking shows a ring of *Lemna* around the center of its upflow, and *Lemna* occupies other low-flow areas in this spring system. Bright green submerged vegetation, barely visible in this photo but periodically abundant, is *Spirogyra.*

Nitrate-N and chloride concentrations were chosen to differentiate between waters of different depths since they commonly originate from fertilizer and road salt application at the land surface. Since these anthropogenic inputs vary both temporally and geographically, their residues may be used to constrain both recharge areas and travel times (Swanson et al., 2001). These anions were measured using a Dionex ICS-1000 Ion Chromatography System. The samples were tested alongside standard solutions of known concentrations in parts per million (Table 1) and de-ionized water. Once the analyses were complete, the standard concentrations were compared to the ICS-1000 output in microsiemen minutes in order to produce standard curves which were then used to compute nitrate and chloride concentrations for the samples.

Table 1. Concentrations of chloride and nitrate-N in standards.

Standard #	*Nitrate-N Conc. (ppm)*	*Chloride Conc. (ppm)*
1	1.03	1.02
2	3.03	10.32
3	5.15	30.34
4	10.13	50
5	15.08	80.23

RESULTS

Table 2 shows the concentrations of nitrate and chloride measured in each sample, along with averages for each sampling location. Although care was taken to ensure repeatability, standard checks showed that machine drift occurred by as much as 25% of original concentrations. The results given by samples taken at Deep Spring show a small (CV=0.12) variation in nitrate concentrations but a larger (CV=0.37) variation in chloride concentrations. This variation in chloride samples is almost entirely due to the presence of one outlier, however, and may represent contamination by another source or analytic error. Samples taken from Lake Waubesa show large (8.95 ppm) average nitrate concentrations but small (3.48 ppm) average chloride concentrations. The small chloride concentrations are surprising given that published data on chloride concentrations in Lake Waubesa show values in excess of 40 ppm (Hausbeck et al., 2004). The values given in this study could represent temporal or physical heterogeneities in concentrations and should not be taken as representative of the lake as a whole.

The results also show differences among waters from the three groundwater sampling locations. Water emerging from well MWU #30 exhibits low average concentrations of nitrate (1.56 ppm) and chloride (0.00 ppm) compared to 5.55 ppm and 33.36 ppm at WDNR #8 and 7.51 ppm and 59.41 ppm at Drinking water spring. The coefficient of variation among samples collected at both locations at Drinking water spring was similar (CV=0.12) to that seen among the nitrate samples at Deep Spring, suggesting that the both the hillside and sand boil locations have a common source. The cation concentrations in the samples sent to the University of Wisconsin Soil & Plant Analysis Lab were unavailable due to a machine malfunction and will not be considered in the remainder of this study.

Table 2. Individual and averaged concentrations of chloride and nitrate at sampled locations.
† Refers to depth below the spring pool surface
‡ Refers to depth below ground surface

	Nitrate-N Conc. (ppm)	*Chloride Conc. (ppm)*
Deep Spring Surface (0’0” †)	3.29	21.62
Deep Spring Surface (0’0” †)	3.71	24.98
Deep Spring Middle (10’2” †)	4.11	28.43
Deep Spring Middle (12’6” †)	3.98	28.50
Deep Spring Middle (14’0” †)	4.50	32.69
Deep Spring Bottom (22’3” †)	4.10	57.95
Deep Spring Bottom (23’5” †)	4.21	30.77
Average	*3.99*	*32.13*
Coefficient of Variation	*0.10*	*0.37*
Lake Waubesa	8.65	2.94
Lake Waubesa	9.25	4.01
Average	*8.95*	*3.48*
Swan Creek	5.33	17.81
Murphy Creek	6.73	34.24
Drinking Water Spring (sand)	8.13	65.36
Drinking Water Spring (sand)	6.02	46.87
Drinking Water Spring (hillside)	8.25	61.17
Drinking Water Spring (hillside)	7.64	64.25
Average	*7.51*	*59.41*
Coefficient of Variation	*0.12*	*0.12*
WDNR #8 (180’‡)	4.88	28.50
WDNR #8 (180’‡)	6.21	38.21
Average	*5.55*	*33.36*
MWU #30 (810’‡)	1.56	0.00
MWU #30 (810’‡)	1.55	0.00
Average	*1.56*	*0.00*

DISCUSSION

The results show that the nitrate and chloride concentrations in groundwater samples correlate well with the depth at which the sample originated. The depths are, in turn, representative of the hydrogeologic unit through which the water flows and the residence time that the water spends within the ground. The water discharged from Drinking water spring most likely travels through the shallow unlithified surface aquifer and has a relatively short residence time on the order of 1 to 10 years (Swanson et al., 2001). Alternatively, the waters flowing upwards out of WDNR #8 originate at depths of 180 feet, and MWU #30 has an open depth range of 330-810 feet below the ground surface which places their sources within the upper bedrock aquifer and lower bedrock aquifer, respectively (Bradbury et al., 1999). Swanson et al. (2001) estimate that similar waters in the upper bedrock aquifer may have residence times from 10 to 15 years and speculate that water within the lower bedrock aquifer may have residence times as long as or greater than 50 years.

The longer residence times in the lower bedrock aquifer may constrain discharge from wells or springs to waters which recharged before road salt and fertilizer application became commonplace. The nitrate-N and chloride concentrations observed in samples from MWU #30 fit this model since they are much lower than those seen in other locations. Although Hausbeck et al. (1999) report chloride concentrations in excess of 100 ppm in one of the deep wells, this well is no longer in use and may have been contaminated. Waters originating in the unlithified and upper bedrock aquifers are generally more difficult to differentiate since both would have been exposed to road salt and fertilizers. Nitrate and chloride concentrations in both these waters would instead depend only on the land usage in the recharge area and in the case of nitrate, on the microbial activity occurring within the subsurface. Nevitzky (1978) saw the highest chloride concentrations entering the Nevin wetland in surface water input, but Swanson et al. (2001) saw similar concentrations in the unlithified and upper bedrock sources and suggest that nitrate and chloride concentrations from water in the unlithified aquifer may be more responsive to discrete application events. They could be expected, then, to show more seasonal variability than concentrations of these anions in water from the upper bedrock aquifer. The samples in this study, however, were all collected on the same or similar dates, preventing such a comparison.

The above relationships between hydrogeologic units and their waters are instrumental in determining the source for Deep Spring. The lower bedrock aquifer exhibits very low chloride concentrations which may mix with the >40 ppm concentrations in Lake Waubesa to produce the observed intermediate concentrations. Such a situation, however, might be expected to show chloride concentrations close to zero at the bottom of the spring pool and a gradual increase in concentration closer to the surface. The samples taken at Deep Spring show the opposite relationship, suggesting that water from the lower bedrock aquifer is not present in appreciable quantities.

The presence of purple sulfur bacteria, however, would indicate low oxygen levels that point to a source long-removed from exposure to atmospheric oxygen. Although dissolved oxygen levels were shown to diminish with depth, values at the deepest depth (10 feet) still showed significant oxygen and do not indicate completely anaerobic conditions. Burke et al.

(1973) observed that purple nonsulfur photosynthetic bacteria more oxidizing environments and are morphologically almost indistinguishable from purple sulfur bacteria. Although no Eh measurements were taken at Deep Spring, the presence of nitrate in the water samples and the absence of a distinct hydrogen sulfide odor, suggests that the spring pool habitat may favor purple nonsulfur bacteria over purple sulfur bacteria. If the colony in the spring pool is actually purple nonsulfur bacteria, then oxygenated water from a shallow source would be consistent with the bacterial presence.

The chloride concentrations from WDNR #8 match up the best with chloride concentrations observed in Deep Spring. Although average nitrate-N is about 30% lower in the spring water, the amount of organic matter contained in the peat may allow for a slight reduction of nitrate within or below the spring pool. Nitrate-N concentrations observed at Deep Spring show slightly higher concentrations at the bottom of the spring, implying that if higher nitrate levels were present at the source, they may be reduced as spring discharge flows past sediments in the peat cone.

As mentioned above, it is difficult to differentiate water from the unlithified aquifer and water from the upper bedrock aquifer since heterogeneity at recharge zones does not allow for common characteristics between all waters from one unit. Assuming, however, that the recharge areas are similar for both WDNR #8 and Deep Spring, the upper bedrock aquifer is a possible water source. Seepage from the unlithified aquifer is also possible, although given the low chloride concentrations in Deep Spring relative to Drinking water spring, it is difficult to imagine that these two springs share common recharge areas. Most likely, the spring discharge is a combination of waters from the upper bedrock aquifer and diffuse seepage from around the wetland area. This interpretation makes geologic sense as well. Given the presence of the wetland, it is reasonable to assume that the area functions as a regional surface water discharge point. At the same time, it has been shown that the upper bedrock aquifer contains layers of high hydraulic conductivity which transport water to points near the Yahara lakes where glacial valleys have cut into the bedrock sequence and allow discharge through the undifferentiated till (Swanson et al., 2006).

CONCLUSIONS

The results above suggest discharge to Deep Spring originates primarily as flow in the upper bedrock aquifer and possibly as diffuse seepage out of the unlithified aquifer. Given these two sources, it is important to recognize the development activities which may adversely affect spring flow. Since recharge to the upper bedrock aquifer may occur at points distant from discharge areas, simply creating a buffer immediately surrounding Deep Spring is not sufficient to protect it. Flow paths within the upper bedrock aquifer may be identified through computer models and used to predict the recharge areas to Deep Spring. These areas should then be developed in such a fashion as to maintain permeable surfaces and reduce runoff and evaporation. As the residence times along these flow paths can also be several years, the lag time necessary to see the effect of land use changes should also be taken into account (Hunt and Steuer, 2001).

ACKNOWLEDGEMENTS

The authors wish to thank: Laura Craig for her help in the Geology lab; the Bogholt's for their land donation; The Nature Conservancy and Wisconsin DNR for being responsible stewards; Nevin Fish Hatchery and Madison Water Utility for their water samples; Quentin Carpenter and Cal DeWitt for their mentoring; and Ruth DeWitt for her baked treats and hospitality.

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