Springdale Dye Trace Report
Olmsted County, Minnesota

2017 Dye Trace Report

Tracing Conducted
April 2017

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Introduction

This report presents the findings of dye tracing that was conducted in April 2017 in east central Olmsted County, Minnesota as part of the ESci 4702 Hydrogeology field exercise at the University of Minnesota. Figure 1 shows the study site's location. Previous dye tracing in the same springshed occurred in 2016 (Larsen et al., 2017). Some of the content included in this report was developed by Alycia Overbo as part of the 4702 Hydrogeology class assignment.

Collaboration between the Minnesota Department of Natural Resources, University of Minnesota Department of Earth Sciences, Minnesota Department of Agriculture, and Soil & Water Conservation Districts (SWCD) has led to many dye tracing investigations in southeastern Minnesota. The results of these investigations are available through an online *Minnesota Groundwater Tracing Database* application developed by the Minnesota Department of Natural Resources (https://www.dnr.state.mn.us/waters/programs/gw_section/springs/dtr-list.html).

Dye tracing and spring chemistry are used to understand groundwater recharge characteristics, groundwater flow direction and velocity, and to assist in determining the size and areal extent of the groundwater springsheds that supply perennial groundwater discharge to springs.

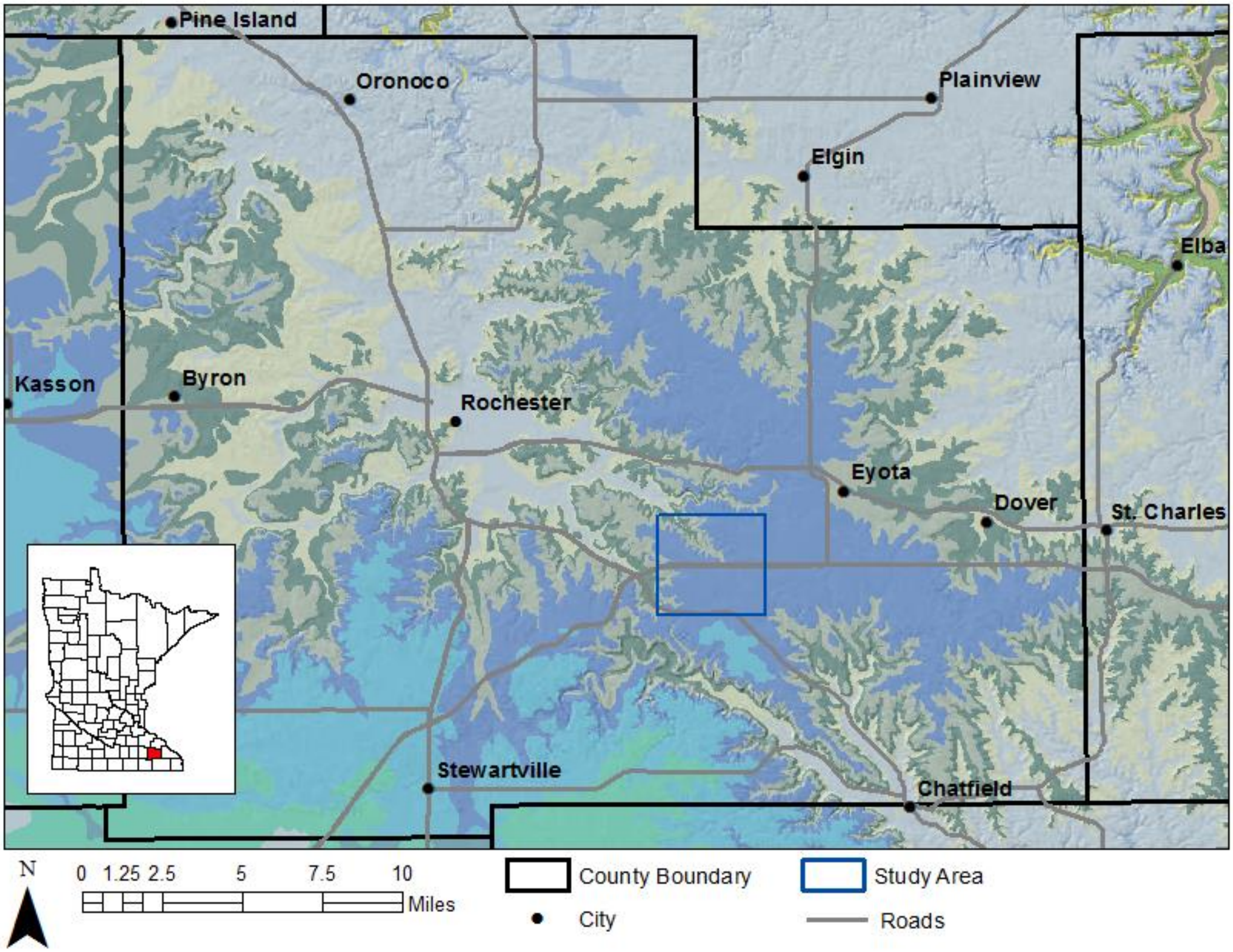

Figure 1. *Location map of the Springdale study area. Geology base map unit colors correspond with colors used in the Formation column of Figure 2.*

Area Geology and Hydrogeology

Underlying the relatively thin veneer of unconsolidated sediments in Olmsted County, such as glacial till, loess, sand, and colluvium, is a thick stack of Paleozoic bedrock units that range from middle Ordovician to Cambrian (Olsen, 1988). Ordovician rocks are generally dominated by carbonates, whereas the Cambrian rocks are generally siliciclastic (Figure 2).

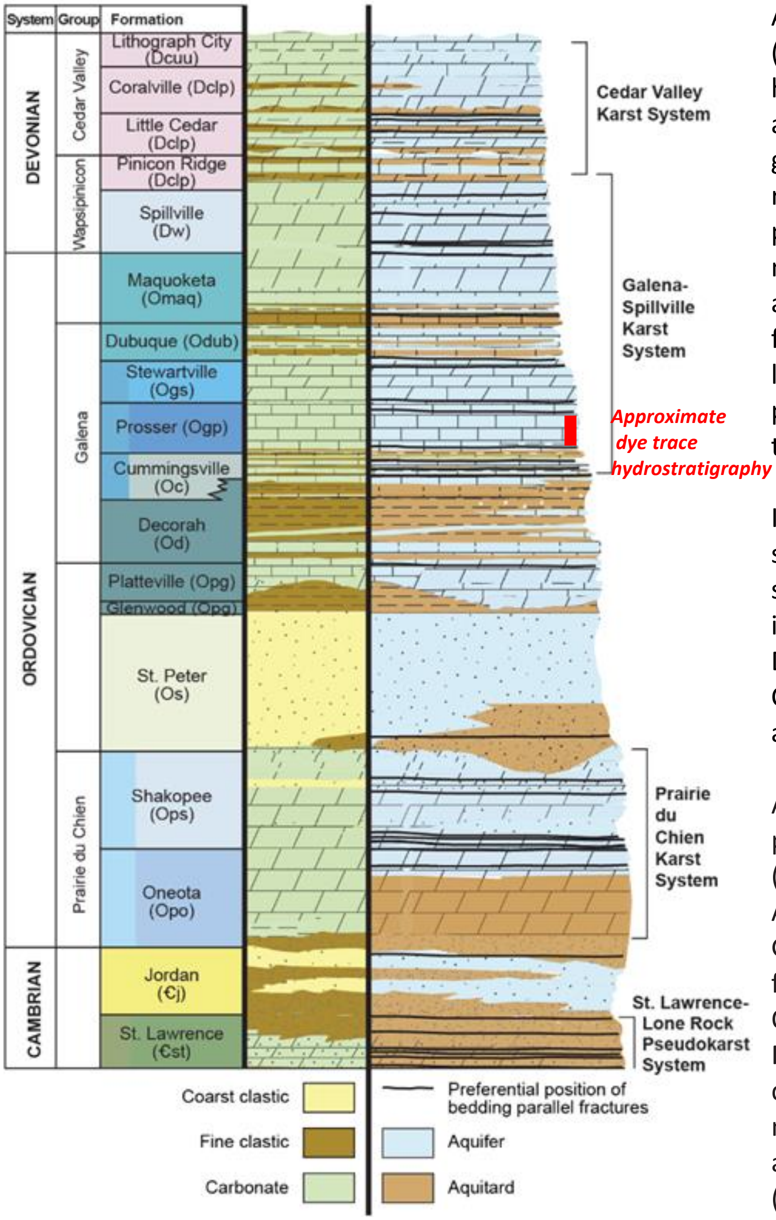

Figure 2. *Geologic and hydrogeologic attributes of Paleozoic rocks in southeastern Minnesota. Modified from Runkel et al. 2013.*

A generalized stratigraphic column for Olmsted County (Figure 2) shows lithostratigraphic and generalized hydrostratigraphic properties (modified from Runkel et al. 2013). Hydrostratigraphic attributes have been generalized into either aquifer or aquitard based on their relative permeability. Layers assigned as aquifers are permeable and easily transmit water through porous media, fractures or conduits. Layers assigned as aquitards have lower permeability that vertically retards flow, hydraulically separating aquifer layers. However, layers designated as aquitards may contain high permeability bedding plane fractures conductive enough to yield large quantities of water.

In southeast Minnesota, springs and groundwater seepage frequently occur at the toe of bluff slopes and at specific hydrostratigraphic intervals. Common intervals include near the contact of Maquoketa-Dubuque, Dubuque-Stewartville, Stewartville-Prosser, Prosser-Cummingsville, Decorah-Platteville, St. Peter-Shakopee, and Shakopee-Oneota (Steenberg and Runkel, 2018).

A hydrogeologic framework that describes four prominent karst systems for southeastern Minnesota (Runkel et al., 2013) is based largely on the work of Alexander and Lively (1995), Alexander et al. (1996), and Green et al. (1997, 2002). The systems described in this framework include the Devonian Cedar Valley, the Upper Ordovician Galena-Spillville, the Upper Ordovician Platteville Formation, and the Lower Ordovician Prairie du Chien Group. Karst characterization and sinkhole mapping in Olmsted County has delineated areas of active karst processes and high sinkhole probability (Alexander and Maki, 1988).

The dye tracing and spring monitoring presented in this report occurred in Prosser Formation in the Galena-Spillville karst, where groundwater velocity can reach up to 1-3 miles/day (Green et al. 2014).

Dye Tracing Methods

Dye tracing is a technique used to characterize the groundwater flow system to determine groundwater flow directions and rates. Traces are designed to establish connections between recharge points (sinkholes and stream sinks) and discharge points (springs and streams). Multiple traces are necessary to delineate the boundaries of springsheds. Dye tracing is accomplished using fluorescent dyes that travel at approximately the same velocity as water and are not lost to chemical or physical processes (conservative tracers). Fluorescent dyes used in tracing are non-toxic, simple to analyze, detectable at very low concentrations, and not naturally present in groundwater.

The presence or absence of dye at springs and other locations can be monitored with three complementary techniques—passive charcoal detectors and two forms of direct water sampling. Passive charcoal detectors, often referred to as "bugs", are deployed prior to introducing the dyes and then changed periodically during the traces. The bugs from before the dye introductions are used to determine background levels of fluorescence in the groundwater. The bugs are then changed periodically during the traces to determine where the dyes go (sometimes more than one place) and to obtain rough groundwater flow velocities. Direct water samples can be collected at one or more locations by hand, using auto-samplers, or can be monitored using flow through fluorometer data loggers. Passive dye detectors and direct water samples collected by the auto-samplers are typically analyzed using scanning spectrofluorophotometers.

If direct water samples or flow through fluorometer data loggers are used, detailed breakthrough curves can be obtained. Those curves contain information about the flow conditions between the dye input point and the sampling locations. If the water flow rates at the sampling points are monitored, then dye recovery can be quantified.

Project Area and Dye Traces

The Project Area is an active karst landscape where groundwater flow is governed by conduits and large solution-enhanced fractures. The sinkholes selected for the dye traces are located in a row crop field south of Interstate 90 and the spring used for intensive monitoring (Springdale Spring) is located on a nearby farmstead. Property access, land access, and water delivery was arranged and coordinated by Martin Larsen of the Olmsted SWCD.

The *Springdale 2017* traces were designed to establish connections between three recharge points (sinkholes) and discharge points (springs and streams) located within the Project Area shown in Figure 3. Previous dye tracing in 2016 (Larsen et al. 2017) documented a connection between one of the sinkholes, 55D833, and Springdale Spring, 55A443. These traces replicated the 2016 trace and included two untraced sinkholes located further from Springdale Spring. Use of auto-samplers for this trace allowed breakthrough curves to be established and thereby more accurate groundwater flow velocity determinations.

In the Minnesota Karst Feature Database (KFD) and the Minnesota Spring Inventory, each mapped feature is assigned a *RelateID* which is a ten-character alpha-numeric code. The first two characters are the number of the county in an alphabetical list of Minnesota Counties -- 55 for Olmsted County in this case. The third character is letter that codes the type of feature -- A = springs and seeps, D = sinkholes, and X = a miscellaneous category used to record bug locations in this case. The following seven digits are the unique number given to the feature upon input to the database. We abbreviate this number in the report by removing the zeros at the start of the unique number (e.g. 55D833 is the abbreviated form of sinkhole 55D0000833).

Eleven bugs were placed in springs and perennial streams around the targeted sinkholes two to four weeks before the dyes were introduced. Those bugs were changed immediately before the dyes were introduced and changed three times after dye introduction at roughly two-week intervals. Ten of the pre-dye injection background bugs contained no evidence of dyes. The background bug in Springdale Spring contained a very small eosin peak -- presumably from the eosin used in the 2016 Springdale Traces.

Three dyes were poured on April 7, 2017 at the locations summarized in Table 1. Since the three dye introduction points were dry sinkholes, dyes were flushed into the sinkholes with water from a tank trailered to each site. Each sinkhole was wetted with water prior to the dye being manually poured into the sinkhole. Each dye was ultimately flushed into the underlying karst aquifer with approximately 800-1000 gallons of water. Water was sourced from Bear Spring (55A406), which had no detectable dye based on background monitoring.

The auto-samplers were installed at Springdale Spring and collected water samples every half hour for 44 hours after dye injection. After dyes were introduced, bugs and water bottles in the auto-samplers were changed periodically by University of Minnesota, Olmsted SWCD, and Minnesota DNR staff until the trace was terminated. The bugs and water samples were transported to the University of Minnesota, Department of Earth Sciences for analysis. Bugs were analyzed by extracting the dyes with an extract of water, sodium hydroxide and isopropanol. The solutions from the bugs and the direct water samples were then analyzed using a Shimadzu RF5000 scanning spectrofluorophotometer and the resultant dye peaks were analyzed with a non-linear curve-fitting software.

All three dyes were clearly detected at Springdale Spring in water samples and in post-dye injection Springdale Spring bugs. Dye was also detected at 55X9, the Co. Rd. 19 site, in the two bugs following dye injection. The 55X9 monitoring location is in the surface stream immediately downstream of Springdale Spring. No dye was detected at any of the other 9 sites monitored with bugs. The results from the bugs are listed in Appendix A. Results from the direct water samples are shown in Figure 6.

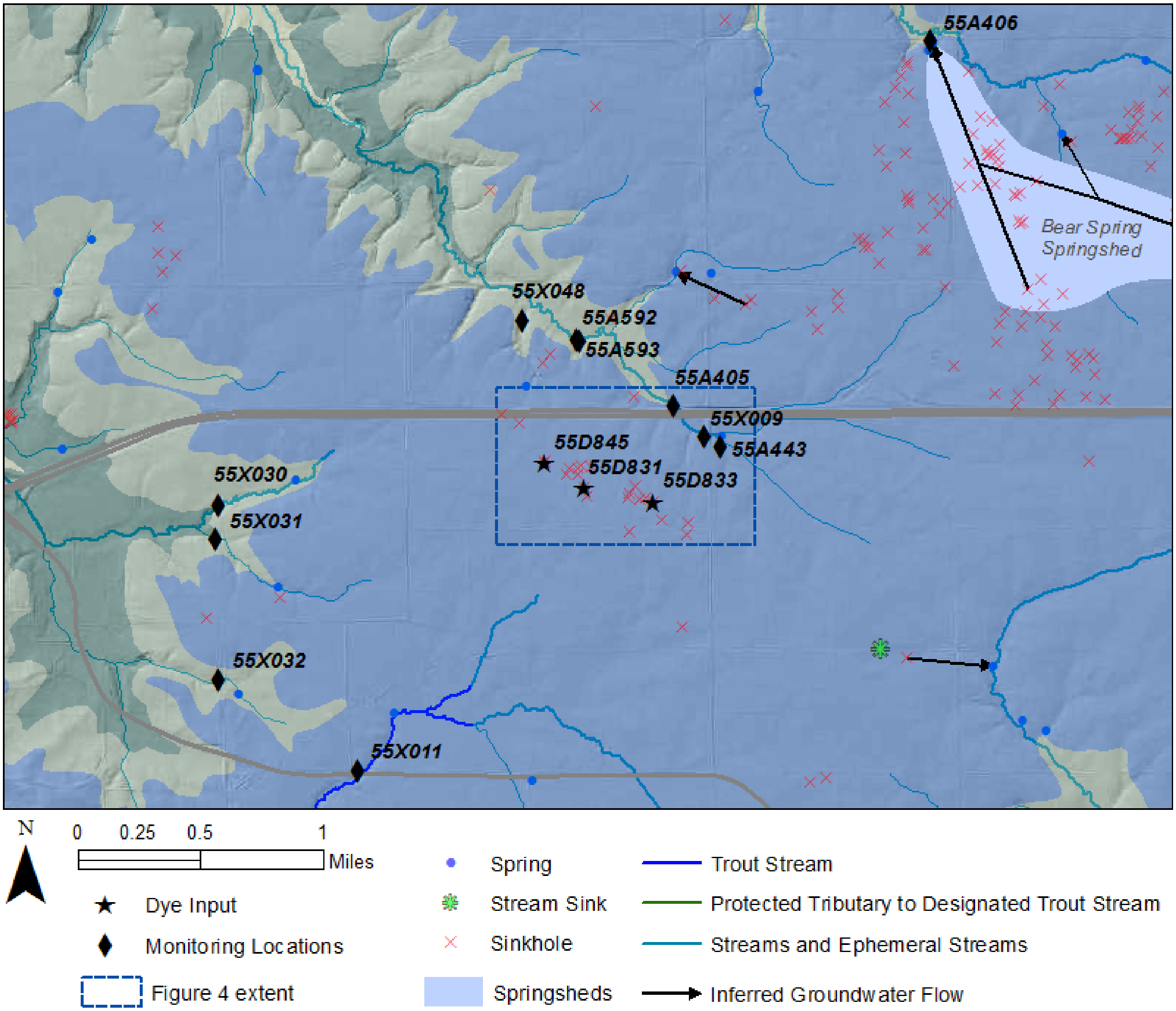

Figure 3. *Dye input points and sampling locations for the 2017 Springdale Traces. Inferred groundwater flow paths and springsheds from previous traces in the general vicinity are also shown.*

Table 1. Summary of pour locations, dye types, and masses.

Date and Time of Dye Input	**Location (KFD #)**	**Dye Type**	**Mass (grams)**	**Approximate volume of water used to flush dye into sinkhole (gallons)**	**Comments**
4/7/2017 13:48	55D833	Sulforhodamine B	174.8	800	Water ponded and dissipated by 14:04
4/7/2017 15:25	55D845	Uranine	176.4	900	No ponding
4/7/2017 16:20	55D831	Eosin	332.1	900	No ponding

Trace Results

Inferred Groundwater Flow Direction and Springshed Delineation

Each of the three dyes introduced in this trace flowed east to Springdale Spring [55A443] (Figures 4, 5 and 6 and Appendix A). Groundwater flow direction from sinkhole 55D833 was consistent with flow direction found in the 2016 Springdale trace (Larsen et al. 2017). The springshed defined by the 2016 and 2017 trace covers 97.6 acres. The arrows drawn in Figure 4 are meant to illustrate the connections. In several cases in southeastern Minnesota it has been possible to map the actual flow paths of the underground conduits/streams in cave systems. Those flow paths are much more complex than the arrows in Figure 4 suggest.

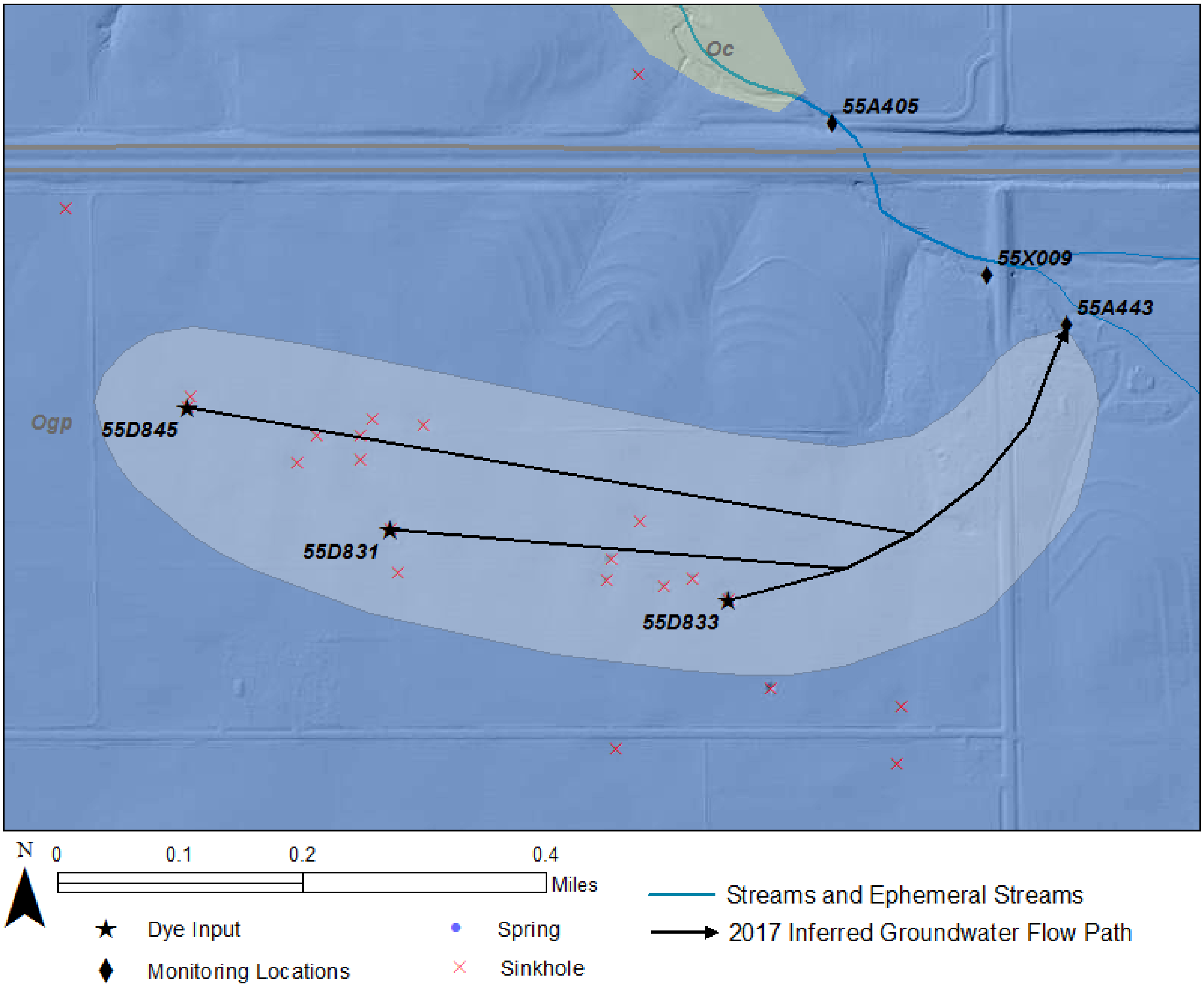

Figure 4. *Inferred groundwater flow paths and aerial extent of the Springdale springshed.*

Groundwater Time of Travel

Figure 5. *Springdale Spring auto-sampler carousel bottles with dyes visible to the unaided eye (photo by Crystal Ng).*

Groundwater time of travel in the Galena group, based on the results from decades of dye tracing in southeast Minnesota, is normally extremely rapid and conduit pathways can extend for miles (Green et al. 2014). Initial dye breakthrough is followed by a steep rise over one or two hours to peak concentrations. The concentration then decays slower than the rise but still rapidly in an exponential decrease to form the primary asymmetric concentration peak. The concentrations then decrease in a second flatter exponential fashion for about a day, then the decrease flattens to an even slower exponential decay that can stretch over a week or more. These exponential tails have not been monitored for long enough to determine when they drop to background. The small “background” eosin peak in the pre-dye injection Springdale Spring bug apparently was the tail of the eosin dye from the 2016 Springdale Trace which occurred 13 months before the 2017 Springdale Traces.

Dye-breakthrough time of travel for these traces was determined using the results of water collected using the auto-samplers at Springdale Spring. Dye concentrations in waters collected at the auto-samplers were high enough to be visible to the unaided eye (Figure 5) and the breakthrough curves are shown in Figure 6.

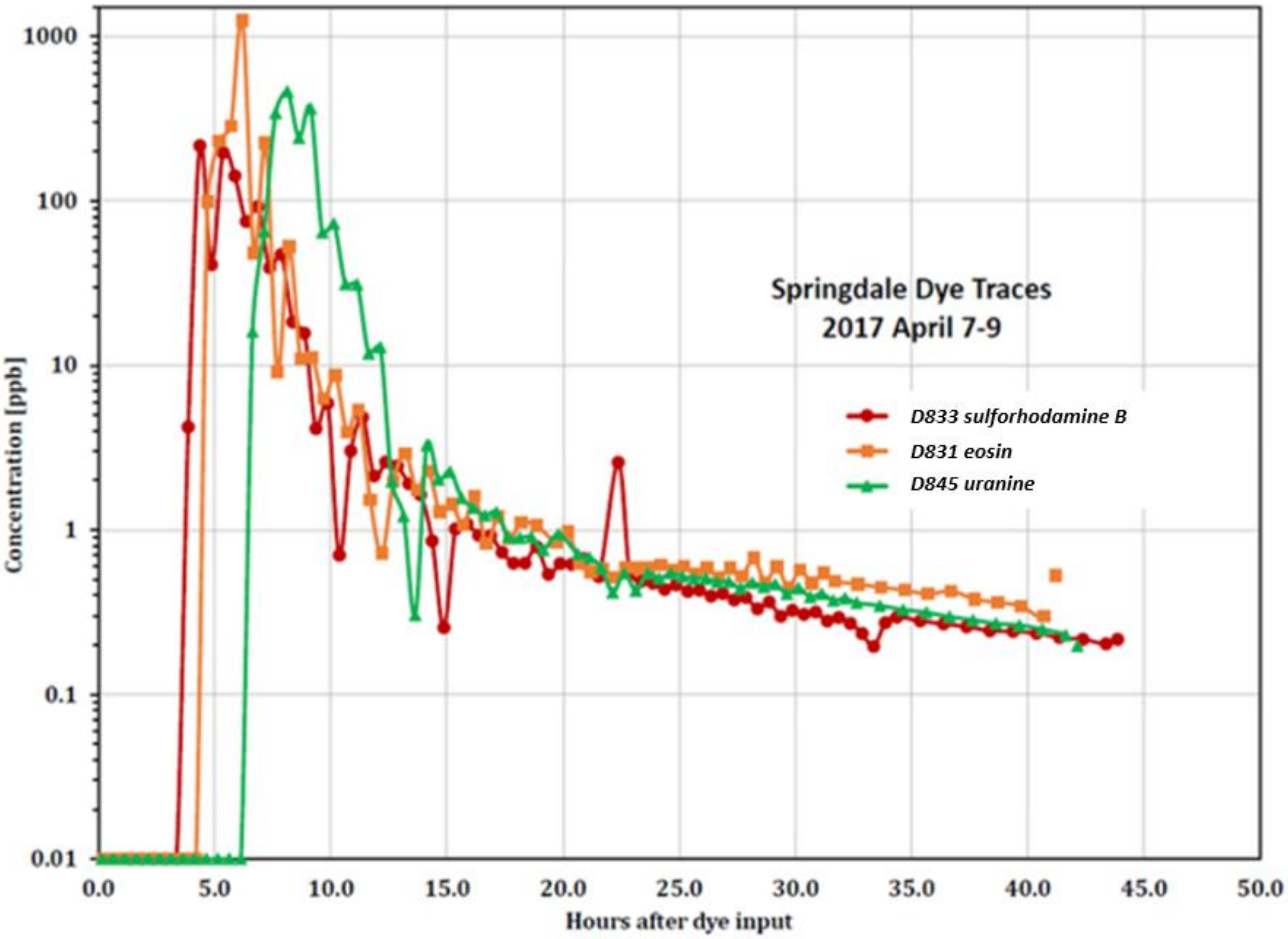

Figure 6. *Breakthrough curves for the April 7-9, 2017 dye tracing in the Springdale springshed.*

The breakthrough curve for each dye has two peaks, with the first peak having the highest concentration for each dye. Eosin had the highest peak concentration, followed by uranine and sulforhodamine B. Sulforhodamine B also had the shortest travel distance between the sinkhole and spring, travel time to dye detection, and time to peak concentration (Table 2).

Table 2. Distance and dye travel times from sinkholes to Springdale Spring.

	Distance from site to spring[a] (ft)	First arrival travel time[b] (h)	Peak Conc. travel time [c] (h)	Time to leading 10% peak concentration (p.c.) (h)	Time to lagging 10% p.c. (h)	Time from peak concentration to leading 10% p.c. (h)	Time from peak concentration to lagging 10% p.c. (h)
Sulforhodamine B (55D833)	1888	3.7	4.2	3.7	8.2	0.50	4.0
Eosin (55D831)	3063	5.6	7.1	5.6	10.1	1.5	3.0
Uranine (55D845)	3281	5.7	7.2	6.2	9.7	1.0	2.5

[a] *Distance reported is the straight-line distance from sinkhole to spring.* [b] *First arrival travel time is elapsed time from dye pour to dye detection.* [c] *Peak Conc. travel time represents peak dye trace concentration.*

The straight-line distances between the individual sinkholes and time of travel were used to estimate the groundwater flow velocities in the Prosser Formation in the Study Area. Straight-line distances were multiplied by 1.5 to include the tortuosity of the actual paths (Fields and Nash, 1997) and divided by the first arrival times and peak concentration times. The average of the three groundwater first arrival time velocities is 3.7 miles/day. The peak concentration arrival times average groundwater velocity is 3.0 miles/day. These values are typical for the shallow Galena conduit flow systems.

By numerically integrating the area under each dye breakthrough curve and multiplying by spring flow rate, the total amount of dye emerging from the spring was calculated. A flow measurement (1.2 cubic feet/second) taken at Springdale Spring on 4/7/2017 was used to estimate percent dye recovery for each dye (Table 3). Note that the breakthrough curves were only monitored for 44 hours. Percent dye recoveries for three dyes are only through the end of water sampling monitoring. Although dye concentrations had dropped by about three orders of magnitude (to 0.1%) of their peak concentrations by the end of water sampling, those concentrations were still well above background and decreasing very slowly. Longer monitoring would have yielded dye recoveries closer to 100%. Uranine had the highest percent dye recovery, followed by eosin then sulforhodamine B.

The bugs in the surrounding springs and drainages did not yield any evidence of dyes reaching other springs. Despite incomplete dye recovery estimates, there is no evidence of divergent flows to streams or springs other than Springdale Spring.

Table 3. Mass of dye poured and recovered at field sites in the first two days.

	Sinkhole	Dye poured in sinkhole (g)	Dye recovered at spring (g)	Percent dye recovered (%)
Sulforhodamine B	D833	174.8	57.87	33
Eosin	D831	332.1	140.6	42
Uranine	D845	176.4	107.5	61

Springdale Spring Flow and Water Chemistry

Springdale Spring's flow, water quality parameters, and water chemistry were measured as part of this project. Spring flow was measured on April 7, 2017 at approximately 15:30 using a Marsh-McBirney flow meter and standard flow measurement techniques. Grassy vegetation in the spring run may have introduced error in the readings. Flow was calculated to equal 1.2 cubic feet/second (539 gallons/minute).

Standard water quality parameters were measured using calibrated Hach rugged probe sensors and are presented in Table 4.

Table 4. Physical parameters of spring water.

	Measurement date and time	Temperature (°C)	Conductivity (µS/cm)	Dissolved oxygen (mg/L)	pH	Oxidation-reduction potential (mV)
Springdale Spring	4/7/17 15:02	9.0	694	9.15	6.93	293.5

A grab sample of Springdale Spring water was collected during the trace and analyzed for general water quality. The analytical laboratory at the University of Minnesota, Department of Earth Sciences performed analysis. Cations were analyzed using ICP-OES; anions were analyzed using ICS. Results are presented as Table 5.

Table 5. Average ion concentrations and select ionic ratios of Springdale Spring.

Cations (ppm)		**Anions (ppm)**	
Al	0.0096	F^-	0.14
Ba^{2+}	0.0631	Cl^-	16.73
Ca^{2+}	100.1	NO_2^-	0.23
Fe	0.0131	Br^-	0.09
K^+	1.5937	NO_3^-	15.00
Li^+	0.0012	SO_4^{2-}	14.24
Mg^{2+}	19.16	PO_4^{3-}	-
Mn	0.0015		
Na^+	4.57	**Ion ratios**	
P	0.0191	$Mg^{2+}:Ca^{2+}$	0.191
Si	4.81	$Cl^-:Br^-$	179
Sr^{2+}	0.0962	$Na^+:Cl^-$	0.273

Discussion and Conclusions

Successful tracing in 2017 expanded and refined the groundwater springshed of Springdale Spring. Although the springshed has been approximated using the techniques outlined in this report, the lateral extent of the springshed is not a sharp boundary and moves dynamically, both horizontally and vertically, in response to changes in groundwater levels. This tracing illustrates the complicated interconnection of the conduit network underlying area and its connectivity to sinkholes on the surface.

The breakthrough curves for the three dyes were largely similar, but the shape and time of the sulforhodamine B curve was different from the other dye curves (Figure 6). This could be reflective of differences in the sinkholes' secondary permeability and porosity. Sulforhodamine B was the first dye detected and had the shortest time from the leading 10% peak concentration to peak concentration (Table 2), which could reflect the shorter distance to the spring or a more direct flow path to the spring along fractures or conduits. The time from peak concentration to lagging 10% peak concentration was the longest of the dyes, which could be reflective of the ponding of water and dye that occurred during the dye pour. The ponding could have slowed dispersal of the sulforhodamine B dye, affected its adsorption onto soil particles, or affected its transport into pore spaces, which could all contribute to the low percent recovery of the dye during the monitoring period (Table 3). The sinkholes with eosin and uranine had similar times from peak concentration to leading and lagging 10% peak concentrations and higher percent dye recovery, which are consistent with their low ponding and similar distances to the spring.

The temperature of the Springdale Spring during the trace was 9.0°C, which fits within the seasonal spring temperature fluctuation recorded at nearby Bear Spring (55A406). Bear Spring, which also emanates from the Galena Group, is located roughly 1.9 miles northeast of Springdale. The water had the conductivity expected for waters near saturation with calcium bicarbonate. The near neutral pH, near saturation dissolved oxygen and a strong positive oxidation-reduction potential are characteristic of well oxygenated near surface karst waters in southeastern Minnesota. The cation and silicon concentrations are normal for southeastern Minnesota karst waters. These are calcium/magnesium bicarbonate waters. The nitrate-nitrogen concentration recorded at Springdale was 15 parts per million (ppm). This concentration is 1.5 times the drinking water standard and roughly 25% lower than concentrations found at Bear Spring (Barry, unpublished data). In the karstlands of southeast Minnesota, the nitrate-nitrogen in shallow groundwater under row cropped fields is typically well above the 10 ppm drinking water standard. Nitrate-nitrogen concentrations greater than 1 ppm are greater than background conditions and indicate that an aquifer has been impacted by activities on the land surface (MDH, 1998 and Wilson, 2012). The chloride level is reasonably low for the physical setting. The Cl/Br ratio of 179 is within the range of precipitation and does not show evidence of chloride loading from road salt, potassium chloride fertilizer, or animal manure. All of these parameters indicate a direct connection between surface runoff and infiltration, a short groundwater residence time, and suggest rapid water transit along preferential flow paths.

Acknowledgments

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Appendix A. Springdale-2017 Bugs Dye Detection Summary Table.

	Field Name	KFD #	Site Type	UTM NAD 83, Zone 15		Background Mar or Apr to 7 Apr 17	Dye Input 7 Apr 2017	7 Apr to 25 Apr 2017	25 Apr to 19 May 2017	19 May to 2 Jun 2017
				Easting	Northing					
1S	**I-90**	MN55:A00405	Spring	556023	4867224	(in: 16 Mar)		**nd**	**nd**	**nd**
2S	**Springdale Spring**	MN55:A00443	Spring	556333	4866958	**Eos** (in: 16 Mar)		**Eos** **SrB** **Uran**	**Eos** **SrB** **Uran**	**Eos** **SrB** **Uran**
3S	**CR 19**	MN55:X00009	Spring Run	556227	4867024	**nd** (in: 16 Mar)		**Eos** **SrB** **Uran**	**Uran**	**nd**
4S	**Higgins Seep**	MN55:A00593	Spring	555410	4867656	**nd** (in: 29 Mar)		**nd**	**nd**	**nd**
5S	**Higgins Spring**	MN55:A00592	Spring	555384	4867657	**nd** (in: 29 Mar)		**nd**	**nd**	**nd**
6S	**Hwy 52**	MN55:X00011	Spring Run	553954	4864837	**nd** (in: 6 Apr)		**nd**	**---**	**nd**
7S	**70th Ave. South**	MN55:X00032	Spring Run	553039	4865430	**nd** (in: 6 Apr)		**nd**	**nd**	**nd**
8S	**70th Ave. Middle**	MN55:X00031	Spring Run	553023	4866351	**nd** (in: 6 Apr)		**nd**	**nd**	**nd**
9S	**70th Ave. North**	MN55:X00030	Spring Run	553044	4866578	**nd** (in: 6 Apr)		**nd**	**nd**	**nd**
10S	**Bird Man Spring**	MN55:X00048	Spring Run	555029	4867783	**nd** (in: 6 Apr)		**nd**	**nd**	**nd**
11S	**Bear Perennial Spring**[1]	MN55:A00406	Spring	557705	4869620	**nd** (in: 27 Mar)		**---**	**---**	**---**

---	**indicates no bug or sample was received by the lab**
Eos	**indicates Eosin dye was detected**
SrB	**indicates Sulforhodamine B dye was detected**
Uran	**indicates Uranine (fluorescein) dye was detected**

[1] Flushing water was sourced at Bear Perennial Spring (55A406) and transported in Martin Larsen's 500 gallon tank on his trailer.