International Trace
Olmsted County, Minnesota

2016 Dye Trace Report

Tracing Conducted
December 2016 through June 2017

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Introduction

This report presents the findings of dye tracing that was conducted in 2016 in southern Olmsted County, Minnesota. Previous dye tracing in southern and east central Olmsted County has occurred over the last two decades in support of water resource management and springshed mapping (Larsen et al., 2017; Larsen et al., 2016; Johnson et al., 2014; Eagle and Alexander, 2007).

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 monitoring is being used to understand groundwater recharge characteristics, groundwater flow direction and time of travel, and to assist in determining the size and areal extent of the groundwater springsheds that supply perennial groundwater discharge to springs.

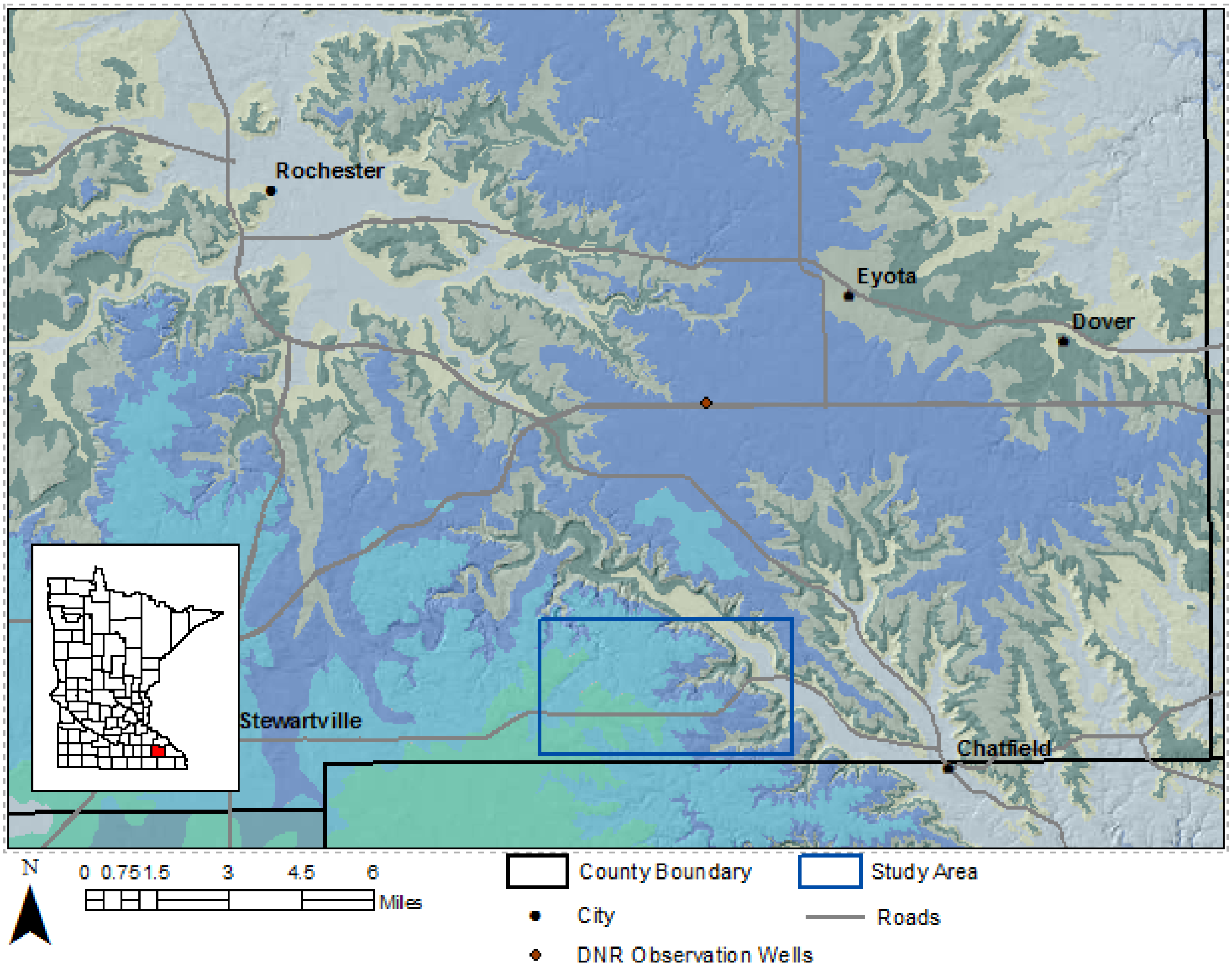

Figure 1. *Location map for the International study area. Geology base map unit colors correspond with colors used in the Formation column of Figure 2.*

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).

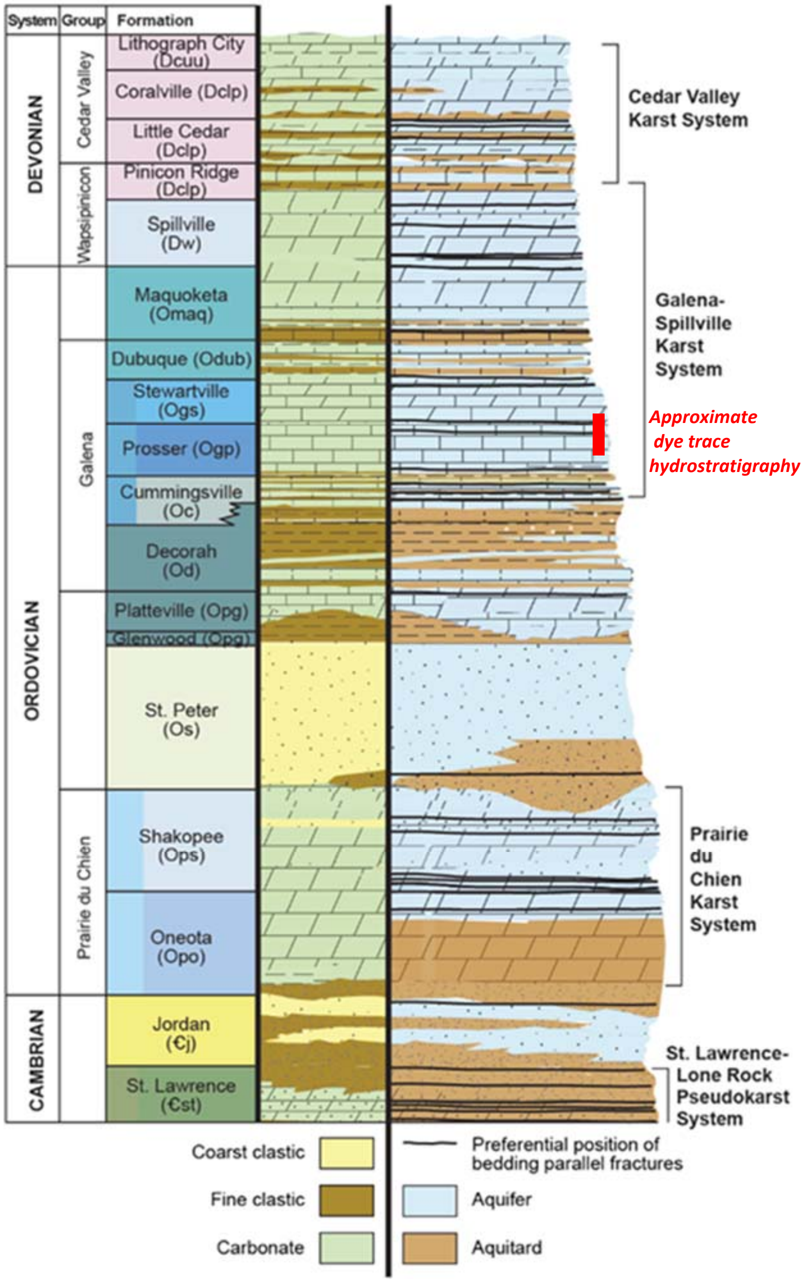

Figure 2. *Geologic and hydrogeologic attributes of Paleozoic rocks in southeastern Minnesota. Modified from Runkel et al., 2013.*

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 occurs 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 the Prosser Formation of the Galena-Spillville karst, where groundwater velocity can reach up to 1-3 miles/day (Green et al., 2014).

Tracing Methods

Dye tracing is a technique used to characterize the groundwater flow system to determine groundwater flow direction and rate. Traces are designed to establish connections between recharge points (sinkholes and stream sinks) and discharge points (springs and streams). Multiple traces are usually necessary to delineate the boundaries of springsheds. Dye tracing was accomplished using fluorescent dyes that travel at approximately the same rate 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 are not naturally present in groundwater.

To detect the presence or absence of dye at springs and other monitoring locations, passive charcoal detectors were used. These detectors, often referred to as “bugs”, were deployed prior to introducing dye to determine background levels of fluorescence in the groundwater. After dyes were introduced, the bugs were changed periodically by Olmsted SWCD and Minnesota DNR staff until the trace was terminated. The time resolution of the dye arrival at the monitored points is limited to how long the charcoal packets were left in the water before being analyzed. Appendix A summarizes the monitoring locations and how frequently the passive detectors were changed.

Passive dye detectors were sent 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 solution was then analyzed using a Shimadzu RF5000 scanning spectrofluorophotometer and the resultant dye peaks were analyzed with a non-linear curve-fitting software and summarized into a table (Appendix A).

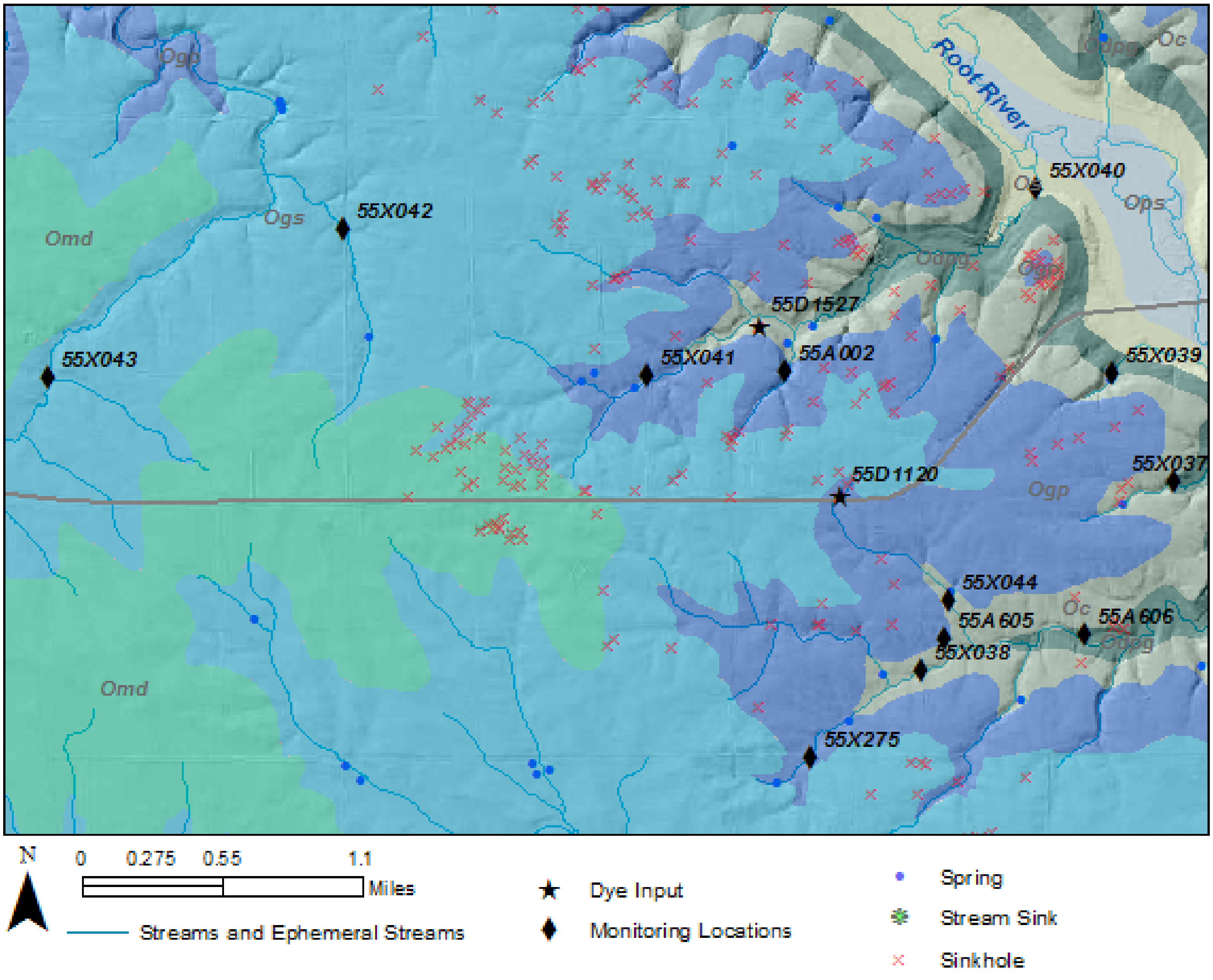

Figure 3. *Dye input points and sampling locations.*

These traces were designed to establish connections between recharge points, the sinkholes located in the uplands, and springs (Figure 3). Identification of potential sinkholes for dye injection, locating un-mapped springs, property access and water tanker access was coordinated by Martin Larsen of the Olmsted SWCD.

Figure 4. After priming the sinkhole with roughly 100 gallons of water, sulforhodamine B dye was introduced and back-flushed with additional water.

The two dye introduction points for these traces were dry sinkholes, therefore dyes were flushed into the sinkholes via hose lengths connected to a trailered water tank (Figure 4). Each sinkhole was wetted with approximately 100 gallons of water prior to the dye being manually poured into the sinkhole. Dyes were then back-flushed with approximately 300 additional gallons. Both dyes were poured on 12/8/2016 at the sinkhole locations summarized in Table 1. The Karst Feature Database identifiers are typically ten character alpha-numeric, but have been abbreviated for the table and figures. (e.g. 55D0001120 is abbreviated to 55D1120).

Date of Dye Input	Location (KFD #)	Dye Type	Mass (grams)
12/8/2016	55D1120	Sulforhodamine B	1127.54 (17.7 weight% solution)
12/8/2016	55D1527	Uranine HS	1104.31 (35 weight% solution)

***Table 1.** Summary of pour locations, dye types, and masses. Dyes were flushed into the sinkholes using approximately 400 gallons of creek water from an unnamed perennial creek (M-009-038) at the CR-139 crossing.*

Trace Results

Inferred Groundwater Flow Direction

Only one of the two dyes used in these traces was recovered. Sulforhodamine B dye was recovered at Pedelty Spring House (55A605) located roughly 3650 feet east-southeast of the sinkhole (Figure 5). The Uranine dye poured at 55D1527 was never recovered. Additional dye tracing in the area would need to be conducted to delineate the springshed to Pedelty Spring (55A605).

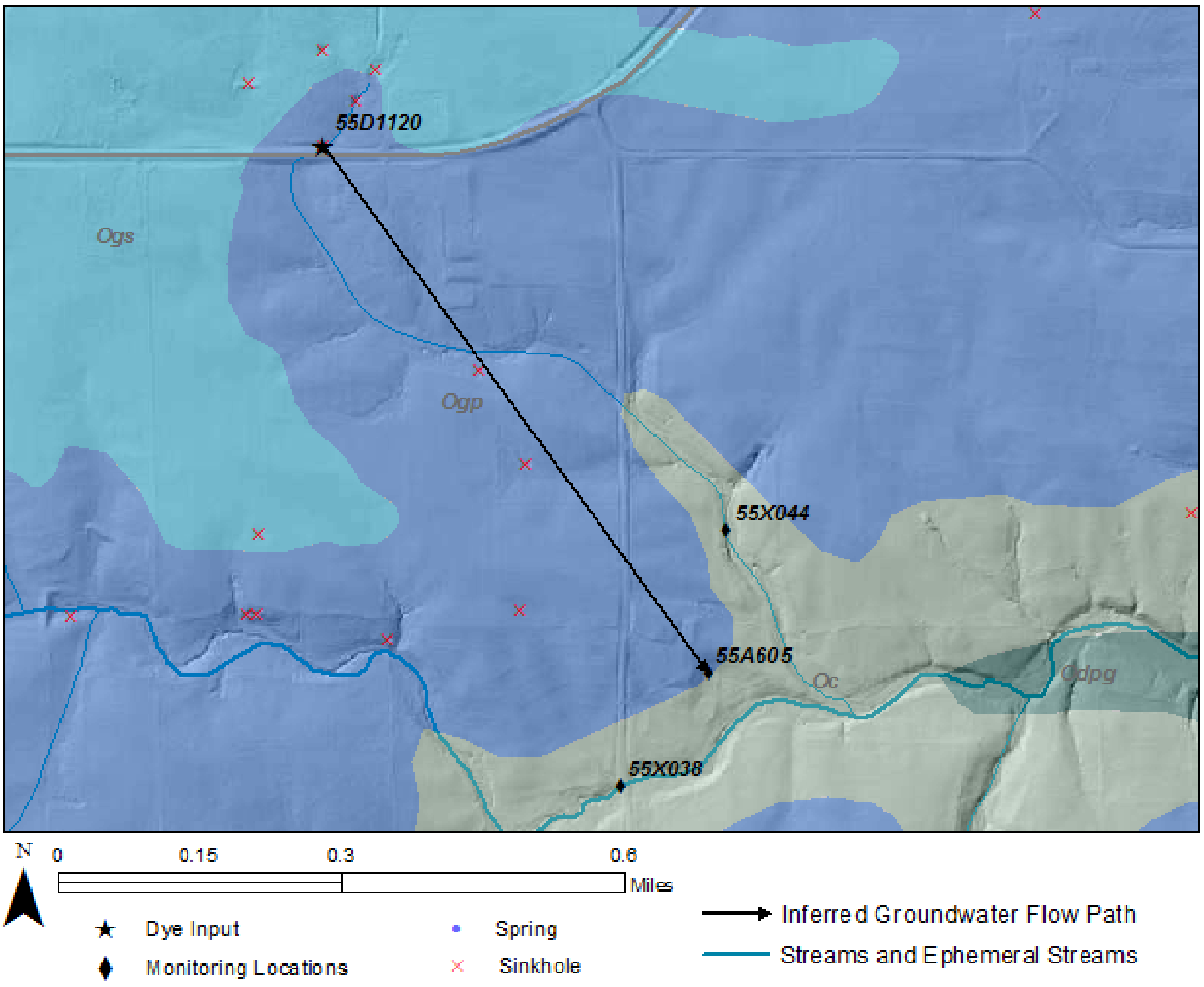

Figure 5. *Inferred groundwater flow path determined for the 2016 International Trace.*

Groundwater Time of Travel

Groundwater time of travel in the Galena Group in Fillmore County and Olmsted County, determined from decades of dye tracing, is typically very rapid and conduit pathways are known to extend for miles. Large conduit systems in the Galena Group have been encountered throughout Fillmore County (county located directly south of Olmsted).

Dye-breakthrough time of travel for this trace was calculated using the straight line distance from the dye injection (3,649 feet), divided by the time elapsed before the dye was detected in passive charcoal detectors from the monitoring locations. The straight-line distance was multiplied by 1.5 to include the tortuosity of the actual paths (Fields and Nash, 1997) and divided by the first arrival time “window”. Only the sulforhodamine B dye was recovered at Pedelty Spring, arriving at the spring between 66 and 100 days following introduction of the dye. The approximate minimum peak groundwater time of travel ranged between 55 to 83 feet/day. These values are atypical for shallow buried Galena Group conduit flow systems.

Discussion and Conclusions

Although dye was recovered from one of the traces conducted for this project, the time of travel approximation is inconsistent with previous traces in the Galena Group in Olmsted and Fillmore counties. The date of this trace, in early December on frozen ground after the first snowfall, may explain the no-recovery of the uranine dye and the atypical groundwater flow rate for the Galena Group of the sulforhodamine B dye. In addition, the local topography of the two dye injection points is quite different. Sinkhole 55D1120, the sulforhodamine B dye input point, is in soil in a roadside ditch on the north side of paved MN 30 Highway at the head of a small valley sloping gently to the south. Overland flow from several acres funnels into this sinkhole when frozen ground impedes normal infiltration or during large precipitation events.

In contrast, sinkhole 55D1527 is a bedrock crevice at the top edge of a steep slope dropping to the north. Its nominal recharge area is only a few square feet of area -- and the crevice may act as a cold trap and remain frozen well into spring. Although sinkhole contains roughly 15 feet of passage, its origin is unclear and it may be a crevice developed from mechanical bluff separation.

Comparison of the timing of this trace to precipitation and aquifer heads levels offer a possible explanation for the "loss" of the uranine dye (55D1527) and for the delayed recovery of the sulforhodamine B dye (55D1120) (Figure 6). The timing of the trace is compared to groundwater elevation from an observation well completed in the Galena Group located roughly 6 miles north of the project area (Figure 1). The DNR maintains a statewide groundwater level monitoring program for assessing groundwater resources, determining long-term trends, interpreting impacts of pumping and climate, and managing water resources. Many of the newer wells in the program are closely spaced wells that are constructed in different aquifers, commonly referred to as well nests. The Galena Group well is paired with a St. Peter well and a Prairie du Chien well. These data are available from the DNR (https://www.dnr.state.mn.us/waters/cgm/index.html).

Groundwater elevation in the Galena well (817784) in that nearby well nest is compared to daily precipitation collected at National Weather Service Reporting Station 217004 located in Rochester, MN (Figure 6). The upper panel of Figure 6 shows the snow depth (in blue) and the daily cumulative precipitation (in black). The lower panel of Figure 6 shows the Galena well's groundwater elevation responses to snowmelt and precipitation events. The bulk of precipitation that fell in the first five weeks following introduction of dyes fell as snow and infiltrated frozen ground conditions in a step pattern on days where the air temperature was greater than 32°F (Figure 6). Groundwater levels in the Galena aquifer rose following a snowmelt event on December 26, 2017, but likely not enough to mobilize the dye that was poured on December 8, 2017. Groundwater levels rose dramatically following a series of snowmelt events over the weeks of December 20, 2017 to January 23, 2017, with levels rising rapidly beginning around January 20, 2017 (Figure 6). Following additional snowfall in late January and early February, snow melting and precipitation began another large recharge event evident in rising groundwater level around February 12, 2017. The first window of time (2/10/2017 – 3/16/2017) where sulforhodamine was recovered from a bug followed this recharge event. Additional sampling for the next 85 days recorded the dye's continuous presence at 55A605.

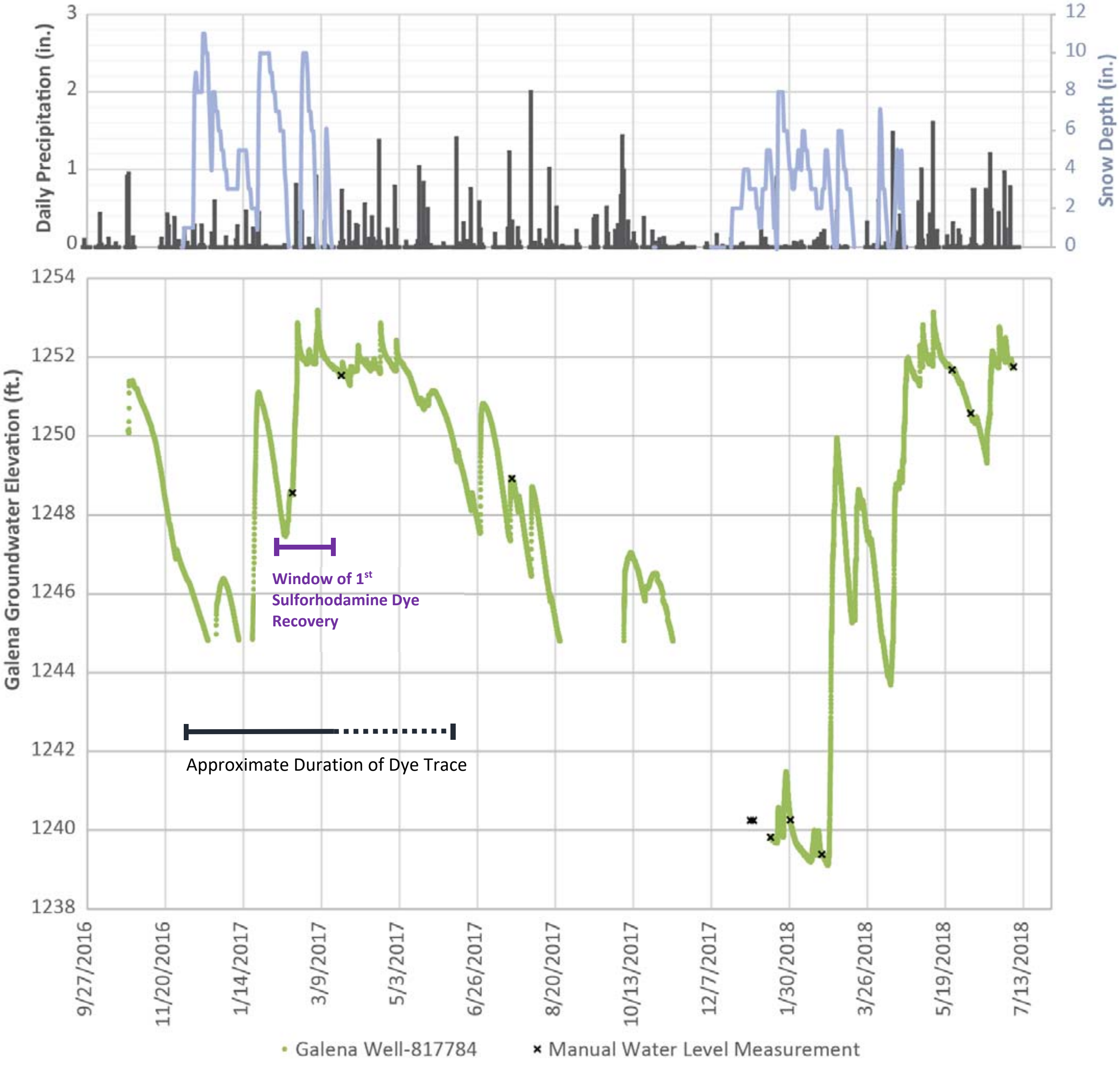

Figure 6. *Hydrograph of Galena well 817784 compared to cumulative daily snow depth and precipitation at NWS 217004.*

The rapid water level response of the Galena well groundwater levels to recharge from snowmelt and precipitation events show karst hydrologic responses of the Galena aquifer. This suggests that the time of travel estimates for the trace are not accurate due to the dye likely being immobile above the water table in low recharge frozen-ground conditions.

There are several possible explanations for the failure to detect the uranine dye. They include:

1) the dye was “frozen” above the water table until after the monitoring was terminated on March 16, 2017 at most of the monitoring points and, when finally mobilized, flowed north to unnamed creek M-009-038.
2) sinkhole 55D1527 is possibly a crevice formed by mechanical separation of the bluff. If so, it may not be connected into karst conduits and the uranine dye may have exited in seepage at the toe of the bluff slope.
3) the dye took longer than the sampling period to reach one or more of the other sampling stations.
4) the dye moved preferentially downward into an underlying aquifer.

This trace provided interesting lessons for winter tracing in Minnesota and helps refine the approach of dye tracing in the Galena Group. Following this trace, it is recommended that dye back-flush volumes for winter traces be two to three times the amounts used on this project. If the proposed future project is not time sensitive, it is recommended that dye be not be poured under frozen ground conditions or only when recharge events can assist in keeping dyes mobile.

Acknowledgments

This project would not have been possible without the cooperation of landowners in project area. Funding for this project was provided by the Minnesota Clean Water Land and Legacy Amendment and the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR). Scott Alexander at the University of Minnesota Department of Earth Sciences analyzed samples and performed peak fitting. Holly Johnson provided graphic editing assistance and review.

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Appendix A. *International-2016 dye detection summary table. Cells highlighted in yellow denote no bug was delivered to lab, nd indicates not detected, and* **SrB** indicates sulforhodamine B dye detected

Field Site #	KFD #	Field Site	UTMs (NAD 83, Zone 15)		xxx to 8 Dec 2016	Dye Input 8 Dec 2016	8 Dec to 15 Dec 2016	15 Dec to 29 Dec 2016	29 Dec 2016 to 9 Jan 2017	9 Jan to 19 Jan 2017	19 Jan to 10 Feb 2017	10 Feb to 16 Mar 2017	27 Mar to 4 May 2017	4 May to 9 Jun 2017
			Easting	Northing										
1S	MN55:X00043	108th St. Crossing (55X43)	552080	4857610	nd (In: 30 Nov 2016)		nd	nd	nd	nd	nd	---	---	---
2S	MN55:X00042	CR - 19 Crossing (55X42)	553937	4858548	nd (In: 30 Nov 2016)		nd	nd	nd	nd	nd	nd	---	---
3S	MN55:X00041	86th Ave. Crossing (55X41)	555859	4857613	nd (In: 30 Nov 2016)		nd	nd	nd	nd	nd	nd	---	---
4S	MN55:X00040	CR - 139 Crossing (55X40)	558302	4858792	nd (In: 30 Nov 2016)		---	nd	---	---	---	---	---	---
5S	MN55:X00039	Hanson Spring Run (55X39)	558781	4857635	nd (In: 30 Nov 2016)		nd	nd	nd (in: 29 Dec 2016)				---	---
6S	MN55:X00038	CR - 138 Crossing (55X38)	557572	4855762	nd (In: 30 Nov 2016)		nd	nd	nd	nd	nd	nd (out: 17 Mar)	nd	nd
7S	MN23:X00275	120th St. Crossing (23X275)	556882	4855219	nd (In: 30 Nov 2016)		nd	nd	nd	nd	nd	nd (out: 17 Mar)	---	---
8S	MN55:A00605	Pedelty Spring House (55A605)	557723	4855956	nd (In: 1 Dec 2016)		nd	nd	nd	nd	nd	SrB (315 σ)	SrB (9.2 σ)	SrB (7.25 σ)
9S	MN55:A00606	Pedelty Spring East (55A606)	558605	4855990	nd (In: 1 Dec 2016)		nd	nd	nd	nd (in: 9 Jan 2017)		nd	---	---
10S	MN55:X00044	Nelson Spring Run (monitoring Nelson Spring 55A610) (55X44)	557754	4856198	nd (In: 1 Dec 2016)		nd	nd	nd	nd	nd	---	---	---
11S	MN55:X00037	Bathtub Spring Run (55X37)	559172	4856947	nd (In: 1 Dec 2016)		nd	nd	nd (in: 29 Dec 2016)			nd	---	---
12S	MN55:A00002	Orion Big Spring (aka, Reichel Spring) (55A2)	556718	4857642	nd (In: 22 Oct 2016)		nd	nd	nd	nd	nd	nd (out: 17 Mar)	---	---
13S		Surprise Spring			---		---	---	---	---	---	---	nd	nd