Crystal Creek
Fillmore County, Minnesota

2018 Dye Trace and Spring Monitoring Report

Traces:
March 14 2018, March 17 2018

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Introduction

This report presents the findings of 2018 dye tracing conducted near Crystal Creek in southern Fillmore County, Minnesota and spring monitoring and nitrate loading at Pond Spring (Figure 1). Previous dye tracing in the Crystal Creek area occurred in 2010, 2011, 2013, and 2016 in support of the Root River Field to Stream Partnership (Kuehner and others, 2017). The Root River Field to Stream Partnership (RRFSP) is a multi-agency effort led by the Minnesota Department of Agriculture (MDA). The primary goal of the partnership is to characterize nutrient losses by agriculture to surface water and groundwater and to apply sustainable best management practices (BMPs) to reduce those losses. The Crystal Creek Watershed is one of the three study areas in the partnership.

Collaboration between the Minnesota Department of Natural Resources (DNR), University of Minnesota-Department of Earth Sciences, MDA, and Soil and Water Conservation Districts (SWCD) has led to many dye tracing projects in southeastern Minnesota. Results of dye tracing investigations conducted in Minnesota 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, 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.

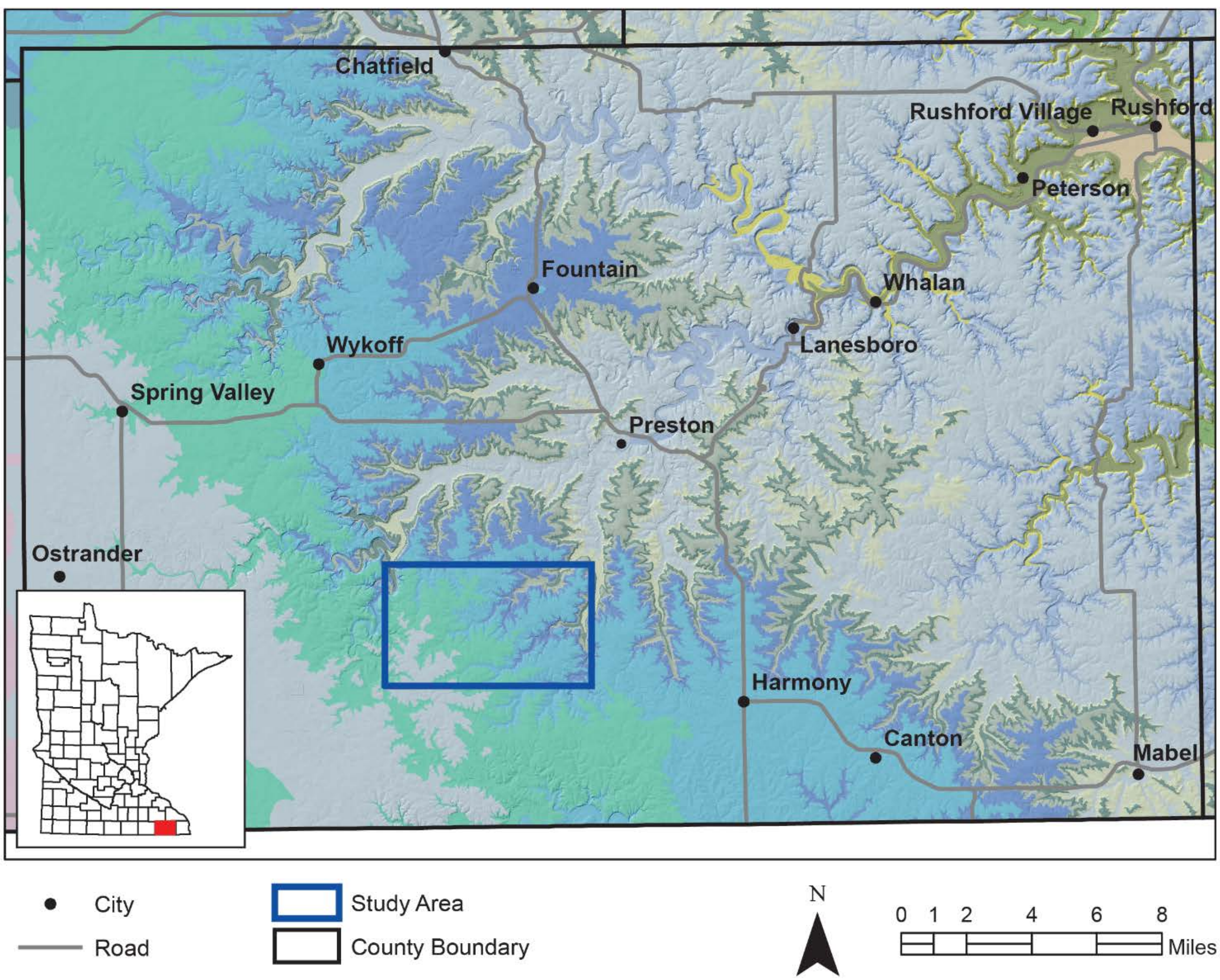


Figure 1. *Location map for the Crystal Creek study area in Fillmore County, Minnesota. Geology base map unit colors correspond with colors used in the Formation column of Figure 2.*

Area Geology and Hydrogeology

Underlying the relatively thin veneer of unconsolidated sediments, such as loess, sand, and colluvium, in Fillmore County is a thick stack of Paleozoic bedrock units that range from the Devonian to Cambrian (Mossler, 1995). Devonian and Ordovician rocks are generally dominated by carbonates, whereas the Cambrian rocks are generally siliciclastic (Figure 2). In Fillmore County, broad plateaus are primarily underlain by resistant carbonate rocks of the Cedar Valley and Wapsipinicon Groups, the Maquoketa and Dubuque Formations, the Galena Group, or the Shakopee Formation (Mossler and Hobbs, 1995). Except in the southwestern portion of the county where unconsolidated deposits are relatively thick, sinkholes are spread throughout the landscape and are visible expressions of underlying karst aquifers.

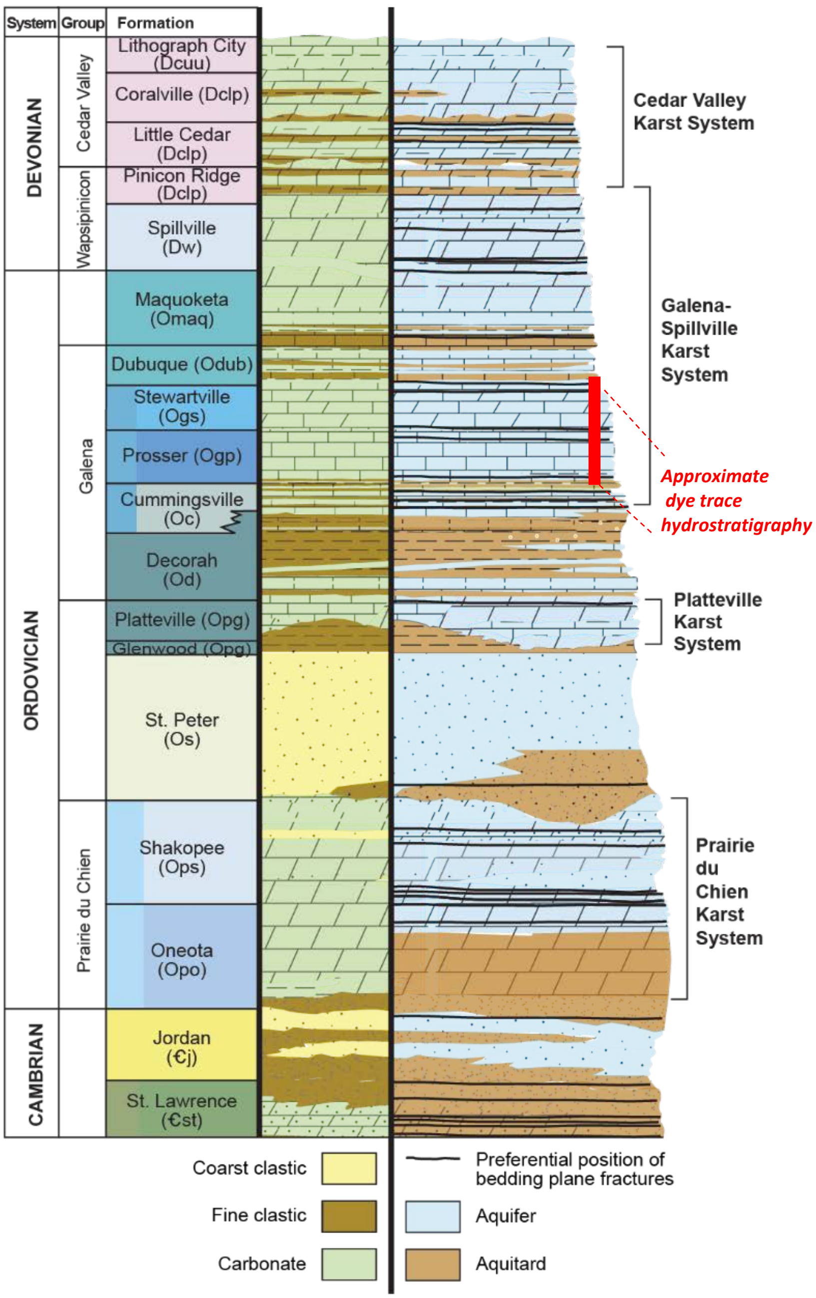


Figure 2. *Geologic and hydrogeologic attributes of Paleozoic rocks in southeastern Minnesota. Modified from Runkel and others, 2013.*

A generalized stratigraphic column for Fillmore County (Figure 2) shows lithostratigraphic and generalized hydrostratigraphic properties (modified from Runkel and others, 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, effectively hydraulically separating aquifer layers. However, layers designated as aquitards may contain high permeability bedding plane fractures conductive enough to yield large quantities of water.

Springs and groundwater seepage frequently occurs at the toe of bluff slopes and in meander scars comprised of St. Peter Sandstone, near the contact of the Decorah and Platteville Shale, and near the contact of the Prosser Limestone and Cummingsville Formation (Mossler and Hobbs, 1995).

A hydrogeologic framework that describes four prominent karst systems for southeastern Minnesota (Runkel and others, 2013) is based largely on the work of Alexander and Lively (1995), Alexander and others (1996), and Green and others (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. The dye tracing and spring monitoring presented in this report occurred in the Galena-Spillville karst, where groundwater velocities can reach up to 1-3 miles/day (Green and others, 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 often used to delineate the boundaries of springsheds. Dye tracing was 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 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 poured, the bugs were changed periodically by Fillmore 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 Fityk version 1.20 non-linear curve-fitting software and summarized into a table (Appendix A).

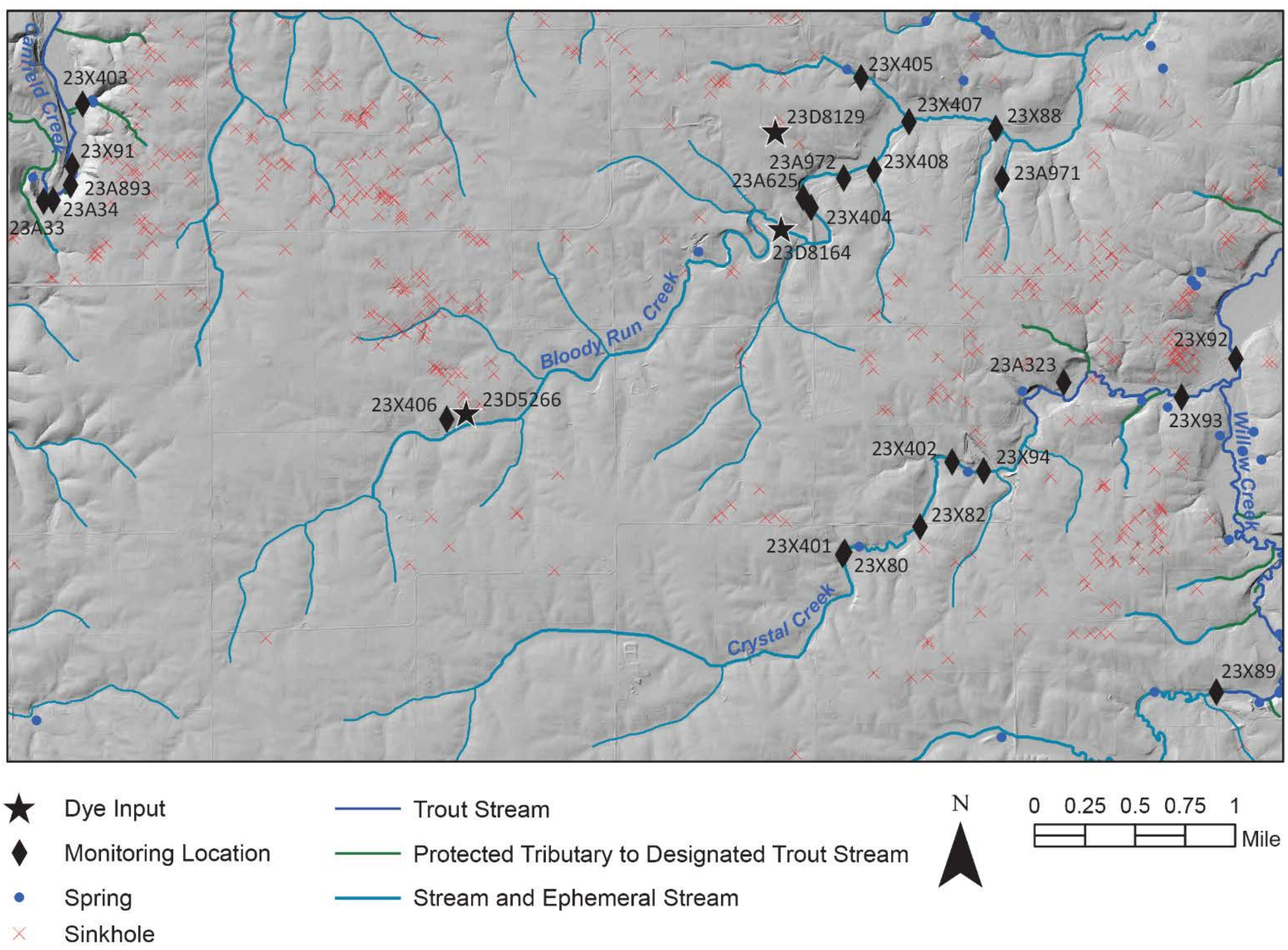


Figure 3. *Dye input points and monitoring locations for the 2018 Crystal Creek traces.*

Figure 4. *Dyes were poured into 23D8164 and flushed into the underlying karst system using snowmelt runoff (photo by J.Barry).*

The *2018 Crystal Creek* traces were designed to establish connections between recharge points, the sinkholes located in the uplands, and perennial springs located along Crystal Creek, Bloody Run Creek, and Canfield Creek (Figure 3). The traces were designed and timed to utilize snowmelt as the water source for flushing dyes into the underlying karst system. Timing tracing to coincide with snowmelt can be difficult, however when timed properly it is an efficacious approach as it negates needing to introduce water via tanker truck at a time when field access can be limited due to muddy conditions.

Two dyes, uranine HS and rhodamine WT, were poured on March 14, 2018 at sinkhole locations where continuous runoff was entering the sinkhole. A third target sinkhole that day did not have sufficient snowmelt to introduce the dye. An alternate location was determined and eosin dye was poured on March 17, 2018 into a sinkhole that had approximately 30 gallons per minute (gpm) of snowmelt runoff entering the depression (Figure 5). Pour locations are summarized in Table 1. The Karst Feature Database (KFD) identifiers are typically ten character alpha-numeric, but have been abbreviated for the table and figures (e.g. 23D8164).

Figure 5. *Sinkhole 23D5266 and snowmelt on March 17, 2018 (photo by K.Kuehner).*

Table 1. *Summary of pour locations, dye type, dye mass, and estimated runoff into sinkhole.*

Date of Dye Input	Location (KFD)	Dye Type	Solution Mass (grams)	Estimated runoff into sinkhole (gpm)
14-Mar-18	23D8164	Uranine HS	989.36	40
14-Mar-18	23D8129	Rhodamine WT	883.29	50
17-Mar-18	23D5266	Eosin	1119.85	30

Trace Results

Inferred Groundwater Flow Direction and Springshed Delineation

Each of the three dyes that were introduced in this 2018 trace were recovered at monitoring locations (Appendix A). Groundwater flow direction determined from the dye introduced to 23D5266 was to the west and is similar to the groundwater flow directions determined in the 1993 tracing that occurred as part of mapping for the Fillmore County Geologic Atlas (Alexander and others, 1996). The springshed delineated during the 1993 work was coined the Starless River Springshed; the 2018 inferred groundwater flow path expanded the east-central portion of the Starless River Springshed (Figure 6a).

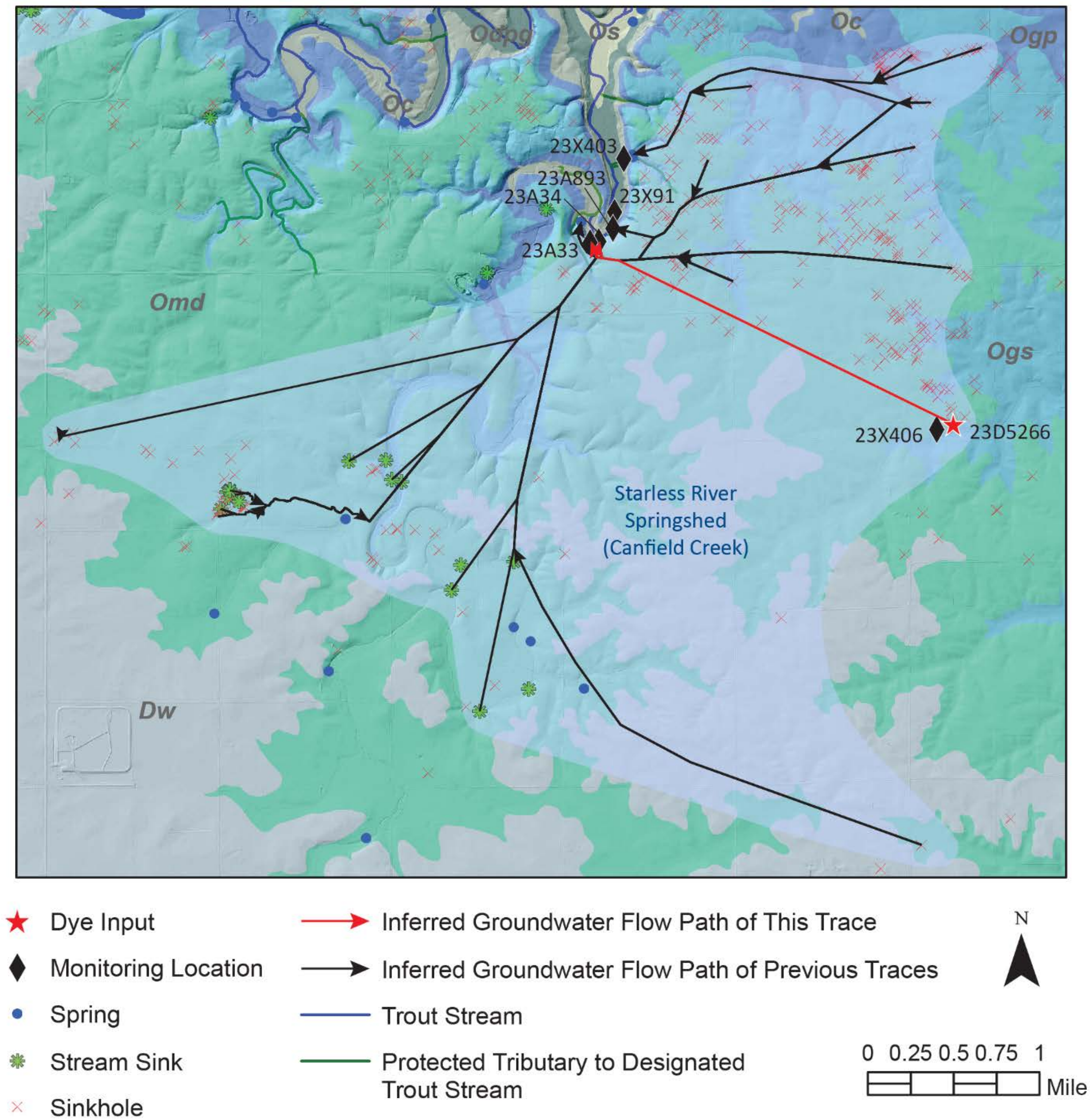


Figure 6a. *Inferred groundwater flow paths and aerial extent of the Starless River Springshed.*

Groundwater flow direction determined from the dyes introduced into 23D8129 and 23D8164 was to the east, emerging at Springsdale Spring (23A625). These traces led to the delineation of a new approximately 65 acre springshed in the project area (Figure 6b.).

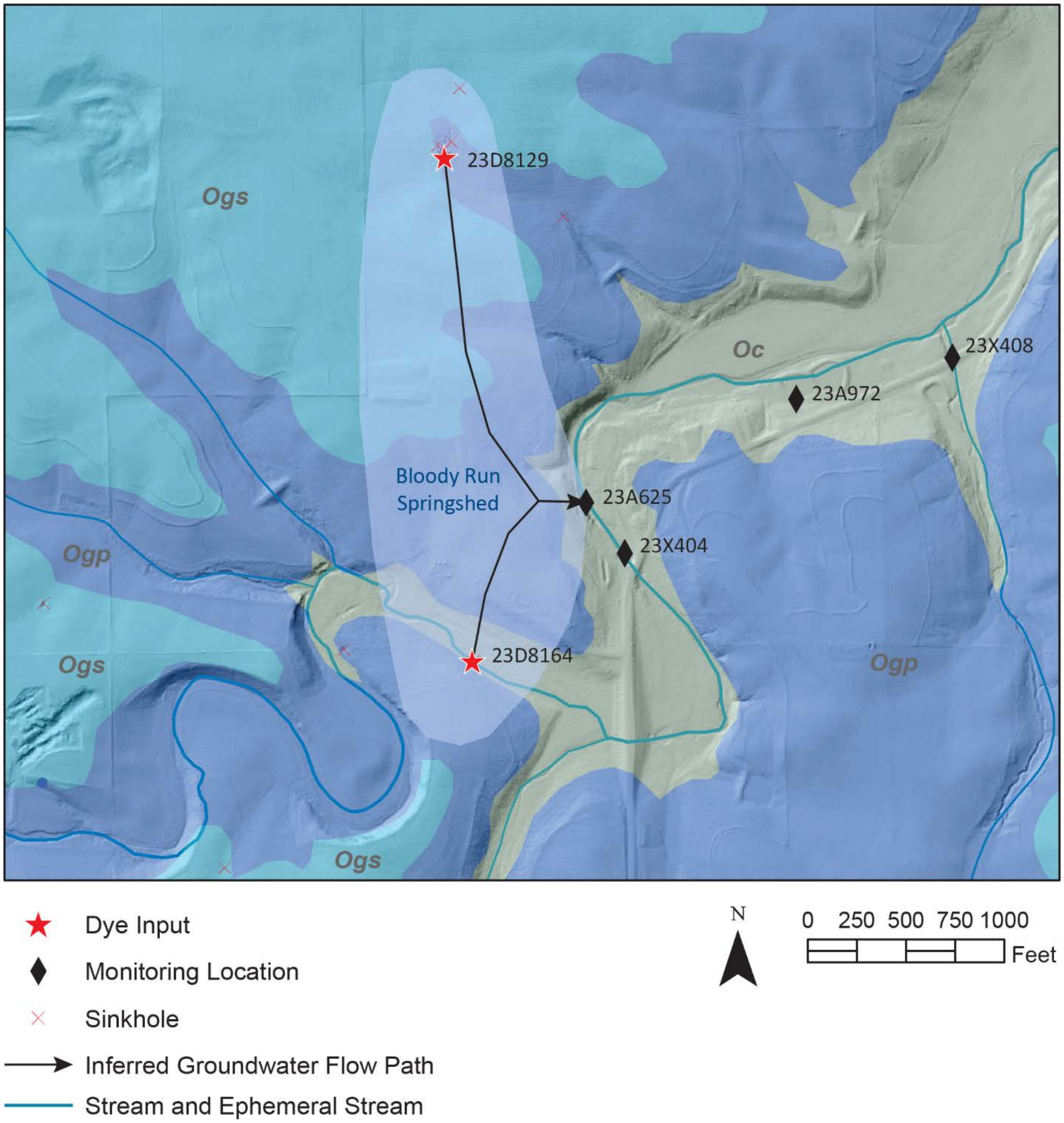


Figure 6b. *Inferred groundwater flow paths and aerial extent of the Bloody Run Springshed.*

Groundwater Time of Travel

Groundwater times of travel in the Galena Group in Fillmore County, determined from decades of dye tracing, are extremely rapid and conduit pathways can extend for miles (Green and others, 2014). Large conduit systems have been encountered throughout the county and cave systems such as Niagara Cave, Goliath's Cave and Holy Grail Cave are within roughly 8 miles of these traces. Groundwater time of travel for the Twin Springs Springshed, located just south of the project area, during a 2011 trace was at least 1.5 miles/day (Kuehner and others, 2017).

Dye-breakthrough time of travel for these traces was calculated using straight-line distances between the individual sinkholes and dye arrival times. The straight-line distances were multiplied by 1.5 to account for tortuosity of the actual flow paths (Fields and Nash, 1997) and were divided by the arrival time envelopes (the time interval from when the first positive bug was deployed and when that bug was replaced).

Dye-breakthrough travel time for the 2018 Crystal Creek traces ranged from approximately 570 feet/day to 1.8 miles/day (Table 2).

Table 2. *Summary of travel distances, dye arrivals, and estimated range of first arrival or breakthrough groundwater velocities.*

Sinkhole (KFD)	Spring (KFD)	Dye	Straight-line Distance (ft.)	"Corrected" Distance[1] (ft.)	Earliest Dye Arrival (days)	Latest Dye Arrival (days)	Earliest First Arrival Ground-water Velocity (ft/day)	Latest First Arrival Ground-water Velocity (ft/day)
23D8129	23A625	RhWT	1,892	2,838	2	5	568	1,419
23D8164	23A625	Uranine	997	1,496	2	-	748	-
23D5266	23A33	Eosin	12,454	18,681	2	6	3,114	9,341

[1] To account for tortuosity of flow paths, the corrected distance is equal to the straight-line distance times 1.5

Rhodamine WT dye was detected at the Highway 15 creek monitoring station (23X88) before dye was detected at the upstream spring location (23A625), suggesting a hydrologic pathway between 23D8129 and the creek or the presence of an additional unmonitored spring. Background levels of uranine and eosin found in bugs deployed in the Crystal Creek area may still be in the hydrologic system from tracing that occurred in April 2016 (Appendix A).

Both uranine and eosin were detected in the March 1-13, March 13-16 and March 16-19 background bugs located at Crystal Spring (23X401). Since no other known dye tracing was conducted in this area, it is possible that these dyes are from a trace conducted on April 21, 2016. During the 2016 trace, uranine was poured into the Holy Grail North Sinkhole (23D5302) and eosine was poured in the Roeloff sinkhole (23D4636). Results from this trace showed a positive connection between Holy Grail North and a spring set in Forestville State Park (Black Rock, Canfield Spring and Canfield Creek). Eosin was detected at Crystal Spring (23A028) but no uranine was detected in 2016. To characterize the presence of dyes in the hydrologic system over longer time scales than are typically measured, additional bugs were deployed in the watershed in October 2018 (Appendix A).

Pond Spring Recharge Response, Temperature, and Nitrate-N Loading Estimations

Site Description

Pond Spring (23A323, PS) is a perennial spring located in the Crystal Creek Watershed. The spring is located roughly 1.5 miles to the east-southeast of the Bloody Run Springshed and emanates from the lower Cummingsville Formation of the Galena Group (Figures 2 and 8, Steenberg and Runkel, 2018). Water quantity and quality monitoring at PS was conducted by the MDA and Fillmore SWCD as part of the RRFSP. PS is one of three groundwater springs monitored on private land in the Crystal Creek Watershed. The main purpose of monitoring these springs is to facilitate a better understanding of aquifer recharge response following precipitation and snowmelt events and to characterize sources, fate, and transport of nitrate-nitrogen in the watershed. Spring discharge, spring water temperature, and nitrate concentration are the emphasis of monitoring at PS with the primary goal of estimating annual nitrate loads. These data combined with additional hydrologic studies conducted at edge of field and small watershed scales provides a unique and comprehensive assessment of pollutant sources and agricultural BMP effectiveness.

The Crystal Creek Watershed is 3,728 acres and is a tributary to Willow Creek which flows into the South Branch of the Root River. Based on previous dye tracing investigations, the springshed area contributing to PS is estimated to be at least 320 acres (Figure 7). Approximately 37% of the Pond Spring Springshed is located outside of Crystal Creek's surface drainage divide (Kuehner and others, 2017). Based on the 2017 cropland data layer (NASS, 2017) and verified with air photos and ground truthing, land use in the Pond Spring Springshed is managed for alfalfa (38%), corn/soybeans (32%), forest (20%) and developed farmsteads/other (10%). For comparison Crystal Creek Watershed land use is 14% alfalfa, 62% corn/soybeans, and 7% forest.

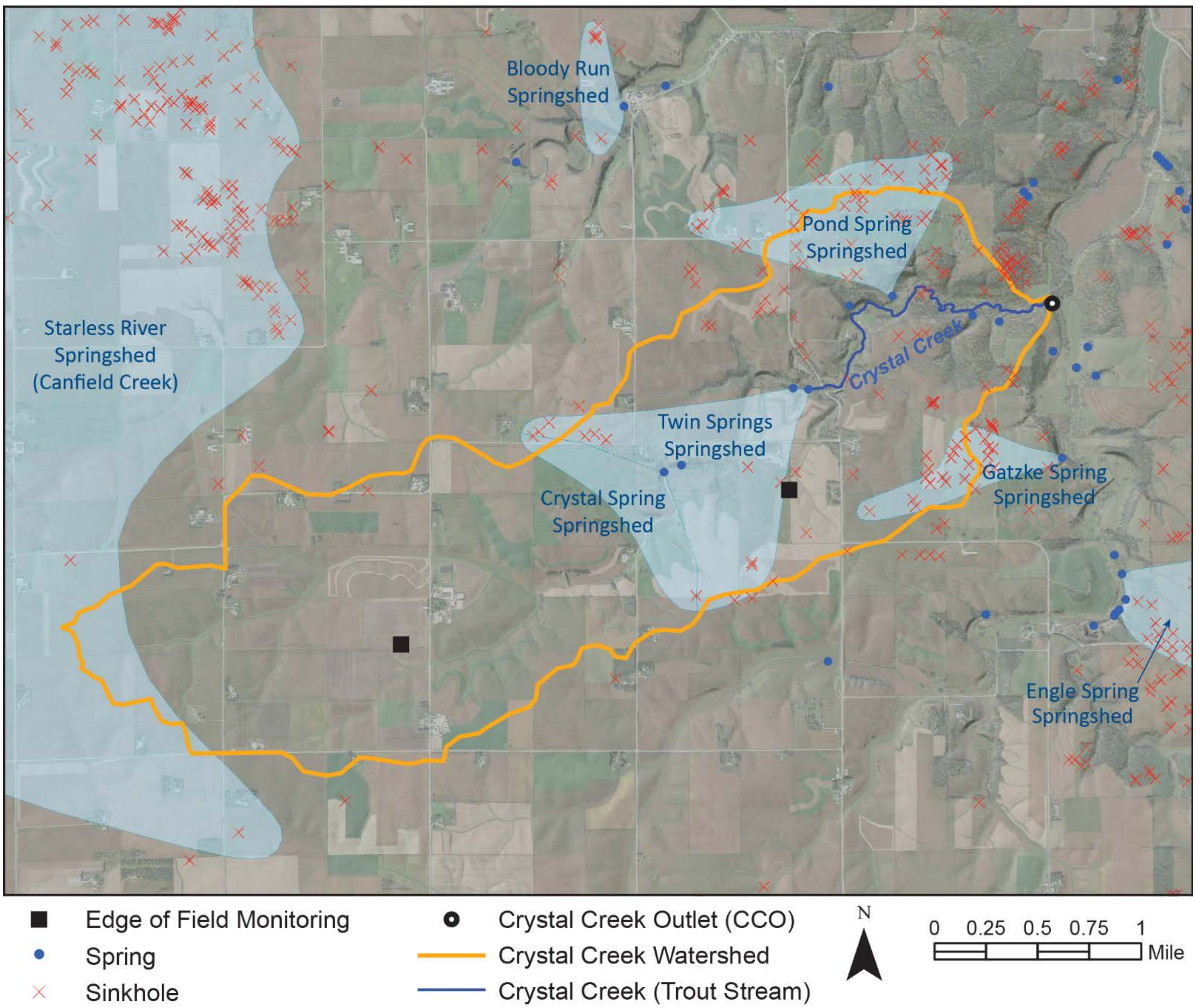


FIGURE 7. *Pond Spring Springshed, nearby delineated springsheds, and the Crystal Creek surface watershed. Sinkholes and springs are common throughout the landscape. Land use is primarily agricultural.*

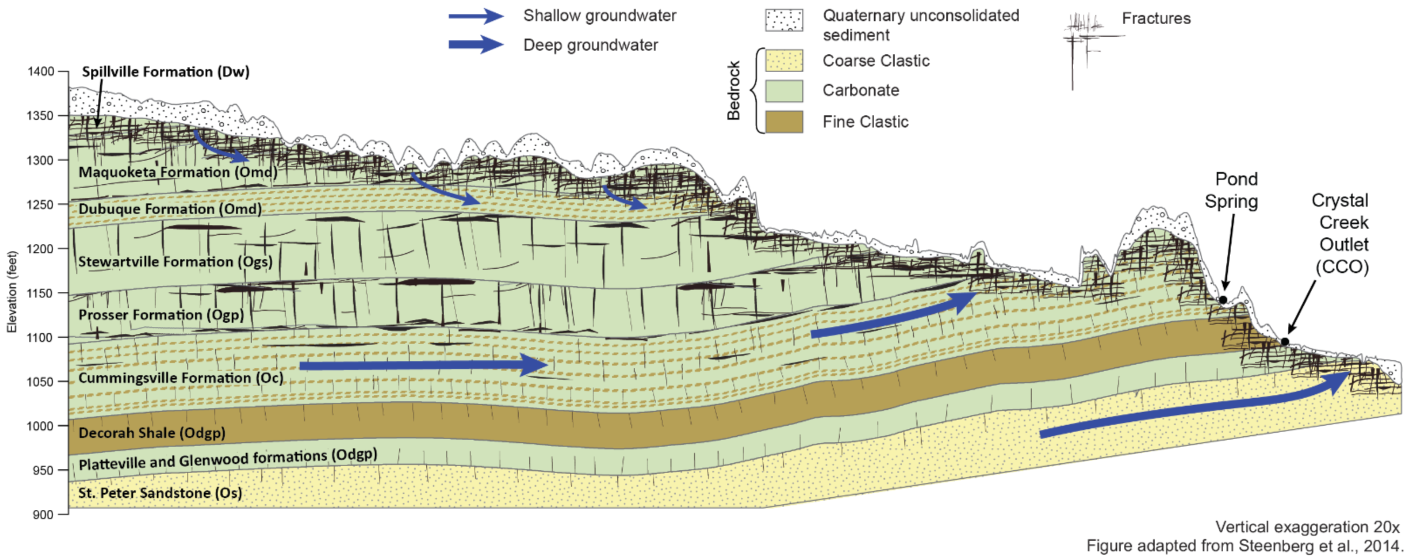


Figure 8. *Geologic and hydrogeologic context of Pond Spring project area. Perspective shown is west to east across the Crystal Creek surface watershed.*

Spring Monitoring Methods

Pond Spring flow rates and temperatures were measured using an Isco 2150 area-velocity sensor installed at the outlet of an eight-inch smooth-walled pipe the landowner had installed to carry flows from the spring to a constructed pond. Measurements were collected every minute and averaged over 15 and 60-minute intervals. Due to limited access to the spring, a modem was installed to remotely download data on a weekly basis. Grab sample nitrate-N concentrations were collected every two weeks over a range of flow and climatic conditions. Nitrate-N samples were analyzed using a benchtop ultraviolet spectrophotometer (Hach DR6000) and samples were typically analyzed within a day of sample collection. Nearby daily precipitation, soil temperature at six-inch depth, air temperature and edge of field surface runoff measurements were referenced to aid interpretation of spring monitoring results. These data were collected at an edge of field monitoring station located one mile southwest of PS. Data presented in this report are for a one-year period, October 23, 2017 through October 23, 2018.

Pond Spring Monitoring Results

Spring flow averaged 358 gallons per minute (gpm) with a range of 68 gpm to 650 gpm (Table 3). Water temperatures averaged 48 degrees Fahrenheit with a range of 37 to 55 degrees.

Table 3. *Summary statistics of hourly average flow and water temperature at Pond Spring.*

	Flow (CFS)	Flow (gpm)	Water Temperature (°F)	Water Temperature (°C)
Period	Oct. 23, 2017 through Oct. 23, 2018			
Measurements	--------------------------------8,748-------------------------------			
Average	0.70	310	48.1	9.0
Median	0.80	358	48.4	9.1
Minimum	0.15	68	37.4	3.0
Maximum	1.40	650	54.8	12.6
Std Dev.	0.39	175	0.94	0.52

Hourly average spring flow, spring water temperature, daily precipitation and nitrate-N concentrations during frozen and non-frozen soil conditions are summarized in Figure 9. Average daily soil temperature at six inch-depth, air temperature and field surface runoff from a nearby edge of field monitoring station are included to aid interpretation.

Normal annual precipitation at Preston (NOAA, 2018) is 35.6 inches. A total of 45.8 inches of rainfall was recorded at Preston during this period which was 29% above normal. Precipitation during the first half of the study period was within 10% of normal (October 2017 through April 2018) while totals during the second half (May through October 2017) averaged 45% above normal (Figure 9D).

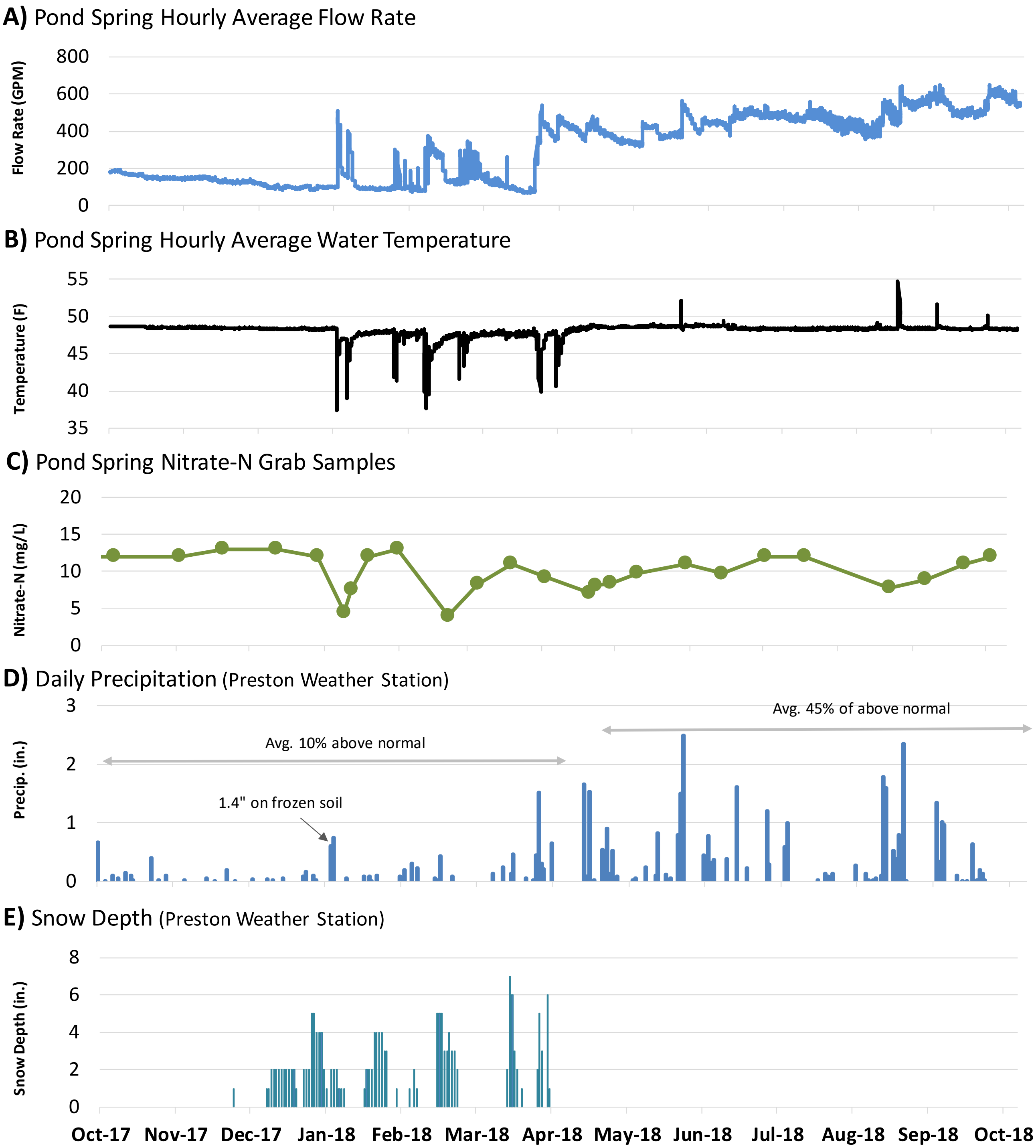
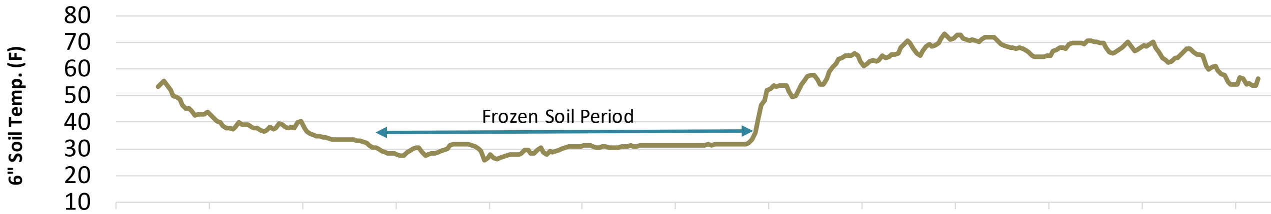
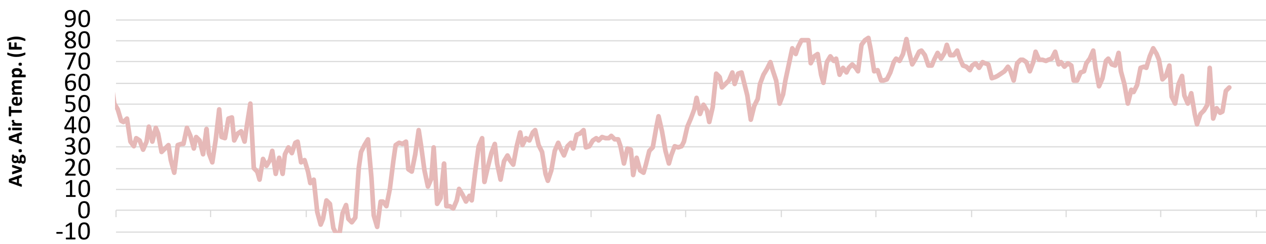


FIGURE 9. *Pond Spring and National Weather Service data: A) spring flow (B) temperature (C) nitrate-N concentration D) precipitation E) snow depth*

F) Average Daily Soil Temperature (Field 3)



G) Average Daily Air Temperature (Field 3)



H) Average Daily Field Surface Runoff (Field 3)

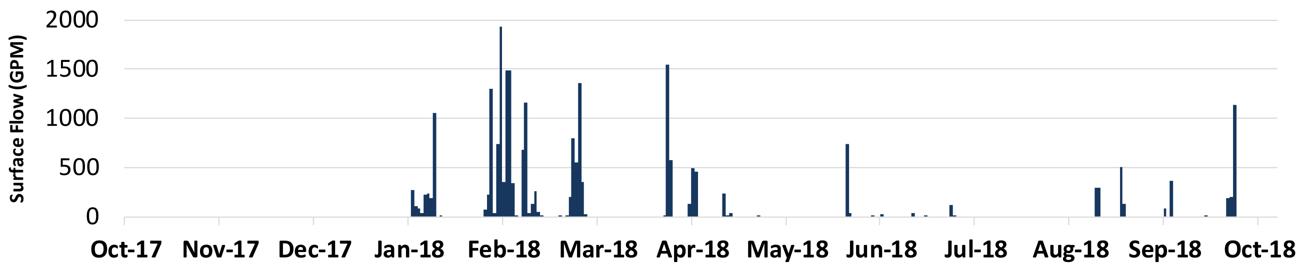


FIGURE 9. (Continued) *Pond Spring edge of field monitoring data: F) daily soil temperature G) average daily air temperature H) average daily surface runoff from nearby edge of field monitoring station CFE.*

On January 22 and 23, 2018, above normal air temperatures combined with 1.4 inches of rainfall on frozen soil resulted in a rapid flow response at both Pond Spring and the watershed outlet monitoring station located 0.6 miles downstream on Crystal Creek (CCO) (Figures 10 and 11).

Figure 10. *Flow conditions at the Crystal Creek Watershed outlet monitoring station after 1.4 inches was received on frozen soil between January 22 and January 23, 2018. (photo by C.Fischer).*

Figure 10 shows elevated, sediment laden streamflow on January 22, 2018 at the CCO. Prior to this event, PS flows were trending downward and were at 111 gpm and snow cover depth was approximately 4 to 6 inches across the watershed. On January 22, 0.6 inches of rain was received followed by another 0.7 inches on January 23, 2018. Immediately after the 0.6 inch rainfall event, flows from PS increased to 540 gpm (Figure 11). Since the upper soil profile was frozen, groundwater recharge through the soil profile was limited. Most of the groundwater recharge to PS was likely derived from surface runoff flowing directly into sinkholes within the springshed. During this recharge event, spring water temperature decreased by more than ten degrees, from 48^{o}F to 37^{o}F (8.9^{o}C to 2.8^{o}C). The rapid temperature decline was caused by the contribution of much colder rain and snowmelt water mixing with the ambient groundwater temperature of 48°F. Field runoff during this event was recorded at the nearby edge of field monitoring station (Figure 9H).

In all cases, when groundwater temperatures in the spring increased or decreased by more than two degrees, field surface runoff was also occurring in the watershed. When air temperatures increased to a peak of 47°F on January 27, a second response was observed due to snowmelt runoff with flows increasing to 400 gpm. Within seven days of the rain and snowmelt events, spring flow returned to pre-event flow conditions of 100 gpm and water temperature of 48°F (8.9°C). The rapid response at PS to recharge events, snowmelt, and precipitation illustrates that PS is well integrated into the local karst hydrologic system.

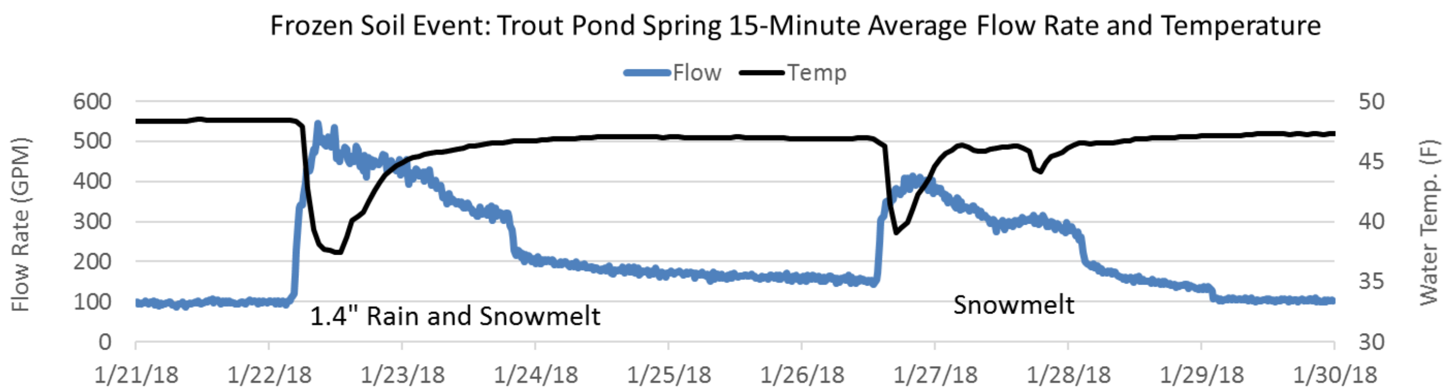


Figure 11. *Pond Spring flow and temperature response to rain on frozen soil and snowmelt runoff in January 2018.*

By late April 2018 most of the frost within the upper four feet of the soil profile had receded. A series of rainfall events totaling nearly three inches increased flow to over 350 gpm. Flows remained elevated during the month of May.

Over a three-day period from June 8-10, 2.6 inches of rain fell (Figure 12). The second highest 24-hour rainfall total observed during the monitored period, 2.0 inches, was measured on the evening of June 9 as part of the event. Flows prior to the event were 360 gpm. Within six hours of the 2.0-inch rainfall event, spring flow rates peaked to 563 gpm. Flows gradually reduced to pre-event conditions after about six days. In contrast to runoff during frozen soil rainfall or snowmelt conditions, water temperatures increased rather than decreased after the precipitation event. Water temperatures prior to the event were 48 degrees and increased to 52 degrees within four hours. Within 20 hours, water temperatures were back to pre-event conditions.

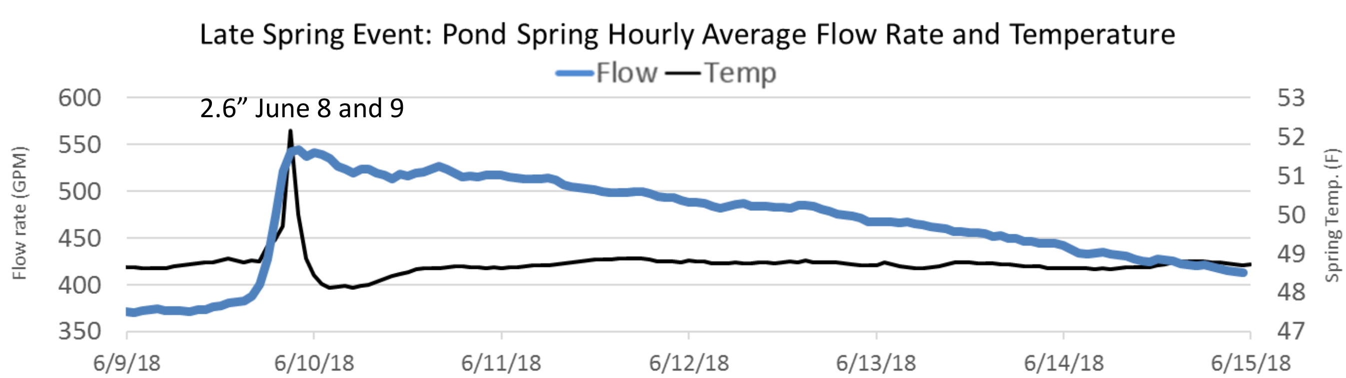


Figure 12. *Groundwater discharge and temperature response to precipitation in late spring 2018 at Pond Spring.*

Above normal rainfall in June maintained flows in the 400-500 gpm range through most of the summer. In late August and early September another wet cycle began. Over seven inches of rain was received during an eight-day period. This increased spring flow rates to 600 gpm, resulting in the highest flows observed during the one-year monitoring period. Baseflow prior to April was approximately 150 gpm, whereas after April 2018 baseflow was above 350 gpm (Figure 9). Baseflow remained elevated throughout the remainder of the monitoring period.

Nitrate-N concentrations at Pond Spring are also sensitive to recharge, with concentrations decreasing during certain recharge events (Figure 9C). This is the result of dilution from low nitrate sources of rain and snowmelt water and is consistent with the results of the higher time resolution, continuous nitrate-N monitoring at a nearby Galena Group spring, Engle spring (Barry and others, 2018). Typical nitrate concentrations at Pond Spring during non-storm-event, baseflow conditions averaged 12 mg/L. When significant rainfall occurred during non-frozen soil conditions, nitrate-N concentrations at Pond Spring were reduced by at least 3 mg/L to 4 mg/L. During frozen soil conditions, nitrates decreased by up to 9 mg/L. These dilution characteristics are similar to observations made at other Galena-based springs monitored in the region (Rowden and others, 2001). It should be noted that since these nitrate concentrations were not measured continuously, concentrations are likely underestimated.

Annual Discharge, Yield and Flow Weighted Mean Concentration of Nitrate-N.

Table 4 provides a summary of the annual discharge and nitrate load from Pond Spring from October 23, 2017 through October 23, 2018. A total of 162.9 million gallons of water was measured during the study period. For comparison, 1,838.5 million gallons of water was measured at the CCO monitoring station during the same monitoring period, indicating that Pond Spring contributes an estimated 9% of the Crystal Creek streamflow.

	Pond Spring (PS)	*Crystal Creek Watershed (CCO)
Monitoring Period	October 23, 2017 to October 23, 2018	
Drainage Area (ac.)	320[1]	3,728
Discharge volume (millions of gallons)	162.9	1,838.5
Precipitation (in.)	45.8	45.8
Discharge Yield (in.)	18.7	18.2
Discharge Yield as % of Precipitation	41%	40%
Nitrate Load (lb)	13,663	135,114
Nitrate Yield (lb/ac)	42.7	37.2
Nitrate FWMC (mg/L)	10.0	9.0

[1] Minimum estimated springshed area based on dye tracing conducted from 2010-2018
*2018 CCO loads are provisional and subject to change.

Table 4. *Discharge, nitrate load, nitrate yield and flow weighted mean concentrations (FWMC) for the period October 23, 2017 through October 23, 2018 at Pond spring. Data from Crystal Creek Watershed outlet is included for comparison.*

To calculate discharge yield, the total discharge measured from Pond Spring was divided by the springshed area. Conceptually, this is the depth of water in inches if the total water volume were evenly distributed across the land surface of the springshed. Dye tracing conducted from 2010-2018 indicates the estimated minimum recharge area of the Pond Spring Springshed is 320 acres. Based on this area, the measured water yield from Pond Spring was calculated at 18.7 inches. Expressed as a percentage of the precipitation received in the watershed (rain and snow), this equates to 41%. For comparison, provisional water yield estimates at CCO was 14.4 inches or 35% of the precipitation received. Nitrate loads were calculated at Pond Spring by combining the flow data and the nitrate grab sample concentrations that were collected approximately every two weeks. In order to estimate nitrate concentration between grab samples, nitrate grab sample concentrations were distributed equally between the midpoint of the preceding or anteceding grab sample (*i.e.*, “half-way” method). Although using this linear interpolation method is not as accurate as using a high resolution in-situ nitrate probe (*e.g.,* Nitratax probe) for obtaining concentrations, a comparison of load estimations for nearby Engle Spring (23A023) (approximately 1.5 miles east-southeast of the Crystal Creek) during the same timeframe showed a five percent difference in total nitrate load between these two methods (unpublished data).

The annual nitrate-N load from Pond Spring was measured at 13,663 pounds for the monitored period (October 2017-October 2018) which equates to an average of 37.4 pounds of nitrate-N per day or 1,139 pounds per month. Figure 13 shows the daily nitrate loading and cumulative rainfall from the Preston weather station. Nitrate loads were proportional to the cumulative rainfall during the non-frozen soil periods with the highest daily loads peaking in early October of 2017. For comparison, the provisional nitrate load calculation for CCO was 135,114 pounds. This indicates that Pond Spring accounts for 10% of the watershed nitrate load.

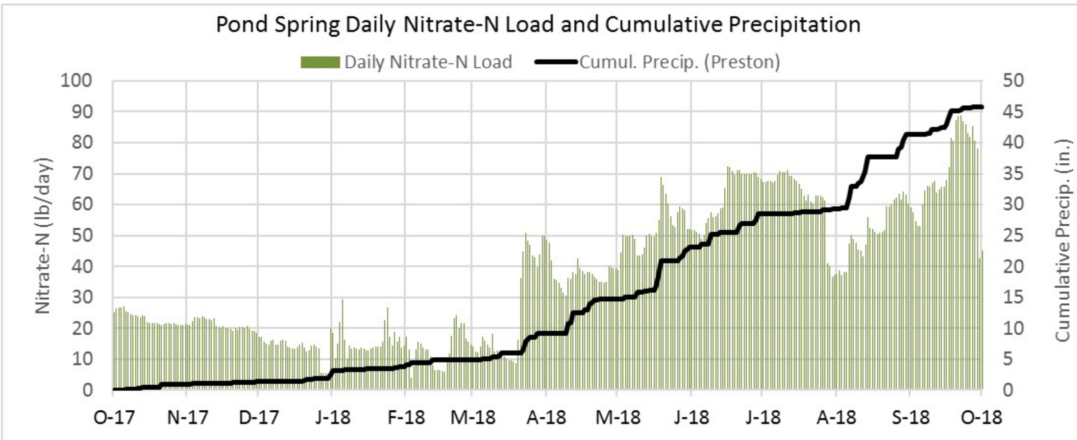


Figure 13. *Daily nitrate-N load and cumulative precipitation during the study period.*

To allow comparison between other springs or monitoring stations, total nitrate load was divided by the springshed area to compute nitrate yield and expressed in pounds per acre. Nitrate yield from Pond Spring was estimated at 43 pounds/acre. For comparison, provisional nitrate yield measured at CCO for this same period was 37 pounds/acre. Similar to normalized yield, the flow weighted mean concentration (FWMC) was calculated by dividing the total nitrogen load by the total water volume during the monitored period. Conceptually, the FWMC is the same as collecting all of the water from Pond Spring for the entire period and storing it in one large, well-mixed container and collecting one sample to obtain an average concentration. The FWMC at Pond Spring was 10.0 mg/L. The provisional FWMC at CCO was slightly less at 9.0 mg/L. The lower nitrate yield and FWMC indicates a reduction of nitrate in the lower section of Crystal Creek. This reduction is likely from regionally sourced groundwater discharge to the creek that has relatively lower nitrate concentrations. Regional sources of relatively low nitrate groundwater in southeast Minnesota have been identified below the Cummingsville-Decorah-Platteville-Glenwood aquitard system (Runkel and others, 2014). This regionally sourced groundwater has a dilution effect on Crystal Creek surface water that lowers the average nitrate-N concentration at CCO. Baseflow nitrate-N concentrations measured at Crystal Spring in the upper Stewartville Formation typically average around 16 mg/L, while concentrations further downstream at a spring located within the Prosser Formation are 14.0 mg/L. Nitrate concentration at CCO typically averages 9.5 mg/L. (Kuehner and others, 2017, Figure 7).

Discussion and Conclusions

The springsheds delineated in these traces were derived from the inferred groundwater flow directions determined through dye tracing. The dyes traveled rapidly from their input locations to the monitored springs, moving through a system of subterranean open conduits in the underlying karst aquifer.

Karst aquifers are often referred to as triple-porosity aquifers (Worthington, 1999). The term triple porosity describes the three primary hydrologic characteristics of a karst aquifer. They represent a continuum of flow including matrix flow, fracture flow, and channel flow. Matrix flow occurs in solid non-fractured portions of the aquifer. The majority of the volume of groundwater stored in an aquifer is contained in the matrix portion of the aquifer. Groundwater flow through the matrix is extremely slow, when compared to flow in fractures or open channels. Fracture flow occurs within a dendritic network of systematic and nonsystematic fractures that are developed from both mechanical and dissolution processes. Groundwater flow through the fracture network is more rapid than matrix flow but slower than flow through open channels. Open channel flow in karst aquifers occurs in portions of the aquifer that have been enlarged through dissolution. The majority of groundwater flow is through the channel portion of the aquifer (Worthington, 1999). Examples of large scale channel flow in the project vicinity are evident in large scale open conduits big enough to crawl and walk through in nearby Niagara Cave, Goliath's Cave and Holy Grail Cave. Figure 14 illustrates these three characteristic karst porosity types visible in a quarry wall in the Crystal Creek Watershed.

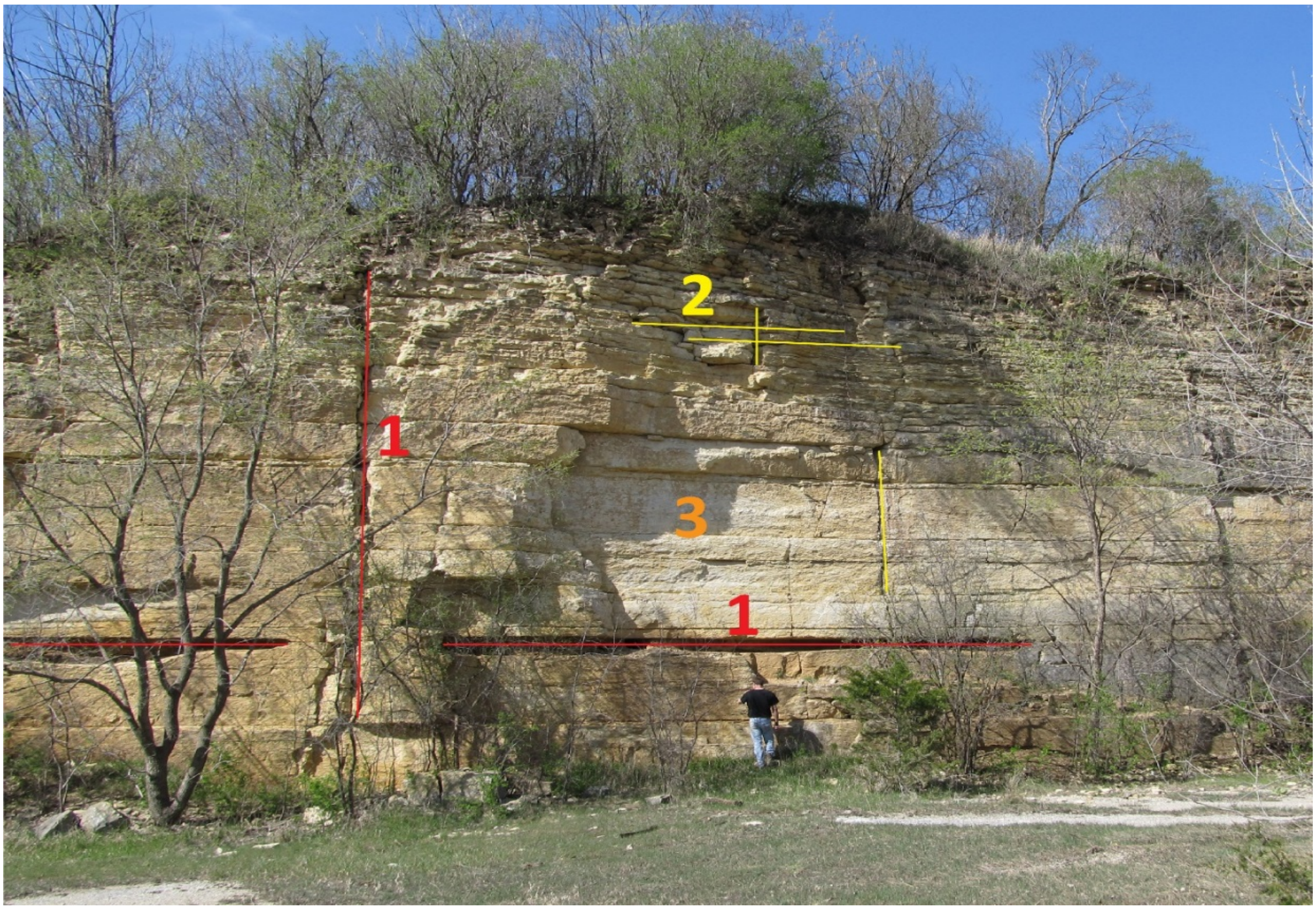


Figure 14. *Prosser Formation Quarry within the Crystal Creek Watershed illustrating triple-porosity aquifer concepts. Number 1 denotes mechanical fractures and dissolution conduits that allow channel flow, number 2 denotes smaller scale fracture flow, and number 3 denotes matrix flow. Person in image is roughly 6 feet tall (photo by J.Green).*

Conceptualizing the Galena karst aquifer system using the triple porosity aquifer classification scheme is useful when reviewing the results of passive charcoal detectors summarized in Appendix A.

Background levels of dye (uranine and eosine, March 1-13) found during this 2018 trace may reflect a multi-year scale recession concentration tail from the 2016 Holy Grail North Sink Traces (Appendix A). Interpretation of the timing of dye breakthrough and subsequent dye detection can be explored using the triple porosity model. Using the model, a large portion of uranine injected in Holy Grail North Sink entered a channel flow path (rapid path) and flowed north to the headwater springs of Canfield Creek (Starless River Springshed). Portions of both dyes also inevitably traveled via slower fracture flow and matrix flow routes. It is these slower routes that may still be releasing dye into Crystal Creek. Ultimately, this may indicate a much larger springshed area for Crystal Spring and Twin Springs (Figure 4) than what was previously understood and highlights the complexity of water soluble pollutant transport in karst landscapes. Dyes recovered in bugs deployed from October 17, 2018 to November 11, 2018 could be slow transport dyes from the 2016 traces, slow moving dyes from the March 2018 traces, a combination of both, or low level dyes present in the watershed from “accidental” introductions of dyes used in antifreeze, cosmetics, drugs, and other products.

Therefore, the inferred groundwater flow paths and springshed areas represent the channel and fracture (large aperture) flow paths of the triple porosity model (rapid paths). These paths are schematically shown in Figure 8 as a veneer of dense fractures near the land surface. These rapid flow paths are also indicated by the data shown in Figures 9, 11 and 12 when spring water temperatures and flows respond rapidly after rainfall and runoff events. The paths are also evident in Figure 14, where it is easy to envision water traveling at different rates within the karst aquifer. Rapid channel flow would occur in paths denoted with the number 1. Intermediate flow would occur in via fracture flow in paths denoted with the number 2. Slow flow would occur throughout the non-fractured matrix rock in areas denoted by number 3. Groundwater and dyes are simultaneously traveling via each of these described routes. Dye tracing in the Crystal Creek Watershed study area is unique in that most dye trace studies do not monitor past the initial dye breakthrough. Post dye trace charcoal bugs will continue to be deployed and will provide a unique opportunity to characterize slower groundwater flow paths to springs in the study area.

This successful 2018 tracing in the Crystal Creek Watershed expanded and refined the springshed area of the Starless River Springshed and delineated a new springshed (Bloody Run Springshed). The springsheds have been approximated using the techniques outlined in this report, however the lateral extent of the springsheds is not sharp and moves dynamically, both horizontally and vertically, in response to changes in groundwater levels. These refined springshed maps have helped improve nitrate-N yield loss computations and spring to stream comparisons as exampled by monitoring conducted at Pond Spring. These findings may also be informative in helping improve groundwater models, informing nutrient lag time and determining where nitrogen management surveys and BMPs should be concentrated. When discussing the importance of strategies to minimize nitrate-N loss from agricultural activities, delineated springsheds have proven to be effective in helping elevate nitrogen BMP discussions and water quality improvement participation by area farmers and crop advisors (Kuehner, 2016).

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Appendix A

Bug Locations					Results																								
Site Id.	Type	UTM E	UTM N	KFD #	01 Mar 2018 - 13 Mar 2018	02 Mar 2018 - 04 Mar 2018	10 Mar 2018 - 13 Mar 2018	12 Mar 2018 13 Mar 2018	14 Mar 2018 Input Uranine & Rhodamine WT	13 Mar 2018 - 16 Mar 2018	17 Mar 2018 Input Eosin	04 Mar 2018 - 19 Mar 3018	16 Mar 2018 - 19 Mar 2018	19 Mar 2018- 23 Mar 2018	19 Mar 2018 - 26 Mar 2018	19 Mar 2018 - 2 May 2018	23 Mar 2018 - 2 Apr 2018	26 Mar 2018 - 02 Apr 2018	02 Apr 2018 - 11 Apr 2018	02 Apr 2018 - 17 Apr 2018	11 Apr 2018 - 17 Apr 2018	13 Apr 2018 - 24 Apr 2018	17 Apr 2018 - 30 Apr 2018	17 Apr 2018 - 01 May 2018	24 Apr 2018 - 30 Apr 2018	30 Apr 2018 - 23 May 2018	*Break in Sampling*	14 Sep 2018 - 17 Oct 2018	17 Oct 2018 - 11 Nov 2018
Crystal Creek Area																													
C9	Bug-Creek	571,927	4,824,261	23X89	nd	---	---	---		nd		---	nd	---	nd	---	---	nd	---	nd	---	---	nd	---	---	---		---	---
C1	Bug-Creek	568,924	4,825,365	23X401	Eos	---	---	---		nd		---	nd	---	Eos	---	---	Uran & Eos	---	Uran & Eos	---	---	Uran & Eos	---	---	nd		---	---
C1S	Bug-Spring	568,939	4,825,389	23X80	Uran & Eos	---	---	---		Uran & Eos		---	Uran & Eos	---	Uran & Eos	---	---	Uran & Eos	---	Uran & Eos	---	---	Uran & Eos	---	---	Uran & Eos		---	Uran & Eos
C1A	Bug-Creek	569,543	4,825,591	23X82	nd	---	---	---		nd		---	---	---	nd	---	---	nd	---	nd	---	---	nd	---	---	---		---	Uran & Eos
C3S	Bug-Spring	570,056	4,826,037	23X94	nd	---	---	---		nd		---	nd	---	nd	---	---	nd	---	nd	---	---	nd	---	---	---		---	Uran & trace Eos
C2	Bug-Creek	569,804	4,826,113	23X402	nd	---	---	---		nd		---	nd	---	nd	---	---	nd	---	nd	---	---	nd	---	---	---		---	trace Uran & trace Eos
CCO/CCOH	Bug-Creek	571,649	4,826,632	23X93	nd	---	---	---		nd		---	nd	---	nd	---	---	nd	---	nd	---	---	nd	---	---	trace Uran		trace Uran	Uran & trace Eos
TPS	Bug-Spring	570,702	4,826,751	23A323	---	nd	---	---		---		nd	---	---	---	nd	---	---	---	---	---	---	---	---	---	---		---	---
WCO	Bug-Creek	572,085	4,826,943	23X92	nd	---	---	---		nd		---	nd	.---	nd	---	---	nd	---	---	---	---	nd	---	---	---		---	---
Springsdale Area																													
WSG	Bug-Spring	570,206	4,828,385	23A971	---	---	---	---		nd		---	nd	---	nd	---	---	nd	---	nd	---	---	nd	---	---	---		---	---
Hwy15 E	Bug-Creek	570,153	4,828,791	23X88	nd	---	---	---		Uran & RhWT		---	Uran & RhWT	---	Uran & RhWT	---	---	Uran & RhWT	---	Uran & RhWT	---	---	RhWT	---	---	---		---	---
A29	Bug-Creek	569,072	4,829,201	23X405	---	---	nd	---		nd		---	nd	---	nd	---	---	nd	---	empty bug	---	---	nd	---	---	---		---	---
STS	Bug-Spring	568,933	4,828,394	23A972	---	---	---	nd		nd		---	nd	---	nd	---	---	nd	---	nd	---	---	nd	---	---	---		---	---
Up A0625	Bug-Creek	568,667	4,828,155	23X404	---	---	nd	---		nd		---	nd	---	---	---	---	---	---	---	---	---	---	---	---	---		---	---
A0625	Bug-Spring	568,607	4,828,234	23A625	---	---	nd	---		Uran			Uran & RhWT	---	Uran & RhWT	---	---	Uran & RhWT	---	Uran & RhWT	---	---	Uran & RhWT	---	---	---		---	---
WCIS	Bug-Cistern	565,738	4,826,454	23X406	---	---	---	---		---		---	---	---	---	---	---	---	---	---	---	nd	---	---	nd	trace Uran		---	---
Co 110 - K, Dnstr.	Bug-Creek	569,457	4,828,844	23X407	---	---	---	---		---		---	---	---	---	---	---	---	---	---	---	---	---	---	RhWT	---		---	---
King Rd, DS Brdg	Bug-Creek	569,175	4,828,458	23X408	---	---	---	---		---		---	---	---	---	---	---	---	---	---	---	---	---	---	nd	---		---	---
Canfield Creek Area																													
Rainy	Bug-Creek	562,810	4,828,988	23X403	---	---	---	---		nd		---	nd	nd	---	---	nd	---	nd	---	nd	---	---	nd	---	---		---	---
Can	Bug-Creek	562,724	4,828,491	23X91	nd	---	---	---		nd		---	nd	Eos	---	---	Eos	---	Eos	---	nd	---	---	nd	---	---		---	---
BPS	Bug-Spring	562,711	4,828,337	23A893	nd	---	---	---		nd		---	nd	Uran	---	---	nd	---	nd	---	nd	---	---	nd	---	---		---	---
BRS	Bug-Spring	562,575	4,828,214	23A34	nd	---	---	---		nd		---	nd	Eos	---	---	Eos	---	Eos	---	Eos	---	---	Eos	---	---		---	---
CBS	Bug-Spring	562,497	4,828,205	23A33	nd	---	---	---		nd		---	nd	Eos	---	---	Eos	---	Eos	---	nd	---	---	nd	---	---		---	---
					01 Mar 2018 - 13 Mar 2018	02 Mar 2018 - 04 Mar 2018	10 Mar 2018 - 13 Mar 2018	12 Mar 2018 13 Mar 2018	14 Mar 2018 Input Uranine & Rhodamine WT	13 Mar 2018 - 16 Mar 2018	17 Mar 2018 Input Eosin	04 Mar 2018 - 19 Mar 3018	16 Mar 2018 - 19 Mar 2018	19 Mar 2018- 23 Mar 2018	19 Mar 2018 - 26 Mar 2018	19 Mar 2018 - 2 May 2018	23 Mar 2018 - 2 Apr 2018	26 Mar 2018 - 02 Apr 2018	02 Apr 2018 - 11 Apr 2018	02 Apr 2018 - 17 Apr 2018	11 Apr 2018 - 17 Apr 2018	13 Apr 2018 - 24 Apr 2018	17 Apr 2018 - 30 Apr 2018	17 Apr 2018 - 01 May 2018	24 Apr 2018 - 30 Apr 2018	30 Apr 2018 - 23 May 2018		14 Sep 2018 - 17 Oct 2018	17 Oct 2018 - 11 Nov 2018

nd = no dye detected from this bug bug from this location during this time interval
"---" = no bug from this location during this time interval
Eos = Eosin dye detcted.
Uran = Uranine dye detected
RhWT = RhodamineWT dye detected