Meyer's Basin Springshed & Forlorn River Springshed dye traces 1996-1999 Fillmore County, Minnesota

Tracing Conducted

May 1996, May 1997, September 1997, August 1998, October 1999

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Introduction

This report presents the findings of dye traces that were conducted from 1996-1999 as part of ongoing groundwater mapping efforts between the Fillmore Soil and Water Conservation District (SWCD), Department of Natural Resources (DNR), and the University of Minnesota (U of M). Nine traces conducted in the project area located west of the Forestville State Park main unit are described in this report (Figure 1). The project area is an active karst area with many sinkholes, caves, and springs. These traces began after the senior author connected with Ernie Meyer III, who owned land directly west of Forestville State Park. Mr. Meyer graciously permitted this work to occur as he wanted to know what happens to the surface water that runs into the sinkholes on his property.

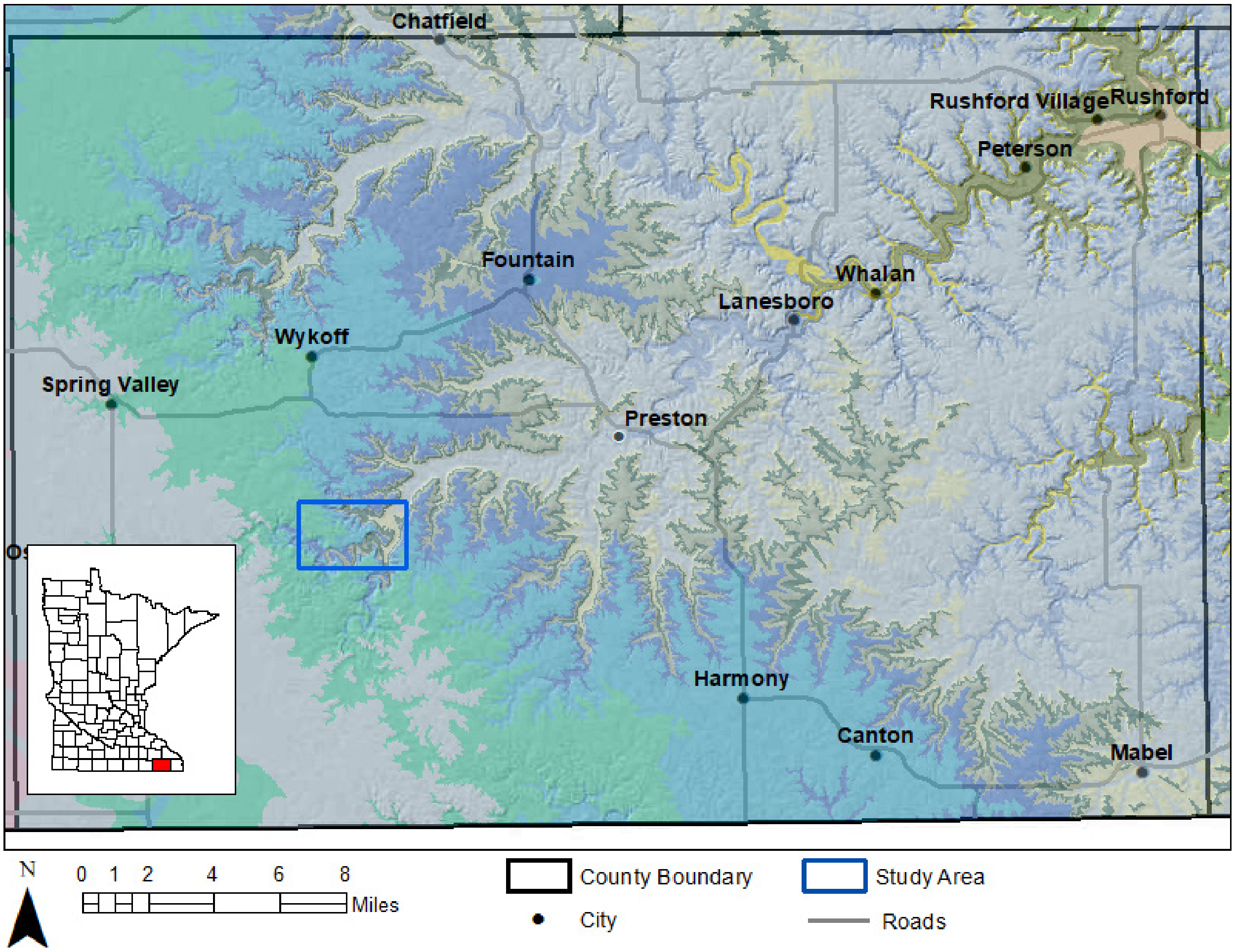

Figure 1. *Location of the Forestville-Meyer's Basin Springshed study area in Fillmore County, Minnesota. Shading used to delineate bedrock geology loosely corresponds to the shading depicted in Figure 2.*

Collaboration between the Minnesota Department of Natural Resources, University of Minnesota Department of Earth and Environmental 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. The application allows users to view the content in the figures below at different scales and to access data associated with these and other trace investigations.

Dye tracing is 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.

Area Geology and Hydrogeology

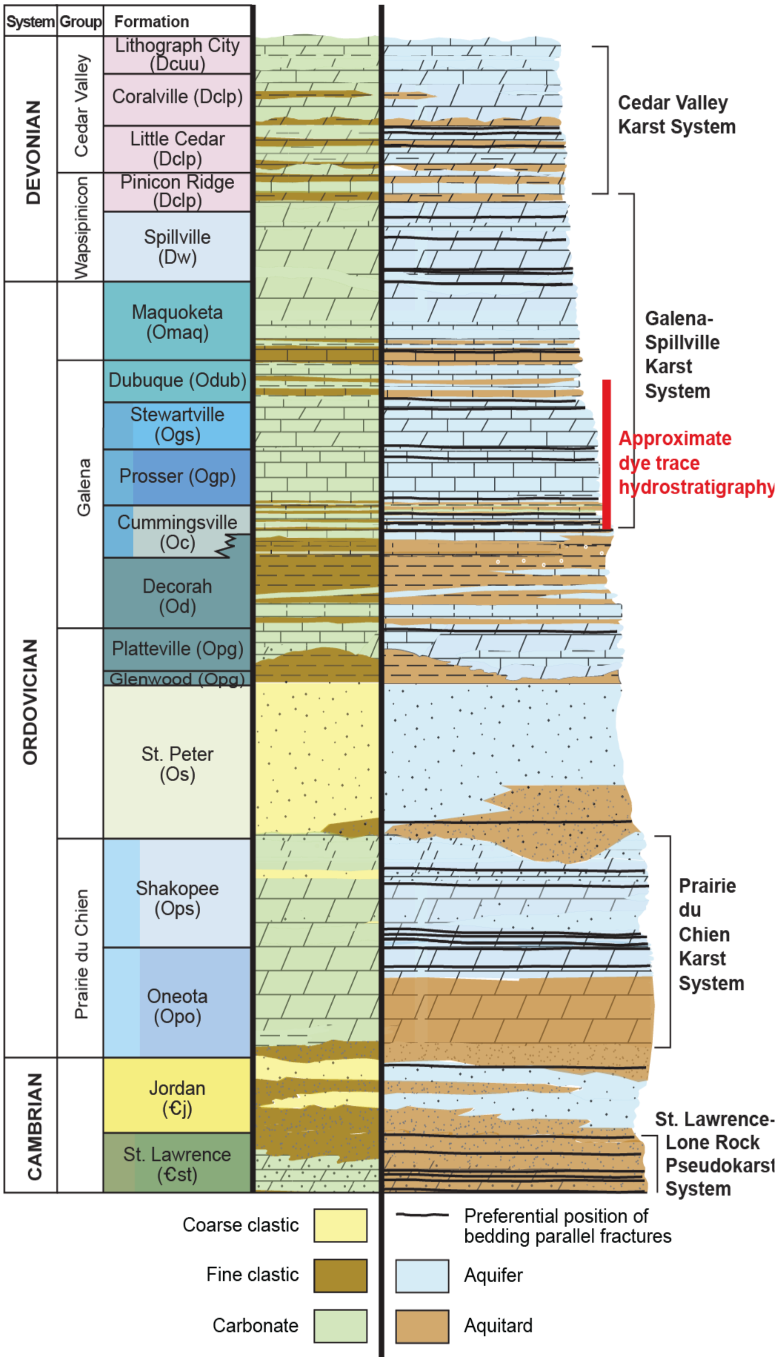

Figure 2. *Geologic and hydrogeologic attributes of Paleozoic rocks in southeastern Minnesota. Red line approximates the range of formations involved in traces.*

Underlying the relatively thin veneer of unconsolidated sediments, such as glacial till, 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).

A generalized stratigraphic column for Fillmore County (Figure 2) shows lithostratigraphic and generalized hydrostratigraphic properties (modified from Runkel et al. 2014).

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. 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 Platteville and Decorah 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 et al., 2014) 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 (Figure 2). The dye tracing and spring monitoring presented in this report occurred in the Galena-Spillville karst, where groundwater time of travel can reach up to 1-3 miles/day (Green et al., 2014)..

Methods and Trace Descriptions

Dye tracing uses fluorescent dyes to determine groundwater flow directions and travel times. Dye is poured into a sinkhole or sinking stream where it then flows through the karst conduit system until it reemerges at a spring or series of springs. For this project, the dyes used were Uranine C (Color Index # 45350, Chem. Abs. # 518-47-8), Eosine Y (Color Index # 45380, Chem. Abs. # 17372-87-1) Rhodamine WT (Acid Red 388, Chem. Abs. # 37299-86-8) and Sulforhodamine B (Color Index #45100, Chem. Abs. #3520-42-1). Both direct water samples and passive charcoal dye detectors were used for monitoring springs and creeks. All the samples were analyzed at the University of Minnesota Department of Earth and Environmental Sciences using a Shimadzu RF-5000 scanning spectrofluorophotometer scanning from 350 to 650 nm (emission wavelength) and delta lambda of 15 nm. Protocols used for dye tracing and springshed delineation are detailed in Green et al. (2014). These traces were designed and executed by Jeff Green, Minnesota DNR and by E. Calvin Alexander, Jr., Scott Alexander, and Daniel Doctor of the University of Minnesota Department of Earth and Environmental Sciences. Scott Alexander of the UofM performed sample analyses, equipment instrumentation, data management, and interpretation.

Locations of the dye input points, monitoring points, and summaries of analytical results are listed in Appendix A. Karst features, dye input locations, and monitoring points are shown in Figures 3, 4, and 5. Monitoring points were located varying distances downstream from the actual springs for logistical and redundancy reasons.

The August 1996 traces were all dry sinkhole traces. Water was hauled to the sinkholes in a trailer tank to flush the dyes into the underlying karst system. The traces at Meyer's #1 (23D3879*) and #2 (23D3882) sinkholes used 1,000 gallons of water each and the trace at Meyer's #3 (23D3881) sinkhole used 500 gallons. Water ponded in the Meyer's #3 sinkhole, as it was a shallow with no visible swallow hole; forcing us to reduce the amount of water. These traces were the first attempt at springshed delineation in this area west of the state park between Forestville Creek and the South Branch Root River.

Additional traces were conducted in 1996, 1997, and 1998 to expand and refine the boundaries of the Meyer's groundwater springshed and the Forlorn River springshed that had been previously delineated in Alexander et al., 1996. All of the subsequent traces were dry sinkhole traces with water introduced using a trailer tank. Based on the success of the August 1996 Meyer #3 trace where 500 gallons of water was sufficient, the same amount was used for the rest of the traces.

**Geospatial data for dye traces, including the locations of karst features and springs, are stored in parallel databases that share a relatable unique identifier. This unique identifier is used in the Minnesota Karst Feature Database (KFD), the Minnesota Spring Inventory (MSI), and the Minnesota Groundwater Tracing Database (MGTD). The unique identifier is a ten-character alpha-numeric field, but has been abbreviated for this report (e.g., 23D0003879 is abbreviated to 23D3879).*

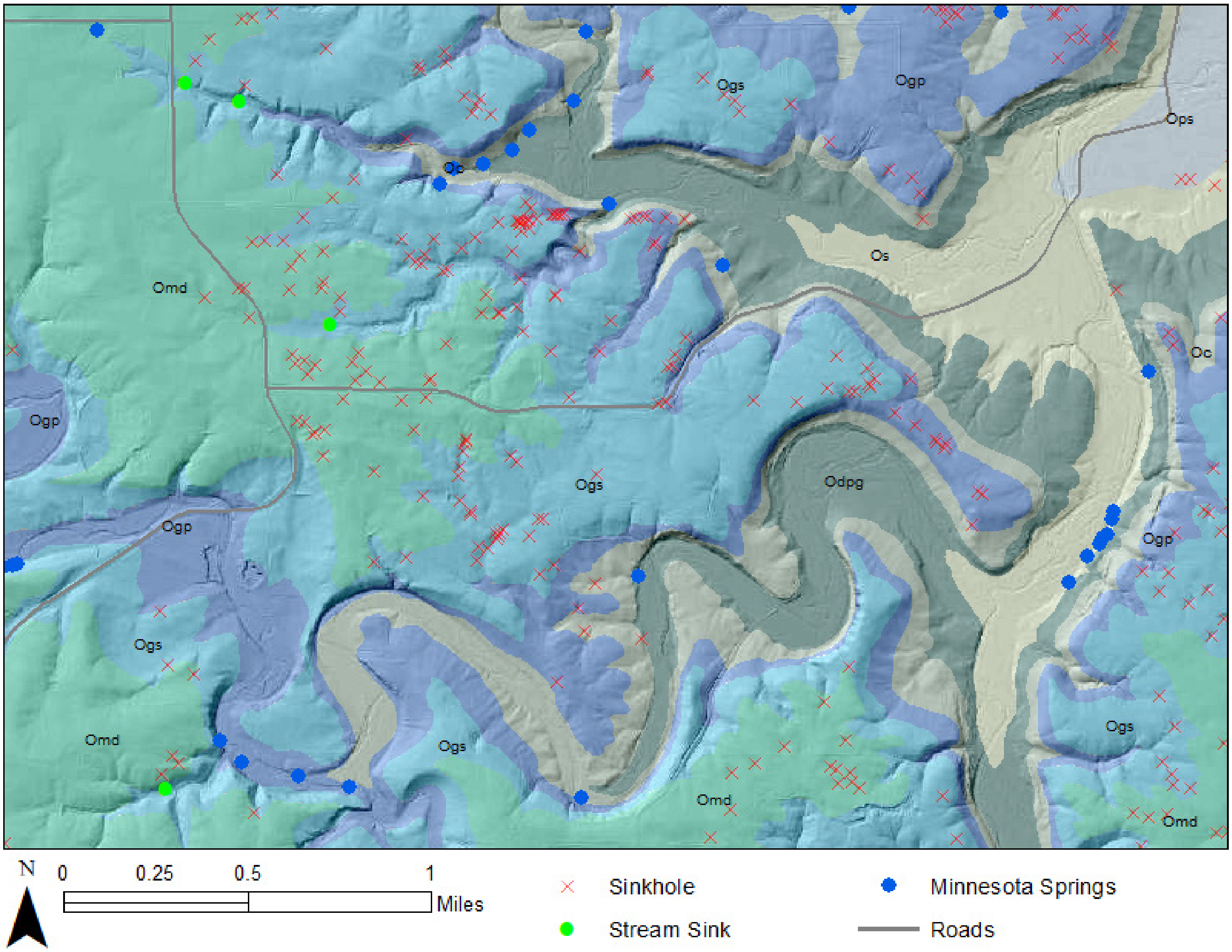

Figure 3. *Geology and karst features mapped in the project study area. Shading used to delineate bedrock geology loosely corresponds to the shading depicted in Figure 2. Map codes of geologic unit correspond to those used in Figure 2.*

In October 1999, a duplicate trace from a project area sinkhole to a spring was conducted to quantify the dynamics of the groundwater flow system using continuous water sampling apparatus. The trace was completed as part of the curriculum for the University of Minnesota Department of Earth and Environmental Sciences Tracers and Karst Hydrogeology course. Four tracers, three dyes and one salt solution, were poured into sinkhole 23D2882. Four automatic water samplers were installed at the Meyer's Basin Outlet Spring to collect high time resolution data for tracer break through curves to be developed. The purpose was to compare and contrast the behavior of the three dye and the conservative tracer NaBr on a previously documented flow path.

Results and Discussion

The results of these traces are summarized in the "Dye Detects" columns of Appendix A and in figures 4 and 5. Dye from the 21 August 1996 traces is inferred to have resurged at spring 23A0875, Meyer's Basin Outlet spring. However, the existence of this spring was unknown prior to the trace, so it was not monitored initially. Dye was detected at the Bridge 1092 monitoring location (23X0250), which is downstream of the Meyer's Basin Outlet spring; finding dye there informed us that there was an unknown spring upstream of the bridge. Following this revelation, the senior author completed spring mapping on the South Branch upstream from Bridge 1092and found one spring (Meyer's Basin Outlet Spring, 23A0875).

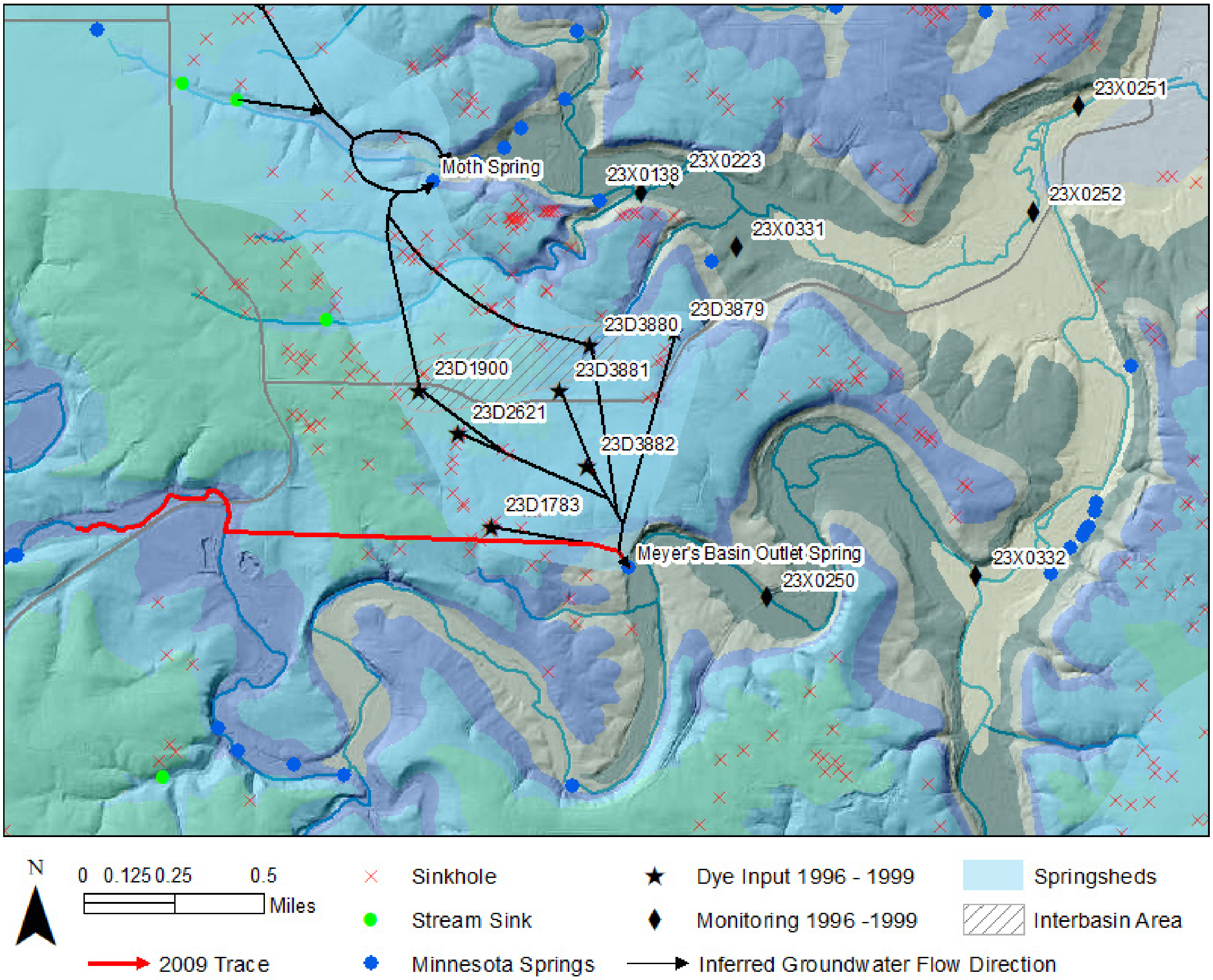

Figure 4. *Dye input locations, dye detection locations, and inferred groundwater flow vectors for the 1996-1999 Forestville-Meyer's Basin traces. The red line symbolizes a trace conducted in 2009 that documented a losing stretch of the South Branch of the Root River that emerges at Meyer's Basin Outlet Spring. The dyes injected into sinkholes 23D1900 and 23D3880 went both to Meyer's Basin Outlet Spring on the South Branch Root River and to Moth Spring, the headwater spring of Forestville Creek. These two sinkholes contribute to both the Myer's Basin Springshed and Forlorn River Springshed.*

Dyes were also detected at the Forestville Ford bug. The bug was located downstream of the ford. This led to an original erroneous conclusion that there was an unknown spring upstream of the ford on Forestville Creek, as there was no dye found in the bug at sample point 23X0138 in the stream. Forestville Creek starts at Moth Spring and had been surveyed multiple times by UofM, DNR, and private cavers and no springs had been located on that reach. The senior author completed additional spring mapping on Forestville Creek upstream of the ford and found no additional springs. It was eventually determined that a Forestville State Park horse trail crosses the South Branch Root downstream of the group camp monitoring location. After the trail crosses the Root, it leads to the Forestville Creek ford crossing. We deduced that horses crossing the South Branch were then crossing Forestville Creek at the ford with wet hair. We surmised that dye in the water came from the horses (horsehair) and was detected at our bug (monitoring point). From then on, we placed the Forestville Ford bug upstream of the trail crossing.

The dye trace from sinkhole Meyer #1, 23D3879, is much closer to Maple Springs, 23A0089, then it is to Meyer's Basin Outlet spring. The trace designers were so sure that the dye would go to Maple Springs that we installed two ISCO automatic water samplers at it to catch the breakthrough. Maple Springs is not insignificant; its flow is estimated to be .25-.75 cubic feet per second. However, as evident in Table 1, that was an erroneous assumption.

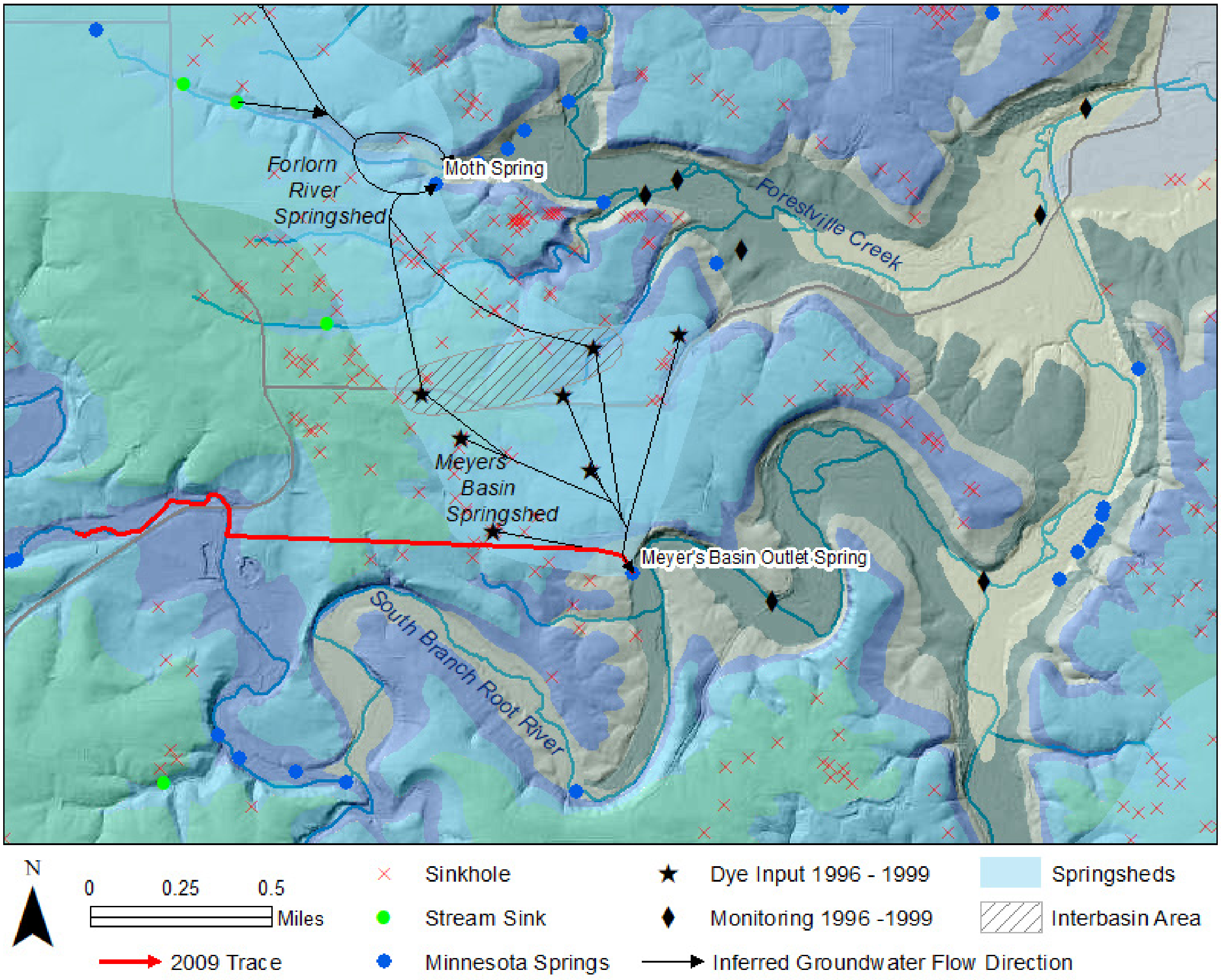

Figure 5. *Traces conducted as part of this work were instrumental in delineating the Meyer's Basin Springshed, added to the delineation of the Forlorn River Springshed (that emerges at Moth and Grabau Springs), and the interbasin area in between.*

The September 1996 traces were completed to further delineate the Meyer's Basin Springshed and verify the trace from sinkhole 23D3879 that went to 23A0875. The uranine that went in to 23D2609 was detected at both Meyer's Basin Outlet Spring (23A0875) and Moth Spring (23A0002), helping to delineate this area as the interbasin area between the two springsheds. The exact divide between the two springsheds, estimated as the interbasin area of figures 4 and 5, fluctuates depending on groundwater level at the time. The eosine dye that was poured into 23D1783 was detected only at the Meyer's Basin Outlet Spring which provides further resolution of the boundary between the Forlorn River system and the Meyer's Basin.

The May 1997 trace was completed from sinkhole 23D2621, which is on a parcel owned by DNR-Forestry. The dye was detected at Meyer's Basin Outlet Spring (23A0875), which pushed the boundaries of the Meyer's Basin Springshed further to the west.

The August 1998 trace was conducted to refine the Meyer's Basin Springshed boundary and to try to determine the springshed of Maple Springs (23A0089). The dye went to both Moth Spring (23A0002) and the Meyer's Basin Outlet Spring (23A0875), delineating it as an interbasin area between the two springsheds. No dye was detected at Maple Springs.

The October 1999 traces were a duplicate trace from the Meyer's #2 Sinkhole (23D2882) to the Meyer's Basin Outlet Spring. Whereas all of the previous traces discussed in this report established connections between sinkholes and springs, this trace utilized automatic water samplers to determine dye breakthrough curves. In well-developed karst, such as the Galena Group, initial dye breakthrough is followed by a steep rise over several 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. Dye-breakthrough time of travel for these traces was determined using the results of water collected using the auto-samplers at Meyer's Basin Outlet Spring (23A0875). Figures 6 and 7 show the fluorescein, uranine, rhodamine WT, and bromide breakthrough curves obtained from the auto-samplers for all of the data obtained. Note that the vertical scale of Figure 6 is logarithmic and extends over 5 orders of magnitude. For economic reasons only a few of the water samples were analyzed for bromide.

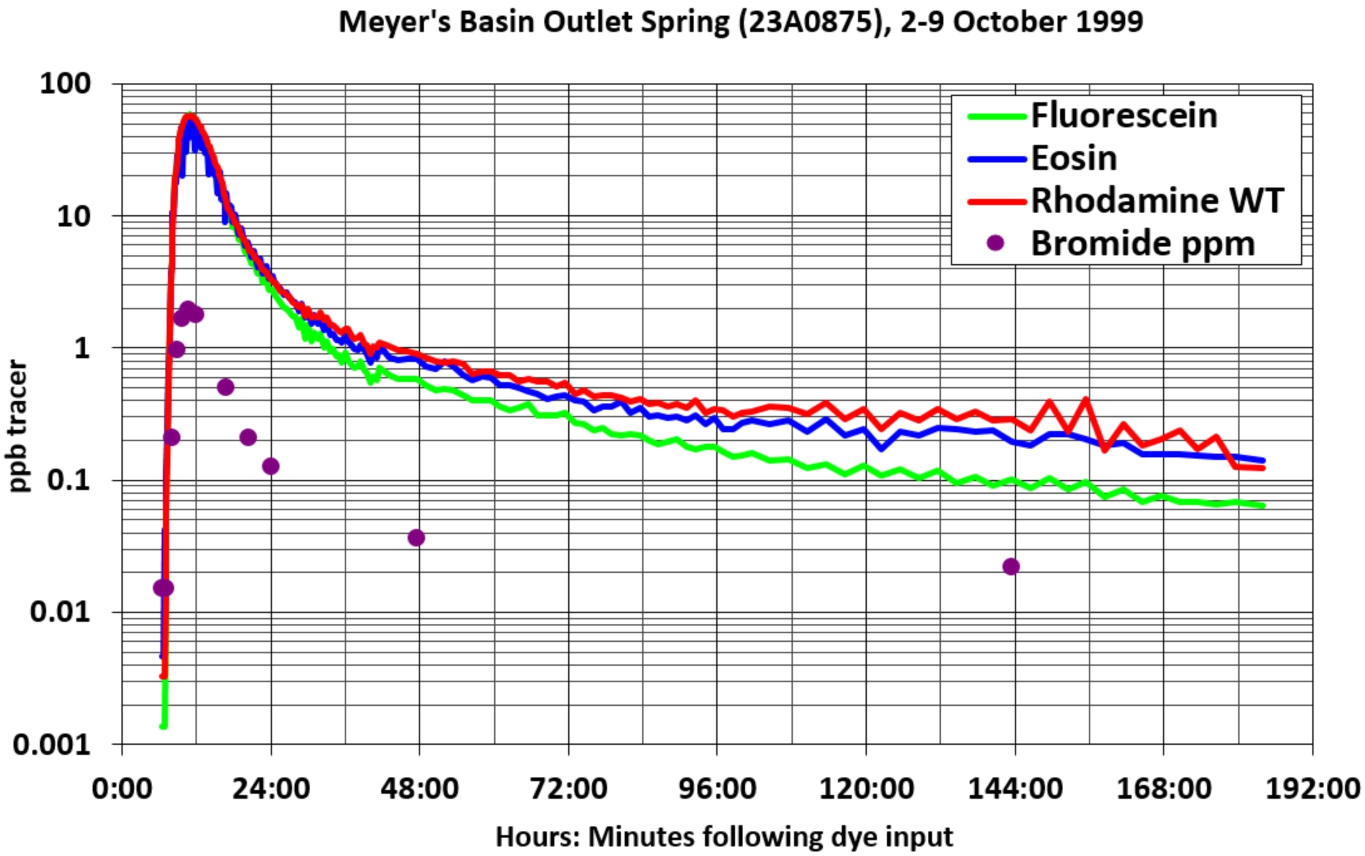

Figure 6. *Log-Linear breakthrough curves for the 1999 dye tracing in the Meyer's Basin Springshed.*

The breakthrough curves of the three dyes and bromide are similar and typical patterns observed for reasonably conservative tracers which travel with the water. The shapes of breakthrough curves are primarily due to mixing dispersion in the turbulent flow karst conduits. The long, low concentration "tails" of the tracers are thought to be due to adsorption/desorption on aquifer materials and/or mixing diffusion into and out of dead-end porosity along the conduit flow paths.

Figure 7 shows the results of the main peak of the breakthrough curves with a linear vertical scale. The large correlated variations in the fluorescein and eosin data are thought to be due to photo-degradation of those two dyes during the decantation of the autosamplers and the subsequent transportation of the water samples and analyses of those two dyes in the laboratory. This trace was one of our first attempts at using fluorescein and eosin dyes in direct water samples from autosamplers and we did not fully understand and anticipate the photo-degradation challenge. Rhodamine WT, which was specifically developed to resist photo degradation for surface water traces, is much less subject to photo-degradation, see Smart and Laidlaw (1977), Roales et al. (2015).

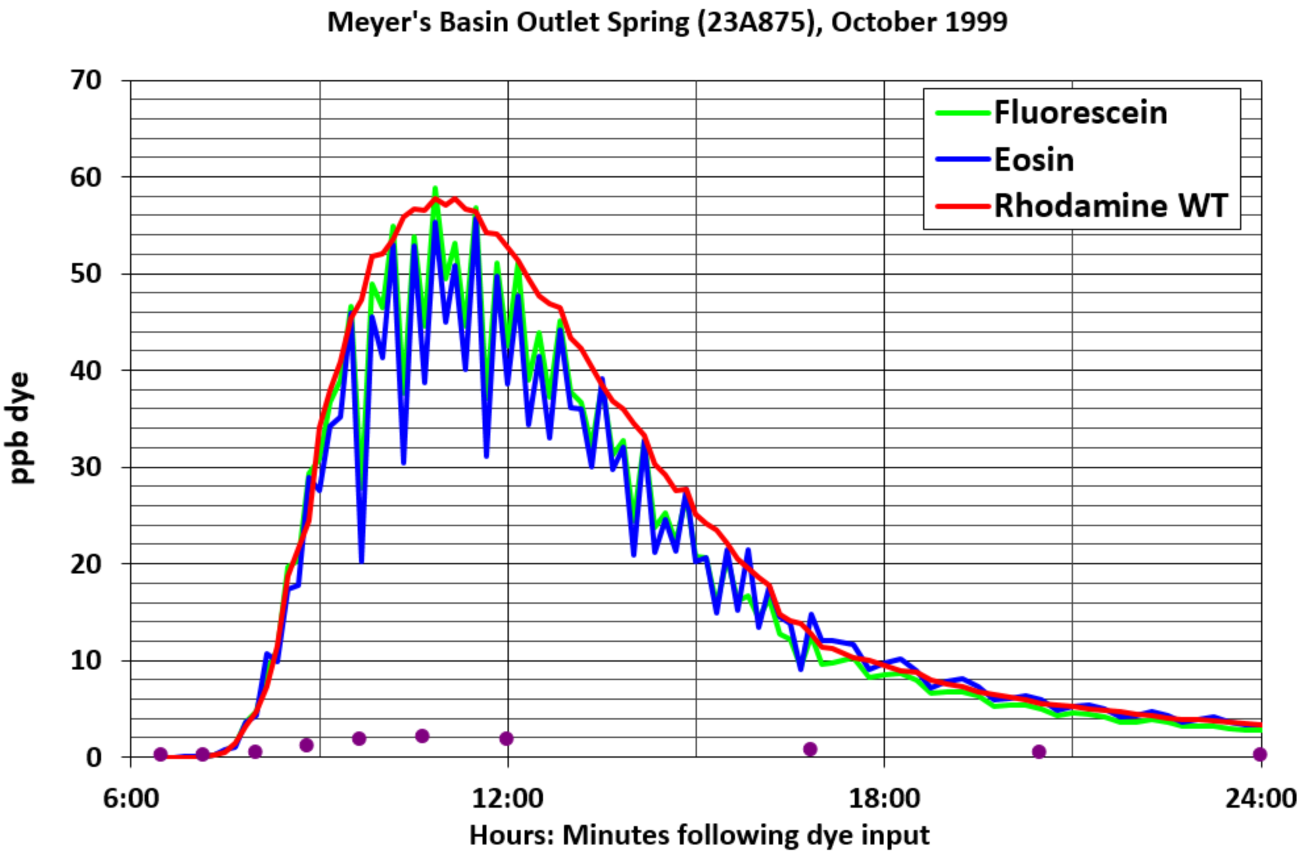

Figure 7. *Linear-Linear breakthrough curves for the main breakthrough curves, the first day of the 1999 dye tracing in the Meyer's Basin Springshed.*

In the October 1999 trace the tracers were poured in the Stewartville Formation and emerged at the base of the Cummingsville Formation (the vertical red line in Fig. 2).The straight-line distance between sinkhole 23D2882 and the Meyer's Basin Outlet Spring (23A0875) and the times of travel determined from the Rhodamine WT breakthrough curves were used to estimate the groundwater flow velocities in the Galena Group in the study area. The straight-line distance, 1610 ft, was multiplied by 1.5 to include the tortuosity of the actual paths (Fields and Nash, 1997) and divided by the first arrival time, 7 hours and 10 minutes, and the peak arrival time, 10 hours and 50 minutes. The time of travel to breakthrough was 1.5 miles/day.The time of travel to the peak of the breakthrough curve was 1.0 miles/day. These travel times are in the middle range of groundwater time of travel values in shallow Galena conduit flow systems. Further discussion of this trace is available in Green et al., 2005.

Conclusions

These traces identified the Meyer's Basin Springshed, a previously unknown groundwater springshed, and expanded the boundaries of the Forlorn River Springshed. The Meyer's Basin is an unusual springshed for this area in that there is very little row crop acreage in it. This opens up the possibility for this springshed to be used for comparison monitoring with a similar sized springshed with more row crop acreage. The two traces that went to both springsheds identified the interbasin overlap area between the two springsheds.The 1999 trace by the UofM tracers class provided valuable data for our efforts to document groundwater travel times in the karst hydrology of the Galena Group bedrock and represent one of the best multi-tracer breakthrough curves ever completed in the state of Minnesota.

Acknowledgments

Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR). We thank Ernie Meyer III, who invited us to study the sinkholes and karst features on his property. John Kelly of DNR Forestry in Preston, MN assisted with equipment and access to the DNR-Forestry land for dye tracing. Mark White and the staff at Forestville State Park provided equipment for tracing.

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Appendix A

Table 1. Meyer's Basin 21 Aug 1996 Traces (3 Traces)

Site	KFD #	UTM, NAD83, Zone 15 Easting/Northing	Feature	Dye Detects
Maple Spring Run Bug Set (downstream of 23A89)	MN23:A00089	561381 / 4831656	Monitoring Point	Negative
Meyer's Basin Outlet Spring (originally called Spring 23A872) (some records also say Vreeman Spring, but this is not that spring)	MN23:A00875	561013 / 4830292	Monitoring Point	**RhWT** **Uran**
Maple Springs Campground Bug	MN23:X00137	561312 / 4831949	Monitoring Point	Negative
New channel Forestville Creek	MN23:X00138	561075 / 4831964	Monitoring Point	Negative
Meyer's Spring Run	MN23:X00139	561057 / 4800373	Monitoring Point	**RhWT** **Uran**
Bridge 1092 (over the South Branch of the Root River) (some bugs mislabeled as Bridge 1067) (aka, So. Branch Root River)	MN23:X00250	561631 / 4830168	Monitoring Point	**Eos** **RhWT** **Uran**
Forestville Creek Upstream	MN23:X00223	561212 / 4832025	Monitoring Point	Negative
Forestville Creek Ford (at the horse trail crossing)	MN23:X00252	562818 / 4831873	Monitoring Point	**Negative**
Group Camp on the South Branch of the Root River (So. Branch Root River, upstream of mouth of Canfield Creek)	MN23:X00332	562566 / 4830258	Monitoring Point	**Eos** **RhWT** **Uran**
Ernie Meyer's #1 Sinkhole 23D3879	MN23:D03879	561222 / 4831347	Dye input 21 Aug 1996, 182.6 g **Rhodamine WT** (20 wt. % solution) at 1345	
Ernie Meyer's #2 Sinkhole 23D3882	MN23:D03882	560829 / 4830747	Dye input 21 Aug 1996, 81.1 g **Eosine** (33 wt. % solution) at 1505	
Ernie Meyer's #3 Sinkhole 23D3881	MN23:D03881	560710 / 4831081	Dye input 21 Aug 1996, 181.2 g **Uranine C** at 1600	

Eos indicates Eosine dye detected

RhWT indicates Rhodamine WT dye detected

Uran indicates Uranine (fluorescein) dye detected

Table 2. Meyer's Basin 19 Sep 1996 Traces (3 Traces)

Site	KFD #	UTM, NAD83, Zone 15 Easting/Northing	Feature	Dye Detects
Meyer's Basin Outlet Spring (originally called Spring 23A872) (some records also say Vreeman Spring, but this is not that spring)	MN23:A00875	561013 / 4830292	Monitoring Point	Uran RhWT Eos
Bridge 1092 (over the South Branch of the Root River) (some bugs mislabeled as Bridge 1067) (aka, So. Branch Root River)	MN23:X00250	561631 / 4830168	Monitoring Point	RhWT Eos
Forestville Creek Upstream	MN23:X00223	561212 / 4832025	Monitoring Point	Negative
Forestville Creek Ford (upstream of the horse trail crossing)	MN23:X00252	562818 / 4831873	Monitoring Point	Uran
Group Camp on the South Branch of the Root River (So. Branch Root River, upstream of mouth of Canfield Creek)	MN23:X00332	562566 / 4830258	Monitoring Point	RhWT Eos
South Branch of the Root River (aka, Root River) (behind Forestville Park picnic shelter bldg	MN23:X00251	563020 / 4832346	Monitoring Point	Negative
DNR Forest Land Sinkhole 23D1783	MN23:D01783	560403 / 4830477	Dye input 19 Sept 1996-90 g **Eosine** OJ (33 wt. % solution)	--
Ernie Meyer's #1 Sinkhole 23D3879	MN23:D03879	561222 / 4831347	Dye input 19 Sep 1996- 67.7 g Rhodamine WT (20 wt. % solution) and 231 g Napthionate/AminoG	--
Meyer's Basin Forestville 1316 Sinkhole 23D2609	MN23:D02609	560086 / 4831090	Dye input 19 Sep 1996- 114.3 g Uranine C (33% weight solution)	--

Eos indicates Eosine dye detected

RhWT indicates Rhodamine WT dye detected

Uran indicates Uranine (fluorescein) dye detected

Table 3. Meyer's Basin 16 May Trace 1997 (1 Trace)

Site	KFD #	UTM, NAD83, Zone 15 Easting/Northing	Feature	Dye Detect
Meyer's Basin Outlet Spring (originally called Spring 23A872) (some records also say Vreeman Spring, but this is not that spring)	MN23:A00875	561013 / 4830292	Monitoring point	**Uran**
Forestville Creek Ford (upstream of the horse trail crossing)	MN23:X00252	562818 / 4831873	Monitoring point	Negative
DNR Forest Land Kelly Sinkhole 23D0002621	MN23D02621	560257 / 4830892	Dye input 16 May 1997- 280.5 g **Uranine C** (35 wt. % solution)	

Uran indicates Uranine (fluorescein) dye detected

Table 4. Meyer's Basin 12 Aug Trace 1998 (1 Trace)

Site	KFD #	UTM, NAD83, Zone 15 Easting/Northing	Feature	Dye Detect
Moth Spring (aka, Spring 23A2)	MN23:A00002	560144 / 4832010	Monitoring point	**Uran**
Grabau Spring (aka, Spring 23A3)	MN23:A00003	560204 / 4832079	Monitoring point	Negative
Maple Spring Run Bug Set (downstream of 23A89)	MN23:X00331	561496 / 4831719	Monitoring point	Negative
Meyer's Basin Outlet Spring (originally called Spring 23A872) (some records also say Vreeman Spring, but this is not that spring)	MN23:A00875	561013 / 4830292	Monitoring point	**Uran**
Forestville Creek (Downstream of Spring 23A684)	MN23:X00138	561075 / 4831964	Monitoring point	**Uran**
Meyer's #4 Sinkhole 23D3880	MN23:D03880	560844 / 4831284	Dye input 12 Aug 1998 - 523 g **Uranine C** (35 wt. % solution)	--

Uran indicates Uranine (fluorescein) dye detected

Table 5. Meyer's Basin Multi-Tracers Test of 1 Oct 1999 (1 Trace)

Input Site Name	KFD #	UTM, NAD83, Zone 15 Easting/Northing	Feature	Dye Detect
Meyer's Basin Outlet Spring (originally called Spring 23A872) (some records also say Vreeman Spring, but this is not that spring)	MN23:A00875	561013 / 4830292	Monitoring Point	**Eos** **NaBr** **RhWT** **Uran**
Ernie Meyer's #2 Sinkhole 23D3882	MN23:D03882	560829 / 4830747	Dye input 1 Oct 1998- 200.2 g **Rhodamine WT** (20 wt. % solution)	--
Ernie Meyer's #2 Sinkhole 23D3882	MN23:D03882	560829 / 4830747	Dye input 1 Oct 1998- 216.2 g **Eosine** (35 wt. % solution)	--
Ernie Meyer's #2 Sinkhole 23D3882	MN23:D03882	560829 / 4830747	Dye input 1 Oct 1998- 153.6 g **Uranine C** (35 wt. % solution)	--
Ernie Meyer's #2 Sinkhole 23D3882	MN23:D03882	560829 / 4830747	Dye input 1 Oct 1998- **NaBr** 2.6 kg	--

Eos indicates Eosine dye detected

RhWT indicates Rhodamine WT dye detected

Uran indicates Uranine (fluorescein) dye detected

NaBr indicates Sodium Bromide detected