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Relationships between surface and ground water velocities determined from dye trace experiments in McConnell Springs and Preston's Cave Spring, Lexington, Fayette County, Kentucky

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Abstract

In mature karst regions, water may flow through large subsurface conduits, expediting flow to surficial karst springs. In the fall of 2015, a dye trace was performed in the Middle Ordovician karst of Lexington, Fayette County, Kentucky in order to measure ground water velocities. Other aspects of the study include (1) comparing these velocities to surface water velocities at discharge points (springs) and (2) comparing karst conduit velocities to granular velocities from previous studies in the region. The locations selected for study include (1) the "Campbell House Sinkhole," (2) McConnell Springs, and (3) Preston's Cave Spring.

Eosine (Acid Red 87) dye was injected into the Campbell House sinkhole during high-flow conditions on September 30, 2015. Discharge recordings were consistently above 0.28 m³/s (10 cf/s) and precipitation remained well above average during the beginning of the sampling period. Data were collected using activated charcoal dye receptors (CDRs) and water grab samples. CDRs and grab samples were collected downstream at McConnell Springs (1.9 km or 1.2 mi) and at Preston's Cave Spring (3.2 km or 2 mi) through October 8, 2015. Sampling

intervals for grab samples were every three hours the first day, and were gradually reduced to one sample per day. CDR samples were collected once per day and were reduced to once every two days.

Dye appeared on October 1, 2015 (six hours after injection) at McConnell Springs, and peaked three hours later. Calculated conduit velocity between the Campbell House sinkhole and McConnell Springs was 5.95 cm/sec (0.133 mph), compared to 76 cm/sec (1.7 mph) for surface-water flow at McConnell Springs, making surface-water velocity approximately 13-times faster than conduit velocity. Although surface water flow was faster than conduit flow, as expected, it is well-understood in mature karst terrains that water flowing through karst conduits is often orders of magnitude faster than water flowing through granular material. This study is a contributory step in understanding conduit-flow velocities in the Lexington area during high-flow conditions.

Introduction

A mature karst terrain is exposed in the Inner Bluegrass Region of Lexington, Fayette County, Kentucky composed of highly weathered, Middle Ordovician limestone. The study sites consist of the Grier Member of the Lexington Limestone Formation. The unit is approximately 55 m (180 ft) thick, containing up to 15 cm (6 in) thick beds of fine- to coarse-grained limestone with interbeds of shale approximately 5 cm (2 in) thick (Figure 1) (Blair, 2009). The soluble limestone bedrock, warm and humid climate, and abundant groundwater activity present in the region is conducive to karst features, such as sinkholes, springs, and conduits.

The study area is located within a single karst drainage basin area of approximately 12 km² (4.6 mi²) Lexington, Kentucky (Spangler, 1982; Currens, 1996). Project locations include the dye-injection location, informally known as the “Campbell House Sinkhole,” a monitoring location at McConnell Springs, and a monitoring location at Preston’s Cave Spring (Figure 2, Figure 3). After briefly exposing in McConnell Springs before again sinking, water ultimately daylight at Preston’s Cave Spring, where it then flows above-ground to Wolf Run and eventually to Town Branch. Though karst drainage basin studies have been conducted in this area (Spangler, 1982), detailed measurements of conduit-flow velocities were not recorded.

Conduit distance from the Campbell House sinkhole to McConnell Springs is 1.9 km (1.2 mi) and 3.2 km (2 mi) to Preston’s Cave Spring. The surface topography within the McConnell Basin does not drastically vary in elevation. The highest elevation in the McConnell Basin is 295.7 m (970’) and the lowest is 274.3 m (900’), yielding a topographic relief of 21.4 m (70’). The difference in elevation between the Campbell House and Preston’s Cave Spring is 12.2 m (40’) over the conduit path of 3.2 km (2 miles), making the stream gradient 6 m per 1.6 km, or 20’ per mile.

The regional dip in the bedrock ranges from 3°-5° NE. While no faults are evident directly in the flow path, the study area lies within the vicinity of several major fault systems, the Kentucky River and Lexington Fault systems, the Cincinnati Arch, and the Jessamine Dome (Black, 1989; McFarlan, 1943). Tectonic activity from these geologic structures has resulted in jointing and fracturing in the local bedrock, opening new paths for groundwater to travel freely and quickly. Groundwater travelling within the jointing allows for the dissolution of the limestone, making caves and sinks common to the area (Johnson, 1966; Miller, 1967). The Grier Member of the Lexington Limestone formation is the dominant lithology of the study area. The limestone unit consists of nodular and fossiliferous argillaceous limestone, with irregular to rubbly and lenticular bedding; interbeds of thin medium-dark-gray shale are found in portions of the unit. The rock acts as a confining bed hydrologically in local areas, and is mostly impermeable (Black, 1965; Johnson, 1966; Miller, 1967).

Kentucky's weather can be highly variable. According to the Kentucky Climate Center, fall is typically Kentucky's dry season; however, precipitation is usually well distributed throughout the year. Average annual rainfall in Kentucky ranges from 107-132 cm (42-52 in); for 2015, annual rainfall was 147.5 cm (58 in). In September 2015, total rainfall was 8.99 cm (3.5 in), with an average of 0.3 cm (0.1 in); while October 2015 total rainfall was 8.8 cm (3.5 in), with an average of 0.28 cm (0.11 in). On September 29th (day before dye injection), total rainfall was 5.03 cm (1.98 in) - well above average. Subsequently, between September 30th, 2015 and October 2nd, 2015 (first 72 hours of dye travel), there was a total of 2.39 cm (0.94 in) of precipitation, (Kentucky Mesonet, 2015).

The objective of this dye trace is to measure conduit-flow velocity and compare to surface-stream velocity and granular (clastic) aquifer velocity. This study was conducted during high-flow conditions (USGS, 2015). Temperature measurements were also collected.

Methodology

Background data were collected September 15, 2015 through September 30, 2015 at McConnell Springs, Preston's Cave Spring, Campbell House, and Town Branch. Eosine (Acid Red 87) dye was selected for comparison with experimental flow tests because it registered lowest background detection in the study area (Figure 4). A "Dye-Trace Notification" permit was submitted to the Kentucky Division of Water on September 30, 2015.

0.15 kg (0.33 pound) of Eosine dye was injected into the flooded Campbell House sinkhole on September 30, 2015, at 7:30pm (it has been observed by us that the Campbell House sinkhole is often dry, other than during heavy rainfall events). Following the injection, data were collected using activated charcoal dye receptors (CDRs) and water "grab samples" using 8 ml borosilicate glass sample vials.

CDRs and grab samples were collected downstream of the injection at McConnell Springs (1.9 km or 1.2 mi) and Preston's Cave Spring (3.2 km or 2 mi) over a period of 2 weeks. Grab samples were collected every 3-4 hours for the first 24 hours, every 6-8 hours the second 24 hours, and were gradually reduced to one sample per day for 2 days. Sampling intervals for CDRs were once per day for 4 days, and then gradually reduced to every other day. Town Branch was sampled intermittently to test for inner-basin spillover. Background data were also collected just upstream of the Campbell House sinkhole. Precautionary measures such as gloves were used to ensure that there was no dye contamination. Water grab samples and CDR samples

were analyzed by personnel at the Crawford Hydrology Laboratory at Western Kentucky University using a Shimadzu RF5301 spectrofluorophotometer.

Surface-flow velocity was measured at both McConnell Springs and Preston's Cave Spring on October 1st and October 2nd, 2015, by using traditional methods (floating objects down the stream, and calculating the time of travel over a 15.2 m (50') distance. This was completed three times at each sampling site and the times were averaged.

Temperature measurements were collected at McConnell Springs and Preston's Cave Spring using a YSI Environmental YSI 556 MPS probe. Temperature measurements at McConnell Springs were measured at the Blue Hole where water first appears at the surface from the injection site, while measurements at Preston's Cave Springs were taken near the opening of the cave where water reappears downstream of McConnell.

Results and Discussion

Eosine dye levels for McConnell Springs and Preston Cave Springs exhibit similar trends, but the McConnell Springs dye peak is stronger and slightly earlier than the Preston's Cave location.

At McConnell Springs, dye first appeared at 1:47 am on October 1st, 2015 and peaked at 7.082 ppb at 4:32 am. Due to location and safety, water grab sample collection at Preston's Cave Spring was not recorded overnight, but was sampled at 8:15 am on October 1st, 2015, yielding 4.058 ppb Eosine dye. Dye at both locations gradually decreased to 0.4 ppb or less 18 hours after injection on October 1st, 2015, (Figure 5). A CDR was placed at Preston's Cave Spring from 8:50 pm on September 30th, 2015 to 7:45 pm October 1st, 2015 to record the dye peak, and measured 111.786 ppb (Figure 6).

Precipitation for September 29th 2015, (day before injection), totaled 5.03 cm (1.98 in). September 30th: 0.2 cm (0.08 in), October 1st: 1.12 cm (0.44 in), October 2nd: 1.07 cm (0.42 in), and October 3rd-8th: 0 cm (0 in) precipitation (Kentucky Mesonet, 2015). Most of these days are well above the daily precipitation average for the months of September and October (<0.3 cm or 0.12 in). Discharge recordings at the USGS Wolf Run Gaging Station were consistently above 0.28 m³/s (10 cf/s), peaking up to 17 m³/s (600 cf/s) on September 30th, 2015 (day of injection). With excess rainfall occurring before and during the beginning of our sampling days, this created flooding/high flow conditions and the rapid movement of dye through the system.

Using the dye peak for calculating conduit velocity between the Campbell House sinkhole and McConnell Springs yields 5.95 cm/sec (0.133 mph), compared to 76 cm/sec (1.7 mph) for surface water flow at McConnell Springs. A USGS stream water monitoring station located at Wolf Run on Old Frankfort Pike, approximately 1.6 km (1 mi) northwest of Preston's Cave Springs Creek, records hourly discharge values (Figure 7). As the average groundwater temperature in Kentucky is 12^oC (54^o F) (Collins, 1925), the daily surface water temperature measurements at each location indicates that the stream water is warmer in high flow conditions. Surface water measured near 17-18^oC (62.6-64.4^oF) when the dye quantity peaked in the first day and gradually decreased to approximately 16-17^oC (60.8-62.6^oF) by 7 pm on October 1st, 2015 fluctuating below that for the remainder of the sampling period (Figure 8).

Conduit velocities in this study, though slower than stream velocities, are very fast compared to hydraulic conductivities in eastern-Kentucky, non-karst aquifers, which often range from 10⁻² cm/sec to 10⁻⁷ cm/sec (10 ft/day to 10⁻⁴ ft/day) , (Figure 9) [refer to Minns (1993) and Garrison (2015) for compilations of eastern-Kentucky hydraulic conductivities].

Conclusion

The primary objective of this study was to measure conduit-flow velocities during high-flow conditions in the Middle Ordovician karst of Lexington, Kentucky. Comparisons were made to surface-stream and granular aquifer velocities. Temperature measurements were also measured. Below is a summary of relevant conclusions:

Dye peaked within 9 hours of the injection at McConnell Springs (1.9 km, or 1.2 mi, downstream) and 9-11 hours at Preston's Cave Spring (3.2 km, or 2 mi, downstream). Conduit flow velocity between the Campbell House sinkhole and McConnell Springs was 5.95 cm/sec (0.133 mph). Conduit velocities are very fast compared to the hydraulic conductivities reviewed in eastern-Kentucky, non-karst aquifers, which range from 10^{-2} cm/sec to 10^{-7} cm/sec (10 ft/day to 10^{-4} ft/day).

Surface water velocity at McConnell Springs measured approximately 76 cm/sec (1.7 mph) making surface water velocity approximately 12 to 13-times faster than conduit velocity. Conduit flow velocity is slower than surface water velocity due to space limitations and friction. However, the high-flow conditions likely facilitated accelerated dye travel time through conduits due to increased hydraulic head caused by flooding at the Campbell House sinkhole.

The regional topographic relief of 21.3 m (70'), stream gradient of 6 m per 1.6 km (20' per mile), and the structural dip of the bedrock (3° - 5° - NE) probably had little influence on the dye's travel time. Quick dye travel is related to heavy precipitation in a short amount of time, with minimal contribution from the surface topography.

The Town Branch CDR detected no dye, corroborating previous studies that suggested there was no connection between the two subsurface karst drainage systems.

Water temperatures measured at karst springs in high-flow conditions is warmer due to excess rainfall from the day prior to dye injection being forced through the karst system, with little time to cool to ambient temperatures.

For future studies, we recommend that dye traces are repeated in both mid-flow and low-flow conditions. The sampling methods in future traces should also occur more frequently to obtain more specific dye peak(s).

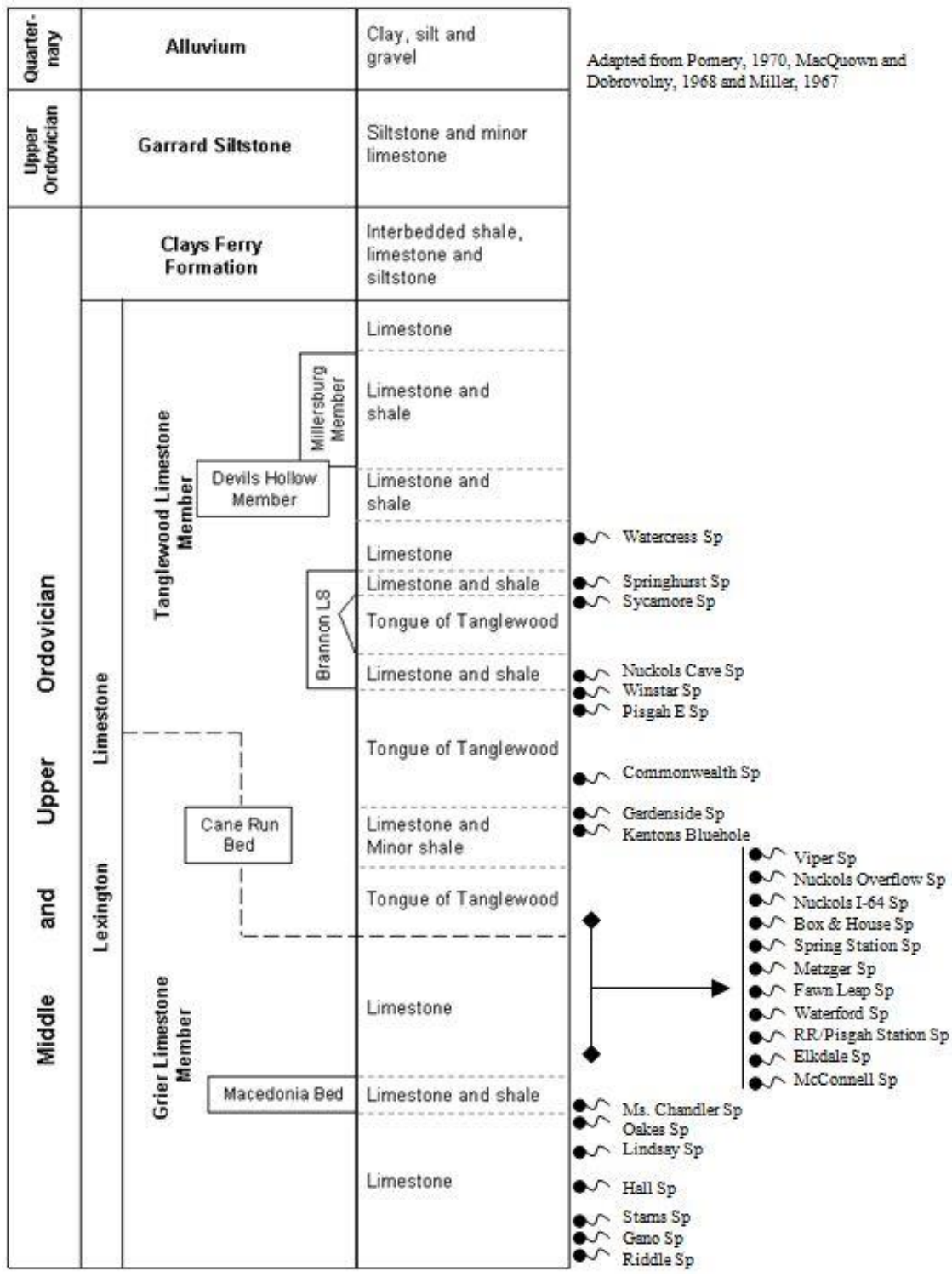


Figure 1: Stratigraphic Column of local Formations, including those within Lexington, Kentucky (Blair, 2009).

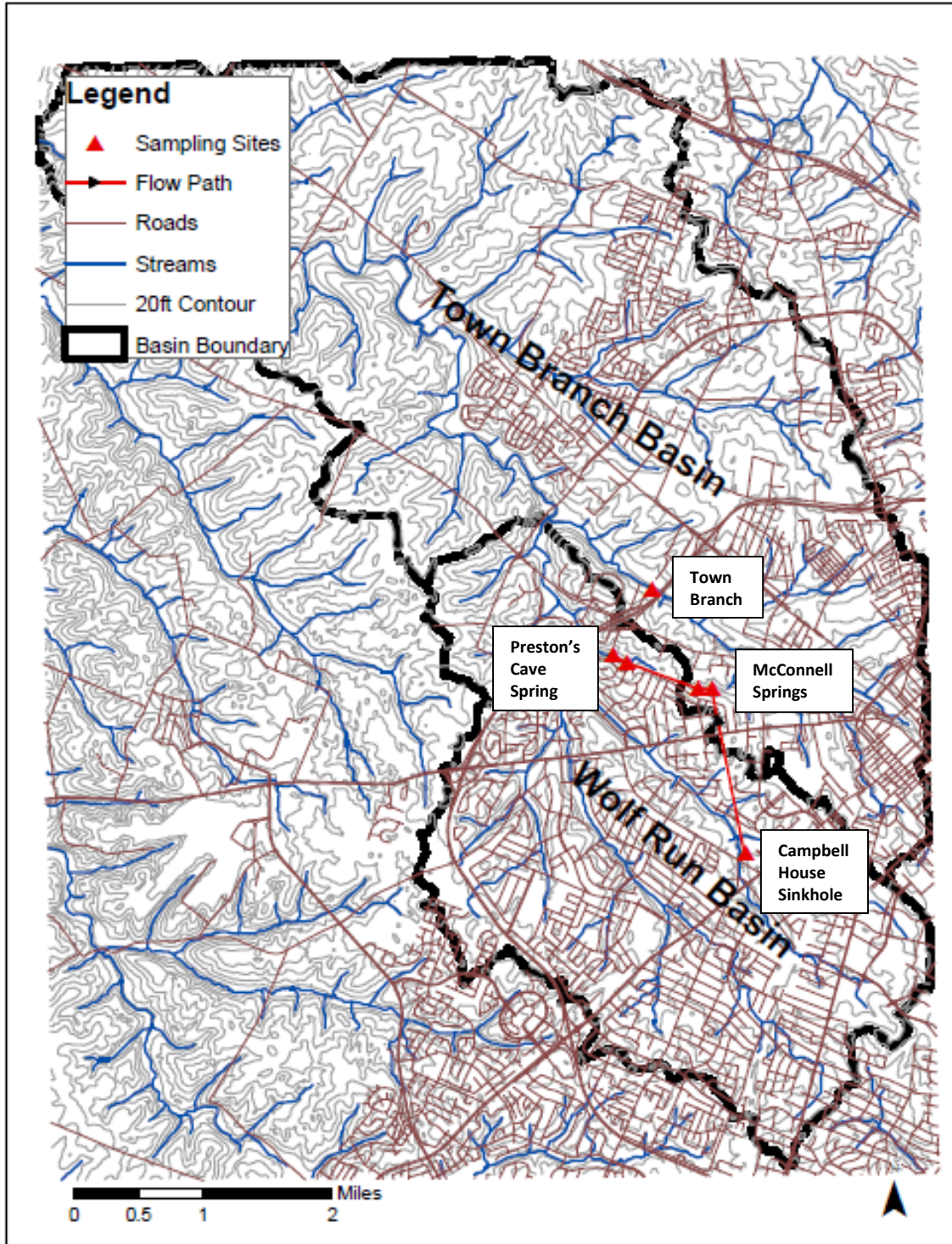


Figure 2: Map of the study area showing sampling sites and their connectivity, or lack thereof, as well as the major surface drainage basins in which the sampling sites are located (the base topography is derived from the Lexington West 7.5' topographic map). These illustrate that groundwater flow paths and connectivity are not affected by surficial drainage basins.

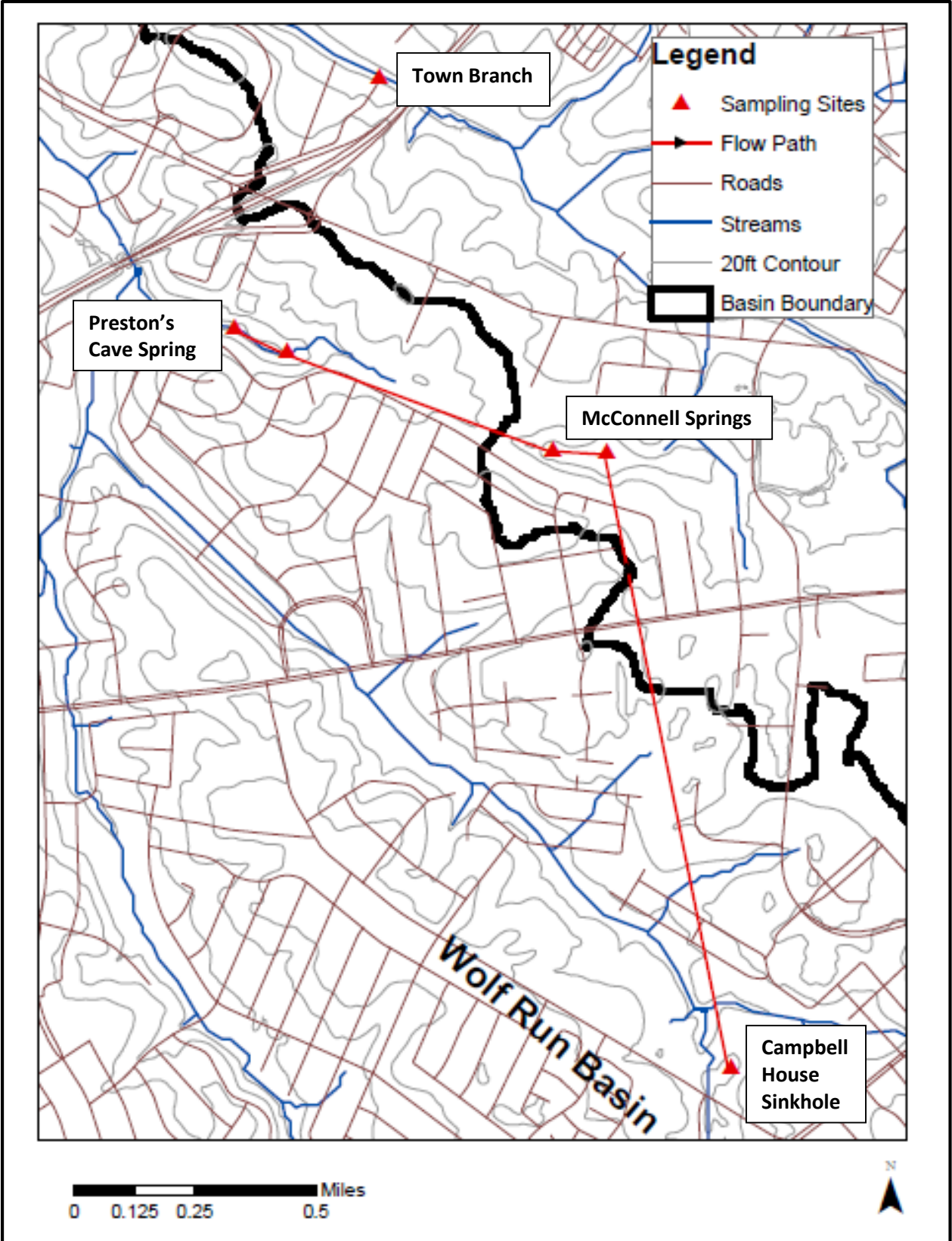


Figure 3: A closer view of the sampling site locations, Lexington, KY.

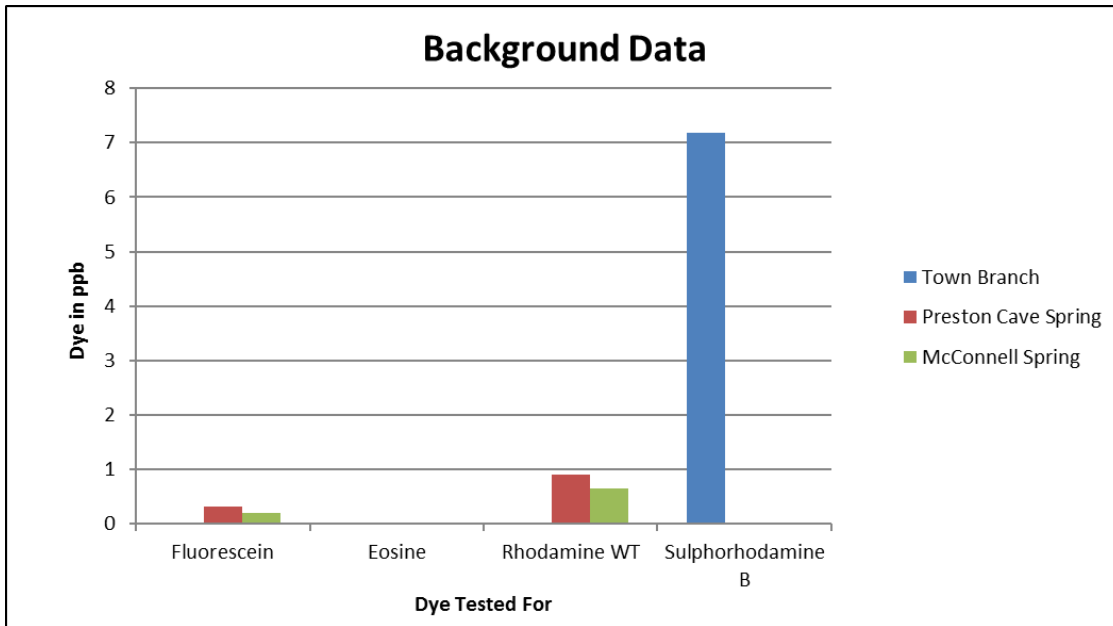


Figure 4: Dye compounds and their concentrations recorded from background data analysis, showing Eosine as the dye that registered lowest detection of the three background sites. Town Branch is located in an industrial area with potential for runoff; a possible reason for the large spike in Sulphorhodamine B at that site.

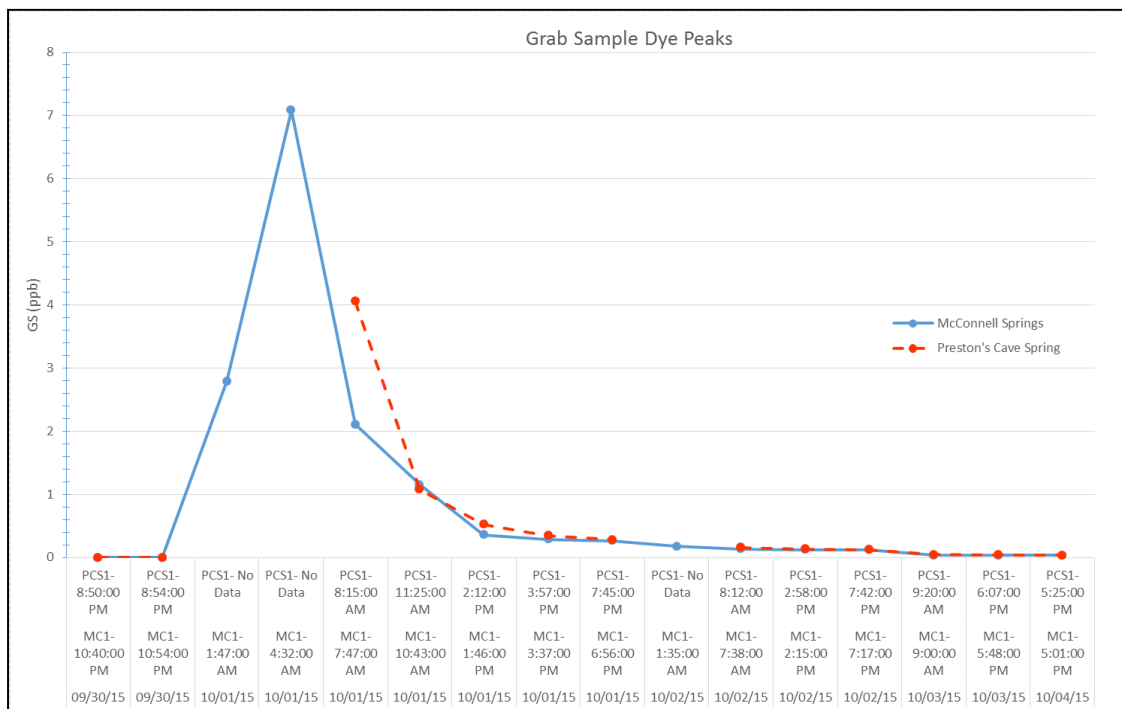


Figure 5: Graph showing peak Eosine detection for McConnell Springs (MC) and Preston's Cave Spring (PCS) using data collected from grab samples (GS). The largest peaks appear at MC1:4:30AM and PCS1:8:15AM. There were brief periods of no data collection at PCS1 on 10/1/2015 and 10/2/2015.

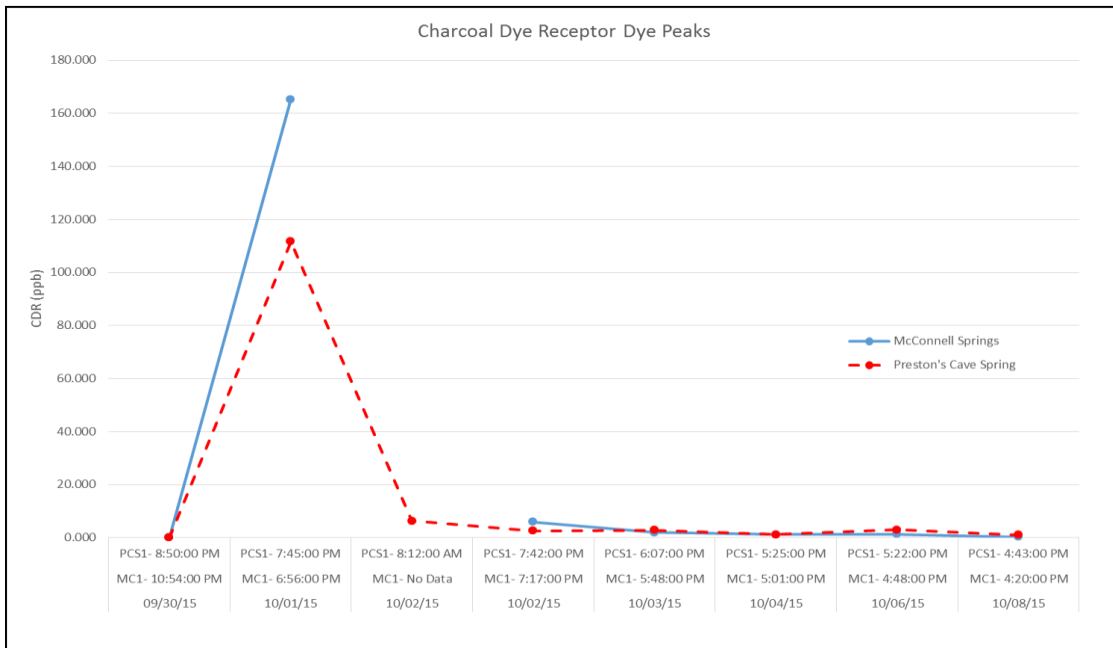


Figure 6: Graph showing peak Eosine detection for McConnell Springs (MC) and Preston's Cave Spring (PCS) using data collected with charcoal dye receptors. The largest peaks occur at MC1:6:56PM and PCS1:7:45PM. An extra CDR was used at PCS1 due to lack of data for the grab samples.

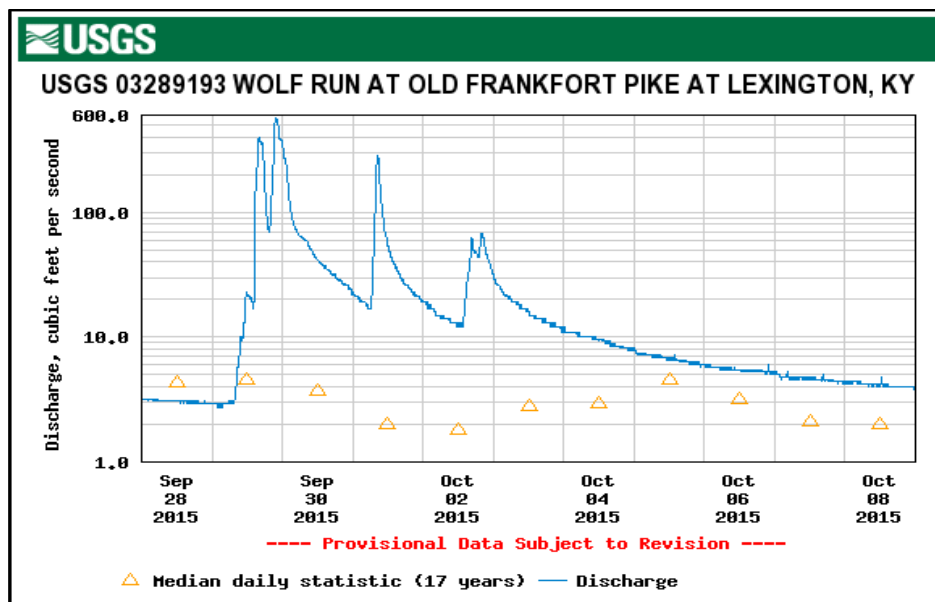


Figure 7: Stream discharge measurements recorded at USGS water monitoring station located at Wolf Run at Old Frankfort Pike at Lexington, KY. The graph shows both high flow and normal flow conditions, from September 28th – October 8th, 2015 (USGS, 2015).

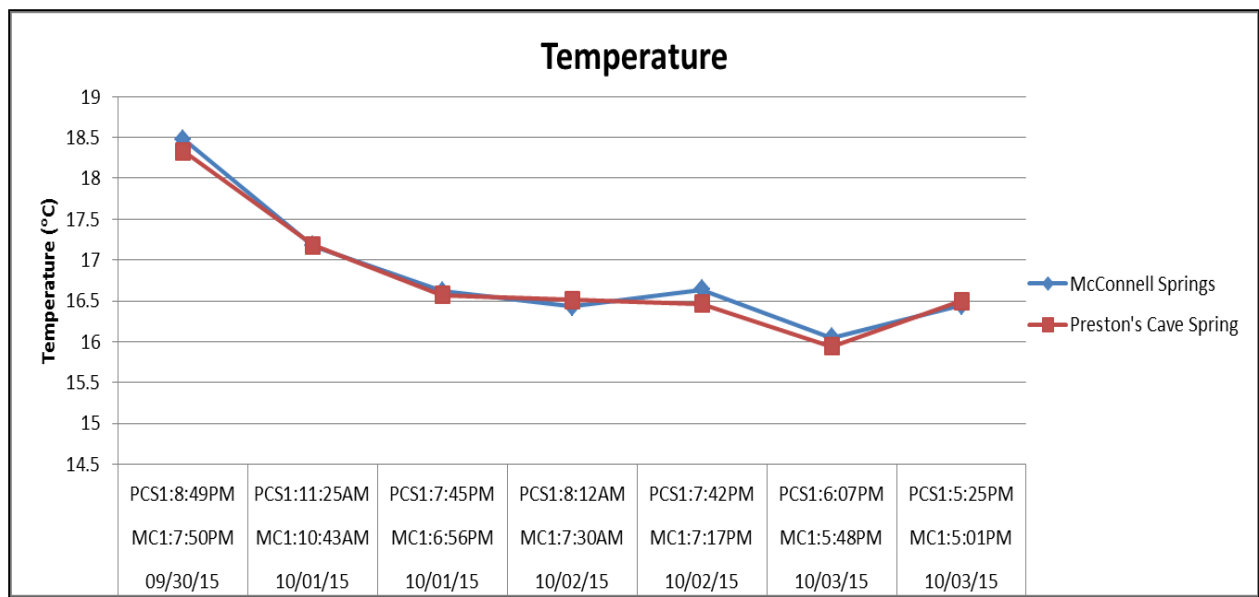


Figure 8: Stream water temperature recorded at McConnell Springs (MC) and Preston's Cave Spring (PCS) for the period September 30 to October 3, 2015.

K (cm/s)	10^2	10^1	$10^0=1$	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
K (ft/day)	10^5	10,000	1,000	100	10	1	0.1	0.01	0.001	0.0001	10^{-5}	10^{-6}	10^{-7}
Relative Permeability	Pervious			Semi-Pervious			Impervious						
Aquifer	Good			Poor			None						
Unconsolidated Sand & Gravel	Well Sorted Gravel	Well Sorted Sand or Sand & Gravel			Very Fine Sand, Silt, Loess, Loam								
Unconsolidated Clay & Organic	Coal Cleat			Peat	Layered Clay		Fat / Unweathered Clay						
Consolidated Rocks	Highly Fractured Rocks			Oil Reservoir Rocks		Fresh Sandstone		Fresh Limestone, Dolomite		Fresh Granite			

Figure 9: Hydraulic Conductivity values found in nature (after Bear, 1972). K range in karst aquifers colored in light blue (Ewers, 2013). K range of 18 clastic aquifers, colored in yellow (Minns, 1993; Garrison, 2015). K ranges in this study are in dark blue.

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