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Vadose Zone Hydrology near the Vicinity of Edna's Dome, Mammoth Cave, Kentucky

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VADOSE ZONE HYDROLOGY NEAR THE VICINITY OF EDNA’S DOME, MAMMOTH CAVE, KENTUCKY

Date Recommended: November 17, 2008

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________________________________________
Dean, Graduate Studies and Research Date
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This study examines the differences in key physical aqueous parameters at two different cave sites separated by only a few tens of meters. One site (FF) has a free falling water component where water descends nearly 30 meters from the ceiling of a vertical shaft. The other location (WW) appears to have continuous water to rock contact as it descends to near the same level in the cave.

Water samples were collected at the two sites in two week intervals from May to August 2002. While both sites were proximal, they demonstrated very different behaviors, particularly during storm events. Differences in flow route may explain differences in relative water parameter data and response to rainfall events. An assumption was made that the WW site has continuous water to rock contact and the FF site does not. Specific conductance (SpC) data consistently suggest that the water apparently does indeed have a greater degree of water to rock contact when compared to the FF site as the pH and SpC values for the site always revealed a higher concurrent reading.
These data suggest that while waters may be located within meters of each other in this karst environment the physical properties of water at each site can vary widely
CHAPTER 1: INTRODUCTION

There is little doubt that karst landscapes are an integral part of the planet’s ecosystem. These karst aquifers may be defined as aquifers that contain dissolution-generated conduits that permit the rapid transport of groundwater, often in turbulent flow (White, 2002). Karst regions are now estimated to account for nearly 25% of the earth’s surface (Assaad, et al, 2004). These areas have also been estimated to supply 25% of the earth’s population with drinking water resources (White, 1988; Ford and Williams, 1989). In Kentucky more than one million citizens rely on karst groundwater for public water supplies and one-half million use groundwater as a private source (Croskrey 2006).

The characteristics intrinsic to karst topographies are: suitable rock, suitable solvent, hydraulic gradient, interconnected fractures and time. Karst can occur on many types of rock from quartzite (Wray, 1997) to basalt (Ford and Williams, 2007). Due to higher solubility karst is most commonly associated with the carbonate rock limestone, and to a lesser degree, dolomite (Palmer, 1981).

The south-central Kentucky karst is located within the broad limestone karst region extending through the Interior Low Plateaus of southeastern United States. This area is among the most extensively developed, best explored and intensively studied karst landscapes of the world (Palmer, 1981; White and White, 1989). Within one part of this region, beneath an area of about 200 km² between the Green and Barren Rivers, over 800 km of cave passages have been explored and surveyed. This includes 592+ continuous kilometers in the Mammoth Cave System (MCS); the longest known cave in the world with exploration still ongoing.
The MCS is located within the Mississippian carbonates of, in descending stratigraphic order, the Girkin, Ste. Genevieve and St. Louis Formations (Granger et al., 2001). These limestones are sparsely interbedded with minor chert and dolomitic layers. Additionally, these limestone layers are overlain by clastic sedimentary rocks, primarily the Big Clifty Sandstone with a thin discontinuous layer of shale at its base.

The vertical extent of the MCS developed in the carbonate sequence is approximately 100 meters. One primary source of input into the cave system is a region known as the Pennyroyal Plateau, which forms an extensive sinkhole plain that possesses thousands of sinkholes that funnel water to the subsurface. From here water travels down dip, regionally on the scale of 0.5° northwest, dissolving the limestone as it goes (Palmer, 1981). All water entering the cave system discharges via springs into the master base level, Green River, which flows at approximately 128 meters above sea level under low flow conditions. Another water transfer component of the system is vertical shafts, the key feature of this study.

Vertical shafts are obvious features in many cave systems. They are roughly cylindrical in shape and have dimensions ranging from a few centimeters to hundreds of meters in height and from centimeters to tens of meters in diameter. They may exist with or without direct openings to the surface (Reams, 1964). Vertical shafts result from dissolution by calcite-undersaturated groundwater descending vertically into the cave system (Brucker et al., 1972). The shafts are relatively much younger features than the passages they may intersect during their development and are believed to form very rapidly (White, 2000). Unquestionably, the epikarst plays a role in also providing water
to the vertical shafts. There is evidence to suggest the epikarst is an important storage unit at the top of the vadose (Klimchouk, 2004; Groves et al., 2005).

Vertical shafts often allow access into other passages or the shaft drain itself may allow new discoveries within cave systems. Geologically, however, vertical shafts are important in karst systems for three reasons:

1. *Vertical shafts represent primary water transfer components for subsurface streams within karst aquifers.*

Water recharging a karst aquifer often does so directly through vertical shafts. Shafts fed by epikarstic recharge represent headwaters of a conduit drainage system developed in the deeper parts of the aquifer (Klimchouk, 2000). The shaft may provide water with its first appearance within the open system environment of the cave. Vertical shaft water chemistry is often highly undersaturated with respect to calcite (Brucker, et al., 1972). The reason for water being undersaturated is because of its path through the soil where microbial activity produces carbon dioxide from the oxidation of decaying plant material. This promotes the production of carbonic acid (Drever, 1997), the primary agent for limestone dissolution within the south-central Kentucky karst aquifer.

2. *Vertical shafts often indicate surface drainage topography.*

The presence of vertical shafts within a cave often directly relates to the surface topography (White, 2000). While some shafts occur under sinking streams, many vertical shafts at Mammoth Cave National Park (MCNP) are located near the contact of the overlying Big Clifty Sandstone unit and the underlying carbonates (Figure 1) (Brucker, et al., 1972). The sandstone capped
karst plateau is ringed with large numbers of vertical shafts that are an integral part of the drainage from the perched groundwater body in the protective caprock (White, et al., 1970). The groundwater from the sandstone discharges horizontally to the edges of the plateau and vertically to underlying formations (Brown, 1966). The underlying formations are highly soluble carbonate strata that which host numerous fractures allowing limestone dissolution to occur vertically as the water is funneled from the surface down into the cave system and ultimately to the water table (Palmer, 1981).

3. *Vertical shafts can provide pathways for pollutants into karst aquifers.*

It is widely known that rapid transportation of pollutants occurs in karst areas (White, 1988). In most aquifers where porous or fractured media laminar flow dominates, the subsurface migration of pollutants can be much slower. Due to rapid pollutant transport and the dependence of many people using karst aquifers for a water supply, it is imperative to understand the developmental aspects of karst recharge zones such as vertical shafts. A study conducted by Krothe (2003) has shown that limestone karst areas capped with sandstone and soil will release contaminants from the soil and sandstone into fractures and vertically descend into the karst.

Another threat posed from contaminated water into vertical shafts via the epikarst is the harm that can be done to faunal communities. Pipan et al. (2006 and Brancelj 2006) conducted studies that proved the epikarst is habitat for numerous genera and species of organisms. As the epikarst and shafts are a primary point of entry for water entering the main cave system it further makes
groundwater protection of karst environments an extreme importance (Pipan and Culver, 2007).

Figure 1 – Location of vertical shafts in relation to surface topography in the Mammoth Cave, Kentucky Region (from Brucker, et al.)
Previous Investigations

Early hypotheses proposed for the development of vertical shafts in a karst environment sense were many and varied. Some authors such as Weller (1927) and Swinnerton (1935) hypothesized that subsurface streams were pirated by the lowering of the water table. William Morris Davis believed shafts were actually created below the water table as vertical joints were enlarged (Davis, 1930); (Bretz, 1942). Some authors were proponents of what was referred to as “Pot-Hole Origin.” Essentially, this hypothesis states that concentrated areas of less soluble rock (i.e. chert) are agitated by a whirlpool. The resulting abrasion from the less soluble rock and simultaneous dissolution by water produces a pot hole (i.e. vertical shaft) (Greene, 1908). Greene also saw the possibility that these “erosion domes” were created by water descending vertically from the surface en route to lower levels of the karst aquifer (Greene, 1908). Green was not alone in this alternate hypothesis. Others such as Farrington (1901), Lobeck (1928), Gardner (1935) and Pohl (1935) also perpetuated the vertically descending water hypothesis. Perhaps no one continued the crusade for shaft creation and evolution as the result of vertically moving waters from the surface more than Pohl. Two decades after discussing the idea of shaft development as the result of vertical seepage he wrote a paper discussing the failures of earlier hypotheses and distinguishing vertical seepage of water as the dominant force in the creation of vertical shafts (Pohl, 1955).

Pohl additionally saw the ridges of south central Kentucky to be intimately related to the underlying vertical shaft features of cave systems. He viewed the shafts as developing as valleys developed headward. As valleys continued to broaden and deepen
shafts were effaced from the landscape. The role of shafts viewed in this light was further bolstered by Quinlan and Pohl (1967). Another study revealed that in addition to vertical seepage some degree of stratigraphic controls were in place helping dictate the development of vertical shafts (Merrill, 1960). Other work conducted in England revealed hypotheses that additionally supported Pohl’s work on a vertical seepage idea (Burke and Bird, 1966; Frumkin, 2000). Today it still remains the dominant theory for the development of vertical shafts within carbonate rock units.

Within the past decade great attention has been paid to the epikarst as an influential component in the transmission of water from the surface to the subsurface. The epikarst is the area below the soil and above the main mass of largely unweathered soluble bedrock, consisting of highly corroded bedrock, residuum, and float. Thickness varies from absent to a maximum of 30 meters. The epikarst is relevant to the storage and transport of water in the karst system, and to foundation stability (Field, 1999). The epikarst is therefore linked to vertical shafts as well. Variable characteristics such as soil thickness and porosity development of the epikarst strongly influence its capacity to store and transmit precipitation (Williams, 2008). This determines the epikarst’s development and the distribution of recharge to a karst aquifer in both space and time (Bauer, et al., 2005); (Clemens, et al., 1999); (Cooley, 2005). Further studies indicate there are two flow components associated with the epikarst. One flow regime quickly responds to storm events while the other is a slower, sustained flow (Gunn, 1983; Perrin, et al., 2003).

Numerous studies have occurred dealing with aqueous geochemistry concerning vertical shafts. Some of this work has demonstrated that both supersaturated and
unsaturated water can occur in this level of the vadose zone (White and White, 1989). This is common in very large shafts or shaft complexes which occur in different positions relative to topographic conditions pertaining to a caprock. Sections of a shaft that occur along the contact of the caprock typically have water that is undersaturated with respect to calcite and thus capable of dissolving the carbonate rock units. Those sections of the shaft located beneath a valley wall may be covered with speleothems such as stalactites or flowstone (White, 2000). The deepening of vertical shafts seem to be perpetuated by not only hydrochemical composition of the water, but may also be impacted by physical/erosive impact (Baron, 2002; Frumkin, 2000).

In addition other work has been conducted to try and determine the rates in which vertical shafts develop. Merideth (2000) made weekly measurements of hydrochemical data \([\text{HCO}_3^-, \text{Ca}^{2+}, \text{temperature (C)}^\circ, \text{pH} \text{ and SpC (mS)}]\) over a nine month period within the Showerbath Spring vertical shaft of the MCS. In addition to recording data, calculations were made to determine calcite saturation indices and CO\(_2\) pressures. These data were then placed into the Plummer, Wigley, Parkhearst equation for limestone dissolution (Plummer and Wigley, 1976). Results showed that the rate of shaft development, based upon dissolution rates, averaged approximately 1 mm/yr. of wall retreat, with storm events increasing dissolution rates. This mean dissolution rate calculated by Merideth is similar to a shaft dissolution rate calculated by White (2000) conducted in shafts located in different states. Additionally, data illustrated that the chemistry is controlled by a mix of relatively high CO\(_2\) storm water and low CO\(_2\) diffuse waters (Merideth et al., 2002). Water sample data revealed that the water was undersaturated with respect to calcite in every case where it was measured (Merideth et
al., 2002). This is opposite to what has been shown in water chemistry in some parts at base level within the Logsdon River of Mammoth Cave (Anthony, et al, 1997). River water there can be oversaturated with respect to calcite for much of the year. Most dissolution at the river level is done during storm and large flood events (Groves and Meiman, 2005).

The focus of this study is to examine the hydrology of two sites that are only separated by approximately 30 meters. However, each site possesses distinctly different characteristics with respect to rock/water contact time. Data collected will illustrate differences in vadose hydrology pertaining to these series of shafts.
CHAPTER 2: FIELD SITE AND METHODOLOGY

Field Site Selection

Vertical shafts are prevalent within the 590+ km long Mammoth Cave System. Selection of a single shaft complex for the study would appear a simple task. However, given the scope of the study and the types of data needed to be attained it was determined a shaft selected for this study should possess some requisite characteristics. The following criteria were used to select a vertical shaft.

1. Perennial water flow

One of the key components is that a shaft possess perennial water flow. A perennial water flow allows water sample collections at anytime of the year as well as continuous monitoring of key physical parameters via data loggers. This is of specific importance as the study runs from late spring through late summer which is among the driest times of the year in south-central Kentucky. A continuous stream of data will be necessary to provide an understanding of the relationship between the aqueous physical parameters and how they may or may not fluctuate from spring to summer season, as well as fluctuations during storm events.

2. Water to rock contact coupled with free falling water away from the rock surface

A shaft containing a stream or dripping of free falling water and a separate section of the shaft complex that possesses continuous water to rock contact simultaneously will enable water chemistry comparisons and/or contrasts between the two parameters. Data from these two monitoring stations will provide insight into how the behavior of key monitored parameters adapts to changing weather conditions from storm events to times
of drier weather as the water flows en route to the phreatic zone deeper within the cave system.

3. Easily, quickly and safely accessible

It is imperative that a shaft be easily, quickly and safely accessible to avoid unnecessary risks to the researcher or sensitive archaeological and/or geologic areas (i.e. fragile speleothems, prehistoric artifacts etc.) Furthermore, in the event of an accident, response and rescue times can be as rapid as possible. Finally, safe, quick and easy accessibility enables quick repair, set-up and take-down of research equipment during the study.

The most efficient means of quick, safe and easy movement within the cave system is along the near twenty kilometers of well-developed tourist trail. These trails traverse a variety of cave passage types including vertical shafts. Therefore, an inventory of all vertical shafts along tourist trails was conducted to reveal a list of shafts of potential interest to the study.

The shaft inventory provided a list of over 30 vertical shafts along toured routes of the cave. Many of these however did not fulfill the other prerequisites for the study. Many did not have perennial water flow, others were still not safely accessible (as they were located off of the main trail areas or did not have a safe means of collecting water), most did not possess among the most important of the criteria of possessing both a free flowing and continuous water-to-rock component water flow regime. A more critical look at the potential vertical shafts revealed only a handful of viable study sites.

Of these sites Edna’s Dome (Figure 2) was the site selected for study. Edna’s Dome is located among a series of vertical shafts near the upstream end of Martel
Avenue near the junction of Bransford Avenue and Hawkins' Pass. The shaft is located approximately 10 meters south/southwest from Einbigler’s Dome. Edna’s Dome measures approximately 30 meters in height and 10 meters in diameter and possesses the smooth cylindrical shape intrinsic to many vertical shafts. The base of the shaft possesses a small drain that is large enough for human access.

The Edna’s Dome vicinity fulfilled all three prerequisites for the study. It contains the perennial water flow critical to understanding the seasonal fluctuations of the aqueous geochemistry. The shaft area itself contains both components of free falling and continuous water-to-rock contact within its complex. Finally it is located along tourist trail proving it to be quickly, easily and safely accessible. The shaft is approximately a 10 minute walk from the Snowball Room where access to an elevator directly to the surface provides the point of entry. One additional benefit of Edna’s Dome as a selection site is that it is only minimally viewed by visitors. Only the Wild Cave Tour gains access to this section of the cave once daily with a maximum of 14 visitors. This minimal viewing of the shaft cuts down on heavy traffic and tampering of equipment that may occur on more busy routes.
Use of GIS and topographic overlays revealed the location of Edna’s Dome in relation to the surface topography. The dome is beneath the sandstone/limestone contact which is so typical to vertical shafts in the vicinity of Mammoth Cave. The surface position of Edna’s Dome is located beneath an area approximately 50 meters northeast from Highway 70 around 2 ½ kilometers from the park entrance road from Cave City (Figure 3).
Collection equipment was placed inside of Edna’s Dome beneath a stream of free falling water in order to monitor the physical parameters of pH, SpC, flow rates and temperature. The graphed data from this site is labeled FF to denote Free-Falling water measurements. A site monitoring surface film waters was selected at an area named the Water Clock, located about 30 meters north direction from Edna’s Dome. Here a perennial water flow occurs beneath a small opening in the ceiling located approximately 0.75 meters above the sampling equipment. The graphed data from this site is later referred to in the results section as WW to denote Wall Water measurement readings.

Figure 4 gives an overview of the vertical shafts located in the immediate vicinity as well as the locations of the sampling sites.
Field Methods

At each sampling site an electronic tipping bucket rain gauge was modified to fit on top of a standard tripod. Holes were drilled into the bottom of the rain gauge and screw-mounted to the top of the tripod. Each tripod was then placed beneath the water collecting sites on the uneven rock surfaces allowing for continuous water collection.

One end of an approximately 1 meter length of Tygon tubing was secured to the base of the rain gauge. The other end was placed in the bottom of a 250 mL sample bottle that was attached by cable ties to one leg of the tripod. Within this sample bottle a specific conductance (SpC), temperature and pH probes were placed to record data to a Campbell Scientific (CSI) CR10X data logger (Figure 5).

The CSI CR10X data logger was housed within a waterproof case along with a battery supply for both the data logger and the data collection probes. One of the most problematic situations of data collection within this environment was the ubiquitous high humidity (90 – 100%) and moisture levels throughout the study period. A desiccant was
placed in each case to combat the effects this potentially has on sensitive electronic equipment. Each desiccant was replaced at each data download period.

Figure 5 – Field set up of data collection equipment located at the Water Clock. This exact array was also set up in the Edna’s Dome study site. Photos by Nathan Talley
With respect to the wetness associated at each sampling site, additional precautions were necessary for the electronic cables that ran from the data logger to the data collection probes. The connection points between the probes and the data logger were sealed with electrical tape then placed within a 250 mL sample bottle inverted and attached to one leg of the tripod. To keep it completely water tight inside this makeshift cable housing, the end of the sample bottle was filled with silicone gel. The point of entry for the electronic cables into each equipment case was also sealed with silicone to keep out unwanted moisture. See Figure 5 for data collection site set-up and layout specifications.

**Data Monitoring Methods**

In order to understand the relationships and fluctuations of the aqueous geochemical data, key physical parameters were monitored from May through August 2002 by electronic sensors linked to digital data loggers. With slight modifications of electronic monitoring protocols used elsewhere in MCNP (Groves et al., 1999) pH,
specific conductance (SpC), temperature and flow rates of both free falling and surface film waters for the shafts were recorded with a fifteen-minute resolution. A CSI CR10X data logger controlled and monitored sensor signals.

The free falling and surface film water within the shafts were monitored for the chemical parameters of pH and SpC values. Physical parameters such as temperature and relative flow rate of incoming water were also monitored. All data values were collected and recorded by the CSI CR10X. Within the 250 mL sample bottle to which the Tygon tubing was directed, a CSI 247-L specific conductance and temperature sensor, along with a pH probe, recorded measurements. Flow rate values were collected by the electronic tipping bucket rain gauge. Each tip of the bucket delivered the equivalent of 1/100th of an inch of water entering the gauge’s opening and subsequently draining through the attached Tygon tubing to the sampling bottle. The data logger reports these flow rate readings as tips/15 minutes.

Every two weeks SpC, temperature, flow rate and pH data were downloaded from the CSI CR10X data logger. The SpC probe was then recalibrated at the field site to ensure minimal shift in the collection of data. This also helped ensure equipment was still monitoring correctly.

The pH probe values were recorded as millivolts within the data logger. These electrical values could be correlated with calibration of pH sample standards of 4.01, 7.00 & 10.00. When tested and graphed in pre-lab testing of pH measurements for this study these correlations provided a near perfect linear fit. A linear regression of the points revealed $r^2$ values of the points were 0.9996. With such high $r^2$ values, the pH electrical millivolt data could be converted to a relevant pH value with use of the equation of a line:
Equation 1 – Line Equation for calculation of pH

\[ y = mx + b \] \hspace{1cm} (1)

Where \( y \) = pH, \( m \) = slope, \( x \) = millivolt reading and \( b \) = y intercept

At the end of each sampling period the pH probe was also recalibrated on site using a 3-point calibration method utilizing 4.01, 7.00 & 10.00 standards as the calibration parameters. The numeric data provided for each of the three parameters would then become the anchor points to which the line equation for the next two weeks data would be based. Therefore, each sampling period required a separate line equation.

**Surface Rainfall Data**

One final parameter of data was required to determine the effect that storm events and/or drier weather patterns would produce on the fluctuations of both free falling and surface film waters. The collection of rainfall data would provide indication of such events. The Science and Resource Management Division at Mammoth Cave National Park continually collect rainfall data with a five minute resolution. Rainfall data are reported with values of mm/5min at the Houchens Meadow air quality monitoring station about 8 km southwest direction from the Edna’s Dome field site. These data were obtained and graphed alongside pH, SpC, flow rate and temperature values providing a direct comparison of an influx of meteoric water to the system to measured water parameters.
CHAPTER 3: RESULTS

Specific Conductance

The table and graph below illustrate Edna’s Dome sampling sites FF (FF – Free Falling) & WW (WW – Wall Water) for SpC values over the four month study period.

SPECIFIC VALUES FOR SpC FROM MAY TO AUGUST 2002

<table>
<thead>
<tr>
<th>SpC Data</th>
<th>FF Site</th>
<th>WW Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.057 ms/cm</td>
<td>0.127 ms/cm</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.204 ms/cm</td>
<td>0.238 ms/cm</td>
</tr>
<tr>
<td>Average</td>
<td>0.164 ms/cm</td>
<td>0.226 ms/cm</td>
</tr>
</tbody>
</table>

Table 1 – FF & WW minimum, maximum and mean SpC values during study period

Figure 6 – Graphed results of SpC values at both WW and FF sampling sites.
Specific Conductance related to this study can be defined as how well water can conduct an electrical current. Conductivity increases due to an increase in the amount and mobility of ions within the water. The ions conduct electricity because they are negatively or positively charged in the water (USGS, 2007). The generations of these ions occur from the breakdown of compounds. One primary source of ions introduced into the cave water system in the Mammoth Cave region (MCR), is the dissolution of limestone (CaCO$_3$). As limestone is dissolved by carbonic acid (H$_2$CO$_3$) the products are Ca$^{2+}$ and HCO$_3^-$ in water. The increase of these ions in turn increases the conductivity of the water. Therefore, specific conductance can be thought of as an indirect measure of dissolved solids. While limestone dissolution is not the only source of ions introduced into the water system of the cave, it contributes greatly to specific conductivity measurements.

Specific conductance is measured using a sensor which measures resistance, or how well something can resist an electrical current. The standard units used in reporting SpC is siemens. Because natural waters are generally much less than one siemen in the MCR, SpC units are reported in millisiemens (ms – 1/1000 siemen) (USGS, 2007).

The following observations were made regarding the data for SpC:

I. At all monitored and sampling periods WW SpC values exceeded the concurrent measurement for FF SpC values.

II. The SpC values drop with similar timing in both the WW and FF sampling sites.

III. The amplitude of the WW SpC line shows a drop in mid-spring, but does decreases in amplitude wane and ultimately shows little to no fluctuation

IV. during precipitation events as time progresses from mid-spring to late summer.
V. The amplitude of the FF SpC line shows a drop that remains similar in behavior throughout the time during seasonal progression.

VI. Over time the general trend of WW SpC values only increases slightly.

VII. Over time the general trend of FF SpC values show a more pronounced increase.

FF SpC values showed the most direct response with storm events in addition to higher flow rates. The minimum FF SpC value occurred just after a late spring storm event on May 17th. Fluctuations of FF SpC values during storm events demonstrated a dramatic shift in values within short periods of time. The largest single drop in a FF SpC was from 0.144 ms/cm to 0.083 ms/cm in a fifteen minute sampling interval. The maximum FF SpC value occurred near the end of the study period in late summer. FF SpC values throughout the study exhibited a pronounced decrease in values during storm events.

WW SpC values also demonstrated the most fluctuations during storm events and increased flow rates. The largest single drop in WW SpC values was from 0.198 ms/cm to 0.150ms/cm in a fifteen minute sampling interval, which also occurred during the storm event on May 17th. The largest maximum SpC data point for the WW site also occurred near the end of the study period with a value of 0.238 ms/cm.

**Flow Rates**

Flow rates during the study were determined via an electronic tipping bucket rain gage, from which water was delivered to the sample bottle recording pH, temperature and SpC measurements. Flow rates at these two locations of cave are directly related to both precipitation events and the storage of water in the vadose zone between the surface and
sampling locations. In general, as more water is introduced into the system, the rate at which water flows into the cave increases, however there are differences in the responses at the two sites, that vary over the spring and summer seasons. This indicates that although the two sites are laterally close to each other in the cave, there are relatively complex differences between the flow paths and storage that create different responses (which vary at different times) at the two sites from the same rainfall inputs.

Flow rates for both WW and FF sites correlated well with precipitation events. The FF site demonstrates a higher sensitivity to fluctuation during storm events than its WW counterpart. The exception to this appears to be in the early data from mid-spring when WW sites showed a greater degree of response than FF sites (See Figure 7).

Response times varied throughout the study period. Both sites were analyzed during storm events. See Table 3 for the breakdown of both sites reaction times.

Flow rate response times to storm events varied throughout the study period. Both sites were evaluated regarding their individual reactions to eight larger storm events over the course of the study. Table 3 provides a list of these storm events and each respective study site times of response. The response times for FF Storm Events #2 & #4 were estimated based on change in SpC levels. Storm Event #2 showed a 23% decrease in SpC levels within one 15-minute sampling period. Storm Event #4 showed a 12% decrease within one 15-minute sampling period.
Figure 7 – Graphed results of flow rates for both WW and FF sampling sites.

Variations in pH

<table>
<thead>
<tr>
<th>Storm Event</th>
<th>Julian Day of Storm</th>
<th>Storm Duration (Hours)</th>
<th>Precipitation Amount (mm)</th>
<th>WW Response Time (hours)</th>
<th>FF Response Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>137</td>
<td>3.2</td>
<td>19.812</td>
<td>3.70</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>137</td>
<td>2.9</td>
<td>28.956</td>
<td>1.70</td>
<td>1.40</td>
</tr>
<tr>
<td>3</td>
<td>163</td>
<td>0.5</td>
<td>19.304</td>
<td>3.40</td>
<td>1.20</td>
</tr>
<tr>
<td>4</td>
<td>164</td>
<td>2.9</td>
<td>23.622</td>
<td>1.75</td>
<td>1.25</td>
</tr>
<tr>
<td>5</td>
<td>190 – 191</td>
<td>3.1</td>
<td>22.606</td>
<td>3.50</td>
<td>0.75</td>
</tr>
<tr>
<td>6</td>
<td>194</td>
<td>3.8</td>
<td>20.066</td>
<td>3.70</td>
<td>3.70.</td>
</tr>
<tr>
<td>7</td>
<td>226</td>
<td>2.3</td>
<td>22.606</td>
<td>Non-Detect</td>
<td>Non-Detect</td>
</tr>
<tr>
<td>8</td>
<td>237 - 238</td>
<td>3.25</td>
<td>26.67</td>
<td>4.25</td>
<td>2.75</td>
</tr>
</tbody>
</table>

Table 2 – Response times for WW & FF sites during storm events
Quantification of pH is essentially the measure of the activity of dissolved hydrogen ions. Water above a pH of seven is reported as basic, while water below a pH of seven is acidic. For water measuring a 7.0, it is said to be neutral. There are a variety of factors that control pH in the MCR. Among the most significant reasons are pollutants in the air that lead to the production of acid rain which reduces pH levels. Typical pH for rain water is approximately 5.5, however, due to gases in the air that react with storm water pH values in the MCR can measure as low as 3.5.

Another major factor in pH readings occurs as water comes in contact with carbonate rock. Hydrogen ions are consumed during the dissolution of limestone. As the activity of hydrogen ions decrease the pH levels increase. Therefore, longer exposure to limestone rock will quickly buffer acidic waters to a more neutral, and in some instances, basic state depending on length of exposure times.

The pH values behaved differently for each site. WW pH values always exceeded the concurrent measurement for the FF site throughout the entire sampling period. In general the WW pH measurements seemed to decrease over the course of the study as the FF pH measurements seemed to increase.

As found in the FF SpC vs. WW SpC values, the FF pH measurements also fluctuated with a greater degree and frequency than WW pH sites. The difference in the maximum and minimum pH values for FF was 0.9 units as compared to the difference of 0.4 units found in the WW samples.

Tables 4 and 5 following give specific values for pH levels recorded over the course of the study. Graph 4 provides a more detailed view of pH levels and fluctuations over the course of the study. The average pH values were calculated by converting pH
into the actual measurements of H+. These H+ values were then averaged and then converted back to pH to provide the most accurate measurements.

**SPECIFIC FF pH VALUES FOR MAY THROUGH AUGUST 2002**

<table>
<thead>
<tr>
<th>pH Data</th>
<th>FF Site</th>
<th>WW Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>6.6007</td>
<td>7.5213</td>
</tr>
<tr>
<td>Maximum</td>
<td>7.5382</td>
<td>7.9848</td>
</tr>
<tr>
<td>Average</td>
<td>7.3356</td>
<td>7.7186</td>
</tr>
</tbody>
</table>

Table 3 – Minimum, maximum & mean pH values over study period

![Figure 8 – Graphed results of pH for both WW and FF sites.](image)
Temperature

SPECIFIC VALUES FOR FF TEMPERATURE FROM MAY TO AUGUST 2002

<table>
<thead>
<tr>
<th>Temperature Data</th>
<th>FF Site</th>
<th>WW Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Value</td>
<td>12.39°C</td>
<td>12.38°C</td>
</tr>
<tr>
<td>Maximum Value</td>
<td>13.34°C</td>
<td>12.68°C</td>
</tr>
<tr>
<td>Average Value</td>
<td>12.51°C</td>
<td>12.52°C</td>
</tr>
</tbody>
</table>

Table 4 – FF minimum, maximum & mean temperature values over study period

Values for FF temperature appeared to be highly variable in the early spring, in response to rain events, but ultimately showed less pronounced fluctuations into summer (Figure 9). The temperature values increased during precipitation events until summer began even though summer precipitation events produced higher flow rates and lower SpC readings. The temperature changes occurring during the spring were directly correlated to storm events. Overall, temperature fluctuations for this parameter were extremely small only resulting in 0.95°C range in the FF site and a range of 0.3°C for the WW site over the 4 month sampling period. Both FF and WW temperature measurements averaged nearly identical at 12.51°C and 12.52°C respectively.

Values for WW temperature demonstrated a very slow increase over the sampling period from May through August. WW temperatures were initially cooler than FF temperatures in the spring; however they shifted to become warmer than FF by early June and remained warmer than FF values for the remainder of the sampling period. The summertime fluctuations of temperature were only on the order of approximately 0.1°C.
Temperatures seemed to overall be fairly well equilibrated by the time they reached the cave system, especially in the summer months.

Figure 9 – Graphed results for temperature at both WW and FF sites.
Figure 10 - Storm event results for WW site over a three day period

Figure 11 - Storm event results for FF site over a three day period
The preceding graphs (Figures 10 and 11) illustrate the variations of monitored parameters for a two storm event over a three day period. The WW graph (Figure 10) indicates the site showed very little change in parameters during the first storm event. These small increase in flow rates, nearly negligible drop in SpC, unchanged temperature and decreases in pH occurred approximately 3.5 hours after precipitation began. As the second wave of precipitation occurred a few hours later the response time decreased at the WW site to 1.75 hours. During this event that occurred just shortly after the first storm the WW site parameters were much more volatile. Flow rates increased ten fold, SpC levels decreased 20% and temperature showed a very small decrease. In this instance however pH levels increased slightly 0.1 unit.

The FF site (Figure 11) demonstrated pronounced differences during each event. SpC levels dropped nearly 30%, pH levels dropped over 0.2 units and flow rates increased 100% during the first storm event. Reaction time to the event was 1.20 hours. Temperature was the only parameter that did not fluctuate near the amount other parameters did. It showed only the slightest increase. During the second storm event all monitored parameters showed large variations. Response time to the second event was nearly the same at 1.25 hours. SpC levels decreased 47%, pH nearly 0.5 units and temperature 0.2°C. Flow rates also increased considerably. The influx of water into the monitoring site flooded the rain gauge to the degree that the gauge was incapable of emptying water as quickly as it was coming in. This yielded spurious data which was removed from the graph. While accurate measurements were not ascertained it is of certainty this second event caused a great increase in flow rates.
CHAPTER 4: DISCUSSION & CONCLUSIONS

Flow Rates and SpC

The SpC rates at the WW site were always higher during both fifteen minute monitoring intervals and bi-weekly sampling. It was hypothesized that the WW site had a greater degree of water to rock contact than the FF site. This is unproven as the outlet for the WW water is only visible approximately 1 meter above the collection site. However, given that data indicate SpC levels are always higher at the WW site it would seem a greater degree of water-rock contact is present along the flow path. This greater contact would have a greater propensity to dissolve limestone and therefore have higher SpC levels than the FF site which by observation has no water-rock contact the last 30 meters before reaching the sampling site.

The behavioral patterns of SpC measurements overall revealed an increasing trend at both sites as the season progressed. One likely explanation may be related to microbial activity within the soil. During the winter and cooler times of the year soil microbes are much less active. As temperature rises, so does the activity of the microbes. These microbes, in turn, will consume more organic material and as a consequence produce more carbon dioxide. As carbon dioxide builds in the soil during the warming in seasonal transitions, water will have the propensity to become more infused with the carbon dioxide. This produces water with a greater ability to dissolve the underlying limestone. As more limestone is dissolved the SpC will increase.

Relating specifically to the WW site, SpC data indicate that it has longer contact with the rock than the FF site. This longer contact provides the WW site opportunity to reach a state that is much closer to equilibrium than the FF site which has less water to
rock contact. Due to this increased contact with the rock over time, the water at the WW site does not show as pronounced increase in SpC levels over time as the FF site.

Both sites exhibited a direct correlation to precipitation events that increased flow rates at each site. The amplitude for the FF site demonstrates that during storm events over the mid-spring to later summer seasonal progression SpC levels show pronounced decreases. The WW site data show SpC levels are impacted primarily in the mid to late spring. As summer ensues and progresses SpC levels do not respond accordingly at the WW site. One possible reason for this lack of SpC fluctuation during seasonal progression lies in the examination of flow rate data. These data show the WW site is hardly impacted during storm events. The FF site continues to show fluctuations in flow rates directly related to storm events. Therefore, the WW site receives a much lesser influx of water related to storm events, the water is not as diluted as the water reaching the FF site during the same periods of precipitation. Since the WW site water has not been influenced by meteoric water the SpC levels remain relatively high and show a less degree of fluctuation.

During storm events both sites initially showed increased flow rates with a minor decrease of SpC values, but after the initial influx of storm water SpC levels show a much more dramatic drop when compared to pre-storm data. One such example is the previously mentioned storm that occurred on June 13 (Julian date 164). This storm increased flow rates at both sites. The WW flow rates increased from 36 tips/min to 141 tips/min. The FF site flow rates increased so great the gauge became flooded and was unable to accurately measure flow rates. While flow rates increased 290% at the WW site and FF flow rates were off the chart, SpC levels dropped only 3% at the WW site.
and 11% at the FF site during the initial surge of storm water. However, 15 minutes after the increased flow rates began, SpC readings had dropped 20% at the WW site from the pre-storm data and the FF site showed a 49% decrease in SpC values from pre-storm data. The relatively minor SpC fluctuations with the initial surge of meteoric waters would seem to indicate the influx of surface water draining into the cave system is pushing stored waters in the feeder tubes for the shaft ahead of it demonstrating a piston-flow component of the hydrology. These stored waters would be much closer to an equilibrium state than water directly occurring during precipitation events due to being in contact with the limestone for longer periods of time. Once these stored waters are pushed out, SpC levels drop dramatically as the precipitation water is rapidly moved through the feeder conduits – resulting in less water to rock and contact and therefore lower SpC levels at both sites.

Response times to storms based on SpC and or flow rate data increase for the FF site over the course of the study. On average late spring response is approximately 1.25 hours while by late summer response time grows to approximately three hours. One reason may lie in the fact that by mid to late summer vegetation is at its peak of moisture absorption and evapotranspiration. Precipitation from storm events occurring during this time may be hindered in its movement to the subsurface strata conduits by soils and plants that are more moisture starved than in spring months.

While FF response times were fairly close in the spring and again more closely aligned during mid to late summer months, WW site response times seemed to vary. During some storms response time was approximately 1 ¾ hours while others were nearly four hours. One conjecture that may be drawn from such large differences in
response time may lie in the timing of storm events. Examination of the data show that when storm events occur within a very short time of each other (i.e. ~ 12 hours) response times at the WW site were much faster than in storm events that were separated by long time intervals. These close storm events may more heavily saturate the soil. This in turn would provide less uptake of water by plants and soil and a greater influx of water into the cave system.

WW site response times did modestly increase as spring turned to mid-late summer with the longest response time occurring during storm events near the end of the study period. However, these changes were much smaller than the FF site, which fluctuated more in every category than the WW site.

One instance, during a storm event occurring on the mid-summer day August 14, (Julian Day 226) neither FF nor WW sites experienced any increase in flow rates or decrease in SpC values. The storm lasted approximately two hours and dropped over 22 mm (0.89 in.) of rain. There are two speculations as to this reason. One is that the last storm event prior to this, producing significant rains, occurred nearly one month earlier. During this time, both soils and plants would become dryer. During the storm event that occurred on August 14 the precipitation would have been readily soaked up by both soils and plants. This would leave only the most minimal waters to making it into the cave system. The second conjecture lies in the location of the rain collection site. Mammoth Cave National Park’s monitoring site is located a few miles straight line distance from the study site. It is possible that the weather monitoring station received an isolated storm on this day while the study site did not.
Temperature values during the course of the study varied little at each site. The WW site varied 0.3 °C and the FF site varied 0.95°C. WW temperatures showed no signs of change during storm events. Instead WW site temperatures showed a slight, yet continual, temperature increase occurring during the change from spring to summer. By the end of the study period in August the rising temperature trend was starting to decrease. It is difficult to extrapolate whether or not this is a cyclic occurrence that occurs during the progressions of the seasons without a longer study period.

The gradual warming of water temperature at the WW site may be directly related to a correlation of cave temperature. Average cave temperature is 12°C. However, even at locations far from entrances cave temperature does fluctuate. The slightly warmer temperatures occur in the summer while the slightly cooler occur in the winter. One site in Mammoth Cave for which data temperature data exists is Wright’s Rotunda. This site is located approximately 2.5 km from the Historic Entrance to Mammoth Cave. Even here, relatively deep into the system, air temperature can vary as much as 0.4°C over the course of the year (Jernigan, 2008). Since the WW water has more continual contact with the cave walls, it is possible it may experience some of the same behavioral patterns of a fluctuating cave temperature.

The FF site showed the greatest amount of temperature fluctuation during late spring storm events. It is perhaps during this time of pre-peak evapotranspiration and also higher soil moisture levels, water entering the cave system may still retain the smallest measure of outside influence related to temperature. In part, this may be due to the degree of vadose saturation in the spring. In general, the spring is among the wettest
seasons for south-central Kentucky resulting in a more saturated vadose. The water received during storm events therefore is not absorbed by the soil. In turn, the speed in which water enters the cave system is faster than in the drier months of summer where much of the water is absorbed in the vadose above the cave system. The faster water enters the cave system from outside, the greater propensity it will have in retaining some of its surficial characteristics such as temperature. However, these fluctuations amounted to less than 1°C. What appears to be the general case is that water has fairly well equilibrated to the cave temperature by the time it reaches the study site, not only for the FF site but also the WW site as average temperatures at both sites only varied by 0.01°C over the four month study.

**Variations in pH**

The pH values at the WW site only varied 0.4 units over the study period while pH values differed by 0.9 units at the FF site. Again the FF site was more responsive for this parameter during the study. FF fluctuations were also more closely related to storm events. Just as SpC values dropped during storm events so did pH values. This is most likely for the same reason – less water to rock contact time inhibits the water from becoming as buffered by the carbonate rock resulting in a lower pH. Data from the Houchens Meadow air quality monitoring station shows average pH of rainwater to be approximately 3.5. The water from storm events appears to have been buffered somewhat as the lowest pH readings at the FF site during precipitation events was 6.6.

WW pH values never dipped below 7.5 over the course of the study. The reason for its lower responsiveness may lie in the characteristics intrinsic to the site. The degree to how long and how much the water being measured at the WW site has contact with the
limestone is unknown. However, it can be deduced through the pH readings gathered over the course of the study that it is quite substantial over the FF site. Concurrent pH levels at the WW site were always higher than those of the FF site. This seems to indicate the water is being buffered better through more continuous contact with carbonate strata. This increased buffering leads to higher pH values at the WW site. By the end of the study the WW site was showing virtually no change in pH values during storm events unlike the FF site.

Just as SpC values for the FF site generally increased over the course of the study, the same trend can be seen regarding pH levels. Mid to late summer months appear to reduce FF’s ability to fluctuate as dramatically as earlier periods in the spring. Flow rates are not as active and SpC values increase as does pH. All of these parameters can be linked once again to soils and plants that retard the movement of water quickly to the subsurface. This slowing of water movement increases the water to rock contact time and ultimately results in the previously aforementioned changes of flow rates, SpC and pH.

**Conclusions**

Although both sites are located within meters of the same aquifer, they experience different behavioral patterns due to storm events and flow paths. Previously conducted dye tracing of the area suggests that the FF site has a smaller drainage basin and is primarily fed by one tributary to a larger encatchment area that directly affects the WW site (Merideth and Talley, 2002). Primarily flow rates and response times of SpC levels to storm events are parameters that demonstrate the highest degrees of fluctuations due to drainage.
Water data of pH, SpC, temperature and flow rates from the two sites provide information regarding the flow path above the shaft outlet. An inference was made that the WW site has continuous water to rock contact and the FF site does not. Visual inspection of the FF site easily determines the water has no rock contact for the last 30 meters before its collection. However, the WW site is only visible as a water outlet less than one meter above the collection site. Data consistently suggest that the water apparently does indeed have a greater degree of water to rock contact when compared to the FF site as the pH and SpC values for the site always revealed a higher concurrent reading.

Overall, FF flow rates were much more responsive to storm inputs. Over the course of the study, the FF site showed a higher degree of variability and response during storm events with regard to flow rates, temperature and SpC values.

WW temperature readings demonstrate an overall (yet small) warming trend during the progression from spring to late summer. This may be a cyclic occurrence based on the shifting of seasons as seen in cave temperature data. A longer study period or one that specifically examines autumn into spring may provide further insight and extrapolation regarding this parameter.

Future study may involve collecting additional water chemistry data pertaining to the quantification of cations and anions. These data combined with temperature, pH and SpC values and existing equations for limestone dissolution may prove useful in the comparing and/or contrasting of limestone dissolution at two different sites within the same area of an aquifer. Longer study periods collecting additional data parameters may
help provide answers to questions involving dissolution kinetics and seasonal behavior of aqueous geochemistry within this shaft area.
References


USGS, 2007. BASIN - City of Boulder/USGS Water Quality Monitoring. [Link](http://bcn.boulder.co.us/basin/data/BACT/info/SC.html)


