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Dye Tracing and the Effects of Infrastructure in Hidden River Cave, Horse Cave, KY

Alexa G. Franks
Fort Hays State University, agfranks@mail.fhsu.edu

DYE TRACING AND THE EFFECTS OF INFRASTRUCTURE IN HIDDEN RIVER CAVE, HORSE CAVE, KY

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by

Alexa G. Franks

B.S. Geosciences, Fort Hays State University

Date 2/2/22 ______________

Approved ______________
Major Professor

Approved ______________
Graduate Dean

This thesis for

the Master of Science Degree

By

Alexa G. Franks

has been approved

Dr. Jeanne L. Sumrall, Committee Chair

Dr. Jonathan Sumrall, Committee Member

Dr. Richard Lisichenko, Committee Member

Chair, Department of Geosciences

ABSTRACT

Hidden River Cave is a stream cave system found in Horse Cave, KY with continuous water flow of its two branches, Wheet River and East River. The infrastructure of the city of Hose Cave, KY was originally designed to utilize natural sinkholes for drainage of all wastewaters. The city uses many of these, now modified, sinkholes for wastewater disposal and storm water drainage. Historically, Hidden River Cave has been severely impacted by unmonitored dumping of contamination. To better understand and identify specific flow paths from sinkholes and infrastructure into Hidden River Cave, this study documented various sinkholes and other infrastructure, such as storm drains, sewer systems, and other undocumented pipes, that could send water from the surface to Hidden River Cave. The study focused on using fluorescent dyes injected into four sites in order to document how the water carrying these dyes moved through the cave system. These dyes were identified using charcoal dye receptors placed at six locations within Hidden River Cave. Additionally, passage cross-sections of two major branches of the cave were measured, while depth and velocity measurements were taken to calculate the discharge of the river in these branches of the cave. Dye trace results identified two flow paths and hypothesized a small groundwater basin based on the detection of various dyes within the cave from multiple injection sites. Discharge results appear to agree with the flow path interpretation derived from the dye traces. The most significant findings of this research include: 1) identifying multiple flow paths from various injection points, 2) determining the relationship between discharge of the Wheet River and East River in Hidden River Cave, and 3) hypothesizing a flow route based on a lack of detection from a previously unidentified injection point. These findings improve the understanding of the relationship between surface water catchment in the city of Horse Cave and the flow into Hidden River Cave.

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INTRODUCTION

CHAPTER I

This chapter describes the history of Hidden River Cave and the history of Horse Cave, KY as a whole. The historical significance of pollution within the cave that has had serious effects on the town's drinking water is highlighted. The information in this chapter describes why this study was conducted.

Underneath the town of Horse Cave, KY, lies Hidden River Cave. Hidden River Cave is managed by the American Cave Museum and the cave can be accessed via a collapsed sinkhole just off of Main St. in Horse Cave. The inside of the cave consists of a network of dendritic streams, canyons, and collapsed domes (Raedts and Smart, 2015). Two main streams are located within the cave: The East River and The South River. The East River is the main waterway within the cave and can be accessed at the entrance near the collapsed sinkhole. The South River is a smaller stream within the cave that has adjoining tributaries known as Kneebuster, Lover's Lane, and Wheet River (Raedts and Smart, 2015).

The development of infrastructure, such as sidewalks and stores along Main Street of Horse Cave, KY, created groundwater contamination that increased in Horse Cave in the 1970s (Osboure, 2018). The injection of pollutants, such as raw sewage, styrofoam, heavy metal waste, creamery waste, and oil refinery waste into sinkholes was a very common practice dating back to when the town was first settled in the 1840s (Quinlan and Rowe, 1977). In 1964, the Horse Cave sewage treatment plant was opened after human and industrial waste was being directly disposed of into sinkholes, however, the treatment plant was disposing of its effluent into a sinkhole until it finally clogged that same year and the waste was then disposed into the South Branch of the

Hidden River Cave system (Feist et. al, 2020). The 1970 opening of the Ken Dec chrome plating plant only increased the waste disposal problem (Manufacturer's News Inc., 1997). This plant was located upstream of the cave but due to the amount of waste being produced, the microbes used in the treatment process were overwhelmed resulting in the sewage being dumped into the already contaminated cave system (Lewis, 1993). One of the most recent examples includes an incident in September 2019 where a man of Horse Cave was charged with violating the Safe Drinking Water Act when his company, Hart Petroleum, injected fluids into a sinkhole that was not permitted (WBKO, 2021). This was not the first time this company was indicted and convicted for violating this act, the first time was in October of 2013. The smell of the contamination of the cave has been described as being an "open sewer" and residents of the town would have to walk on the opposite side of the street from the mouth of the cave (Kambesis, 2007).

The cave has had a long history as a tourist attraction and hydroelectric site, however, Hidden River Cave was used as a dumpsite for raw sewage for decades. In 1987, the American Cave Conservation Association moved its headquarters to Hidden River Cave and the remedial efforts began (Taylor, 1987). A sinkhole located near Lover's Lane tributary and the South River was used as a dumping ground for the sewage and untreated industrial waste from the surrounding community and industry (Raedts and Smart, 2015). This water contamination led to eutrophic, anoxic conditions, and killed cave fauna, making Hidden River Cave and the town of Horse Cave foul (Quinlan and Rowe, 1977). This issue was brought to the attention of the public in 1983 and a regional sanitary sewer system was then established to help with the remedial efforts (Raedts and Smart, 2015). The contamination of water is a karst hazard that presents major challenges for effective monitoring (Gutierrez et al., 2014). The most common method of establishing connections for more accurate monitoring within karst systems involves using dye tracing.

Within the past 20 years, Hidden River Cave has experienced an increase in major flood events. The American Cave Museum and the American Cave Conservation Association has been observing and tracking these events. The floods have been more frequent and more intense which has become a danger to the safety of people who enter the cave (David Foster, personal correspondence, May, 2021). These floods also have a negative economic impact for the American Cave Museum because tours and educational programs are cancelled and cleanup efforts from the flood sediments left behind is messy, time consuming, and potentially dangerous. Climate changes may have a large impact on the increased frequency and intensity of these flood events, however, it is also plausible that the infrastructure of the town of Horse Cave could be affecting the drainage patterns of precipitation runoff. Dye tracing is an important method in determining these drainage patterns to gather a better understanding of flow regime within the major and minor drainage basins that contribute to water levels within the cave.

The use of dye tracing began in 1871 to determine the flow of water and the transportation of solids that are being moved by water flow. Fluorescent dye is added to the upstream sections of the water source being studied. This is known as a flow tracer. The location and path that the dye takes is then traced and analyzed. Fluorescein is a fluorescent dye that was developed to trace the water flow in areas where light could not illuminate the area being studied (Crawford, 1985). Rhodamine WT (RWT), Uranine, Pyranine, and Sulphorhodamine B (SRB) are other fluorescent dyes that are the most effective (Crawford, 1985). The primary purpose of dye tracing in karst systems is to be able to trace the flow of water through a cave system in order to mitigate and prevent polluted water from spreading into a non-polluted area. Dye tracing can identify pathways of waterflow in order to help prevent water pollutants from entering a water supply that is used for drinking, farming, or water management for city use.

Analyses of tracer dye can be either qualitative or quantitative and measured using a fluorometer or rhodamine sensor. Qualitative tracing is a process in dye tracing that is used when there is insufficient water flow through a cave system or karst aquifer. Qualitative methods include visual observation of the dye or absorption of dye to charcoal receptor bags, also called 'bugs' and detectors. Quantitative dye traces involve the calculation of the absorbed dye to water and generally requires more sampling frequency and higher flow rates.

This study aides in understanding the effects that storm drain infrastructure in Horse Cave has on the hydrology of Hidden River Cave by using dyes injected into four storm drains within the city. Geographic information systems (GIS) are used to accurately represent the flow of the dye into the subsurface cave. This study also provides documentation of the connection of the city's storm water system to Hidden River Cave, and how pollution carried to storm drains impact the cave's hydrology and ecosystem.

GEOGRAPHIC AND GEOLOGIC SETTING

CHAPTER II

This section describes the study location and the surrounding Mammoth Cave area both geographically and geologically. A large portion of this chapter covers the climatology of the area and its precipitation due to the recent increase of runoff and flooding in the Horse Cave, KY area. Types of precipitation, land cover, and activities that affect runoff in the area are also discussed.

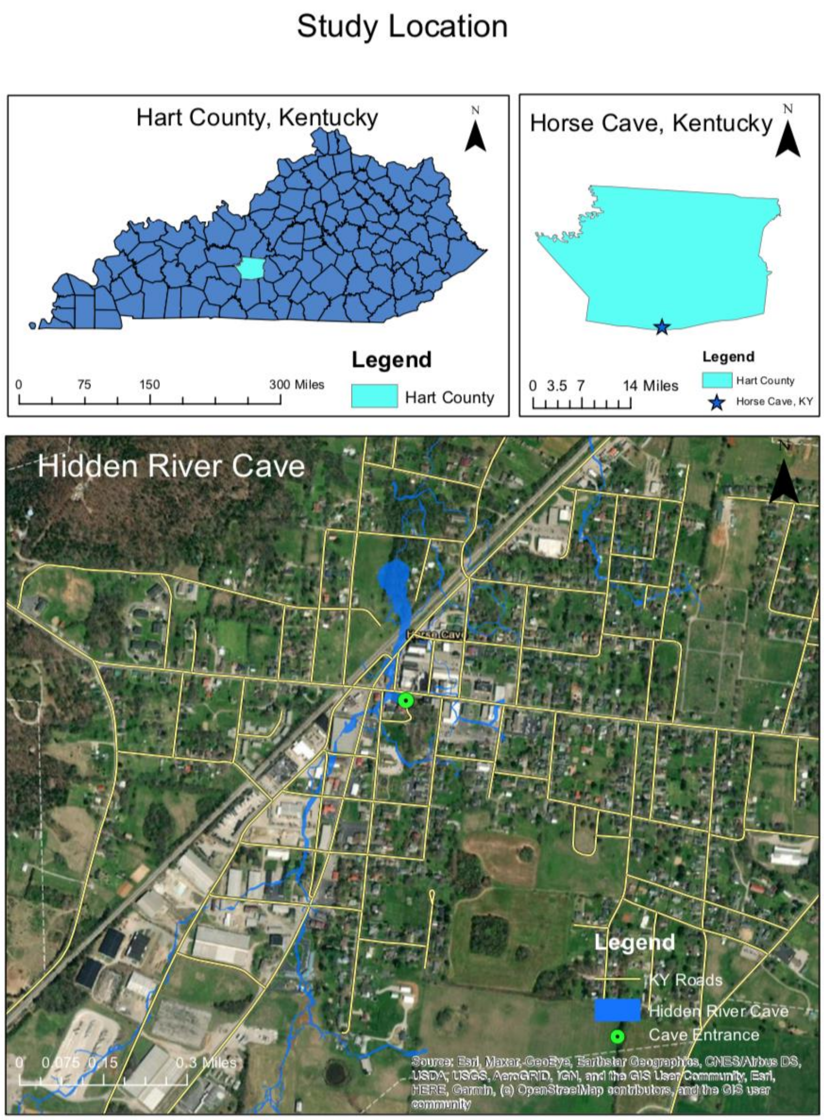

Figure 1: Research Study Location

The Appalachian chain is a Paleozoic megastructure that is located along the eastern part of the North American continent; this feature runs from Newfoundland, Canada to the northeast part of Alabama (Bally and Palmer, 1989). The orogeny consists of sedimentary and volcanic rocks deposited in graben and half-grabens during the early Mesozoic era and the Triassic to Jurassic age (Bally and Palmer, 1989). The sediments deposited in the Triassic to Jurassic ages are the weakly deformed cover of the region and the younger Quaternary age strata is what makes the Atlantic Coastal Plains that create the sinkholes that cover the southeastern region of the United Sates (Pierce, 1965).

The karstic landscape and sinkhole plains can be described as a hydrogeologic terrain with highly interconnected surface water and ground water systems that have one dynamic and single flow system (White, 1993). An indication of the presence of karst is commonly the occurrence of a distinct physiographic feature due to the dissolution of a soluble bedrock such as limestone or dolostone (White, 1988; Ford and Williams, 1989; Field, 2002; Palmer, 2006). A well-developed karst environment, such as the Hidden River groundwater basin, can include identifying karst features such as sinkholes, sinking streams, caves, and karst streams (White, 1988; Ford and Williams, 1989; Palmer, 2006; Taylor and Greene, 2008). Karst also has specific hydrologic features that help to determine its presence. These include: internal drainage of surface runoff through sinkholes, underground diversion or partial subsurface piracy of surface streams, temporary storage of groundwater in a shallow epikarst zone, rapid and turbulent flow through subsurface pipe-like or channel-like conduits, and discharge of subsurface water from conduit by way of perennial springs (White, 1988; Ford and Williams, 1989; Palmer, 2006; Taylor and Greene, 2008).

The topography of this region shows that the Appalachian uplands are generally higher to the northwest and lower toward the Atlantic Ocean to the southeast (Hack, 1980). Continuing into current times, faulting and domal uplift occurs in Appalachia (Brown and Oliver, 1976). These processes have resulted in more than 2,000 meters of rock being eroded from these mountains while the duration of this uplift is not yet even settled (Hack, 1980). Meso-Cenozoic fossils have recently been located in sinkholes on erosional surfaces that are well below present day peaks in the range.

The United States Geological Survey first began surveying these mountains in 1843. This was done by the brothers W.B. Rogers and H.D Rogers. More modern studies of this area have included gathering borehole and geophysical information from the subsurface extension of the Appalachian Mountains that lies underneath the Atlantic Ocean (Higgins and Zietz, 1983; Thomas, 1985; Lefort and Haworth 1984; Thomas et al. 1989, Hutchinson et al, 1988).

2.1 Climatology

2.1.1 Factors of Precipitation

For precipitation to form, there needs to be moisture. Precipitation that falls between the midlatitudes is approximately 25 mm a year (Trenberth and Guillemot 1996). Rainfall is not very efficient because only about 30% of storm-ingested water vapor is converted to precipitation (Fankhauser 1988; Ferrier et al. 1996). The mid-latitude teleconnections can explain a majority of the variability in precipitation events across the Appalachian region, but an onshore flow of atmospheric air from the Gulf of Mexico is more correlated to the seasonal precipitation of the area (Henderson, 2013). Rainfall events west of the Appalachian Mountains are linked to the westerly and south-southwesterly moisture circulations coming from the Mississippi River

Valley and the Gulf of Mexico while rainfall events southeast of the mountains are linked to the southerly to southeasterly moisture circulation from the Atlantic Ocean (Konrad, 1994).

Orographic uplift occurs as air flows over mountain ranges; this holds instabilities in atmospheric air heating (Trenberth, Dai, Rasmussen, Parsons, 2003). This type of lift along a front occurs when the cold air pushes underneath the warmer air, or warm air glides over the colder air, either way causing air to rise (Trenberth, 2003). Orographic precipitation along with the proximity to the Atlantic Ocean allows the southern and southeastern slopes of the Appalachian Mountains to have high frequencies of heavy rainfall, even in the cooler seasons (Konrad, 1994) The other side of the mountain range is slightly sheltered from moisture sources, therefore, resulting in a slightly lower number of heavy rainfall events although similar amounts of total rainfall (Figure 2) (Konrad, 1994).

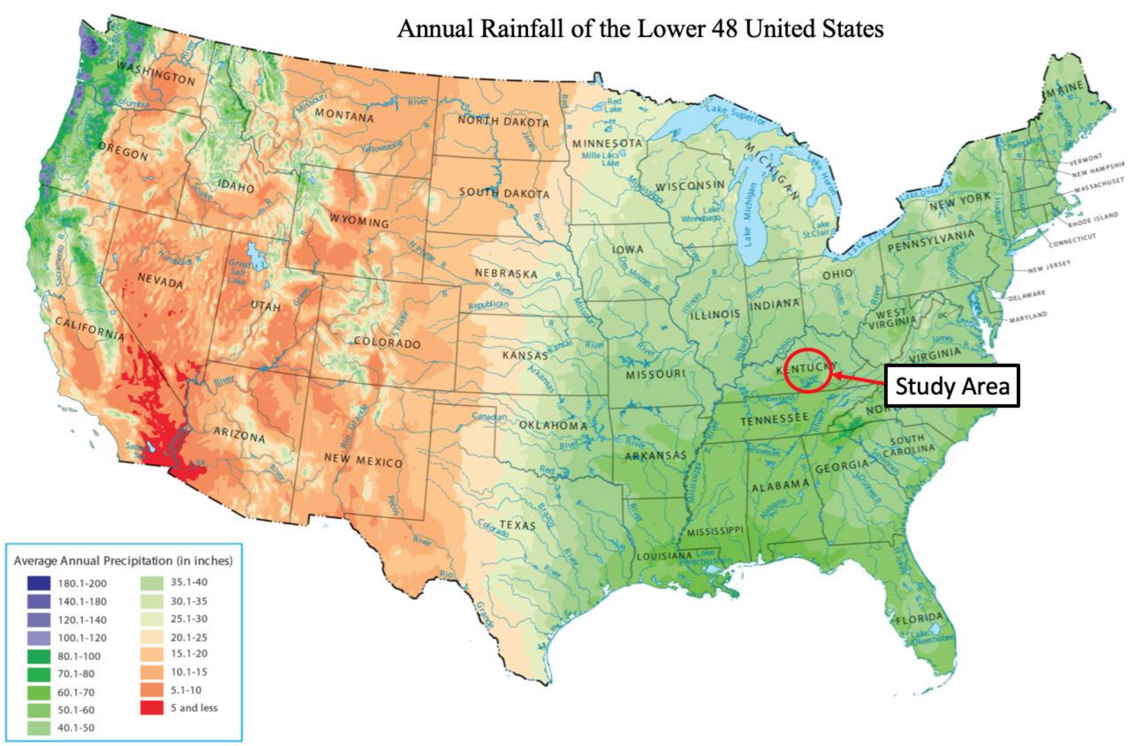

Figure 2: Precipitation patterns of the contiguous United States (Modified from GISGeogrpahy 2021).

2.1.2 Rainfall

Appalachian rainfall events that occur during the warm seasons develop from thermal advection patterns that are categorized by the origin of where said pattern forms (Konrad and Meetenmeyer, 1994). Increasing Appalachian rainfall trends have rainfall events extending from northeastern Texas into the Appalachian Mountains while a weaker trend of the heavy rainfall events in this area was detected along the East Coast; there is potential for this trend to be linked to the migration of the Bermuda High (Keim, 1997).

2.1.3 Spatial Distribution of Rainfall

Rainfall in the southern Appalachian region varies greatly due to the mountainous terrain (Figure 2). The surface winds across this area vary according to the season. Low-level southerly winds form across the southern region and are associated with the synoptic-scale systems that bring the moisture up from the Atlantic Ocean (Gaffin and Hotz, 2000).

During the winter and spring months, the normal precipitation patterns revealed that there is a gradient from southwest North Carolina and Georgia up to western North Carolina and Tennessee (Reitan 1974; Zishka and Smith, 1980). These patterns are linked to the synoptic storm tracks that originate to the west and north of the southern portion of the Appalachian Mountains (Reitan 1974; Zishka and Smith, 1980). These storm tracks normally produce a strong, southerly upslope of wind movement up into the mountains (Gaffin and Hotz, 2000).

The summer months produce a different precipitation pattern. More rainfall occurs at higher elevations in the mountain range than any other season, making this the wettest season in Appalachia (Gaffin and Hotz, 2000). This is due to the fewer synoptic scale systems that are affecting the fins field that acts as a propelling mechanism for thunderstorm development (Gaffin and Hotz, 2000).

The autumn months are the driest months in Appalachia because the high-pressure systems dominate the region and bring in the cool and dry conditions. Autumn is the season with the most potential for precipitation variability and this is due to tropical systems hitting land and brining in large amounts of rainfall in single events (Gaffin and Hotz, 2000).

2.1.4 Rainfall Studies

Appalachian studies have been conducted on heavy precipitation events focusing on identifying synoptic features of these events (Konrad, 1997) and flash flood and heavy rainfall events (Crysler et al. 1980; Guttman and Ezell 1980, and Muller and Maddox 1979; Crysler et al. 1982). A 2014 study concluded that warm rainfall microphysics of the southern Appalachian Mountains results in orographic enhancement through the low-level seeder feeder interactions (Wilson and Barros, 2014). A study conducted in 2015 looked at landform controls on low level moisture convergence on the diurnal cycle of the warm season of orographic rainfall in the Appalachian region and concluded that moisture produced from rainfall events resulted in a moisture convergence pattern that follows the peaks and valleys of the mountainous terrain of the region (Wilson and Barros, 2015). It was also concluded in 2015 that with more heavy rainfall events there is a link to more soil erosion when looking at the measurement of uncertainty in rainfall kinetic energy and intensity relationships of the soil in the southern Appalachian Mountains (Angulo-Martínez and Barros, 2015).

2.1.5 Snowmelt

Snowfall and snow depth are both measured as physical depths of the deposited frozen precipitation, snowfall as the depth of the freshly accumulated precipitation, and snow depth in an area not affected by snow drift (Graybeal and Leathers, 2006). There have been numerous snowmelt events that have resulted in flooding throughout the Appalachian region of the United States (Figure1). The National Climatic Database and Storm Events Database records these events that caused at least $50,000 worth of property damage (Graybeal and Leathers, 2006). In the data collected and observed from these databases, only two floods of this nature were observed in North Carolina while in Pennsylvania a flood of this level occurred every one to two years (Robinson, 2004). While the potential for snowmelt related flooding is very high throughout this region, the historical risk has yet to be given evaluation according to state climate summaries, federal government research, and monitoring protocols (Crockett 1978; LaPenta et al. 1995; Gaffin and Hotz 2000; National Operational Hydrologic Remote Sensing Center 2000).

Between 1996-2006, there were two snowmelt-related 100-year floods that occurred in the Appalachian Mountain region; these events affected Pennsylvania to North Carolina (Graybeal and Leathers, 2006). The flooding event of 1996 was caused by a large midlatitude cyclone that occurred during months when snow already packed the ground. This resulted in a flood from multiple factors such as the frozen ground and soils, unusual amounts of rainfall, melting of snow, rapid melt rate, and winds in a small 24-hour time frame (Leathers et al. 1998). $1.5 billion of damages and 30 deaths were reported from this event (NCDC 1996; Yarnal et al. 1997). Just two years later, in 1998, another major snowmelt occurred. In January of that year, a week-long snow melt occurred in the mountains on the border of Tennessee and North Carolina that was soon followed by a heavy rainfall. This resulted in severe local flooding that resulted in major property damage and loss of life (NCDC, 1998). These studies concluded that when there are mixed-process flood generation mechanisms, in these cases snowmelt and heavy rainfall, there is large potential for extreme flood events to occur in the Appalachian Mountains (Brooks and Thiessen 1937).

2.1.6 Climate Change Effects

There is a consensus among climate experts that as the climate continues to warm, the main change in precipitation will be change in intensity, frequency, and duration of events (Trenberth, 2003). Frequent and abrupt changes in temperature and precipitation is a cause of soil erosion and land degradation (Peizhen et al., 2001; Warrick et al., 2012). The impacts that climate change has on soil erosion has been studied in depth by (Nearing et al., 2005; Poesen et al., 2003) through modeling (Baartman et al., 2012; Favis-Mortlock and Boardman, 1995; Li et al., 2011; van Oost et al., 2000; Williams et al., 1996), laboratory experiments (Berger et al., 2010; el Kateb et al., 2013; Römkens et al., 2002), and field studies (Angel et al., 2005; Baartman et al., 2012; Capra et al., 2009; Hancock and Evans, 2010; Smith and Dragovich, 2008; Wei et al., 2010). The Appalachian Mountain is considered to be one of the most biodiverse regions of the United States due to its topographic diversity, microclimate diversity, and rare habitats (Burke et. al, 2021). Due to the region's mountainous temperate forests and heavy rainfall throughout the year, climate change is causing a slightly warming trend but also is increasing the variability of rainfall (Burke et. al, 2021). The change in variability is causing drier dry years, wetter wet years, and more extreme storms, flooding and landslides (Lasester et. al, 2012). The changes are believed by climatologists to have environmental repercussion such as changes in seasonal patterns of soil and moisture streamflow, changes in forest tree species, changes of animal species, a decrease in the trout population, and an increase change of invasive plant species that enter the region (Gragson et. al, 2008b; Gustafson et. al, 2014).

2.2 Land Cover in Appalachia

Land cover is an important component of such land surface and atmospheric interactions such as evapotranspiration, low-level turbulence, convection, precipitation, infiltration, soil water-holding capacity, and run-off (Eastman, Coughenour, and Pielke 2001; Matthews et al. 2003; Narisma and Pitman 2003; Pitman et al. 2004; Schneider and Eugster 2005; Gero et al. 2006; Adegoke, Pielke, and Carlton 2007; Mahmood, Pielke, and McAlpine 2016; Pielke and Mahmood 2016, Rodgers et al. 2018). Any change in land cover has an effect on albedo, vegetation fraction, radiation, and energy partitioning (Matthews et al. 2003; Narisma and Pitman 2003; Gero et al. 2006; Pielke et al. 2007; Wang, Miao, and Zhang 2015, Rodgers et al. 2018). Land cover change alters tree canopy height which in turn then leads to the potential for the occurrence of eddies, turbulence, moisture, and energy transfer (Narisma and Pitman 2003; Pitman et al. 2004; Gero et al. 2006; Siqueira, Katul, and Porporato 2009; Mahmood, Leeper, and Quintanar 2012, Rodgers et. al. 2018). Land cover also plays a role in the moisture availability in the atmosphere at a certain location. This is done by modification of evapotranspiration which is dependent upon vegetation and its root system (Matthews et al. 2003; Siqueira, Katul, and Porporato 2009, Rodgers et. al. 2018).

2.2.1 Land Cover Study

A study conducted by Loveland and Acevedo in 2012 analyzed land cover change in the United States from 1973 to 2000. This study was aiming to characterize the locations of land cover change, changes in land cover types, the types of changes, the rates of change, and the cause of the change. The United States was split up into “eco regions” and in the eastern United States alone there are 20 different eco-regions; the eastern Kentucky Appalachian region encompasses 3 of these regions. These are the Southwestern Appalachians, the Central Appalachian, and the Western Allegheny Plateau (Rodgers et. al, 2018). Between the years of 1973 and 2000, there was 16% of land cover change in Southwestern Appalachia, 30-57% of land cover change in the Central Appalachian, and the Western Allegheny Plateau’s land change was directly related to mining (Sohl, 2012; Sayler 2012).

2.2.2 Soil Erosion

Soil erosion is known globally to be one of the main causes for land degradation (Luffman, 2015). Up to 10 million hectares of crop land is lost per year due to soil erosion in the Appalachian region (Pimentel, 2006), while soil develops at a rate 10-40 times slower than the degradation. Harvesting crops on the steep slopes of the Appalachian Mountains has also been shown as a link to soil erosion (Kochenderfer el al., 1997). Logging activities in this region during the mid-twentieth century increases mass wasting and soil erosion (Eschner and Patric, 1982; Kochenderfer et al., 1997). When soil erodes away, that means there is less soil to absorb water. This has led to a decrease in soil moisture of up to 300 mm per hectare per year (Pimentel, 2006). Increased soil erosion leads to increased sediment deposition in streams and lakes which is a direct cause of polluted drinking water samples, increased turbidity, and disruption of aquatic ecosystems (O’Geen and Schwankl, 2006; Pimentel, 2000; Robertson et al., 2004). With this sediment accumulating in streams and lakes, there is now less space in those reservoirs for water storage which increases flood risk and the potential for flood damage (Kron, 2005; Plate, 2002).

2.3 Mining in Appalachia

Surface mining in the Appalachian Mountain region has been one of the main forms of industry since the 1930s and uses 1.8 million hectares of land (Demchak, Skousen, and McDonald 2004). The process of surface mining occurs in three different phases; phase one consists of removal of vegetation and upper-level soils, phase two consists of the removal of overbearing rocks before they are returned after mining in the area is completed, and the third phase is when soil is placed back onto the surface and is then seeded (Simmons et. al. 2008).

Mountain top removal, a form of surface mining, gained popularity in Appalachia during the 1970s (Fox 1999). This type of mining requires the removal of up to 500 feet of surface material and then is deposited in nearby valleys, which can affect waterflow of nearby headwaters (Hartman et. al 2005).

A study was conducted by Phillips (2004) to look at the impacts that mountain top removal practices have on flash floods. Because hydrological conditions in the Appalachian region are very unpredictable, the study did not come to a firm conclusion. However, it was observed that in the restoration process of areas where mining occurred, the soil is usually compacted and of poor quality which in turn can lead to no future forest development in said area (Fox 1999; Simmons et al. 2008). For forests in these areas to be restored, it could take up to thirty-five years for the area to return to its native vegetation types (Holl, 2002).

2.4 Flooding in Appalachia

Flash flooding is defined by the National Weather Service as flooding that occurs within six hours of a heavy or excessive rainfall event. Because of Appalachia’s mountainous terrain coupled with availability of precipitation and tendency for heavy rain events, flash flooding remains a constant threat to the people and industry of this region. According to the storm data from the NCDC, a report is taken from every county of the Appalachian region and the effects on these areas that thunderstorms had. Between the years of 1960 and 1999, there were 190 heavy rainfall events that produced at least an inch of water in a one-hour period (Gustoff and Holtz, 2000). The flash flood reports have been drastically increasing and is thought to be due to emphasis by the National Weather Service on accurately reporting these events. Recognizing synoptic patterns that can produce heavy rainfall does not mean that there is a direct relation between heavy rainfall events and flash floods (Brooks and Stensrud, 2000), but the knowledge of frequency and distribution of heavy rainfall with hourly precipitation can help mitigate the potential for a flood occurring.

2.5 Background Geology

During the Mississippian Period (360 to 325 million years ago), Kentucky was completely submerged by a shallow ocean that resulted in thick sequences of limestone deposition (Figure 3) (Livesay, 1953; McGrain, 1962; McGrain, 1983; Palmer, 1989; White, 1988; Ford and Williams, 1989; Palmer, 2006). The limestone formed from the mineral matter and shells that once lived in the ocean covering this area (Livesay, 1953 and McGrain, 1962, White, 1988; Ford and Williams, 1989; Palmer, 2006). The St. Louis Limestone, Ste. Genevieve Limestone, and Paoli Member of the Girkin Formation are the dominant cave forming strata in the region, with minor cave development in the Ste. Genevieve Limestone (Figure 4) (Palmer, 1989). Rivers carried nearby sediments to the Mississippian seas that were then deposited and hardened into the shales and the sand and gravel hardened into the sandstones (Livesay, 1953 and McGrain, 1962, White, 1988; Ford and Williams, 1989; Palmer, 2006). During the

Pennsylvanian Period, crustal movements occurred that caused the seas to move away from this area and resulted in this region warping upwards (Livesay 1953 and McGrain, 1962; Palmer, 1989). Rivers and streams then rose to the surface and began depositing sediments in a delta like formation, resulting in the Cincinnati Arch and the different layers of sediments seen today (Figure 2) (Livesay, 1953 and McGrain, 1962; Palmer, 1989).

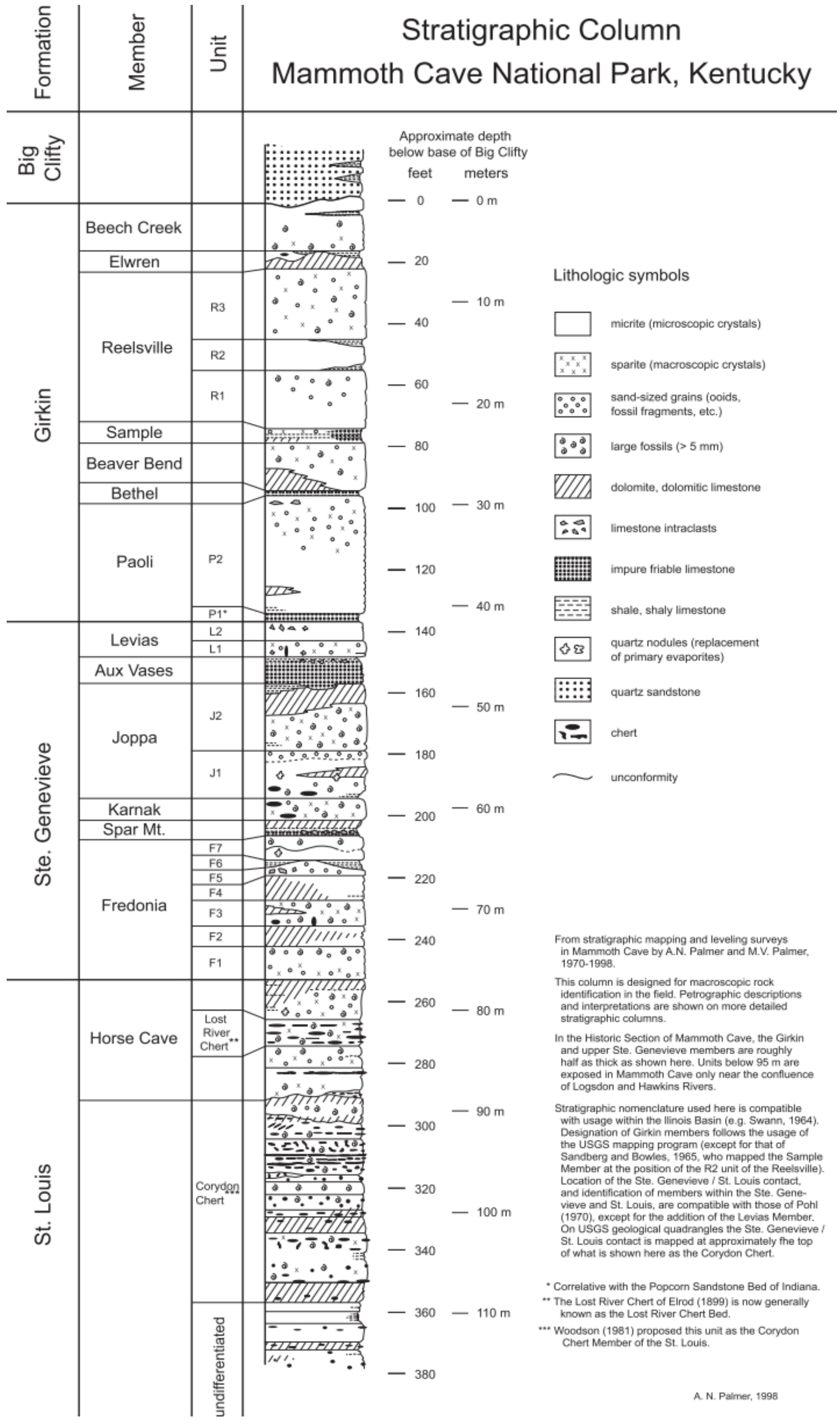

Figure 3: Stratigraphic Column of Mammoth Cave area geology (Modified from Palmer, 1998).

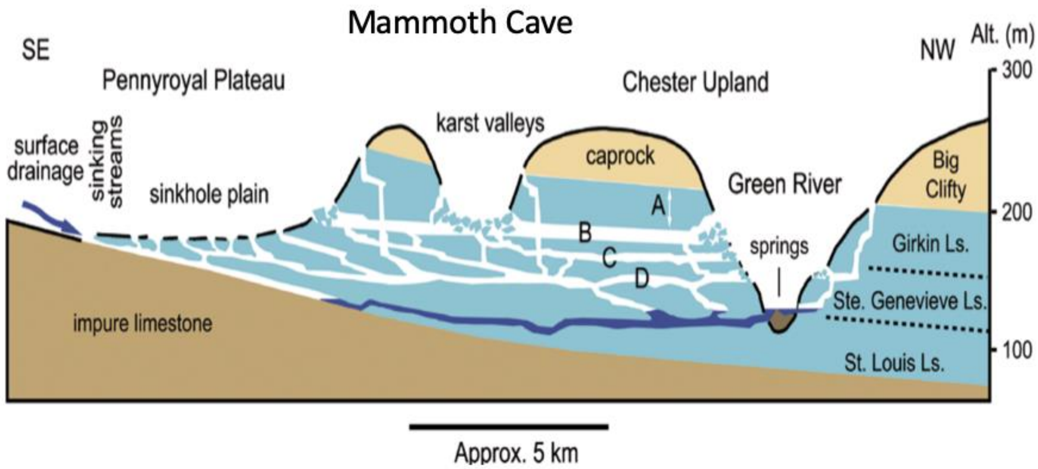

Figure 4: Mammoth Cave Area Hydrologic System (Modifed from Palmer, 2016)

The present landscape seen in western Kentucky was formed mainly by erosion caused by the uplifting events that reactivated the streams in the region that eventually lead to the landscape features seen today (Figure 5) (Livesay, 1953 and McGrain, 1962, White, 1988; Ford and Williams, 1989; Palmer, 2006). Carbonation is a weathering process described as gasses that form the air, such as carbon dioxide, dissolve in the water and then form carbonic acid (Livesay, 1953 and McGrain, 1962, White, 1988; Ford and Williams, 1989; Palmer, 2006). The carbonic acid is able to dissolve limestone in the area very rapidly and water is then able to carry away these dissolved substances resulting in the production of geologic features; caves being the most famous in the region (Livesay, 1953 and McGrain, 1962, White; 1988, Palmer, 1989; Ford and Williams, 1989; Palmer, 2006).

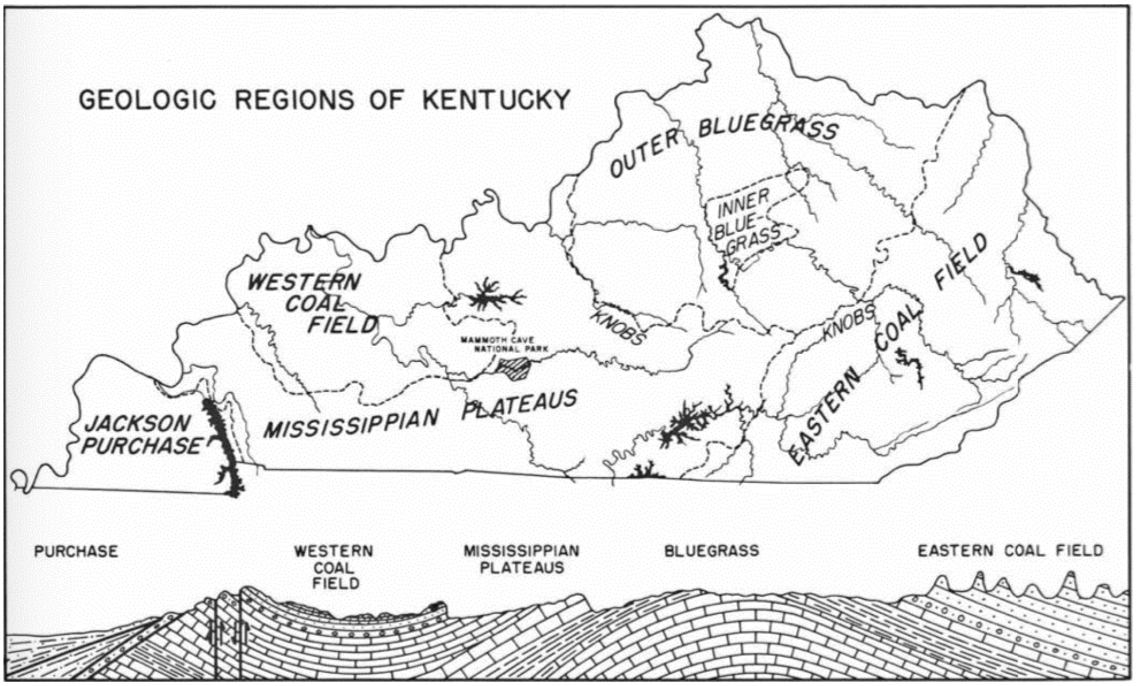

Figure 5: General geology of the regions of Kentucky (Modified from Liversay, 1953; McGrain, 1962).

This region has distinct surface features created from the geology of the subsurface. The solubility of limestone creates pitted depressions across the land surface that are known as sinkholes and are created from the limestone being dissolved away beneath the surface (Livesay, 1953 and McGrain, 1962; Palmer, 1989). The large number of sinkholes present in this region lead to geologists dubbing this area as the Southern Sink Hole Plain (Livesay, 1953 and McGrain, 1962). The landscape feature is known as the Dripping Springs Escarpment and is home to Mammoth Cave National Park and the surrounding cave systems (Figure 6) (Livesay, 1953 and McGrain, 1962).

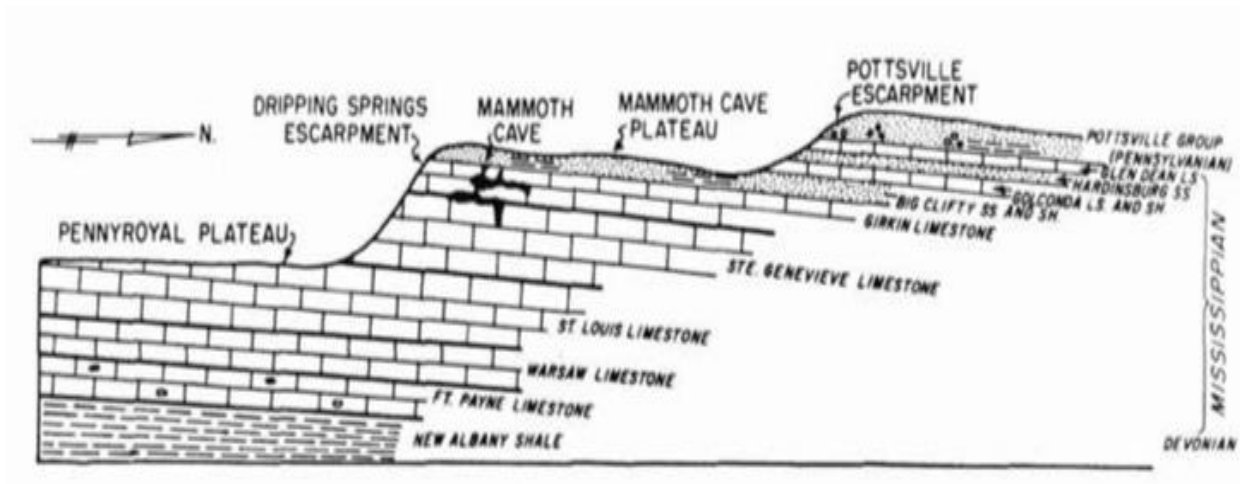

Figure 6: Cross-section of Mammoth Cave geologic area (Modified from Livesay, 1953; McGrain, 1962).

The only major surface rivers in the area are the Green and Nolin River; this is due to the common trend of the rivers entering a sinkhole or a joint in the limestone and them disappearing underground (Livesay, 1953 and McGrain, 1962). These underground streams are what are working to carve out more cave passages in the area (Livesay, 1953 and McGrain, 1962, Palmer, 1989).

The carbonate strata of the Mammoth Cave area are capped by the sandstone and shale of the Big Clifty and Fraileys' members of the Golconda formation (Palmer, 1989; Quinlan and Ewers, 1989) The Lost River Chert bed of the uppermost of the St Louis Formation and the lower most silty shale of the St Louis formation act as local barriers to cave development as well (Palmer, 1989; Quinlan, and Ewers, 1989).

The Chester Cuesta surface, between its escarpment and the Green River, is intercepted by dry valleys that used to be tributaries to the Green River (Quinlan and Ewers, 1989; Palmer, 1989). The morphology of the valleys suggest that they previously extended across the current Sinkhole Plain (Quinlan and Ewers, 1989; Palmer, 1989).

LITERATURE REVIEW

CHAPTER III

This chapter outlines the major literature needed to understand the project, specifically outside of the geographic and geologic background. It also describes karst characteristics and formation, karst recharge and discharge, dye tracing, dye traces done in the Mammoth Cave and surrounding areas, and groundwater pollution history in the area. This section provides an outline for the study and a view into what work has previously been done in the area.

3.1 Origin of Karst

Karst can be described as a hydrogeologic terrain with highly interconnected surface water and ground water systems that have one dynamic, single flow system (See References Therein White, 1988; Ford and Williams, 1989; Palmer, 2006). An indication of the presence of karst is commonly the occurrence of a distinct physiographic feature due to the dissolution of a soluble bedrock; limestone or dolostone (White, 1988; Ford and Williams, 1989; Field, 2002a; Palmer, 2006). Features of a well-developed karst landscape include features such as sinkholes, sinking streams, caves, and karst streams (White, 1988; Ford and Williams, 1989; Palmer, 2006; Taylor and Greene, 2008). Karst also has specific hydrologic features, including: internal drainage of surface runoff through sinkholes, underground diversion or partial subsurface piracy of surface streams, temporary storage of groundwater in a shallow epikarst zone, rapid and turbulent flow through subsurface pipe-like or channel-like conduits, and discharge of subsurface water from conduit by way of perennial springs (White, 1988; Ford and Williams, 1989; Palmer, 2006; Taylor and Greene, 2008).

3.2 Karst Recharge and Discharge

Water enters karst aquifers as recharge by various mechanisms, such as sinkholes, sinking streams, percolation through soil, or direct infiltration on limestone terrain (White, 1988; Ford and Williams, 1989; Palmer, 2006). Recharge in karst aquifers can be classified as two main types: allogenic and autogenic. Allogenic recharge occurs when runoff draining from large areas of soluble rock or low permeability soils flow directly to adjacent soluble bedrock (White, 1988; Ford and Williams, 1989; Palmer, 2000; Palmer, 2006). The recharge going back to the karst aquifer occurs along a sinking stream through infiltration of the surface water thought a porous streambed or fracture (White, 1988). Autogenic recharge comes entirely from rainfall that falls onto the karst area and the runoff of non-karstic rocks. Allogenic drainage from non-karstic rocks are highly aggressive towards carbonate rocks and has varying discharge (Palmer, 2001). Allogenic waters form caves with a more dynamic developmental history compared to autogenic recharge from karst on the surface (Palmer, 2001). Allogenic recharge enlarges cave passages at a faster rate than autogenic water and can also determine the entire pattern of the passage due to the interaction with solution pockets, anastomoses, blind fissures, and mazes (Palmer, 2001). No matter the type of recharge, the growth of a conduit can only increase is discharge increases (Palmer, 2001).

The vadose zone is located above the water table and consists of conduits with free-surface streams like those that occur on the surface and the phreatic zone is located below the water table and contains closed-conduit flow that occurs on gentle gradients (Figure 7) (White, 1988; Ford and Williams, 1989; Palmer, 1991; Palmer, 2006, Audra and Palmer, 2011). Water in the vadose zone moves downward due to the forces of gravity and water in the phreatic zone flows following the most efficient path (White, 1988; Ford and Williams, 1989; Palmer, 1991;

Palmer, 2006, Audra and Palmer, 2011). Cave passages formed in the vadose zone have a downward trend following the steepest available openings and have vertical voids in the rock where water has descended along the fracture; the ideal vadose flow path is vertically downward along a vertical fracture (Palmer, 1991; Palmer, 2006; Audra and Palmer, 2011). At the transition zone of the vadose and phreatic zones, the downward trend moves to a more tubular and fissure passage type, the passage gradient diminishes, and the way water in a vadose formed passage takes the steepest path is no longer the main trend (Palmer, 1972). Phreatic cave passages tend to have downward loops that occur more frequently and deeper within the rock (Audra and Palmer, 2011).

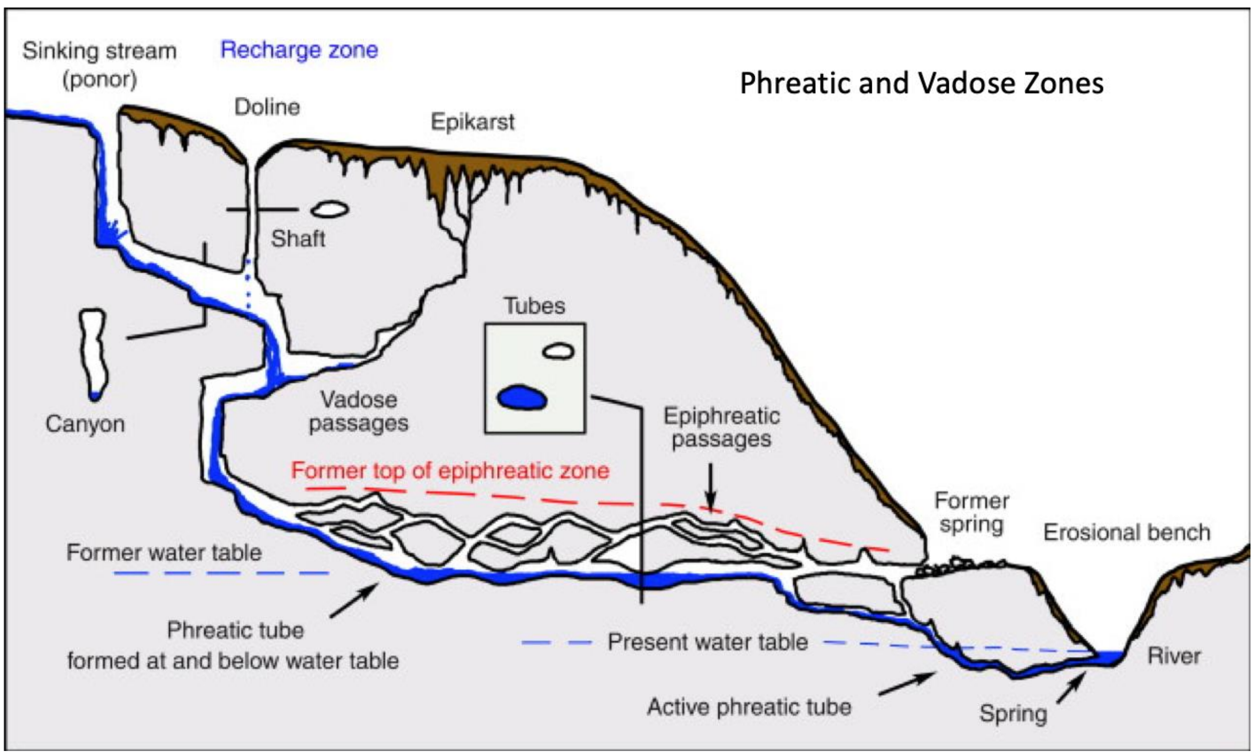

Figure 7: Phreatic and Vadose Zones of a Cave Passage (Modified from Audra and Palmer, 2011).

In a karst system, discharge refers to the volume of water flowing through the system during a given time. In terms of cave hydrology, discharge is often measured similarly to surface waters. Discharge is the volumetric rate of flow of water (volume per unit of time) in an open channel, including any sediment or other solids that may be dissolved or mixed with it that adhere to the Newtonian physics of open-channel hydraulics of water (USGS, 2010). The USGS uses the unit cubic feet per second (cfs) to express their discharge measurements. In order to calculate discharge, stream width, stream depth, and streamflow velocity are all needed variables (Figure 8) (USGS, 2018). Using discharge measurement is a better indicator of the stream or river being measured rather than using gage height measurements (USGS, 2011). Gage height, or stage, is the water height or water elevation at a specific point, not along the entire stream or river (USGS, 2011). A rating curve is often used to correlate stage to discharge to allow discharge to be measure by proxy instead of volumetrically. As long as a cave passage is partially air-filled, it will adhere to the same principles as open channel flow; however, during flooding conditions, the systems shift to phreatic conditions and backflooding may result in epiphreatic development (Palmer, 1989).

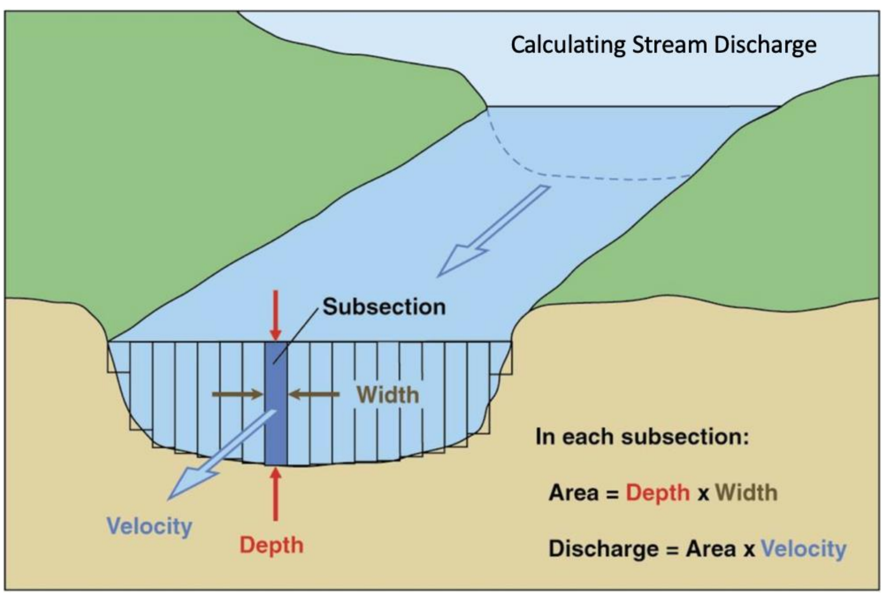

Figure 8: Cross-section of Stream modified from USGS 2018

3.3 History of Karst of the Mammoth Cave Region

Due to the abundance of karst in Kentucky, there are issues that arise as human population and industrialization increases (Randall, 2002). Kentucky karst has been studied in-depth, especially around the Mammoth Cave area (Figure 5) (Livesay, 1953 and McGrain, 1962) for years and has changed the way scientists look at caves (White, 1970). The study of karst aquifers, specifically using dye tracing, are considered to have been perfected in the Central Kentucky sinkhole plains (Thrailkill, 1972). The 1970s and 1980s saw a rise in popularity of cave mapping in Kentucky due to the lack of knowledge of the cave systems; many groups explored the caves in the region, mapping the caves for themselves (Florea, 2002). There was a lack of cooperation throughout the caving community, including a lack of trust causing individuals not wanting to share their data. This led to the delay in utilizing technology such as Geographic Information Systems (GIS) when it came to research. The lack of data sharing and geospatial data availability (such as city and rural infrastructure maps) are some of the largest issues when it comes to mitigating environmental issues in the central Kentucky area (Florea et. al, 2002)

3.4 Dye Tracing

Fluorescent dye tracing helps to study the movement of groundwater (Quinlan, 1977; White, 1988; Palmer, 2006; Crawford Hydrology Lab, 2021). Dye tracing is conducted when a problem of origin, destinations, routing, and velocity of groundwater flow needs to be solved (Quinlan, 1977; White, 1988; Palmer, 2006; CHL, 2021). Dye tracing is also needed to obtain the first information about aquifer monitoring, pollution prevention, and water resource management and or development (Quinlan, 1977; White, 1988; Palmer, 2006; CHL, 2021).

Dye tracing, also referred to as water tracing with fluorescent dyes, is commonly used to establish water fluxes in karst flow environments (Quinlan, 1977; White, 1988; Palmer, 2006; Taylor and Greene, 2008). Dye tracing may determine flow direction, velocity, and other hydraulic features of a conduit in a karst environment that are related to recharge and discharge (Quinlan, 1977; White, 1988; Palmer, 2006; Taylor and Greene, 2008). Dye-tracing of groundwater flow has been deemed one of the most direct forms of study to understand the flow of water (Aley, 1972). These dyes are composed of organic chemicals that absorb ultraviolet light during analysis (Käss, 1998). Smart and Laidlaw (1977) and Field (1995) described an optimal tracer as one that can be introduced into the aquifer with ease, will travel at or near the flow rate of the water, not easily lost through the absorption process, is stable with regard to the chemistry of the water, can be easily detected at a low concentration, and has no long-term threat to humans or animals in regard to toxicity (Quinlan, 1977; White, 1988; Palmer, 2006). Fluorescent dyes fit these characteristics.

The use of passive charcoal receptors in a dye trace is a method used to monitor dye resurgence in a qualitative dye trace (Quinlan, 1977; White, 1988; Palmer, 2006; Quinlan, 1989; Taylor and Greene, 2008). Dye traces done in the 1990s by (Mull and Peck, 1990) used these receptors and these receptors are instructed by the Kentucky Geological Survey to be used in any trace done in the state (Cobb, 2013). The detectors are normally fiberglass screen packets filled with granular activated charcoal. The size, shape, and amount of charcoal inside the fiberglass packet is not critical; however, the detector needs to be durable enough to withstand the water flow and placed in a location where water can flow evenly through the packet (Quinlan, 1977; White, 1988; Palmer, 2006; Taylor and Greene, 2008). The detector is placed and attached to the predetermined location with an anchor system, whether that be wire-and-concrete or wire-andbrick anchor in deep water (Quinlan, 1977; White, 1988; Palmer, 2006; Taylor and Greene, 2008). For shallow water placement, a monofilament line like that sold for fishing tackle is appropriate to use for attachment.

Using charcoal receptors can be an advantage due to their economical availability and the ease that they provide for doing groundwater reconnaissance studies that involve multiple dye insurgent sites (Quinlan, 1977; White, 1988; Palmer, 2006; Taylor and Greene, 2008). In an area where the flow path or basin boundary is relatively unknown, the charcoal receptors are best used because a visual observation of the dye is not needed for this method to be accurate. Receptors are relatively discrete; therefore, the risk of vandalism and interruption of the trace is diminished with their use. The handling, storage, and transportation of the receptors is not critical as long as the procedure to eliminate misidentification and cross contamination is followed (Jones, 1984a). Disadvantages of the charcoal receptor method can include variables in the field changing, differences in the adsorption efficiently into the receptor, and any discrepancy in the lab analysis (Smart and Simpson, 2001, 2002).

Background analysis to evaluate of ambient fluorescence is more important in the charcoal receptor method because the receptors in the field can capture organic molecules that cause complexity of adsorption, accessibility, and composition and duration of flow (Smart and Simpson, 2001). Without background spectrofluorometric analysis, the organic molecules could cause confusion with, or be confused as, dye spectral peaks (Smart, 1998).

The injection of dye occurs as a “slug” of a previously known weight, mass, or volume (Quinlan, 1977; White, 1988; Palmer, 2006; Taylor and Greene, 2008). An insufficient amount of dye injected will result in an inconclusive dye trace. Too high of dye concentrations result in over saturation causing inconclusive results as well. The subsurface flow of water and its route is not always predictable; therefore, the concentration of dye may need to be adjusted for the area of injection. The amount of dye needed is usually based on the distance the dye is expected to travel, the volume of water in the aquifer, and the anticipated resurgence point (Quinlan, 1977; White, 1988; Palmer, 2006; Taylor and Greene, 2008). Dye injection is most successful at a location where the tracer can have a rapid and direct transport through the conduit to reduce the chance of losing dye (Quinlan, 1977; White, 1988; Palmer, 2006; Taylor and Greene, 2008). If there is a lack of naturally occurring water flow, water can be injected from a tanker truck, large carboy, or fire hose to help flush the dye into the karst system.

There are multiple ways to monitor and analyze for tracer dye; this includes visual observation, fluorometric analysis obtained from granular activated charcoal, and in-situ, continuous-flow fluorometry (Taylor and Greene, 2008). Fluorometric analysis is conducted by measuring the fluorescent intensity of a water sample (Duley, 1986). A range of light wavelengths is used to “excite” the sample and then the wavelength fluorescent intensity is measured on the emission spectrum (Käss, 1998).

Dye tracing has a rich history in karst environments, but it also has utility in other surface and groundwater systems. For example, a study by the USGS using dye tracing on the Kansas River was conducted to trace the rate that water flows through the Kansas River in order to be prepared for any future contamination events that could affect the safety of the river for drinking or recreational activities (USGS, 2021). Another USGS dye trace study was conducted on the Kootenai River by USGS scientists in Bonners Ferry, ID (USGS 2017), to help protect the native fish species and aid them in natural reproduction in their native river. Additionally, (Wilson and Rankl, 1994) conducted a study using dye tracing was conducted to help determine the time of travel, dispersion, and dilution capacity of water sources within the state of Wyoming from 1967-1994.

3.4.1 Dye Tracing in Hidden River Cave and Surrounding Area

Historically water pollution in the Hidden River Cave is very high; therefore, proper control of substances is needed. Surface water can easily enter the subsurface of a karst system which makes a karst environment so susceptible to contamination; this is especially the case due to the 45% of Kentucky land being a karst environment (Mahler et al., 1999; Ford and Williams, 2007; Raedts and Smart, 2015). The people of Horse Cave have depended on the stream that runs through Hidden River Cave as a source of water beginning in 1887 (Lewis, 1993) A drought occurred in 1930 that only intensified the town's dependence on this stream (Lewis, 1993). Industry and population began to increase in the town in the 1930s which in turn created the action of disposing of human usage and industrial waste directly into sinkholes (Lewis, 1993). Any community that relies on water that passes through a karstic system for potable water, such as the city of Horse Cavy, KY has a need for concern of contamination (Feist, et. al, 2020) This is where dye-tracing can come into play and be extremely helpful. The more mature a karst system is, the higher the transport rate is due to the wider or well-developed cave passage (Hess and White, 1989). An injection of sewage effluent, very heavy-metal-rich, occurred in Horse Cave, KY. This became an issue and sparked a long-term study of heavy metals in springs, wells, cave streams, and the Green River area (Quinlan and Rowe, 1977). The prediction that there is a cave system behind Hicks Spring and its accompanying tributary waters occurred because of chemistry predictions from the waters mentioned above (Quinlan et al., 1977). Tracking contaminants through these passages is the method of treating the water quality issue of Hidden

River Cave. The regional groundwater flow pathways were originally mapped using dye tracing by Quinlan and Jay in 1981 (Figure 9).

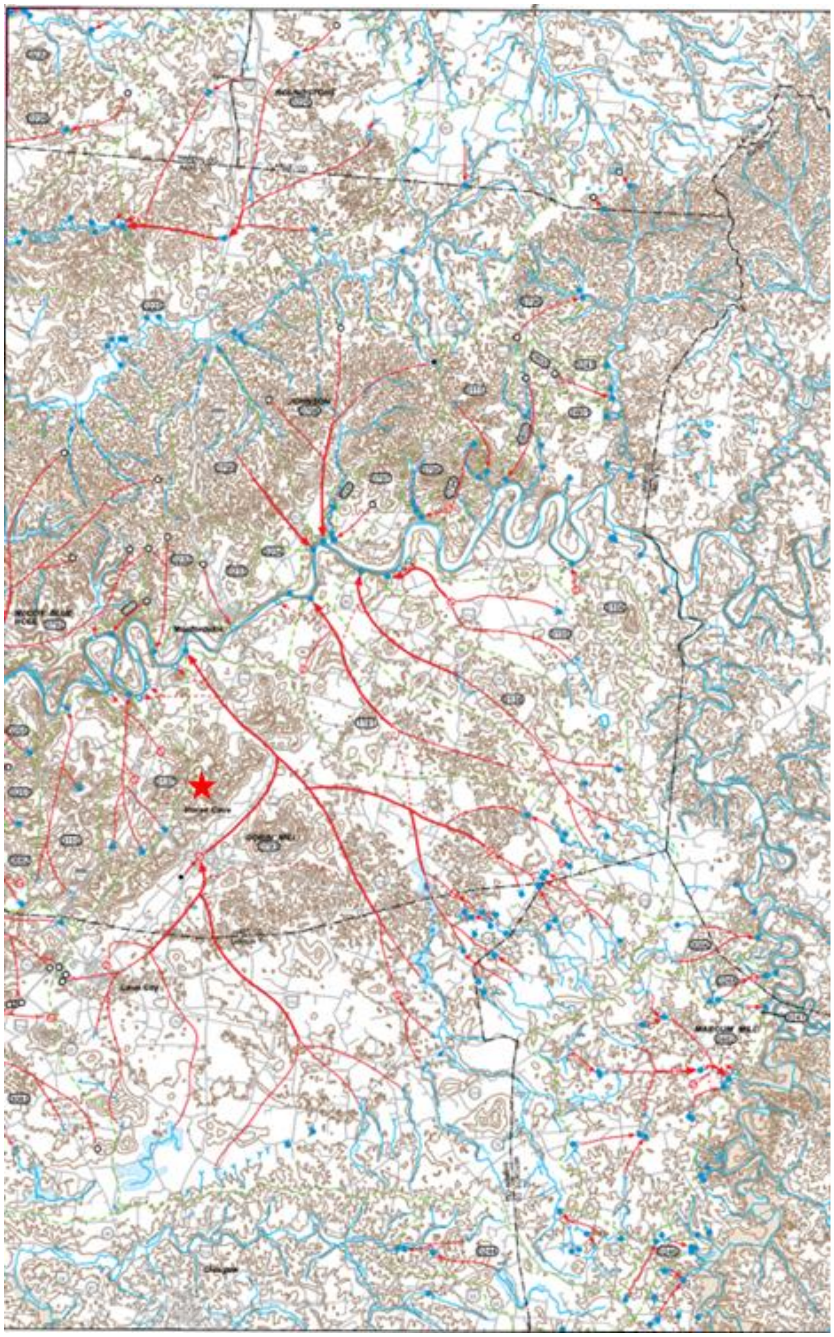

Figure 9: Dye traces conducted in Mammoth Cave Area by Quinlan and Jay, 1981. (Modified from the Kentucky Geological Survey.)

One of the most successful groundwater analyses was completed by Quinlan and Rowe in 1977. This study led to the discovery that groundwater was being contaminated in the Hicks-Hidden River Cave System located in the Gorin Mill (Bear Wallow) groundwater basin that lies within the Graham Springs Groundwater Basin. Human actions were concluded as being the cause of contamination.

Cave mapping and potentiometric surface mapping were used to locate groundwater dives for the groundwater trace study of the Green River area; these were then verified by the dye tracing process (Quinlan and Ewers, 1989). Fluorescein, Rhodamine WT, CL Direct Yellow 96, and Optical Brighteners were the dyes used in the groundwater trace. Cave radios, or magnetic induction equipment, transmit a low-frequency signal from a cave passage filled with either air or water, and these were used to help locate observation sites or to build cave entrances in other instances (Quinlan and Ewers, 1989). Although extensive dye tracing of the Green River area has been done, only 70% of dye tracing north of the Green River is complete (Quinlan and Ewers, 1989).

3.4.2 Subsurface Drainage in Mammoth Cave Area

Research of the surface drainage in the Mammoth Cave area began in 1973 by Quinlan and Rowe as described by (Crawford, 1985; 1986); this was long after most of the geologic and hydrologic research of this famous area had been published. The area of Mammoth Cave and the Lost River groundwater basin is one of the most studied areas of the country when it comes to cave mapping, dye tracing, potentiometric surface mapping, and water quality monitoring (Crawford, 1985; 1986). This is mainly since the data collected in this area is relevant to many and the area provides the ability for data to be easily generated (Quinlan and Ewers, 1989).

Between the years of 1975-1987, there were 500 dye traces ran in this area; 100 were done north of the Green River; and up to nine traces were done at one time in different drainage basins. In the Mammoth Cave area, dye tracing, drafting, and data reduction are done in the rainy season, and potentiometric surface mapping is done in the dry season (Quinlan and Ewers, 1989).

When carbonate rock is above the water table, water moves vertically until it is interrupted by a cave system where water flow is horizontal; this occurs in the conduits, convergent, uppermost fringe of the phreatic zone, and to springs that drain a groundwater basin (Quinlan and Ewers, 1989; Palmer, 1989). Conduit system flow is described by both pipe and channel flow equations; both flow types are fed by tributaries and diffused flow through the surrounding bedrock or sediment, and both are characterized by rapid, turbulent flow for most of the system length (Quinlan and Ewers, 1989; Palmer, 1989). Discharge points of a karst terrain groundwater basin will usually be a spring at the base level or a fault; if the base level is lowered then the spring will continue to move to lower elevations (Quinlan and Ewers, 1989; Palmer, 1989).

According to hydrodynamic and geochemical models, the tributary pattern of the cave should eventually lead to a distributary passage. The cause of distributary passages can be due to the following; enlargement of small and pre-existing anastomoses between floodwater filled passages, collapse and blockage of a spring which causes the development of a discharge route, diversion of cave streams to lower routes, enlargement of vadose conduits that intersect the anastomoses and other passages in response to a change in stage of a river, and pollutants at a point source in the headwaters of a groundwater basin or sub-basin (Quinlan and Ewers, 1989; Palmer, 1989).

3.4.3 Groundwater Basins in Mammoth Cave and Horse Cave Area

Surface water will always flow in a distinguished surface water basin; however, groundwater flow is not as easily recognized when it comes to what groundwater basin it is flowing in (Thailkill, 1985). Groundwater within a groundwater basin normally flows where the basin is divided and is adjacent to the surface water basin so they do not interfere with one another (Quinlan and Ewers, 1989). A typical groundwater basin in a mature karst environment consists of inputs from sinking streams and water in soil from an epikarstic zone, tributary conduits, and a point of discharge in the form of spring or group of springs Williams, 1983). For example, in the Mammoth Cave area, groundwater basins normally discharge at a base-level stream by a singular or a group of streams (Quinlan and Ewers, 1989; Palmer, 1989). These steams and springs are fed from the flow by a dendritic system which should cause some seepage discharge to be present at the rivers, however, none has yet been detected (Quinlan and Ewers, 1989; Palmer, 1989). Both seepage discharge and recharge occur contiguously to the surface streams of the Glasgow Upland and Sinkhole Plain (Quinlan and Ewers, 1989; Palmer, 1989).

The Turnhole Spring groundwater basin, along with its accompanying Echo River, Pike Spring, and Sand Cave groundwater basins all have water discharge at moderate and flow flood conditions (Quinlan and Ewers, 1989). These are all in the most hydrologically studied range in the Park area. In the Turnhole Spring groundwater basin, Parker cave is one of the most significant features. This cave is located one mile southwest of Park City; the flow velocity between Parker Cave and the Mill Hole range from 0.25 cm/sec at base flow to 12.7 cm/sec during flood flow; this cave included 5 subparallel, trellis steams that are about 150 meters apart; and has been studied in detail about its clastic sediment and its relation to the development of surface and subsurface drainage within the basin (Quinlan and Ewers, 1989). Interpretation from the data collected indicates how intermediate flow over route water can be rerouted from one groundwater basin into a different one (Quinlan and Ewers, 1989).

The Bear Wallow (Gorin Mill) groundwater basin is the largest groundwater basin in the Mammoth Cave area; about 500km^2 in size (Quinlan and Ewers, 1989). This basin's significant features consist of the Hidden River groundwater sub basin and the Horse Cave system, the shared headwaters, and distributaries (Quinlan and Ewers, 1989) The Horse Cave Sewage Treatment Plant has been discharging heavy-metal effluent into the ground for almost 20 years; this still continues today but the effluent concentrations are now at a permissible level; 10 mg/l of chromium (Quinlan and Ewers, 1989). Studies of this environmental issue have shown that the discharged effluent travels as far as 1.6 km NE to the Hidden River Cave, 6-8 km north of the sewage treatment plant where it is then discharged at up to 46 springs into the Green River (Quinlan and Ewers, 1989). Analysis of the Hicks Springs water chemistry led to the excavation at one of the high-level orifices that then generated the discovery of more than 32 km of new cave passages in the Hidden River Complex (Quinlan and Ewers, 1989). Water flow at Hidden River Cave is only 25% of the base flow discharge of the surrounding springs (Quinlan and Ewers, 1989). These springs, located and determined by dye tracing, are the only reliable source for monitoring spills or pollutants due to their drilled well (Quinlan and Ewers, 1989).

The Graham Springs groundwater basin is a group of four springs that is also known as Plum Springs. The two easternmost springs of the basin are high level overflow routes that do not discharge during base flow conditions (Quinlan and Ewers, 1989). During the construction of the Northside Water District, there was a spring, later named Waterworks Spring that was discovered beneath the construction site. With the knowledge of this spring's location, it was decided to use this water and treat it for human use and consumption, resulting in one million gallons of treated spring water daily (Quinlan and Ewers, 1989). The Waterworks groundwater basin is not well understood, but the perennial springs within the basin have been monitored (Quinlan and Ewers, 1989). It is thought that the springs within the Waterworks basin could be in existence because of fracture permeability of the laying of Lost River chert that is directly above it (Quinlan and Ewers, 1989). This chert prevents soil from being flushed into the subsurface which causes the turbidity of the spring in the basin to be lower than other springs in the surrounding area (Quinlan and Ewers, 1989).

The Graham Springs and Bear Wallow basin are the largest in size; both of their ancestral springs were formed first and the springs in both basins today are at a lower point than the earliest breaching possible (Quinlan and Ewers, 1989). The Bear Wallow basin springs are located farther upstream while the Graham Springs basin has no comparable ancestral spring (Quinlan and Ewers, 1989). The extension of the Bear Wallow basin upstream from the Garvin-Beave and Lawler basin is what gives it the inverted mushroom shape; this is also caused by groundwater flow of the area and erosion processes (Quinlan and Ewers, 1989). The Cedar Springs Valley is the largest and deepest, which is what increases the feasibility of inputs being located closer to the spring than in other valleys and nearby basins (Quinlan and Ewers, 1989).

3.5 Groundwater Basin Evolution in the Mammoth Cave and Hidden River Area

In the Mammoth Cave area and south of the Green River, there are 27 recognized groundwater basins and additional sub basins that discharge at springs on the Green River, Barren River, and Little Barren River (Quinlan and Ewers, 1989; Palmer, 1989). The 27 groundwater basins were delineated by the process of dye tracing that resulted in a range of shapes that make them unique. Turnhole Spring and Bear Wallow groundwater basin have the shape of an “inverted asymmetric mushroom” that are near the Green River while the other basins are narrower and have more of a pear shape (Quinlan and Ewers, 1989; Palmer, 1989).

Karst aquifers must form in a topographic setting where meteoric water or allogenic surface runoff can access soluble rock and has the ability for fluid potential to be achieved (Quinlan and Ewers, 1989; Palmer, 1989). The Green River and Barren River have geological structure and stratigraphy that alludes to an opening in the limestone for karstification to occur (Quinlan and Ewers, 1989; Palmer, 1989). There is unique porosity that occurs at the eastern margin of the Green River and the western margin of the Barren River. The two rivers’ discharge areas generate a strong solution porosity; however, the solution porosity that occurs in the center of the exposed limestone belt is very slow and sluggish (Quinlan and Ewers, 1989; Palmer, 1989). The porosity drainage moves headward, leading to the creation of two main drainage basins. The porosity and permeability of the limestone is modified by dissolution a short way into the rock, and voids form only near discharge points (Quinlan and Ewers, 1989; Palmer 1989). Springs are far more prevalent in areas where limestone has been breached, leading to a small discharge and a smaller recharge area (Quinlan and Ewers, 1989; Palmer, 1989). A spring has formed at the bottom of a tributary and has been deemed unimportant because it is fed by shallow and weak water circulation (Quinlan and Ewers, 1989; Palmer, 1989).

3.6 Karst Recharge

Karst recharge can be defined as water flow that penetrates the vadose zone and that is not released into the atmosphere by evapotranspiration (Livesay, 1953; McGrain 1962; Palmer, 1989; Olliver, 2020). Karst environments are different than other geological environments for the fact that they can have multiple sources of recharge that can all vary in their water residence time and the amount of water they contribute to the conduit network (Taylor and Greene, 2008). Karst recharge sources can be either concentrated or diffuse, and either autogenic or allogenic; this depends on if the recharge originates as precipitation on karstic or non-karstic environments (Gunn, 1983). The characterization of the type of recharge is important because that can determine the distribution and connection of conduits in a karst environment while the timing and contribution of water fluxes, whether that be from allogenic and autogenic, will affect spring discharge and water chemistry (Ford and Williams, 1989).

Potentiometric high and the topography with the highest recharge areas are both related to structural high (Quinlan and Ewers, 1989). An example would be the potentiometric slope of Park City, KY; the groundwater south of Park City lies on a silt and shale sediment bed in the lower part of the St. Louis Formation which causes water to "cascade" down the "steep" slope (Quinlan and Ewers, 1989). Maximum flow data was interpreted using a potentiometric map and it was shown that the flow coincides with large caves that have underground rivers, such as Horse Cave, KY (Quinlan and Ewers, 1989).

3.7 Groundwater Pollution in Mammoth Cave Region

Groundwater pollution in the Mammoth Cave Region is problematic for many reasons; however, due to high flow rates found in this karst region, polluted waters move faster from their source when compared to non-karst aquifers. The flow rate in the area moves up to six times faster than it does through other rocks and because 55% of Kentucky's underground is karstified limestone, pollution can travel very quickly (Quinlan, 1977). The city of Horse Cave used the water from Hidden River Cave for their city use until 1912 (Quinlan, 1977). The water usage was changed to a well because typhoid fever began running rampant through the citizens around the area, mainly resulting from consuming water carrying human waste (Rowe, 1977). Today, water to the city and surrounding area comes from the Green River Valley Water District, which was built on the north side of the Green River (Quinlan, 1977). Before the water treatment plant was built, the residents disposed of their waste and sewage directly into wells or sinkholes, polluting the karst streams flowing through the caves of the region (Rowe, 1977).

3.8 Geographic Information Systems (GIS) in Kentucky

Landscape in Kentucky is a major part of the state's geology with almost 55% of the state made of karstic limestone (Florea, 2002). The coal fields of eastern and western Kentucky are also an influential role in the topography of the state. Because there are so many varying hydrological conditions, the cave systems in the state can offer unique characteristics (Florea, 2002). A growing population in the area also means that there is a growing environmental impact on the land along with the lack of knowledge of the karst environment beneath the ground (Florea, 2002).

GIS is increasing in importance when it comes to karst environments in the state of Kentucky. The Kentucky Geological Survey and the Office of Geographic Information has developed databases of GIS data (Florea, 2002). The Kentucky Geological Survey began creating an atlas of karst for the state in 1996. With the increase is GIS data of the area, the karst data that is available has increased and is only helping the cause of planning and mitigating environmental factors that affect the surrounding areas (Randall, 2002). GIS projects in the central Kentucky area have consisted of groundwater dye tracing, cave entrance mapping, georeferencing of the area, and sinkhole digitization (Florea, 2002).

METHODS

CHAPTER IV

This chapter describes the methods and techniques used in conducting a dye trace in Horse Cave, KY and collecting discharge measurements within the cave. The chapter starts by describing the historical records of infrastructure in Horse Cave, KY and then describes the methods of using GPS to create more accurate records of the storm drain infrastructure in the town. The chapter then describes what materials and processes are needed in order to conduct a proper dye trace. The method to collect discharge measurements inside a cave is described along with cross-sections of the rivers within the cave.

4.1 Historical Records

Historical records from the city of Horse Cave, KY were examined to determine the location of storm drains (See Appendix A). The quality and antiquated nature of these records required ground surveying to be conducted. The locations of these features throughout the city were measured using a Garmin® eTrex 10 handheld GPS unit with a spatial accuracy of +/- 7 feet (Figure 10). This study utilized ArcMap 10.6 GIS software towards generating maps and representing GPS acquired locations.

4.2 Injection Site Location and GPS Data Collection

Five locations were determined in Horse Cave, KY as injection sites for the dye trace. These sites were determined by walking the town and marking the location of each storm drain using a GPS. 22 possible injections sites and 69 additional storm drain locations were identified by ground truthing. These GPS points were then uploaded into GIS to create a shapefile and then overlaid on an aerial map of the town and cave. The shapefile was created using ArcMap, where the GIS point data representing the GPS identified locations was created. This allowed for the storm drains to be visible in a way that the water drainage direction could be determined in relation to Hidden River Cave. The storm drains selected were in locations that are believed to flow into the cave from different directions and believed would be detected at receptors placed throughout the cave. (Figures 11, 12, and 13).

Figure 10: Ground truthing in Horse Cave, KY. A. Sinkhole located in the industrial section of town. B. Garmin® eTrex handheld device recording location at cave entrance. C. Sinkhole located on the edge of town. D. Storm drain in town. E. Train tracks separating the side of the town with infrastructure from the side lacking infrastructure. F. Well pipe that was drilled into Horse Cave. G. Major sinkhole on the edge of the industrial section of town.

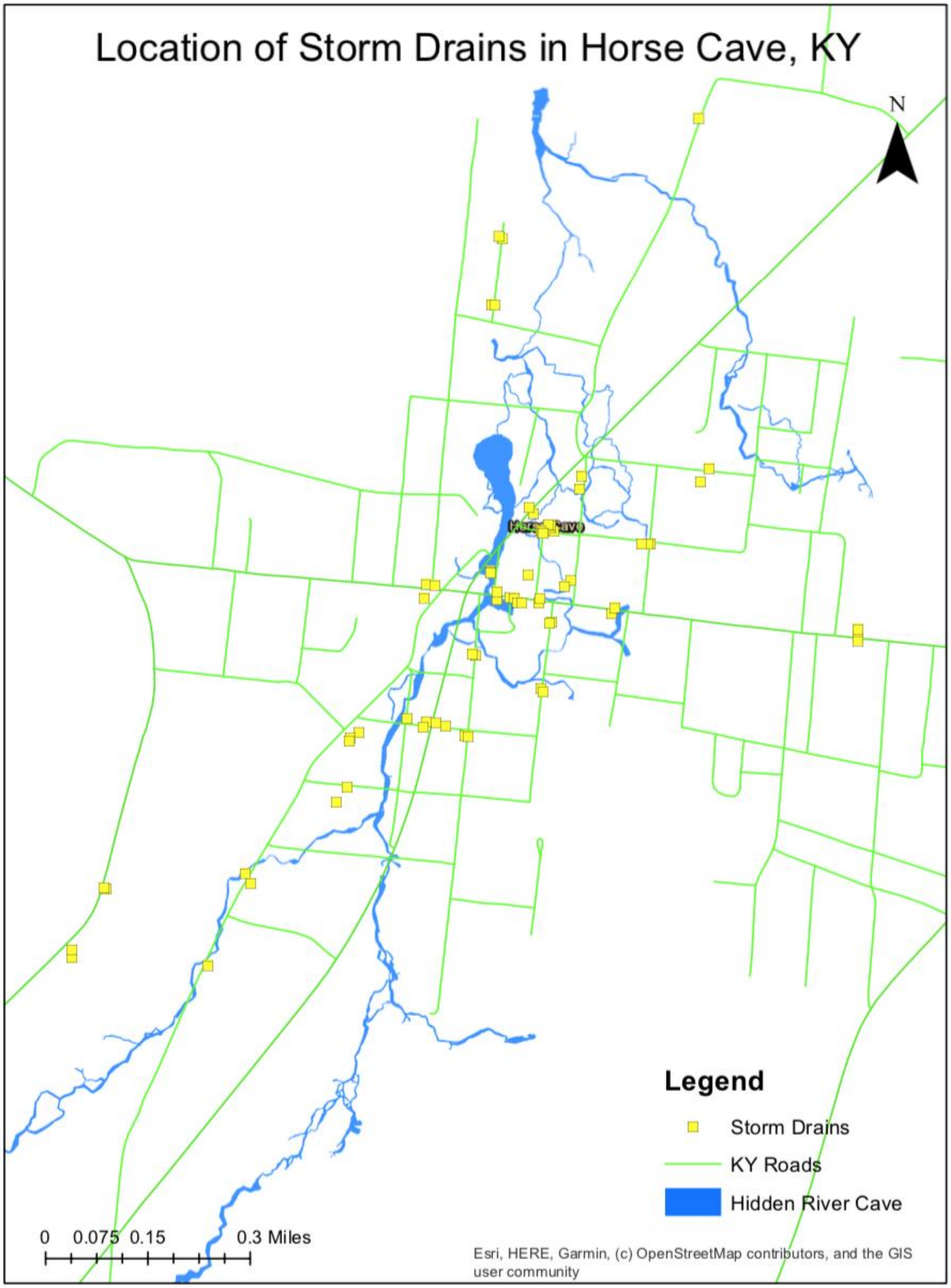

Figure 11: Storm Drain Locations in Horse Cave, KY.

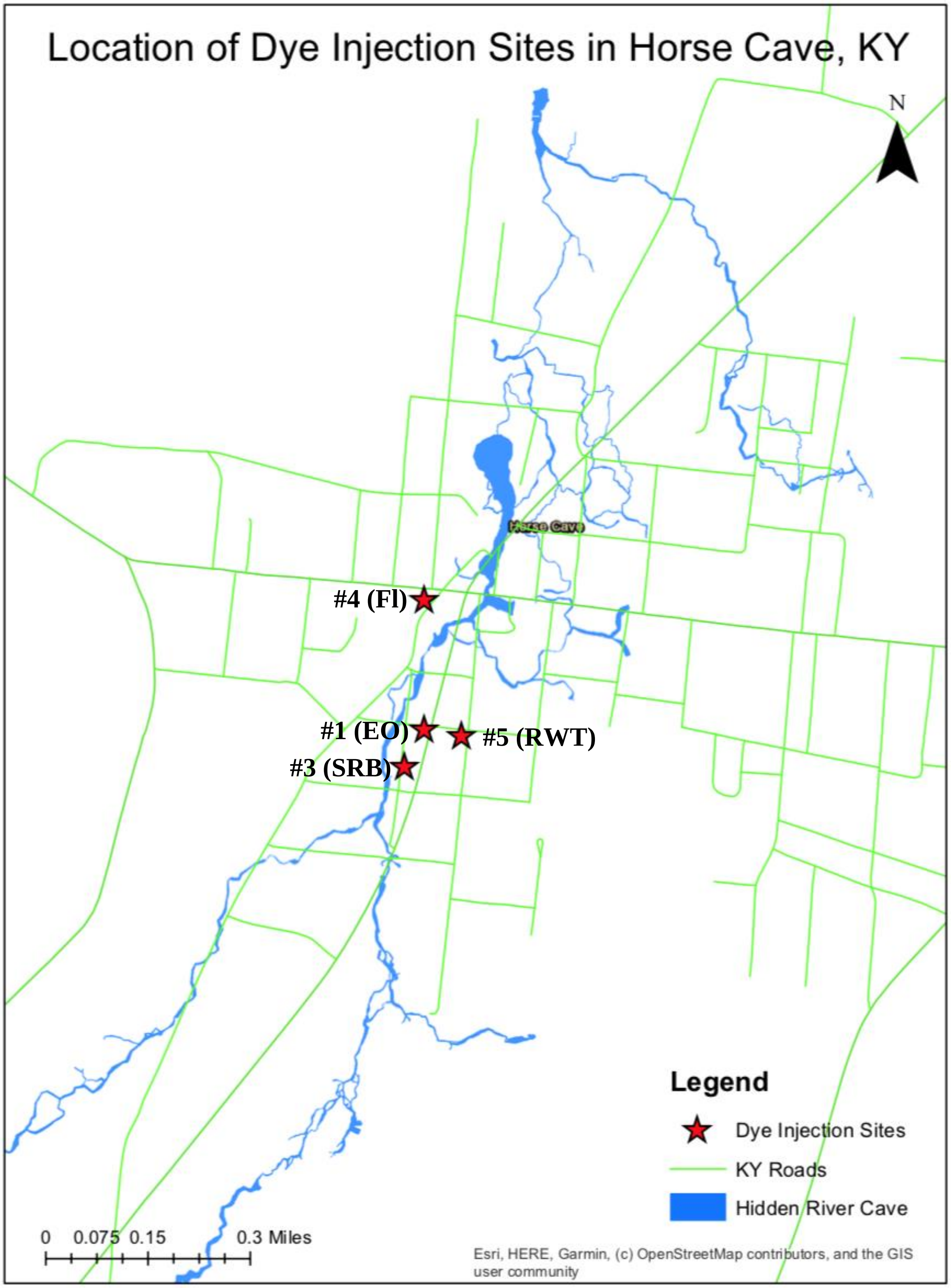

Figure 12: Injection Site Locations in Horse Cave, KY.

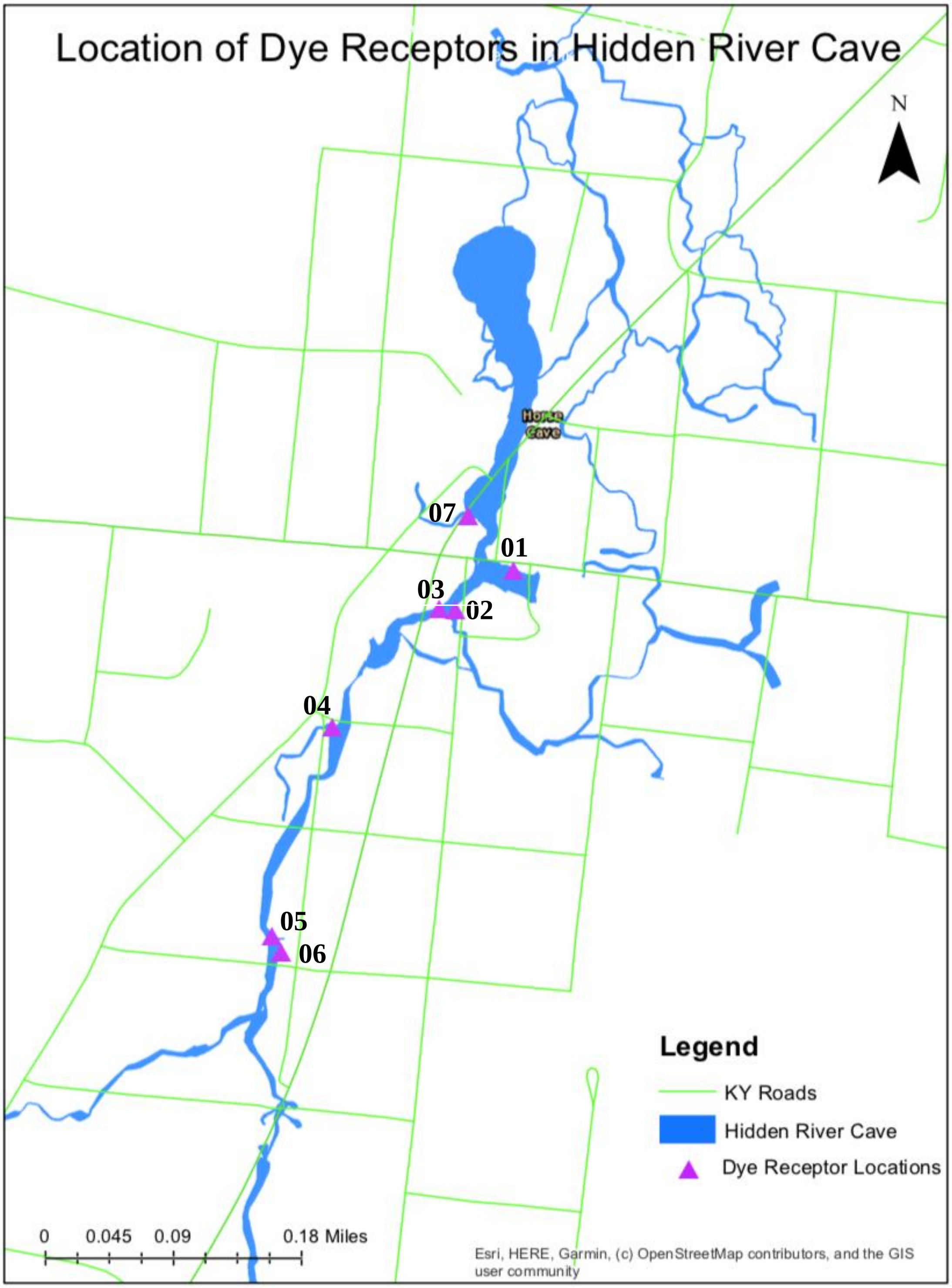

Figure 13: Dye Receptor Locations within Hidden River Cave.

4.3 Dye Trace Conduction

Dye receptors were purchased from the Crawford Hydrology Laboratory at Western Kentucky University (Figure 14). These receptors were approximately 4” by 2” in size, composed of plastic mesh bags, and filled with activated charcoal (Figure 14). Dyes were donated by the Crawford Hydrology Laboratory at Western Kentucky University. The dyes were premixed in quart-sized plastic containers (Figure 15).

Figure 14: Dye receptor from Crawford Hydrology Laboratory deployed in Hidden River Cave.

Figure 15: Dye donated by the Crawford Hydrology Laboratory used in dye trace.

The locations of the charcoal receptor sites within the cave were both upstream of the manmade dam and downstream in the Wheet River, also referred to as the East River (Figure 9). The locations are referred to as East River (01), Kneebuster (02), City Spring (03), Spring Window (04), CC's Pool (05), Waterfall Room (06), and Jingle Bell Passage (07). The charcoal receptors were placed by securing monofilament line to a rock or permanent object that would not be displaced by strong moving water (Figure 16). A loop was tied in the monofilament line and the receptor is then attached to that loop. The receptor was then placed where water completely submerges or flows directly over the receptor. Standard Crawford Laboratory protocols were followed to ensure no contamination of receptors occurred. Rubber gloves were worn when placed and collecting receptors, each receptor had its own individual and clean bag, and each bag was labeled and recorded in a field notebook. The process was repeated for all 7 locations. The first round of receptors was placed to run background analysis before the dye injection and dye tracing process begins.

Figure 16: Attaching a receptor to a rock using monofilament line.

The dyes chosen for injection use were Eocene, Rhodamine WT, Sulphorhodamine B, and Fluorescein. The injection sites were named the following: Site #1 – Car Wash, Site #3 – Cement Plant, Site #4 – Gas Station, Site #5 – Apartment Complex. Site #2 was skipped because there was not a direct pipeline to the cave. Dye injection involved pouring the selected dye directly into the storm drain (Figure 17).

Table 1: Injection Sites, Dye Types, and Dates of Injection.

Injection Site	Dye Type	Date
1- Car Wash	Eosine	16 May 2021
3- Cement Plant	SRB	19 May 2021
4- Gas Station	Fluorescein	21 May 2021
5- Apartment Complex	RWT	16 May 2021

Figure 17: Injecting Dye into storm drains in Horse Cave, KY.

The dye receptors were initially placed on 22 March 2021 for background dye levels determination. Receptor location was determined based on the presence of any visible water flow routes within the cave and according to cave managers (Figure 18). Those receptors were collected, replaced with new receptors, and analyzed for background Levels at the Crawford Hydrology Laboratory. The second round of receptors were placed on 14 May 2021. These receptors were collected and transported to Crawford Hydrology Laboratory for analysis on 21 May 2021.

Figure 18: Placing charcoal receptors in Hidden River Cave.

4.4 Measuring Cave Discharge

Discharge is the calculation of the volume of water moving down a stream or river per unit of time, Discharge = Area x Velocity. The area of the water in a channel cross-section was multiplied by the average velocity of the water in that cross-section. In Hidden River Cave, this process began by observing that tourists were noticing the rapidly changing water levels in the cave during their visits (Figure 19). A cross-section was created of the Wheet River and the East River which are the two main waterways near the tourist entrance of the cave (Figure 20). In order to measure both the cross-section dimensions and the stream depth and velocity, a variety of methods were used, including the use of a kayak (Figure 21). The water depths and water velocity of each cross-section was measured every two feet. Then, the discharge equation mentioned above, discharge was calculated. The average discharge calculated was 10,321 gallons per minute for the rainy season of Kentucky. This was repeated for each discharge measurement made during the study period.

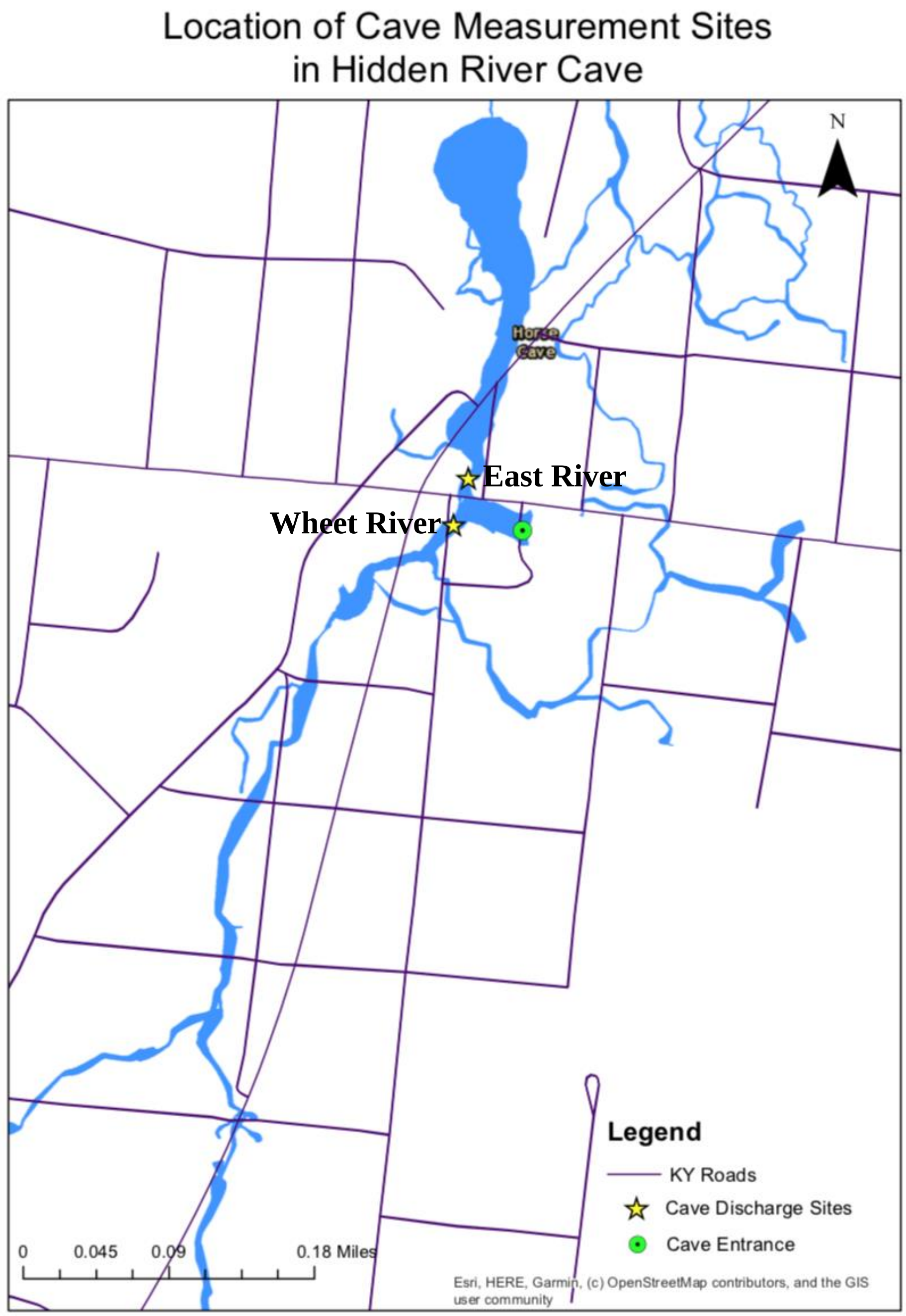

Figure 19: Sites where cave discharge was measured inside Hidden River Cave.

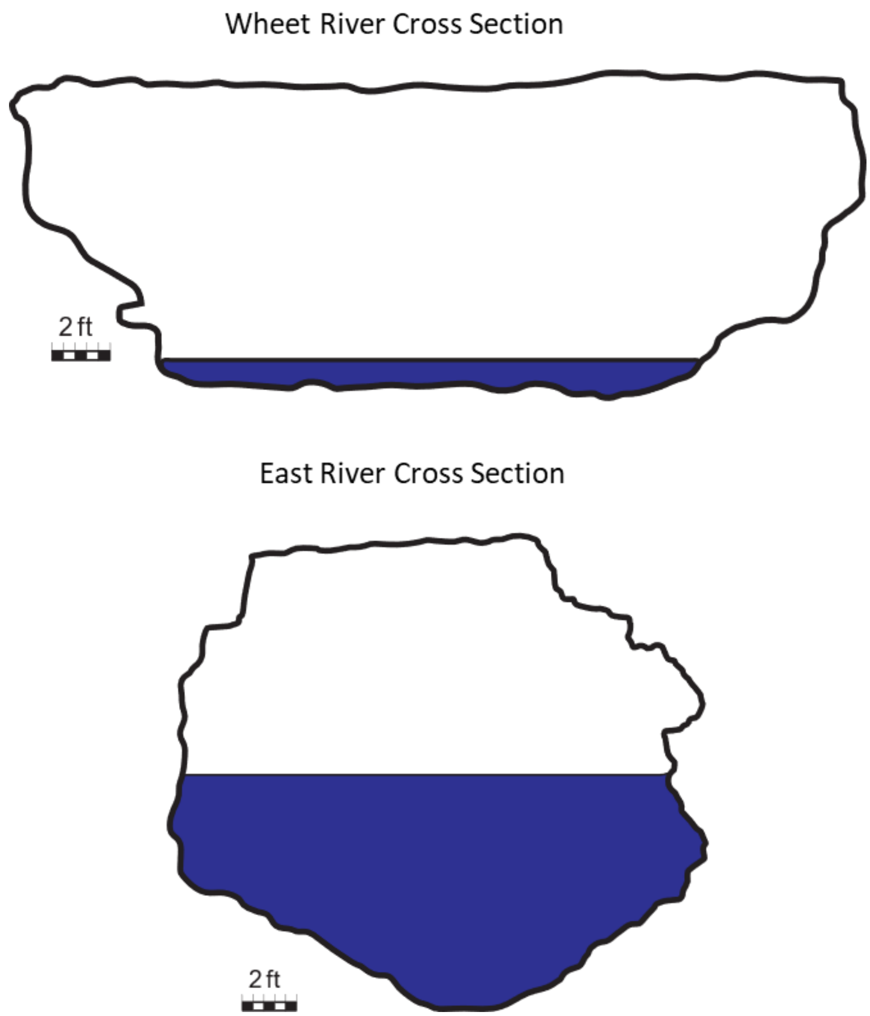

Figure 20: Cross-sections of Wheet River and East River where discharge measurements were measured.

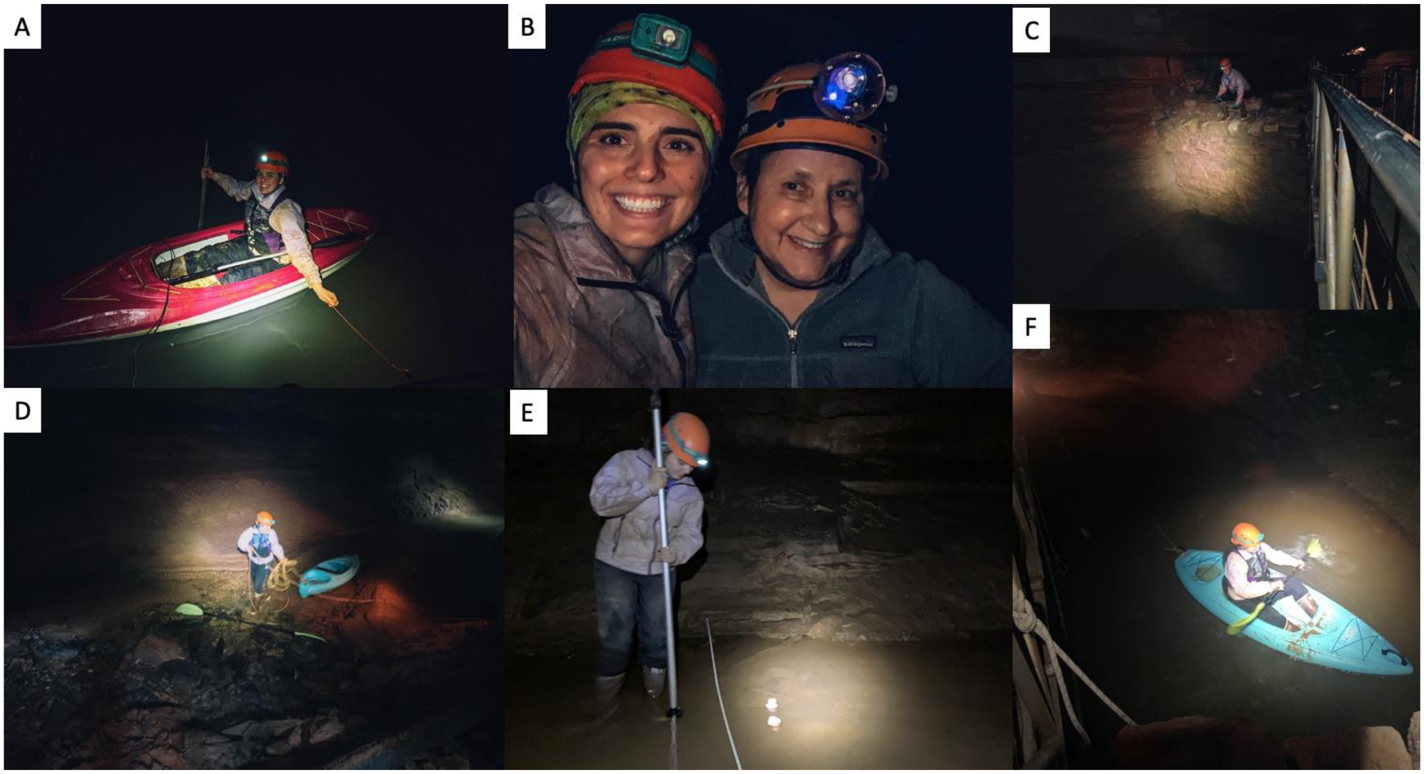

Figure 21: Taking Discharge Measurements in Hidden River Cave.

RESULTS

CHAPTER V

This chapter describes the results of the dye trace conducted in Horse Cave, KY. Maps of each of the four dyes and where in Hidden River Cave the dye was detected illustrate these results gathered. The results from the Crawford Hydrology Laboratory and a summary table of detection versus non-detection is included. Discharge measurements of the two rivers within the cave are shown in a table. Precipitation data of Hart County, KY during the time with study was conducted is included in a graph below.

5.1 Dye Trace Results

Dye trace results are located in Table 2. Below a summary of results for each type of injected dye is given (Table 3). Table 2 shows Crawford Hydrology Laboratory results with samples along rows and color-coded columns for each dye detected. Protocol for dye detection is compared to initial background samples (IB) and displayed at the bottom of the table and includes the following categories: B – Background, ND – No Detection, + - Positive (10 times background), ++ - Very Positive (100 times background), +++ - Extremely Positive (1000 times background), and +? – Questionable Positive. These categories were combined into either Not Detected or Detected for simplification and then summarized in Table 3.

Table 2: Dye Trace Detection Results analyzed by Crawford Hydrology Lab.

* *Hydrogeologists, Geologists, Environmental Scientists*
* *Karst Groundwater Investigations * Fluorescent Dye Analysis*

Bowling Green, KY 42101
(270) 745-9224
E-mail: Crawford.Hydrology@wku.edu

LABORATORY REPORT SHEET

FLUORIMETRIC ANALYSIS RESULTS

Hidden River Cave

	FLUORESCEIN	EOSINE	RHODAMINE WT	SULPHORHODAMINE B
Color Index:	Acid Yellow 73	Acid Red 87	Acid Red 388	Acid Red 52
Dye Receptor:	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal
Analysis by:	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer

						CHARCOAL RECEPTORS												
						FLUORESCEIN PQL in Eluent: 0.005 ppb PQL in Water: 0.010 ppb λ in Eluent: 517.2 nm λ in Water: 510.6 nm			EOSINE PQL in Eluent: 0.005 ppb PQL in Water: 0.010 ppb λ in Eluent: 542.0 nm λ in Water: 536.1 nm			RHODAMINE WT PQL in Eluent: 0.010 ppb PQL in Water: 0.010 ppb λ in Eluent: 569.8 nm λ in Water: 576.8 nm			SULPHORHODAMINE B PQL in Eluent: 0.010 ppb PQL in Water: 0.010 ppb λ in Eluent: 579.7 nm λ in Water: 583.9 nm			
Lab ID	Event	Date Collected	Site Location	TIME	Peakfit	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	C
EH-001-D	BG1	04/09/21	6			ND			IB	197.600	540.6	ND			ND			DILUTED 1:10
EH-001-0	02	05/26/21	6	-		ND			B	47.116	541.0	ND			+++	16.350	579.2	
EH-001-D	03	06/03/21	6	-	X	ND			B	306.600	543.0	B	20.700	563.7,POR	+++	672.5	578.8	DILUTED 1:100 PEAKFIT RESULTS
EL-002-0	BG1	04/09/21	5			ND			ND			ND			ND			AKA -CC'S POOL
EL-002-0	02	05/26/21	5	-		ND			ND			ND			ND			AKA -CC'S POOL
EL-002-0	03	06/03/21	5	-		ND			ND			ND			ND			AKA -CC'S POOL
EH-003-0	BG1	4/9/21	4		X	IB	0.404	522.3*	IB	0.814	541.5	ND			ND			PEAKFIT RESULT
EH-003-0	02	05/26/21	4	-		ND			+	17.066	541.8	ND			ND			AKA - STREAM WINDOW
EH-003-D	03	06/03/21	4	-		ND			++	187.400	542.0	ND			ND			AKA - STREAM WINDOW DILUTED 1:100
EL-004-0	BG1	04/09/21	3			IB	0.380	521.8	IB	0.332	541.9	ND			ND			PEAKFIT RESULT
EH-004-0	02	05/26/21	3	-		ND			ND			+++	65.597	569.2	ND			
EH-004-D	03	06/03/21	3	-		ND			+?	84.400	542.8	+++	125.200	568.6	ND			DILUTED 1:100
EL-005-0	BG1	04/09/21	2			IB	0.157	515.0	ND			ND			ND			
EH-005-0	02	05/26/21	2	-		ND			ND			+++	16.544	569.2	ND			
EH-005-0	03	06/03/21	2	-		ND			+?	5.085	543.4	+++	19.368	569.0	ND			
EH-006-0	BG1	04/09/21	1			ND			ND			ND			ND			
EL-006-0	02	05/26/21	1	-		ND			ND			ND			ND			
EH-006-0	03	06/03/21	1	-		ND			+?	7.118	543.4	+?	26.165	569.4	ND			
EL-007-0	02	05/26/21	7	-		ND			ND			B	0.013	561.0,POR	ND			NO BACKGROUND RESULTS?
EL-007-0	03	06/03/21	7	-		ND			ND			ND			ND			

Approved by: L. Bledsoe on 6/17/21

Comments: * PEAKFIT RESULTS FOR 003: FL ONLY 0.1NM POR IN PEAKFIT, ROUNDING DIFFERENCE BETWEEN SOFTWARE

IB = Initial Background
B = Background (<10 times background or lowest detection limit)
POR = Peak Out of Range (>5nm, <10nm from dye peak center)
ND = No Detection
NPI=No Peak Indicated
EL - Eluent Low- High Sensitivity Scan
EH - Eluent High- Low Sensitivity Scan

+ = Positive (10 times background or lowest detection limit)
++ = Very positive (100 times background or lowest detection limit)
+++ = Extremely positive (1000 times background or lowest detection limit)
+? = Questionable Positive, needs two hits in a row to equal +
Q = Lab Duplicate
QA = Quality Assurance/Quality Contol Laboratory Dye Standards
PeakFit Utilized (Statistical Analysis Peakfitting Software)

Table 3: Summary Table of Detection Results.

Site Number	Fluorescein	Eosine	Rhodamine WT	Sulphorhodamine B
1	ND	D	D	ND
2	ND	D	D	ND
3	ND	D	D	ND
4	ND	D	ND	ND
5	ND	ND	ND	ND
6	ND	D	D	D
7	ND	ND	D	ND
ND – Not Detected D – Detected				

5.1.1 Fluorescein

Fluorescein dye was not detected at any of the seven dye receptor sites (Table 3). (Fluorescein dye was detected in the initial background at Sites 2, 3, and 4 (Table 2). Figure 22 shows Fluorescein detection at receptor locations.

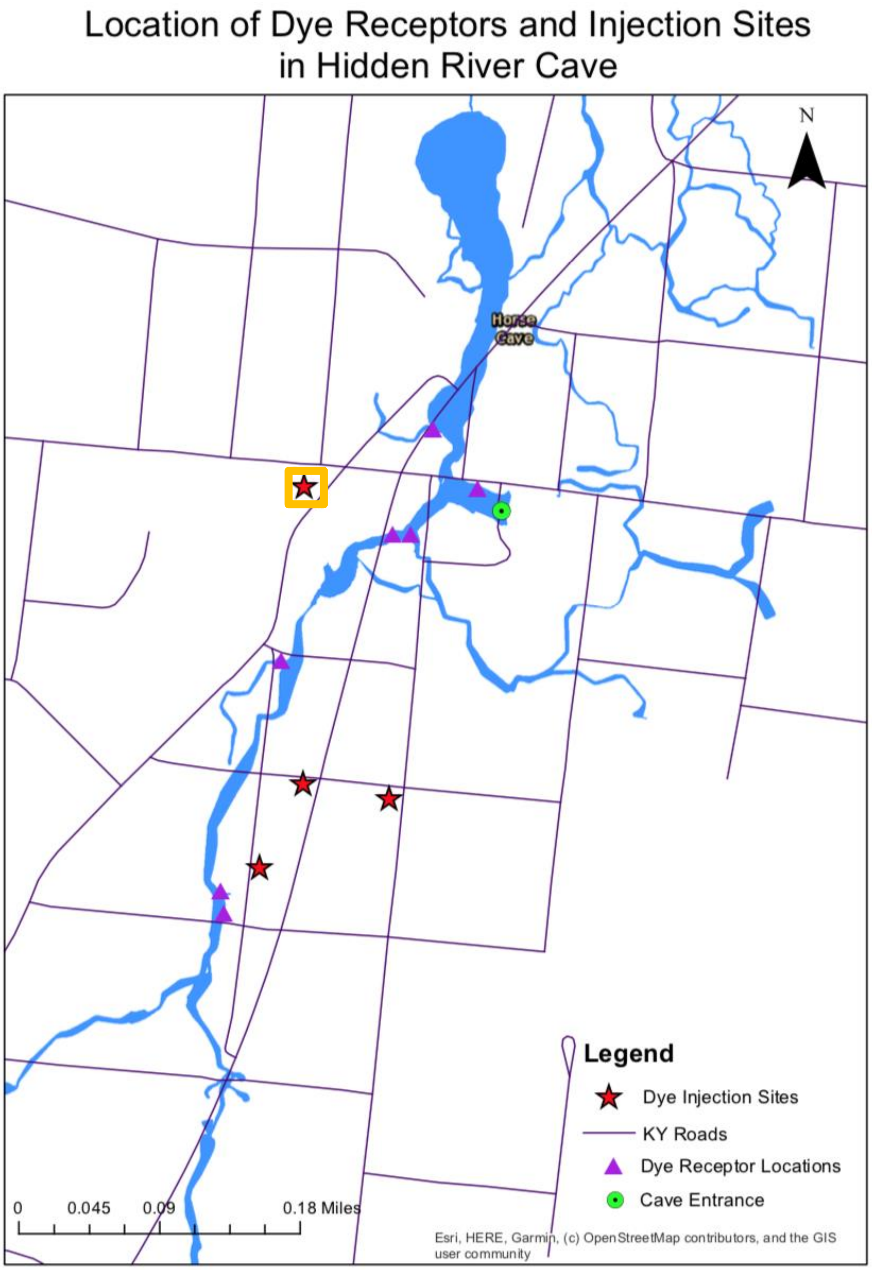

Figure 22: Injection site of Fluorescein with no detection at receptor locations within Hidden River Cave.

5.1.2 Eosine

Eosine dye was detected at five of the seven dye receptor sites (Table 3). Eosine dye was detected in the initial background at Sites 3, 4 and 6. At Site 4, positive and very positive amounts of Eosine were detected. There was a questionable positive result at Sites 1, 2 and 3 (Table 2). Figure 23 shows Eosine detection at receptor locations.

Location of Dye Receptors and Injection Sites
in Hidden River Cave

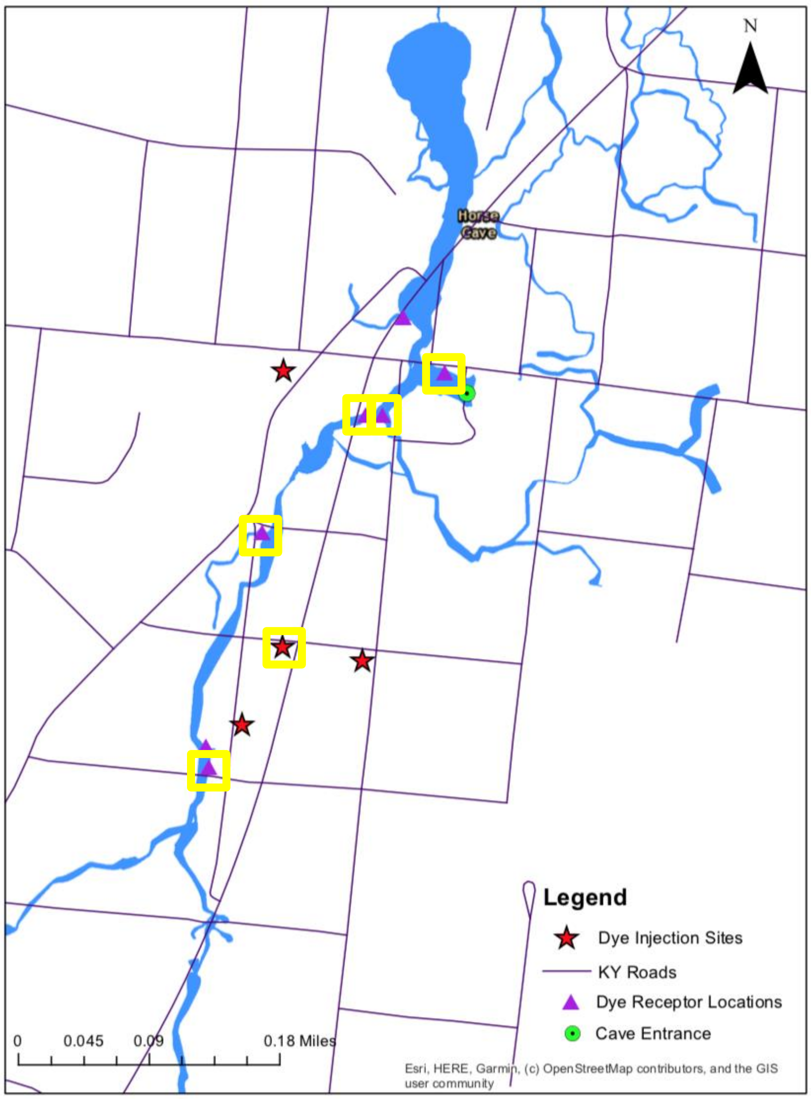

Figure 23: Injection site of Eosine with five detections at receptor sites within Hidden River Cave.

5.1.3 Rhodamine WT

Rhodamine WT was detected at five of the seven dye receptor sites (Table 3). Rhodamine WT dye was detected at concentrations equal to initial background but not exceeding 10 times background levels at Sites 6 and 7. Rhodamine WT was detected as extremely positive at Sites 2 and 3. It was detected as a questionable positive at Site 1 (Table 2). Figure 24 shows Rhodamine WT detection at receptor locations.

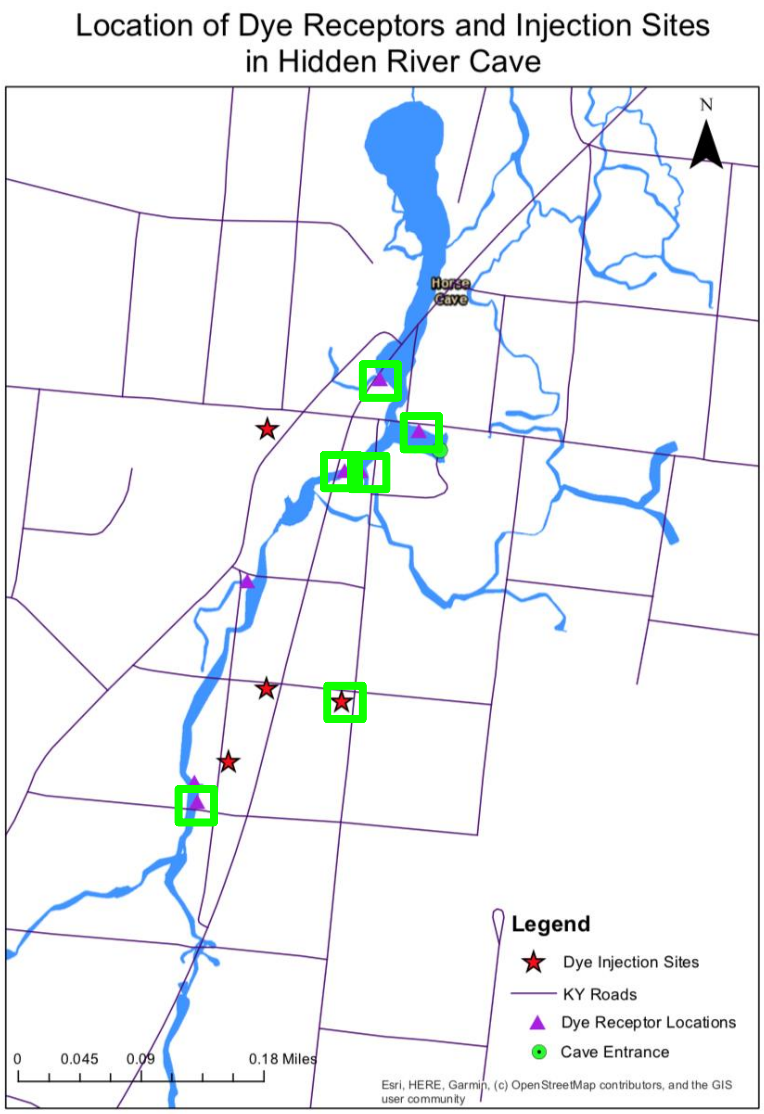

Figure 24: Injection site of Rhodamine WT with five detections at receptor sites within Hidden River Cave.

5.1.4 Sulphorhodamine B

Sulphorhodamine B was detected at one of the seven dye receptor sites (Table 3). Sulphorhodamine B was detected as extremely positive at Site 6 (Table 2). Figure 25 shows Sulphorhodamine B detection at receptor locations.

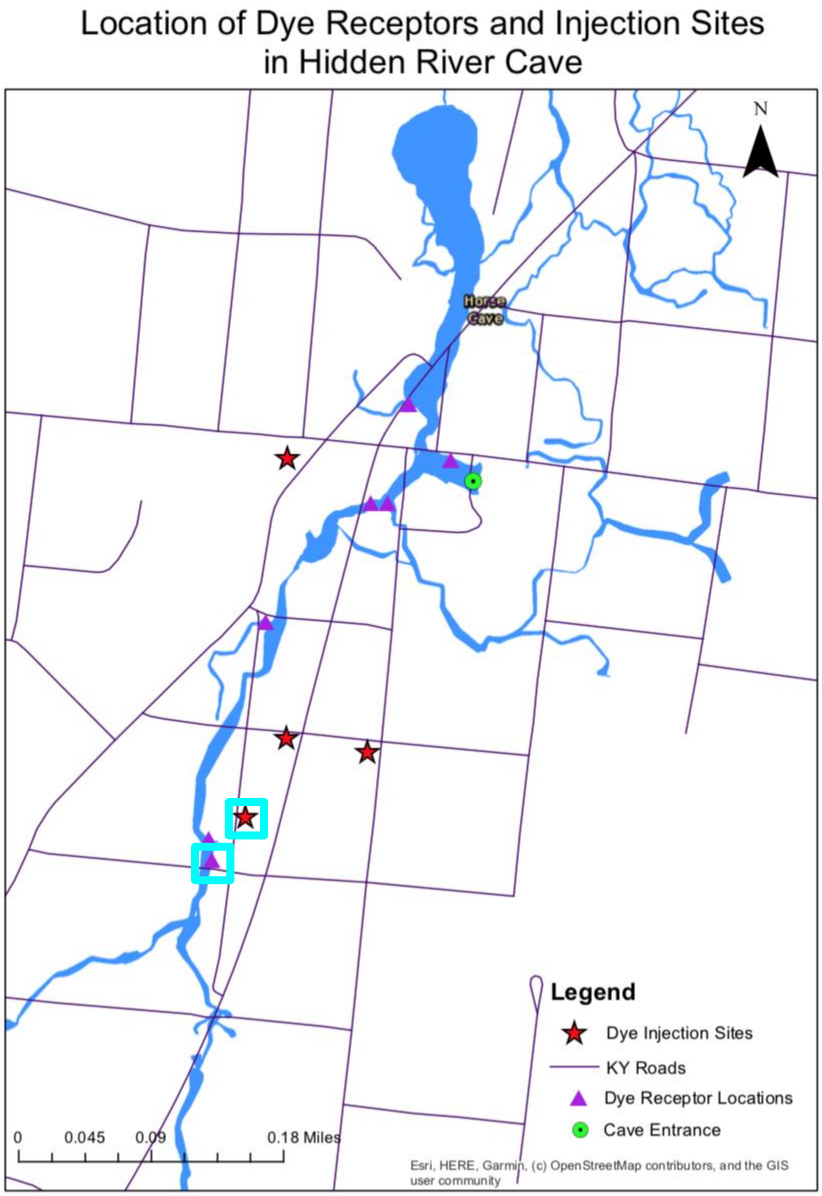

Figure 25: Detection of Sulphorhodamine B in Hidden River Cave.

5.2 Discharge Results

Discharge data are summarized in Table 4. The East River and Wheet River combine to create the total amount of discharge coming from Hidden River Cave. The East River discharge measurement site recorded between 85.37% and 98.83% of the total discharge. The average discharge coming from this river in 87.72%. The Wheet River discharge measurement site recorded between 0.81% and 14.63% of the total discharge. The average discharge coming from this river is 3.18%. Discharge measurements were not collected during storm flood events, a total of 6 times, when it was deemed too dangerous to take measurements. Table 5 summarized the calculations done each day to calculate the discharge at each of the two sites.

Table 4: Discharge Measurements for the East and Wheet Rivers in Hidden River Cave.

Date	Q at dam (m^3/s)	Q at upstream (m^3/s)	Q East River (m^3/s)	% East River	% Wheet River
5/18/21	0.374	0.0089	0.3651	97.6	2.4
5/19/21	0.357	0.0065	0.3505	98.2	1.8
5/20/21	No Measurements Taken Due to Safety Concerns				
5/21/21	0.406	0.0056	0.4004	98.6	1.4
5/22/21	0.628	0.0146	0.6134	97.7	2.3
5/23/21	0	0	0	0	0
5/24/21	No Measurements Taken Due to Safety Concerns				
5/25/21	0.988	0.0116	0.9764	98.8	1.2
5/26/21	0.981	0.0132	0.9678	98.7	1.3
5/27/21	No Measurements Taken Due to Safety Concerns				
5/28/21	No Measurements Taken Due to Safety Concerns				
5/29/21	No Measurements Taken Due to Safety Concerns				
5/30/21	0.456	0.0037	0.4523	99.2	0.8
5/31/21	No Measurements Taken Due to Safety Concerns				
6/1/21	0.571	0.0069	0.5641	98.8	1.2
6/2/21	1.71	0.2501	1.4599	85.4	14.6
6/3/21	0.269	0.0214	0.2476	92	8

Table 5: Example of Discharge Calculations.

Station	Date	Time	Width (m)	Depth (m)	Velocity (m/s)	Discharge (m^3/s)
1	5/18/21	4:00 PM	1.79	1.55	0.085	0.2358325
2	5/18/21	4:00 PM	1.29	1.95	0.0115	0.02892825
3	5/18/21	4:00 PM	1.3	2.26	0.01	0.02938
4	5/18/21	4:00 PM	3.11	1.64	0.07	0.357028
		Total Discharge:	0.65116875	m^3/s		
			172.0192487	gallons/s		
			10,321	**gallons/min**	**(for cave)**	

5.3 Precipitation Data

Precipitation data were downloaded from Kentucky Mesonet hosted by Western Kentucky University. Dates of data correspond to the discharge measurement dates. The weather station is located at Latitude: 37.26°; Longitude: -85.78° (Figure 26). During the study period, precipitation ranged between zero inches to 1.38 inches. The highest precipitation event occurred on 02 June 2021 (Figure 27).

Figure 26: Location of the weather station (star) and the city of Horse Cave, KY (circle).

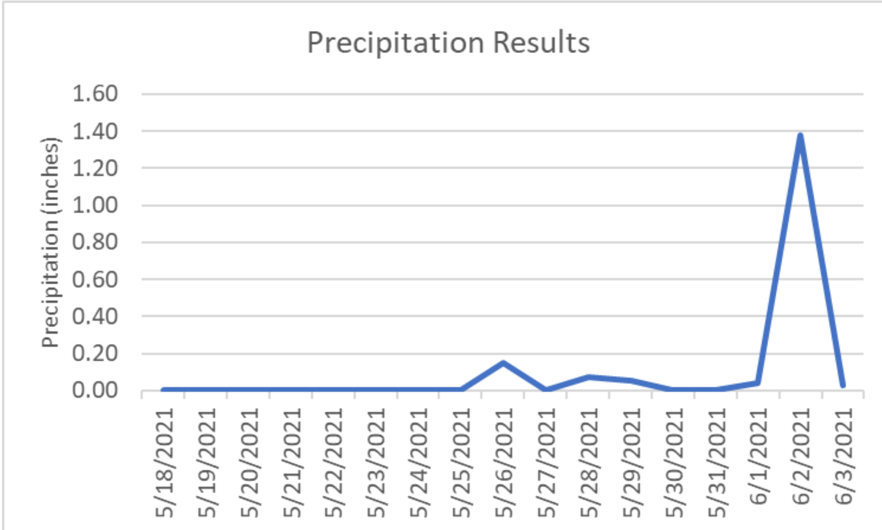

Figure: 27: Precipitation results during the period when discharge was measured.

DISCUSSION

CHAPTER VI

This chapter discusses the interpretations of dye trace results and discharge measurements in relation to daily precipitation in Hart County, KY. The first four sections interpret the flow of dye from each injection site and its potential flow path and flow direction within the cave system. The fifth section interprets the percentage of cave discharge from two rivers near the cave entrance and how daily precipitation rates affect that percentage. The sixth section discusses limitation present in this study and what future studies could be done to gain a further understanding of this hydrological area.

6.1 Fluorescein Flow Direction

The injection site for Fluorescein has not had dye previously injected according to previous literature. There were no detections at receptor sites within Hidden River Cave of Fluorescein dye during this study (Figure 13). However, there was Fluorescein dye detected in the initial background samples (Table 2). One explanation for the lack of detection of Fluorescein is that previous traces within Hidden River Cave may have left dye signatures within sediments that were deposited in the cave passages. These sediments may be slowly leaching dye which would account for the initial background signatures observed. It is possible that dye from this study was either trapped within sediment along the flow route or did not enter the cave where anticipated. Based on the overall direction of flow demonstrated by previous studies (Quinlan and Ewers, 1989) it is more plausible that the flow route carrying Fluorescein dye from the injection site entered Hidden River Cave downstream of receptor location 7. A hypothesized flow route from this new injection site would most likely either take the dye into the Sunset

Dome portion of the cave or possibly miss the cave system completely (Figure 28). Alternatively, the dye flow path may trend in a direction completely in the opposite direction of the cave; however, future studies will need to examine the exact nature of the flow path and its relationship to the Hidden River Cave System.

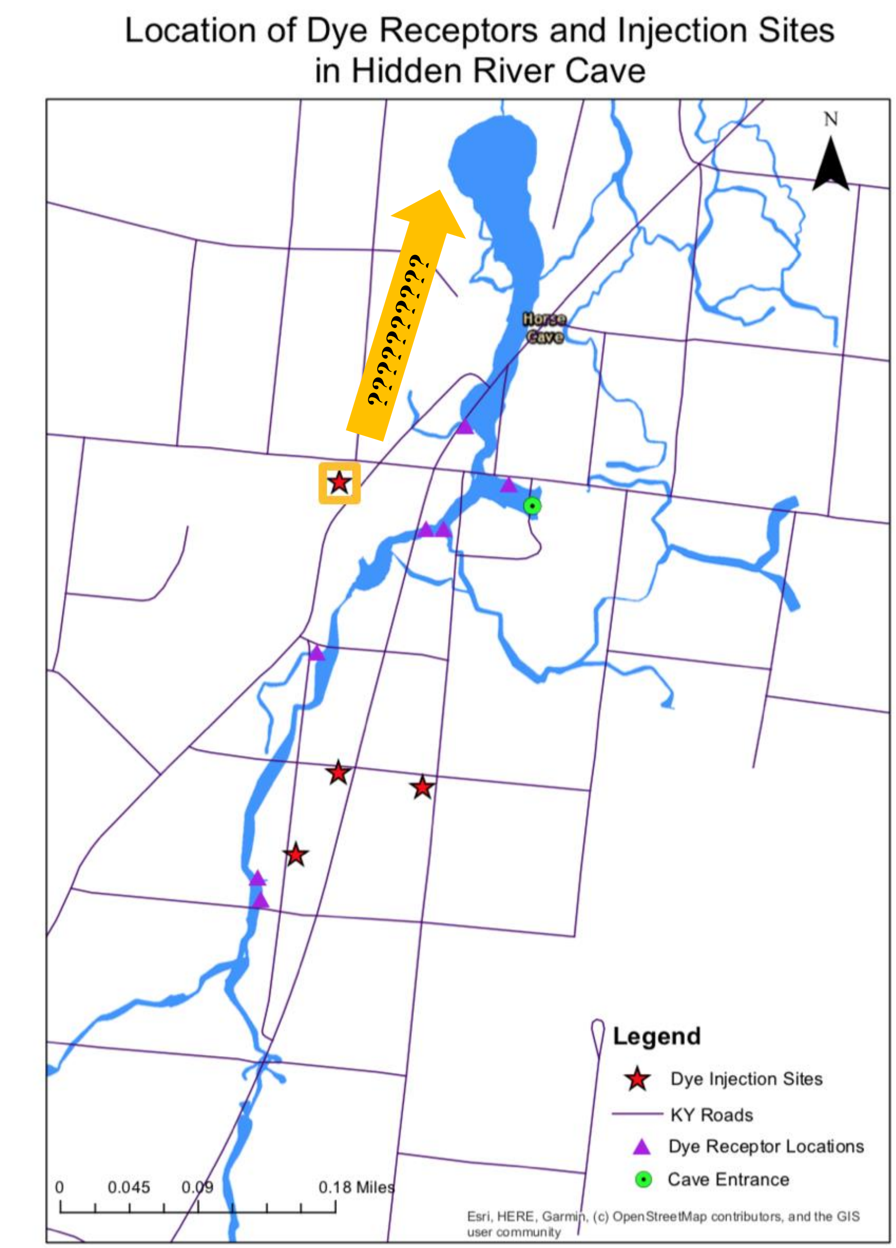

Figure 28: Fluorescein dye potential flow pathway based on no detection at receptor locations within Hidden River Cave.

6.2 Eosine Flow Direction

Eosine flow from injection site 1 was detected at dye receptor locations 1, 2, 3, 4 and 6 (Figure 13). While a qualitative trace was conducted, the concentration of dye detected within samples from receptor site 4 was higher than the other sites (Table 2). This suggests that a more direct flow path exists between the injection site for Eosine and receptor location 4 (Figure 29). Additionally, dye was detected at lower concentrations upstream at receptor location 6 (Table 2). This flow was in the opposite direction which suggests either there was dye in the cave system from a previous dye trace or there is a drainage divide that could cause a small portion of the water carrying dye to flow in opposite directions. More than likely, there is a small drainage divide that divides a portion of the waterflow towards the southwest. This is based on direct observation of waterflow and dye detection at receptor site 6 (Figure 29). At this location, there is a waterfall that emerges from the cave ceiling that flows at a relative constant rate.

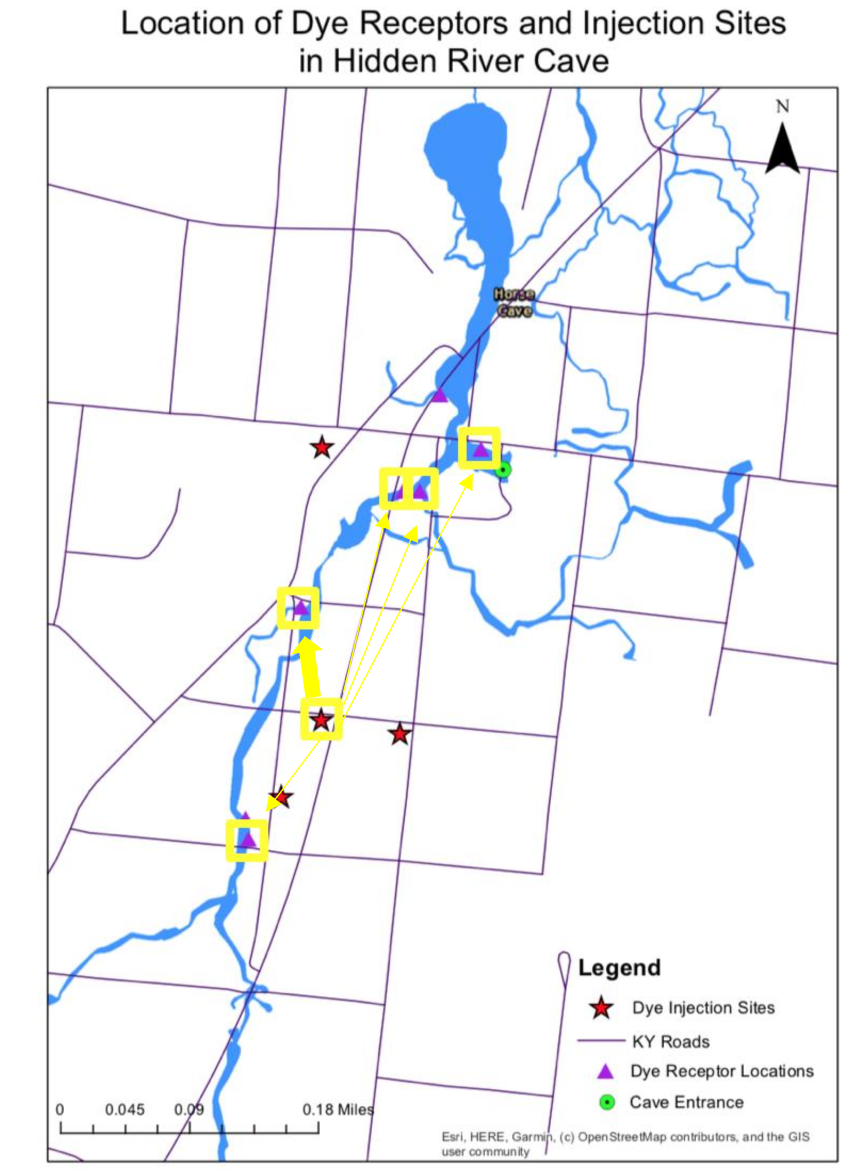

Figure 29: Eosine dye flow pathways interpreted from detection results.

6.3 Rhodamine WT Flow Direction

RWT flow from injection site 5 (Figure 12) was detected at dye receptor sites 1, 2, 3, 6, and 7 (Figure 13). Dye was detected at the two furthest dye receptor locations from each other (locations 6 and 7). This suggests that RWT enters the cave system at multiple locations because not all dye receptors in the cave detected RWT (Figure 30). Samples from receptor locations 2 and 3 were higher than the other detected location concentrations, similar to the Eosine results. When coupled with the Eosine results, one dye receptor location (location 6) follows a similar secondary flow path to the southwest (Figure 30). This suggests that the hypothesized small drainage divide affects waters entering the aquifer from this general region of the city of Horse Cave.

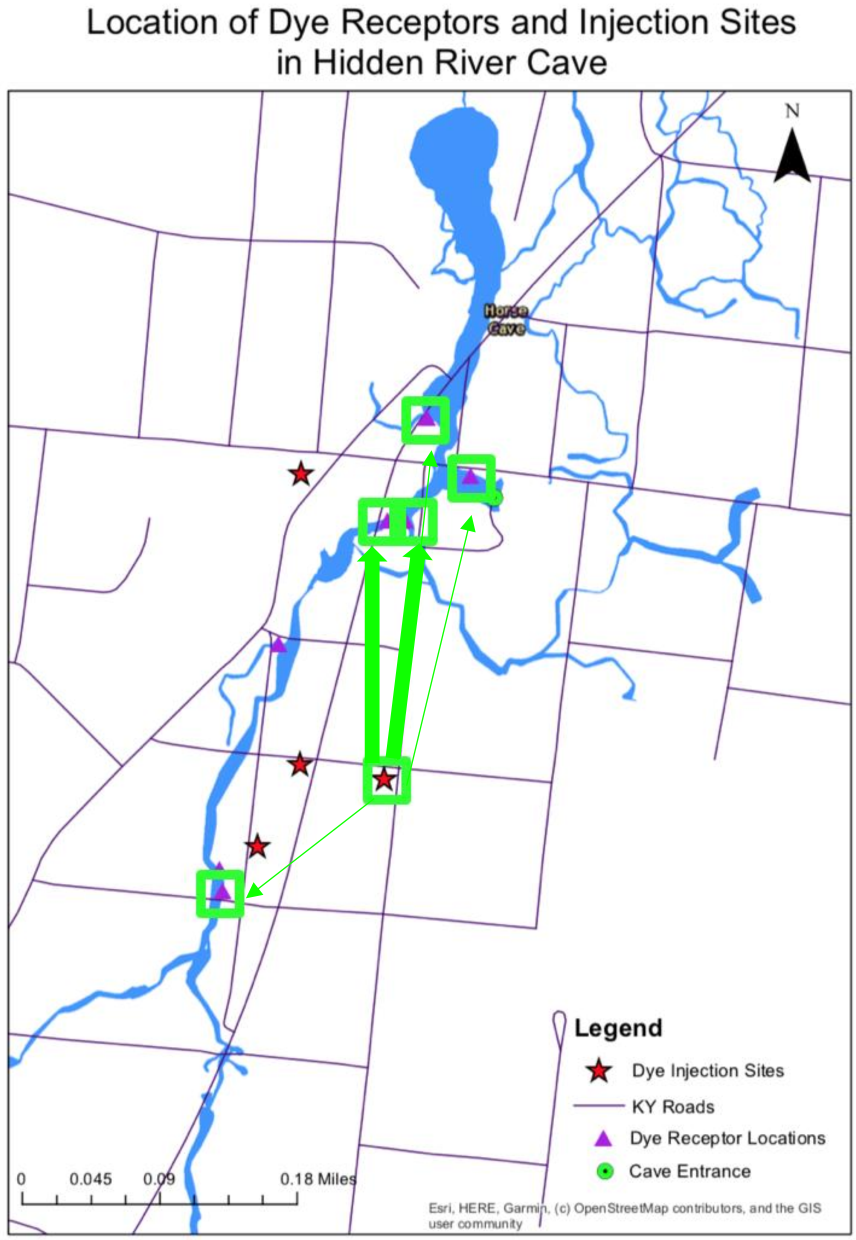

Figure 30: Rhodamine WT dye flow pathways interpreted from detection results.

6.4 Sulphorhodamine B Flow Direction

SRB flow from injection site 3 (Figure 12) was only detected at dye receptor location 6 (Figure 13). It was not found at dye receptor location 5 which was the next closest receptor locations. This suggests the SRB enters the cave system somewhere between the injection site and location of the dye receptor. The overall direction of the flow path, assuming a straight line, is approximately southwest in direction, matching the hypothesized flow path of Eosine and RWT (Figure 31). Unlike Eosine and RWT's flow path and concentration trends, SRB's flow path does not follow similar trends in concentration and detection, suggesting that this injection point is completely within the hypothesized small groundwater basin. These data suggest that small groundwater basins exist in proximity to the cave and city managers, businesses, and individual property owners should be aware of these smaller basins in order to prevent contamination and pollution from entering into somewhat remote locations within the aquifer.

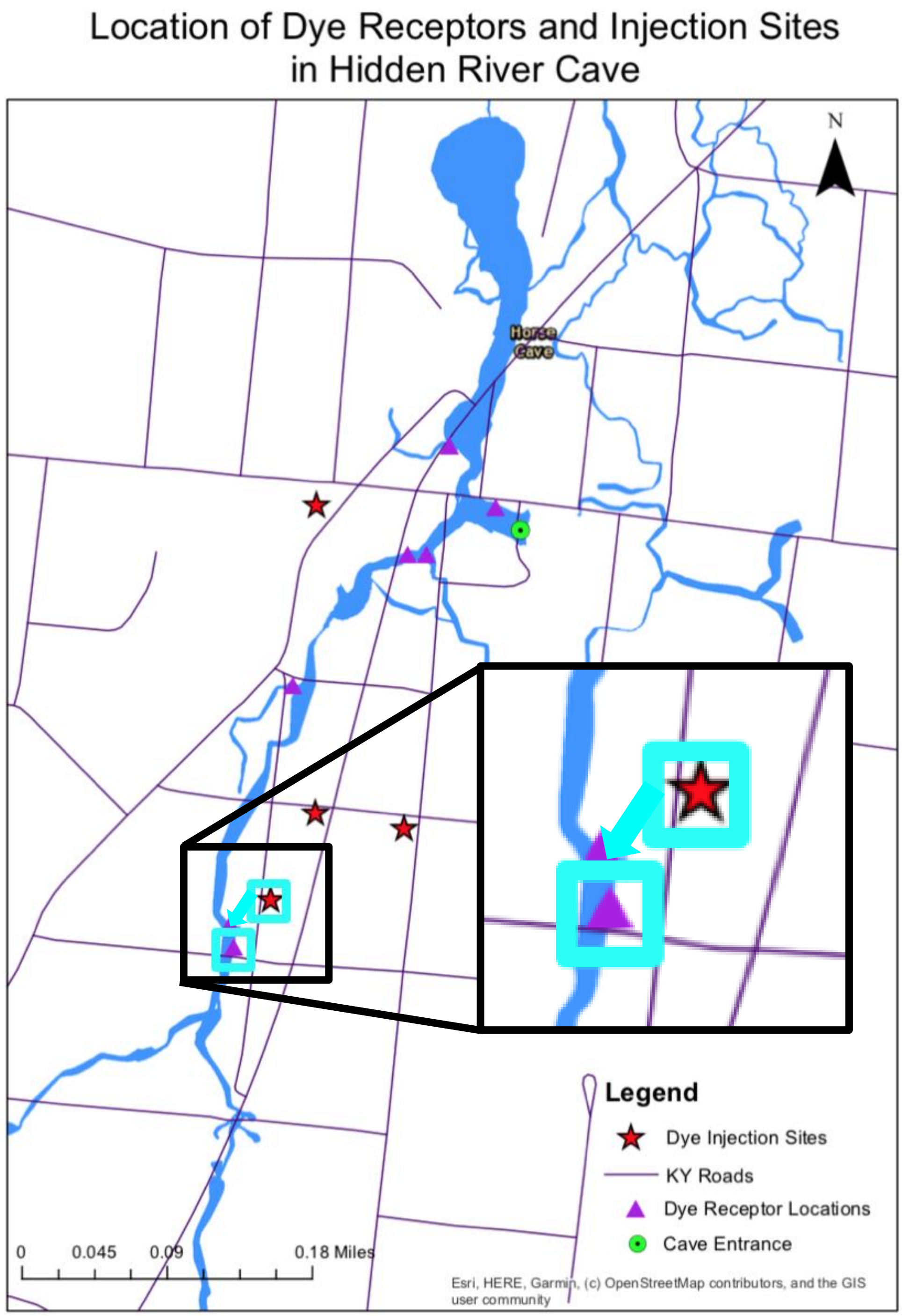

Figure 31: Sulphorhodamine B dye flow pathways interpreted from detection results.

6.5 Cave Discharge and Surface Precipitation

Discharge of these two rivers largely vary when it comes to amount of discharge. The East River contributes the largest of amount of water in terms of total cave discharge (Table 4). The East River has a more consistent contribution to discharge regardless of the low flow or flood condition. The Wheet River shows the highest variance, appearing to be most influenced by the rainfall at the surface (Figure 32). Recharge of the Wheet River appears influenced by surface water, and the flow within the East River appears to be dominated by groundwater discharge. Overall, most of the water discharge is coming from the East River.

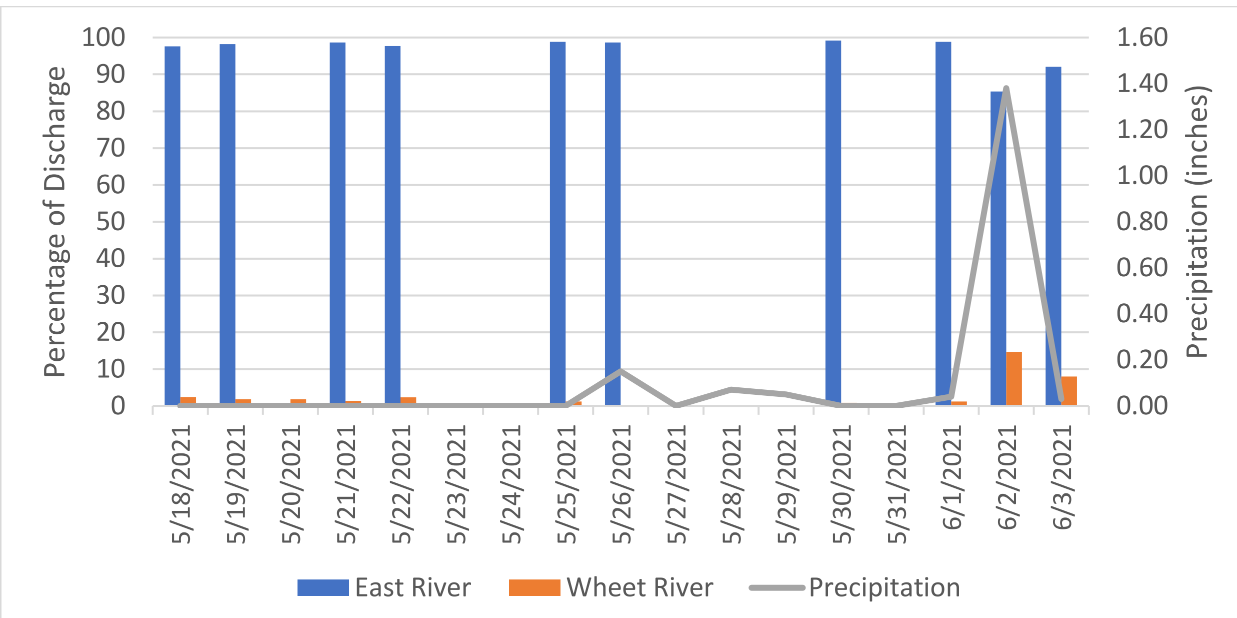

Figure 32: Discharge of Hidden River Cave Percentages

When examining the discharge data with dye trace results, it appears that the East River receives a majority of its volume from regional groundwater flow. This corresponds to the higher concentrations of dyes (Eosine and RWT) seen along the proposed flow path. The East River runs through the cave passages where these dye receptors were located. The Wheet River appears to be influenced by smaller catchment areas on the surface, and recharge follows flow paths of the hypothesized small groundwater basin. These shorter flow paths as illustrated by the dye traces of Eosine, RWT, and SRB correspond with the nature of discharge in the Wheet River. Since rainwater entering at the surface has shorter flow paths and smaller catchments, the Wheet River discharge appears much more influenced by surface precipitation and lower in overall discharge when compared to the East River discharge. The East River appears to be recharged by longer, regional groundwater flow paths that are less influenced by surface precipitation.

6.6 Limitations and Future Work

The limitations of the dye trace portion of this research include the distribution of dye receptors, the use of dyes that recent studies used, the temporal resolution of sampling and dye tracing. Other limitations include the lack of a local rain gauge within the city of Horse Cave, interpretations associated with precipitation data from a rain gauge >5 miles away, using higher resolution data (such as hourly rainfall amounts instead of daily). In general, the temporal and spatial extent of the study should be expanded, especially to map the hypothesized small drainage basins identified in this study.

Additional analyses that should be conducted in future research should include land cover/use change, further mapping and understanding of the drainage basins that influence discharge in the East and Wheet Rivers, potential long term storativity of waters and dyes held within sediments, and expansion of the qualitative dye trace to a quantitative dye trace to understand mass flow in the Horse River Cave System.

CONCLUSIONS

CHAPTER VII

This chapter is a recap of the findings of this thesis and what the hypothesized findings mean in terms of the area of Horse Cave, KY.

In this study, a dye trace was conducted in the town of Horse Cave, KY. Four dyes (Fluorescein, Eosine, RWT, and SRB), were injected at four different injection sites found in Horse Cave. These injection sites were located by ground truthing and locating storm drains and areas believed to have potential to drain into Hidden River Cave. The injection sites used were four storm drains. Seven dye receptors were placed inside Hidden River Cave. The dye receptor locations were determined by looking for any water flow within the cave and with the direction of cave experts. After the four dye injections, these dye receptors were collected and sent to Crawford Hydrology Laboratory of Western Kentucky University for analysis. Once the results were obtained, GIS maps of Hidden River Cave were created to illustrate where the injection site, dye receptor location, and where the detection of dye was observed. Flow direction was then hypothesized using previous literature coupled with dye detection results. Cross-sections were created of these two rivers inside Hidden River Cave. Discharge measurements of both the Wheet and East River were calculated from cross-section, water depth, and water velocity measurements. Precipitation data from Hart County, KY were analyzed against cave discharge percentages.

First, this study found that the injection site west of Hidden River Cave appears to not flow into the cave system where the dye receptors were placed. The lack of dye detection from this injection site suggests that there is a different flow path on that side of the cave or there was not adequate dye receptor coverage to detect the dye injected on that side of the cave. Looking at the Hidden River Cave map, it is possible to hypothesize a flow route that bypasses current cave passages and that flows directly into the Sunset Dome of the cave, a place where a dye receptor was not placed.

Second, the three remaining dye injection sites on the east side of the cave system have a more direct flow into Hidden River Cave. Water from two of the three dye injection sites appeared to follow the regional northwestern groundwater flow trend pointed out by previous dye trace and groundwater studies done by Quinlan and Ewers in 1989. Additionally, smaller detections of dye concentrations from injection sites to the Wheet River portions of the cave occurred. This suggests a separation of flow possibly due to the presence of a smaller groundwater basin that flows towards the southwest portions of Hidden River Cave. This is supported by the detection and lack of detection of dye by the dye receptors.

Finally, the dye trace data coupled with the cave discharge data reinforce the interpretations of flow distribution to Hidden River Cave from the injection points. These flow paths appear to explain the differences in the East and Wheet River in terms of percentage of discharge each river contributes. The Wheet River contributes less discharge that is hypothesized to have a different catchment area that flows to receptor location 6. The East River contributes the most amount of discharge that is hypothesized to have more influence from the regional groundwater flow that flows to the remaining receptors. This supports the hypothesized flow path connection of the smaller drainage divide.

This research improves the knowledge of Hidden River Cave's tie to groundwater flow, and it is a starting point for more refined and quantitative dye traces to map smaller groundwater basins within the Hidden River Cave system. The most significant findings of this research include identifying multiple flow paths from various injection points, the relationship between discharge of the Wheet River and East River in Hidden River Cave, and a lack of detection from a previously unidentified injection point. These findings improve the understanding of how surface waters enter Hidden River Cave and their influence to the discharge of the rivers within the cave.

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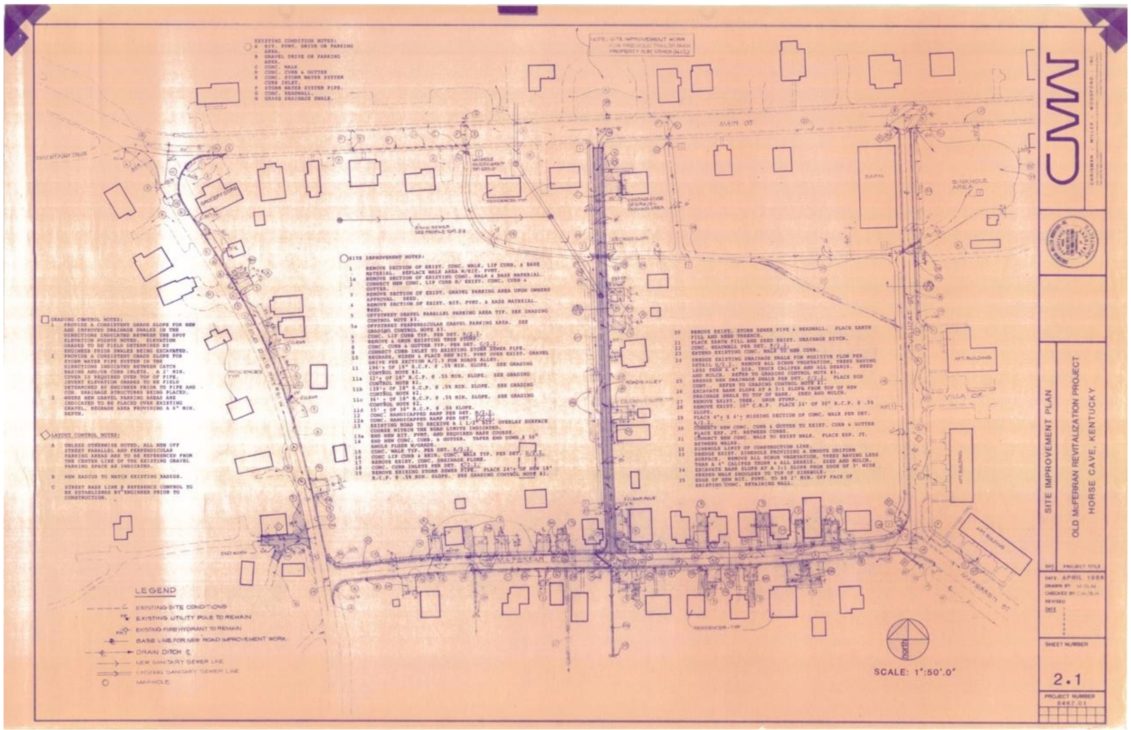
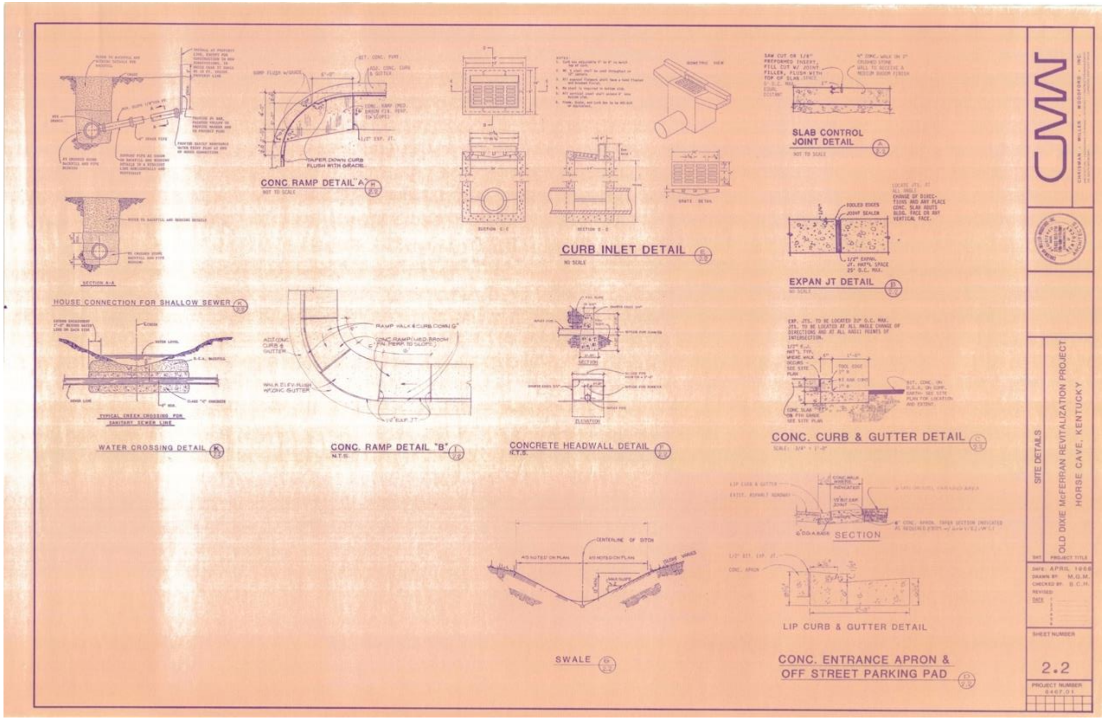
Appendix A

Original Storm Infrastructure Maps of Horse Cave, KY

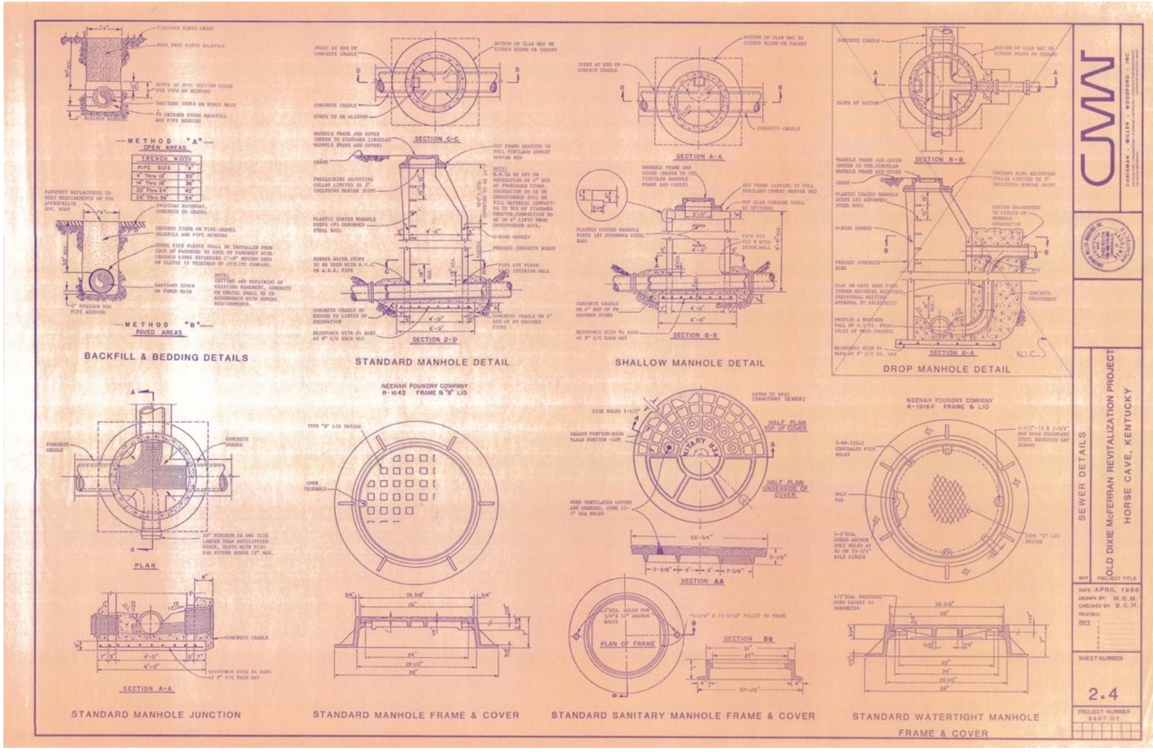
A.1



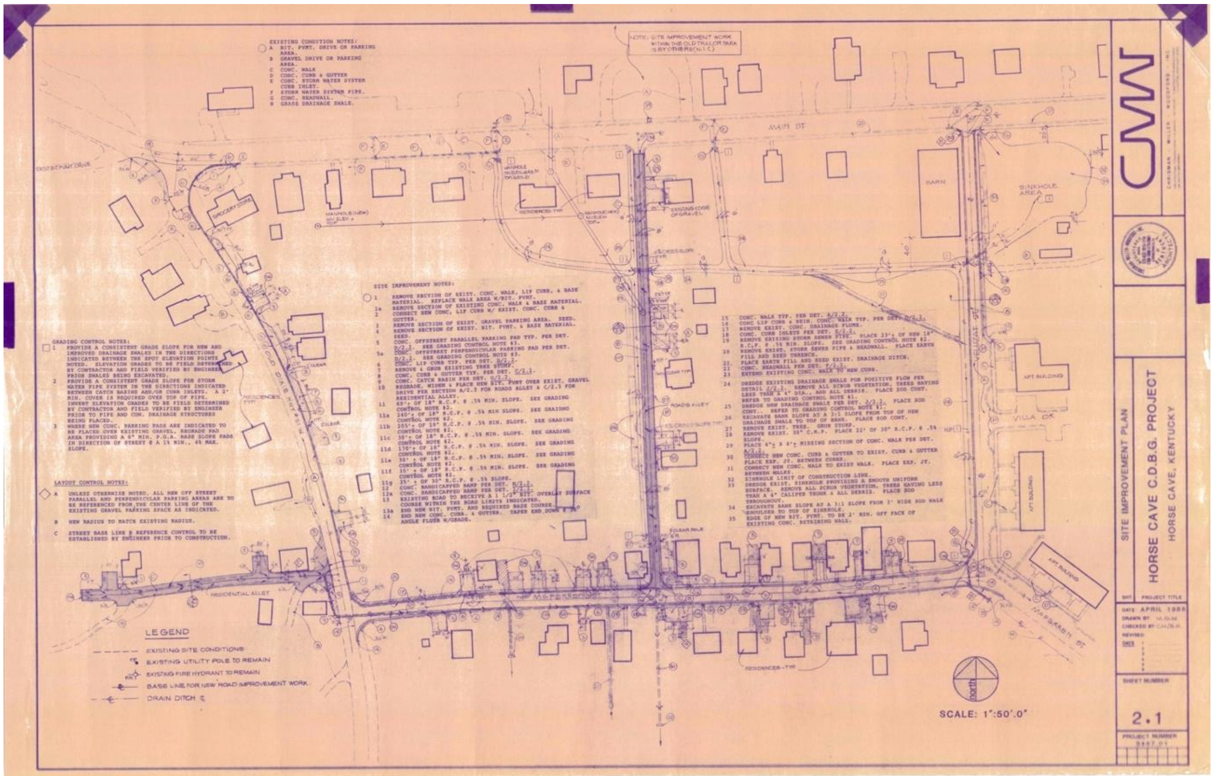
A.2


HOUSE CONNECTION FOR SHALLOW SEWER
CONC RAMP DETAIL A
CURB INLET DETAIL
SLAB CONTROL JOINT DETAIL
EXPAN JT DETAIL
WATER CROSSING DETAIL
CONC. RAMP DETAIL "B"
CONCRETE HEADWALL DETAIL
CONC. CURB & GUTTER DETAIL
SECTION
LIP CURB & GUTTER DETAIL
SWALE
CONC. ENTRANCE APRON &
OFF STREET PARKING PAD
SITE DETAILS
OLD DIXIE McFERRAN REVITALIZATION PROJECT
HORSE CAVE, KENTUCKY
2.2

A.3

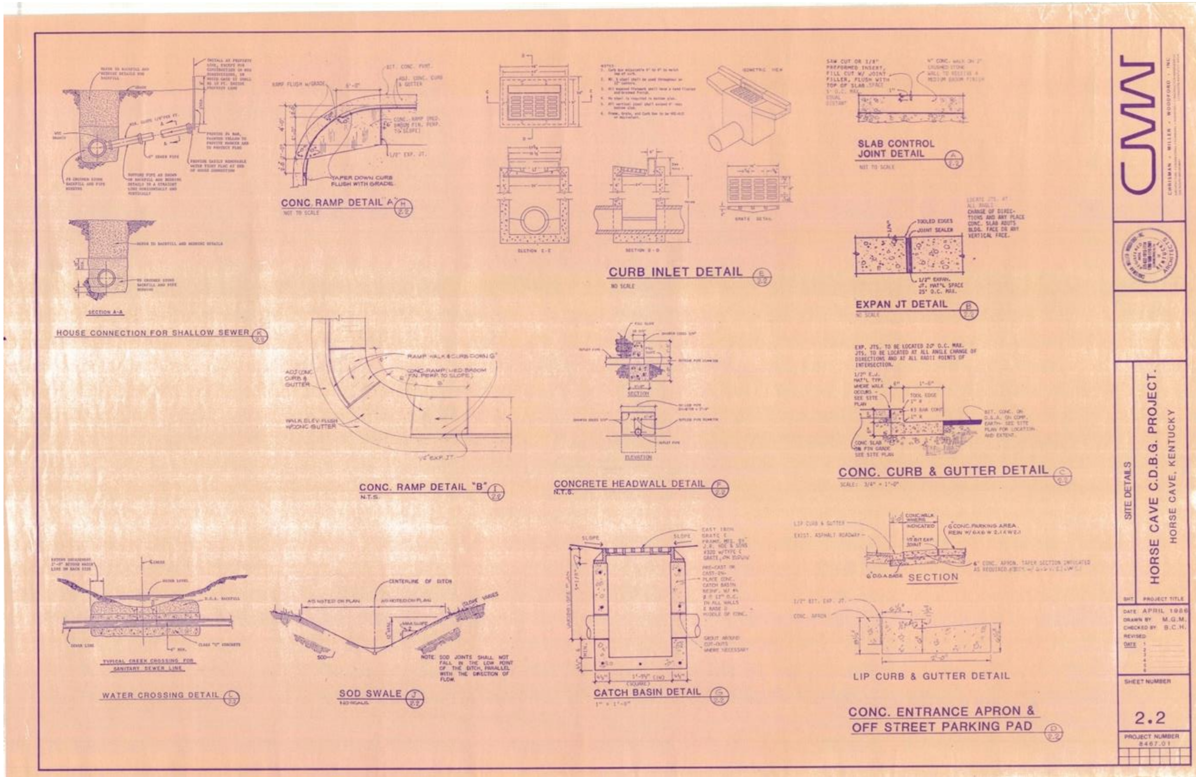

BACKFILL & BEDDING DETAILS
STANDARD MANHOLE DETAIL
SHALLOW MANHOLE DETAIL
DROP MANHOLE DETAIL
STANDARD MANHOLE JUNCTION
STANDARD MANHOLE FRAME & COVER
STANDARD SANITARY MANHOLE FRAME & COVER
STANDARD WATERTIGHT MANHOLE FRAME & COVER
SEWER DETAILS
OLD DIXIE McFERRAN REVITALIZATION PROJECT
HORSE CAVE, KENTUCKY
2.4

A.4



SITE IMPROVEMENT PLAN
HORSE CAVE C.D.B.G. PROJECT
HORSE CAVE, KENTUCKY
LEGEND
EXISTING SITE CONDITIONS
EXISTING UTILITY POLE TO REMAIN
EXISTING FIRE HYDRANT TO REMAIN
BASE LINE FOR NEW ROAD IMPROVEMENT WORK
DRAIN DITCH
SCALE: 1":50'.0"
MAIN ST
2.1

A.5



CONC. RAMP DETAIL "A"
CURB INLET DETAIL
SLAB CONTROL JOINT DETAIL
EXPAN JT DETAIL
HOUSE CONNECTION FOR SHALLOW SEWER
CONC. RAMP DETAIL "B"
CONCRETE HEADWALL DETAIL
CONC. CURB & GUTTER DETAIL
WATER CROSSING DETAIL
SOD SWALE
CATCH BASIN DETAIL
LIP CURB & GUTTER DETAIL
CONC. ENTRANCE APRON & OFF STREET PARKING PAD
SECTION
SITE DETAILS
HORSE CAVE C.D.B.G. PROJECT.
HORSE CAVE, KENTUCKY
2.2

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Author: Alexa Franks
Signature:

Date: 03/07/2022