Land-Use Impacts on the Hydrology of the Hidden River Groundwater Subbasin, Horse Cave, Hart County, Kentucky

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LAND-USE IMPACTS ON THE HYDROLOGY OF THE HIDDEN RIVER GROUNDWATER SUBBASIN, HORSE CAVE, HART COUNTY, KENTUCKY

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Master of Science

By
Cesalea N. Osborne

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LAND-USE IMPACTS ON THE HYDROLOGY OF THE HIDDEN RIVER GROUNDWATER SUBBASIN, HORSE CAVE, HART COUNTY, KENTUCKY

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In memory of J.F. Quinlan. Your work in the south-central Kentucky karst region was phenomenal, and your legacy continues through this research.
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The research herein is very dear to me, and it is my hope that future generations will continue to work toward creating a pristine environment for Hidden River Cave. Not only does this research support the goals of the ACCA, but also the overall conservation and preservation of karst landscapes.
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Subsurface drainage basins are highly interconnected in karst regions, as groundwater is quickly transported through conduits created by the dissolution of carbonate bedrock. South-central Kentucky is a classic example of a well-developed karst landscape and includes the longest-known cave system, Mammoth Cave. The Mammoth Cave karst aquifer contains 28 major groundwater basins, of which the Hidden River groundwater subbasin has been severely impacted by anthropogenic contaminants.

Hidden River Cave, located in the city of Horse Cave, Kentucky, forms one of the main tributaries of the Hidden River groundwater subbasin that spans parts of Barren, Hart, and Metcalf counties. Hidden River Cave formed in Mississippian-aged carbonates and consists of a dendritic network of canyons and collapsed domes. A major trunk stream flows through the cave, contributing recharge to the Mammoth Cave aquifer, and supports myriad subsurface ecosystems. Poor land-use practices, including changing residential, commercial, and industrial boundaries, historically have contaminated the cave stream. As a result, the hydrology of the Hidden River groundwater subbasin has been extensively studied using fluorescent dye-tracing techniques. Recent developments in groundwater resource management have improved cave conditions; however, land-use boundaries in Horse Cave that intersect with areas of recharge may still influence how contaminants are introduced into the groundwater system. This research characterizes recharge to Hidden River Cave via fluorescent dye-tracing, cave stream discharge
measurements, and geographic information systems analysis. Land-use practices in Horse Cave are examined, as groundwater resource management varies between municipalities and counties. In addition, this research provides a more detailed description of the Hidden River groundwater subbasin and provides scientific data to the American Cave Conservation Association for more informed management of Hidden River Cave. Further, these methods can be used to evaluate groundwater resource management in other transboundary karst regions.
Chapter 1. Introduction

Institutions and policies that govern groundwater management at local, regional, and global scales often are either lacking or absent. This is particularly true, and even more challenging, in regions with aquifers that cross the geographic boundary of one or more political domains. Approximately 263 transboundary groundwater resources exist globally, many of which lie in karst regions. Karst, characterized by the chemical dissolution of carbonate bedrock, comprises 15-20% of the Earth’s ice-free landscape and generally includes karst aquifers, which provide 25% of the world’s population with drinking water. In karst regions, surface and groundwater flow are highly interconnected, and drainage occurs rapidly through conduits created by dissolution. Thus, the distribution and availability of groundwater resources are highly variable. Further, contaminants that enter the subsurface of karst regions can easily be dispersed throughout the system and across political boundaries.

Some of the challenges associated with policy development regarding transboundary karst aquifers include a limited understanding of recharge and discharge mechanics, and uncertainties in the spatial and temporal components of subsurface flow (Theesfeld 2010; Bauer-Gottwein et al. 2011; Milanović 2016). Some transboundary karst aquifers, such as the Dinaric karst aquifer in southeastern Europe, the Yucatán Peninsula karst aquifer in Central America, and the Arbuckle-Simpson karst aquifer in North America, have benefited from hydrogeologic analyses, such as groundwater dye-tracing and the development of groundwater flow models, to characterize subsurface flow, which provides data for the implementation of groundwater protection policies. However, challenges related to the lack of systematic monitoring and inconsistent land-
use zoning have limited the ability to implement best management practices (BMPs) for the protection of karst aquifers.

Few karst regions in the world have been studied and, more notably, dye traced than the south-central Kentucky karst. South-central Kentucky is a classic example of a well-developed karst landscape and includes the longest-known cave system, Mammoth Cave. Three physiographic regions comprise this area, including the Mammoth Cave Plateau, the Dripping Springs Escarpment, and the Pennyroyal Plateau, as well as a shallow, well-developed karst aquifer that formed in the Girkin, Ste. Genevieve, and St. Louis limestones. The once widely accepted concept of “out of sight, out of mind,” coupled with rapid recharge and discharge rates, historically led to contamination of the Mammoth Cave aquifer via point-source pollution, specifically the intentional, direct injection of waste into the subsurface.

Between 1975 and 1987, regional hydrogeologic investigations, including over 500 groundwater dye traces, were conducted in the south-central Kentucky karst to determine sources of contamination, during which 28 major groundwater basins were delineated (Quinlan and Ewers 1989; Meiman et al. 2001). Of these 28, the Hidden River groundwater subbasin was the most anthropogenically impacted. The Hidden River groundwater subbasin is a transboundary basin that spans multiple counties in south-central Kentucky, including Barren, Hart, and Metcalfe counties, and includes L&N Cave in Cave City, Hidden River Cave in Horse Cave, and the Hidden River Complex, situated near the Green River, which have been connected via groundwater dye-tracing. All serve as subsurface tributaries of the Hidden River groundwater subbasin, where water flows north and resurges through 46 springs along the Green River.
Infrastructural development, along with point-source groundwater contamination, increased in Horse Cave during the 1970s. Pollutants were commonly injected into the subsurface through sinkholes, and included contaminants such as raw sewage, heavy metals from a chrome plating plant, creamery waste, and oil refinery waste, among others. Based largely on the regional hydrogeologic investigations of Quinlan and Rowe (1977) and the Environmental Protection Agency (EPA 1981), a new wastewater management facility was developed in 1989, which has significantly improved the water quality of Hidden River Cave. Additionally, the American Cave Conservation Association (ACCA) has established good working relationships with the industries that have directly impacted recharge to the cave system.

Despite these changes in groundwater resource management, land-use boundaries in the City of Horse Cave intersect with areas of groundwater recharge that may still introduce contaminants into the groundwater system. Thus, dye-tracing on a more local scale, particularly regarding Hidden River Cave, is necessary to reveal further ongoing contamination events. A lack of discharge data also exists for Hidden River Cave, which could ultimately be used to determine the volume of water that transits the cave system. Further, geographic information systems have begun to play a vital role in understanding contaminant transport and the vulnerability of karst regions (Florea et al. 2002; Pfaff 2003). This study characterizes recharge to Hidden River Cave by combining groundwater dye-tracing techniques, cave stream discharge measurements, and geographic information systems analysis, including an analysis of land-use in Horse Cave, to answer the following questions:
• What can dye-tracing reveal about local land-use impacts on recharge to Hidden River Cave?

• How can stream stage data characterize the hydrology of Hidden River Cave and its potential for contaminant dispersal?

• How do political jurisdictions limit the impact of groundwater resource management in karst regions?

The data collected and discussed herein highlight the importance of groundwater resource management, particularly regarding transboundary karst aquifers, and refine existing dye-tracing maps produced by Quinlan and Rowe (1977) and Ray and Currens (1998). This research also provides scientific data to the ACCA for a more informed management of Hidden River Cave and, ultimately, the Hidden River groundwater subbasin. Further, the methods herein can be applied to other transboundary karst regions for improved groundwater resource management or the implementation of Best Management Practices.
Chapter 2. Literature Review

Understanding the basic concepts of hydrology is critical for contextualizing the hydrological relationships between the surface and the subsurface in karst regions. Several reservoirs exist that constitute the Earth’s hydrosphere, which contains approximately 1.39 billion km³ (333 million mi³) of water (Shiklomanov and Rodda 2003; Tarbuck et al. 2016). While 71% of the Earth is covered by water, 97.2% is saline, 2.14% is glaciated, 0.61% is groundwater, 0.009% is surface water, 0.005% is soil moisture, and 0.001% is contained in the atmosphere (Fetter 2014; Tarbuck et al. 2016). Thus, less than 1% is available as fresh water to supply over seven billion people on Earth, with expectations of continued population growth (Utton 1982; Bergman and Renwick 2002).

The study of the movement, storage, and properties of water, including the relationships water has with the environment and living organisms, is known collectively as hydrology (Freeze and Cherry 1979; Black 1996; Christopherson 2005). While the volume of water on Earth remains relatively constant, the partitioning of water into Earth’s reservoirs, including saline and atmospheric water, ice, and fresh water, varies depending on regional climatic conditions. The transport of water throughout the hydrosphere is characterized by the hydrologic cycle (Figure 2.1). The hydrologic cycle constitutes the continuous circulation of water between the ocean, atmosphere, and land, and forms the foundation for understanding freshwater resources and their response to changes in climate and anthropogenic activities (Freeze and Cherry 1979; Fetter 2014).
The hydrologic equation provides a quantitative method for evaluating the hydrologic cycle and forms a critical component of hydrology that represents the ubiquitous nature of water in the hydrosphere. Every process within the hydrosphere is included in this equation, which accounts for the overall flux of water on Earth over time and is widely used to determine water availability for human use (Bergman and Renwick 2002; Shiklomanov and Rodda 2003). In Fetter’s (2014) rendition, the hydrologic equation is expressed as:

\[
\text{Inflow} = \text{outflow} \pm \text{changes in storage} \quad \text{(Eq. 1)}
\]

where inflow represents recharge, or the water entering a system, outflow represents discharge, or the water leaving a system, and changes in storage represent the differences in the volume of water within a system.

Solar radiation provides a constant source of energy that continually moves water from one reservoir to another in various phases, including evaporation, transpiration,
(collectively called evapotranspiration), condensation, precipitation, overland flow, infiltration, and subsurface flow. Subsurface, or groundwater, flow provides the majority of fresh water to the world’s population and largely depends on precipitation; however, less than 1% of precipitation infiltrates the subsurface as groundwater, while the remainder either evaporates or occurs as overland flow to the oceans through rivers or streams. The distribution of precipitation directly impacts water resources, as well as the populations that depend on them. Thus, hydrologists are often interested in the amount and location of precipitation, the intensity and duration of an event, and the effect it has on the landscape (Shiklomanov and Rodda 2003; Fetter 2014; Tarbuck et al. 2016).

The geographic distribution of groundwater is closely related to the geomorphological development of the landscape, including the composition of geologic deposits that facilitate flow, as well as post-depositional processes, such as structural deformation. Groundwater flow occurs in unconsolidated surficial deposits that have been created by aeolian, deltaic, fluvial, glacial, and lacustrine geologic processes (Freeze and Cherry 1979). For example, the groundwater regime in the lowlands of the Republic of Ireland has been widely influenced by glacial deposits that occurred during the Pleistocene (Drew 2008). In some regions of the world, groundwater is stored for a relatively short time (Hess and White 1989; Ford and Williams 2007). Landscapes that are composed of carbonate bedrock, such as limestone or dolomite, often contain large openings, or conduits, that transmit groundwater relatively quickly (Tarbuck et al. 2016). Thus, these regions, known as karst, are particularly vulnerable to anthropogenic contamination (Veni et al. 2001; Aley 2002; Meus et al. 2006; Raedts and Smart 2015).
2.1 Karst Hydrology and Methodologies

The subsurface processes that occur in karst form a critical component of this study, especially as recharge to karst systems is often exposed to contamination, and few regulatory practices or laws exist to protect karst aquifers. To encourage the implementation of such regulations in karst regions, it is first necessary to understand the formation of these landscapes, recharge and discharge mechanics, and the highly dynamic nature of subsurface flow as it relates to groundwater basins. Karst makes up 15-20% of the Earth’s ice-free landscape, and generally includes karst aquifers, which provide 25% of the world’s population with drinking water, hence one reason why their protection is critical (Quinlan 1989; White and White 1989; Ford and Williams 2007; Palmer 2007).

The occurrence of dissolution as a geomorphic agent distinguishes karst from any other landscape on Earth (White and White 1989). Karst environments are created by the chemical dissolution of soluble bedrock such as limestone or dolomite and, less commonly, evaporites such as gypsum, halite, and marble (Palmer 1981; White and White 1989; Ford and Williams 2007). The most regionally broad and extensively developed karst regions lie on limestone and include surface features such as thin soils, sinkholes, and sinking streams, as well as highly elaborate and integrated subsurface drainage systems that include conduits, caves, and springs (Figure 2.2) (White and White 1989; Ford and Williams 2007; Palmer 2007). Each solution-derived karst system is a unique combination of five widely accepted components: the type of bedrock present, the fluid involved in dissolution, the presence of joints and fractures, the hydraulic gradient, and time (Ford and Williams 2007; Palmer 2007; Jackson 2017).
The permeability and porosity of carbonate bedrock ultimately control recharge and the volume of water that is stored in the subsurface (Whitley 1977). In solution-derived karst systems, spaces between granular particles (i.e., soil, sediment, or bedrock), vertical joints, and horizontal bedding planes are referred to as the rock’s porosity, and the measure of the ability of the rock to transmit fluid is known as permeability (Palmer 2007). An important characteristic of karst that distinguishes it from any other landscape is that its porosity and permeability dramatically changes over time as dissolution progresses (Ford and Williams 1989).

Primary porosity in carbonate bedrock is formed during lithification; however, as the rock undergoes temporal diagenesis, these primary voids are reduced because of the overlying pressure of sediment deposition. Later, chemical and physical diagenetic processes (i.e., dissolution and structural deformation) create secondary porosity along penetrable fractures, which continue to enlarge as groundwater circulation continues (Ford and Williams 1989). Relatively thick beds of limestone coupled with consistent precipitation must exist for dissolution to continue at a depth that causes the alteration of surface landforms and the creation of subsurface conduits and cave systems (Whitley
Palmer (1991) determined that a period ranging from 10,000 to 100,000 years is necessary to develop large, cavernous porosity (Ford and Williams 1989; White and White 1989).

Karst porosity develops when meteoric waters become enriched with carbon dioxide gas (CO$_2$) taken from the atmosphere and soil, which forms a carbonic acid solution (H$_2$CO$_3$) that effectively dissolves carbonate sedimentary rocks in a chemical weathering process known as dissolution. Limestone is the most commonly occurring soluble rock and is largely composed of calcium carbonate (CaCO$_3$) that strongly reacts with carbonic acid to produce calcium (Ca$^{2+}$) and bicarbonate (HCO$_3^-$), which is easily removed by water (Ford and Williams 2007; Palmer 2007). The following equation represents the dissociation of CaCO$_3$ into calcium and bicarbonate (Jackson 2017):

$$2H_2O + CO_2 + CaCO_3 \leftrightarrow H_2O + Ca^{2+} + 2HCO_3^- \quad (\text{Eq. 2})$$

Carbonate bedrock is the most permeable type of rock and yields a significant water resource through carbonate aquifers, or stratigraphic units with enough permeability to transmit significant volumes of water (White 1988; Ford and Williams 1989). The hydrologic composition of an aquifer includes the vadose zone, also known as the unsaturated zone, and the phreatic, or saturated zone. The vadose zone occurs above the water table, the surface on which the fluid pressure is equal to atmospheric pressure (Freeze and Cherry 1979; Ford and Williams 2007; Fetter 2014). Water percolates downward in this zone until either it reaches the water table or becomes obstructed by a localized impermeable layer, such as chert or shale. Saturated zones known as perched aquifers can sometimes occur above these localized layers, which are suspended above the water table (Ford and Williams 1989). The phreatic zone occurs below the water
table, where the fluid pressure is greater than the atmospheric pressure. While intergranular pores provide some permeability, joints, fractures, and conduits facilitate most of the dissolution that occurs in the subsurface (Whitley 1977; Palmer 2007).

Very little water occurs on the surface of karst regions due to the direct connections that enable recharge from the surface to the subsurface. Recharge to karst is characterized as autogenic, allogenic, or mixed (Figure 2.3) (Hess and White 1989; Palmer 1991; Ford and Williams 2007; Zhou 2007). Autogenic recharge occurs when water falls directly on exposed soluble bedrock, such as on the Pennyroyal Plateau of south-central Kentucky, where allogenic recharge occurs when water flows from a nearby catchment that consists of relatively insoluble bedrock, such as on the Big Clifty sandstone that overlies portions of Mammoth Cave in south-central Kentucky. Ford and Williams (2007) explained that most karst regions contain both autogenic and allogenic recharge.

![Figure 2.3. Representation of the types of recharge to carbonate aquifers. Source: Ford and Williams (2007, 79).](image-url)
Recharge to karst is often constrained by groundwater drainage basins, which are defined as the catchment area of the water that discharges to a common outlet, such as a spring. Palmer (2007) explained that drainage divides, or physical boundaries between groundwater basins, can be difficult to determine due to the three-dimensional nature of groundwater flow. Drainage divides can overlap one another, with water at different elevations draining to different springs. They can also shift as flow rates change, such as during flood events. It is common during periods of high flow for otherwise dry cave passages to become reactivated again. For example, Parker Cave in south-central Kentucky includes five sub-parallel, trellised streams as well as dry, higher-level passages (referred to by Quinlan and Ewers (1989) as intermediate level overflow routes) that only flow during and after storm events and transport water to multiple groundwater basins. Recharge to a cave is often controlled by the size of its respective catchment area and the amount of precipitation that occurs within the catchment.

Discharge is perhaps the most important characteristic of groundwater flow, as temporal variations in discharge can provide insight into the storage and transport characteristics of an aquifer (Sasowsky 2000; Palmer 2007). Discharge depends highly on the hydraulic gradient, or slope, of a region and often occurs at the lowest elevation of the respective drainage basin; the greater the drainage basin area, the more water accumulation occurs. Discharge refers to the volume of water moving down a river or stream per unit of time and is commonly expressed in m³/s (ft³/s), as shown by the following equation:

\[ Q = v \ (m/s) \times A \ (m^2) \]  

(Eq. 3)
where discharge (Q) is equal to the sum of the average flow velocity (v) multiplied by the cross-sectional area of flow (A) past a particular section of a river or stream. From these data, a rating curve (a graph of discharge (x-axis) vs. stage (y-axis) for a given point on a stream) can be established by correlating the stage and discharge of a stream segment over a specified period to obtain a continuous record of discharge. Discharge is characterized by the type of water flow in carbonate aquifers, which is classified either as diffuse or conduit flow (Quinlan and Ewers 1985; Jiang et al. 2018).

In diffuse flow aquifers, water movement occurs through relatively small, interconnected joints and bedding planes and includes low velocities, deep circulation, and multiple springs, whereas conduit flow aquifers are characterized by water transport through well-integrated channels from which few springs discharge, although discharge is more significant and can become very rapid (Figure 2.4) (Quinlan and Rowe 1977). Conduit flow is distinguished by turbulent flow over much of the network length; groundwater in carbonate aquifers can be transmitted in unpredictable patterns at six or more orders of magnitude faster than non-carbonate aquifers due to the formation of subsurface conduits.

Figure 2.4. Flow characteristics of karst groundwater basins. Source: Quinlan and Ewers (1985).
Unlike converging tributaries, distributaries are common with carbonate aquifers and involve the downstream divergence of cave passages as well as water overflow into adjacent cave passages during flood pulses. Through conduit flow, distributaries may be created by one or more of the following circumstances: (1) the enlargement of small, pre-existing anastomoses (sinuous tubes that are interconnected in a maze-like pattern along bedding planes due to dissolution, especially during flood pulses) in response to significant differences in elevation between flooded passages and their discharge locations; (2) the development of alternative discharge routes due to the collapse or blockage of a spring outlet; (3) the diversion of cave streams to lower passages as the base level becomes lowered; and (4) the expansion of conduits in the vadose zone that converge with anastomoses and other passages located at the potentiometric surface, or by changes in the stage of a river that cause the water table to fluctuate (Quinlan and Ewers 1989). Diffuse flow and conduit flow can be distinguished by the spring or output response that is classically characterized by a hydrograph (a time-series of discharge measurements) (Florea and Vacher 2006; Li et al. 2016).

Smart and Hobbs (1986) determined that hydrographs describe a three-stage aquifer response: recharge, storage, and transmission. Further, White (1988) distinguished conduit and diffuse flow based on the “flashiness” of a hydrograph, which represents the output ratio of maximum-to-mean discharge (Figure 2.5). During significant precipitation events, increased recharge to karst aquifers can cause a rapid increase in the hydraulic head, which abruptly increases the subsurface discharge due to the high velocity of the compressional (or acoustic) wave in the water. The compressional wave subsequently transmits a change in pressure downstream to establish a new pressure
gradient between the upstream inputs and the downstream outputs, resulting in an overall change of conduit flow and discharge (Li et al. 2016). The increased head at input locations can also displace water and contaminants from the conduits into the surrounding matrix, including the epikarst, which can ultimately flow back into the conduits when there is a decrease in hydraulic pressure (Goldscheider 2005; Li et al. 2008).

Figure 2.5. Parts of a spring hydrograph, where $t_L$ represents the length of time between the flood pulse and the peak discharge, $t_B$ represents the return time to baseflow, $\alpha$ represents the recession coefficient, and $t_R$ represents the response time.

Source: Fiorillo (2016).

A pronounced peak, or flashy response, in the hydrograph (known as the rising limb) following the main precipitation event is indicative of telogenic karst aquifers that are dominated by allogenic recharge and made up of well-developed conduits resulting in low storage, and rapid transmission (Vacher and Mylroie 2002; Florea and Vacher 2006;
Murdoch et al. 2016). During recession, the falling limb of the hydrograph is the most stable and can express some geometrical and hydraulic characteristics of the aquifer, as it corresponds to changes from rapid storm event flow to base flow (Dewandel et al. 2003; Bailly-Comte et al. 2010; Knierim et al. 2015). Conversely, karst that is dominated by diffuse flow, poorly developed conduits, and little allogenic recharge produces a more subdued response (White 1988; Fiorillo 2016).

2.1.1 Groundwater Dye-tracing

A key approach of this study is the use of dye-tracing techniques to determine groundwater flow mechanisms. Previous studies have suggested that groundwater dye-tracing is the most efficient way to understand and characterize groundwater flow (Aley 1972; Mull et al. 1988; Goldscheider et al. 2008); however, the ability to distinguish dyes used for tracing from background fluorescence in a hydrologic system has simultaneously become more helpful and challenging with modern technology, as background fluorescence can often resemble common dyes (White 2007). While the purpose of dye-tracing for this study is to determine if engineered drainage features recharge Hidden River Cave, background fluorescence resembling common contaminants and dyes is present throughout the cave streams (Raedts and Smart 2015). Thus, it is important to implement proper dye-tracing protocols and to understand thoroughly the results of fluorescence analyses, including the distinctions between dyes, natural, and anthropogenic fluorescence.

The potential for groundwater contamination is often high in mature karst systems due to the rapid transport of contaminants via well-developed conduits (Hess and White 1989; Vesper et al. 2001; Worthington 2011; Jiang et al. 2018). Thus, it is necessary to
understand the methodologies that have been employed to track contaminants and remediate impacted water resources, such as those observed in Hidden River Cave. Karst drainage provides ideal conditions for groundwater dye-tracing; countless dye-tracing investigations have been conducted in karst regions to determine connections within the subsurface that are not humanly traversable either due to passage size or flooding (Quinlan and Rowe 1977, 1978; Komatina 1985; Quinlan and Ewers 1989; Crawford 2003). Understanding karst hydrogeology requires knowledge of the direction of groundwater flow and how rapidly flow occurs within the bedrock.

Groundwater traces are conducted to study the movement of water by injecting an artificial tracer (i.e., fluorescent dye) into the subsurface and recovering it downstream at a predetermined location (Hubbard et al. 1982; Aley 1984). Groundwater tracing has been conducted using a variety of methods and materials since the 19th century; however, fluorescent dye use, including fluorometric analyses, became a more common technique for groundwater tracing in the 1960s (Davis et al. 1985; Aley 2002; White 2007). Several applications of groundwater dye-tracing exist, including subsurface basin delineation, determining groundwater residence time or stream dispersion and discharge, and identifying sources of contamination and the impact they have on groundwater resources. Dye-tracing has proven to be most successful in karst regions, although any setting in which preferential flow routes exist can facilitate a dye trace (Aley 2002).

White (2007, 18) explained that “dye-tracing is one of the most powerful tools in the karst hydrologist’s toolkit.” Groundwater dye-tracing, combined with hydrogeological observations, is the most accepted methodology to delineate groundwater flow paths (Goldscheider et al. 2008). The current, and widely accepted, dye-tracing
Methodologies used in karst regions include a karst hydrogeologic inventory (KHI), a background fluorescence analysis, dye injection, dye receptor retrieval, and dye receptor analysis, and were developed by pioneers such as Aley (1972, 1975, 2002), Quinlan (1989), and Crawford (1984a, 1984b, 1989, 2003, 2005). It is important to consider that these karst hydrogeologists, as well as several others, suggested that robust groundwater dye-tracing studies are generally developed over time with experience (Quinlan and Alexander 1990; Capps 2001).

Several fluorescent substances exist for dye-tracing investigations, each with different chemical and fluorometric characteristics; however, fluorescent dyes remain the tracer of choice due to their high detectability (Capps 2001; White 2007). Fluorescent dyes can be classified into three groups: optical brighteners (blue fluoresce), xanthene dyes (green to red fluoresce; includes uranine, eosine, and rhodamine), and other fluorescent dyes (blue to green fluoresce) (Käss et al. 1998). Aley (2002) explained that many fluorescent dyes are used for groundwater tracing, but the most common dyes are fluorescein, eosine, rhodamine WT, and sulforhodamine B (Figure 2.6).

Figure 2.6. Common dyes used for groundwater tracing. Source: Photo by the author (2018).
Fluorescent dyes are synthetic organic compounds that are analyzed using a scanning spectrofluorophotometer, which uses light of a specific wavelength to activate or “excite” the dye sample (excitation) and then measures the luminescence (emission) of the dye. Each fluorescent dye used for groundwater tracing is characterized by specific excitation and emission spectra (Goldscheider et al. 2008). Table 2.1 describes the properties of the above common dyes, as well as optical brightener tinopal CBS-X, as this dye is commonly encountered in background samples collected from Hidden River Cave. Detailed analytical methodology can be found in Quinlan and Alexander (1990) and Aley (2002). Additionally, European practices are described by Käss et al. (1998).

Table 2.1. Properties of commonly used groundwater tracing dyes, including their maximum emission in eluent (a liquid used to extract dye from charcoal receptors) and water in nanometers (nm).

<table>
<thead>
<tr>
<th>Dye</th>
<th>Chemical Formula</th>
<th>λ in Eluent (nm)</th>
<th>λ in Water (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tinopal CBS-X (Fabric Brightening Agent 351)</td>
<td>C_{26}H_{29}Na_2O_6S_2</td>
<td>397.7</td>
<td>397.2</td>
</tr>
<tr>
<td>Eosine (Acid Red 87)</td>
<td>C_{26}H_{30}BrNa_2O_5</td>
<td>541.3</td>
<td>535.3</td>
</tr>
<tr>
<td>Fluorescein (Acid Yellow 73; Uranine)</td>
<td>C_{20}H_{12}O_5</td>
<td>517.4</td>
<td>511.1</td>
</tr>
<tr>
<td>Rhodamine WT (Acid Red 338)</td>
<td>C_{26}H_{29}N_2NaO_5</td>
<td>568.9</td>
<td>577.1</td>
</tr>
<tr>
<td>Sulforhodamine B (Acid Red 52)</td>
<td>C_{27}H_{29}N_2NaO_7S_2</td>
<td>579.7</td>
<td>583.4</td>
</tr>
</tbody>
</table>

Source: modified from Käss et al. (1998); CHL (2018).

An important property of modern scanning spectrofluorophotometers is that they are capable of simultaneously analyzing multiple dyes within a sample. This property has improved the ability to distinguish multiple dyes from one another, as well as from natural and anthropogenic sources of fluorescence. The increased sensitivity of modern spectrofluorophotometers also allows dye emissions to be measured in parts per trillion. These enhanced capabilities, however, have established the necessity for more careful protocols, as background interference is more easily detected (White 2007). The types of background interference that can become problematic when analyzing dye samples include: the emission spectrum of natural fluorescence, which consists of a mixture of
broad, overlapping peaks; anthropogenic fluorescence, which produces localized spikes; and instances of cross-contamination, where dye peaks are present due to lack of improper protocols.

Natural substances produce fluorescence peaks that are broader, more irregular, and less symmetrical than those produced by dyes. Sources of natural fluorescence in water include algae, dissolved organic matter, fulvic and humic compounds, and inorganic minerals (Wilson et al. 1986; Aley 2002). Interferences in analysis caused by humic acids occur at excitations between 350 and 450 nanometers (nm). Smart and Karunaratne (2002) demonstrated that most other natural background fluorescence occurs at around 400 nm and declines steadily up to 600 nm. Dyes that fluoresce orange (540-600 nm) are least prone to organic background interference, whereas green (490-540 nm) and blue (390-490 nm) dyes are the most susceptible.

Anthropogenic contaminants tend to display more specific background fluorescence peaks and peak clusters, particularly at ultraviolet (short) wavelengths. Suburban areas with large population centers, heavy industrial activity, and landfill sites can introduce pollutants such as heavy metals, oils, sewage effluent, chemical waste, and solid waste, which often have fluorescence characteristics that resemble the dyes used for tracing, particularly fluorescein and tinopal (Veni et al. 2001; Aley 2002). Receiving streams that are polluted with sewage can contain high background levels of optical brightener, which is commonly encountered in Hidden River Cave (Raedts and Smart 2015). In rural and agricultural areas, groundwater is often exposed to contamination from sources such as chemical fertilizers, herbicides, pesticides (including their breakdown products), and animal waste, which increase following seasonal applications.
Dye-tracing studies in caves present the opportunity for hydrologists to directly observe and characterize groundwater flow and transport inside the karst aquifer (Goldscheider et al. 2008). It is necessary, however, to follow careful protocol when injecting dye and traversing dye traced stream passages. Smart and Laidlaw (1977) and Smart and Karunaratne (2002) provide detailed information on the properties of dyes used for tracing and background fluorescence, including the challenges associated with distinguishing multiple dyes from one another and distinguishing dyes from background interference. Because background fluorescence is often contingent on recharge processes and contaminant history, knowledge of past and present land-use is an important aspect of quality assurance in groundwater dye-tracing investigations, particularly when the flow regime transcends multiple physical and political boundaries.

2.1.2 Applications of GIS in Karst Regions

Coupled with cave stream discharge measurements and groundwater dye-tracing, an analysis of land-use changes over the Hidden River groundwater subbasin using remote sensing techniques and GIS can further explain the impacts that infrastructure can have on recharge waters to Hidden River Cave. GIS analysis in karst regions is becoming increasingly common and, facilitated by companies such as the Environmental Systems Research Institute (Esri), data sharing is becoming a standard practice among end users, which can be particularly valuable for the collaboration and potential remediation of contaminated karst groundwater resources.

Szukalski (2002) explained that a geographic information system (GIS) is a software capable of capturing, storing, analyzing, managing, and presenting geospatial data. GIS was developed in the late 1960s and has since grown into a platform that is not
only used by geographers but also by broad sectors of society (Kerski 2015; Reeder 2016). There is a growing realization that all data contain an inherent geographic location at various scales with specific spatial distributions and temporal components, which can be queried to produce maps that characterize these data and help the end user understand trends and relationships among them (Szukalski 2002; Kerski 2015). Kerski (2015) argued that maps are essential tools for studying global issues.

GIS has become an increasingly popular field and can be used for virtually any discipline; however, the use of GIS for the study and management of karst regions is a relatively new concept that is rapidly expanding. The Federal Cave Resources Protection Act of 1988 encouraged federal government agencies (i.e., the National Park Service, Bureau of Land Management, and U.S. Forest Service) to use GIS for managing and protecting cave resources. Additionally, independent caving organizations and cave and karst conservancies have also begun to use GIS for conservation and preservation practices. For example, the Kentucky Karst Conservancy uses LiDAR (light detection and ranging) to create a detailed three-dimensional representation of Big Bat Cave in Breckinridge County, Kentucky, which can serve to better manage and protect the cave system and its biota (Shinabery and Bailey 2015). At Jewel Cave, GIS has been used to implement best management practices, particularly regarding the use of herbicides near recharge features over the cave, and to better identify where cave passages cross political boundaries (Ohms and Reece 2002).

GIS technology is also commonly used to understand and mitigate the impacts of land-use changes in karst areas by providing tools and techniques for a holistic approach to the study of karst groundwater contamination (Szukalski 2002; Pfaff 2003). For
example, Pfaff (2003) used GIS and remote sensing techniques to examine the relationships between land use in Kentucky and water quality in karst watersheds, the results of which determined target areas for the implementation of a BMP, especially regarding the need for sustainable freshwater resources. Moreover, GIS has been used in several studies to determine karst areas that are vulnerable to development (Stark et al. 1999; Davis et al. 2002; Arthur et al. 2005; Gao and Zhou 2008; Capri et al. 2009; Khan et al. 2011; Sener and Davraz 2013; Edet 2014; Jasrotia and Kumar 2014; Tokatli 2014; Barroso et al. 2015; Bozdag 2015; Baalousha et al. 2018). A GIS study conducted by Leman et al. (2016) used a variation of these methods to establish environmentally sensitive areas (ESA) in Langkawi, Malaysia, an area that has recently experienced extensive economic growth, tourism, and overexploitation of resources; some of the ESAs included karst regions. Further, Leman et al. (2016) discussed the various methods that have been employed to establish ESAs using GIS.

GIS, coupled with the physical processes of karst aquifers, is essential for karst aquifer management (Li et al. 2016). Remote sensing applications, especially regarding the thermal properties of groundwater, have been used to analyze the interactions between groundwater and surface water (Oikonomidis et al. 2015; Elbeih 2015; Sener et al. 2005; Al-Adamat et al. 2003; Khalaf and Donoghue 2012; Tamborski et al. 2015; Wawrzyniak et al. 2016; Wilson and Rocha 2012). Wilson and Rocha (2016) used GIS and remote sensing tools via the USGS (2001) GloVis facility to develop a qualitative assessment of groundwater-surface water interactions in Irish lakes, the results of which were used to conduct quantitative assessments of groundwater discharge using geochemical tracers.
More commonly, GIS is being used for surface and groundwater modeling and management to understand the spatial relationships within cave systems and to identify relationships these have with the external environment (Szukalski 2002). For example, Ross (2009) used hydrological analysis, network analysis, and spatial interpolation techniques, as well as inferred dye-tracing pathways, to understand stormwater transport in karst, the results of which predicted the behavior of stormwater runoff between contaminant sites, their corresponding injection points and, ultimately, their output springs. Ross (2009) explained that these results, as well as a more complete dataset of stormwater features using Esri products, can be useful in developing more informed stormwater management in karst regions.

Esri offers an entire suite of products by which geospatial data can be stored, analyzed, manipulated, and shared for the investigation of local-to-global issues (Kerski 2015). More specifically, the advanced rendering capabilities of ArcGIS Pro are being used to visualize and model caves and other karst features in 3D (Szukalski 2002; Reeder 2016; Szukalski 2018). Esri has made it very easy to add, analyze, and update these 2D or 3D geospatial data to a web-based mapping platform known as ArcGIS Online, where data-driven visualization (Smart Mapping) allows users to explore visually, understand, and portray meaning through thematic mapping. These web-based tools can be easily used by anyone to share data among colleagues or to communicate to the public the importance of the data.

Wright (2016) explained that, globally, governments are adopting principles of open data, where data are made free to the public for access and reuse and include information on county, state, and national boundaries, land ownership, urban and rural
transportation, topographic and bathymetric data, and water pathways and drainage areas. For example, agencies and organizations in Kentucky (i.e., the Kentucky Geological Survey and the Office of Geographic Information) have recently developed databases for statewide karst data availability (Florea et al. 2002). By taking advantage of online data sharing, knowledge of karst regions and their complex flow regimes, as well as their sensitivity to groundwater contamination, can be shared more widely among the public. Currently, there is no comprehensive GIS inventory of Hidden River Cave that is publicly available, and an inventory ultimately could increase awareness and promote the use of Best Management Practices in transboundary karst regions.

2.2 The Mammoth Cave Karst Aquifer

As the study area in this research lies within the Mammoth Cave karst aquifer, it is important to understand how this region has been explained and described more broadly by past researchers. Several well-developed karst regions cover a significant portion of Kentucky (approximately 50%), including the well-studied Mammoth Cave system. Mammoth Cave is one of the oldest tourist caves in the United States, as the historic entrance allowed immediate access to a network of large, high-level trunk passages. It is also perhaps one of the most rigorously analyzed karst regions of the world, with many groundbreaking studies (Quinlan and Rowe 1977; Palmer 1981; Quinlan and Ray 1981; White and White 1989; Ray and Currens 1998).

Mammoth Cave became a national park (Figure 2.7) on July 1, 1941, and was later designated a UNESCO World Heritage Site (1981) and International Biosphere Reserve (1990) (Algeo 2004). It has been popularized as the longest mapped cave system in the world, surveyed at a length of over 650 km (404 mi) with ongoing discovery and
survey, and hosts Flint Ridge, Roppel, and Procter Caves, as well as notable karst features such as Cedar Sink and Turnhole Bend (Worthington et al. 2000; MCNP 2018; Jackson 2017). White and White (1989) explained that few karst regions exist in the United States in which several cave passages occur regionally and represent unique hydrologic functions. Indeed, south-central Kentucky is a classic example of an intensely karstified carbonate aquifer that has been studied for over 150 years (White and White 1989). To understand the spatial extent of the Hidden River groundwater subbasin and the recharge relationships it has with neighboring groundwater basins in the south-central Kentucky karst, it is important first to examine the properties of the Mammoth Cave karst aquifer.

Figure 2.7. Mammoth Cave National Park, including surrounding counties and municipalities. Source: Algeo (2004).

The south-central Kentucky karst region spans an approximate area of 1,500 km² (580 mi²) and contains a mature triple porosity carbonate aquifer that formed in nearly flat-lying Mississippian-aged limestones, including the St. Louis, Ste. Genevieve, and Girkin formations (Figure 2.8). The aquifer is approximately 120 m (394 ft) thick, with strata that subtly dip 0.25–5° to the northwest. The Green River is the hydrologic base
level (128 m; 420 ft asl) for this region and receives most of the aquifer’s discharge (McGrain and Currens 1978; Palmer 1981; Hess et al. 1989; Meiman 2006; Blair et al. 2012).

**Figure 2.8.** Stratigraphy of the Mammoth Cave region. Source: Palmer (1981).

Three physiographic regions span south-central Kentucky, including the Mammoth Cave Plateau, the Dripping Springs Escarpment, and the Pennyroyal Plateau, or Pennyroyal sinkhole plain (Figures 2.9 and 2.10). The Mammoth Cave Plateau is underlain by Mississippian clastic rocks that lie beneath the Pennsylvanian sandstone of the Illinois Basin (Western Kentucky Coal Fields) (McGrain and Currens 1978; Florea et
The Dripping Springs Escarpment is a cuesta that faces southward and separates the higher sandstone-capped Mammoth Cave Plateau from the Pennyroyal sinkhole plain, a significant recharge area that developed southeast of the Mammoth Cave Plateau that is underlain by lower Mississippian argillaceous limestones and shales (Whittley 1977; Quinlan 1989; White and White 1989). Significant stratigraphic controls of this region include the sandstone cap and shales of the Big Clifty and Fraileys members of the Golconda Formation, the Lost River Chert bed of the uppermost St. Louis Formation, and the impermeable silty and shaly units in the lower third of the St. Louis limestone, all of which can function as aquicludes or, at some locations, as aquitards.

The climate of the region is characterized by tropical marine influences from the Gulf of Mexico, which yield significant precipitation (~1,147 mm; 45 in annually) to recharge the aquifer. Horizontal bedding planes, in which many Mammoth Cave passages are developed, contribute the most to groundwater recharge (Palmer 1981; Worthington et al. 2000). Hess and White (1989) determined that nearly all of the discharge from the aquifer to the Green River is by conduit flow. Approximately 16% of the catchment is protected by the Big Clifty sandstone, where most of the caprock runoff enters directly into conduits via vertical shafts, and 28% of the catchment contributes surface runoff to the aquifer via sinking streams. The remaining 56% of the catchment occurs in the Pennyroyal sinkhole plain, which may represent half of the total recharge received by the aquifer, especially after significant precipitation events (Hess et al. 1989; Worthington et al. 2000).
Quinlan and Rowe (1977, 1978) and Quinlan and Ray (1981) delineated 28 major groundwater basins (13 of which are shown in Figure 2.11) to determine the transport characteristics and quality of groundwater in the region via potentiometric surface mapping, water chemistry analyses, and groundwater dye-tracing; over 500 dye traces were conducted for this study between 1975 and 1987 (Meiman et al. 2001). Their
analyses determined that the Hidden River and Graham Springs groundwater basins were severely contaminated and that the distributary nature of several of the groundwater basins identified can disburse contaminants over a significant area. Both groundwater basins are adjacent to the Turnhole Bend groundwater basin (the most thoroughly studied groundwater basin in the park) in Mammoth Cave National Park (MCNP), which discharges into the adjacent Echo River, Pike Spring, and Sand Cave groundwater basins via high-level overflow routes in Parker Cave during moderate and flood-flow conditions. Dyes injected in conduits within these catchments are rapidly discharged to the Green River because of the dendritic nature of channeling (Worthington et al. 2000). This has especially been a concern at MCNP because of its proximity to Interstate 65, where vehicle contaminant spills can quickly infiltrate the park boundaries via sinkholes (Capps 2001; Meiman 2006).

![Diagram of groundwater basins]

Figure 2.11. Original groundwater basin boundaries delineated by Quinlan and Rowe (1977, 1978) and Quinlan and Ray (1981).

Incorporating the work of Quinlan and Rowe (1977) and Quinlan and Ray (1981), as well as numerous other researchers and cavers, the Kentucky Geological Survey
(KGS) began the development of a karst atlas of Kentucky in 1996 composed of five 30 x 60-minute quadrangle maps at a scale of 1:100,000. Each map displays sections of the modern karst groundwater basins of south-central Kentucky using historical dye-trace data and the locations of major karst springs and swallets (Ray and Currens 1998; Capps 2001; Paylor and Currens 2002; Florea et al. 2002). Although extensive dye-tracing has been conducted in this region, it is important to note that many of these studies have been conducted on a regional scale. The study herein is more localized and aims to expand the research conducted by Quinlan and Rowe (1977) to shed light on potential future contamination issues in Hidden River Cave that have been largely identified by Raedts and Smart (2015) and the staff of the American Cave Museum, and thus establish an incentive for a more specific BMP strategy.

2.2.1 Historical Contamination of Hidden River Cave

One of the aims of this research is to contribute to a BMP strategy that can better incorporate challenges related to contaminated groundwater. The determination of the ability of the Mammoth Cave karst aquifer to transmit contaminants quickly, as well as the need for the remediation of the aquifer from contamination in the past, ultimately encouraged the implementation of better management practices (Quinlan and Rowe 1977; EPA 1981; Meiman 2006; Foster 2009; Worthington 2011). Still, and ever-present within carbonate aquifers worldwide, groundwater contamination in the Mammoth Cave region remains a primary concern. This was once, and may still be, especially true within the Hidden River groundwater subbasin.

Hidden River Cave has a particularly rich history of resource exploitation, tourism, and degradation from anthropogenic contaminants (Lewis 1995; Veni et al.
2001; Raedts and Smart 2015). From 1890 until 1912, Horse Cave received its water supply from Hidden River Cave (Lewis 1995). Afterward, wells became the primary source of water supply to the city until a drought in 1930 once again encouraged the use of the cave’s water. It became common practice for businesses and residents to dump their waste into septic tanks, tile fields, or sinkholes, ultimately degrading the water quality of Hidden River Cave; most people were unaware that sinkholes form direct connections to groundwater resources (Ford and Williams 2007). Oil refinery waste, among other contaminants, was discovered in 1931, which had been dumped into a sinkhole south of the cave. Consequently, many cases of typhoid fever developed within the community. Cave life also degraded as conditions worsened over the years and the cave tours that began in 1916 were discontinued by 1943 because of the severe pollution (Lewis 1995).

In 1964, the Horse Cave sewage treatment plant was developed and received all of Horse Cave’s waste. A sinkhole was first used as the plant’s disposal site, but two injection wells were created when the sinkhole became clogged. Both disposal methods introduced effluent into the south branch of the cave. Nearby, Cave City created a similar plant, where its effluent was dumped into a sinkhole that drained into the east branch of the cave. Additionally, several industries developed along State Road 31W in Horse Cave beginning in the 1970s, including a chrome plating plant, which contributed nearly two-thirds of the wastewater at the Horse Cave sewage treatment plant (Quinlan and Rowe 1977; EPA 1981). Lewis (1995, 217) explained that an “unbearable stench emanated from the caves polluted streams and ever-present sewage community.” Groundwater
contamination became problematic enough to launch a long-term study of heavy metals and sewage effluent in wells, cave streams, springs, and the Green River.

Using various methods, including extensive groundwater dye-tracing, Quinlan and Rowe (1977) and several other cavers and researchers determined that the effluent from the Horse Cave Sewage Treatment Plant, among other contaminants, discharged to the Green River from the Hidden River groundwater subbasin. From that study, the EPA (1981) proposed a new regional sewage treatment facility in 1981 that involved terminating subsurface effluent discharge by creating a pipeline that would channel wastewater to a new treatment plant in nearby Munfordville. The sewage treatment plant began operating on December 16, 1989, and currently cleans wastewater in Horse Cave, then pumps it to Munfordville, where it is treated again before being released into the now highly protected Green River (Lewis 1995; Raedts and Smart 2015). The American Cave Museum (ACM), a nonprofit environmental institution managed by the American Cave Conservation Association (ACCA), opened in 1992 and limited tours of the cave began again in 1993 after 50 years of closure. In 1995, extended tours began, and an educational division was created to inform visitors about the protection and conservation of caves and karst (Lewis 1995; Foster 2009).

While the recovery of the cave ecosystem has been successful overall, reports of the absence of some biota and poor water quality have been made by staff at the ACM. Since the beginning of the 21st century, a significant increase in industrial development has occurred over the catchment area of Hidden River Cave. Raedts and Smart (2015) conducted background fluorescence analyses from 2008-2014 to characterize potential contaminant transport from industrial sites in Horse Cave. During this study, several
contaminants were observed in the cave, including evidence of light non-aqueous phase liquids (LNAPLs), dense non-aqueous phase liquids (DNAPLs), foam and soap suds, and solid waste. Vesper et al. (2001) outline the types and significance of contaminants that karst is often exposed to, including their transport mechanisms. Coupled with dye tracing, various integrative techniques exist to assess groundwater contamination in karst that can effectively link such events to land-use practices (Crawford 1984b; Quinlan and Ewers 1985; Ryan and Meiman 1996; Rhodes et al. 2001; Li et al. 2010; Reed et al. 2011; Knierim et al. 2015).

Inadequate human and financial resources exist to create, update, and maintain geospatial data in the city of Horse Cave. This can be seen by the significant temporal gap that exists between issuances of land-use zoning maps. A new online map was published in 2017; however, the most recent map before this was published in 1989. Additionally, storm drainage data (as well as many other data critical to the regular maintenance of the city) are not readily available, and the management of storm drains is not prevalent in Horse Cave (Raedts and Smart 2015). Additionally, there is little consideration in local policy development or management practices of the impacts of transboundary inputs, where water and/or contaminants may enter the local political jurisdiction from surrounding areas.

More broadly, research on boundary issues related to the management of water resources has grown significantly in recent years, driven in part by concerns over the hydrological impacts of climate change. At the meso-scale, recent research has examined transboundary water governance to determine science-policy strategies (Giordano et al. 2002; Eckstein and Eckstein 2005; Zaisheng et al. 2008; Foster and van der Gun 2016;
Shrestha and Ghate 2016; Karar 2017; Lipponen and Chilton 2018). Three specific karst regions are selected here to demonstrate the complexity of the issue and to highlight how transboundary water governance has evolved.

2.3 Challenges of Transboundary Karst

All groundwater, globally and locally, traverses political boundaries at some point in the hydrologic cycle (Minghi 1963). While the implications of transboundary groundwater governance have been increasingly addressed in the literature, management varies across governments, sometimes with goals that are unclear. Thus, broad principles rather than normative practices should be implemented (Jarvis et al. 2005; Armitage et al. 2015; Woodhouse and Muller 2017). For example, the International Shared Aquifer Resources Management program, Worldwide Hydrogeological Mapping and Assessment Program, and the International Ground Water Resources Assessment Center have begun to implement broad transboundary collaboration efforts via mapping, data management, and data sharing (Ganoulis and Aureli 2010; Chen et al. 2017). Examples such as these, coupled with discharge analyses, groundwater dye-tracing, and GIS analyses (Stevanović et al. 2016) conducted for the protection of karst waters are, in part, the inspiration behind the methodologies of this study.

Because surface and groundwater are naturally occurring systems that regularly transcend the geographic boundaries of one or several political territories, they can create conflicts between political units based on the location of the boundary and the distribution, quality, and availability of freshwater resources (Ganoulis 2007). Jarvis et al. (2005) explained that the hydrologic link between surface and groundwater is recognized, but poorly understood. Because of this, few laws exist globally regarding groundwater
management; however, the protection of groundwater resources has become more urgent over the past fifty years with an increase in global population.

Transboundary aquifers are those that cross the geographic boundary of one or more political territories (Figure 2.12) (Minghi 1963). There are approximately 263 significant transboundary groundwater basins globally, many which lie in karst regions (Jarvis et al. 2005). Some of the challenges associated with policy development regarding transboundary karst aquifers include a limited understanding of recharge and discharge characteristics and uncertainties in overall subsurface flow regimes. Additionally, the spatial component of subsurface flow within many transboundary karst aquifers is not well understood.

![Figure 2.12. Example of a transboundary aquifer spanning two political boundaries. Source: Jarvis et al. (2005, 768).]

The need for the implementation of boundary studies in karst regions can be exemplified by examining case studies where policies on groundwater are either absent or weak. These examples emphasize the need for the implementation, or the advancement, of hydrological methodologies such as the characterization of discharge, groundwater dye-tracing, and land-use analyses using GIS. Additionally, the issues of groundwater
distribution, quality, and availability are highlighted, as are the ongoing (and suggested) efforts to remediate conflicts between neighboring countries, states, or counties.

2.3.1 The Dinaric Karst Aquifer

Many examples exist of transboundary karst aquifers that receive recharge on one side of a geographic boundary, while discharge and, often, more significant freshwater yields are received on the other side of the boundary. The Dinaric karst region of southeastern Europe is made up of well-developed carbonates that span from the Crasso region near Trieste, Italy, to southwestern Albania. This region not only is considered the world’s classic karst region, and the birthplace of karst geoscience as a discipline, but it also represents the redistribution of freshwater resources that was induced by political upheaval.

The breakup of Yugoslavia in the 1990s created several new sovereign states whose boundaries have altered groundwater availability between neighboring countries. For example, nearly 95% of the Trebisnjica Springs catchment is situated in Bosnia and Herzegovina, while discharge occurs in Montenegro; international transboundary flow conflicts did not exist when these states were unified, although inter- or intraregional disputes did occur over access to, and management of, water resources and the introduction of pollutants (Jancar-Webster 1987). Along the Neretva River valley, the largest springs are Buna and Bunica, which recharge in the Federation of Bosnia and Herzegovina and discharge to the Republic of Serbska (Figure 2.13). Additionally, transboundary connections between sinkholes and springs, such as Plitvice-Klokot and Trebišnjica-Ombla, often introduce pollutants from one country into another (Milanović 2016; Stevanović et al. 2016).
Over 650 groundwater dye traces have been conducted to characterize groundwater flow in the former Yugoslav states, including 281 in eastern Bosnia and Herzegovina, 99 in the Cetina River basin, and 77 in the Skadarsko Lake basin (Komatina 1985; Milanović 2000). Based on 380 tracer experiments, Komatina (1985) suggested that, during the wet season, dye travels two to five times faster than under base flow. Although many dye-tracing investigations have been implemented in this classic karst region, several basins have not yet been properly delineated.

Figure 2.13. Transboundary karst aquifer flow in Eastern Herzegovina. Source: Milanović (2016, 109).

Except for Croatia, the characterization and monitoring of groundwater in the Dinarides does not adhere to the European Union Water Framework Directive. Stevanović et al. (2016) suggested that deficiencies exist in the implementation of
legislation and development of by-laws due to the lack of human and financial resources. Because of this, the DIKTAS (Protection and Sustainable Use of the Dinaric Karst Transboundary Aquifer System) project was created and includes Albania and the former Yugoslav territories of Bosnia and Herzegovina, Croatia, and Montenegro. The purpose of the project has been to improve the understanding of shared water resources between local water users, to promote their sustainable utilization, and to protect the dependent ecosystems. Stevanović et al. (2016) explained that, on a regional scale, the Dinaric karst has been heavily investigated; however, because of the complexity of the subsurface flow regime, detailed survey and systematic monitoring should be further improved.

2.3.2 The Yucatán Peninsula Karst Aquifer

The Yucatán Peninsula karst aquifer is shared between Belize, Guatemala, and Mexico and forms a significant freshwater resource in the region. The Yucatán aquifer is dominated by turbulent conduit flow and contains major cave systems, including the world’s longest underwater cave, Sistema Sac Actun (Palmer 2018). Seawater intrusion into the aquifer is extensive and often reaches tens of kilometers inland, restricting fresh groundwater to a relatively thin zone (10–100 m; 33-328 ft thick) (Bauer-Gottwein et al. 2011). Inadequate wastewater management, agricultural practices, and tourism have also negatively impacted the quality of freshwater resources, further limiting freshwater availability.

Groundwater management on the Yucatán Peninsula is mostly concerned with water quality, which is heavily impacted by wastewater discharge. For example, in the Mérida metropolis, freshwater is only available 60 m (197 ft) beneath the city, as the upper 20 m (65 ft) are contaminated by septic tank effluent. Thus, one-third of the
potential water supply is unfit for human consumption. In southern Quintana Roo, groundwater contamination occurs from agricultural practices, and excessive development and population growth on the Riviera Maya introduces substantial amounts of wastewater and solid waste to the subsurface, particularly from landfill sites. Wastewater management in this region is not well regulated, as many of these contaminants are transported by groundwater to neighboring states (Figure 2.14).

![Figure 2.14. Regional groundwater flow in the Yucatán Peninsula. Source: Bauer-Gottwein et al. (2011, 516).](image)

Land-use zoning is one of the primary challenges of groundwater resource management in the Yucatán, including the lack of established groundwater protection areas; however, the establishment of protected groundwater resources can be created via groundwater basin and aquifer vulnerability maps (Bauer-Gottwein et al. 2011). Significant progress in characterizing the hydrology of the Yucatán Peninsula has been achieved over the last few decades. For example, conduits in the Riviera Maya have been delineated using scuba diving, dye-tracing, and geophysical techniques. Cave systems
and their flow regimes have also been mapped in Quintana Roo using similar methods. Additionally, multiple dye traces were conducted to determine the flow regime and residence times of the Aktun Ha cave system, the results of which exhibited highly heterogeneous local flow systems (Beddows and Hendrickson 2008).

Despite these investigations, a need for hydrological research and practical groundwater management in the Yucatán Peninsula remains. Bauer-Gottwein et al. (2011) suggested that additional groundwater dye-tracing projects could be valuable in determining intermediate and small-scale conduit flow. Further, they explained that the management of the Yucatán karst aquifer requires collaboration and exchange of knowledge across federal and national boundaries, a practice that is currently not prevalent in this region.

2.3.3 The Arbuckle-Simpson Karst Aquifer

The Arbuckle-Simpson Aquifer spans five counties in south-central Oklahoma (Figure 2.15) and has been designated a sole-source aquifer by the EPA (1989) because it is the primary source of water for approximately 45,000 people in the region. The Arbuckle-Simpson Aquifer also holds cultural significance, as it has been an important resource for the Chickasaw and Choctaw Native American tribes since the Indian Removal Act of 1830. In 2002, the Central Oklahoma Water Resource Authority proposed to purchase rights to the aquifer to acquire water for various industrial operations via a 142-km (88 mi) pipeline from the aquifer to Canadian County in central Oklahoma. Local residents, citizen groups, and the National Park Service were concerned that significant groundwater withdrawals from the aquifer would decrease discharge to
streams and springs, which would ultimately limit the availability of freshwater resources.

Figure 2.15. The Arbuckle-Simpson karst aquifer in south-central Oklahoma. Source: Christenson et al. (2011, 3).

In 2003, the state of Oklahoma passed Senate Bill 288, which put a moratorium on the transportation of water out of the Arbuckle-Simpson Aquifer and required the Oklahoma Water Resources Board (OWRB) to determine the amount of water that could be withdrawn from the aquifer without interfering with the natural flow regime (Layden 2015). The OWRB, along with other state and government agencies, conducted a hydrologic study, which included the characterization of subsurface flow and the creation of a water budget. Using MODFLOW software from the United States Geological Survey, a groundwater flow model was created to simulate discharge, which determined that increased withdrawal of groundwater from the aquifer would result in fewer discharge features (Christenson et al. 2011; Layden 2015). Thus, the hydrology study effectively dismissed the proposed withdrawal of groundwater.
Several hydrological investigations have occurred in this region; however, no evidence of groundwater dye-tracing exists. Additionally, in conjunction with using MODFLOW, hydrological modeling using tools available through Esri’s software suit could provide a more thorough analysis of overall groundwater characteristics, especially as MODFLOW is designed to characterize groundwater flow in non-carbonate aquifers. Although the Arbuckle-Simpson Aquifer is protected from excessive groundwater withdrawals, these methods could solidify the results of the investigation, thus producing a more viable case if future issues were to arise.

As seen in each case study presented, as well as the problems presented by Hidden River Cave, there is an inherent lack of human and financial resources to implement the regulations and BMPs that are necessary to sustain groundwater resources. This also inhibits the need for proper, updated zoning protocols. While many of these studies have been conducted on a regional scale, it is sometimes necessary to gather details in a more localized setting and to identify the management issues within, which may then be applied to larger regions. Further, there is a lack of data exchange and collaboration in these often-overlooked karst landscapes. This research aims to fill a gap in the literature by evaluating land-use and recharge relationships at the local scale and by using modern techniques, such as ArcGIS Online, to share the information and data gathered from this study. This, in turn, could raise awareness about the significance of groundwater contamination in karst regions and the urgent need for BMPs and regulations to protect the groundwater resources on which we highly depend.
Chapter 3. Study Area

The study area has been selected in part because of its historical and regional significance within the wider south-central Kentucky karst region, and due to the importance of Hidden River Cave to the local economy and community. The Gorin Mill groundwater basin is one of the largest in south-central Kentucky, draining an area of 394 km$^2$ (152 mi$^2$) (Quinlan and Rowe 1977; Ray and Currens 1998; Blair et al. 2012). The most significant features of this groundwater basin include the inner Hidden River groundwater subbasin (324 km$^2$; 125 mi$^2$) (Figure 3.1) and its associated cave systems. The westernmost part of the study area lies on the Mammoth Cave Plateau, while the rest lies on the Pennyroyal Plateau, where the terrain is gently sloping and pitted with sinkholes (McGrain and Currens 1978; Mitchell 1993).

![Figure 3.1. Contemporary map of groundwater basins in south-central Kentucky, including the Hidden River groundwater subbasin that makes up most of the larger Gorin Mill groundwater basin. Source: Created by the author (2018).](image-url)
Using groundwater dye tracing via the study mentioned in section 2.2.1, Quinlan and Rowe (1977) determined that effluent from the Horse Cave Sewage Treatment Plant, among other contaminants, traveled 1.6 km (1 mi) northeast to Hidden River Cave and then 6-8 km (4-5 mi) north toward the Green River, where it could be dispersed to as many as 46 springs over an 8-km (5 mi) span of the Green River (Figure 3.2).

![Figure 3.2. Inferred groundwater flow paths determined by Quinlan and Rowe (1977).](image)

Hidden River Cave forms one of the main tributaries of the Hidden River groundwater subbasin and is the focal point of this study due to its proximity to industrial development, its history of significant contamination, and its direct connection to the Mammoth Cave karst aquifer. Industrial activity has increased in recent decades, along
with an inherent risk of further contamination of the cave. This, in turn, not only could harm cave biota and the revenue that is generated by tourism to upkeep the American Cave Museum (ACM), but also the well-being of the overall Hidden River groundwater subbasin that recharges the Mammoth Cave aquifer and resurges at the Green River, on which many communities depend for freshwater resources. Hidden River Cave lies in the town of Horse Cave, Hart County, Kentucky (Figure 3.3).
Land use in Horse Cave is divided between agricultural, residential, commercial, and industrial districts, as well as a central business district. Nearly half of the 108,051 hectares (ha) (267,000 acres) of gently rolling terrain in Hart County is designated as farmland, although the number of growers has decreased over time. Those that continue growing, however, have effectively increased the number of acres they grow. Once a major tobacco hub, Hart County is now a national leader in alfalfa production.

Recently, Hart County has become more focused on industrial growth and hosts a variety of industries. Most of the manufacturing and commercial companies of Hart County are located in Munfordville and Horse Cave. Since 2006, two major industries have developed in the county, while several other existing businesses have expanded. The Dart Container Corporation is the county’s largest employer and has expanded nine times since its opening in 1980, occupying ten buildings that cover nearly 27 ha (67 ac) of land in Horse Cave. Nearly 1,500 employees from Hart County and the surrounding region operate this facility. In addition, T. Marzetti Company (founded 2006) and Sister Schubert’s Homemade Rolls (2007) are among the newest industries in Hart County and are housed in an 8,547 m² (92,000 ft²) manufacturing plant located in Progress Park in Horse Cave. The Geothermal Supply Company, Irving Materials, Inc., and Kentucky Chrome Works are also located in Horse Cave; Kentucky Chrome Works has established a plan for expansion soon. This ongoing growth in industrial areas and the weakness of groundwater and land-use regulations raise questions about whether the town utilizes BMPs effectively. Despite the strong bonds that exist between the ACM and the city, discreet contamination of the cave’s streams may still be ongoing.
The Hidden River groundwater subbasin includes L&N Cave (surveyed at 3 km; 2 mi) in Cave City, Hidden River Cave (16 km; 10 mi) in Horse Cave, and the Hidden River Complex (32 km; 20 mi) situated near the Green River. The Hidden River Complex is a cave system that is only accessible for a few months throughout the year when the Green River is at base level conditions (Quinlan and Ewers 1989). The Hidden River groundwater subbasin exhibits distributary flow, where flooded, low-level conduits have created a system of interconnected passages that flow north toward Munfordville and resurge through 46 springs situated on, slightly above, and below the Green River (Quinlan and Rowe 1978; Quinlan and Ewers 1986; Lewis 1995; Meiman 2006). Previous dye-tracing confirmed that groundwater from the confluent streams (the East River and the South River) of Hidden River Cave discharge through this distributary system. All or most of the base flow discharges to Gorin Mill Spring, which receives the largest volume of base flow in Kentucky at 0.7 m³/s (24 ft³/s) (Quinlan and Rowe 1977; White and White 1989; Blair et al. 2012).

The town of Horse Cave is centered around the cave on which its name and historical water supply were derived. Hidden River Cave is a major tourist attraction for Horse Cave and lies 45 m (150 ft) beneath the town, approximately 15 km (9 mi) east of the historic entrance to Mammoth Cave. Hidden River Cave is part of the extensive Mammoth Cave karst aquifer and lies in the St. Louis limestone (Figure 3.4), the upper part of which consists of the Lost River chert and tends to perch groundwater locally (Blair et al. 2012). The entrance to Hidden River Cave is located in a 30 m (98 ft) deep collapsed sinkhole (Figure 3.5) that is managed by the ACM (McGrain and Currens 1978; Foster 2009). Hidden River Cave is comprised of a dendritic network of canyons
and collapsed domes. Large river passages exist in the cave, with high, interspersed breakdown rooms (White et al. 1970; Quinlan and Ewers 1989; Worthington et al. 2000).

Figure 3.4. Surface geology of Horse Cave. Hidden River Cave lies 45 m (150 ft) below Horse Cave in the St. Louis Limestone. Source: Created by the author (2018)
3.1 Site Selection in Hidden River Cave for Dye-tracing and Discharge Calculations

Areas in Hidden River Cave that were the focus of investigation include the East River, South River, areas in the Breakdown Canyon (Breakdown Canyon entrance, CC’s Pool, and the well casings), the Waterfall Room, and the headwaters of Wheet River. The main stream is known as the East River and begins at the bottom of the cave’s collapsed entrance, where guided cave tours begin, and drains an area of approximately 150 km$^2$ (57 mi$^2$). The South River is a smaller stream that is a tributary of the East River and, based on dye-tracing (Quinlan and Rowe 1977), drains an area of approximately 8 km$^2$ (3 mi$^2$). Wheet River is the main upstream tributary of Hidden River Cave and is suggested also to form the main tributary of the South River. Several smaller tributaries and seeps are also suggested to be connected to the South River and recharged via surface sinkholes. Based on background fluorescence analyses, Raedts and Smart (2015)
explained that each of these sites exhibit background fluorescence characteristics similar to optical brighteners and fluorescein.

The entrance to Breakdown Canyon serves as a monitoring site due to its location between Wheet River and South River. A more recent area of investigation includes a passage north of the Breakdown Canyon entrance known as CC’s Pool. This passage contains solid waste, roots and lawn clippings, and beetles from the surface, which indicate that a relatively direct connection exists nearby. A stream passage lies at the bottom of CC’s Pool, where surface and cave crayfish are commonly found.

Raedts and Smart (2015) found that the most notable source of contamination is located in Breakdown Canyon between the South River and Wheet River, where one of two 152.4 mm (6 in) drainage wells (Figure 3.6) is inferred to open on the surface near a concrete mixing plant. An apparent concrete substance and short wavelength emitters that are typical of diesel fuels, lubricants, and soaps were observed in seeps and drips near the well casing. These events exhibited inconsistent spectra during Raedts and Smart’s (2015) background fluorescence analysis, which they suggested may be indicative of various contaminants.

Additionally, recharge to the Waterfall Room (Figure 3.7) is steady, regardless of drought conditions, and consistently exhibits a very low, ambient fluorescein peak (515 nm) and a distinctive chlorine odor. Raedts and Smart (2015, 331) explained that the consistent spectra suggested the release of a dye in which no apparent release mechanism exists. Thus, for this site to be the focus of dye-tracing investigations, considerations must be made of the types of dye used during tracing.
Figure 3.6. 152.4 mm (6 in) well casings in Breakdown Canyon, observed by P. Nims in Hidden River Cave. Source: Photo by the author (2017).

Figure 3.7. The Waterfall Room (003), Hidden River Cave, observed by A. Posani. Source: Photo by the author (2017).
Four sites were chosen on the surface for dye-injection locations in Horse Cave (Figure 3.8). A long-lasting suspicion that some storm drains and injection wells drain to the cave system has been based on historic contamination of the cave stream as well as ongoing visible solid waste, evidence of soaps and diesel fuels, and pungent smells of chlorine and diesel fuel. Additionally, storm drainage (Raedts and Smart 2015, 333) and sewage data are not readily available, and the management of storm drains is not apparent in Horse Cave. Thus, the integrity of the city’s utility infrastructure is not certain. Three storm drains and two injection wells were selected for dye-tracing. These include a storm drain associated with the Horse Cave Car Wash, an injection well that is frequently used to drain runoff waste from a local concrete mixing plant, and two storm drains near the now retired Horse Cave recycling center, where contaminants from waste were observed flowing into the storm drains (Raedts and Smart 2015, 333). These features were chosen among many to understand how infrastructural boundaries intersect with natural areas of recharge. While numerous sinkholes may facilitate a dye trace, this study focuses on infrastructure that has long been questioned to determine if engineered drainage features are directly recharging the cave system.
Figure 3.8. Dye injection locations in Horse Cave, with C. Ballard and S. Ray observing. Source: Photos by the author (2017).
Chapter 4. Methodology

4.1 Dye-tracing Geodatabase

A dye-tracing geodatabase was created to house the data therein and included a shapefile of Hidden River Cave that was obtained from ArcGIS Online (Szukalski 2013) and aerial imagery of Horse Cave that was obtained from the Kentucky Division of Geographic Information online. Geologic data were obtained from the American Cave Conservation Association (ACCA) (Russel 2018) and the Kentucky Geological Survey (KGS 2010). Additionally, engineered drainage features in town that have been suggested to contribute recharge to Hidden River Cave (Raedts and Smart 2015; Nims 2018) were chosen as dye injection sites and georeferenced using Collector for ArcGIS. Dye receptor sites in the cave were chosen based on a literature review of previous studies, observations of contaminants (including LNAPLs, DNAPLs, soaps, and solid waste), and areas of recharge relative to the drainage features (Figure 4.1). Each surface and subsurface site was photodocumented and given a unique inventory name and number (Table 4.1).

Table 4.1. Dye-tracing feature inventory.

<table>
<thead>
<tr>
<th>Dye Injection Sites</th>
<th>Dye Receptor Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site ID</td>
<td>Location</td>
</tr>
<tr>
<td>DT1</td>
<td>Horse Cave Carwash</td>
</tr>
<tr>
<td>DT2</td>
<td>Injection Well</td>
</tr>
<tr>
<td>DT3</td>
<td>Recycling Center Storm Drain A</td>
</tr>
<tr>
<td>DT4</td>
<td>Recycling Center Storm Drain B</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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</table>

Source: Created by the author (2018).
Two phases of groundwater dye-tracing occurred during this study that included background analyses. Phase I dye-tracing consisted of the placement of 9 receptors and dye injection at two sites (DT1 and DT2), while Phase II consisted of the placement of 10 receptors and dye injection at two sites (DT3 and DT4). Each receptor inventory number corresponds to its respective trace. For example, the Waterfall Room (003) is denoted 003-1 for Phase I dye-tracing and 003-2 for Phase II dye-tracing.
4.2 Fluorescent Dye-tracing

4.2.1 Background Fluorescence Analysis

Background fluorescence monitoring occurred before each dye injection to detect dyes used in previous studies, pollutants, or natural compounds with fluorescence properties similar to the dyes used by the Crawford Hydrology Laboratory (CHL) at Western Kentucky University. Dye receptors consisted of 50.8 mm (2 in) mesh bags filled with approximately three grams of activated coconut charcoal. Receptors were installed in the main flow of each site using 22.7 kg (50 lb) monofilament fishing line to ensure flood conditions could not flush the receptors away from their respective sites, paper clips to secure the receptors onto the fishing line, and rocks to anchor the receptors. Monitoring occurred for one week for each background analysis. After the one-week monitoring period, each dye receptor was washed in the respective cave stream to free the sample of any accumulated sediment, carefully placed into a clearly labeled, sealable plastic bag, and stored in a cooler to be transported to the laboratory for analysis. New receptors replaced the background samples in anticipation of the upcoming dye traces.

To prepare for analysis, dye was extracted from one gram of weighed out charcoal from each sample using eluent made up of a mixture of N-Propanol, ammonium hydroxide, and distilled water at a ratio of 5:2:3. The elutant (the solution of eluent and dye) was analyzed using synchronous scanning on the Shimadzu RF-6000 Spectrofluorophotometer, which can easily identify dye concentrations up to parts per trillion (Shimadzu Corporation 2015). The order of analysis (as per protocol (CHL 2016)) was: 1. distilled water or eluent blank, 2. control standard for each dye being analyzed, 3. sample set under low concentrations, 4. sample set under high concentrations (if...
necessary), 5. distilled water or eluent blank, and 6. the control standard for each dye.
The emission spectra of the synchronous scans were then produced and plotted on a laser printer. The results of the analysis were recorded using Microsoft Excel.

For background analysis, a sample is considered to exhibit positive fluorescence spectra if the concentration is: 1. greater than or equal to the practical quantitation limit of a particular dye, 2. the shape of the curve from the synchronous scan exhibits the characteristic symmetrical shape of the particular dye, and 3. the recorded peak of the emission curve is within + or – 5 nm of a particular dye peak. The results of each background analysis were used to choose a dye for injection that is distinguishable from background concentrations.

4.2.2 Dye-tracing Procedures

Fluorescent dyes for each trace were chosen based on the analysis and interpretation of background fluorescence spectra. The quantity of dye for each injection was calculated via the following equation as per Aley and Fletcher (1976):

\[
W_d = 1.478 \sqrt{dQ/V}
\]  
(Eq. 4)

where \( W_d \) = weight of the dye to be used (kg)

\( d \) = distance between injection and receptor sites (km)

\( Q \) = discharge (m\(^3\)/s)

\( V \) = stream velocity (m/s)

Several equations exist that are specific to either uranine or spore tracers; however, Aley (2002) stated that the quantity of dye to use for different types of tracers can be considered using the following generality:

Dye Quantity: Fluorescein < Eosine < Rhodamine WT < Sulforhodamine B
Before any of the dye injections occurred, a dye trace notification was submitted to the Kentucky Division of Water to inform the public about ongoing traces. Dye injection occurred at four sites in Horse Cave and included the injection of eosine (EO) and rhodamine WT (RWT) during Phase I and fluorescein (FL) and sulforhodamine B (SRB) during Phase 2. Each dye was carefully injected into the respective drainage site using CHL (2016) protocols and either naturally flushed via precipitation or by assistance from the Horse Cave fire chief. Monitoring occurred for one to two weeks for each dye trace.

After the monitoring period, each dye receptor was collected and stored as outlined in section 4.2.1 and transported to the laboratory for analysis. In preparation of analysis, the charcoal samples were weighed and eluted. The elutant was analyzed using synchronous scanning on the Shimadzu RF-6000 Spectrofluorophotometer. For the results to be considered positive, the concentration of dye extracted from each receptor must be ten times greater than either the practical quantitation limit (PQL) of the particular dye or the initial background concentrations.

4.2.3 Phase I Dye-tracing

Phase I background monitoring occurred on March 9, 2018, and consisted of the placement of 9 receptors at all but one site (007) outlined in Table 4.2. The background receptors were retrieved on March 16, 2018, and a six-dye background analysis was conducted on March 20\textsuperscript{th} to determine which of the dyes available at the CHL would display fluorescence peaks other than those found in the background samples. The six dyes for which the background samples were analyzed included Tinopal CBS-X (OB),
FL, EO, D&C Red 28 (R28), RWT, and SRB standards. The Phase I background monitoring data are presented in Table 4.2.

Table 4.2. Results of the background fluorescence analysis conducted for Phase I dye-tracing.

<table>
<thead>
<tr>
<th>Feature ID</th>
<th>Result Conc. (ppb)</th>
<th>Result Peak Ctr. (nm)</th>
<th>Fluorescein</th>
<th>Result Conc. (ppb)</th>
<th>Result Peak Ctr. (nm)</th>
<th>D&amp;C Red 28</th>
<th>Result Conc. (ppb)</th>
<th>Result Peak Ctr. (nm)</th>
<th>Rhodamine WT</th>
<th>Result Conc. (ppb)</th>
<th>Result Peak Ctr. (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel River (001-1)</td>
<td>B</td>
<td>1.023</td>
<td>399.4</td>
<td>B</td>
<td>4.757</td>
<td>401.4</td>
<td>B</td>
<td>0.012</td>
<td>522.6,POR</td>
<td>B</td>
<td>7.555</td>
</tr>
<tr>
<td>Board Room (002-1)</td>
<td>B</td>
<td>1.096</td>
<td>404.8,POR</td>
<td>B</td>
<td>0.962</td>
<td>563.6</td>
<td>B</td>
<td>0.485</td>
<td>563.6,POR</td>
<td>B</td>
<td>3.826</td>
</tr>
<tr>
<td>Well Casing A (004-1)</td>
<td>B</td>
<td>0.721</td>
<td>395.6</td>
<td>B</td>
<td>0.120</td>
<td>514.4</td>
<td>B</td>
<td>0.026</td>
<td>521.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Well Casing B (005-1)</td>
<td>B</td>
<td>0.885</td>
<td>398.6</td>
<td>B</td>
<td>0.035</td>
<td>514.4</td>
<td>B</td>
<td>0.045</td>
<td>521.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Well Casing C (006-1)</td>
<td>B</td>
<td>0.026</td>
<td>398.6</td>
<td>B</td>
<td>0.035</td>
<td>514.4</td>
<td>B</td>
<td>0.045</td>
<td>521.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>South River (009-1)</td>
<td>B</td>
<td>0.026</td>
<td>398.6</td>
<td>B</td>
<td>0.035</td>
<td>514.4</td>
<td>B</td>
<td>0.045</td>
<td>521.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

= Initial Background. B = Background (< 10 times background or lowest detection limit). POR = Peak Out of Range (< 5 nm from peak center).

Source: Created by the author (2018).

Four dyes were detected in the background samples, including OB, FL, R28, and RWT. Based on these results, in conjunction with a literature review, it was determined that RWT would be used to trace the car wash storm drain (DT1) that was suggested to be associated with recharge to the Waterfall Room (003) and EO would be used to trace the injection well (DT2). The amount of dye needed for Phase I tracing was determined using Equation 4.1 and the data in Table 4.3, which include baselevel velocity and discharge data from the Wheet River resurgence and the distances from the injection sites on the surface to the anticipated discharge site in the cave.

Table 4.3. Velocity, discharge, and distance data used to determine the proper dosage of dye for Phase I tracing.

<table>
<thead>
<tr>
<th>Site ID</th>
<th>Injection Site</th>
<th>Distance (km)</th>
<th>Base Flow Q (m³/s)</th>
<th>Base Flow V (m/s)</th>
<th>Dosage (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT1</td>
<td>Car Wash Storm Drain</td>
<td>0.18</td>
<td>0.04</td>
<td>0.45</td>
<td>0.19</td>
</tr>
<tr>
<td>DT2</td>
<td>Injection Well (EO)</td>
<td>0.07</td>
<td>0.04</td>
<td>0.45</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Source: Created by the author (2018).

However, because the equation used is specific to FL, twice the amount of dye was injected. Phase I dye injection occurred during the evening of April 6th, and included the injection of 0.49 kg (kilograms) (1.1 lb) of RWT into the storm drain near the Horse Cave carwash (DT1) and 0.34 kg (0.75 lb) of EO through the injection well located near...
the concrete mixing plant (DT2), two areas that have long been speculated to contribute recharge to the cave (Raedts and Smart 2015). Both dyes were injected before a rain event to ensure proper flushing of each drainage feature. Monitoring occurred for two weeks, after which the receptors were retrieved on April 20, 2018. Analysis was conducted on April 26th using the procedures outlined in section 4.2.2, which are based on CHL protocols.

4.2.4 Phase II Dye-tracing

Phase II background monitoring consisted of the placement of 10 receptors (Table 4.4) on July 20, 2018, which included an additional site in Breakdown Canyon known as CC’s Pool (007-2). The background receptors were retrieved on July 27, 2018, and a five-dye background analysis was conducted on August 1st using OB, FL, EO, RWT, and SRB standards. The results of the Phase II background analysis are presented in Table 4.4.

Table 4.4. Results of the background fluorescence analysis for Phase II dye-tracing.

<table>
<thead>
<tr>
<th>Feature ID</th>
<th>Tinopal CBS-X</th>
<th>Fluorescein</th>
<th>Eosine</th>
<th>Rhodamine WT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Result Conc. (ppb) Peak Ctr. (nm)</td>
<td>Result Conc. (ppb) Peak Ctr. (nm)</td>
<td>Result Conc. (ppb) Peak Ctr. (nm)</td>
<td>Result Conc. (ppb) Peak Ctr. (nm)</td>
</tr>
<tr>
<td>Wheel River (001-2)</td>
<td>B 0.155 513.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterfall Room (003-2)</td>
<td></td>
<td>B 905.992 543.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well Casing A (004-2)</td>
<td>B 0.184 519.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well Casing C (006-2)</td>
<td></td>
<td></td>
<td>B 1.838 563.8</td>
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</tr>
<tr>
<td>CC’s Pool (007-2)</td>
<td>B 0.412 394.2</td>
<td></td>
<td>B 0.242 537.4 POR</td>
<td>8.095 568.4</td>
</tr>
<tr>
<td>Breakdown Canyon (008-2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East River (010-2)</td>
<td>B 0.027 516.6</td>
<td></td>
<td>B 1.203 539.0</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Feature ID</th>
<th>Tinopal CBS-X</th>
<th>Fluorescein</th>
<th>Eosine</th>
<th>Rhodamine WT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Result Conc. (ppb) Peak Ctr. (nm)</td>
<td>Result Conc. (ppb) Peak Ctr. (nm)</td>
<td>Result Conc. (ppb) Peak Ctr. (nm)</td>
<td>Result Conc. (ppb) Peak Ctr. (nm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B = Initial Background, B = Background (< 10 times background or lowest detection limit), POR = Peak Out of Range (< 5 nm from peak center)

Source: Created by the author (2018).

Four dyes were detected in the background samples, including OB, FL, EO, and RWT. Additionally, Phase II background investigations revealed that both EO and RWT were detected at CC’s Pool (007-2). Based on these results and the previous injection of EO and RWT, it was determined that FL would be used to trace the recycling center storm drain (DT3) and SRB would be used to trace the storm drain adjacent to the
recycling center (DT4). The amount of dye needed for Phase II tracing was determined using Equation 4.1 and the data in Table 4.5, which include base level velocity and discharge data from the Wheet River resurgence and the distances from the injection sites on the surface to the anticipated discharge site in the cave. Smart and Karunaratne (2002) suggested that, if necessary, issues with background fluorescence can be resolved either by choosing a dye that is not present in background concentrations or by increasing the amount of dye used. Because FL was present in the background for some samples, twice the amount was used for injection. Twice the amount of SRB was also used, as the equation is specific to fluorescein injections.

Table 4.5. Phase II velocity, discharge, and distance data used to determine the proper dosage of dye for tracing.

<table>
<thead>
<tr>
<th>Site ID</th>
<th>Injection Site</th>
<th>Distance (km)</th>
<th>Base Flow Q (m³/s)</th>
<th>Base Flow V (m/s)</th>
<th>Dosage (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT3</td>
<td>Recycling Center Storm Drain A (SRB)</td>
<td>0.27</td>
<td>0.04</td>
<td>0.45</td>
<td>0.23</td>
</tr>
<tr>
<td>DT4</td>
<td>Recycling Center Storm Drain B (FL)</td>
<td>0.26</td>
<td>0.04</td>
<td>0.45</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Source: Created by the author (2018).

Phase II dye injection occurred on August 3, 2018, and included the injection of 0.5 kg (1 lb) of SRB into the old recycling center storm drain (DT3) and 0.5 kg (1 lb) of FL into a storm drain across the street from the old recycling center (DT4). Both dyes were flushed with the help of the Horse Cave fire chief, and monitoring occurred for one week. Dye receptors were retrieved on August 14, 2018. Analysis was conducted on August 16th using the procedures outlined in section 4.2.2, which are based on CHL protocols.

4.3 Characterization of Stream Stage and Discharge in Hidden River Cave

Stage height (water level rise and fall) was determined at the South River and the East River (refer to Table 4.1) from June 10, 2018, to September 29, 2018, to gauge the responses of each stream to precipitation-related recharge events, which can provide data
for further implementation of BMPs by examining the time it can take for contaminants to infiltrate and traverse the trunk streams of Hidden River Cave. Discharge measurements were also taken at Wheet River, Breakdown Canyon, and South River to gauge the differences in volumetric flow between each site, as they are inferred to be hydrologically connected to one another (see Figure 4.2). Discrete volumetric discharge measurements were taken weekly (when the cave was accessible) from December 15, 2017, until September 15, 2018, at Wheet River and the Breakdown Canyon entrance using the float method (Turnipseed and Sauer 2010). A Global Water flowmeter (model FP111) was used to determine discharge measurements at the South River from December 15, 2017, until June 1, 2018. Discharge was not recorded at the East River due to limited site accessibility; however, after June 1, 2018, an Onset HOBO pressure transducer was installed at each site to record high-resolution stage data at the East River and the South River. This study thus establishes the first recorded, high-resolution flow conditions in Hidden River Cave. Figure 4.2 shows the locations of monitoring stations used for stage and discharge measurements in Hidden River Cave.
4.3.1 Discrete Discharge Measurements

Discrete discharge was calculated at the South River using the area-velocity method, where the area of the respective channel cross-section is multiplied by the average velocity of the water flowing through the cross-section. Area (A) was calculated by measuring the width of the cross-section and then dividing it into equidistant vertical subsections to measure the depth of each subsection; the area represents the product of
the widths and depths of the vertical subsections. The velocity of each vertical subsection was calculated using a Global Water flowmeter (model FP111) at 2/10 and 8/10 depths to account for flow variability. The total discharge was then calculated using the following equation:

\[ Q = \Sigma v \ (m/s) \times A \ (m^2) \]  
(Eq. 5)

where \( Q \) = total discharge in m\(^3\)/s
\( A \) = cross-sectional area in m\(^2\)
\( v \) = average velocity (m/s)

From these data, a rating curve was established by correlating the stage and discharge of the stream segment over the study period for the South River, and by using the power function in Microsoft Excel to establish an R\(^2\) value, which was then used to estimate instantaneous discharge based on five-minute interval water level measurements from the HOBO sonde (Tagne and Dowling 2018).

Discharge was calculated at Wheet River and Breakdown Canyon using the float method. A float distance of 3.5 m (12 ft) was established between two cross-sectional areas along the straightest reach of each stream. As conducted during the area-velocity method, area (A) was calculated by measuring the width of one of the cross-sections and then dividing it into equidistant vertical subsections to measure the depth of each subsection; the area represents the product of the widths and depths of the vertical subsections. A stopwatch was then used to record the time it took for a fishing bobber to travel between the two cross-sections. The bobber was released and timed three times to account for flow variability. The following equation was then used to determine total discharge:
\[ Q = \Sigma A \cdot \nu (d/t_{avg} \cdot 0.85) \]  

(Eq. 6)

where \( Q \) = total discharge in \( m^3/s \)

\( A \) = cross-sectional area in \( m^2 \)

\( \nu \) = average velocity (m/s)

\( d \) = distance in m

\( t \) = time in seconds

0.85 = coefficient used to convert surface velocity to average velocity

The discrete discharge data from Wheet River and Breakdown Canyon were graphed using SigmaPlot (11.0) and compared to daily average precipitation data acquired from the Kentucky Mesonet HDYV monitoring station located in Munfordville (Collins 2018). Additionally, the discrete discharge data at the South River were compared to discrete discharge data from Wheet River and Breakdown Canyon to understand the differences in discharge between these sites, as they are inferred to be connected.

4.3.2 Instrument Installation and Data Processing

Two Onset HOBO pressure transducers (model U20L-02) were installed at the South River and East River on June 10, 2018, to capture high-resolution stage data that were used to understand water level responses to precipitation events and to calculate discharge at the South River (Figure 4.3) (Murdoch et al. 2016).
The stilling well for the East River sonde was attached to the Thomas Boardwalk and consisted of a 38.1 mm (1.5 in) diameter, 3.17 m (10.4 ft) long PVC pipe with fitted caps and small holes drilled throughout the bottom half of the stilling well to allow water to flow through it. The housing at the South River was bolted to the bedrock along the Wild Tour route and is similar to the East River housing, except for the length of the stilling well (2.01 m; 6.62 ft). The HOBO pressure transducers were used for this study until September 9, 2018. The South River sonde collected five-minute resolution water-level data during the study, except when pulled to download the data and log in-cave barometric pressure. The East River sonde also collected five-minute resolution water level data, except from Julian dates 180 to 201 and when pulled to download data. A hydrograph was created to characterize stream stage at the South and East rivers using the five-minute, high-resolution water level data recorded by the HOBO pressure...
transducers. A second hydrograph was created to characterize discharge at the South River using the rating curve established from the discrete discharge data and the high-resolution water level data.

In-cave barometric pressure used to calculate the high-resolution discharge data was determined for barometric pressure compensation of water-level data by exposing the HOBO pressure transducer to cave air conditions for approximately 15 minutes at the initial, and each subsequent, deployment. A water level reference reading was also taken at the time of each data download. The high-resolution discharge data were processed using Onset HOBOware Pro (v 3.7.15), which incorporated the water level reference reading and barometric pressure compensation to report pressure readings as water levels. The processed water level data were organized in a spreadsheet in Microsoft Excel.

Discrete discharge data were used to generate a rating curve for South River, where regression analysis determined an $R^2$ value of 0.91 for the South River (Figure 4.4).

Figure 4.4. Rating curve for South River discharge generated from measured stage height (m) and calculated discharge ($m^3/s$). Source: Created by the author (2018).
The stage data for the South and East rivers, as well as the discharge data calculated for the South River, were graphed using SigmaPlot (11.0) and compared to five-minute precipitation data acquired from the Kentucky Mesonet HDYV monitoring station located in Munfordville (Collins 2018). Additionally, the South and East River stage data were compared to 15-minute Green River stage data, and the South and East River discharge data were compared to 15-minute Green River discharge data acquired from the USGS (Munfordville site 03308500) to determine relationships between the parameters.

4.4 Geographic Information Systems Analysis

4.4.1 Land-use over the Hidden River groundwater subbasin

Developing analysis schemes for using data collected via satellites with multispectral band sensors is possible by using methods such as supervised and unsupervised classification, which reclassifies the satellite imagery into separate land types to improve interpretation. The supervised classification method allows the user to decide which classes are in the imagery based on a chosen schema and is ideal for small study areas that the user is familiar with. Unsupervised classification allows the software, rather than the user, to use algorithms to create classes based on differences in the spectral characteristics of the pixels (Keranen and Kolvoord 2014; Deindorfer 2016). Using unsupervised classification is ideal for large study areas that are remote or secluded to the author.

Previous analyses determined that supervised classification would better represent land-use changes over the Hidden River groundwater subbasin due to the author’s familiarity with the study area. An analysis of land-use change over the Hidden River
groundwater subbasin was conducted from 1989 to 2017 (a 28-year period between the publications of the respective city zoning maps) using 30 x 30 m (100 x 100 ft) Landsat 5 (10/22/1989) and Landsat 8 (09/26/2017) multispectral imagery collected from the USGS Global Visualization Viewer (GloVis 2001), as well as supervised land-use classification techniques in ArcGIS Pro (version 2.2). Table 4.6 highlights the properties of the satellite imagery.

The study area included a feature class of the Gorin Mill groundwater basin collected from the Kentucky Geological Survey that was modified to represent the associated Hidden River groundwater subbasin according to the extent defined by Ray and Currens (1998). Using the Hidden River groundwater subbasin feature class and the clip tool in the analysis tab, both images from GloVis were clipped to the basin boundaries. A qualitative analysis comparing the 1989 and 2017 imagery was conducted using supervised classification, which included the creation of training samples, reclassifying the imagery, and performing post-classification processing. The results of the reclassification were then compared quantitatively by determining the percentage of land-cover classes for each image, and an assessment was conducted to determine the accuracy of the classification method used.
Table 4.6. Properties of the Landsat 5 TM (1989) and Landsat 8 (2017) satellite imagery of the Hidden River groundwater subbasin from GloVis.

<table>
<thead>
<tr>
<th>Raster Metadata</th>
<th>1989</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Name</td>
<td>Landsat-5-TM</td>
<td>Landsat 8</td>
</tr>
<tr>
<td>Acquisition Date</td>
<td>10/22/1989 15:48</td>
<td>9/26/2017 16:17</td>
</tr>
<tr>
<td>Number of Bands</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Cell Size X (m)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Cell Size Y (m)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Pixel Depth</td>
<td>8 Bit</td>
<td>16 Bit</td>
</tr>
<tr>
<td>Geographic Coordinate System</td>
<td>GCS WGS 1984</td>
<td>GCS WGS 1984</td>
</tr>
<tr>
<td>Projected Coordinate System</td>
<td>WGS 1984 UTM Zone 16N</td>
<td>WGS 1984 UTM Zone 16N</td>
</tr>
<tr>
<td>Linear Unit</td>
<td>Meters (1.0)</td>
<td>Meters (1.0)</td>
</tr>
</tbody>
</table>

| Band Metadata | | |
|---------------|-------------------------------|
| Band 1        | Min λ (nm) | 450 | 430 |
|               | Max λ (nm) | 520 | 450 |
| Band 2        | Min λ (nm) | 520 | 450 |
|               | Max λ (nm) | 600 | 510 |
| Band 3        | Min λ (nm) | 630 | 530 |
|               | Max λ (nm) | 690 | 590 |
| Band 4        | Min λ (nm) | 760 | 640 |
|               | Max λ (nm) | 900 | 670 |
| Band 5        | Min λ (nm) | 1550 | 850 |
|               | Max λ (nm) | 1750 | 880 |
| Band 6        | Min λ (nm) | 2080 | 1570 |
|               | Max λ (nm) | 2350 | 1650 |
| Band 7        | Min λ (nm) | NA  | 2110 |
|               | Max λ (nm) | NA  | 2290 |
| Band 8        | Min λ (nm) | NA  | 1360 |
|               | Max λ (nm) | NA  | 1380 |

Source: Created by the author (2018).

Supervised classification involves the creation of training samples (manually chosen examples of a known land-cover type) to obtain spectral properties of the imagery, which are then used to produce a reclassified image. Training samples are created via a polygon superimposed onto a raster, where the raster acts as a background.
and is used as a reference to identify areas that represent a specific land-cover type.

Supervised classification was conducted for each image using the Classification Wizard in ArcGIS Pro (2.2), and training samples were created for each image (Figure 4.5) using the Training Samples Manager, which allows the user to create and manipulate new classes to customize the schema. Training samples were created using the schema provided by the Environmental Systems Research Institute (Esri) from the USGS 2011 National Land Cover Dataset (NLCD), which includes the following land-use classes: (1) water, (2) developed, (3) forest, and (4) agricultural.

Figure 4.5. Training samples of the 2017 Landsat 8 imagery created to perform supervised classification. Source: Created by the author (2018).

Supervised classification was conducted using the training samples, which generated a reclassified raster. Post-classification processing was then applied to the reclassified image by using generalization tools, which remove noise that is generated by isolated pixels or small, misclassified regions. Generalization tools help identify these errors and automate the assignment of more reliable values to the cells that include the misclassified areas. Post-processing included using the majority filter tool to remove
isolated pixels from the reclassified raster and the boundary clean tool to smooth the class boundary edges and group the classes (Keranen and Kolvoord 2014). This, in turn, produced an organized reclassified image of land use in the study area.

The total number of pixels (Count) in each reclassified image was determined using the summary statistics tool. This number was then divided by the number of pixels for each land cover type (SUM_Count) in the reclassified imagery and multiplied by 100 to determine the percentage of land cover; a new field named Percent (data type float) was added to the attribute tables of the reclassified rasters, and the field calculator tool used the following formula to generate the percentage of land cover types:

$$\text{Percent} = \frac{\text{Count}}{\text{Value of SUM_Count}} \times 100$$  \hspace{1cm} (Eq. 7)

A graph was then created to characterize these percentages and to determine the changes that have occurred over the Hidden River groundwater subbasin over the past 28 years.

4.4.2 Accuracy Assessment of Supervised Classification

To determine the accuracy of the performed supervised classification, the errors of omission and commission were determined. Omission errors account for features that have been omitted from the classified imagery that truly exist, where commission errors include features that do not exist but have been included in the reclassified imagery (Keranen and Kolvoord 2014). The errors of omission and commission were calculated by generating an error matrix from ground-truthed data. Ground-referencing compares reclassified imagery to higher resolution aerial imagery; the newly classified imagery was compared to the Kentucky statewide 0.5 m (2 ft) aerial imagery (2016) acquired from the National Agriculture Imagery Program (NAIP).
Twenty-five random ground-truthed points were generated for each image using the create random points tool (Figure 4.6). Because the imagery includes 30 x 30 m resolution, a buffer of 30 meters was created around the random points using the buffer tool from the geoprocessing window to represent the approximate area that a single pixel spans. The buffered areas were then ground-truthed using the high-resolution imagery. Because high-resolution imagery is not available to ground-truth the 1989 imagery, the NAIP Kentucky statewide aerial imagery was used with some considerations made of the possible land-use changes that could have occurred over time. For example, the quarry in the western section of the Landsat 8 imagery covers a smaller area of land in 1989.

![Randomly Generated Points](image)

**Figure 4.6.** Example of random point generation; a 30 x 30 m buffer was created around each point to identify the land type within the buffer. Source: Created by the author (2018)

Using the editor tool, a new field was added to the random point feature class called GT (ground-truth) to record the correct type of land-use within the buffer according to the high-resolution imagery. Upon completion of ground-referencing, the
extract values to points tool was used on the reclassified imagery, which extracted the values of land use from each raster that the random points represent and added them to the attribute table of the random point feature class. The final attribute table included the ground-truthed values and the reclassified supervised classification values (Figure 4.7), which were used to determine accuracy.

<table>
<thead>
<tr>
<th>ID</th>
<th>Shape</th>
<th>CID</th>
<th>GT_2017</th>
<th>Supervised_2017</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Point</td>
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<td>Point</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 4.7. Extraction of data from the reclassified 2017 imagery to compare to ground-truthed data. Source: Created by the author (2018).

From ground-referencing, an error matrix was constructed, which is a table that compares the classes determined by the ground-truthed, higher resolution imagery to the classes in the reclassified imagery. To complete the matrix, the select by attributes tool was used to identify matching classifications. For example, to determine the number of points that were classified as 1, the following query was used:

\[
\text{“GT\_2017” = 1 AND “Supervised\_2017” = 1}
\]
The same query was used to determine each corresponding land-use type for both images. From these data, the total classification accuracy percentages were calculated to determine the errors of omission and commission.
Chapter 5. Results

5.1 Phase I Dye-tracing

Phase I dye-tracing occurred on April 6, 2018, and included the injection of 0.49 kg (1.1 lb) of RWT into the storm drain near the Horse Cave carwash (DT1) and 0.34 kg (0.75 lb) of EO through the injection well located near the concrete mixing plant (DT2).

The results of Phase I dye-tracing are presented in Table 5.1.

Table 5.1. Results of Phase I dye-tracing. RWT was detected at Well Casing A, Breakdown Canyon, South River, and East River. Questionable results include Well Casing A, which contained initial background concentrations of RWT; a stronger peak was detected post-injection. EO was detected at the Waterfall Room, Breakdown Canyon, South River, and East River.

<table>
<thead>
<tr>
<th>Feature ID</th>
<th>Eosine</th>
<th>Rhodamine WT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterfall Room (003-1)</td>
<td>+++</td>
<td></td>
</tr>
<tr>
<td>Well Casing A (004-1)</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Breakdown Canyon (008-1)</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>South River (009-1)</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>East River (010-1)</td>
<td>+++</td>
<td>+++</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feature ID</th>
<th>Con. (ppb)</th>
<th>Peak Ctr. (nm)</th>
<th>Con. (ppb)</th>
<th>Peak Ctr. (nm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>542.2</td>
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<tr>
<td>Well Casing A (004-1)</td>
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<td>542.6</td>
<td>5.828</td>
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<td>Breakdown Canyon (008-1)</td>
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<td>439.969</td>
<td>573.0</td>
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<td>South River (009-1)</td>
<td>42.972</td>
<td>542.4</td>
<td>346.927</td>
<td>571.6</td>
</tr>
<tr>
<td>East River (010-1)</td>
<td>20.927</td>
<td>569.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

Result: +++ = Extremely positive (1000 times background or lowest detection limit)
Result: ++ = Very positive (100 times background or lowest detection limit)
Result: + = Positive (10 times background or lowest detection limit)
Result: ?+ = Questionable Positive

Source: Created by the author (2018).

The calibration curves used by the CHL for the Shimadzu RF-6000 are designed for concentrations up to 100 parts per billion (ppb); as concentrations increase, dye curves tend to get wider, and the calibration does not remain linear within the CHL’s analytical parameters for peak height (Bledsoe 2018). Thus, the concentration of RWT and EO for each site in Table 5.1 was diluted 1:100 to obtain a more precise measurement (Table 5.2).
Table 5.2. Results of Phase I dye-tracing after 1:100 dilution.

<table>
<thead>
<tr>
<th>Feature ID</th>
<th>Eosine</th>
<th>Rhodamine WT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Result</td>
<td>Conc. (ppb)</td>
</tr>
<tr>
<td>Waterfall Room (003-1)</td>
<td>+++</td>
<td>222.266</td>
</tr>
<tr>
<td>Well Casing A (004-1)</td>
<td>++</td>
<td>5.828</td>
</tr>
<tr>
<td>Breakdown Canyon (008-1)</td>
<td>+++</td>
<td>14.962</td>
</tr>
<tr>
<td>South River (009-1)</td>
<td>+++</td>
<td>9.172</td>
</tr>
<tr>
<td>East River (010-1)</td>
<td>++</td>
<td>0.692</td>
</tr>
</tbody>
</table>

Eosine: +++ = Very positive (100 times background or lowest detection limit)
Rhodamine WT: ++ = Positive (10 times background or lowest detection limit)
Rhodamine WT: +++ = Extremely positive (1000 times background or lowest detection limit)
Rhodamine WT: ?+ = Questionable Positive

Source: Created by the author (2018).

It was anticipated that EO would discharge along the walls of Well Casing B (005-1) due to suspected breaks in the casing and that RWT would discharge at the Waterfall Room (003-1). Conversely, a very high concentration of EO was detected at the Waterfall Room (003-1) rather than RWT. No dye was recovered at Well Casing B (005), and, although a direct connection cannot be deemed certain, a higher concentration of RWT was detected at Well Casing A (004-1) than what the results of the background fluorescence analysis determined. Additionally, the peak center associated with Well Casing A is more indicative of R28; thus 004-1 can be considered a questionable positive. A significant concentration of RWT was ultimately recovered at the Breakdown Canyon entrance (008-1) and detected at each receptor downstream thereafter.

5.2 Phase II Dye-tracing

Phase II dye injection occurred on August 3, 2018, and included the injection of 0.5 kg (1 lb) of SRB into the old recycling center storm drain (DT3) and 0.5 kg (1 lb) of FL into a storm drain across the street from the old recycling center (DT4). The results of Phase II dye-tracing are presented in Table 5.3.
Table 5.3. Results of Phase II dye-tracing. FL and SRB were detected in high concentrations at South River and East River. All other sites were non-detect.

<table>
<thead>
<tr>
<th>Feature ID</th>
<th>Fluorescein</th>
<th>Sulphorhodamine B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Result</td>
<td>Conc. (ppb)</td>
</tr>
<tr>
<td>South River (009-2)</td>
<td>+++</td>
<td>277.419</td>
</tr>
<tr>
<td>East River (010-2)</td>
<td>++</td>
<td>3.907</td>
</tr>
</tbody>
</table>

+++ = Extremely positive (1000 times background or lowest detection limit)
++ = Very positive (100 times background or lowest detection limit)
+ = Positive (10 times background or lowest detection limit)

Source: Created by the author (2018).

Because Phase I dye-tracing confirmed that engineered drainage features still contribute contaminants to cave waters, it was anticipated that Phase II dye-tracing would produce common results; however, FL and SRB were only detected at the South River (009-2) and the East River (010-2). A significantly higher concentration of each dye was detected at the South River site (009-2). Because only one receptor was placed in the downstream section of the South River, continued monitoring occurred at the headwaters of the South River at an area known as the Cave City Springs Confluence. Two water samples were collected on August 24, 2018 (a week after dye receptors were collected for Phase II tracing), where water discharges to the Cave City Springs Confluence through two visible outlets (Figure 5.1). Analysis was conducted on August 29th using the procedures outlined in section 4.2.2, which are based on CHL protocols. Results revealed low-level fluorescence, shown in Table 5.4.
Figure 5.1. The headwaters of the South River known as the Cave City Springs Confluence, where low concentrations of FL and SRB were detected during post-monitoring of Phase II dye-tracing. Source: Photo by the author (2018).

Table 5.4. Results of continued monitoring at the headwaters of the South River showing low-level concentrations of FL and SRB.

<table>
<thead>
<tr>
<th>Feature ID</th>
<th>Fluorescein</th>
<th>Sulphorhodamine B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Result</td>
<td>Conc. (ppb)</td>
</tr>
<tr>
<td>South River A (009-3)</td>
<td>+</td>
<td>0.006</td>
</tr>
<tr>
<td>South River A (009-3A)</td>
<td>+</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Source: Created by the author (2018).

Both samples revealed similar results, and, although these concentrations display low-level fluorescence that is less than ten times the PQL of FL and SRB water standards, it is an indication of how the dye may have been transported to the South River. While neither Phase I or Phase II dye-tracing produced the results expected, all dyes were ultimately discovered in Hidden River Cave, indicating that engineered drainage features are contributing directly to cave-water contamination. Figure 5.2 displays the inferred groundwater flow paths determined by Phase I dye-tracing.
5.3 Characterization of Stream Stage and Discharge in Hidden River Cave

5.3.1 Characterization of Stream Stage at the South and East Rivers

Stage height (water level rise and fall) was determined at the South River (009; refer to Table 4.1) and the East River (010) from June 10, 2018, to September 29, 2018, and compared to five-minute precipitation data acquired from the Kentucky Mesonet HDYV monitoring station located in Munfordville to gauge the responses of each stream to precipitation-related recharge events. Figure 5.3 is the graphed result of stage
responses at each site compared to precipitation data during that period. Julian dates (JD) are used from here on in this section to describe hydrograph responses.

Figure 5.3. Stage height differences between the East River (010) and the South River (009) from June 10, 2018, to September 29, 2018. Source: Created by the author (2018).

The East River produced overall higher stage values than the South River. Baseflow for the East River during this study occurred at 0.27 m (0.8 ft), where baseflow for the South River occurred at 0.15 m (0.49 ft). The maximum flow for East River occurred at 5.46 m (17.91 ft), while the maximum flow for South River occurred at 2.34 m (7.67 ft). The average stage height for the East River was 1.07 m (3.51 ft), while the average for the South River was 0.31 m (1.02 ft), indicating that the East River stage height is nearly an order of magnitude higher than the South River. Several storm events can be seen in each hydrograph, including the remnants of Tropical Storm Gordon (JD
Most summer total liquid accumulations were generally associated with summertime thunderstorms, while most rain events during the second half of September were associated with frontal passages (NOAA 2018). Four major precipitation events were chosen from these data to examine stream responsiveness (Table 5.5).

Table 5.5. Dates, event numbers, and types of significant storm events that impacted stage height at the South and East rivers in Hidden River Cave from June 10, 2018, to September 29, 2018.

<table>
<thead>
<tr>
<th>Date</th>
<th>Julian Date</th>
<th>Event</th>
<th>Convective Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/25-07/01</td>
<td>176-182</td>
<td>1</td>
<td>Thunderstorm</td>
</tr>
<tr>
<td>08/16-08/24</td>
<td>228-236</td>
<td>2</td>
<td>Thunderstorm</td>
</tr>
<tr>
<td>09/08-09/13</td>
<td>251-256</td>
<td>3</td>
<td>Tropical Storm Gordon</td>
</tr>
<tr>
<td>09/21-09/27</td>
<td>264-270</td>
<td>4</td>
<td>Frontal Passage</td>
</tr>
</tbody>
</table>

Source: Created by the author (2018).

Event S1: Scattered thunderstorm events occurred from JD 176 at 0055 to JD 179 at 0420 and produced the highest rainfall values during this study (Figure 5.4). Water levels began to rise at the South River on JD 176 at 0110. Maximum rainfall (11.10 mm; 0.43 in) occurred on JD 176 at 1145, which produced only a small peak in flow (0.38 m; 1.24 ft). Maximum stage height, however, peaked on JD 177 at 1405 (1.24 m; 4.06 ft), where the maximum amount of precipitation that influenced this peak only reached 7.80 mm (0.30 in) at 1300. Stage levels did not begin to recede until JD 179 at 1645, after which near baselevel conditions were met on JD 182 (three days after the final precipitation event). The water level did not begin to rise at the East River until JD 176 at 0200. The maximum rainfall, as with the South River, had little impact on the East River. The maximum precipitation value for JD 177 (7.80 mm at 1300), however, produced a significant peak in the East River (3.67 m; 12.04 ft at 1430), as seen in Figure
5.4. Water levels began steadily declining in the East River on JD 179 at 1930, after which near baselevel conditions were met on JD 182.

Figure 5.4. Results of stream stage responses from JD 176 at 0055 to JD 179 at 0420, for the South and East rivers during storm events. Source: Created by the author (2018).

Event S2: A series of four precipitation events occurred from JD 228 at 0535 to JD 233 at 0340 that caused subsequent peaks in the South and East River hydrographs. The first event was sustained over several hours on JD 228 (from 0535 to 1220) causing the largest of the three peaks in each hydrograph (Figure 5.5) with maximum rainfall levels reaching 3.58 mm (0.14 in) at 1115. Water levels did not begin to increase at the South River until JD 228 at 0650, peaking at 1015 (0.94 m; 3.08 ft), and declining until another event with the maximum amount of precipitation during this period (5.05 mm; 0.19 in at 0010) caused a subsequent peak (0.58 m; 1.90 ft) on JD 229 at 0025. A third
sustained rain event occurred on JD 230 with a maximum precipitation of 2.89 mm (0.11 in) at 1230 that caused water levels to increase to 0.35 m (1.14 ft) at 1640. Lastly, a fourth rain event occurred on JD 233 with a maximum precipitation of 4.98 mm (0.19 in) at 0055, which caused another peak in water levels (0.58 m; 1.64 ft at 0400) until the stage began to recede at 0625. Although a relatively minor precipitation event occurred afterward around 2000, a steady decline is seen in the South River hydrograph over a period of about a week. The stream, however, did not reach the baselevel determined via this study.

Water levels during this period did not begin to increase at the East River until JD 228 at 0730. The maximum stage height peaked at 2.69 m (8.82 ft) on 228 at 1105 and abruptly declined until the maximum precipitation event (5.05 mm on JD 129 at 0010) caused another peak at 2.25 m (8.2 ft) on JD 229 at 0045. The third rain event (maximum of 2.89 mm on JD 230 at 1230) produced a maximum stage height of 1.15 m (3.77 ft) on JD 230 at 1640, the same time seen in the South River hydrograph. The fourth rain event (maximum of 4.98 mm on JD 233 at 0055) produced an abrupt increase in the East River on JD 233 at 0435 (1.58 m; 5.18 ft), which declined for a short period until water levels continued to increase at 0900 to a maximum of 1.84 m (6.03 ft) on JD 234 at 0500, after rainfall had ceased on JD 233 at 2045. A steady decline is also seen in the East River hydrograph over a period of about a week, although the stream did not achieve the baselevel determined by this study.
Event S3: Results from Tropical Storm Gordon are seen in each hydrograph from JD 251 at 0135 to JD 252 at 1715 (Figure 5.6). The initial impacts of Gordon began on JD 251 at 0135 (maximum precipitation of 0.48 mm; 0.02 in at 0320) and lasted until 0515, causing a small peak in water levels (0.42 m; 1.37 ft at 0540); however, precipitation from Gordon occurred throughout the entire day on JD 252 beginning at 0610 and ending at 1725. Water levels began to rise at the South River on JD 251 at 0320 and slowly receded thereafter. Water levels began to rise again on JD 252 at 0615 after some sustained precipitation, and maximum precipitation reached 5.06 mm at 0745. Water levels peaked to 0.8 m (2.62 ft) on JD 252 at 1050 before falling between 0.5-0.6 m (1.6-1.9 ft), which became sustained during the continued afternoon precipitation.
Precipitation ended on JD 252 at 1715, after which water levels began to recede around 1725. Water levels returned to near baseflow on JD 256, four days after precipitation ended.

Water levels in the East River began to rise at 0400 from the small precipitation event that occurred on JD 251 (maximum precipitation of 0.48 mm; 0.02 in at 0320) and slowly receded afterward. Following the steady onset of precipitation on JD 252, water levels began to rise again at 0640. Stage height peaked at 2.87 m (9.41 ft) on JD 252 at 1120 before receding at 1805 (after precipitation ended at 1715) and steadily returning to near baseflow on JD 256.

Figure 5.6. Results of stream stage responses from JD 251 at 0135 to JD 252 at 1715, for the South and East rivers during Tropical Storm Gordon. Source: Created by the author (2018).
Event S4: The most significant storm event during this study occurred during the fall season’s first major cold front, which brought rainfall from JD 264 beginning at 0720 to JD 267 ending at 1725 (Figure 5.7). Hurricane Florence occurred over the Carolinas prior to this event, although scattered precipitation events from the outer bands of the hurricane brought little precipitation to the Horse Cave area. Intermittent rain events from the cold front, however, slowly increased the water levels of the South River on JD 265 at 0745; water levels in the East River began rising at 0810. This event occurred over a 4-day span; maximum rainfall (5.97 mm, 0.23 in) occurred on JD 265 at 0015. After rainfall had ceased on JD 267 at 1725, the water levels of the South River reached a maximum of 2.34 m (7.67 ft) at 1910 and began to recede at 1945. The maximum stage height for the East River was 5.46 m (17.91 ft), also at 1910, and began receding at 2115.

Figure 5.7. Results of stream stage responses from JD 264 at 0720 to JD 267 at 1725, for the South and East rivers during storm events. Source: Created by the author (2018).
The overall stage data for the South and East rivers were compared to 15-minute Green River stage data acquired from the USGS (Munfordville site 03308500) to determine relationships between the parameters (Figure 5.8). Table 5.6 quantitatively compares the minimum, maximum, and median stream stages between Hidden River Cave and the Green River.

Figure 5.8. South and East River stage data compared to stage data from the Green River (Munfordville site 03308500). Source: Created by the author (2018).
Table 5.6. Comparison of stage heights in Hidden River Cave and the Green River.

<table>
<thead>
<tr>
<th>Site</th>
<th>Stage (m)</th>
<th>Julian Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>South River</td>
<td>Min 0.150</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td>Max 2.344</td>
<td>267</td>
</tr>
<tr>
<td></td>
<td>Med. 0.291</td>
<td></td>
</tr>
<tr>
<td>East River</td>
<td>Min 0.270</td>
<td>182</td>
</tr>
<tr>
<td></td>
<td>Max 5.460</td>
<td>267</td>
</tr>
<tr>
<td></td>
<td>Med. 0.813</td>
<td></td>
</tr>
<tr>
<td>Green River</td>
<td>Min 0.800</td>
<td>249</td>
</tr>
<tr>
<td></td>
<td>Max 4.380</td>
<td>268</td>
</tr>
<tr>
<td></td>
<td>Med. 1.010</td>
<td></td>
</tr>
</tbody>
</table>

Source: Created by the author (2018).

As shown in Figure 5.8, stage responses similar to those in Hidden River Cave are seen in the Green River during events S1-S4, although these responses appear to be more variable than those seen in the South and East rivers, presumably due to the morphology of the Green River stream bed versus the morphology of the trunk streams in Hidden River Cave. The Green River responded to S1 at nearly the same time that the South River did; however, it was slower to respond to S2 than both trunk streams in Hidden River Cave. During S3, an increase in stage was not seen until JD 252 at 1515, indicative of the relatively small impacts that prior precipitation (pre-Gordon) had on the region. On JD 265, however, increased stage height is seen prior to any response seen in the trunk streams of Hidden River Cave. This is likely due to: a) sustained precipitation during this period; b) the Green River being a surface stream that directly receives precipitation; and c) contributions of increased discharge from the karst groundwater basins that resurge at the Green River, or a combination of these factors.

After S1, water levels did not begin to recede at the Green River until JD 181, after the Hidden River Cave trunk streams approached baselevel conditions. After S2, water levels in the Green River began to recede on JD 234 at 1830, also after the cave streams had already approached near-baselevel conditions. During S3, the Green River
stage began receding two days after the cave streams had receded and, after S4, it took the Green River one day to recede after the cave streams had receded. Thus, the stage heights in the Green River during this study were generally slower to respond and recede than those seen in the in the major trunk streams of Hidden River Cave, the cause of which is likely dependent on the differences in the morphology of each site and the control of the upstream dam on the Green River. These data, however, are important to consider, as the Hidden River groundwater subbasin is part of the overall Gorin Mill groundwater basin that contributes 10% of the discharge received by the Green River (Blair et al. 2018).

5.3.2 Discrete Discharge Measurements

Discharge was calculated weekly at Wheet River and Breakdown Canyon using the float method (Turnipseed and Sauer 2010) to understand the upstream hydrology of Hidden River Cave. These data were compared to discrete discharge data from the South River (Figure 5.9) that were calculated via the area-velocity method to determine if South River discharge is greater than the combined discharge of Wheet River and Breakdown Canyon, as these tributaries are exposed for only a short distance before disappearing beneath Breakdown Canyon, and are inferred to resurge at the headwaters of the South River (Nims 2018). Thus, higher volumes of discharge to the South River may be indicative of additional, concealed tributaries flowing beneath Breakdown Canyon.
Figure 5.9. Comparison of discrete discharge data from Wheet River (001), Breakdown Canyon (008), and the South River (009) from January 6, 2018, to June 1, 2018, versus daily total precipitation data acquired from the Kentucky Mesonet HDYV monitoring station in Munfordville. Source: Created by the author (2018).

Discharge to Breakdown Canyon was consistently higher than to Wheet River, and the South River generally received higher volumes of discharge than both streams combined, although the differences are not significant. In some cases, discharge to the South River was less than the combined streams. Table 5.7 quantitatively compares the differences in discharge between each site.
Table 5.7. Comparison of discrete discharge at the upstream sites and South River.

<table>
<thead>
<tr>
<th>Site</th>
<th>Discharge (m³/s)</th>
<th>Julian Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Wheet River</td>
<td>0.007</td>
<td>0.013</td>
</tr>
<tr>
<td>Breakdown Canyon</td>
<td>0.017</td>
<td>0.074</td>
</tr>
<tr>
<td>South River</td>
<td>0.020</td>
<td>0.110</td>
</tr>
</tbody>
</table>

Source: Created by the author (2018).

The data in Table 5.7 indicate that the South River received the highest volume of discharge during the study period; however, as seen in Figure 5.9, the discharge was slightly lower at the South River on JD 6, 19, and 138. Consideration should be given to the differences in methodology used to calculate discharge between the upstream and downstream sites. Conversely, these results could be indicative of either inactive tributaries during baseflow conditions, the diversion of flow into other tributaries during high-flow storm events, or the possibility that Breakdown Canyon is a separate tributary and that recharge to this site is more direct (as Breakdown Canyon produced the highest volume of discharge on JD 138, during which the most significant precipitation event occurred).

5.3.3 High-Resolution Discharge at the South River

Discharge was calculated at the South River from June 10, 2018, to September 29, 2018, using the high-resolution stage data from the Onset HOBO pressure transducer and the discrete discharge data calculated via the area-velocity method. These data were then graphed alongside high-resolution, five-minute precipitation data acquired from the Kentucky Mesonet HDYV monitoring station located in Munfordville to explore visually relationships between these parameters. These data are represented in Figure 5.10.
Discharge at the South River ranged from 0.13 m$^3$/s during baseflow conditions in June (JD 173) to peak flow conditions recorded at 0.31 m$^3$/s in September (JD 267). Similar to the stage heights of the South River, peaks associated with the storm events outlined in Table 5.5 can be seen in the calculated discharge data. The highest volume of discharge at the South River during events S1-S4 was 0.252 m$^3$/s (JD 177 at 1405), 0.231 m$^3$/s (JD 228 1015), 0.218 m$^3$/s (JD 252 at 1050), and 0.311 m$^3$/s (JD 252 at 1050), respectively.

A more robust discrete discharge dataset was produced for the South River; however, also characterizing the volume of discharge from the East River could better describe the overall hydrology of Hidden River Cave and the total volume of water that may resurge to Gorin Mill Spring and thus, the Green River.
5.3.4 Characterization of Preliminary Discharge at the East River

The methods outlined in section 4.3.2 were applied to the East River; however, limitations in site accessibility produced broad discrete discharge data that could only be used to generalize the volume of discharge at the East River. Data collection at the East River proved to be difficult and dangerous at times and, as observed later in the study by the author and others, the water that exits the dam consistently formed an eddy near the Thomas Boardwalk despite variations in stage height. Thus, the cave infrastructure (i.e., the antique waterworks and the Thomas Boardwalk) likely influence the hydrology of this site.

Despite the lack of robust discrete data collected from the East River, it is likely that more flow occurs to the East River via the breakdown pile that forms the entrance of Hidden River Cave. This result is especially visible during high-flow conditions, where the entire breakdown pile discharges to both the South and East rivers; during moderate to low flow, the breakdown only contributes flow to the East River. Thus, before the collapse that formed the entrance, the East River may have been part of a more significant stream that now is impeded by the impacts of breakdown upstream.

5.4 Geographic Information Systems Analysis

5.4.1 Land-use over the Hidden River groundwater subbasin

A land-use analysis of the Hidden River groundwater subbasin was conducted to determine changes in land-use between 1989 and 2017, the years that land-use zoning maps were produced for Horse Cave. The results of land-use changes within this 28-year span are displayed in Figures 5.11 and 5.12.
Land use over the Hidden River groundwater subbasin is predominantly agricultural for both years, although agricultural areas appear to decline over time. Forested areas make up the second highest percentage of land cover and have expanded...
since 2017, as has water. Developed areas are arguably the most important to analyze for the purposes of this study, as they directly impact Hidden River Cave and the overall Hidden River groundwater subbasin, according to the dye-tracing investigations herein. As per the supervised classification, land use over the Hidden River groundwater subbasin increased between 1989 and 2017. Developed areas made up 1.9% of land-use in 1989, whereas, in 2017, developed areas covered 8.9% of the study area. While developed areas do not make up the predominant land-cover type, they are the most important to understand based on the history of groundwater contamination in this region and the current, discreet contamination events that have occurred since remediation began in 1989.

5.4.2 Accuracy Assessment of Supervised Classification

An accuracy assessment was conducted by comparing the results of the reclassified 1989 Landsat 5 TM and the 2017 Landsat 8 aerial imagery to ground-truthed data using the 2016 Kentucky statewide 0.5 m (2 ft) aerial imagery. Overall accuracy was calculated by dividing the number of correct pixels in the error matrix (the sum of the diagonal) by the total number of pixels. Additionally, the errors of commission (column total) and omission (row total) were calculated by dividing the number of correct pixels in a land-use category by the total number of pixels in that category (Keranen and Kolvoord 2014). Tables 5.8 and 5.9 show the accuracy and errors of commission and omission for the reclassified 1989 and 2017 Landsat imagery. Results revealed that the reclassified 1989 aerial imagery produced a slightly lower accuracy than the results of the 2017 imagery when compared to ground-truthed data (84% vs. 88%), although these
percentages reflect that the supervised classification methodology produced relatively accurate results.

Table 5.8. Accuracy assessment of the reclassified 1989 Landsat imagery.

<table>
<thead>
<tr>
<th>Classified Category</th>
<th>(1) Water</th>
<th>(2) Developed</th>
<th>(3) Forest</th>
<th>(4) Agriculture</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Water</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(2) Developed</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>(3) Forest</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>(4) Agriculture</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>14</td>
<td>25</td>
</tr>
</tbody>
</table>

Producer's Accuracy (Errors of omission) (1/1)(100) = 100%, (1/1)(100) = 100%, (6/9)(100) = 66.7%, (14/14)(100) = 100%

Accuracy (21/25)(100) = 84%

Source: created by the author (2018).

Table 5.9. Accuracy assessment of the reclassified 2017 Landsat imagery.

<table>
<thead>
<tr>
<th>Classified Category</th>
<th>(1) Water</th>
<th>(2) Developed</th>
<th>(3) Forest</th>
<th>(4) Agriculture</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Water</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>(2) Developed</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>(3) Forest</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>(4) Agriculture</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>13</td>
<td>25</td>
</tr>
</tbody>
</table>

Producer's Accuracy (Errors of omission) (1/1)(100) = 100%, (4/4)(100) = 100%, (7/7)(100) = 100%, (10/13)(100) = 76.9%

Accuracy (22/25)(100) = 88%

Source: created by the author (2018).

The errors of commission for the reclassified 1989 imagery revealed that, when compared to higher resolution imagery, developed and forested areas of land were entirely accurate, while agricultural regions were nearly 78% accurate. Water produced zero accuracy, as very little exists on the surface in this region. These data represent areas of land use that have been accounted for that do not truly exist. The errors of omission for the reclassified 1989 imagery revealed that developed and agricultural areas produced 100% accuracy and that forested regions were classified with 66.7% accuracy. Because water was not accounted for during the generation of random points, the percentage shows total inaccuracy. These data represent areas of land-use that have not been accounted for that truly exist.
The errors of commission for the 2017 reclassified imagery were also compared to the high-resolution imagery used for ground-truthing and revealed that water, developed, and agricultural areas of land-use were entirely accurate, while forested areas were nearly 64% accurate. The errors of omission revealed that water, developed, and forested areas produced 100% accuracy, while agricultural regions were nearly 77% accurate.

Although these results support the observation that development has increased since the 1970s, it is important to note that the classification used does not account for all developed land within the study area. For example, the road seen dissecting the study area is not complete. Thus, it is possible that these percentages may not reflect all development, but they do differ enough to conclude that development has increased.
Chapter 6. Discussion and Recommendations

6.1 Phase I and II Dye-tracing

Based on background fluorescence analyses and field reconnaissance, Raedts and Smart (2015) suggested that acute point-source contamination events could be linked to land-use practices in Horse Cave. The dye tracing conducted during this study ultimately confirmed that engineered drainage features directly recharge Hidden River Cave, as all dyes were detected at most of the sites that were suggested to experience contamination.

Although EO was recovered at the Waterfall Room (003-1) during Phase I dye-tracing, it is uncertain where water is flowing between the Waterfall Room and Breakdown Canyon (008) and where the dye may have exited the well casing. An orange tint was detected at a pool in the Kneebuster tributary, which was not included in the dye-tracing procedures herein (Nims 2018). This observation, however, is not surprising, as a small tributary exists that connects the headwaters of the South River and the Kneebuster passage, known as Blind Fish Alley. A deep red tint was also observed by the ACM staff in CC’s Pool (007), but because the passage was unknown to the author before Phase I dye-tracing, a receptor was not placed there. This red pool (Figure 6.1), as well as an orange tint to the cascade in the Waterfall Room, was observed less than one day after Phase I dye injection took place (Russell 2018). Although it is not quantifiable from this study, it is likely that the time of travel of recharge from these features on the surface to the cave is very abrupt. While a quantitative trace could provide additional data on the time of travel of recharge to the cave system, it is important to first establish a connection via qualitative tracing.
No EO was detected at Well Casing A (004-1). Rather, Well Casing A produced questionable results that may be representative of a higher background concentration of another dye, such as R28, or the recovery of the RWT that was injected into the car wash storm drain; however, significant recovery of RWT was not made until the dye reached Breakdown Canyon (008-1). Thus, it is unknown whether the higher dye concentration detected at this site was merely background fluorescence or RWT, and it is unknown where exactly water is discharging to the cave from the car wash storm drain. Because consideration was not made of RWT being detected anywhere aside from the Waterfall Room and the peak centers for RWT and R28 are relatively close to one another (CHL 2018), it is suggested that another trace is conducted with a different dye, such as SRB. Alternatively, radiolocation can be used to determine the location of the well casing in...
relation to the surface, as few data exist regarding its installation and ownership; however, based on records of geochemical monitoring, it is likely that the well was drilled in the 1950s (KGS 1997). It is possible that the well casing seen on the surface is unrelated to either of those seen in the subsurface. This inference is based on the misalignment of the GPS data used to georeference the well casing with respect to the locations of the casings in the cave (Figure 6.2). Therefore, further investigation can include georeferencing the cave to confirm its locational accuracy.

Figure 6.2. Location of georeferenced well casing compared to locations of well casings in Hidden River Cave. Source: Created by the author (2018).

Although the South River (009) could have involved additional receptors, it is confirmed that concentrations of FL and SRB were detected at the headwaters of the South River after Phase II dye injection. Because no dye was detected at the Breakdown Canyon entrance (008-2) during Phase II tracing, other, concealed groundwater flow paths may exist beneath the breakdown or in tributaries that lie outside of the cave.
boundaries that ultimately discharge to the South River. The South River also could have been an outlet for more dye, either because it is a more direct route from the injection location, it experienced more flow during the monitoring period, or because the flow patterns at the South River where the receptor was deployed were ideal (or a combination of these possibilities). It is also possible that the East River has an additional input (i.e., the headwaters suggested to recharge the East River) that diluted the dye traveling from 009-2 to 010-2, resulting in lower dye concentrations.

The results of the background fluorescence spectra determined by Raedts and Smart (2015) showed that some tributaries in the cave exhibited consistent spectra, suggesting chronic contamination. Indeed, these results align with the consistent spectra seen in sites such as Wheet River, the Waterfall Room, and the South and East rivers. Several other sites in Hidden River Cave may be the focus of further investigation, including the Kneebuster tributary and upstream East River, where distinctive and consistent peaks exist that are characteristic of optical brighteners in raw domestic sewage (Raedts and Smart 2015). In-cave dye-tracing should also occur to confirm the implied connections between sites, such as Wheet River and Breakdown Canyon. Additionally, further dye-tracing at infrastructural sites, such as the Horse Cave Laundromat and sinkholes associated with development (i.e., the retention pond built for the waste management facility) (Raedts and Smart 2015), may further solidify the dye-tracing results from this study. Lastly, these methods can be applied to other tributaries of the Hidden River groundwater subbasin (i.e., L&N Cave and the Hidden River Complex) to develop a larger dataset, which may serve to protect these groundwater resources from further contamination.
As exemplified by this study, dye-tracing is a common tool used to understand the impacts of development and the transport of contaminants in karst groundwater resources (Stephenson et al. 1999; Jiang et al. 2018). For example, Murdoch et al. (2016) determined stream stage responses to storm events via monitoring wells and surface stream sites to characterize the underlying karst hydrogeology, and documented the effectiveness of monitoring wells for the injection of dye to understand the groundwater velocity. Thus, spatial analyses using qualitative dye-tracing data, coupled with stream responses to precipitation events can provide information about the physical processes of flow within the subsurface that is valuable for calculating the fate and transport of contaminants (Li et al. 2016; Jiang et al. 2018).

### 6.2 Characterization of Stream Stage and Discharge in Hidden River Cave

Because the high-resolution stage data recorded by the HOBO pressure transducers are more robust, this study, similar to Murdoch et al. (2016), focused more heavily on the water levels of the South and East rivers and their response to precipitation events. As observed during field days throughout this study, the South and East rivers become fully merged when the stage at the East River is around 1.8 m (6 ft). Before crossing the dam, the boardwalk becomes submerged at about 2.1 m (7 ft). Therefore, some flooding may have occurred during this study that could have limited accessibility, hence why the HOBO pressure transducers are important in providing continuous, high-resolution data.

Because of this, it is critical to note the relative time it takes for water to rise at these sites given certain weather conditions, especially as the Wild Tour has risked high waters before. As seen by the storm events discussed in section 5.2.1, there is some lag in
water level response between the South and East rivers (i.e., JD 176-179 and JD 228-233). The South River seems to respond more quickly to precipitation events and thus recedes more quickly; however, when the East River has experienced sustained precipitation, response times are similar to those observed in the South River. For example, antecedent rainfall that occurred from JD 264 to 267 may have saturated the soil to cause quick responses in stage levels (Massei et al. 2006; Tagne and Dowling 2018); this event produced the largest increase in stage for both sites. Therefore, stage seems to respond more quickly during precipitation events when the system is saturated, where it can take longer for stream stage to increase during dry periods (Knierim et al. 2015). Except for antecedent precipitation, it appears that, on average, it takes anywhere from 40 minutes to one hour for the South River to respond, while the East River takes longer (approximately 1 to 1.5 hours). Additionally, a peak can be seen in the East River hydrograph approximately thirty minutes after a peak occurs in the South River.

Generally, it takes three to four days for both streams to reach baselevel after precipitation events end, aligning with Fiorillo’s (2016) suggestion that hydrograph recession can occur over several days.

The same stream stage conditions observed in the South and East rivers, however, may not be applied upstream, as recharge to the Wheet River tributary may occur at different rates. This may also be true in certain pockets of the cave; for example, CC’s Pool (007) may become inundated quicker based on its apparent direct connection to the surface (according to observations made by the ACM staff after Phase I dye injection and the author's observations of surface debris and odor of diesel fuels). Additionally, Breakdown Canyon (where a designated overpass with ropes and a ladder exists for
explorers when water levels become too high to traverse the canyon passage) may also experience more rapid recharge.

This study assumed relatively similar precipitation events over Horse Cave and Munfordville, although non-uniform rainfall distribution likely occurred and may have slightly impacted some of the changes seen in response times. It is suggested that future hydrological studies use both precipitation values from the Metcalf County and Hart County Mesonet stations to understand stream responses to precipitation events that occur from the Glasgow Upland portion of the Hidden River groundwater subbasin to Horse Cave. A rain gage or weather station could also be installed on site (Groves et al. 2013; Knierim et al. 2015; Schreiber et al. 2015; Murdoch et al. 2016; Jiang et al. 2018) to provide more accurate, real-time precipitation data that can ultimately be used for flood prediction. Further, coupling Mesonet data with on-site, real-time data can confirm the accuracy of the proposed rain gage or weather station.

Nonetheless, the flashy nature of the stream hydrographs is indicative of low storage, high transmissivity, and rapid drainage (Murdoch et al. 2016). While this study occurred over a short period, the HOBO pressure transducers that were installed at the South and East rivers provide important parameters to assess flood events, where human passage is virtually impossible without high risk, such as that shown in Figure 6.3.
6.2.1 Discharge Calculations

Discharge to Breakdown Canyon was consistently higher than at Wheet River and, generally, the South River produced more discharge than both streams combined, although the differences are not significant. These results could be indicative of variations in the respective catchment sizes of the streams, variations in the matrix permeability and porosity (i.e., diffuse vs. conduit flow), storage, or karstification of the cave system (or a combination of these), as well as either inactive tributaries during low flow or the diversion of flow via increased discharge during storm events. In some cases, however, discharge to the South River was less than the combined streams; thus, these data should also be refined. HOBO pressure transducers, therefore, may also be installed at sites such as Wheet River and Breakdown Canyon, as discreet discharge measurements only provide a glimpse of the hydrologic conditions at these sites.

While the data from the South and East rivers provide insight to the hydrologic conditions of Hidden River Cave, further studies should examine discharge over a longer period to capture varying flow regimes and seasonality. Daily potential evapo-transpiration (PET) should also be determined via on-site precipitation monitoring and
incorporated into the further study of recharge and discharge mechanics of Hidden River Cave (Tagne and Dowling 2018).

Although the staff at Hidden River Cave pay close attention to precipitation events, the cascade at the Waterfall Room can serve as a good indicator to Wild Tours of incoming waters from precipitation (based on the author’s observations of increased flow at the Waterfall Room during such an event). As exemplified by Western Kentucky University’s Crumps Cave research, discharge measurements could be taken at the Waterfall Room with the construction of a funnel-shaped tarp that can account for discharge from the entire cascade (Groves et al. 2013). A similar tarp system is seen in Schreiber et al. (2015). Additionally, a station such as this could be beneficial for determining recharge rates (especially as dye-tracing confirmed that engineered drainage features discharge to this site) and for hydrogeochemical analyses, such as those investigated in the Laolongdong karst underground river in Nanshan, southwest China (Jiang et al. 2018). Indeed, several researchers have either conducted or suggested combining hydrogeochemical analyses with hydrograph data, which can be used to characterize contamination to karst groundwater (Scanlon 1989; Ryan and Meiman 1996; Grasso et al. 2003; Knierim et al. 2015; Schreiber et al. 2015; Jiang et al. 2018; Brkic et al. 2018). Hydrogeochemical analyses can also better characterize the epikarst, parameters that have not been examined in Hidden River Cave (Li et al. 2016).

As dye-tracing has indicated that contaminants can continue to infiltrate the passages of Hidden River Cave, the installation of water instruments at sites such as those mentioned above and the Waterfall Room could be used to further characterize the hydrology of the cave system and better determine the fate and transport of contaminants.
Additionally, the continued exploration and survey of L&N Cave and the Hidden River Complex can introduce a much larger dataset to the study of the Hidden River groundwater subbasin, especially as sumped passages prevent the physical connection of the two cave systems (Nims 2018).

It is important to reiterate that the Hidden River groundwater subbasin makes up most of the Gorin Mill groundwater basin; the remaining portion, however, should be further studied to build upon the knowledge of the overall Gorin Mill groundwater basin. In addition to including more instrumentation in Hidden River Cave, it would be beneficial to install a pressure transducer at Gorin Mill Spring to better characterize the overall hydrology of the Gorin Mill groundwater basin. With these recommendations in mind, it is important to understand the percentage of land cover that may increase runoff due to development in the tributary catchments, as the impermeable nature of infrastructure often has an impact on the stage and discharge of subsurface streams (Knierim et al. 2015; Jiang et al. 2018).

6.3 Geographic Information Systems Analysis

A land-use analysis of the Hidden River groundwater subbasin via supervised classification determined that all land types except for agricultural areas expanded over time, aligning with the statement made by the Hart County Chamber of Commerce (HCCC 2013) that agricultural production has decreased over time. The analysis determined that agricultural areas decreased by 25%, while forested areas increased by 17.7%; it is possible that more agricultural land was converted to forest after several events, such as abandonment, ownership conversion, or restoration efforts. A 0.6% increase in water can also be seen. During the creation of the training samples for the
supervised classification, there were several discrepancies between land-use types, which can be attributed to the lower resolution (30 x 30 m, or 98.42 x 98.42 ft) imagery. For example, water bodies in the imagery tend to appear either varying shades of green or brown and therefore contain similar reflectance values as the forested and agricultural areas in the imagery. Some industrial buildings have green roofs, which may have also skewed the classification; some discrepancy is visible in the reclassified 2017 imagery, where water appears to surround developed areas. Additionally, it is possible that several more sinkholes have developed since 2017 that contain water. The amount of precipitation in the study area during the time the imagery was taken should also be considered, as well as the development of engineered water bodies, such as Creacy Lake in Horse Cave.

More importantly, supervised classification determined that development increased by 7% and, although it is not the dominant land-cover type over the Hidden River groundwater subbasin, these areas can significantly modify the natural processes of subsurface recharge via features such as impermeable surfaces (i.e., parking lots and landfills) and subsurface utility networks (Zhou 2007).

Modern construction includes extensive paving over the natural soil surface, which can effectively decrease local recharge by lessening percolation areas while simultaneously increasing the amount of surface runoff to otherwise relatively inactive parts of the groundwater system through features such as irrigation trenches and leaking water, wastewater, or sewage networks (Jiang et al. 2018). Thus, the peak flows witnessed in a hydrograph could be, in part, representative of increased flow from development, which may also increase the magnitude of flooding in karst. Kaushal and
Belt (2012, 425) coined the term “urban karst” to define the network of utility piping that can influence groundwater flow via leaks, cracks, and fissures through the high-permeability trenches that surround the pipes. Figure 5.11 shows that the entire cave system is covered by development. Thus, the impervious nature of development in Horse Cave has most likely altered the recharge and discharge mechanics of Hidden River Cave. This is likely also true near L&N Cave, as it lies beneath Cave City.

Using ArcGIS (10.2), Denizman (2018) analyzed land-use changes near major cave systems associated with the Florida aquifer to examine potential causes of nutrient overload to surface streams and springs. This study took into account the percentage of septic systems and hazardous waste sites surrounding the caves, and effectively confirmed that the cause of nitrates was from development. Thus, further investigation of land use over the Hidden River groundwater subbasin can consider the percentage of the population that relies on septic systems rather than city sewage systems and, using U.S. Census data, population changes over time can consider the increased stress that may be imposed on sewage systems (Knierim et al. 2015). This is especially important to consider because it is possible that some of the wastewater infrastructure has degraded to include leaks (as suggested by groundwater dye-tracing), which can cause effluent to continue infiltrating the cave systems associated with the Hidden River groundwater subbasin (Raedts and Smart 2015).

Additionally, many rural parts of Kentucky, as well as other karst regions, such as those seen in the Ozark Plateau physiographic province (Brahana et al. 2014; Knierim 2015; Murdoch et al. 2016), are home to concentrated animal feeding operations (CAFOs), which commonly do not consider risks to karst groundwater (Tagne and
Dowling 2018). Taking into account the CAFOs and other agricultural activities in the region (as a supervised classification determined approximately 35% of the groundwater basin is made up of agricultural areas) could tell a more detailed story about the potential contaminants entering the groundwater system. This may also further support the evidence of suds seen in the main tributaries of the cave, which are commonly associated with agricultural fertilizers.

Employees that work for the City of Horse Cave could potentially adopt GIS practices in either Esri software or open-source GIS software, such as QGIS, where an inventory of various features in Horse Cave could be developed (i.e., storm drains and a detailed layout of the sewage system). Further, Wilson et al. (2016) explained that combining GIS and remote sensing techniques can be advantageous for conducting spatial, spectral and temporal analyses through the rapid manipulation of data that can cover extensive and often inaccessible areas within a short time frame. Thus, the option to download freely available satellite imagery from sites such as GloVis provides the unique opportunity to complete various cost-effective, broad-scale analyses of karst regions. It is also possible through collaboration with other local or state entities that some free or relatively inexpensive employee training regarding this software could be employed to build and upkeep this inventory. Provided the City of Horse Cave could implement such a program, and that past and previous researchers are open-minded to the provision of GIS data, a more detailed, publicly available GIS database should be established.

Some additional analyses that can be conducted for the region using the hydrological tools in ArcGIS Pro include modeling the dye-tracing conducted herein to
develop more accurate, rather than inferred, groundwater flow paths. This may allow a better explanation of the both Phase I and II dye-tracing. Further, a visual, interactive model of the Hidden River groundwater subbasin that can be made available to the public can further provide a relatively simple way to explain the importance of groundwater protection in karst regions.

6.4 Groundwater Regulations and Strategy for Best Management Practices

The suggested potential for mitigating further contamination of the Hidden River groundwater subbasin through the techniques used in this research can be supplemented by examining the existing policies regarding karst groundwater, including the implementation of best management practices, at national, state, and local levels. Various frameworks exist that are specific to the major transboundary karst regions discussed herein (Marín et al. 2000; Escolero 2002; Bauer-Gottwein et al. 2011; Christenson et al. 2011; Ravbar and Šebela 2015; Stevanović et al. 2016), and several studies exist that provide the scientific basis to support the need for further protection in karst regions (Christenson et al. 2011; Bauer-Gottwein et al. 2011; Nedvidek 2014; Stevanović et al. 2016; Castro 2017; Turpaud et al. 2018); however, a prevalent theme is the lack of the implementation of such practices. (Fleury 2009; Ravbar and Šebela 2015; Richardson 2018). This appears especially true for Horse Cave.

Except for the management of federally owned land, where laws such as the Endangered Species Act (1973) and the Federal Cave Resources Protection Act (1988) indirectly protect karst resources, the U.S. federal government is limited in its authority to address local concerns related to water quality in karst regions (Richardson 2017). The Clean Water Act (1972), for example, only protects against the contamination of surface
waters, and the Safe Drinking Water Act (1974) mentions groundwater but regulates only those karst areas that happen to also contain sole-source aquifers (Nedvidek 2014; Richardson 2018). Rather, state governments and, to the extent granted by the state, local governments hold the primary authority to regulate karst groundwater; however, this is often not conducted in a meaningful way (Fleury 2009).

Each county in Kentucky has set regulations to monitor groundwater, some with more focus on protection than others. For example, groundwater protection is more prevalent in Mammoth Cave National Park (Meiman 2006), whereas small townships, such as Horse Cave, either fail to mention karst drainage or briefly mention things that “should” be done to protect groundwater sensitive regions (HCPC 2014). Although the state of Kentucky identifies karst groundwater via the Groundwater Protection Plan regulation, 401 KAR 5:037 (KDOW 1994), preventative measures to avoid groundwater contamination are vaguely outlined, and merely highlight preventative maintenance procedures for proposed facilities.

Karst groundwater is mostly mentioned in the EPA 303(d) report that is required to be updated every two years and only includes springs and surface stream segments flowing from groundwater sources, thus excluding the potential recharge areas of these water bodies and the potential sources of contamination that may impact them (Keller and Cavallaro 2008). Meaningful regulations, however, cannot be implemented if the entire system is not included in a comprehensive BMP plan. While the state policy does acknowledge karst and karst features, it fails to provide specific preventative measures to protect these resources. Similarly, Hart County’s comprehensive plan repeatedly mentions the importance of the protection of karst and karst features but provides no
foundational plan or BMP to do so. Thus, the following BMPs, as per those outlined in the literature (Zhou 2007; Fleury 2009; Denizman 2018), are recommended for the region spanning the Hidden River groundwater subbasin, with modifications made to fit the specific geology of the area (i.e., the Pennyroyal Plateau).

- Acknowledgment should be made of the regional karst groundwater basins using the relevant literature and ACCA resource in Horse Cave;
- Training services can be implemented for Hart County and local City officials to begin using open or closed source GIS software to create and manage a detailed geodatabase inventory of karst features, such as those determined by a KHI;
- Stronger zoning and subdivision ordinances are needed to control development on the Pennyroyal Plateau, including the regular revision of such ordinances (i.e., on an annual to bi-annual basis);
- Buffer zones, or mandatory setbacks, should be implemented on a case-by-case basis (i.e., regarding proposed building sites near sinkholes);
- Potential impacts on stormwater management and groundwater quality should be identified, assessed, and addressed using professional studies and preventative maintenance practices before a development proposal is approved (i.e., increased vegetation density or porous pavement, as impervious material increases runoff volumes and peak flows);
- Stormwater regulations in Hart County, particularly regarding development, should adhere to the six guidelines established by the EPA’s Phase II stormwater program.
Fleury (2009) explained that setbacks, or no-build areas, essentially are buffers that can be created around sensitive karst areas (i.e., sinkholes) to prevent the encroachment of development. Mandatory setbacks as a regulatory tool can be effective in controlling structural density, especially in areas where sinkholes are abundant (i.e., the Pennyroyal Plateau). Buffer zones could be implemented in Horse Cave on a “case-by-case” basis, which is made simpler in a setting such as this because it has a smaller urban footprint.

Stormwater runoff ordinances are perhaps the most common way to regulate land use on karst in the U.S., commonly due to the visibility of the problem and universal applications (i.e., in non-karst regions as well) across the country. Stormwater management could also be modeled after Bowling Green (its regional neighbor) (Richardson 2018). Additionally, detailed inventories of karst features, such as those determined by a KHI, are critical for environmental assessment and BMP implementations.

BMPs such as those described above can effectively reduce the impact that development has on karst groundwater; however, the attitudes of land-use professionals are critical in developing and implementing karst land-use regulations. Thus, educational outreach is a critical component of policy-making decisions in karst regions. Further, Fleury (2009, 130) suggested that “a voting public with a well-developed understanding of karst and the need for its protection” can effectively weaken poor regulations. Indeed, several authors suggested that public outreach may weaken some of the barriers that exist between poor policy-making decisions in karst and best management practices (LaMoreaux et al. 1997; Fleury 2009; Richardson 2018; Turpaud et al. 2018). In light of
weaker groundwater policies and BMPS, educational outreach is made prevalent in Horse Cave through the staff at the ACM. Perhaps this outreach, combined with the research conducted herein, could encourage the public and begin to provide a foundation for further study and eventual implementation of best management practices in Horse Cave
Chapter 7. Conclusions

An integrative approach combining dye-tracing techniques, high-resolution stream stage data, and supervised classification in ArcGIS Pro was used to assess the impacts that land use has on Hidden River Cave and the overall Hidden River groundwater subbasin. This study highlighted the following issues:

- The fluorescent tracing discussed herein was conducted to demarcate areas of land use that are negatively impacting cave waters and provided data for more informed management of Hidden River Cave. While the integrity of the utility structures beneath the streets of Horse Cave is unknown, it can be concluded that engineered drainage features are directly discharging to Hidden River Cave. Additionally, existing dye-tracing maps from Quinlan and Rowe (1977) and Ray and Currens (1998) can be refined to provide more detail on the influences of anthropogenic contamination on recharge to the Hidden River groundwater subbasin;

- This study provided the first high-resolution hydrology study in Hidden River Cave that effectively described stream responses to precipitation events, which often transport contaminants into the subsurface. Following on from the early research of Quinlan and Rowe (1977) and others thereafter, this study provides a contemporary benchmark for future discharge studies in the cave;

- A lack of human and financial resources is evident in Horse Cave; thus, there exists a lack of appropriate inputs to develop quality BMPs. Documentation of changes in land use suggested opportunities for a more informed management of
Hidden River Cave and provided more specific data for the implementation of BMPs;

- The study provided data and graphics to enhance the educational outreach at the American Cave Museum;
- Finally, the methods developed in this study could be used in other transboundary karst regions.

As with studies by Knierim et al. (2015) and Murdoch et al. (2016), this study addressed gaps in the literature by evaluating land-use and recharge relationships at the local scale. By now, it is no secret that karst regulations are few, and those that do exist are not enforced locally and regionally as effectively as they could be. Perhaps a smaller community setting such as Horse Cave could become an exemplar of effective BMPs in a karst region that has undergone extensive contamination. It is even possible that, someday, Horse Cave will raise the bar in terms of statewide BMP policies that focus on karst environmental issues. With the good-standing relationships between the ACM and the city of Horse Cave, it is entirely possible, especially as Hidden River Cave serves as an important economic and cultural resource for Horse Cave and the wider region
References


Capps, A. 2001. *Dye Tracing to Delineate Drainage Basins and Determine Groundwater Sensitivity, Mammoth Cave, Kentucky; With Special Reference to Potential Groundwater Contamination from Spills along Interstate I-65*. Master’s Degree in Geography, Department of Geography and Geology, Western Kentucky University, Bowling Green, KY. Available at: http://digitalcommons.wku.edu/theses/681/


CHL (Crawford Hydrology Laboratory), 2016. *Standard Operating Procedures*. Bowling Green, KY: Crawford Hydrology Laboratory

CHL (Crawford Hydrology Laboratory), 2018. *Practical Quantitation Limits*. Bowling Green, KY: Crawford Hydrology Laboratory


EPA (Environmental Protection Agency), 1989. *Arbuckle-Simpson Aquifer of South Central Oklahoma Sole Source Aquifer; Final Determination*. Oklahoma City, OK: EPA. Available online at: https://www.owrb.ok.gov.


HCCC (Hart County Chamber of Commerce), 2013. *Discover Hart County, Kentucky*. Munfordville, KY: HCCC. Available at: https://www.hartcountyky.org/Directory_To_Print.pdf


Jackson, L., 2017. Epikarst Hydrogeochemical Changes in Telogenetic Karst Systems in South-Central Kentucky. Master’s in Geoscience, Department of Geography and Geology, Western Kentucky University, Bowling Green, KY. Available at: http://digitalcommons.wku.edu/theses/2018


Szukalski, B., 2013. An Interactive Map of Hidden River Cave, Horse Cave, Kentucky.. Redlands, CA: Environmental Systems Research Institute (Esri), ArcGIS Online. Available at: https://www.arcgis.com/home/item.html?id=6f54199a4e714857b5c6e97b4f431968


