Karst Groundwater Tracer Tests and Basin Delineation, Wayne and Clinton Counties, South Central Kentucky

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- Special thanks to Mr. Bill Walden, in memoriam, who provided a wealth of knowledge and experience that greatly benefited our understanding of karst resources in South Central Kentucky.

CONVERSION FACTORS

Multiply	by	To obtain
acre	43559.66	ft^2
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
gallon (gal)	3.785	liter (L)
gallon per minute (gpm)	0.06308	liter per second (L/s)
cubic feet per second (ft^3/s)	0.02832	cubic m per second (m^3/s)
$ft^3/s/mi^2$ (cfsm)	10.931	$L/s/km^2$ (lsk)
foot per mile (ft/mi)	0.1894	meter per km (m/km)
square mile (mi^2)	640	acres
mi^2	2.59	km^2
acre (ac)	0.4047	hectare (ha)
ounce (oz)	28.35	gram (g)
pound (lb)	0.454	kilogram (kg)
km	0.621	mi
$L/s/km^2$	0.0915	$ft^3/s/mi^2$
km^2	0.386	mi^2
meter	3.28	feet
m^3/s	35.31	ft^3/s
m/km	5.28	ft/mi
kg	2.2	lb
hectare	2.471	acre

Executive Summary

This study was focused on mapping karst spring basins in south central Kentucky, primarily in Wayne and Clinton counties. Previous and concurrent investigations provided a wealth of useful knowledge that served to guide and inform the authors. As part of this study 57 new springs were inventoried for the Division of Water (DOW) Consolidated Groundwater Database. In addition, 37 reconnaissance groundwater traces over three years were conducted as part of this research that were recovered at 24 unique springs and karst features. Combined with previous research, this allowed for full or partial delineation of 36 karst-spring basins. All data have been forwarded to the Kentucky Geological Survey (KGS) Groundwater Data Repository. Records of each dye trace conducted for this project and GIS files developed to document results are available upon request.

Introduction and Background

The Division of Water (DOW) has adopted an integrated approach to the management of water resources. The approach, known as the Kentucky Watershed Framework, is *". . . a means for coordinating and integrating the programs, tools and resources of stakeholders to better protect, maintain and restore the ecological composition, structure and function of watersheds and to support the sustainable uses of watersheds for the people of the Commonwealth"*. Under this system, the watersheds of the state are subdivided into five Basin Management Units (BMUs). Monitoring and assessment of water resources rotates through each of these five BMUs. The initial groundwater assessments in each BMU were designed to obtain cursory understanding of ambient conditions and baseline geochemistry. Subsequent groundwater assessments in each BMU were developed to focus on smaller watersheds or regions identified as either problematic or lacking evaluation.

Water resources must be physically quantified in order to determine proper management strategies to protect, maintain and restore watersheds. Therefore, aquifer characterization and groundwater flow mapping must be conducted prior to groundwater resource monitoring and assessment. The study presented in this report was focused on mapping karst basins in south central Kentucky to begin the process of evaluating regional groundwater resources.

Karst Hydrology

Because of the characteristics of karst terrane, rates of groundwater recharge, flow velocities, and dispersion within the study area can be extremely high. These groundwater systems can be rapidly recharged by widespread influx of precipitation and snow melt through soil macropores, runoff into sinkholes, and concentrated flow from losing and sinking streams. Groundwater velocity through conduits often matches runoff in surface channels, which may travel several miles per day. Likewise, karst groundwater flow can be dispersive, potentially distributing pollutants over broad areas at relatively long distances from the source(s). Three major hydrologic parameters of *recharge, flow, and dispersion* were used to assess the groundwater sensitivity to pollution from surface activities in Kentucky (Ray and others, 1994). Hydrogeological sensitivity was rated on a scale of 1 (low) to 5 (high), based on quantitative assessments of these three parameters. Documentation of conduit-flow velocities in karst aquifers by numerous tracer tests was especially useful for rating the important *flow* component in a particular hydrologic setting. In the karst terrane of the Mississippian Plateau, *recharge* porosity can range up to several feet in diameter, which is exemplified by stream infiltration into a cave or vertical shaft. *Flow* velocity within trunk conduits may range from 30 ft/hr at low flow to 2500 ft/hr during flood conditions (Ray & O'dell, 1993). *Dispersion* of contaminants within this karst aquifer is usually linear or bi-directional, but widespread to radial flow patterns do occur. Because of these extreme ranges, the study area is rated as “5”, which is the most sensitive hydrogeologic setting for potential pollution from surface activities and nonpoint sources.

The relatively shallow karst aquifers of Kentucky, formed in dense Paleozoic carbonates, typically contain low to moderate long-term storage of groundwater (White, 1988). Most seasonal groundwater storage is within the soil and regolith cover, the underlying weathered bedrock zone called the *epikarst*, and in bedrock fractures. Long-term storage within the epikarst, commonly in the form of a perched water zone, continually seeps and percolates down through fractures and shafts, and collects within the regional conduit drainage network. The karst flow system is typically an interconnected dendritic, or branched, horizontal network that discharges at large springs (Palmer, 1990). These convergent conduit networks tend to form distinct, contiguous groundwater drainage basins. These drainage networks can gather pollution over a broad area, allowing it to coalesce in the karst system and be concentrated at the discharging spring(s). Hydrologic interconnections between basins are typically localized along basin boundaries. However, inter-basin transfer from one trunk conduit to another may occur locally during overflow (high-water) conditions. Near the basin discharge zone, divergent distributaries are common and are usually overflow networks (Ray, 1997). Perennial-flow distributaries are less common. Figure 1 (Currens, 2001) shows the surface and subsurface elements of a typical karst aquifer in the study area.

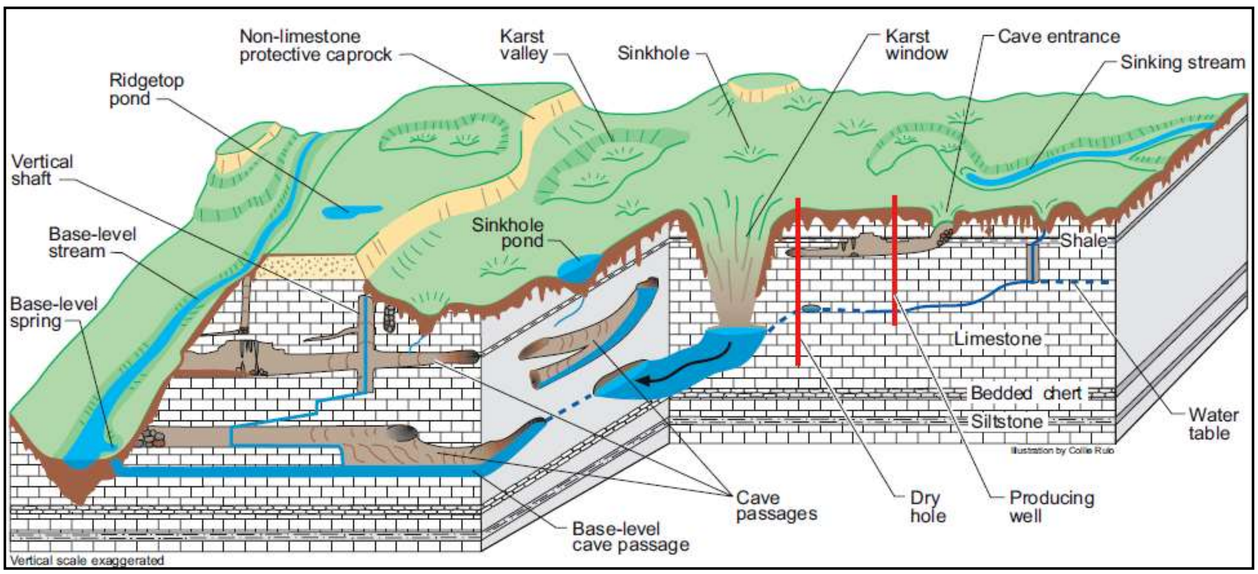

Figure 1. Karst Aquifer Block Diagram (Currens, 2001)

Project Description

The purpose of this project was to expand upon karst-basin mapping within the study area, which increases our knowledge and understanding of regional and local groundwater resources. This sets the stage for subsequent groundwater quality monitoring and assessment projects. Additionally, karst-basin mapping can verify the accuracy of watershed boundary delineations, from which groundwater-flow paths may deviate. This has important implications relative to potential and confirmed water contamination and response to environmental emergencies.

Previous groundwater tracing and cave mapping projects have been conducted by several researchers, which were focused on local karst basins. This project had a regional focus to inventory karst features and map groundwater flow across parts of Pulaski, Wayne, Clinton, Russell and Cumberland counties. The study area is bounded by the following US Geological Survey (USGS) 7.5-minute quadrangles: Wolf Creek Dam, Albany, Jamestown, Cumberland City, Savage, Jabez, Parnell, Powersburg, Mill Springs, Monticello, Parmleysville, Frazer, Coopersville, Bell Farm, Burnside and Nevelsville (Figure 2).

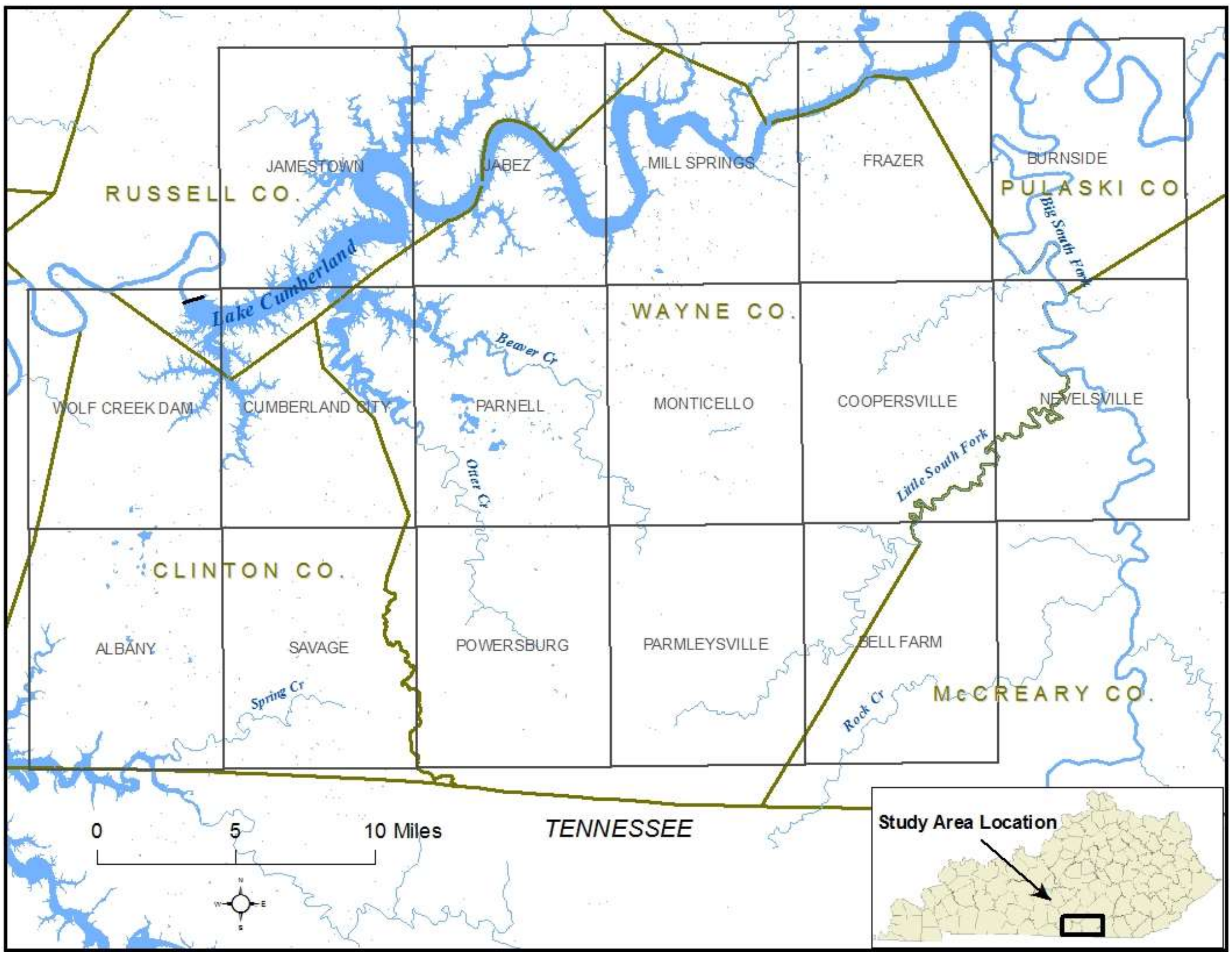

Figure 2. Study Area Map

Upper Cumberland River Basin

The Cumberland River rises on the western flanks of the Appalachian Mountains in southeastern Kentucky and northeastern Tennessee. The Kentucky portion of the Upper Cumberland River Basin (HUC 051301) encompasses 5,183 square miles. The headwater streams are generally confined to narrow, steep-sided valleys. Ridgetops are capped with sandstone and shale of Pennsylvanian age (~300 Ma), with the underlying Mississippian-aged limestones (~350 Ma) exposed in valley walls and bottoms.

Major tributaries to the Upper Cumberland River in the study area are the Big South Fork, Beaver Creek, Otter Creek and Indian Creek. The Cumberland River is impounded at the Wolf Creek Dam forming Lake Cumberland, which marks the northern boundary of the study area. Below the dam, the Cumberland River flows generally southwest and exits Kentucky from eastern Monroe County on the Tennessee border.

The southwestern study area is partly bounded by Dale Hollow Lake, which is an impoundment of the Obey River near Celina, Tennessee where it meets the Cumberland River. Tributaries of the Obey River in Kentucky include Spring Creek, Sulphur Creek and Illwill Creek.

Population centers in the study area include Monticello in Wayne County and Albany in Clinton County. Smaller towns are scattered across the region in a rural setting that is predominantly agricultural and timber land.

Physiographic Region

The study area occurs entirely within the Mississippian Plateau Physiographic Region and is bounded on the east by the Eastern Coal Field. The Mississippian Plateau, also known as the Pennyroyal or Pennyrile, is characterized by relatively flat-lying Mississippian-age carbonate rocks, primarily limestone with some dolostone, with ridgetops capped by sandstone and shale. However, in this area bedrock dips significantly to the southeast in association with the Appalachian Mountains. Well-developed karst drainage occurs in this region with an abundance of sinkholes, caves and sinking streams. Groundwater flow is primarily through solutionally enlarged conduits, but fracture flow and flow along bedding planes also occurs and can be locally important (Brown and Lambert, 1963).

Hydrogeologic Setting of Study Area

Well-developed karst drainage in the study area occurs mainly in the Ste. Genevieve and St. Louis limestones of the Meramecian Series of the Mississippian System (325-345 Ma). These limestones were deposited primarily in shallow seas. The purity and high solubility of the limestones make the terrane highly conducive to karst development. Long-term bedrock dissolution of these limestones has strongly influenced the Mississippian Plateau's characteristic flat-lying to undulating topography, which contains numerous sinkholes, caves, losing and sinking streams, dry valleys, intermittent lakes, and large springs (Ray and others, 2006). Above the Ste. Genevieve Limestone lie sandstone, shale and limestone units of the Chesterian Series of the Mississippian System. Karst development in the overlying Chesterian Kidder and Bangor limestones is intense, but the rock units have limited geographic extent. Karst features identified in these upper limestones include small caves, bedrock shafts and sinkholes that seem to represent headwater areas for regional spring basins. Beneath the St. Louis Limestone is the Salem and Warsaw Limestone. This unit is sometimes mapped as part of the St. Louis and the contact can be difficult to recognize. Karst development is generally limited in the Salem and Warsaw Limestone, unless it is exposed over a large geographic area. The Salem and Warsaw Limestone is underlain by the Fort Payne Formation, which has limited exposure due to Lake Cumberland. The rock formations found in the study area are described below in descending stratigraphic order. These descriptions are drawn largely from the U.S. Geological Survey Geological Quadrangle Maps and Sable and Dever (1990), and observations made during the course of field work for this study. The map in Figure 3 shows the potential for karst development across the study area based on the outcrop of soluble carbonate rocks. Figure 4 is a generalized stratigraphic column for the study area with karst-forming rock units highlighted.

Pennsylvanian Strata of the Lee Formation

Higher ridgelines and peaks across the study area are mainly capped with sandstone, shale and conglomerate, with minor coal seams. These rock units are generally mapped as the Lee Formation, but on some of the USGS quadrangles the unit is mapped as the Breathitt and Lee Formations. The most notable marker bed within the unit is the conglomerate of the Rockcastle Sandstone Member, which is composed of white quartz pebbles in a sand matrix (Lewis, 1977).

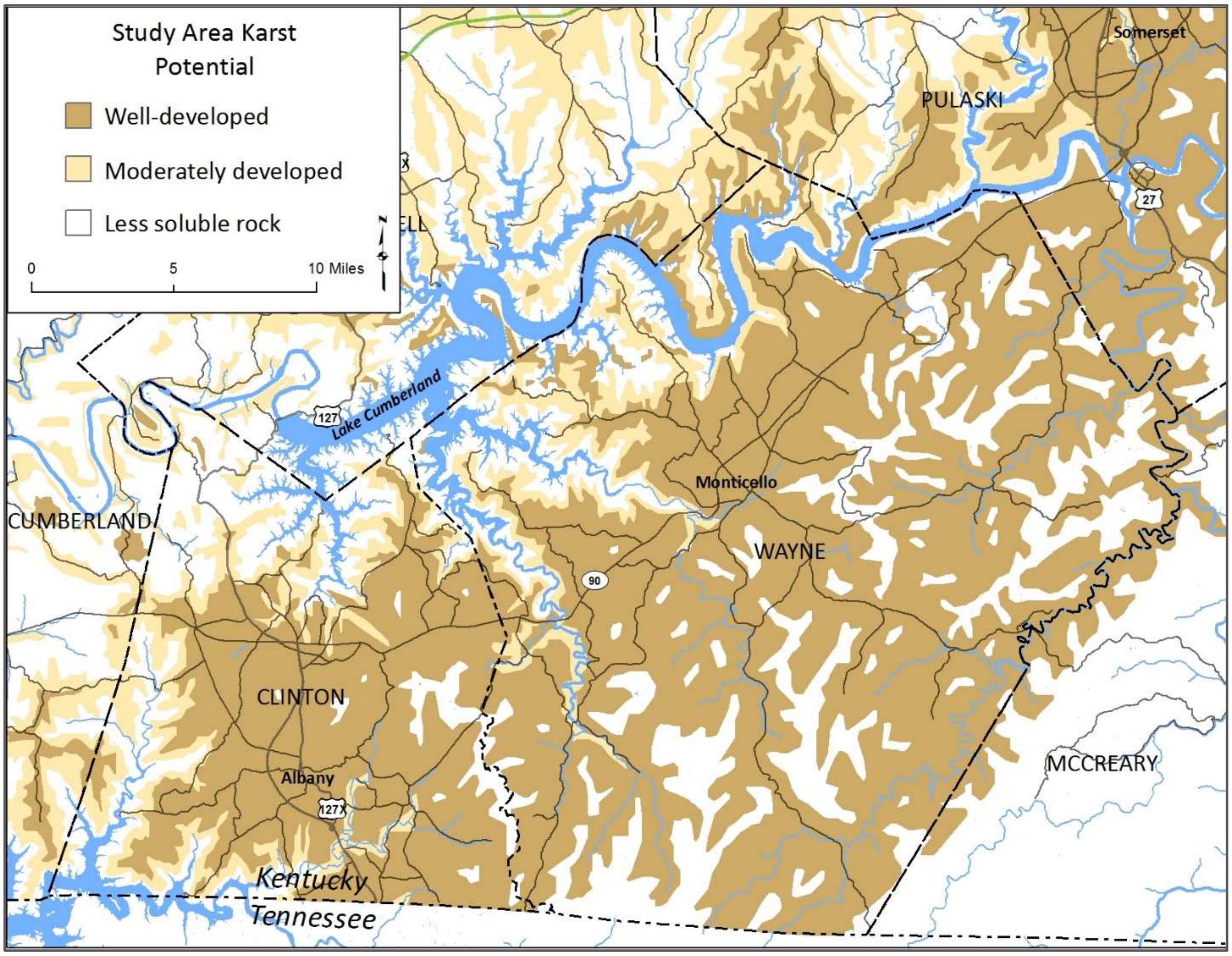

Figure 3. Study Area Karst Potential Map (adapted from Paylor and Currens, 2001)

Pennington Formation

The Lee Formation is underlain by the Mississippian-aged Pennington Formation, which is primarily shale with minor sandstone and siltstone. Limestone and dolostone occur near the base of the unit (Taylor, 1976). This unit is exposed on and near ridgetops and in valley walls. Both the Lee and Pennington formations typically impede water infiltration from precipitation events.

Bangor Limestone

The Bangor Limestone is a relatively thin unit that is mainly exposed on hillsides and valley walls, but also forms the tops of some lower-elevation ridges in the study area. This unit is described by Taylor

(1976) and Lewis (1977) as dark to medium gray and fine to coarse-grained limestone that is thick-bedded at the base. Bedding becomes thinner and has shale partings near the top of the unit. Several small spring systems have developed in this unit, most of which are perched by the underlying Hartselle Formation. The Bangor Limestone is likely the stratigraphic equivalent of the sequence of Glen Dean Limestone, Hardinsburg Sandstone and Haney Limestone of western Kentucky (Taylor, 1976; Sable and Dever, 1990).

Hartselle Formation

The Hartselle Formation is a thin unit of shale and sandstone that may locally impede groundwater circulation between the limestone units above and below. The shale is greenish- to blueish-gray and occurs in thin, even beds. The sandstone is very fine grained and quartzose, and typically greenish-gray (Taylor, 1976). The overlying shale tends to form moderately-steep slopes above the low bluffs formed by the sandstone. The Hartselle Formation is likely the stratigraphic equivalent of the Big Clifty Sandstone Member of the Golconda Formation (Sable and Dever, 1990), but may correlate to the Hardinsburg Sandstone of western Kentucky (Lewis, 1977).

Kidder Limestone

The Kidder Limestone is a fairly thick sequence of limestone with minor interbedded siltstone and shale. The unit is medium- to light-gray, generally fine grained and thickly bedded. The Kidder is generally found on hillsides and valley walls. It grades into the underlying Ste. Genevieve Limestone and the contact is often difficult to discern (Taylor, 1976). In most of the study area this unit was mapped with the Ste. Genevieve Limestone as the upper member of the Monteagle Limestone, and in some areas the two units are not differentiated. Significant karst development has occurred in the Kidder Limestone with numerous vertical bedrock shafts and caves identified during this study and previous research.

Ste. Genevieve Limestone

The Ste. Genevieve is composed of thick-bedded, light-colored, medium- to coarse-grained, oölitic and bioclastic calcarenite; light-colored to gray, bioclastic calcirudite; gray calcilutite; and gray, very finely crystalline dolomite. Minor amounts of chert occur as nodules, thin beds and stringers, and siliceous replacements of fossiliferous beds (Sable & Dever, 1990). The Lost River Chert is a distinctive 5- to 10-

feet thick zone of nearly continuous chert that occurs at or near the base of the Ste. Genevieve Limestone. This chert is highly fossiliferous with fenestrate bryozoans, brachiopods, and gastropods. It is nearly indistinguishable from surrounding light gray limestone when freshly exposed, but when weathered it reveals characteristic porous blocks of chalky-white chert stained with red soil. The Ste. Genevieve Limestone occurs at the base of hillsides and valley walls. Significant karst development has occurred in this unit.

St. Louis Limestone

The St. Louis Limestone, which underlies the Ste. Genevieve Limestone, consists of a very fine-grained, micritic, cherty, argillaceous, and dolomitic limestone. It is characteristically gray to dark gray, fossiliferous, and thick-bedded to massive (Sable & Dever, 1990). The upper part of the St. Louis Limestone is highly cherty, which helps to locally perch groundwater. This unit averages 150 feet in thickness across most of this region and occupies valley bottoms and broad lowlands in the study area. The largest springs identified in the study area discharge from this rock unit.

Salem and Warsaw Formations

The Salem and Warsaw Formations are composed of limestone and siltstone (Taylor, 1976). In some areas these rock units are mapped separately, and in others the Salem Formation is mapped as the lower part of the St. Louis Limestone. This formation is only exposed in the deeper valleys associated with the Otter Creek, Beaver Creek and the Cumberland River, especially along the southern shore of Lake Cumberland. Karst development is generally limited in this unit because it has little surface exposure and the upper portion of the unit is largely siltstone. However, these rocks form a distinctive perching unit and numerous small springs discharge from the middle and lower parts of this formation where it is exposed in steep valleys overlooking Lake Cumberland.

<table>
<tr><th>System</th><th>Series</th><th>Formation</th><th>Dominant Lithology</th><th>Hydrogeology</th></tr>
<tr><td>Penn-sylvanian</td><td>Lower</td><td>Lee Fm and Rockcastle Conglomerate</td><td>Sandstone and shale</td><td>Fracture Flow</td></tr>
<tr><td rowspan="8">Mississippian</td><td rowspan="4">Chester</td><td>Pennington Fm</td><td>Shale and sandstone</td><td>Perching unit</td></tr>
<tr><td>Bangor Limestone</td><td>Limestone</td><td rowspan="3">Primary Karst System Recharge</td></tr>
<tr><td>Hartselle Fm</td><td>Shale and sandstone</td></tr>
<tr><td>Kidder Limestone</td><td>Limestone and siltstone</td></tr>
<tr><td rowspan="3">Meramec</td><td>Ste. Genevieve Limestone</td><td>Limestone</td><td rowspan="2">Primary Karst System Discharge</td></tr>
<tr><td>St. Louis Limestone</td><td>Limestone</td></tr>
<tr><td>Salem and Warsaw Fm</td><td>Limestone and shale</td><td>Minor Karst Development</td></tr>
<tr><td>Osage</td><td>Ft. Payne</td><td>Siltstone and shale</td><td>Perching unit</td></tr>
</table>

Figure 4. Generalized Stratigraphy of Study Area (adapted from Sable and Dever, 1990)

Land Cover

Land cover analysis is based on the 2011 National Land Cover Dataset (USGS, 2011), which is somewhat dated. However, observations during fieldwork and comparison to recent aerial imagery suggest that only minor changes have occurred since these data were compiled. For this analysis, subcategories were combined such that all levels of urban and residential land cover are considered as one. Additionally, impervious areas such as roads are included in the urban/residential category. Similarly, all forested areas have been combined (deciduous, evergreen and mixed), as well as agricultural areas (pasture and row crop). This results in three main categories of land cover: Urban/Residential (impervious), Forest and Agriculture (Figure 5).

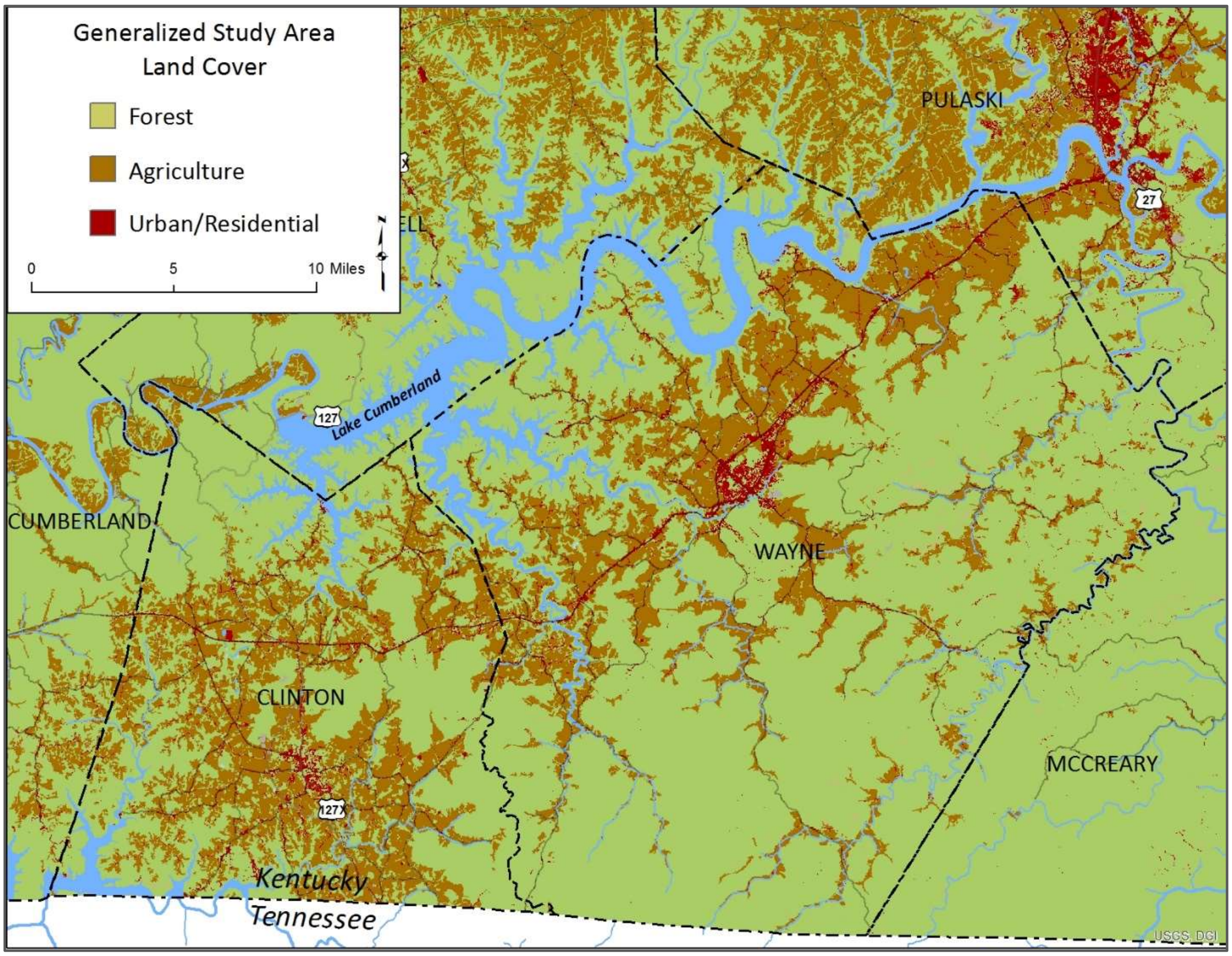

Figure 5. Generalized Study Area Land Cover Map

The predominant land cover type within the study area is forested at 61%, which is followed by agriculture at only 27%. Urban/Residential (impervious) areas comprise only 7% of the total area, with surface water, wetlands and barren land making up the remaining 5%. Table 1 shows the break down of land cover types in the study area along with some of the potential water quality impacts associated with each.

Table 1. Study Area Land Cover

Land Cover Type	% in Study Area	Potential Water Quality Impacts
Forest – including logging and silviculture	61	Pesticides, nutrients, sediment, pH
Agriculture – including row crop production, livestock grazing, fuel/pesticide storage	27	Pesticides, nutrients (esp. nitrate-n), salts/chloride, volatile organics, bacteria
Urban/Residential – including commercial and light industry	7	Pesticides, nutrients, volatile organics, chlorides, bacteria

Groundwater Use

Groundwater is widely used for a number of purposes within the study area. Several springs have been developed for irrigation and livestock watering. Many undeveloped springs are accessible to livestock and used as water sources. A few springs were identified during field surveys that are currently used for domestic drinking water supplies. There are several small communities around Lake Cumberland that are not served by public water suppliers and residents rely on private, domestic wells. The water table near the lake is artificially elevated and these wells are subject to water loss if the lake level gets too low. This was seen in 2006 and 2007 when repairs to Wolf Creek Dam required the lake to be partially drained.

Previous Investigations

Van Couvering (1962) conducted reconnaissance of large springs in Kentucky and this included data collection on one spring in the study area. His publication included discharge measurements and the hypothesized groundwater recharge area for Town Mill Creek Spring in Albany, KY.

The United States Geological Survey (USGS) has published Hydrologic Atlases (HA) for the entire state. HA-35 (Lambert and Brown, 1963) provides a general description of geologic units and groundwater occurrence, availability and geochemistry for Wayne, Clinton, Pulaski, Cumberland, Russell, Adair, Casey and Taylor counties. Several of the springs investigated in this study appear on their maps along with discharge estimates. Brown and Lambert (1963) co-authored a more in-depth report of groundwater reconnaissance across the entire Mississippian Plateau. In this work they provide some detailed measurements for groundwater withdrawal rates from water wells and discharge measurements of larger springs.

Currens and McGrain (1979) compiled a bibliography of karst publications for the state. This report includes a large number of publications that describe historical research and water quality in the karst regions of Kentucky. Simpson and Florea (2009) provide an excellent description of the geologic and physiographic setting of caves in the Cumberland Plateau Region. This includes a brief history of cave exploration, as well as descriptions and maps of several noteworthy caves.

Caving groups are active in southern Kentucky and have identified and mapped numerous caves and springs throughout the region. Much of the data and information they have gathered is archived by the Kentucky Speleological Survey (KSS). The knowledge, information and assistance provided by cavers during this project were extremely important. Groundwater-flow paths presented in this report that are based on cave maps are represented by the same curvilinear vectors as dye-trace data that connect areas of recharge to discharging springs. Cave maps can be requested from the KSS through their website (http://ksscaves.com/).

Several dye-trace studies have occurred within the study area that were mainly focused on individual spring basins. Tracer data for 15 springs were identified prior to, and during the course of, this study. The results of tracer tests and cave maps completed prior to this project are summarized below with maps to illustrate the associated groundwater-flow paths.

Materials and Methods

Introduction

The primary goal of this project was to map karst groundwater flow and delineate spring basins in support of subsequent water quality monitoring. Groundwater quality monitoring programs are more meaningful and beneficial if the source recharge areas are known. The methods utilized to identify karst features, delineate groundwater-flow paths, illustrate karst basins and document tracer test results are summarized below.

Graphical Methods

Maps used to show results of tracer tests conform to the standards used in the Kentucky Karst Atlas map series published by the Kentucky Geological Survey with the Kentucky Division of Water. This dye trace map legend is shown in Figure 6. Mapped karst features and the associated tracer data are displayed in color overlain on black and white 7.5-minute topographic quadrangles. Topographic contours and cultural features are displayed in gray tone for improved discrimination of the color-coded tracer data. Inferred groundwater-flow routes are illustrated as minimum straight-line to curvilinear distances, which are shorter than actual conduit pathways. Surveyed cave passages are not shown on the accompanying maps, but are depicted with generalized groundwater-flow paths illustrated as dye trace vectors. Some basin boundary segments are delineated based on topographic divides when tracer data are lacking. The dashed boundary line indicates the imprecise nature of karst groundwater divides (Ray, 2001). Groundwater recharge within about 1000 feet on each side of a mapped divide should be assumed to potentially drain to both associated basins. Tracer tests for this study are identified in the report and on accompanying maps by the year and sequence in which they were conducted (i.e. Tracer 13-11 was the eleventh tracer test conducted by DOW in 2013).

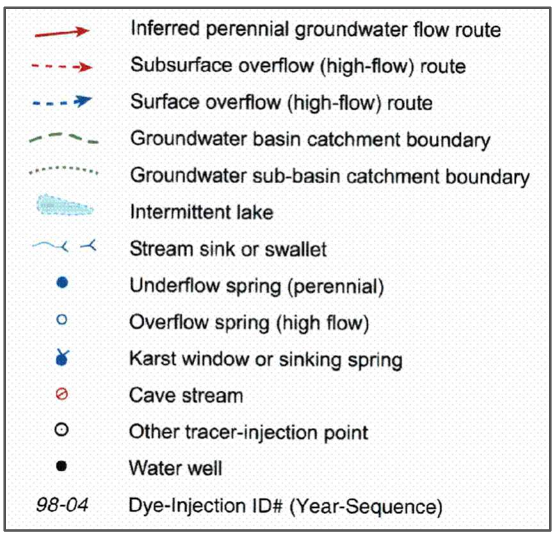

Figure 6. Karst Atlas Legend

All maps were created with ArcMap 10 software using data obtained from the Kentucky Geography Network, Kentucky Division of Water and data files created by the authors specifically for this project.

Hydrogeologic Inventory

This study began with reconnaissance and inventory of springs and other karst-related features, as well as a general survey of the karst-forming rock units in the area. Many springs were identified by topographic and hydrologic analysis, which was followed with field verification. Several other springs were identified by local land owners interviewed during the course of field surveys.

A unique eight-digit identification number, called an AKGWA number, is assigned to each spring that is inventoried and maintained in the Department for Environmental Protection (DEP) databases. The spring inventory form notes details of the date, site, including owner's name and address, location, spring development, yield and flow conditions and topographic map location. The data are then entered into DEP's electronic database and forwarded to the Groundwater Data Repository at the Kentucky Geological Survey. The spring forms are scanned and stored in a database as an indexed electronic image. A total of 57 new springs and karst features were added to the groundwater database as part of this project.

Tracer Test Methods

Qualitative groundwater tracer tests, as described by Quinlan (1986) and Aley (2002), were conducted using three non-toxic fluorescent dyes. The names of dyes used in this study are shown in bold in Table 2:

Table 2. Fluorescent tracer dyes used and number of injections for each

Dyes Used	Trade Name	Color Index	Number of Injections
SRB (Sulforhodamine B)	Ricoamide Red XB	Acid Red 52	12
Eosine	15189 Eosine OJ	Acid Red 87	14
Uranine (Fluorescein)	Uranine Conc (Disodium Fluorescein)	Acid Yellow 73	11

As indicated by Schindel and others (1994) and Field and others (1995), these fluorescent dyes are optimal for use in groundwater-basin delineation because of non-toxicity, availability, analytical detectability, moderate cost, and ease of use. Prior to fieldwork, powdered dye was dissolved in water at a concentration of 8 ounces per gallon.

The quantity of fluorescent dye used for each test was determined utilizing two methods. The first method comes from Ray and others (2006), which was determined empirically over several years of field experience. For uranine and eosine, the liquid-dye mixtures were injected into active stream swallet sites at a rate of about 0.25 gallon per mile of expected flow distance (equivalent to about 2 ounces of powdered dye per mile). Depending on conditions, up to twice as much SRB dye was used for equivalent flow distances. Dye quantities are roughly doubled when used at dry sinkhole sites flushed with hauled water or during high-flow conditions. The second method is derived from Worthington and Smart (2003) where tracer mass is calculated based on apparent flow distance, spring discharge and the desired concentration of tracer at the discharge point using the equation:

$$M = 19(LQC)^{0.95}$$

where M is tracer mass (g), L is flow distance (m), Q is spring discharge (m^3/s) and C is the desired dye concentration at the discharge point (g/m^3). These two methods generally calculated very similar quantities of tracer dye necessary for each test. However, when the methods did not give roughly equivalent figures, the greater amount was chosen.

During movement of tracers through monitored sites, fluorescent dyes were adsorbed and accumulated onto activated carbon samplers. In some cases, when the dye receptor was missing, dye presence was determined by collecting a water sample for laboratory analysis. The carbon dye receptors were deployed in flowing water of springs, streams, and caves and anchored with either a modified "gumdrop" anchor (Quinlan, 1986), or a brick fitted with a vinyl-clad copper wire. The receptors were secured to the anchor with a commercially available "trot line clip" (Figure 7).

Figure 7. Dye Receptors and Anchors

Background dye receptors were usually deployed, exchanged, and analyzed prior to dye injection in the study area. These background dye receptors served as controls for comparison with subsequently recovered receptors. In a few cases, prior background assessment with charcoal dye receptors was omitted in order to take advantage of unusual field opportunities to inject dye. In those cases, background water samples were carefully collected on the same day as the expedited dye injection in lieu of the background assessment. Dye receptors were typically exchanged every 2 to 7 days.

Sample preparation and analysis was conducted at the DOW Groundwater Laboratory. For analytical processing, samples of the retrieved carbon dye receptors were rinsed with de-ionized water and eluted at room temperature for at least 15 minutes in a solution of 50% 1-propanol, 30% de-ionized water, and 20% ammonium hydroxide (NH_4OH). The eluted samples were analyzed for the absence or presence and relative intensity of tracer dye using a scanning spectrofluorophotometer (Shimadzu RF-5301). All results of dye analyses are archived as PDFs. Figure 8 shows typical dye curves analyzed on the spectrofluorophotometer. The horizontal position (x axis) of a dye peak indicates the fluorescence wavelength, which identifies the type of dye. The vertical height (y axis) of the curve indicates the relative fluorescence intensity of the recovered dye and thus the qualitative confidence level of the positive dye recovery.

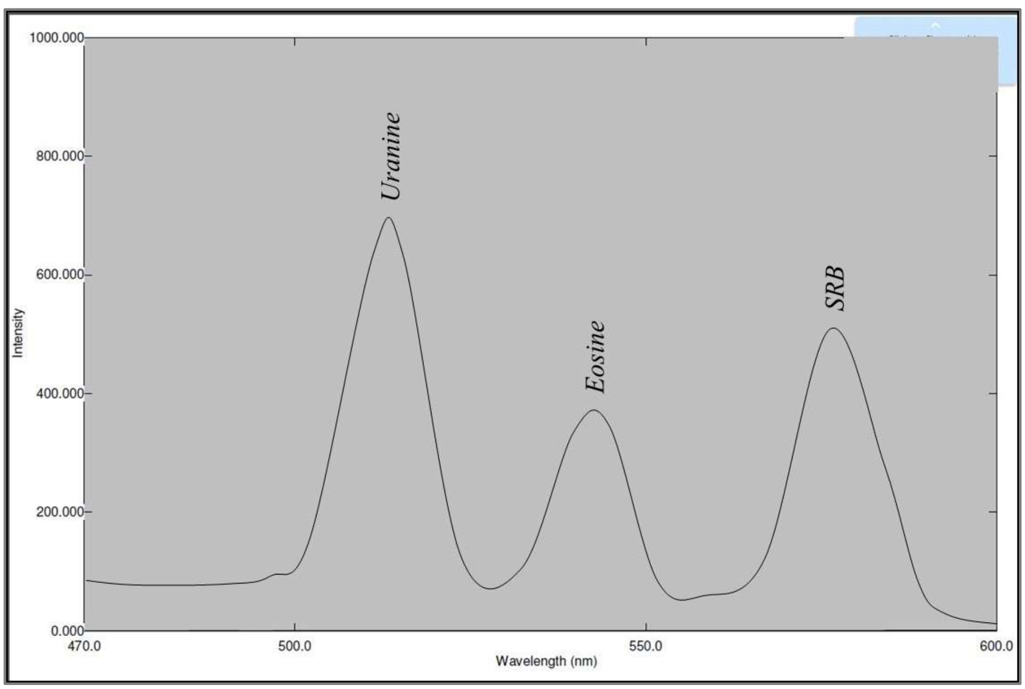

Figure 8. Typical Dye Curves on Spectrofluorophotometer

Documentation of Tracer Tests

During this project, 37 reconnaissance groundwater tracer tests were conducted for the purpose of basin delineation and verification or modification of inferred watershed boundaries. Tracer tests were recovered at 24 springs, cave streams and karst windows, which fully or partially delineated 18 karst drainage basins. The results of these investigations are discussed individually for each spring, and are listed under abbreviated dye trace ID numbers using the year and the sequence (e.g. 11-02). Analyzed dye-intensity level from recovered dye receptors is indicated by the following symbols, which represent the qualitative confidence level of a dye recovery and hydrologic connection:

– Negative result

? Inconclusive (< 4X background)

+ Positive (> 4X background; < 1000 intensity units)

++ Very Positive (1000-10,000 intensity units)

+++ Extremely Positive (> 10,000 intensity units)

Positive dye recovery was determined when fluorescence intensity exceeded background by at least four times (4X); fluorescence of positives typically exceeded background by more than 10X. An inconclusive result indicated that dye was recovered at less than 4X the background level. Two or more successive dye detections at less than the criterion of 4X the background level may be judged to be a positive recovery in certain situations. The use of minimal quantities of tracer dye sometimes resulted in lower than desired levels of dye detection. In some cases water samples were collected to compare with carbon samples or to substitute the carbon sample when a dye receptor was missing at the monitoring site.

All dye trace results were recorded on DOW Dye Trace Record Forms. This form includes dye injection site information and a detailed record of each dye receptor recovered and analyzed during the study. The Dye Trace Record Forms for this study are available upon request.

Previous Karst Mapping Studies

Prior to this study, several karst basins had been mapped during tracer tests and cave surveys. Below is a brief summary of most of the karst basins that had been previously delineated, each presented with a map to illustrate those results. Mapped cave passages are illustrated as dye trace vectors for simplification. As noted above, cave maps can be requested from the KSS website (http://ksscaves.com/).

Karst basins with existing data that were also part of this study are discussed in more detail later in this report, and the previous and new groundwater-flow data are presented together. On maps with both historic and current data, historic tracer tests are shown as orange lines and identified by their primary author to distinguish them from results obtained through this project.

Minimal records were found in DOW files for dye traces conducted at three springs near Burnside, Kentucky. These are located in Pulaski County on the USGS Burnside 7.5 minute quadrangle. Two of these springs are identified as "J6" [N36.992222°/W84.579167°] and "J7" [N36.991397°/W84.581315°] and are located on the north shore of Lake Cumberland across from Burnside. The three traces associated with these springs are attributed to Sendlein and others (1990). The third spring seems to be unnamed and is located on the south shore of Lake Cumberland at Burnside [N36.995833°/W84.601389°]. The record of a single dye trace recovered at this spring is attributed to Ewers Water Consultants (1990). The map in Figure 9 illustrates the results of these tracer tests.

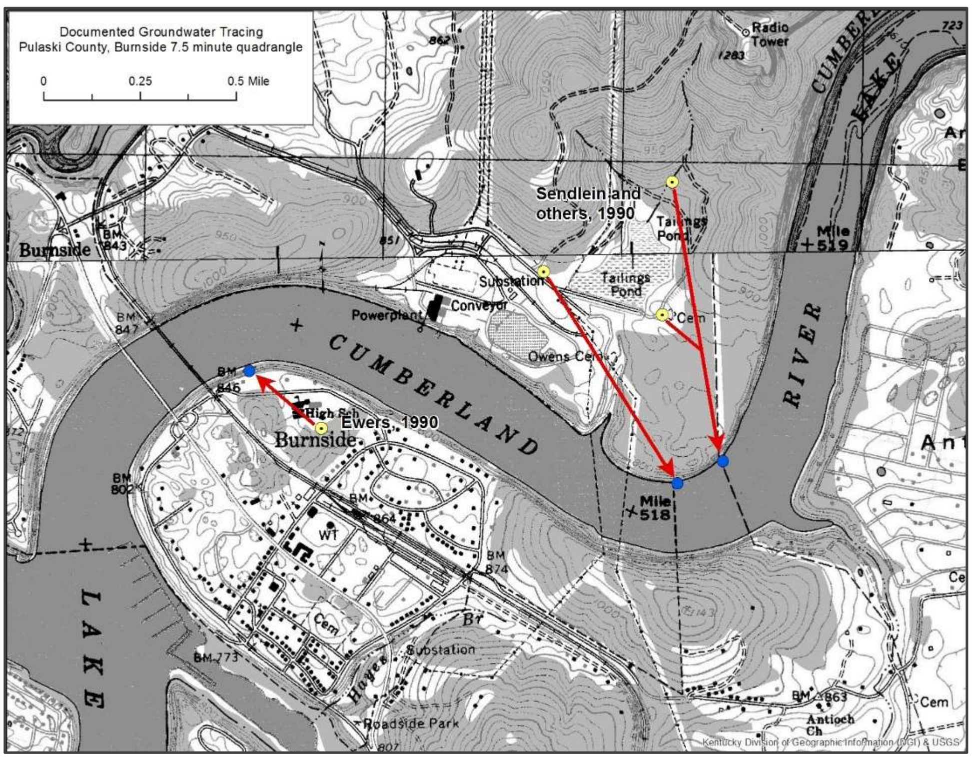

Figure 9. Documented groundwater tracing at Burnside, KY

Several dye traces were conducted by DOW to characterize a few of the larger springs in the study area in the late 1990s (Ray, 1997a and 1999). These traces are well-documented and records of dye injections and analyses are available for each. The following springs were fully or partially delineated:

Monticello (Old Town) Spring (9000-1483), Telegraph Spring (9000-1471), Bell Spring (9000-3988), Dry Hollow Spring (9000-2540), and Bridgeman Mountain Spring (9000-2539). Additional investigation of Monticello Spring was conducted by Dr. Lee Florea (2013) and students from Ball State University. Brown and Lambert (1963) report a low flow measurement at Monticello Spring of 0.7 ft^3/s. Work to delineate the recharge area for Sandy Spring (9000-3556) has been conducted by cave mappers and dye tracing (Gibson and Walden, 2013; Florea, 2013). Results of this work are illustrated on the maps in Figures 10, 11 and 12.

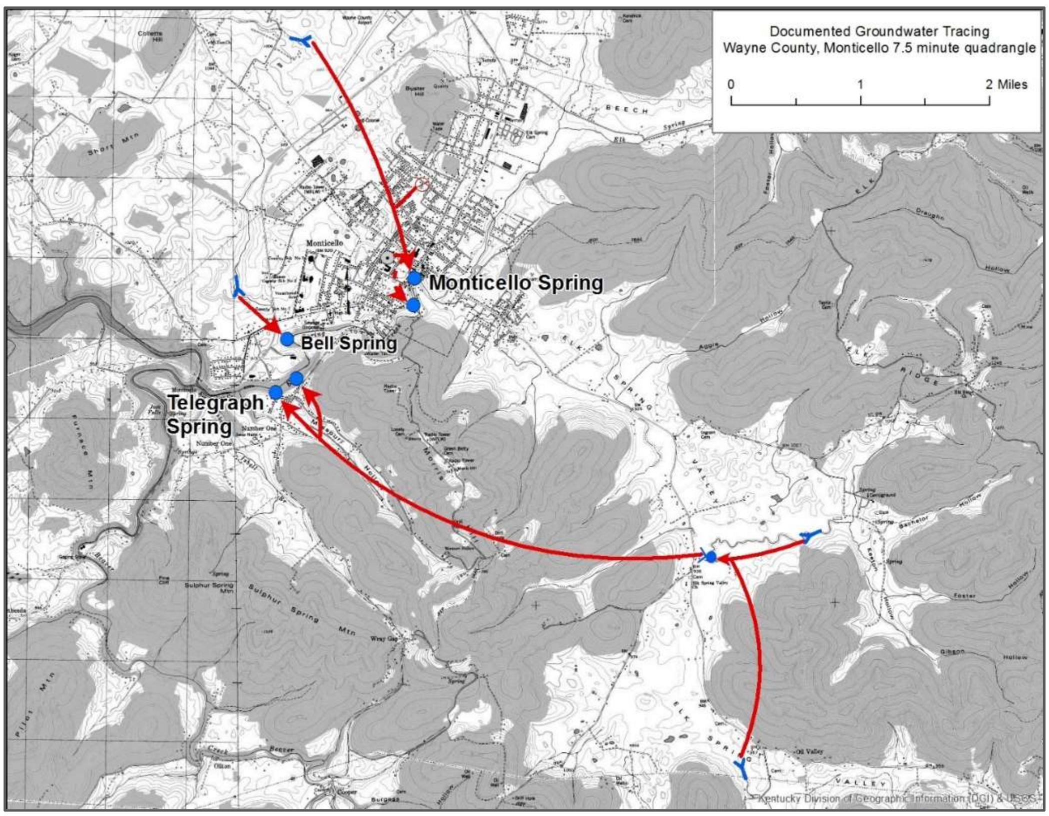

Figure 10. Documented groundwater tracing at Monticello, KY

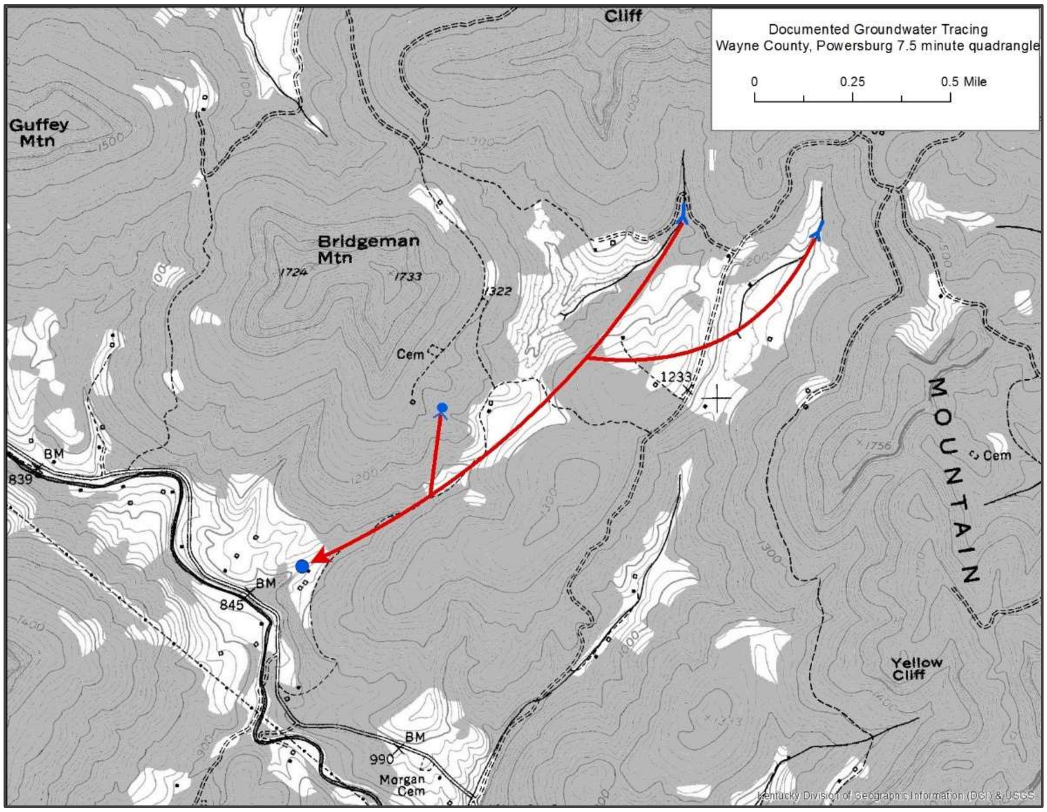

Figure 11. Documented groundwater tracing at Bridgeman Mountain Spring

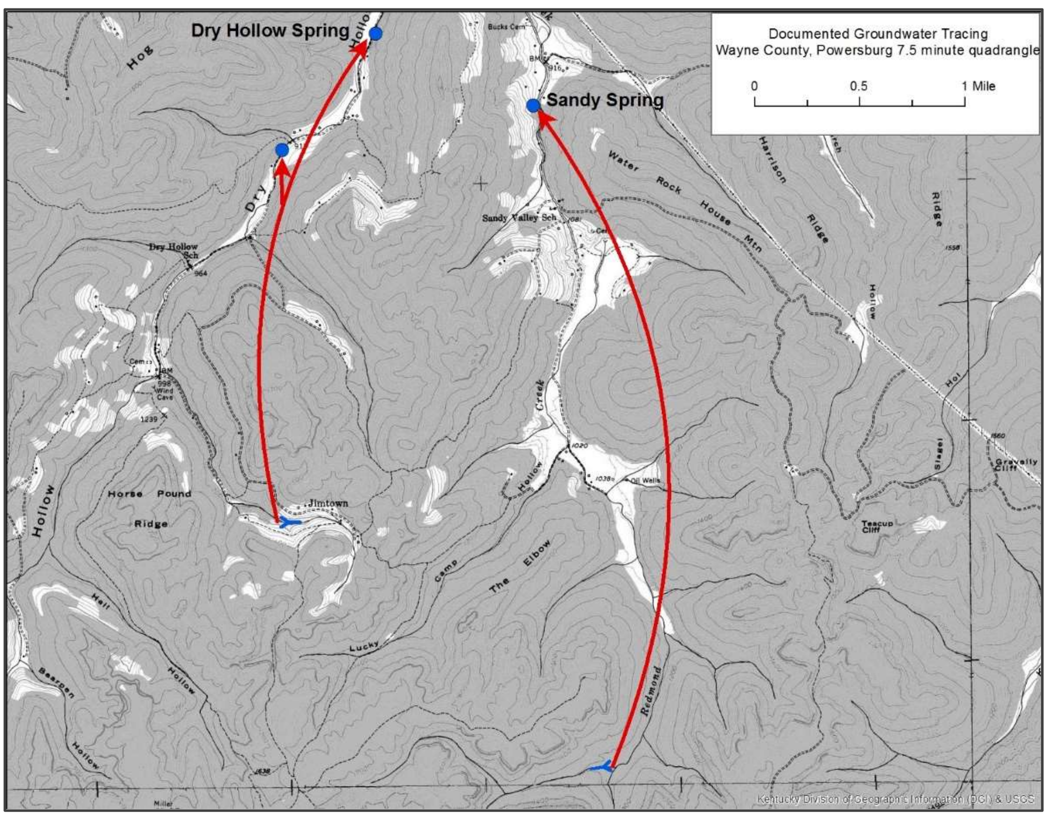

Figure 12. Documented groundwater tracing at Dry Hollow and Sandy springs

An extensive project to map groundwater flow around the former Cagle's-Keystone poultry processing plant was conducted by QORE Property Science (1999). This area is located near the head of Indian Creek, which forms "76 Falls" where it enters Lake Cumberland. McKinley Spring (9000-2525) and several other minor springs were delineated as part of this project. These results are illustrated on the map in Figure 13.

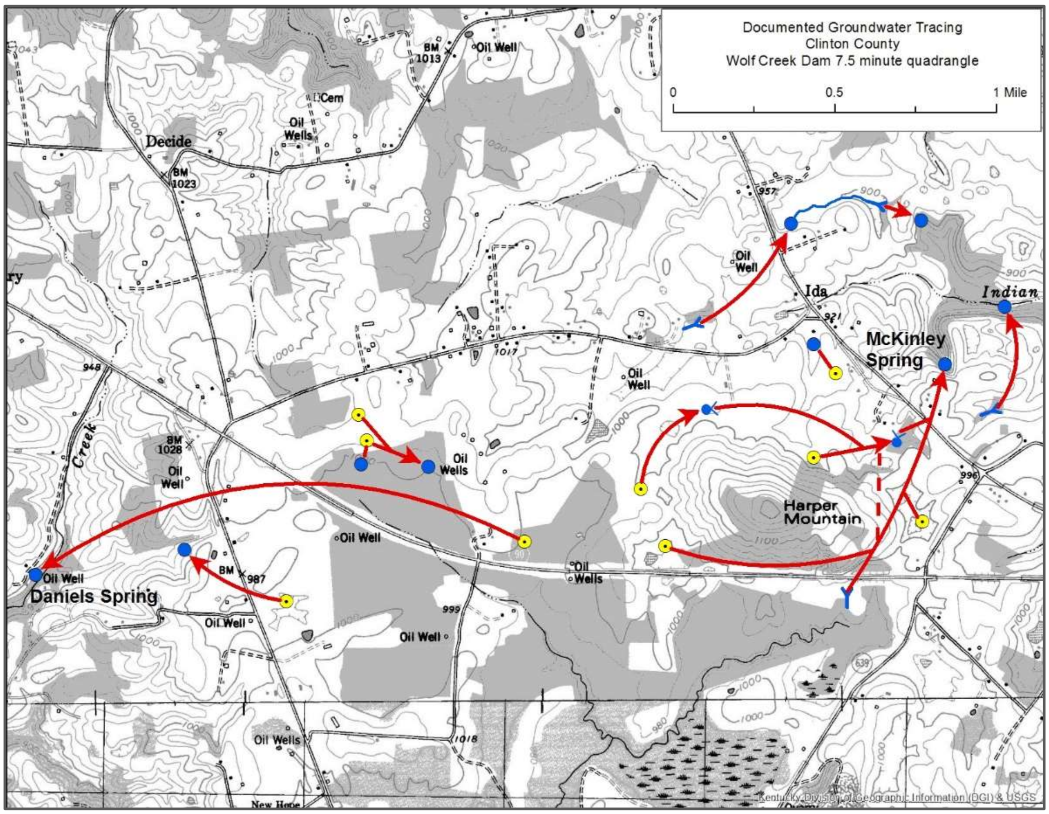

Figure 13. Documented groundwater tracing at Cagle's-Keystone site

A small-scale groundwater study was led by the KGS with help from local cavers (Currens and Walden, 2010) to delineate the recharge area for Coal Trace Cave (9000-3287), which included dye traces recovered at a few surrounding springs. Additionally, two of these dye traces were only recovered at an in-stream failsafe monitoring location and the relevant spring was not located. These results are illustrated with inferred groundwater flow to the failsafe location, indicated by a question mark (?) on the map. These results are illustrated on the map in Figure 14.

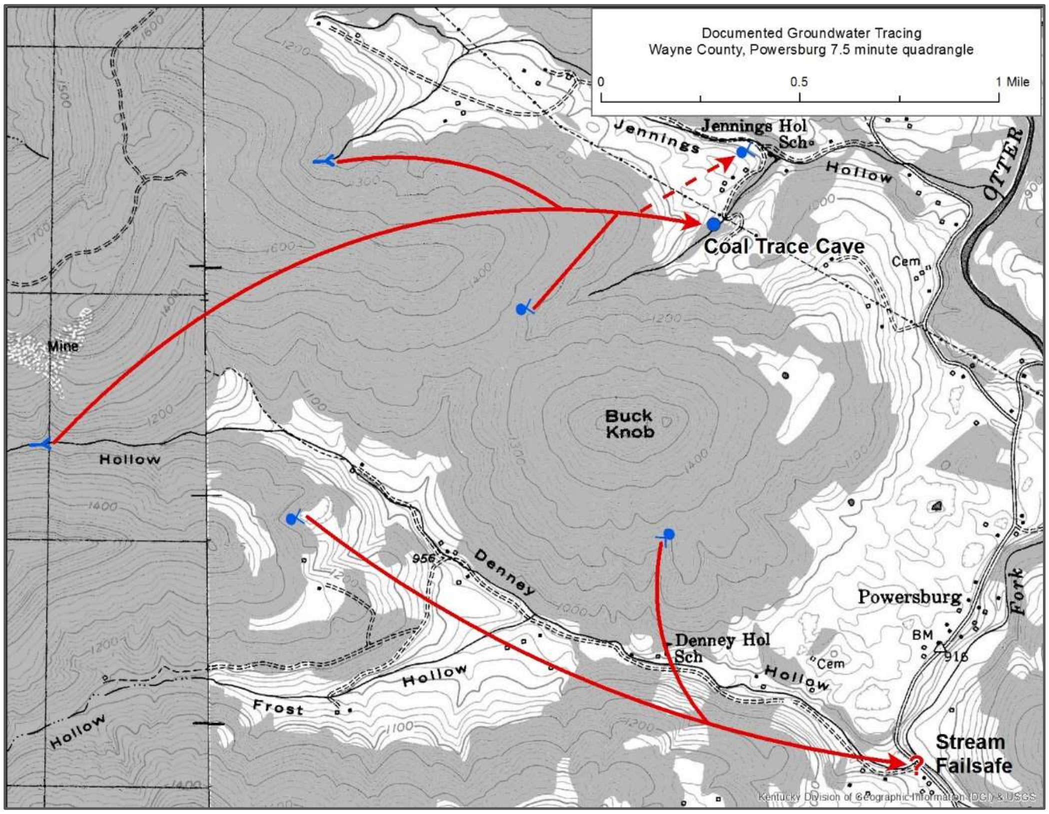

Figure 14. Documented groundwater tracing at Coal Trace Cave

RESULTS OF DYE TRACE INVESTIGATION

Sloans Valley Cave

Some of the initial dye tracing for this study was in response to a fuel spill in the Sloans Valley area of southern Pulaski County. Sloans Valley Cave has been studied and mapped over the course of several decades (Jillson, 1954; Beiter and others, 2001; Currens and Paylor, 2008). Extensive and highly detailed cave maps are available for this area and a few dye traces were conducted prior to this study. Available cave maps can be requested through the KSS.

The outlet of this cave system is now submerged beneath Lake Cumberland and most of the lower section of cave is inundated. The farthest down-gradient cave access is at the Great Rock Sink (9000-3977), which was used for water quality and dye trace monitoring. The fuel spill occurred on the eastern flank of the cave system, just beyond the area that had been thoroughly surveyed. Reconnaissance of the valley was conducted by Kentucky's Environmental Response Team to identify all relevant karst features and potential monitoring points. Three dye traces were conducted to determine the fate of fuel that spilled on US HWY

27, which ran down a dry creek bed for several hundred feet before completely sinking into the subsurface. These traces are summarized below and shown on the map in Figure 15.

Trace # 14-02: Gholson Swallet is a moderate-flow sink point of the intermittent creek that received the fuel spill. Following the spill, fuel was observed reaching this location and sinking into the subsurface at a small pool in the channel. On February 22, 2014 a precipitation event created enough runoff to reach this swallet pool so that dye could be injected. Approximately 0.1 ft^3/s of water was sinking into the swallet pool and 3.75 pounds of Uranine was introduced. Excessive amounts of dye were utilized due to flow conditions and the unknown nature of the creek channel overlying the karst aquifer. This trace was recovered 3 days later only at Great Rock Sink. Four subsequent dye receptors exchanged over the course of three weeks at Great Rock Sink showed positive Uranine recovery.

Table 3. Gholson Swallet Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Gholson Swallet N36.933818°/ W84.531320° Feb. 22, 2014	Swallet # 14-02	Uranine – 3.75 lbs (*Natural Flow-* 0.1 ft^3/s)	**Great Rock Sink** N36.941405 °/W84.530092°	0.9

Trace # 14-03: MW-2 to Lower Pond Swallet is a losing reach of the intermittent creek approximately 500 feet upstream of Gholson Swallet. Fuel was observed sinking into this reach of the creek bed that is roughly 50 feet long. This trace was designed to determine if the subsurface connection was similar to that of Gholson Swallet. On March 6, 2014 the stream was carrying approximately 0.15 ft^3/s of water at the upper end of the losing reach (MW-2) and was decreased to a trickle downstream at the Lower Pond. Roughly 4.5 pounds of Eosine was introduced at the upper reach and allowed to sink throughout the length of this losing section of stream. A visual positive was reported at Gholson Cave Spring the following morning, within 16 hours of the injection. Dye receptors showed that Eosine was recovered at Gholson Cave Spring and Gholson Karst Window one day after the injection. This dye was recovered at Great Rock Spring 5 days after the injection on March 11. All of these sites remained positive for Eosine over a 6 week period with weekly dye receptor exchanges.

Table 4. MW-2 to Lower Pond Swallet Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
MW-2 to Lower Pond Swallet N36.933588°/ W84.528904° March 6, 2014	Losing Stream # 14-03	Eosine – 4.5 lbs (*Natural Flow*- 0.15 ft^3/s)	**Gholson Cave Spring** N36.931734 °/W84.534028° **Gholson Karst Window** N36.931208 °/W84.535904° **Great Rock Sink** N36.941405 °/W84.530092°	0.3 0.4 1.3

Trace # 14-04: Gholson Cave #1 is perched on the southern valley wall of the impacted stream, approximately 40 feet above the valley floor. Fumes from the fuel spill had prohibited safe entry of this cave until March 21, 2014. The cave entrance is partially blocked by roof collapse and about 0.02 ft^2/s of water was flowing out of a small conduit in the ceiling behind the breakdown pile. The water dropped nearly three feet into a talus-filled fracture and disappeared. Roughly 8 ounces of SRB was injected at the sink point within the cave. Four days later, on March 25, dye was recovered at Gholson Cave Spring and Gholson Karst Window. The dye receptor at Great Rock Sink could not be exchanged on March 25 due to high water in the cave. However, dye receptors exchanged on April 8 showed that SRB had reached Great Rock Sink.

Table 5. Gholson Cave #1 Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Gholson Cave #1 N36.932822°/ W84.529009° March 21, 2014	Cave Stream # 14-04	SRB – 8 oz (*Natural Flow*- 0.02 ft^3/s)	**Gholson Cave Spring** N36.931734 °/W84.534028° **Gholson Karst Window** N36.931208 °/W84.535904° **Great Rock Sink** N36.941405 °/W84.530092°	0.3 0.4 1.3

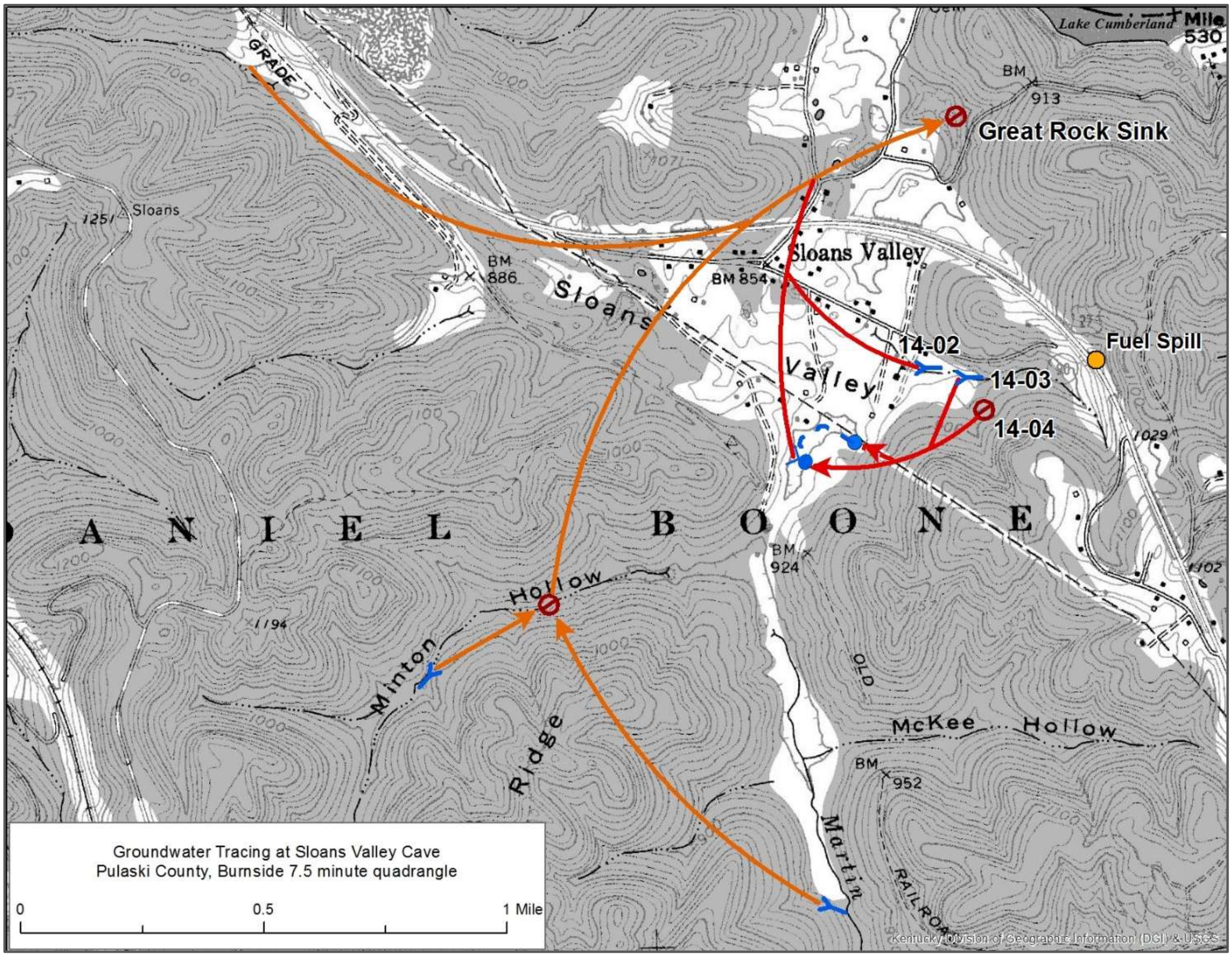

Figure 15. Sloans Valley Cave Tracer Tests

Cedar Sinking Creek Rise

Cedar Sinking Creek Rise (9000-4009) is a spring that discharges as a bluehole and a series of gravity springs near the mouth of Cedar Sinking Creek, where it meets the South Fork of the Cumberland River. At normal lake pool elevation this spring is submerged approximately 15 feet beneath Lake Cumberland. It was identified during a boat survey while the lake was drawn down for repairs at Wolf Creek Dam. A single dye trace was conducted prior to completion of dam repairs and the spring once again being inundated by lake water.

Trace # 14-13: Kidder Swallet on Cedar Sinking Creek is in a moderate to high-flow losing reach of the stream. Numerous other swallets were identified upstream of this location, but could only be utilized for dye injection during low flow conditions. On November 14, 2014 three ounces of Uranine was introduced to the terminal swallet of this losing reach, where approximately 0.5 ft^3/s of water was infiltrating the stream bed. Dye was recovered at Cedar Sinking Creek Rise six days later on November 20. This spring remained positive for Uranine for nearly one month. Results are summarized below and shown on the map in Figure 16.

Table 6. Kidder Swallet Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Kidder Swallet N36.9257480°/ W84.646176° Nov. 14, 2014	Swallet # 14-13	Uranine – 3 oz (*Natural Flow-* 0.5 ft^3/s)	**Cedar Sinking Creek Rise** N36.937824 °/W84.623987°	1.5

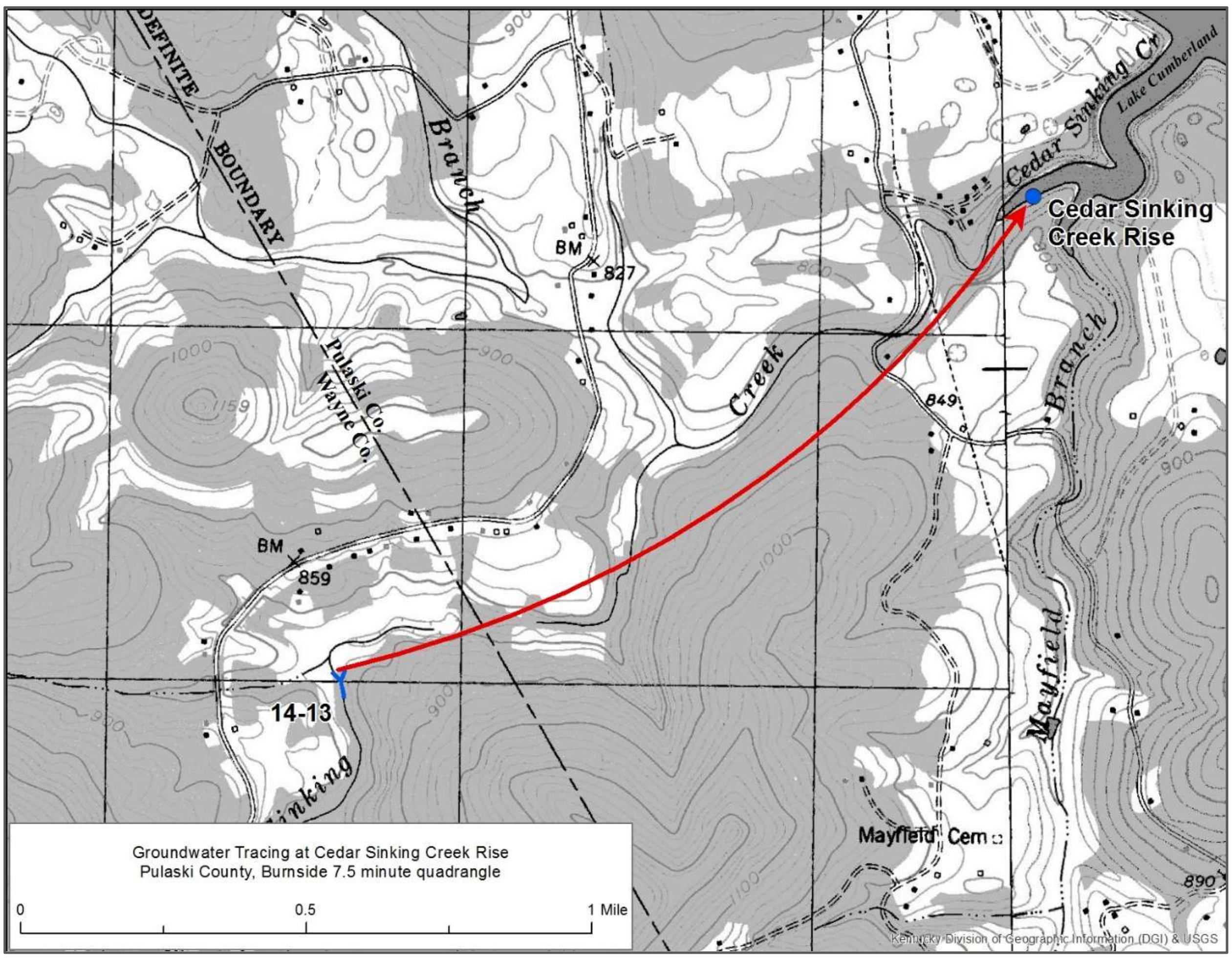

Figure 16. Cedar Sinking Creek Rise Tracer Test

Ramsey Spring-South

Ramsey Spring-South (9000-3966) discharges from a large conduit in a pocket valley adjacent to Lake Cumberland. A large karst window with five minor spring outlets is located on the plateau above and approximately 0.5 mile due east of the spring. Results are summarized below and shown on the map in Figure 17.

Trace # 13-13: Jaibo Swallet is the terminal swallet of the blind valley of a small unnamed stream that drains a wetland area located on the south side of KY 90. On November 15, 2013, four ounces of SRB was introduced into the trickle of water sinking into this swallet. Dye was recovered four days later at Ramsey Spring-South and the two southernmost of five minor springs in the karst window.

Table 7. Jaibo Swallet Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Jaibo Swallet N36.933686°/ W84.750010° Nov. 15, 2013	Sinking Stream # 13-13	SRB – 4 oz (*Natural Flow-* Trickle)	**Cooley Springs (karst window)** N36.941111 °/W84.760726° **Ramsey Spring-South** N36.941785 °/W84.770448°	0.8 1.4

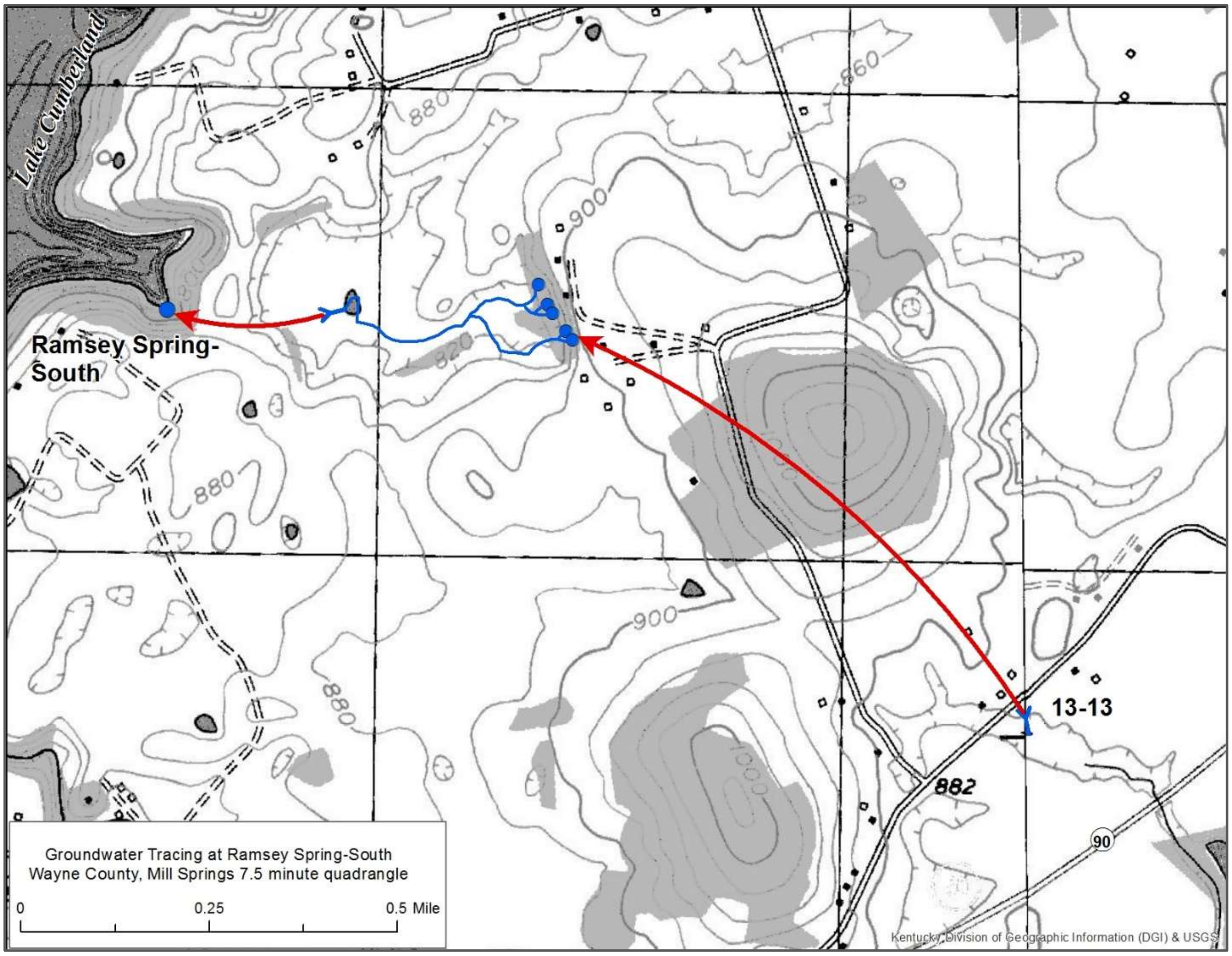

Figure 17. Ramsey Spring-South Tracer Test

Meadow Creek Springs

Meadow Creek Springs – Upper (9000-3964) and Lower (9000-3963) are a distributary system on opposite sides of Meadow Creek, approximately 500 feet apart. The upper spring issues from a small conduit just above the left bank in a tight bend of the creek and is relatively small compared to the lower spring. The lower spring discharges from a wide, low conduit in a small pocket valley just off the right bank of the creek and is used as a livestock water supply. During base flow conditions Meadow Creek is dry upstream of these springs for more than half of a mile. The two dye traces recovered at these springs are summarized below and illustrated on the map in Figure 18.

Trace # 13-11: Ramsey Swallet on Meadow Creek is located directly behind the Mill Springs Methodist Church on State Route 1276. This is a moderate to high-flow losing reach of stream, with several other sink points and swallets located upstream. The swallet appears as a bedrock shaft that is roughly three feet deep and partially filled with gravel. On November 7, 2013, nearly 2 ft^3/s of water was sinking into this swallet and three ounces of Eosine was injected. Dye was recovered at both Meadow Creek Springs – Upper and Lower – seven days later. A subsequent dye receptor exchange on November 19 showed only weak dye recovery, likely owing to the short flow distance and rapid dye movement through the system.

Table 8. Ramsey Swallet Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Ramsey Swallet N36.930784°/ W84.767352° Nov. 7, 2013	Swallet # 13-11	Eosine – 3 oz (*Natural Flow-* 2 ft^3/s)	**Meadow Creek Springs-Lower** N36.932976°/W84.773027°	0.35
			Meadow Creek Springs-Upper N36.931650 °/W84.772917°	0.3

Trace # 14-11: Denny Karst Window is located just north of KY 90, near the intersection with State Route 1276 at Touristville. This karst window is an opening in the bedrock about 5 feet in diameter and appears to have been developed for historical livestock watering, but is no longer used. Water forms a pool in the bedrock opening and was flowing so slowly through the karst window that an accurate estimate could not be made. On November 13, 2014 three ounces of Eosine was injected into this feature. Seven days later both Meadow Creek Springs – Upper and Lower – were positive for Eosine. A subsequent exchange on November 26 showed that dye concentrations were just below positive criteria.

Table 9. Denny Karst Window Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Denny Karst Window N36.926529°/ W84.760447° Nov. 13, 2014	Karst Window # 14-11	Eosine – 3 oz (*Natural Flow-* Undetermined)	**Meadow Creek Springs-Lower** N36.932976°/W84.773027°	0.8
			Meadow Creek Springs-Upper N36.931650 °/W84.772917°	0.8

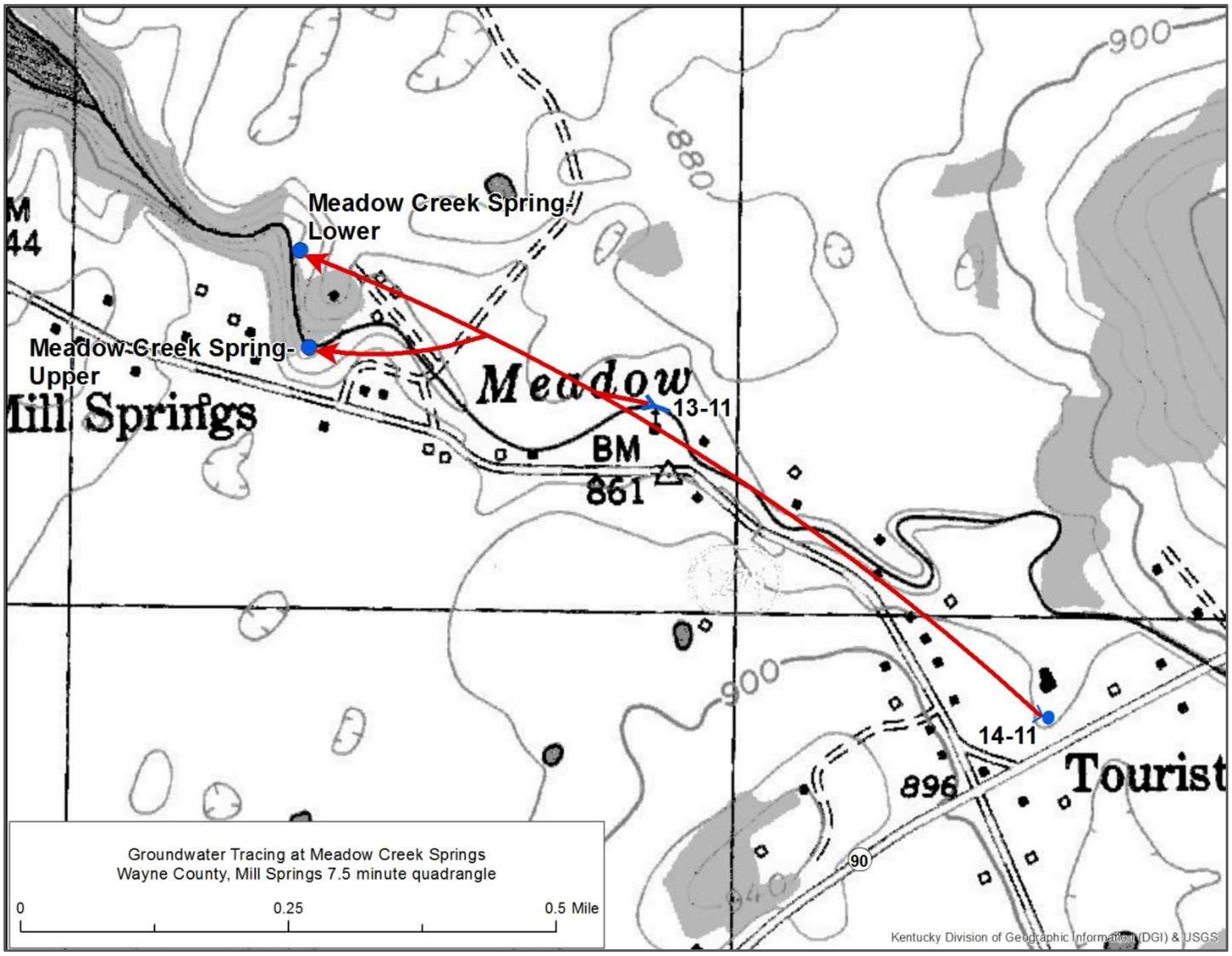

Figure 18. Meadow Creek Springs Tracer Tests

Mill Springs

Mill Springs (9000-1822) is a large distributary spring perched on a cliff directly above Lake Cumberland. During base-flow conditions there are four main spring outlets that span approximately 100 feet across an arcing horizon at the contact of the St. Louis Limestone and the underlying Salem and Warsaw Formation perching unit. At higher flows as many as 10 spring outlets can be active across this horizon. Limited measurements indicated that base flow at this spring is 1.3 ft^3/s. A stonework trough has been constructed along the entire length of the spring horizon to divert water to the historic mill that is still on site. The six tracer tests recovered at Mill Spring are summarized below and illustrated on the map in Figure 19.

Trace # 14-07: Cooley Swallet-Well is an old, hand dug well at the terminus of a small sinking valley, located approximately one mile due south of Mill Springs. The well was likely constructed for the historic home on this site that is part of the local history tour. The well now has a roughly 3-foot diameter steel casing set in place, with stone work visible inside the well and above the water line. On September 18, 2014, a dry set of four ounces of Uranine powder was lowered to the bottom of the well and left in place. Each of the four primary outlets of Mill Springs were extremely positive for Uranine on September 23. Positive Uranine recovery was documented at Mill Springs for more than 2 months. Results are summarized below in Table 10.

Table 10. Cooley Swallet-Well Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Cooley Swallet Well N36.917694°/ W84.7777° Sept. 18, 2014	Swallet/Well # 14-07	Uranine – 4 oz (*Natural Flow-* Undetermined)	**Mill Springs** N36.933943°/W84.778197°	1.2

Trace # 14-08: Montana Cabin Sinkhole is a small cover-collapse that drains through two near-vertical shafts, each roughly 8 inches in diameter. The sinkhole is perched on a hillside roughly 1.5 miles southwest of Mill Springs on the eastern slope of Hannah Hill, next to a small cabin. On September 18, 2014, approximately 400 gallons of hauled water were used to inject six ounces of SRB. On September 23 each of the four primary outlets of Mill Springs were very positive for SRB. Positive SRB recovery was documented at Mill Springs for 2 months. Table 11 is a summary of these results.

Table 11. Montana Cabin Sinkhole Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Montana Cabin Sinkhole N36.92524°/ W84.800578° Sept. 18, 2014	Sinkhole # 14-08	SRB – 6 oz (*Hauled water-* 400 gallons)	**Mill Springs** N36.933943°/W84.778197°	1.6

Trace # 14-12: Huddleston Cave is located near the head of a dry valley north of Gap in the Ridge and about two miles south-southwest of Mill Springs. The cave entrance is in the bottom of a large, relatively shallow sinkhole with bedrock exposed. On November 14, 2014 six ounces of SRB was injected into the cave with 600 gallons of hauled water. Mill Springs was extremely positive for SRB on November 20, and remained so through early December. Results of this dye trace are summarized in Table 12.

Table 12. Huddleston Cave Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Huddleston Cave N36.908051°/ W84.795481° Nov. 14, 2014	Cave/Sinkhole # 14-12	SRB – 6 oz (*Hauled water-* 600 gallons)	**Mill Springs** N36.933943°/W84.778197°	2.2

Trace # 14-14: Oak Hole is a small cover-collapse located on a hillside in the same dry valley as Huddleston Cave and about 0.5 mile west-northwest. The small collapse is approximately 1 foot in diameter and opens into a significant soil void with some bedrock exposed in the bottom. It is located almost directly beneath an oak tree, and the tree roots are likely all that has kept this from forming a larger collapse feature. Eight ounces of Eosine was injected into Oak Hole on December 4, 2014, using 200 gallons of hauled water. On December 11 Mill Springs was very positive for Eosine and remained so through mid-January 2015. The results of this dye trace are summarized in Table 13.

Table 13. Oak Hole Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Oak Hole N36.910355°/ W84.805058° Dec. 4, 2014	Sinkhole # 14-14	Eosine – 8 oz (*Hauled water-* 200 gallons)	**Mill Springs** N36.933943°/W84.778197°	2.7

Trace # 15-01: Edd Stamper Cave is located directly beneath State Route 1808 about 1 mile southeast of Steubenville. There is a large cave entrance in a sinkhole on the north side of the road and the cave has been explored and confirmed to daylight again on the south side of the road. There is a sizable room in the cave directly beneath the road where groundwater forms a small pool before exiting beneath a ledge that is too low for further exploration. Eleven ounces of SRB was injected into this pool on January 23, 2015. On January 29 two of the four primary outlets of Mill Springs were weakly positive for SRB, but dye recovery was considered inconclusive. On February 3 all four of the primary Mill Spring outlets were very positive for SRB and remained so for three subsequent dye receptor exchanges through the end of February. Results of this dye trace are summarized in Table 14.

Table 14. Edd Stamper Cave Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Edd Stamper Cave N36.878552°/ W84.783228° Jan. 23, 2015	Cave Stream # 15-01	SRB – 11 oz (*Natural flow-* Undetermined)	**Mill Springs** N36.933943°/W84.778197°	3.9

Trace # 15-02: Dodson Sinkhole is a bedrock shaft that is roughly 4 feet in diameter and a little more than 6 feet deep with loose cobbles and gravel in the bottom. It is located in a field approximately one mile due south of Steubenville, near the southeast end of Boston Hill. On April 14, 2015, one pound of Eosine was injected using 200 gallons of hauled water. This injection took place following a very rainy period with significant flooding. On April 22 each of the primary outlets of Mill Springs was very positive for Eosine. On that same day the Head of Fall Creek Spring (9000-3999) was also very positive for Eosine. One day later, on April 23, dye receptors showed that all of the sites were negative for Eosine. Due to the single dye recovery at each site the test was replicated. Once flooding had receded, 12 ounces of Uranine was injected on April 30 with 200 gallons of hauled water. On May 7 all of the primary Mill Springs outlets and Head of Fall Creek Spring were extremely positive for Uranine. All of these sites remained extremely positive for Uranine for two subsequent dye receptor exchanges through the end of May. This confirmed that the original test was valid and that this sinkhole is located on the hydrologic divide between the two spring basins. These results are summarized in table 15.

Table 15. Dodson Sinkhole Replication Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Dodson Sinkhole N36.872418°/ W84.801941° Apr. 30, 2015	Sinkhole # 15-02	Uranine – 12 oz (*Hauled water-* 200 gallons)	**Mill Springs** N36.933943°/W84.778197° **Head of Fall Creek Spring** N36.908833°/W84.820703°	4.6 2.7

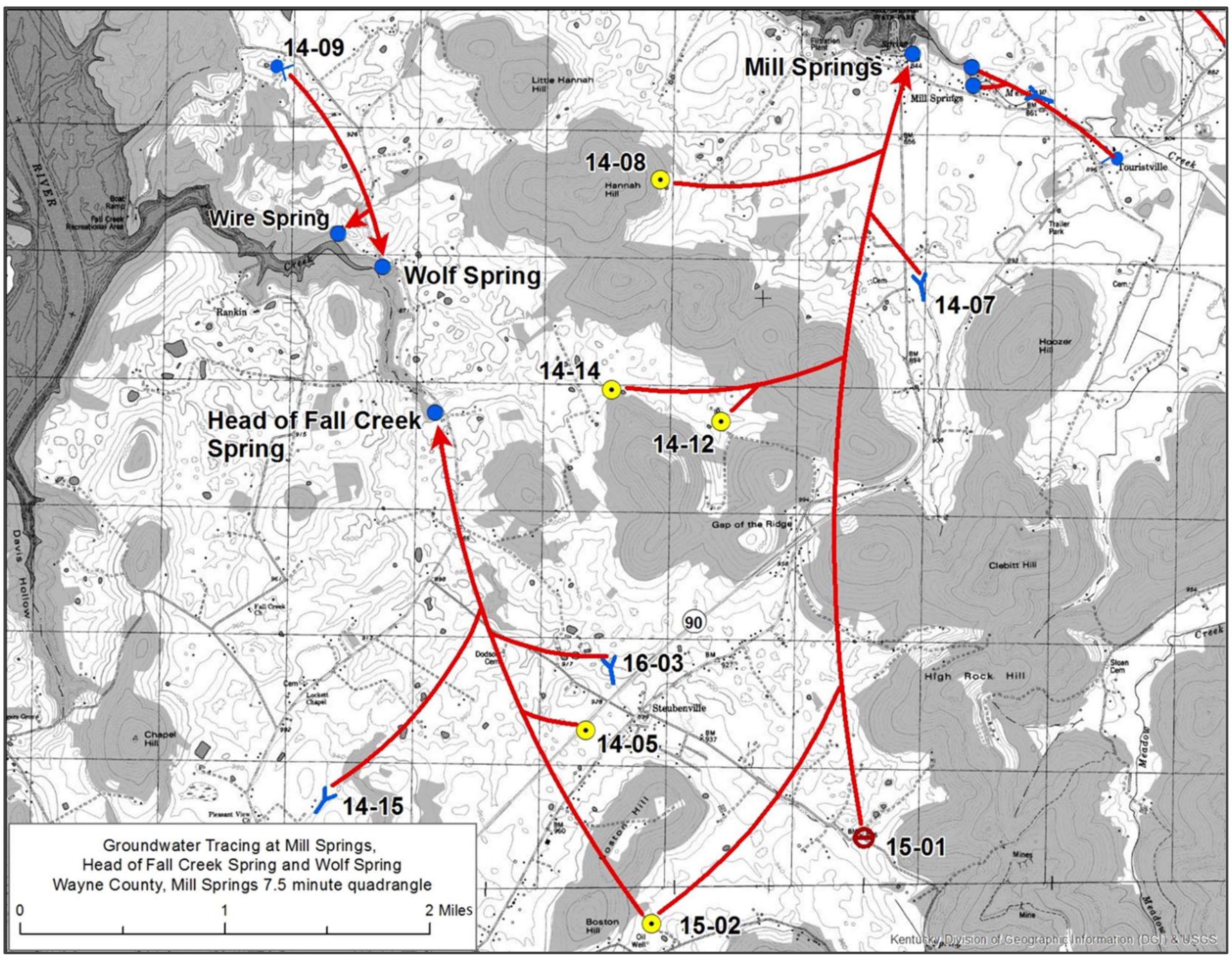

Figure 19. Mill Springs, Head of Fall Creek Spring and Wolf Spring Tracer Tests

Head of Fall Creek Spring

Head of Fall Creek Spring (9000-3999) discharges from multiple outlets clustered together at the head of a pocket valley, near the intersection of KY 1275 and Pete Upchurch Road. A large pool is formed below the spring before water drops over a short waterfall and infiltrates the subsurface, during base-flow conditions. The water rises again through bedrock fractures in the stream channel, flows for roughly 100 feet and sinks again into a bedrock swallet on the right bank. The spring rises one final time just upstream of the bridge at Pete Upchurch Road and then flows nearly 2 miles to Lake Cumberland. A single low-flow measurement of this spring's discharge was 1.2 ft^3/s in September of 2015. Four tracer tests were recovered at Head of Fall Creek Spring, one of which (Trace #15-02) was discussed above. The three remaining tracer tests are summarized below and illustrated on the map in Figure 19.

Trace # 14-05: The Highway 90 Sinkhole at State Route 3106 west of Steubenville was identified by Wayne County highway maintenance crews. This sinkhole is a cover-collapse into a bedrock shaft in the ditch on the south side of Highway 90, and was hypothesized to drain to Mill Springs. Eight ounces of Eosine was injected into this sinkhole on August 14, 2014, using 400 gallons of hauled water. On August 19 the Head of Fall Creek Spring was extremely positive for Eosine and remained positive for three dye receptor exchanges through early September. The results of this trace are summarized in Table 16.

Table 16. Highway 90 Sinkhole Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Highway 90 Sinkhole N36.886280°/ W84.807752° Aug. 14, 2014	Sinkhole # 14-05	Eosine – 8 oz (*Hauled water-* 400 gallons)	**Head of Fall Creek Spring** N36.908833°/W84.820703°	1.9

Trace # 14-15: The Pleasant View Church Swallet is in the losing reach of a small pond-fed stream about 1.5 miles west-southwest of Steubenville and behind Pleasant View Church. On December 18, 2014, six ounces of Uranine was injected into this swallet with approximately 0.05 ft^3/s of natural flow in the stream.

On December 23 Head of Fall Creek Spring was extremely positive for Uranine. The second dye receptor exchange on January 15, 2015 showed that Head of Fall Creek Spring was still very positive for Uranine. Three subsequent dye receptor exchanges through early February showed weak-positive Uranine recovery. The results of this dye trace are summarized in Table 17.

Table 17. Pleasant View Church Swallet Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Pleasant View Church Swallet N36.881458°/ W84.830786° Dec. 18, 2014	Swallet # 14-15	Uranine – 6 oz (*Natural flow-* 0.05 ft^3/s)	**Head of Fall Creek Spring** N36.908833°/W84.820703°	2.2

Trace # 16-03: The Steubenville Sinking Stream-North originates at a small spring roughly 2 miles southeast of Steubenville and flows northwest. The unnamed stream sinks into a large swallow hole at the base of a hill several hundred feet north of HWY 90. On March 15, 2016, six ounces of Eosine was injected into this stream, just north of HWY 90 when it was flowing at about 1.5 ft^3/s. On March 18 the dye receptor at Head of Fall Creek Spring was extremely positive for Eosine. A water sample was collected during the dye receptor exchange on the same day and found to be positive for Eosine. No further monitoring was conducted for this tracer test. The results are summarized in Table 18.

Table 18. Steubenville Sinking Stream-North Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Steubenville Sinking Stream-North N36.890647°/ W84.805470° Mar. 15, 2016	Sinking Stream # 16-03	Eosine – 6 oz (*Natural flow-* 1.5 ft^3/s)	**Head of Fall Creek Spring** N36.908833°/W84.820703°	1.7

Wolf Spring

Wolf Spring (9000-4021) discharges from a conduit through talus and large collapsed blocks of stone just off the right bank of Fall Creek. The spring is perched on a hillside at the base of a limestone bluff that is directly below and west of KY 1275. This is a relatively small spring with base flow estimated to be less than 0.5 ft^3/s.

Wire Spring

Wire Spring (9000-4020) discharges from a small conduit perched on a steep hillside above the right bank of Fall Creek. At this location Fall Creek is the backwaters of Lake Cumberland at normal summer pool elevation. The spring has the remnants of a gravity pipe that catches its discharge. A heavy steel wire still runs from the spring to a small stone building at the top of the hill. The owner reports that this spring was used as a drinking water supply and that a bucket was sent down the wire to the end of the gravity pipe, then pulled back up the wire once full. This is a very small, but reliable, spring and flow was generally estimated to be 0.05 ft^3/s or less.

Trace # 14-09: Wade Park Sinking Spring (9000-4019) is a small sinking spring on the east end of a large sinkhole located at the intersection of Wade Park Drive and KY 2393. On October 16, 2014, eight ounces of Eosine was injected into this sinking spring with approximately 0.1 ft^3/s of natural flow. On October 21 Wire Spring was extremely positive for Eosine and remained so for two dye receptor exchanges through mid-November. Wolf Spring had not been identified when this dye injection was made and it was initially located on October 23. On that day a water sample was collected from Wolf Spring and found to be very positive for Eosine. A dye receptor was placed in Wolf Spring and monitored through early December, each of the three dye receptor exchanges during this time showed very positive Eosine recovery. This dye trace is summarized in Table 19 and illustrated on the map in Figure 19.

Table 19. Wade Park Sinking Spring Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Wade Park Sinking Spring N36.933396°/ W84.834176° Oct. 16, 2014	Sinking Spring # 14-09	Eosine – 8 oz (*Natural flow-* 0.1 ft^3/s)	**Wolf Spring** N36.919288°/W84.825160° **Wire Spring** N36.921614°/W84.829071°	1.1 1.0

Lovell Spring

Lovell Spring (9000-4000) discharges from beneath a limestone ledge at the base of High Rock Hill in the headwaters of Meadow Creek. The spring is a few hundred feet from the left bank of Meadow Creek on the east side of Sloan Hollow Road. The single dye trace recovered at Lovell Spring is described below and illustrated on the map in Figure 20.

Trace # 14-06: The Head of Meadow Creek Sink is a large sinkhole on the west side of Sloan Hollow Road. This injection point was hypothesized to possibly drain to Mill Springs. On August 28, 2014, eight ounces of Uranine was injected into this sinkhole with 350 gallons of hauled water. On September 2 and 5, Lovell Spring was extremely positive for Uranine. This location is on the map in Figure 19, but the tracer test was too short to illustrate at that scale. The results are summarized in Table 20 and shown in Figure 20.

Table 20. Head of Meadow Creek Sink Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Head of Meadow Creek Sink N36.887811°/ W84.762095° Aug. 28, 2014	Sinkhole # 14-06	Uranine – 8 oz (*Hauled water-* 350 gallons)	**Lovell Spring** N36.888526°/W84.759939°	0.1 (700 ft)

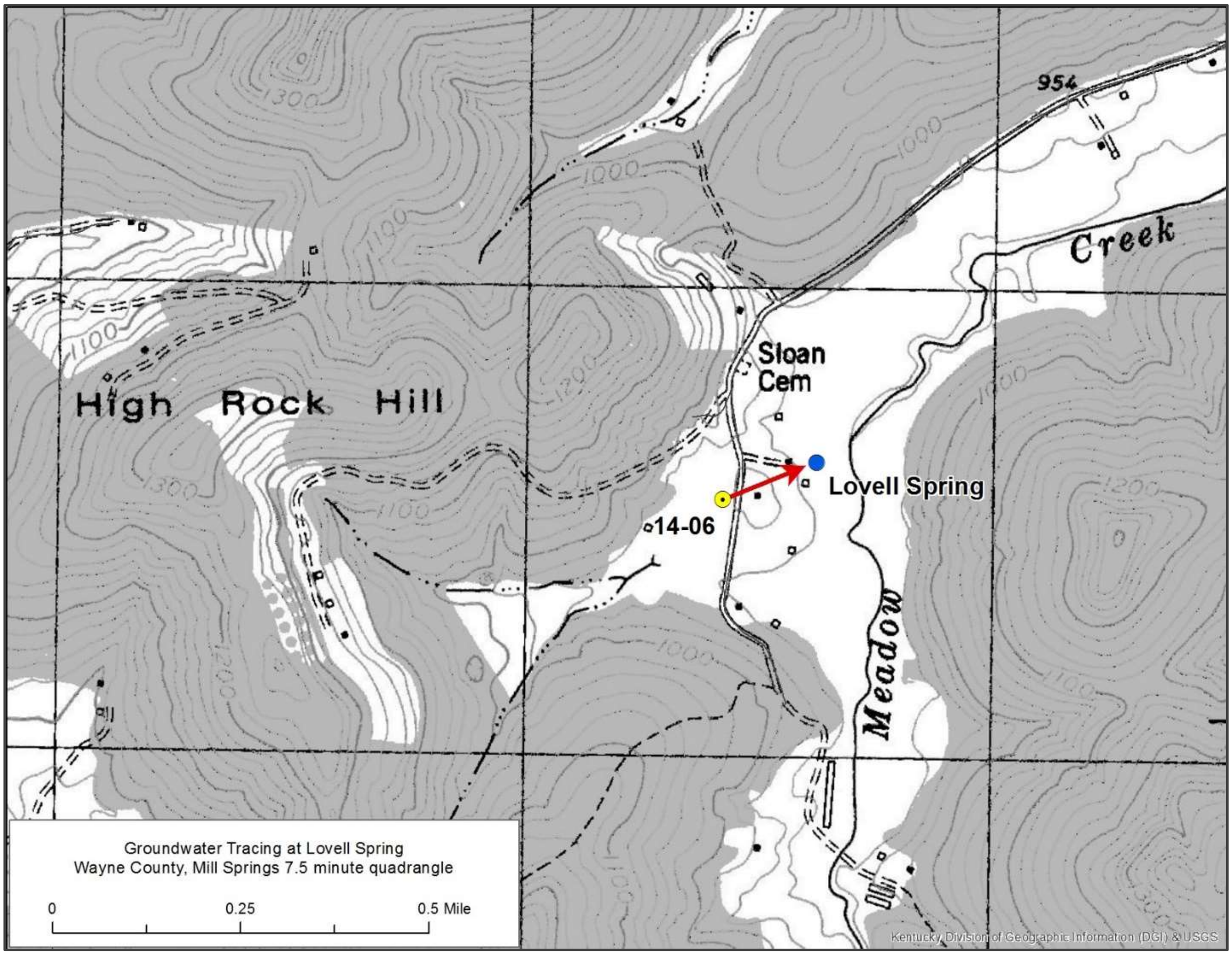

Figure 20. Lovell Spring Tracer Test

Head of Kennedy Creek Spring

Head of Kennedy Creek Spring (9000-4082) discharges from a conduit at the base of a 10 feet high limestone bluff. This forms the head of Kennedy Creek during moderate to low flow conditions. Estimates indicate that this spring may have a base flow of 1.0 ft^3/s or more, but no flow measurements were taken. Some local residents refer to this stream as "Canada" Creek, but the USGS maps apply the name Kennedy Creek. The single trace recovered at this spring is described below and illustrated on the map in Figure 21.

Trace # 17-06: Big Spring Church Swallet is located near the head of Burfield Hollow, directly behind the Big Spring Church. The swallet is fed by a small spring during low flow and is the beginning of a losing reach of the creek during higher flows. Twelve ounces of Uranine was injected on May 4, 2017, when the swallet was taking in about 0.5 ft^3/s of discharge from the spring. Head of Kennedy Creek Spring was extremely positive for Uranine on May 11. Uranine was recovered from two more dye receptor exchanges through the end of May. The results of this tracer test are summarized in Table 21.

Table 21. Big Spring Church Swallet Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Big Spring Church Swallet N36.740212°/ W84.781931° May 4, 2017	Swallet # 17-06	Uranine – 12 oz (*Natural flow-* 0.5 ft^3/s)	**Head of Kennedy Creek Spring** N36.765553°/W84.744799°	2.8

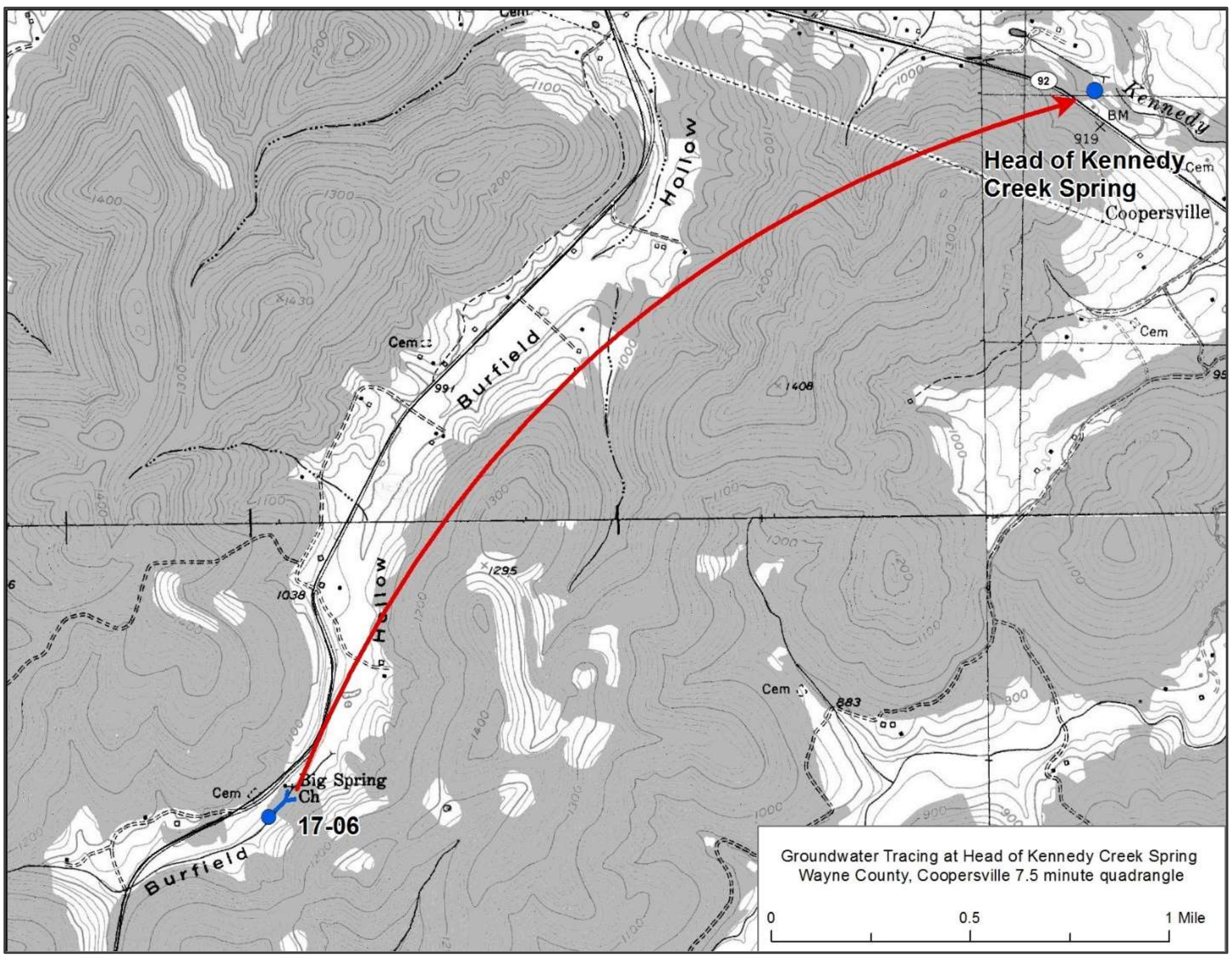

Figure 21. Head of Kennedy Creek Spring Tracer Test

Koger Rise Spring

Koger Rise Spring (9000-3980) is a small distributary spring system with two outlets that discharge from conduits that are just a few feet apart. The spring is located on the west side of Turkey Ridge in a small, narrow valley that is tributary to Simpson Branch. The flow at this spring is relatively small, but no measurements were taken and only limited estimates were made. The single dye trace recovered at this spring is described below and illustrated on the map in Figure 22.

Trace # 14-01: Koger Cave is perched on the eastern slope of Turkey Ridge about six miles southwest of Monticello, Kentucky. A significant portion of this cave has been surveyed and mapped by Bill Walden (Walden, 2012), who hypothesized its potential connection to several springs. The cave entrance is in the bottom of a sinkhole, under a limestone ledge with a passage that is relatively large and dry. About 100 feet into the cave a small stream of water discharges from the ceiling and sinks into a large breakdown pile. Another 100 feet beyond the breakdown pile a small cave stream is flowing through the back corner of a large room. On January 24, 2014, four ounces of Eosine was injected into this cave stream that was flowing at approximately 0.1 ft^3/s. At the first dye receptor exchange on January 29 no dye was recovered at any of the monitored sites. However, on February 2, and again on February 7, Koger Rise Spring was very positive for Eosine. The results of this tracer test are summarized in Table 22.

Table 22. Koger Cave Stream Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Koger Cave N36.766181°/ W84.925617° Jan. 24, 2014	Cave Stream # 14-01	Eosine – 4 oz (*Natural flow-* 0.1 ft^3/s)	**Koger Rise Spring** N36.766248°/W84.948683°	1.3

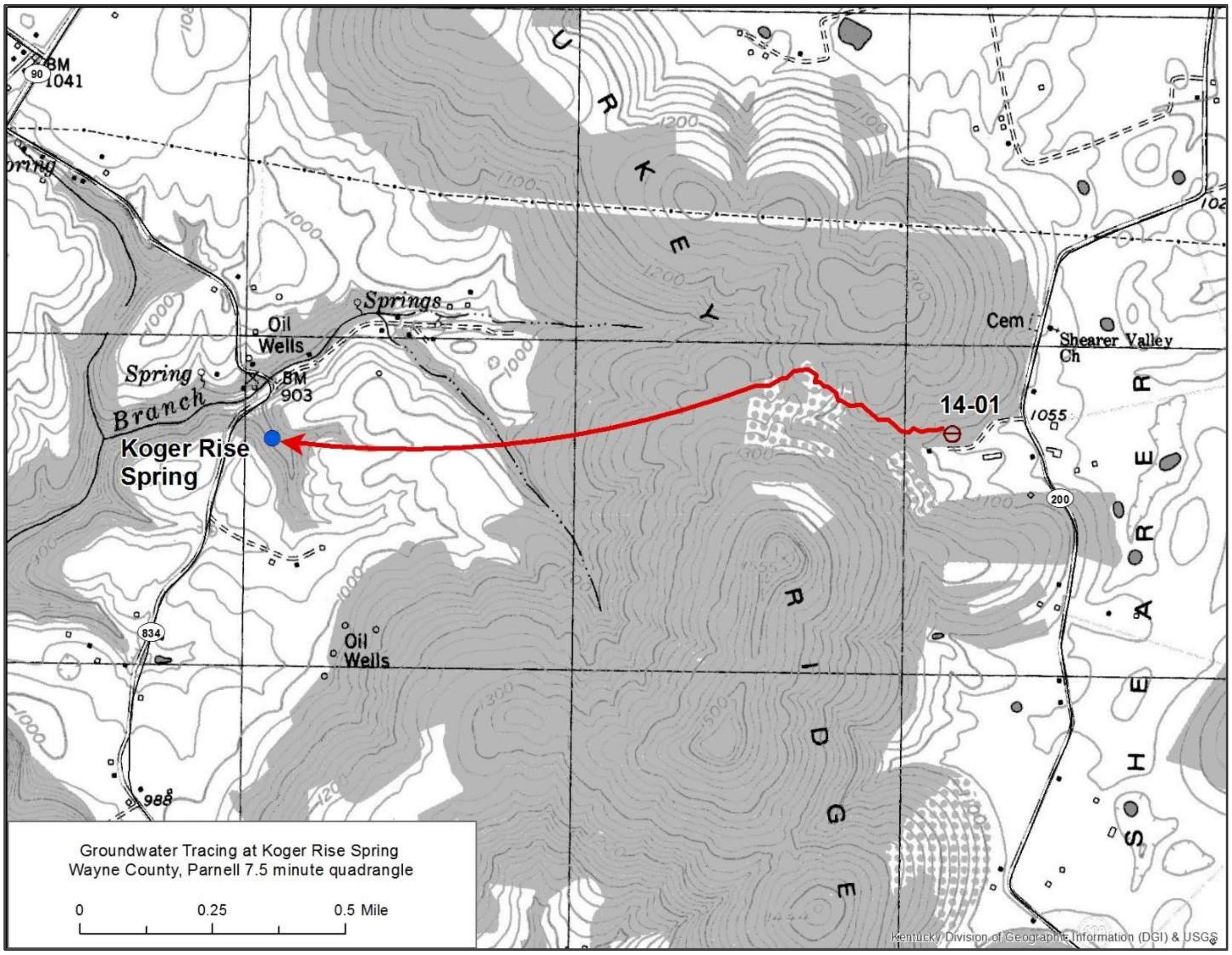

Figure 22. Koger Rise Spring Tracer Test

Blowing Cave and Midway Spring

Midway Spring (9000-4055) is the underflow spring for the Blowing Cave System, which has been extensively mapped by Paylor (2011). Blowing Cave is located at the head of Carpenter Fork, with a large entrance at the base of a limestone bluff. Paylor mapped several miles within Blowing Cave and conducted at least three tracer tests. One of these tracer tests was unknowingly replicated by the authors prior to obtaining all information on Blowing Cave. The map in Figure 23 shows the results of Paylor's work and identifies the tracer test replicated for this study. Paylor's work is displayed as an orange dye trace vector that follows the general course of the mapped cave. Midway Spring rises through multiple fractures on the left bank of Carpenter Creek, a few hundred feet downstream of Blowing Cave. The dye trace replicated for this study is described below.

Trace # 15-10: Homestead Cave is a small cave perched on a hillside south of Long Cliff and Chestnut Grove. The cave floor slopes steeply to the south and encounters a small cave stream flowing roughly west. On November 24, 2015, four ounces of Eosine was injected into the cave stream that was flowing at approximately 0.15 ft^3/s. On December 1 Midway Spring and the small spring at Blowing Cave were both extremely positive for Eosine. Both of these sites were still positive for Eosine at the next dye receptor exchange on December 10. These results are summarized in Table 23.

Table 23. Homestead Cave Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Homestead Cave N36.632588°/ W84.978208° Nov. 24, 2015	Cave Stream # 15-10	Eosine – 4 oz (*Natural flow-* 0.15 ft^3/s)	**Midway Spring** N36.649800°/W84.969624° **Blowing Cave Upper Spring** N36.647685°/W84.970398°	1.3 1.2

Halfmoon Spring

Halfmoon Spring (9000-4052) is a small spring that discharges from an arch-shaped conduit on the right bank of Carpenter Fork near a low-water ford. The spring discharges at creek level and is located roughly 1000 feet downstream of Blowing Cave. The single dye trace recovered at this spring is described below and illustrated on the map in Figure 23.

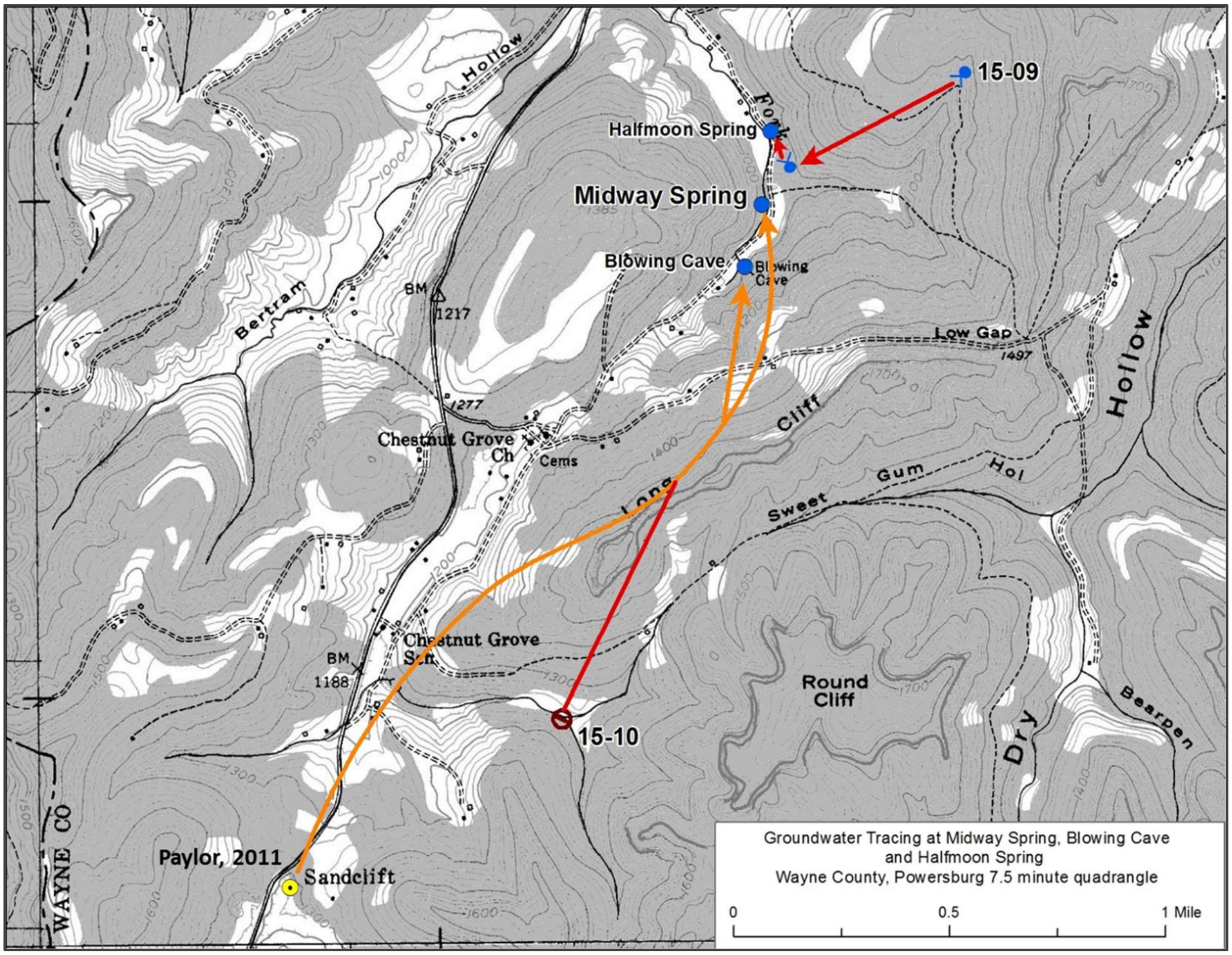

Figure 23. Midway Spring, Blowing Cave and Halfmoon Spring Tracer Tests

Trace # 15-09: Tommy Spring (9000-4054) is perched near the head of a steep valley and discharges from a small conduit. Spring water flows a short distance across a farm road and then sinks into the sand and gravel channel. On November 24, 2015, two ounces of SRB was injected at the sink point into approximately 0.05 ft^3/s of flow from Tommy Spring. On November 25 the landowner reported visual observation of SRB at Halfmoon Spring and a small karst window (9000-4053) a few hundred feet to the south. Unfortunately, Halfmoon Spring was not identified prior to the dye injection and had not been monitored with a dye receptor. Therefore, a water sample was collected at Halfmoon Spring at the next visit and SRB recovery was confirmed. The dye receptor at the small karst window was extremely positive for SRB on December 1. These results are summarized in Table 24.

Table 24. Tommy Spring Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Tommy Spring N36.653780°/ W84.961690° Nov. 24, 2015	Sinking Spring # 15-09	SRB – 2 oz (*Natural flow-* 0.05 ft^3/s)	**Halfmoon Spring** N36.652295°/W84.969220° **Overflow Karst Window** N36.651232°/W84.968556°	0.5 0.45

Eli Mac Springs

Eli Mac Springs (9000-3282 and 9000-3284) are a distributary system with two perennial spring outlets that are roughly 500 feet apart. The upstream outlet discharges from the base of a hill at the head of a short, unnamed tributary to Smith Creek. A pond constructed next to this spring has partially intercepted its groundwater discharge. The lower outlet is a small cave on the left bank of the unnamed tributary and discharges near the confluence with Smith Creek. An overflow spring is situated approximately halfway between the two on the left bank of the unnamed tributary. A single low-flow measurement of 1.1 ft^3/s was taken in September 2015. The three tracer tests recovered at this spring are described below and illustrated on the map in Figure 24.

Trace # 15-07: Hurst Karst Window (9000-4049) is a minor feature located on the east side of Sugar Valley Road, a short distance east-southeast of Eli Mac Springs. It is easily seen from the road and was identified while driving past, on the way to Eli Mac Springs. On August 11, 2015, the karst window was flowing with just a trickle of water and 1.5 ounces of SRB was injected. On August 18 Eli Mac Springs was very positive for SRB and remained so for two more dye receptor exchanges through the end of the month. These results are summarized on Table 25.

Table 25. Hurst Karst Window Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Hurst Karst Window N36.710361°/ W85.072770° Aug. 11, 2015	Karst Window # 15-07	SRB – 1.5 oz (*Natural flow-* trickle)	**Eli Mac Springs** N36.713758°/W85.084379°	0.8

Trace # 15-08: The Head of Gap Creek Sinking Spring discharges from the base of a bluff and flows about 40 feet before infiltrating the subsurface at a bedrock swallet. This injection point was utilized by Currens and Walden (2010) and was hypothesized to drain eastward to Coal Trace Cave. Unfortunately, Currens and Walden did not identify Eli Mac Springs until several days after their dye trace was not recovered at any of their monitored springs. Their samples from Eli Mac Springs indicated weak dye recovery, and results were considered inconclusive. Therefore, Jim Currens recommended that the authors replicate their tracer test to confirm the connection to Eli Mac Springs. On August 20, 2015 eight ounces of Uranine was injected into this bedrock swallet during very low flow conditions. Eli Mac Springs was extremely positive for Uranine on August 26 and again on September 3, confirming the previous results, where water flowed beneath a local topographic divide. This tracer test is summarized in Table 26.

Table 26. Head of Gap Creek Sinking Spring Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Head of Gap Creek Sinking Spring N36.724330°/ W85.034299° Aug. 20, 2015	Sinking Spring # 15-08	Uranine – 8 oz (*Natural flow-* 0.01 ft^3/s)	**Eli Mac Springs** N36.713758°/W85.084379°	3.0

Trace # 17-03: Sumner Karst Window is the remnants of a large, collapsed cave passage perched on a hillside on the eastern valley wall of Huff Branch. Water discharges from a small cave and flows a short distance before sinking into rubble in the base of the karst window. On February 17, 2017, six ounces of

Uranine was injected into flowing water at the discharge point and allowed to infiltrate over this broad area. On February 22 Eli Mac Springs was extremely positive for Uranine, and remained so for two subsequent dye receptor exchanges through mid March. These results are summarized in Table 27.

Table 27. Sumner Karst Window Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Sumner Karst Window N36.711389°/ W85.045894° Feb. 17, 2017	Karst Window # 17-03	Uranine – 6 oz (*Natural flow-* 0.1 ft^3/s)	**Eli Mac Springs** N36.713758°/W85.084379°	2.3

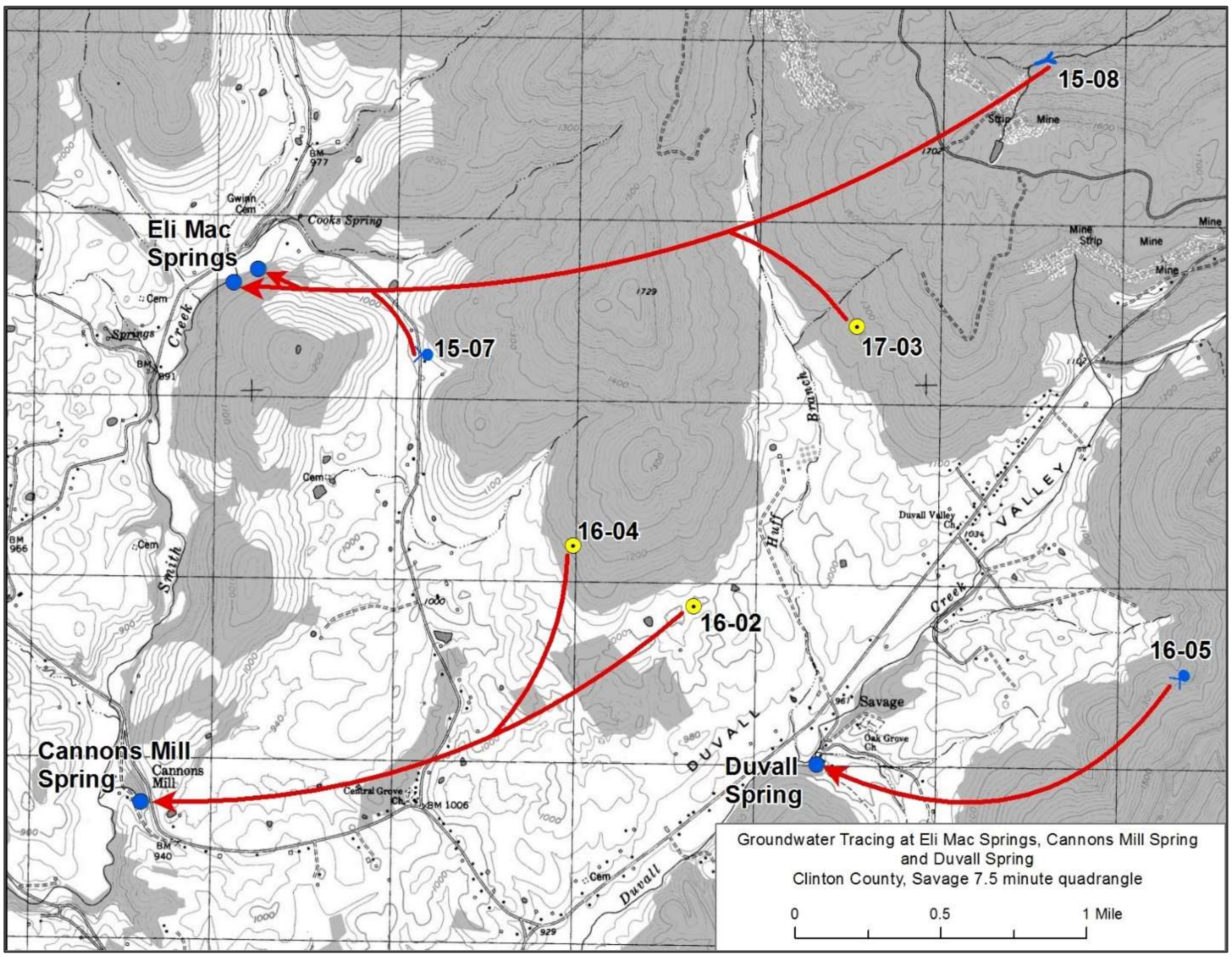

Figure 24. Eli Mac Springs, Cannons Mill Spring and Duvall Spring Tracer Tests

Cannons Mill Spring

Cannons Mill Spring (9000-3946) discharges from multiple outlets across a 20 foot horizon at the base of a steep hill, in a pocket valley on the east side of Smith Creek. The old mill is still in place and identified on the USGS topographic maps, which also illustrates the impoundment above the mill. However, the spring was not identified on the USGS maps. The spring owner reports that several local residents still collect drinking water from this spring. Two low flow measurements collected at this spring in September 2015 and November 2016 indicate base flow is roughly 1.2 ft^3/s. The two dye traces recovered at Cannons Mill Spring are described below and illustrated on the map in Figure 24.

Trace # 16-02: Dalton Sinkhole is a large cover-collapse in the bottom of a sinkhole in the north-central portion of Duvall Valley. On February 11, 2016 six ounces of Uranine was injected into this sinkhole with 200 gallons of hauled water. On February 18 Cannons Mill Spring was extremely positive for Uranine and remained so for the second dye receptor exchange on March 8. The results of this dye trace are summarized in Table 28.

Table 28. Dalton Sinkhole Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Dalton Sinkhole N36.697658°/ W85.055980° Feb. 11, 2016	Sinkhole # 16-02	Uranine – 6 oz (*Hauled water-* 200 gallons)	**Cannons Mill Spring** N36.687889°/W85.090310°	2.1

Trace # 16-04: The Dryden Property Bedrock Shaft is located in a dry gully that drains a forested hillside east of Sugar Valley Road. The shaft receives infiltrating water only during runoff events and is situated in an area that was inaccessible for hauling water to flush tracer dye. On March 24, 2016 thunderstorms produced about one half inch of precipitation, which caused a runoff event that allowed for six ounces of Eosine to be injected at this location. On May 8 Cannons Mill Spring was extremely positive for Eosine and remained so for two dye receptor exchanges through the end of the month. These results are summarized in Table 29.

Table 29. Dryden Bedrock Shaft Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Dryden Bedrock Shaft N36.700543°/ W85.063462° Mar. 24, 2016	Bedrock Shaft # 16-04	Eosine – 6 oz (*Natural flow-* trickle)	**Cannons Mill Spring** N36.687889°/W85.090310°	2.0

Duvall Spring

Duvall Spring (9000-4067) rises at the base of hill, a short distance off the left bank of Duvall Creek. The spring has been modified with a poured concrete basin to collect water and pump it to the farm on the north side of the creek. Water is mainly used for agricultural purposes including livestock and irrigation, but is occasionally collected for drinking water. The single dye trace recovered at Duvall Spring is described below and illustrated on the map in Figure 24.

Trace # 16-05: Grey Karst Window is relatively small and perched on the hillside above Duvall Valley. On April 15, 2016, four ounces of SRB was injected into approximately 0.1 ft^3/s of water flowing through the karst window. On April 29 Duvall Spring was extremely positive for SRB and no other dye receptor exchanges occurred. These results are summarized in Table 30.

Table 30. Grey Karst Window Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Grey Karst Window N36.693611°/ W85.026111° Apr. 15, 2016	Karst Window # 16-05	SRB – 4 oz (*Natural flow-* 0.1 ft^3/s)	**Duvall Spring** N36.689599°/W85.048581°	1.4

Wallace Springs

Wallace Spring-Major (9000-4062) and Wallace Spring (9000-4061) are a distributary system that discharge from the base of a hill just off the right bank of Duvall Creek. Although the spring is no longer used, there is an old springhouse around the smaller, upstream spring. Only one trace was recovered at Wallace Springs and it is described below and illustrated on the map in Figure 25.

Trace # 16-01: Litrell Swallet is a large collapse feature on the east side of KY 1076 and captures intermittent drainage from the west side of the road. On February 4, 2016, approximately 2 ounces of SRB was injected into the swallet while the intermittent stream was flowing about 1.5 ft^3/s. On February 11 Wallace Springs were both extremely positive for SRB. The subsequent dye receptor exchange on February 18 showed that both springs were negative for SRB, likely due to the short distance and high flow into the swallet. These results are summarized on Table 31.

Table 31. Litrell Swallet Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Litrell Swallet N36.668641°/ W85.071339° Feb. 4, 2016	Sinking Stream # 16-01	SRB – 2 oz (*Natural flow-* 1.5 ft^3/s)	**Wallace Spring-Major** N36.665338°/W85.067218°	0.3
			Wallace Spring N36.666473°/W85.06588°	0.35

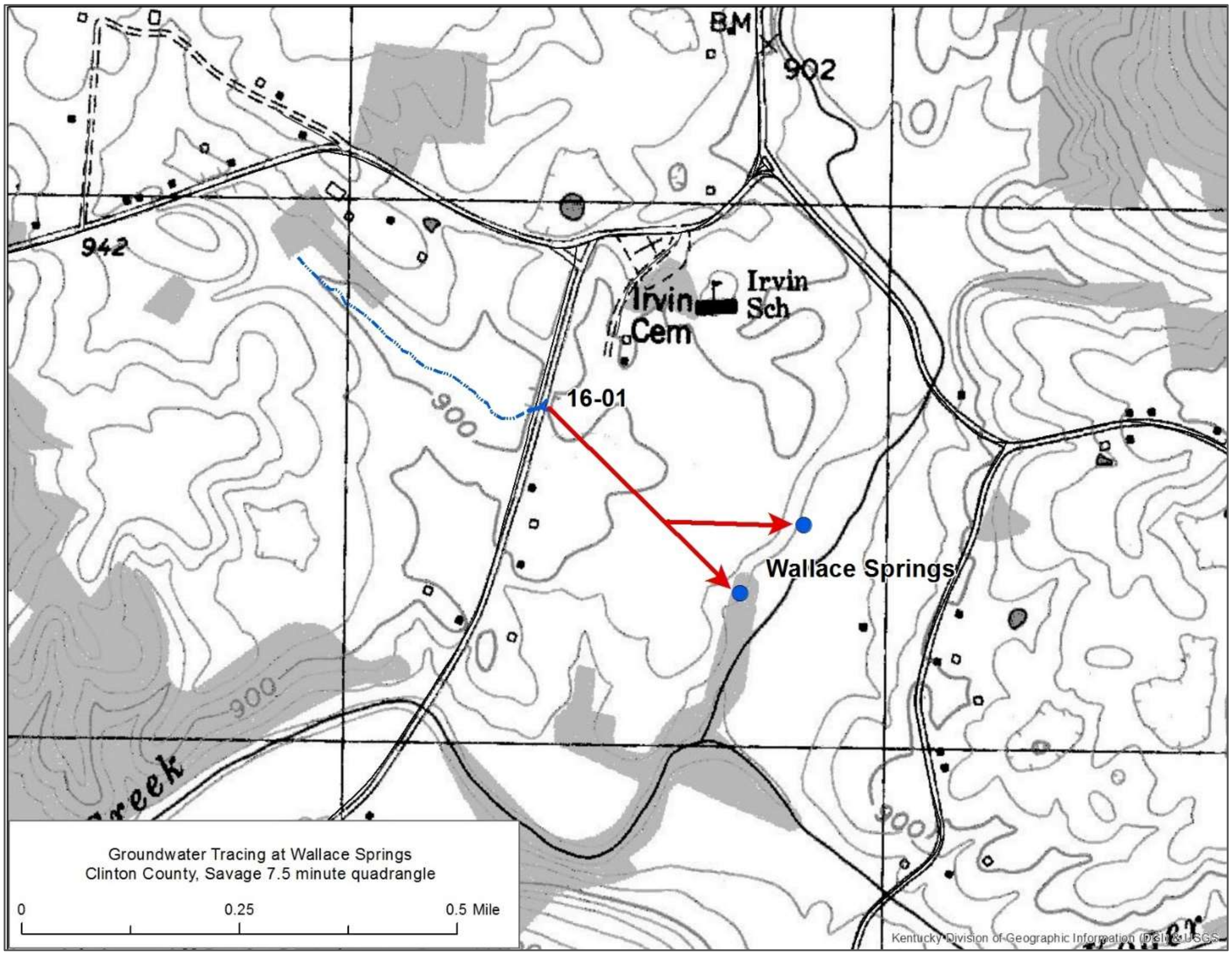

Figure 25. Wallace Springs Tracer Test

Town Spring

Town Spring (9000-1830) is the former drinking water supply for Albany, Kentucky, but has not been used in many years. The spring discharges from an old spring box at the base of a high bluff that lies directly below US HWY 127 (Water Street) in downtown Albany. A single low-flow measurement collected in November 2016 for this study was 0.7 ft^3/s. The one dye trace recovered at Town Spring is described below and illustrated on the map in Figure 26.

Trace # 16-07: Owens Bedrock Shaft is located at the base of a low bluff near the end of Mountain Lane, on the west side of Sewell Mountain. The shaft is roughly three feet in diameter and estimated to be 30 feet deep. On September 2, 2016, eight ounces of SRB was flushed into the shaft with 400 gallons of hauled water. The first dye receptor exchange occurred on September 8, and dye was not recovered at any of the monitored sites. On September 16 Town Spring was extremely positive for SRB and no other dye receptor exchanges were made. These results are summarized on Table 32.

Table 32. Owens Bedrock Shaft Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Owens Bedrock Shaft N36.720092°/ W85.128323° Sep. 2, 2016	Bedrock Shaft # 16-07	SRB – 8 oz (*Hauled water-* 400 gallons)	**Town (Albany) Spring** N36.688611°/W85.134722°	2.2

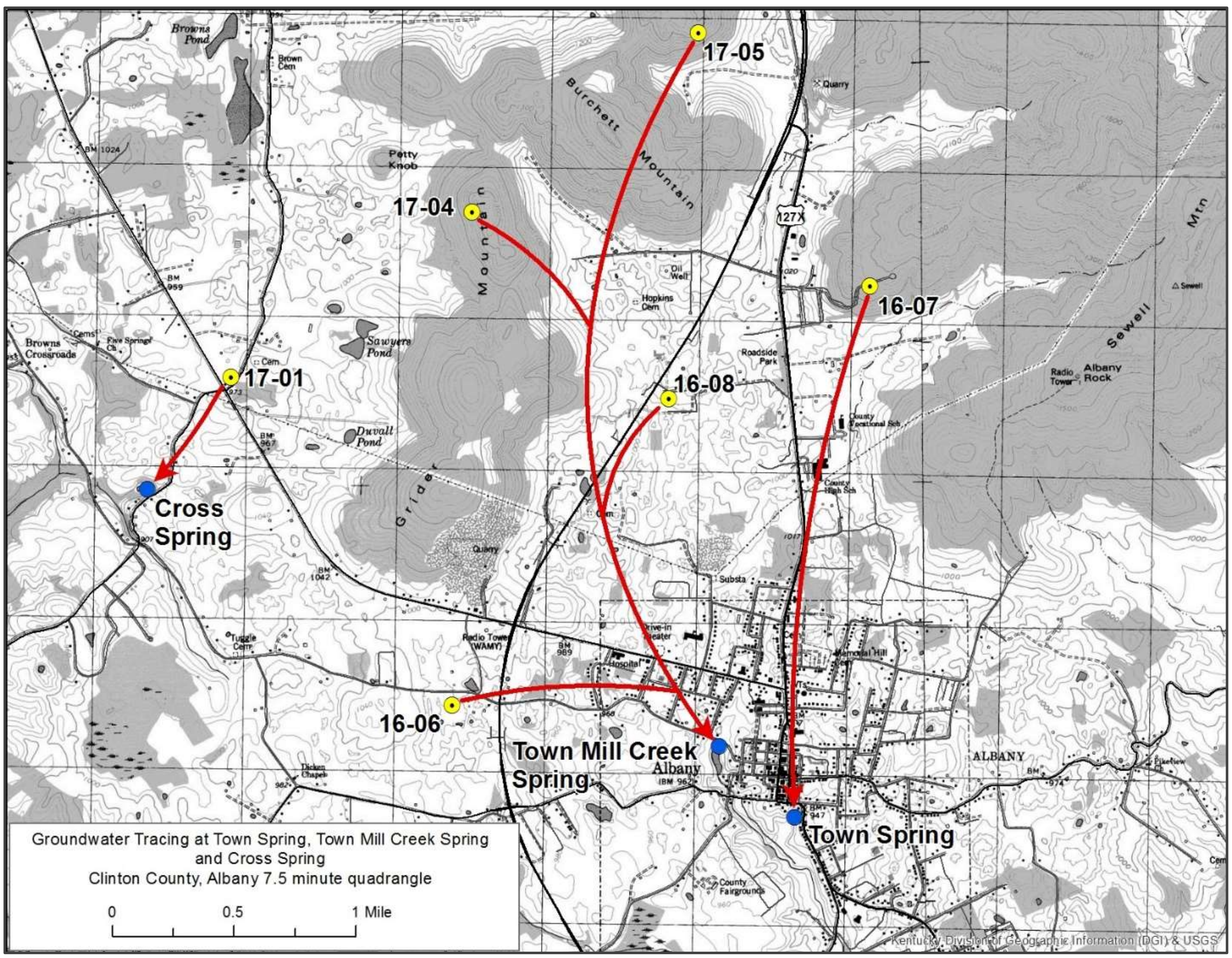

Figure 26. Town Spring, Town Mill Creek Spring and Cross Spring Tracer Tests

Town Mill Creek Spring

Town Mill Creek Spring (9000-1829) discharges at the base of steep hill on the west side of Albany, just south of Wood Street. This spring forms the head of Clear Fork Branch and the remnants of the mill it powered can be seen near the KY 553 bridge. Brown and Lambert (1963) report a low flow measurement at this spring of 0.6 ft^3/s. Van Couvering (1962) reports flow measurements at this spring from 1953 to 1960, and the median annual low flow derived from this research is 1.0 ft^3/s. The four tracer tests recovered at this spring are described below and illustrated on the map in Figure 26.

Trace # 16-06: McWhorter Sinkhole is located approximately one mile west of Albany, on the south side of Old Burkesville Road. It is a large sinkhole with a cover-collapse near the center. On August 19, 2016, two ounces of Uranine were flushed into the sinkhole with 200 gallons of water. On August 26 Town Mill Creek Spring was extremely positive for Uranine. The spring remained positive for Uranine for three more dye receptor exchanges through mid-September. The results of this tracer test are summarized on Table 33.

Table 33. McWhorter Sinkhole Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
McWhorter Sinkhole N36.695169°/ W85.159883° Aug. 19, 2016	Sinkhole # 16-06	Uranine – 2 oz (*Hauled water*- 200 gallons)	**Town Mill Creek Spring** N36.692734°/W85.140238°	1.2

Trace # 16-08: The Grider Well is an old, hand dug well that is lined with cut stone. The well is roughly two feet in diameter and 20 feet deep with a minor amount of groundwater observed flowing across bedrock at the bottom. On November 4, 2016, three ounces of Eosine was injected into the well with 600 gallons of hauled water. On November 18 Town Mill Creek Spring was extremely positive for Eosine and remained so for one more dye receptor exchange in early December. These results are summarized on Table 34.

Table 34. Grider Well Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Grider Well N36.713356°/ W85.143775° Nov. 4, 2016	Water Well # 16-08	Eosine – 6 oz (*Hauled water-* 600 gallons)	**Town Mill Creek Spring** N36.692734°/W85.140238°	1.6

Trace # 17-04: Grider Mountain Sink is a bedrock shaft perched on a hillside on the northwestern end of Grider Mountain. The shaft is approximately 40 feet deep with no flowing water observed. On February 28, 2017, eight ounces of SRB was injected into the shaft during a rain event. Over the next 48 hours the area received more than one inch of rainfall, which provided runoff to flush dye into the karst system. On March 9 Town Mill Creek Spring was extremely positive for SRB, and remained so for three more dye receptor exchanges through March 30. These results are summarized on Table 35.

Table 35. Grider Mountain Sink Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Grider Mountain Sink N36.724664°/ W85.158260° Feb. 28, 2017	Bedrock Shaft # 17-04	SRB – 8 oz (*Runoff event-* undetermined)	**Town Mill Creek Spring** N36.692734°/W85.140238°	2.5

Trace # 17-05: Hay Sink is a small bedrock shaft at the base of a limestone bluff located north of Burchett Mountain on the west side of US HWY 127. On March 30, 2017, eight ounces of Eosine was injected into a trickle of water entering the shaft, in anticipation of additional runoff from a forecasted precipitation event the following day. On April 6 Town Mill Creek Spring was extremely positive for Eosine and remained so for the subsequent dye receptor exchange on April 12. These results are summarized on Table 36.

Table 36. Hay Sink Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Hay Sink N36.735217°/ W85.141343° Mar. 30, 2017	Sinkhole # 17-04	Eosine – 8 oz (*Natural flow-* trickle)	**Town Mill Creek Spring** N36.692734°/W85.140238°	3.1

Cross Spring

Cross Spring (9000-3956) is a small spring located at the head of a pocket valley that is tributary to an unnamed sinking stream. The spring discharges from three outlets that span nearly 30 feet across a horizon that is perched about eight feet above the valley floor. The single dye trace recovered at this spring is described below and illustrated on the map in Figure 26.

Trace # 17-01: Cummings Sink is a small sinkhole on the north side of the intersection between KY 1590 and KY 639. On January 31, 2017 three ounces of Uranine was flushed into the sinkhole with 600 gallons of hauled water. On February 3 Cross Spring was extremely positive for Uranine dye, and remained so for three subsequent dye receptor exchanges through early March. These results are summarized on Table 37.

Table 37. Cummings Sink Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	Inferred Distance (mile)
Cummings Sink N36.714938°/ W85.176248° Jan. 31, 2017	Sinkhole # 17-01	Uranine – 3 oz (*Hauled water-* 600 gallons)	**Cross Spring** N36.708282°/W85.182484°	0.6

Head of Indian Creek Spring

The Head of Indian Creek Spring (9000-3957) is a large cave located at the head of a narrow valley approximately one mile upstream of 76 Falls into Lake Cumberland. Indian Creek is initially formed by McKinney Spring (9000-2525), which is discussed in the Previous Karst Mapping Studies section of this report. The creek flows roughly 1.5 miles and then sinks into Summers Cave on the west side of KY 734. The creek reemerges at the Head of Indian Creek Spring, which is approximately 1000 feet east of Summers Cave. The single dye trace conducted to verify this connection is described below and illustrated on the map in Figure 27. Following this dye trace the cave was surveyed by Dr. Lee Florea (2014) and students from Ball State University, and was found to be 1084.5 feet long.

Trace # 13-12: Summers Cave is located on the west side of KY 734, just north of the intersection with KY 639. The cave entrance is very large and is the terminal sink point of Indian Creek. On October 17, 2013, at 3:50 pm one ounce of SRB was introduced into approximately 2 ft^3/s of water entering the cave. A charcoal dye receptor was previously deployed and water samples were collected in an attempt to determine the actual time of travel through the cave. The initial water sample collected at 4:20 pm was negative for SRB. At 4:42 pm slight discoloration was observed and a second water sample was collected, which was confirmed to be positive for SRB. Three subsequent water samples collected on 10 minute intervals were extremely positive for SRB, at which point the water discoloration was apparent. Using the measured cave length from Dr. Florea yields an apparent groundwater velocity of 21 ft/min. These results are summarized on Table 38.

Table 38. Summers Cave Dye Trace Summary

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site Lat/Long	*Measured* Distance (feet)
Summers Cave N36.770612°/ W85.143169° Oct. 17, 2013	Cave Swallet # 13-12	SRB – 1 oz (*Natural flow-* 2 ft^3/s)	**Head of Indian Creek Spring** N36.770873°/W85.139597°	1084.5

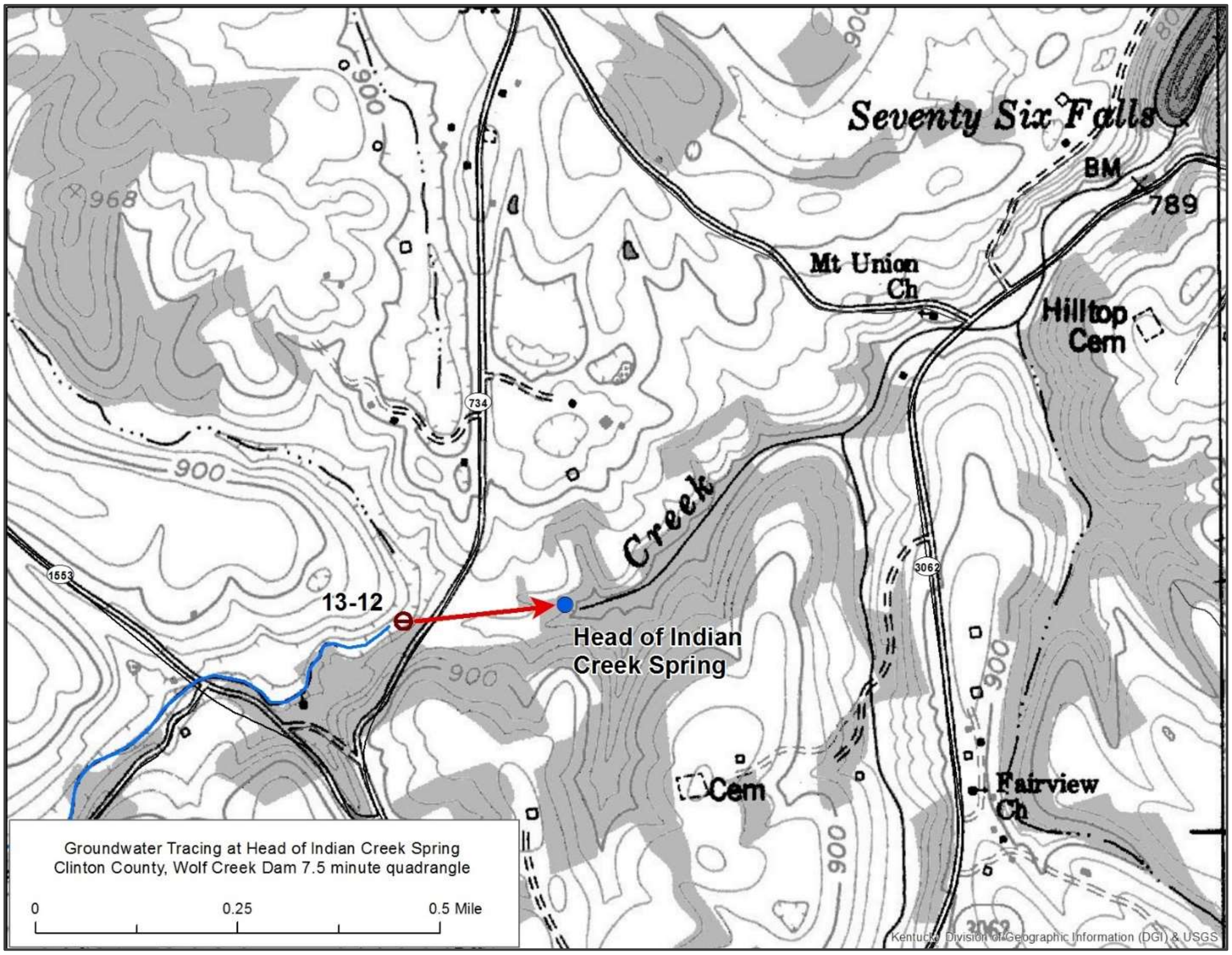

Figure 27. Head of Indian Creek Spring Tracer Test

CONCLUSIONS

A considerable amount of research into karst occurrence and groundwater-flow mapping has been conducted in south central Kentucky. This study represents a compilation of previous, current and concurrent research into karst groundwater resources of this region. During this project, 37 reconnaissance groundwater tracer tests were conducted for the purpose of basin delineation and verification or modification of inferred watershed boundaries. Tracer tests were recovered at 24 springs, cave streams and karst windows, which fully or partially delineated 18 karst drainage basins. Although 36 karst spring basins have been partially or fully delineated to date, a considerable amount of work remains to be done. Further field study to identify, map and quantify karst groundwater resources is necessary.

In addition, proper assessment of groundwater quality and evaluation of its influence on surface water resources should be conducted. The karst basin mapping presented in this report can guide future water quality studies by delineating these drainage areas.

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