Integrated Surface Water and Groundwater Assessment of Large Springs in the Western Pennyrile Karst Region of Kentucky

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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 project is the second groundwater study in one of Kentucky's karst regions to integrate surface water and groundwater quality assessment approaches. Karst terranes represent areas of direct connection between surface water and groundwater systems. Surface water assessments (§305b report) in the well-developed karst areas of Kentucky are limited due to a relative lack of flowing surface streams. Subsurface drainage can only be assessed via springs and caves or by water pumped from conduit-intercepting wells. In order to adequately evaluate these large spring basins, the approach must meet the requirements for surface water assessment.

The study area is located in the Western Pennyrile Karst Region of Kentucky within the Lower Cumberland River Basin, and encompasses portions of Crittenden, Livingston, Lyon, Caldwell and Trigg counties. This area is underlain primarily by Mississippian-aged carbonate rock units that are highly prone to dissolution and the development of karst basin drainage. The study area overlaps the southern end of the Kentucky-Illinois Fluorspar District. This region is characterized by extensive faulting, minor geological structural deformation and significant mineralization.

Previous hydrogeological research has been conducted in this region by numerous authors, which was extremely useful to the project described here. In particular, work by the U.S. Geological Survey and Western Kentucky Speleological Survey provided maps, data and hypotheses on groundwater connections in the karst aquifers. Groundwater tracing with fluorescent dyes was conducted as part of this project to expand our knowledge of karst flow paths and basin drainage. Of the 43 tracer tests conducted, 38 were recovered at 29 separate cave streams and springs, which allowed for the delineation of 11 additional karst basins.

Nine springs with delineated karst basins were selected for groundwater monitoring utilizing the integrated approach. Chemical samples were collected once per month for 12 consecutive months at each spring from October 2012 to September 2013. Five bacteria samples were collected from each of the springs in a 30-day period during August 2013. Data were evaluated and water quality assessments were made in accordance with the standards set forth in 401 KAR 10:031 (Kentucky Water Quality Standards).

Evaluation of these data showed that 7 of the springs were fully supporting for aquatic habitat and 2 of the springs were partially supporting for aquatic habitat. When evaluated using the Primary Contact Recreation standard, 3 springs were fully supporting and 6 springs were partially supporting. The main contributors to poor groundwater quality were *E. coli* and low dissolved oxygen.

Eight of the nine springs monitored for water quality were also evaluated for benthic macroinvertebrates using passive sampling (Hester-Dendy samplers). Taxonomic identification was predominantly done to the genus level; however, worms were left at the order level. A total of 2,137 individuals from 52 taxa were observed in this study. The majority of taxa found are considered to be tolerant macroinvertebrate groups. No strong statistical correlations were found between macroinvertebrate populations and water chemistry, spring basin size or base flow discharge. Genus richness at individual springs ranged from 9 to 23 taxa with a median value of 13.

INTRODUCTION and BACKGROUND

Before 1995, ambient groundwater quality data throughout the state were inadequate to assess groundwater quality on a regional, basin-wide or statewide scale. In order to address this situation, the Kentucky Division of Water (DOW) initiated statewide ambient groundwater monitoring in 1995 to begin the long-term, systematic evaluation of groundwater quality throughout the state. In 1998, legislation established the Kentucky Interagency Groundwater Monitoring Network, which formalized groundwater assessment efforts. Oversight for this network is through the Interagency Technical Advisory Committee on Groundwater, which includes the DOW and other state and federal agencies.

The DOW regularly collects ambient groundwater samples throughout the state. To date, the division has collected more than 6000 samples from approximately 1600 sites. The information from these samples is used for a variety of purposes, including: 1) assessment and characterization of local and regional baseline groundwater quality, 2) documentation of spatial and temporal variations in groundwater quality, 3) support of public water systems, especially through source water characterization and Wellhead Protection, 4) development of Total Maximum Daily Loads (TMDLs) for surface water in areas where groundwater directly influences this resource, 5) support of the state's pesticide management plan, 6) development of groundwater quality standards and aquifer classification and 7) to address compliance and nonpoint source pollution issues. The Division of Water forwards analytical data to the Kentucky Geological Survey (KGS) Groundwater Data Repository where it is available to the public. Data requests can be made via their website (http://kgs.edu/KGS/home.htm), by phone at (859) 257-5500, or by mail at 228 Mining and Minerals Resources Building, University of Kentucky, Lexington, KY 40506.

The 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 assessment.

Project Description

The purpose of this project was to assess groundwater in the Western Pennyrile Karst Region of Kentucky for nonpoint source (NPS) pollution impacts. This was accomplished by integrating groundwater and surface water quality data to better define the nexus between these two systems. Karst systems are characterized by turbulent groundwater flow through conduits and caves. Surface features in karst areas include springs, cave entrances, sinkholes and sinking or losing streams. Groundwater and surface water are conjunctive systems and this link is very direct in karst terrane. Surface water assessments in the well-developed karst regions of Kentucky have been limited by the relative lack of flowing surface streams. In these regions, karst aquifers represent large areas of contribution to our streams and rivers that have not been properly assessed.

The study area springs of the Western Pennyrile Karst Region are located in the Lower Cumberland River Basin (BMU 3), which encompasses portions of Crittenden, Livingston, Lyon, Caldwell and Trigg counties. The USGS 7.5-minute quadrangles for the study area include: Burna, Calvert City, Cobb, Crider, Dycusburg, Eddyville, Fredonia, Gracey, Grand Rivers, Lamasco, Lola, Princeton East, Princeton West and Salem. The project area is bounded by the Cumberland River and Lake Barkley on the west and the Dripping Springs Escarpment on the east. This region of Kentucky is known by many names including Pennyrile, Pennyroyal and Mississippian Plateau. While local caving clubs have been very active in this region, only minimal groundwater tracing data were available prior to this study. Before groundwater quality monitoring could begin, tracer tests were conducted to delineate spring recharge areas and basin boundaries. A total of 43 tracer tests were conducted for this project, of which 38 were recovered at 29 springs and caves throughout the study area. The nine largest springs were chosen for groundwater quality assessment and are summarized in Table 1. Springs are listed in descending order according to base flow discharge. The AKGWA Numbers for all springs in the Groundwater Database are preceded by "9000-". This prefix has been dropped for text, tables and figures in this report, such that Martin Spring (AKGWA No. 9000-3740) is simply reported as **Martin Spring (3740)**. Figure 1 shows a map of the study area with springs monitored for water quality identified.

Table 1. Springs assessed for water quality

Spring Name	AKGWA	Latitude	Longitude	Base Flow (L/s)	County	Quadrangle	Receiving Stream
Harpending	1823	37.03785	-87.934026	77	Caldwell	Princeton W	Eddy Cr
Wallace Branch	1855	37.070627	-87.929466	62	Caldwell	Princeton W	Eddy Cr
Mill Bluff	1825	37.189992	-88.073043	60	Caldwell	Fredonia	Livingston Cr
Martin	3740	36.970278	-87.782825	48	Caldwell	Cobb	Kenady Cr
Puckett	1853	37.234474	-88.200454	40	Livingston	Dycusburg	Claylick Cr
Cohorn	3741	37.142708	-88.108847	37	Lyon	Fredonia	Skinframe Cr
Conway	3861	37.192653	-88.100335	31	Crittenden	Fredonia	Livingston Cr
Ruben Ray	3742	37.184334	-88.08343	28	Caldwell	Fredonia	Livingston Cr
Big	1145	37.108072	-87.881517	14	Caldwell	Princeton W	Eddy Cr

Previous Investigations

Van Couvering (1962) conducted reconnaissance of large springs in Kentucky and this included data collection on four springs in the study area: Martin Spring (3740), Harpending Spring (1823), Mill Bluff Spring (1825) and Puckett Spring (1853). His publication included discharge measurements and hypothesized groundwater recharge areas for these springs. Those measurements and groundwater flow hypotheses will be discussed within the individual spring descriptions.

The United States Geological Survey (USGS) has published Hydrologic Atlases (HA) for the entire state. HA-34 (Lambert and Brown, 1963) provides a general description of geologic units and groundwater occurrence, availability and geochemistry for Todd, Christian, Trigg, Lyon, Caldwell, Crittenden and Livingston 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.

Plebuch (1976) published an extensive study of the hydrology surrounding the city of Princeton in Caldwell County. This study included flow measurements for water well withdrawals and spring discharges, as well as information regarding surface water resources. Of particular interest was the groundwater-level contour map produced as part of that study. This map served as guidance for some tracer tests conducted for this study. Plebuch and others (1985) produced a potentiometric surface map and reported on water quality in the primary aquifer of the Mississippian Plateau – rock units of the Meramecian Series.

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.

The Western Kentucky Speleological Survey (WKSS) has published numerous caving guide books for this part of the state. The most recent guide book, *Report 1985 – 2005* (WKSS, 2005), is a compilation of previous and recent work conducted by the organization and its members. It contains detailed cave descriptions, maps and hypothesized groundwater flow routes for the area of the Mississippian Plateau that is bounded on the east by the Barren River and on the west by the Ohio River. This work also served as an excellent guide for the study described in this report. Several of the cave maps and groundwater flow hypotheses were pertinent to this study and will be discussed with individual spring descriptions.

Groundwater tracing conducted by Ewers Water Consultants (1990) and by DOW (Dever and Ray, 1994) were the only known tracer data for this area prior to the current study. Ewers conducted traces to Big Spring (1145) and Lisanby Spring (3853) (aka Powerline Spring), both in Princeton, Caldwell County, Kentucky. DOW traced groundwater flow through a small cave to Rogers Spring (1388), near Cerulean Springs, Trigg County, Kentucky.

Fisher, Davidson and Goodmann (2004) summarized groundwater quality data for BMUs 3 & 4. Monitoring sites utilized for BMU 3 data included wells and springs in the Upper and Lower Cumberland River, Tennessee River and Mississippi River basins. They found definite impacts to groundwater quality from nutrients, pesticides and volatile organic compounds.

Three springs within the study area have been part of the Ambient Groundwater Monitoring Network since its inception in 1995 – Big Spring (1145), No Bottom Spring (1149) and Hayes Spring (1343). Each of these springs has been sampled 2-4 times per year in that time frame. However, those data had not been used for a region-specific analysis of groundwater quality.

PHYSIOGRAPHIC and HYDROGEOLOGIC SETTING

The Cumberland River Basin (BMU 3) is represented by the USGS Hydrologic Unit Code (HUC) 0513 and covers 45,843 km^2 in Kentucky and Tennessee. The headwaters rise in southeastern Kentucky and northeastern Tennessee and meander westward to the confluence with the Ohio River near Smithland, Kentucky in Livingston County. The study area is located in the Lower Cumberland Basin (HUC 051302), which drains an area of 18,518 km^2 (USGS, 2009). This 6-digit HUC is further divided into six sub-basins, two of which – Lower Cumberland River (HUC 05130205) and Red River (HUC 05130206) – are partially in Kentucky. The Cumberland River has been impounded by Barkley Dam at Grand Rivers, Kentucky, forming Lake Barkley.

Lower Cumberland River Basin

The Lower Cumberland River crosses into Kentucky in Trigg County, at which point it forms the backwaters of Lake Barkley. The Kentucky portion of the Lower Cumberland River Basin (HUC 05130205) encompasses 3500 km^2. Major tributaries to the Cumberland River in the study area are Muddy Fork of the Little River, Eddy Creek, Livingston Creek and Claylick Creek. Figure 2 illustrates the surface hydrography and generalized geology of the Kentucky portion of the Lower Cumberland River Basin within the study area. The study area receives approximately 114 cm of precipitation annually. [Side Note: The USGS maps show two separate *Skinframe Creeks*, one in western Caldwell County that ends in a blind valley and one in eastern Lyon County that is a tributary to Livingston Creek. For clarity these will be referred to as Skinframe Creek-east (Caldwell Co.) and Skinframe Creek-west (Lyon Co.). During moderate to base flow conditions, Skinframe Creek-west flows into Livingston Creek, and Skinframe Creek-east sinks, diverting it from joining Skinframe Creek-west. However, during extreme flood conditions there is continuous overland flow, which connects the two creeks and creates one Skinframe Creek that discharges to Livingston Creek.]

Population centers in the study area include Princeton and Fredonia in Caldwell County, and Eddyville in Lyon County. Smaller towns are scattered across the region in a rural setting, which is dominated by agricultural land.

Physiographic Region

The study area occurs entirely within the Mississippian Plateau Physiographic Region. 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. 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 (Lambert and Brown, 1963).

Hydrogeologic Setting of Study Area

Well-developed karst drainage in the study area occurs primarily in the Ste. Genevieve and St. Louis limestones of the Meramecian Series of the Mississippian System (325-345 Ma). These limestones were deposited mainly 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 and caves, losing and sinking streams, dry valleys, intermittent lakes, and large springs (Ray and others, 2006). Above the Ste. Genevieve Limestone lie several sandstone, shale and minor limestone units of the Chesterian Series of the Mississippian System. While karst development does occur in some of these carbonate rock units, the extent is generally limited.

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. The Ste. Genevieve typically ranges in thickness from 60 to 80 m in the study area (Sable & Dever, 1990). The Lost River Chert is a distinctive 1- to 3-meter 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.

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. Although this unit ranges from 100-145 m in thickness, most of the karst groundwater circulation relevant to this study occurs in the upper portion.

Kentucky-Illinois Fluorspar District

The project area encompasses a large portion of the fluorspar district of western Kentucky and southern Illinois. This area has been described by numerous authors including Ulrich and Smith (1903), Jillson (1921), McFarlan (1943), Hardin and Trace (1959), Trace and Amos (1984) and Nelson and Lumm (1987). The following is a summarized description of the geologic setting and history.

The study area is located near the southern end of the Eastern Interior (or Illinois) Basin, which contains a thick sequence – up to 3950 m – of Paleozoic rocks. These are predominantly sedimentary rocks of Cambrian to Mississippian-age that filled the basin overlying pre-Cambrian basement rocks. Extensive faulting and significant structural features are found within and surrounding the area (Nelson and Lumm, 1987).

In general, the area is dissected by normal faults that trend northeast – southwest and form a horst and graben complex, blocks of land between two faults that have shifted higher or lower, respectively, than the surrounding land. In the north some of these faults join the Shawneetown-Rough Creek Fault System and in the south they meet the Tabb-Pennyrile Fault System, which both trend roughly east – west. Trace and Amos (1984) note that the rocks in grabens tend to dip toward the middle creating slight folds, while rocks in the horsts tend to maintain their original dip toward the northeast. Faults are most numerous in the northwest portion of the study area and become less prevalent in the southeast. Tolu Arch in western Crittenden County is a south-trending extension of the Hicks Dome located in southern

Illinois. Lateral offset in the southern end of the arch through the horst and graben complex has led some researchers to hypothesize a horizontal component of fault displacement. Concentrated in the vicinity of Tolu Arch are northwest trending mafic dikes and sills. These igneous intrusions have been classified as mica peridotites and lamprophyres (Koenig, 1956).

To briefly summarize the tectonic history, the extensive faulting was produced by a combination of factors over the span of several geologic time periods. Rifting occurred sometime around the late Precambrian or early Cambrian period (about 500 million years ago) and was followed by only minor activity during the Ordovician through Pennsylvanian periods (300 million years ago). Late in the Paleozoic Era (roughly 250 million years ago) tectonic activity increased as up-welling magma caused tensional faulting and placement of the igneous dikes and sills. Vertical displacement along some faults was as much as 1000 m. In the later phases of activity, hydrothermal solutions moved upward and filled many of the faults and fractures in the middle and upper Mississippian rock units, forming the mineral deposits seen today (Nelson and Lumm, 1987; Nelson, 2008).

This activity has created a very complex setting within the Mississippian carbonates where karst aquifers have developed. Many faults cut through areas with highly soluble limestone on both sides, while vertical displacement on some faults has left the limestones juxtaposed with less soluble shale and sandstone units. Van Couvering (1962) and Plebuch (1976) both hypothesized that faults in the former setting would be hydraulically transmissive, and that faults in the latter setting would act as hydrologic boundaries. Although this is true in many cases, tracer tests and reconnaissance conducted for this study proved that this rule does not always hold. Lambert and Brown (1963) investigated water well yields and report, "[*y*]*ields from fault zones generally are greater than shown by the availability pattern; however, some wells yield much less than is shown by the pattern*." Specific examples will be discussed with results of pertinent tracer tests later in this report.

Significant karst development has also occurred within the portion of the fluorspar district in southern Illinois. The eastern Shawnee Hills Karst Region, located in Hardin and Pope counties in Illinois, is underlain by many of the same Mississippian carbonate rock units. This area is described as having well-developed karst drainage, containing numerous sinkholes and caves (Panno and others, 1997).

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 flow velocity through conduits often matches runoff in surface channels, which may travel several kilometers 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 meters in diameter, which is exemplified by stream infiltration into a cave or vertical shaft. *Flow* velocity within trunk conduits may range from 10 m/hr at low flow to 800 m/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/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. 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 3 (Currens, 2001) shows the surface and subsurface elements of a typical karst aquifer in the study area.

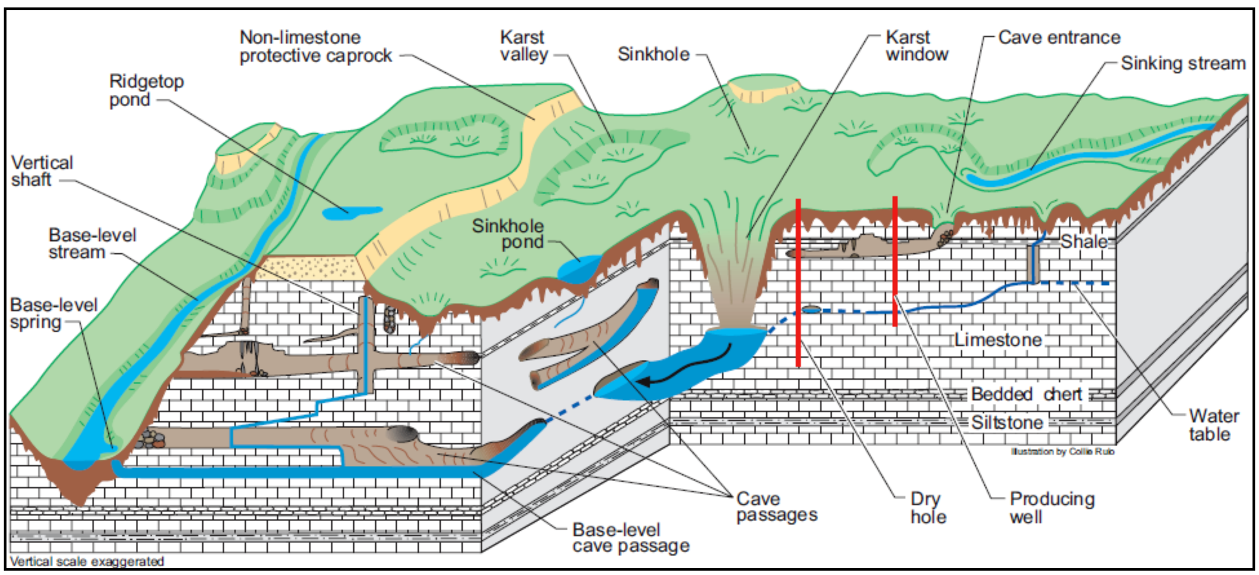

Figure 3. Karst Aquifer Block Diagram (Currens, 2001)

Land Cover and Land Use

Land cover analysis is based on the 2001 National Land Cover Dataset (USGS, 2001). While these data are somewhat dated, observations during fieldwork suggest that only minor changes have occurred since these data were compiled. The main changes would be a slight increase in the amount of agricultural areas (mainly row crop) and the corresponding decrease in forested areas. For this analysis, subcategories were combined such that all levels of urban and residential land cover are considered as one. Additionally, all forested areas have been combined (deciduous, evergreen and mixed), as well as agricultural areas (pasture and row crop). The result is three main categories of land cover: Impervious (Urban/Residential), Forest and Agriculture (Figure 4).

The predominant land cover type within the study area is agriculture at roughly 50%, which is followed closely by forest at 43%. Impervious (Urban/Residential) areas comprise only 5% of the total area, with surface water and wetlands making up the remaining 2%. Table 2 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 2. Land cover types and relative amounts found in the study area.

Land Cover Type	% in Study Area	Potential Water Quality Impacts
Agriculture – including row crop production, livestock grazing, fuel/pesticide storage	50	Pesticides, nutrients (esp. nitrate-n), salts/chloride, volatile organics, bacteria
Urban/Residential – including commercial and light industry	5	Pesticides, nutrients, volatile organics, chlorides, bacteria
Forest – including logging and silviculture	43	Pesticides, nutrients, sediment, pH

Land cover analysis has also been conducted for the 9 spring basins in the study area that were delineated through tracer tests and assessed for water quality. Table 3 shows the relative percentages of the three land cover categories used for each of these spring basins, along with the total drainage areas. Once again, agriculture is the dominant land cover type, seen in 8 out of 9 spring basins. The only deviation is in the Big Spring basin, which is located in downtown Princeton and drains the majority of that urban and residential area. Additionally, forested and agricultural areas are roughly equivalent in the Conway Springs basin.

Table 3. Land cover types and relative percentages within assessed spring basins.

Spring Name	AKGWA	Land Cover Category			Spring Basin Area (km^2)	Base Flow (L/s)
		% Urban/Res.	% Forest	% Agriculture		
Harpending	1823	4.6%	22.1%	72.5%	41.7	77
Wallace Branch	1855	8.7%	28.4%	62.6%	26.7	62
Mill Bluff	1825	5.4%	27.8%	66.4%	105.0	60
Martin	1855	4.7%	34.3%	60.6%	66.5	48
Puckett	1853	5.2%	39.0%	54.6%	40.9	40
Cohorn	3741	6.1%	33.2%	59.7%	37.0	37
Conway	3861	4.2%	47.3%	47.8%	27.7	31
Ruben Ray	3742	5.2%	18.9%	75.0%	11.7	28
Big	1145	39.0%	33.0%	27.9%	6.5	14

Groundwater Use

In general, groundwater production from wells varies widely according to the size of any enlarged water-filled fractures or conduits encountered by the well-bore and can range from less than a few liters per minute (Lpm) to more than one hundred Lpm (Lambert and Brown, 1963). Although their use is not extensive, the majority of water wells identified during the study are used for irrigation. A few wells found during this study had been used for domestic water supplies until municipal water became available in the area.

Springs developed on these thick and generally pure carbonate sedimentary rocks tend to have moderate base flow discharges, with the capacity for extremely high flows. However, springs located in the study area have smaller base flows than those of the Eastern Pennyrile Karst Region. Several springs located throughout the study area are utilized for irrigation and livestock watering. Agricultural-use water withdrawals were active in the Wallace Branch Spring (1855), Mill Bluff Spring (1825) and Martin Spring (3740) basins. Additionally, springs maintain flow in surface streams during the dry season and drought periods, and numerous agricultural-use stream withdrawals were noted throughout the study area. Agricultural water withdrawals do not require permitting or reporting, and therefore usage amounts are unknown. Hayes Spring, which is within a karst window in the Wallace Branch Spring basin, is the former public water supply for the town of Princeton, Kentucky in Caldwell County. The low-head dam and pump house from this operation are still located at the spring.

MATERIALS and METHODS

Introduction

Historical Nonpoint Source (NPS) groundwater assessments conducted by the DOW generally took one of two forms: 1) Thirty monitoring sites (wells and springs) spread throughout a major river basin, sampled quarterly over the course of one year, or 2) Fewer monitoring sites in a sub-region or watershed sampled at a greater frequency - 6 to 8 times - over the course of one year with the intent of creating a more statistically robust dataset. Samples were analyzed for a broad range of parameters including bulk parameters, major inorganic ions, nutrients, metals, pesticides, volatile organic compounds (VOCs) and occasionally bacteria. Both of these approaches served to increase knowledge of ambient groundwater conditions and impacts from NPS pollution. However, due to aspects such as sampling frequency and parameters analyzed, the data were not completely comparable to surface water data in the same watersheds.

As previously noted, groundwater and surface water are interconnected systems. These connections are especially pronounced in regions of well-developed karst drainage. Therefore, this project was designed to address discrepancies between surface water and groundwater data sets by integrating surface water assessment protocols into a groundwater study. Ultimately, the goal was to have these nine springs assessed and reported in the *Integrated Report to Congress on Water Quality in Kentucky*.

Groundwater quality sample results were compared to the Surface Water Standards found in 401 KAR 10:031 for Warm Water Aquatic Habitat and Primary Contact Recreation (LRC, 2007). The parameters assessed are shown in Table 4, which is a simplified checklist created for this project. Ten analytes are listed as "NO DATA" in the *Impairment Level* column. These analytes were not available for analysis through the state laboratory contracted by DOW. However, their omission did not preclude assessment. Physicochemical samples were collected monthly from each of the nine springs for twelve consecutive months beginning in October 2012 and ending in September 2013. Five bacteria samples were collected from each of the nine springs in a 30-day period during the month of August 2013.

Sample Collection Methods

Consistent with the division's other ambient groundwater monitoring efforts, samples of groundwater were collected at each spring and analyzed for major inorganic ions; nutrients; volatile organic compounds; total organic carbon; pesticides, including the most commonly used herbicides, insecticides and fungicides; and dissolved and total recoverable metals. The analytical methods, containers, volumes collected, preservation and sample transport are consistent with the DOW Kentucky Ambient/Watershed Water Quality Monitoring Standard Operating Procedure Manual, prepared by the Water Quality Branch (2002c). Parameters to be measured, volume required for analysis, container type and preservative are shown on the attached Chain-of-Custody Form (Appendix II).

Major inorganic ions are used to establish background groundwater chemistry and also to measure impacts from nonpoint source pollutants such as abandoned mine lands and abandoned hydrocarbon production operations by measuring pH, alkalinity, chloride, sulfate and fluoride. Nutrients and total organic carbon are used to measure impacts from agricultural operations (ammonia-N, nitrate-N, nitrite-N, total phosphorous and orthophosphate) and/or improper sewage disposal (nitrates, ammonia). Pesticides are measured to determine both rural agriculture and urban domestic-use and commercial-use impacts on groundwater. Metals are useful to establish rock-groundwater chemistry, local and regional background levels and to determine nonpoint source impacts from active or abandoned coal mining operations. Volatile organic compounds determine impacts from urban run-off, oil and gas production, and other point and nonpoint source impacts to groundwater.

Pathogen samples were collected, preserved and analyzed in accordance with the procedures outlined by the DOW, Groundwater Section's Pathogens in Ground Water SOP 104.1. These samples were analyzed for Total Coliform and *E. coli* bacteria, utilizing the Groundwater Section's mobile bacteria laboratory. Bacteria determine impacts from agricultural operations and failing septic and sewer systems. Bacteria sources could not be differentiated based on the analyses conducted. Parameters to be measured, volume required for analysis, container type and preservative are shown on the attached Chain-of-Custody Form (Appendix II). Bacteria sample results are reported as the Most Probable Number (MPN) of Colony Forming Units per 100 mL sample.

Benthic macroinvertebrate samples were collected using Hester-Dendy plate samplers. Each sampling unit consisted of three arrays of 15-plate columns. Sampling units were attached to cinder blocks and deployed in the spring runs for six weeks during March and April 2013. Specimens from the Hester-Dendy samplers were preserved in the field and returned to the laboratory for identification. Taxa were identified using Epler (1995), Thorp and Covich (2001), Stewart and Stark (2002), Merritt and others (2008) and Anderson and others (2013), according to DOW (2015) procedures. Taxonomic identification was predominantly done to the genus level; however, worms were left at the order level. Kruskal Wallis tests were used to examine differences in population densities per site, taxa richness per site and relationships to water quality parameters. Paired samples were collected at each spring using a multi-habitat jab net method. However, those samples could not be evaluated due to resource constraints. These data will be examined and compared to the Hester-Dendy samples at a future time.

All samples collected to meet grant commitments were analyzed by the Environmental Services Branch (ESB) and DOW laboratories according to appropriate U.S.EPA methods.

Graphical Methods

Maps created to display assessment results utilize graduated color points based on each spring's use support level. These are overlain on a simplified land use map with county boundaries, major surface streams, tracer test results and karst basin boundaries.

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 5. Tracer data and stream coverage 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. 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 300 m on each side of a mapped divide should be assumed to potentially drain to both associated basins.

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 lead author specifically for this project. In electronic versions of this report, all figures are accessible by clicking the blue reference "hyperlink". In paper reports these same figures are available in an addendum.

Site Selection

The Groundwater Section selected springs for monitoring based on numerous criteria. Preference was given to springs where dye trace data were sufficient to delineate the recharge area. Also, springs with larger base flow discharges were preferred. A spring's base flow *typically* varies directly with groundwater basin size; thus springs with larger base flows require assessment of larger basin areas. Several of these springs had been identified by previous researchers and some appear on the USGS 7.5-minute topographic and/or geologic maps.

Because this study was designed to assess ambient groundwater conditions, areas with known point source discharges were eliminated from consideration. For example, sites affected by leaking underground storage tanks or landfills were not sampled as part of this study. Finally, other important considerations included physical accessibility of the site and landowner permission to access sites located on private property.

A unique eight-digit identification number, called an AKGWA number, is assigned to each spring that is inventoried and maintained in DEP's 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 51 new springs and caves were added to the groundwater database as part of this project. Of those 51 new data points, 19 of them appeared on the USGS 7.5-minute quadrangle maps and 15 were referenced in other literature (WKSS, 2005).

Tracer Test Methods

Qualitative groundwater tracer tests, as described by Quinlan (1986) and Aley (2002), were conducted using five non-toxic fluorescent dyes. The names of dyes used in this study are shown in bold in Table 5:

Table 5. 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	14
Eosine	15189 Eosine OJ	Acid Red 87	13
Uranine (Fluorescein)	Uranine Conc (Disodium Fluorescein)	Acid Yellow 73	13
RWT (Rhodamine WT)	Keyacid Rhodamine WT	Acid Red 388	2
Pyranine	Solvent Green 7	D & C Green 8	1

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 60 g per liter.

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 1-1.5 L per kilometer of expected flow distance (equivalent to about 60-90 g of powdered dye per km). Depending on conditions, up to twice as much SRB and RWT 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 6).

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 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 7 to 14 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 7 shows a typical dye curve 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.

Documentation of Tracer Tests

During this project, 43 reconnaissance groundwater tracer tests were conducted for the purpose of basin delineation and verification or modification of inferred watershed boundaries. 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 during the study. The Dye Trace Record Forms for this study are available upon request.

TRACER TEST RESULTS

Seven Springs (3859) – Trigg County/Cobb 7.5-minute quadrangle

Seven Springs [N36.933768°/W87.800847°] is a series of gravity springs, discharging from the left bank on the downstream end of a large meander loop of the Muddy Fork of Little River. As implied by the name, during moderate flow conditions there are seven separate spring outlets. These are positioned about a meter or less above the stream level along a single horizon spanning roughly 120 m. When this spring was inspected and inventoried on September 18, 2007, only five of the seven spring outlets were active. During this visit pH, conductivity and temperature measurements were taken at each of the five active discharge points. Each of the parameters showed only minor variation between the springs, with pH ranging from 6.82 to 6.89 S.U.; conductivity ranging from 339 to 343 µS/cm; and temperatures ranging from 19.2° and 19.7° C – confirming that the springs are part of a distributary system. Combined flow of the five active springs was estimated at 14 L/s.

During this inspection, a strong odor of rotting flesh was noted, though no animal carcass was observed in the vicinity. Following the spring inspection, the upstream end of the meander loop was inspected for stream swallets or other sink points, with the hypothesis that Seven Springs was the discharge of a subterranean meander cutoff of the river. A large swallet [N36.936306°/WW87.796488°] was discovered at the upper end of the meander loop on the left bank (left or right bank is determined while facing downstream), submerged just below stream level. The swallet was roughly 500 m northeast of the spring. A deer carcass was caught in the swallet and all water entering the subsurface was flowing through and over it. Due to the proximity of the swallet, the presence of the deer carcass and the associated odor emanating from the springs, it was concluded that these factors constituted an adequate groundwater trace. Figure 8 shows the inferred subterranean meander cutoff of the Muddy Fork of Little River from Dead Deer Swallet to Seven Springs, with groundwater flow beneath the narrow dividing ridge.

Martin Spring (3740) – Caldwell County/Cobb 7.5-minute quadrangle

Martin Spring [N36.970278°/W87.782825°] is a large gravity spring located directly behind the owner's residence, just north of the Caldwell – Trigg county-line. This spring is mapped on the USGS 7.5-minute quadrangle maps, but its location is shown – incorrectly – just south of the county line. During base base-flow conditions this spring is the head of Kenady Creek, which is tributary to Muddy Fork of Little River. A series of five karst windows exposing trunk conduit flow are located directly upstream from the spring over a distance of 900 m. Van Couvering (1962) collected numerous flow measurements at this spring from 1955 to 1960. Combining Van Couvering's flow measurements with those collected by DOW prior to and for this study yields a base flow of 48 L/s. Van Couvering also hypothesized that the spring's drainage basin was "*…a long, narrow ridge between Kenady Creek and Little River.*" This is essentially an area trending north-northeast from the spring, which is roughly in line with the series of five karst windows. The WKSS (2005) has produced maps for the Harmony Church Cave, which is an extensive system located in the central and northern portions of Martin Spring basin. Dyas and Forsythe (1997) mapped a segment of Shoulders Cave [N36.974589°/W87.765037°], which is located on the right bank of Muddy Fork of Little River, approximately 1.6 km east-northeast of Martin Spring. Tracer tests showed that Shoulders Cave has a subsurface overflow connection with the Martin Spring system.

The five tracer tests used to delineate the Martin Spring basin were recovered at the spring and at nine other monitoring points within and adjacent to its karst watershed. Following the two initial tracer tests that established the trunk conduit flow route for this system, the series of five karst windows were no longer monitored in an attempt to save time and resources. Those dye injections and their results are summarized in Tables 6 – 10 and illustrated in Figure 9.

A sixth tracer test was conducted in an attempt to identify the location of the subsurface overflow connection to Shoulders Cave. This injection was made into the karst window furthest up-gradient in the series of five (Hoffman Karst Window-North) during high-flow conditions on January 16, 2010. That dye was not recovered at the Shoulders Cave monitoring sites. This demonstrated that the overflow connection was most likely up gradient of that point. The inferred location of the overflow, shown in Figure 9, is based on the results of this tracer test and the cave map completed by Dyas and Forsythe (1997).

Trace #09-09: Millwood Creek is a sinking stream that flows roughly south and sinks into an enlarged bedrock fracture located just north of Mashburn Road. Flow in this creek is intermittent and discharge reaching the terminal swallet is generally storm-related runoff. Surface flow beyond this blind valley is illustrated on the USGS 7.5-minute quadrangle maps, but was never observed.

Table 6. Millwood Creek sinking 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 (km)
Millwood Creek Sink N37.021631°/ W87.789256° Nov 5, 2009	Sinking Stream # 09-09	SRB-680g (*Natural flow-* 7 L/s)	**Martin Spring** N36.96981°/W87.782773°	6.2
			Cundiff Karst Window-South N36.97187°/W87.782497°	6.0
			Cundiff Karst Window-Central N36.974598°/W87.781536°	5.7
			Cundiff Karst Window-North N36.975221°/W87.780908°	5.6
			Hoffman Karst Window-South N36.976802°/W87.78101°	5.4
			Hoffman Karst Window-North N36.977797°/W87.780529°	5.3
			Turner Cave (*Harmony Church*) N37.002601°/W87.795563°	2.2
			Shoulders Cave (high flow only) N36.974589°/W87.765037°	6.9
			Fracture Spring (high flow only) N36.974064°/W87.763041°	7.2

Trace #09-10: Battle Creek is a sinking stream that flows generally southwest and sinks below a head wall at the terminus of a blind valley. The actual sinking point was obscured with fallen trees and terminal stream debris, and could not be observed. This perennial stream is fed by a small spring approximately 3 km upstream from the sink point. A flood-stage sinkhole complex is shared by Millwood and Battle Creeks during high-flow events and is illustrated on the USGS 7.5-minute quadrangle maps.

Table 7. Battle Creek sinking 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 (km)
Battle Creek Sink N37.023076°/ W87.787485° Nov 5, 2009	Sinking Stream # 09-10	Uranine-454g (*Natural flow-* 140 L/s)	**Martin Spring** N36.96981°/W87.782773°	6.3
			Cundiff Karst Window-South N36.97187°/W87.782497°	6.1
			Cundiff Karst Window-Central N36.974598°/W87.781536°	5.8
			Cundiff Karst Window-North N36.975221°/W87.780908°	5.7
			Hoffman Karst Window-South N36.976802°/W87.78101°	5.5
			Hoffman Karst Window-North N36.977797°/W87.780529°	5.4
			Turner Cave (*Harmony Church*) N37.002601°/W87.795563°	2.3
			Shoulders Cave (high flow only) N36.974589°/W87.765037°	7.0
			Fracture Spring (high flow only) N36.974064°/W87.763041°	7.3

Trace #10-09: Burns Creek is a losing stream that flows southwest to its confluence with the dry segment of Millwood Creek, at which point they form Kenady Creek. The creek is fed by Groom Spring, which appears on the USGS 7.5-minute quadrangle maps, located approximately 2.5 km upstream from the swallet. During base flow conditions all water sinks at Burns Creek Swallet. In moderate flow conditions, water bypassing the swallet is diverted to a cave a short distance to the west. Dyas (1978) notes this cave's location and gives a brief description. He also states that it, "*almost certainly resurges at Martin Spring*". Only during flood conditions does water continue downstream past the swallet.

Table 8. Burns Creek swallet dye trace summary (*karst windows up-gradient of Martin Sp not monitored)

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site* Lat/Long	Inferred Distance (km)
Burns Creek Swallet N36.99352°/ W87.787733° Aug 13, 2010	Losing Stream # 10-09	SRB-170g (*Natural flow-* 0.3 L/s)	**Martin Spring** N36.96981°/W87.782773°	2.8

Trace #10-10: Bridges Cave is located in the bottom of a sinkhole measuring 7800 m^2. The center of the sinkhole contains an elliptical pit into limestone bedrock that is 10 m long, 5 m wide and 10 m deep. The cave entrance is on the northeast end of the ellipse and is usually inundated with water to the top of the pit. Anecdotal evidence indicates that portions of this cave have been explored by canoeists during low water periods. This cave is also referred to as "Black Patch War Pit" (WKSS, 2005 p39).

Table 9. Bridges Cave dye trace summary (*karst windows up-gradient of Martin Sp not monitored)

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site* Lat/Long	Inferred Distance (km)
Bridges Cave N37.009343°/ W87.809242° Aug 27, 2010	Cave/Sinkhole # 10-10	Uranine-227g (*Natural flow-* Flooded cave)	**Martin Spring** N36.96981°/W87.782773° **Turner Cave (*Harmony Church*)** N37.002601°/W87.795563° **Jones Karst Window** N36.009819°/W87.800014°	5.6 1.6 0.8

Trace # 12-04: Hopson Sinkhole is located in a row crop field, adjacent to an access road. The sink has been backfilled with limestone cobbles to a reported depth of 5 m, with an orange plastic standpipe installed in the center to enhance subsurface drainage.

Table 10. Hopson Sinkhole dye trace summary (*karst windows up-gradient of Martin Sp not monitored)

Injection Site Name Lat/Long Date	Injection Site Type Trace #	Dye Type-Amount (Flush Water Amount)	Recovery Site* Lat/Long	Inferred Distance (km)
Hopson Sinkhole N37.010466°/ W87.831294° Feb 10, 2012	Sinkhole # 12-04	Eosine-680g (*Hauled water-* 1500 L)	**Martin Spring** N36.96981°/W87.782773°	7.3

Harpending Spring (1823) – Caldwell County/Princeton West 7.5-minute quadrangle

Harpending Spring [N37.03785°/W87.934026°] is a moderate sized spring with a small overflow spring located approximately 5 m to the south. The perennial spring rises from beneath a rock ledge from within a narrow alcove and then flows approximately 150 m to its confluence with Eddy Creek. This spring is mapped on the USGS 7.5-minute quadrangles as "*Harpending Springs*" near the left bank of Eddy Creek, about 800 m west of the intersection of SR 903 and SR 515. Van Couvering (1962) collected numerous flow measurements at this spring from 1955 to 1960, which he called "Harpending (Twin) Springs". Combining Van Couvering's flow measurements with those collected by DOW prior to and for this study yields a base flow of 77 L/s. This spring has the largest base flow discharge of any spring identified in the study area. Van Couvering also hypothesized that the *"[s]pring is fed by numerous small sinkholes on the plateau,"* referring to the karst plateau lying east of the spring. The spring is subject to ephemeral flooding due to its proximity to Lake Barkley. The three tracer tests described below were used to delineate the recharge area for Harpending Spring. The results of those tracer tests are summarized in Tables 11 – 13 and the map in Figure 10.

Trace # 11-19: The 139 Swallet is a low flow sink point of Dry Creek, approximately 350 m downstream from the KY 139 bridge. The stream bed is composed of large gravel and sand. The stream ceased flowing on the surface at a terminal swallet pool; flow entered the pool at 3 L/s.

Table 11. 139 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 (km)
139 Swallet N37.023574°/ W87.87783° Nov 4, 2011	Swallet # 11-19	Uranine-227g (*Natural Flow-* 3 L/s)	**Harpending Spring** N37.03785 °/W87.934026°	5.3

Trace # 11-20: Cook Brothers Sink is a small cover collapse sinkhole located northwest of HWY 1272, 1.5 km west of its intersection with KY 139. The sinkhole was being utilized to partially drain a farm pond about 260 m to the northeast. The farmer constructed a trench from the edge of the pond and installed drain tile leading to the sinkhole. This pond had been actively draining for approximately 2 days prior to the injection and was discharging 1.5 L/s when dye was introduced.

Table 12. Cook Brothers 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 (km)
Cook Bros. Sink N37.011484°/ W87.885449° Dec 2, 2011	Sinkhole # 11-20	Eosine-340g (*Natural Flow*- 1.5 L/s)	**Harpending Spring** N37.03785 °/W87.934026°	5.7

Trace # 12-05: Have-at-it Sinkhole is a large, wooded sinkhole on the east side of KY 139, 2.5 km north of the bridge over Dry Creek. A cover collapse had occurred in the bottom of the sinkhole, with evidence of recent surface runoff infiltrating at this point.

Table 13. Have-at-it 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 (km)
Have-at-it Sinkhole N37.046606°/ W87.879905° Feb 10, 2012	Sinkhole # 12-05	SRB-454g (*Hauled Water*- 750 L)	**Harpending Spring** N37.03785 °/W87.934026°	5.5

Sandhole Spring (3894) – Caldwell County/Princeton West 7.5-minute quadrangle

Sandhole Spring [N37.055867°/W87.926761°] is a small bluehole spring rising into Eddy Creek, just inside the left bank. This spring does not appear on the USGS quadrangle maps. During normal flow conditions the creek surface was typically up to 15 cm above the top of the submerged sand levee formed at the spring orifice. The light-colored bluehole of the spring was in stark contrast to the dark, tannic water in this section of Eddy Creek. Direct flow measurements were not taken at Sandhole Spring, but estimates made during dye receptor exchanges were generally in the 12-20 L/s range. Raymond Spring (3839) [N37.05756°/W87.927433°] is an overflow spring for this system and is located 225 m upstream and 3 m outside the left bank, but does not appear on the USGS maps.

The geologic quadrangle maps of the area show a mapped fault trending roughly east to west, crossing Eddy Creek in the location of Raymond Spring (Sample, 1965 and Trace, 1972). The fault line is shown to extend for several kilometers on each side of the creek. Faulting is obvious in the bedrock exposed in outcrops on the right bank of Eddy Creek directly opposite Sandhole and Raymond Springs. The eastern extension of this fault contains a small karst window (Bond Karst Window) and is in close proximity to the sinking stream at Travis Dairy described below. The single tracer test conducted for this spring system is summarized in Table 14. The map shown in Figure 11 includes a dashed black line for the mapped fault, with down-thrown (D) and up-thrown (U) sides marked. Based on the spring locations coinciding with faults, groundwater flow is inferred to follow the mapped fault line. This tracer test shows that the faults cutting through soluble, carbonate rocks can be transmissive.

Trace #10-03 and #10-03 Replication: Travis Dairy Sink is the terminal swallet of a small sinking stream. The stream flows roughly northwest to southeast, parallel to KY 128, near the small town of McGowan. The swallow hole is 4-5 m wide and 3 m deep into soil with a small bedrock conduit exposed in the base. Sandhole Spring had not been identified when the initial dye injection was conducted and it was assumed that Raymond Spring was the perennial, underflow spring for this system. When Raymond Spring was observed to stop flowing and was thus recognized as an overflow, further reconnaissance revealed Sandhole Spring. This dye trace was replicated with Sandhole Spring as a monitoring point to confirm its connection.

Table 14. Travis Dairy 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 (km)
Travis Dairy Sink N37.055107°/ W87.848806° Feb 12, 2010 Nov 17, 2011	Sinking Stream # 10-03 # 10-03 *Rep.*	Eosine-340g (*Natural Flow-* 7.0 L/s)	**Sandhole Spring** N37.055867 °/W87.926761° **Raymond Spring** N37.05756 °/W87.927433° **Bond Karst Window** N37.057121 °/W87.863637°	7.0 7.0 1.4

Displacement Spring (3846) – Caldwell County/Princeton West 7.5-minute quadrangle

Displacement Spring [N37.057469°/W87.928245°] is a small gravity spring that discharges from a mapped fault where it intersects the right bank of Eddy Creek. This spring is directly across Eddy Creek from Raymond Spring (3839). Several centimeters of fault displacement are apparent in the bedrock exposed around this spring, which is not mapped on the USGS 7.5-minute quadrangle maps. No direct measurements of the spring discharge were made, but base flow estimates were roughly 7 L/s. The single tracer test conducted for this spring is summarized in Table 15. The map shown in Figure 12 includes a dashed black line for the mapped fault, with down-thrown (D) and up-thrown (U) sides marked. Based on the spring location coinciding with the fault and the fault's proximity to the injection point, groundwater flow is inferred to follow the mapped fault line. This tracer test provides further evidence of faults cutting through soluble, carbonate rocks that are transmissive.

Trace # 11-12: Tays Sinkhole is located roughly 30 m east of Caldwell Chapel Road and 790 m south of its intersection with SR 293. The sinkhole is a cover collapse that is 3 m in diameter and 2 m deep, with a large open throat in the bottom. This tracer test was replicated several months later with Sandhole Spring (3894) monitored, but dye was not recovered at that site.

Table 15. Tays 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 (km)
Tays Sinkhole N37.060984°/ W87.964274° June 3, 2011	Sinkhole # 11-12	Uranine-227g (*Hauled Water-* 1500 L)	**Displacement Spring** N37.057469 °/W87.928245°	3.25

Wallace Branch Spring (1855) – Caldwell County/Princeton West 7.5-minute quadrangle

Wallace Branch Spring [N37.070627°/W87.929466°] is a large gravity spring that discharges from the base of a limestone bluff that is about 5 m high. The spring forms the head of Wallace Branch and flows roughly 1.5 km to its confluence with Eddy Creek. Two small, shallow karst windows are located nearly adjacent to the main spring. One of these karst windows is outfitted with a pump that withdrawals groundwater for irrigation. The spring is located approximately 6 km southwest of Princeton and 225 m south of SR 293. Previous flow measurements by DOW and those made for this study yield a base flow of 62 L/s for this spring. This spring is not mapped on the USGS 7.5-minute quadrangle maps. Hayes Spring (1343) [N37.084668°/W87.934252°] is a large karst window located 1.6 km north-northeast of Wallace Branch Spring. Hayes Spring, which is mapped on the USGS 7.5-minute quadrangles, was once used as a public water supply spring. The old pump house and dam are still intact next to the spring outlet. A few years prior to this study, a conduit-intercepting irrigation well was constructed approximately 100 feet east of the spring. On several occasions both Wallace Branch and Hayes springs were observed when both irrigation systems were actively withdrawing water. Although discharge was significantly diminished, neither spring ever ceased flowing.

Five tracer tests were utilized to delineate the drainage area for Wallace Branch Spring and four of these tracers were also recovered at Hayes Spring. Those tracer tests are summarized in Tables 16-20 and illustrated on the map in Figure 13. This figure also shows results of dye traces conducted by Dr. Ralph Ewers (Ewers, 1990) that were recovered at Big Spring (1145) and Lisbany Spring (3853) (aka Powerline Spring). These tracer tests show that the headwaters of Wallace Branch Spring and Big Spring are in the vicinity of the roughly east-west trending I-69 (former Western Kentucky Parkway). Any hazardous materials spilled on this section of I-69 pose a significant threat to these karst systems and their receiving stream, Eddy Creek. In addition, significant cave surveys have been conducted in both Big Spring (Ganter and others, 2005) and Lisanby Cave (Dyas and others, 2005). Both of these springs are mapped on the USGS 7.5-minute quadrangles, but no official name is given for Lisanby Spring.

The Princeton West 7.5-minute Geologic Quadrangle Map (Sample, 1965) shows faults trending generally parallel to the interstate corridor, just north of dye injection sites, forming a minor dropped-down block. These faults are the western extensions of the Bishop and Crabtree faults, mapped on the Dawson Springs 7.5-minute Geologic Quadrangle Map (Kehn, 1966). The faults cut through the St. Louis and Ste. Genevieve limestones, both highly soluble, karst-forming carbonate rock units. Furthermore, this fault zone can be seen on the map in Figure 2, overlain with sinkhole occurrence, trending from Eddyville to the north side of Princeton. The map shows that sinkholes are not present throughout the majority of this fault zone. These faults are shown on Figure 13, with down-thrown (D) and up-thrown (U) sides marked. This would seem to indicate faulting through carbonates that has formed a subsurface hydrologic boundary, which is counter to the hypothesis of transmissive faults.

Trace #11-04: Young Swallet is an intermediate sink point near the center of a blind valley formed by a minor unnamed stream. The sink point is a soil collapse measuring 2 m wide, 4 m long and 2 m deep. The swallet is only 300 m south of the Western Kentucky Parkway, and roughly 7 km west of Princeton. While there was evidence of a surface overflow channel beyond this swallet, no bypassing water was ever observed.

Table 16. Young 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 (km)
Young Swallet N37.108115°/ W87.962194° Mar 11, 2011	Sinking Stream # 11-04	Uranine-142g (*Natural Flow-* 1.5 L/s)	**Wallace Branch Spring** N37.070627 °/W87.929466° **Hayes Spring** N37.084668°/W87.934252°	5.5 3.9

Trace # 11-06: Old Wheatley Lane Sinkhole is a medium-sized cover collapse located adjacent to the intersection of Old Wheatley Lane and KY 1495. A culvert draining from the west, under Old Wheatley Lane, pours directly into the sinkhole. Attempts had been made to backfill the sinkhole with shot-rock, but it still presents a threat to road stability.

Table 17. Old Wheatley Lane 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 (km)
Old Wheatley Ln Sinkhole N37.094522°/ W87.91505° Mar 25, 2011	Sinkhole # 11-06	SRB-170g (*Hauled Water-* 750 L)	**Wallace Branch Spring** N37.070627 °/W87.929466°	3.1

Trace # 11-07: Tollgate Swallet is the terminal sink point of a blind valley with ephemeral flow. All flow enters the subsurface through a small conduit opening at the base of a 4-m high limestone bluff. The swallet is located approximately 4 km west of Princeton and 125 m south of Interstate-69 (former Western Kentucky Parkway), near the former tollgate booth.

Table 18. Tollgate 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 (km)
Tollgate Swallet N37.114461°/ W87.92598° Apr 22, 2011	Sinking Stream # 11-07	Eosine-397g (*Natural Flow-* 43 L/s)	**Wallace Branch Spring** N37.070627 °/W87.929466°	5.2
			Hayes Spring N37.084668°/W87.934252°	3.6

Trace # 11-08: Training Center Sinkhole is a relatively small sinkhole, measuring 3 m in diameter and 1 m deep, with a bedrock conduit exposed in the bottom. The sinkhole is located near the entrance of the Caldwell County Fire Training Center, 100 m south of US 62 and 4 km west of Princeton.

Table 19. Training Center 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 (km)
Training Center Sinkhole N37.107776°/ W87.927368° Apr 22, 2011	Sinkhole # 11-08	RWT-198g (*Natural Flow-* 1 L/s)	**Wallace Branch Spring** N37.070627 °/W87.929466°	4.5
			Hayes Spring N37.084668°/W87.934252°	2.8

Trace #12-06: Howton Swallet is an intermediate sinking point of a small, ephemeral stream. The swallet is formed in a soil collapse that is 3 m in diameter and 2 m deep. When the swallet is inundated, surface overflow bypasses to the terminal swallet a few hundred meters to the south. Howton Swallet is located 150 m south of US 62 and approximately 7.5 km west of Princeton.

Table 20. Howton 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 (km)
Howton Swallet N37.103815°/ W87.969057° Feb 16, 2012	Sinking Stream # 12-06	SRB-454g (*Natural Flow-* 1 L/s)	**Wallace Branch Spring** N37.070627 °/W87.929466° **Hayes Spring** N37.084668°/W87.934252°	5.8 4.2

Cohorn Spring (3741) – Lyon County/Fredonia 7.5-minute quadrangle

Cohorn Spring [N37.142708°/W88.108847°] is a large spring directly adjacent to the right bank of Skinframe Creek-west. It is located roughly 6 km north-northwest of Eddyville and 1 km upstream of the SR 1943 bridge over Skinframe Creek-west. The spring has both gravity and rising discharge points that are perennial. The gravity discharge issues from a large conduit at the base of a 2-m high limestone outcrop. The rising discharge creates a boil in the creek roughly 2 m from the gravity spring. The spring's proximity to the creek makes it difficult to recognize in base flow conditions and it can easily be submerged during floods. Previous flow measurements by DOW and those made for this study yield a base flow of 37 L/s for this spring. Cohorn Spring is not mapped on the USGS 7.5-minute quadrangle maps.

The work conducted by Plebuch (1976) resulted in a groundwater level contour map for the area surrounding Princeton, Kentucky in Caldwell County. In particular, the northwestern portion of that map shows a significant trough in the water table surface from the general area of the Western Kentucky Correctional Complex to Skinframe Creek-west and Cohorn Spring. Though it is not explicitly stated as a hypothesis for groundwater flow in the Cohorn Spring basin, it was used as a guide when searching for potential injection points.

The six tracer tests conducted to delineate this karst basin are summarized in Tables 21-26 and illustrated on the map in Figure 14. One of those dye traces was also recovered at Sutton Spring (3853) [N37.133196°/W88.094703°], which is a small bluehole on the left bank of Skinframe Creek-west. This spring is located about 2 km upstream of Cohorn Spring. Approximately 300 m downstream from Sutton

Spring is a large swallet on the right bank of Skinframe Creek-west. This swallet creates a subterranean cutoff from Skinframe Creek-west to Cohorn Spring, capturing some discharge from Sutton Spring. A second, minor spring located on Livingston Creek, just upstream of the Tabor Road bridge appears to have an overflow connection to the Cohorn Spring basin. Four of the dye traces recovered at Cohorn Spring were also recovered at Bennett Spring (3983) [N37.157241°/W88.115876°], but three of the recoveries were generally weak positives or inconclusive results. Therefore, the overflow connection is represented with a question mark in the appropriate tables below to indicate the tentative nature of those results.

Trace # 11-18: Powerline Sinkhole is a small cover collapse in a row crop field. It is located about 600 m south-southwest of the intersection of SR 1943 and Bennett Jones Road, almost directly beneath a power line.

Table 21. Powerline 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 (km)
Powerline Sinkhole N37.138877°/ W88.079026° Oct 7, 2011	Sinkhole # 11-18	Uranine-227g (*Hauled Water-* 750 L)	**Cohorn Spring** N37.142708 °/W88.108847° **Bennett Spring** N37.157241°/W88.115876°	2.8 4.5

Trace 12-02: Cash Swallet is a moderate to low flow sink point on Skinframe Creek-west, located 75 m downstream of the US 641 bridge. This losing reach is characterized by a streambed composed of large gravel and sand, and may extend for 200 m depending upon flow conditions. During base flow conditions it is fed by Cash Spring (2554) [N37.119528°/W88.059972°]. This minor spring is about 1.5 km upstream of the US 641 bridge.

Table 22. Cash 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 (km)
Cash Swallet N37.128643°/ W88.070296° Jan 13, 2012	Losing Stream # 12-02	Eosine-454g (*Natural Flow-* 28 L/s)	**Cohorn Spring** N37.142708 °/W88.108847° **Bennett Spring (?)** N37.157241°/W88.115876°	3.8 5.5

Trace # 12-07: Field 13 Swallet is part of a large swallet complex in the upper reaches of the Skinframe Creek-west. This is an ephemeral reach of the creek and flow duration is storm-related. The swallet and most of its drainage area are located on the Western Kentucky Correctional Complex property.

Table 23. Field 13 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 (km)
Field 13 Swallet N37.144858°/ W88.043458° Mar 9, 2012	Sinking Stream # 12-07	SRB-454g (*Natural Flow-* 57 L/s)	**Cohorn Spring** N37.142708 °/W88.108847° **Bennett Spring (?)** N37.157241°/W88.115876°	6.2 7.8

Trace # 12-08: Field 1 Collapse is a large cover collapse near the middle of a row crop field on the Western Kentucky Correction Complex property. The diameter is roughly 5 m, but the depth was undetermined due to backfilling with gravel and debris. The cover collapse receives sheet flow runoff from the surrounding field.

Table 24. Field 1 Collapse 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 (km)
Field 1 Collapse N37.150067°/ W88.045234° Mar 9, 2012	Sinkhole # 12-08	Eosine-454g (*Natural Flow-* 7 L/s)	**Cohorn Spring** N37.142708 °/W88.108847° **Bennett Spring (?)** N37.157241°/W88.115876°	6.4 8.0

Trace # 12-09: Martin Swallet is the terminus of a large blind valley and is located 1 km southeast of the intersection of SR 373 and Bennett Jones Road. Flow in this valley is ephemeral and the swallet is subject to inundation and flooding for long periods following storm events.

Table 25. Martin 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 (km)
Martin Swallet N37.121014°/ W88.098489° Mar 9, 2012	Sinking Stream # 12-09	Uranine-227g (*Natural Flow-* 21 L/s)	**Cohorn Spring** N37.142708 °/W88.108847° **Sutton Spring** N37.133196°/W88.094703°	3.1 1.4

Trace # 13-04: Oak Grove Loop Sinkhole is a large sinkhole located adjacent to the south side of SR 1943. It is approximately 500 m east of the western intersection of Oak Grove Loop and SR 1943 and 3.5 km northwest of SR 1943's intersection with US 641. The sinkhole contains a swallow hole that is roughly 5 m long and 1 m wide, and drains through a near-vertical shaft in the soil and bedrock.

Table 26. Oak Grove Loop 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 (km)
Oak Grove Loop Sinkhole N37.152499°/ W88.096776° Feb 21, 2013	Sinkhole # 13-04	Eosine-227g (*Natural Flow-* 21 L/s)	**Cohorn Spring** N37.142708 °/W88.108847° **Bennett Spring (?)** N37.157241°/W88.115876°	2.0 3.8

Trace # 12-10: Following multiple apparent dye recoveries at Bennett Spring, it was hypothesized that it may be a partial subterranean cutoff of Skinframe Creek-west downstream of Cohorn Spring. However, no swallet could be identified on this reach of creek despite several attempts. Therefore, a simple tracer test was conducted by introducing about 65 g of Eosine into Skinframe Creek-west at the point where Cohorn Spring discharges. No dye was recovered at Bennett Spring, and it was therefore assumed that Bennett Spring has a subsurface overflow connection to the Cohorn Spring's trunk conduit. This dye introduction point is not illustrated on the tracer map for Cohorn Spring. The fact that Bennett Spring has a relatively minor flow suggests that its overflow conduit has a constricted capacity.

Ruben Ray Spring (3742) – Caldwell County/Fredonia 7.5-minute quadrangle

Ruben Ray Spring [N37.184334°/W88.08343°] discharges from a large conduit at the base of a 5-m limestone bluff about 15-20 m off the left bank of Livingston Creek. This is gravity spring, discharging from beneath a rock ledge. However, the spring run has filled with sand and sediment, in effect creating a dam and a pool. This has submerged the spring under 2-3 m of water, creating the appearance of a rising, or bluehole, spring. The spring is located about 3.25 km southwest of Fredonia, Kentucky at the end of a farm road off of Mill Bluff Lane. The spring does not appear on the USGS maps and is not discussed in any of the literature reviewed for this study. A limited number of flow measurements collected for this study indicate that this spring's base flow is 28 L/s. This is a significant portion – nearly 1/3 – of the base flow in Livingston Creek at that point.

The four tracer tests used to delineate this spring basin are summarized in Tables 27-30 and illustrated on the map in Figure 15.

Trace # 11-17: Ike's Sinkhole is a small cover collapse within a large sinkhole on the southern end of a row crop field. It is located adjacent to the north side of Coleman-Doles Road, about 380 m west of its intersection with US 641.

Table 27. Ike's 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 (km)
Ike's Sinkhole N37.163127°/ W88.056584° Oct 7, 2011	Sinkhole # 11-17	SRB-227g (*Hauled Water-* 1500 L)	**Ruben Ray Spring** N37.184334°/W88.08343°	3.6

Trace # 12-03: Thorny Sinkhole is a small cover collapse that is part of a large compound sink covering several hectares. The collapse created a drain that is nearly 1 m in diameter and extends 2-3 m into the subsurface before turning out of sight. It is located on the southern edge of a crop field about 1.3 km southwest of Ike's Sinkhole and 0.9 km west of US 641.

Table 28. Thorny 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 (km)
Thorny Sinkhole N37.155365°/ W88.06729° Feb 12, 2012	Sinkhole # 12-03	Uranine-454g (*Hauled Water-* 1500 L)	**Ruben Ray Spring** N37.184334°/W88.08343°	3.6

Trace # 13-01: Patton Pond Sinkhole is one of numerous cover collapses located within a large sinkhole on the eastern end of Oak Grove Loop. It is located inside Oak Grove Loop about 725 m north of its eastern intersection with SR 1943. The sinkhole is adjacent to the southern end of the pond on the Patton property.

Table 29. Patton Pond 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 (km)
Patton Pond Sinkhole N37.155149°/ W88.081496° Jan 25, 2013	Sinkhole # 13-01	SRB-397g (*Hauled Water-* 1500 L)	**Ruben Ray Spring** N37.184334°/W88.08343°	3.5

Trace # 13-02: Patton House Sinkhole is one of several small cover collapses within a broad, shallow sinkhole behind the Patton house. It is located inside Oak Grove Loop about 1.1 km north of its eastern intersection with SR 1943.

Table 30. Patton House 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 (km)
Patton House Sinkhole N37.158225°/ W88.080967° Jan 25, 2013	Sinkhole # 13-02	Uranine-227g (*Hauled Water-* 1500 L)	**Ruben Ray Spring** N37.184334°/W88.08343°	3.2

Mill Bluff Spring (1825) – Caldwell County/Fredonia 7.5-minute quadrangle

Mill Bluff Spring [N37.189992°/W88.073043°] is a large cave spring discharging from the base of a 20-m limestone bluff at the head of a pocket valley. The cave mouth is roughly 50 m wide with two main passages whose ceilings are at least 3m high. The northern passage is an overflow route that can have seasonal and storm-related discharge. The southern passage is perennial, but does not discharge water during base flow. Instead, a large pool forms just inside the southern passage and discharge is diverted to a number of small springs issuing from talus 10 m downstream from the cave mouth on the left bank of the spring run. The spring run meanders westward for 1.25 km to its confluence with Livingston Creek. During base flow conditions Mill Bluff Spring forms the head of Livingston Creek. This spring is located about 2 km south of Fredonia, Kentucky just below a tight curve in Mill Bluff Lane. This spring does not appear on the USGS maps, but the area is labeled as "The Bluff".

Van Couvering (1962) collected numerous flow measurements at this spring, which he called "Bluff Spring", from 1952 to 1960. Combining Van Couvering's flow measurements with those collected by DOW prior to and for this study yields a base flow of 60 L/s. Van Couvering hypothesized that the spring was fed by the unnamed stream that sinks into a large cave swallet 0.9 km due east. The stream shown on the USGS maps is ephemeral and contributes drainage to the cave swallet only during runoff events. The cave swallet is within White Karst Window (3855) [N37.190154°/W88.061347°], and its spring discharge provides perennial flow to the karst system. The spring run through this karst window is impounded by a low-head dam, forming a pool from which water is withdrawn for irrigation.

Van Couvering's flow hypothesis was confirmed by cave survey in 1978 (Dyas and others, 1997). The survey team mapped nearly 1 km of cave trunk, from the mouth eastward, and were forced to stop where the passage became water-filled. This point is perhaps tens of meters shy of connecting with the sink point of the stream described by Van Couvering. Adding side passages and dry routes, the team mapped a total of nearly 2.5 km of cave. In an early description of the cave, Dyas (1978) notes a side passage from the north and states, "[*t*]*his may represent the trunk of Sinking Fork of Livingston*

Cr[*eek*]…" This is a minor sinking stream located a few kilometers east of Fredonia, Kentucky. Confirmation of this flow hypothesis is described below.

Several other caves in the southern headwaters of the Mill Bluff Spring basin have been surveyed and/or described, including Crider Mill Cave, McElroy Cave, Phelps Cave, Skinframe Sinks Cave and Skinframe Log Jam Cave. All of these were hypothesized to drain to Mill Bluff Spring by members of the WKSS (Dyas, 1978). Those flow hypotheses were confirmed by the tracer tests described below. A sketch of the Skinframe Sinks Cave, which was used to illustrate a segment of a dye trace discussed below, was provided by Mr. Doug Carroll (WKSS member). However, the entire survey team is unknown and the cave sketch is therefore referenced based on the description from Dyas (1978).

The four tracer tests used to delineate this spring basin are summarized in Tables 31-34 and illustrated on the map in Figure 16. Additionally, a section of the Tabb Fault System is shown on the Fredonia 7.5-minute Geologic Quadrangle Map (Rogers and Hays, 1967). A generalized representation of the fault zone is included on the tracer map with down-thrown (D) and up-thrown (U) sides marked. The fault system trends roughly east-west and forms a prominent ridge that is the northern boundary of the Fredonia Valley. The St. Louis Limestone is mapped on the south side of the faults and younger, less-soluble sandstone and shale units are mapped on the north side. These data indicate that the fault is acting as a hydrologic boundary, as suggested by previous researchers.

Trace # 11-13: Union Grove Swallet is a low-flow swallet on the Sinking Fork of Livingston Creek, located just a few meters west of Union Grove School Road. This swallet is approximately 1 km upstream of the terminal swallet for Sinking Fork of Livingston Creek shown on the USGS maps. This trace confirmed the flow hypothesis made by Dyas (1978).

Table 31. Union Grove 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 (km)
Union Grove Swallet N37.214611°/ W88.023692° Jun 16, 2011	Sinking Stream # 11-13	Eosine-454g (*Natural Flow*- 3 L/s)	**Mill Bluff Spring** N37.189992°/W88.073043° **Hooks Karst Window** (overflow) N37.208787°/W88.03009°	5.7 0.8

Trace # 11-14: Skinframe Log Jam Cave is a very large swallet, roughly 8-10 m deep and covering an area of nearly 1000 m^2. The swallet captures surface overflow from Skinframe Creek-east, but is dry during base flow conditions. When this swallet is inundated, surface overflow is directed to the terminal sink point of the creek at Skinframe Sinks Cave, about 1.4 km to the west. While the cave sketch obtained from Mr. Carroll does not have these two caves connected, it does show the mapped cave within 200 m of the swallet. Therefore, flow of tracer dye through that area is illustrated as following the cave map. The segment of cave extending south to the sink point of Brewster Creek is also included. This dye trace shows that Skinframe Creek-east is entirely diverted northward, in the subsurface, to Mill Bluff Spring. Furthermore, it confirms flow hypotheses from members of the WKSS (Dyas, 1978).

Table 32. Skinframe Log Jam 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 (km)
Skinframe Log Jam Cave Swallet N37.149103°/ W88.006556° Jun 28, 2011	Sinking Stream # 11-14	Uranine-397g (*Natural Flow*- 142 L/s)	**Mill Bluff Spring** N37.189992°/W88.073043° **White Karst Window** N37.190154°/W88.061347°	8.6 7.5

Trace # 11-16: Hooks Karst Window is a relatively deep, narrow, and steep-sided feature. It is located in a wooded area surrounded by row crops on the south side of KY HWY 70 about 2 km east of Fredonia, Kentucky. Dye injected at Union Grove Swallet was weakly recovered at this site, and therefore was considered to have an overflow connection. Dye was injected at Hooks Karst Window to determine if its flow was tributary to the northern passage that bypasses White Karst Window. The results in Table 33 show that dye was only recovered at Mill Bluff Spring and that drainage from this site does not pass through White Karst Window.

Table 33. Hooks 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 (km)
Hooks Karst Window N37.208787°/ W88.03009° Oct 6, 2011	Karst Window # 11-16	Eosine-142g (*Natural Flow-* 4 L/s)	**Mill Bluff Spring** N37.189992°/W88.073043°	5.0

Trace # 12-01: One Tree Sink is a relatively small sinkhole located on the east side of US 641 about 4 km south-southeast of Fredonia, Kentucky. The sinkhole is about 30 m in diameter and 4-5 m deep with numerous soil collapses around a single tree. The sinkhole is about 500 m west-southwest of the Fredonia Quarry, where mining operations reportedly encountered a large conduit several decades ago. This conduit is reported to carry perennial flow, but the quarry manager would not allow access due to safety concerns. This tracer test was conducted to determine if the quarry had intercepted trunk flow to Mill Bluff Spring, or if the area might drain to Ruben Ray Spring.

Table 34. One Tree 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 (km)
One Tree Sink N37.170062°/ W88.040842° Jan 12, 2012	Sinkhole # 12-01	SRB-680g (*Hauled Water-* 750 L)	**Mill Bluff Spring** N37.189992°/W88.073043° **White Karst Window** N37.190154°/W88.061347°	4.3 3.1

Conway Springs (3861) – Crittenden County/Fredonia 7.5-minute quadrangle

Conway Springs [N37.192653°/W88.100335°] is a distributary system that discharges from multiple points along 20 m of the right bank of the Dry Fork of Livingston Creek. The primary outlet is a bluehole spring that rises in the creek. Several small gravity springs are located downstream of the bluehole. During base flow conditions this distributary is the head of Dry Fork. The bluehole and gravity springs were monitored for each dye trace to confirm that this is a perennial distributary system. A limited number of flow measurements collected for this study indicate that the springs' base flow is 31 L/s. The springs are located roughly 4 km west-southwest of Fredonia and 1.75 km upstream of the SR 902 bridge over Dry Fork. The springs do not appear on the USGS maps and are not discussed in any of the literature reviewed for this study.

The roughly east-west trending Tabb Fault System is about 3 km north of the springs. As previously noted, the St. Louis Limestone is mapped south of the fault and various sandstone and shale units occur north of the fault. Considering this along with the tracer data, it is assumed that the fault marks the northern end of the spring basin boundary. Numerous historic mineral mines are located on the fault zone in this area. Most of these were likely just open-pit workings, but some may have significant mined-out tunnels. What influence this might have on local or regional groundwater flow is unclear.

The three tracer tests used to determine this spring's recharge area are summarized in Tables 35-37 and illustrated on the map in Figure 17.

Trace # 12-11: Parish Sinkhole is a medium-sized sinkhole with a cover collapse that is 2-3 m in diameter and a little over 1 m deep. The sinkhole is located about 600 m east of SR 855 South and 1 km south of the Tabb Fault System at the end of a farm road.

Table 35. Parish 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 (km)
Parish Sinkhole N37.206147°/ W88.125817° May 4, 2012	Sinkhole # 12-11	SRB-284g (*Hauled Water*- 1500 L)	**Conway Springs** N37.192653°/W88.100335°	2.9

Trace # 12-21: Parish Cabin Sinkhole is a large sinkhole with a central cover collapse that has been backfilled with limestone cobble. The backfilled area has a steel standpipe that is roughly half a meter in diameter and extends to an unknown depth. Recent minor surface collapses were observed in this area.

This trace is notable because it passed beneath intermittent Caldwell Spring Creek, en route to Conway Springs, inferring that the headwaters of Caldwell Spring Creek also drain to Conway Springs.

Table 36. Parish 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 (km)
Parish Cabin Sinkhole N37.190819°/ W88.090236° Nov 2, 2012	Sinkhole # 12-21	Uranine-170g (*Hauled Water-* 1500 L)	**Conway Springs** N37.192653°/W88.100335°	3.6

Trace # 13-03: Feeder Swallet is a bedrock swallet on the right bank of Dry Fork at the base of a 3-m high limestone outcrop. Numerous dissolution-enlarged fractures were evident at the base of the outcrop and flowing water could be heard from within each of them. Only a fraction of the water flowing down the creek was observed being diverted into the subsurface.

Table 37. Feeder 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 (km)
Feeder Swallet N37.20799°/ W88.11012° Feb 7, 2013	Stream Swallet # 13-03	SRB-170g (*Natural Flow-* 3 L/s)	**Conway Springs** N37.192653°/W88.100335°	2.1

Doan Spring (1854) – Crittenden County/Dycusburg 7.5-minute quadrangle

Doan Spring [N37.227479°/W88.174574°] is a relatively small spring issuing from the base of a steep limestone slope that is roughly 50 m high. The spring discharges through large talus boulders at the toe of the slope. A small cave entrance in the form of a high, narrow fracture can be accessed on the south side of the spring. The land owner reported that this opens up into a large cave, but it has not been surveyed. Limited flow measurements by the USGS (Lambert and Brown, 1963) and DOW indicate that this spring's base flow is about 7 L/s. This spring is located 3 km west-northwest of Frances, Kentucky and appears on the USGS 7.5-minute quadrangle maps. The spring run, called Doan Spring Creek, flows 1.7 km to its confluence with Claylick Creek.

Doan Spring has formed on the Hodge Fault System, as shown on the USGS Dycusburg 7.5-minute Geologic Quadrangle Map (Amos and Hayes, 1974). The fault zone trends southwest to northeast and is dotted with historic mineral mines and pits. Again, what influence these mines might have on local or regional groundwater flow is unclear. This is part of a much larger, complex fault zone near the point where Hodge Fault joins the Mexico and Tabb fault systems. The St. Louis Limestone is mapped on the north side of the Hodge Fault, while younger sandstone and shale units are mapped on its south side.

The one tracer test recovered at this spring is summarized in Table 38 and illustrated on the map in Figure 18. A generalized representation of the fault zone is included on this map with down-thrown (D) and up-thrown (U) sides marked.

Trace # 12-18: Frances Road Swallet is a low-flow sink point of a minor, unnamed sinking stream. A small spring discharges from the right bank of the creek just upstream of Frances Road. During low flow events, the water flows through the culvert near the intersection of Frances Road and KY HWY 855 North, and forms the swallet pool directly downstream of the road culvert. Under moderate- to high-flow conditions, the creek flows on to a terminal swallet that is mapped directly on top of the Hodge Fault System (Amos and Hayes, 1974). Although the injection was made during low flow, a moderate rain and runoff event occurred within a few hours. Therefore, it was concluded that this tracer followed or paralleled the fault, which is counter to the hypothesis regarding groundwater flow along faults in this setting.

Table 38. Frances Road 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 (km)
Francis Road Swallet N37.238279°/ W88.154963° Sep 6, 2012	Sinking Stream # 12-18	SRB-227g (*Natural Flow-* 2 L/s)	**Doan Spring** N37.227479°/W88.174574°	2.3

Puckett Spring (1853) – Livingston/Crittenden counties/Dycusburg 7.5-minute quadrangle

Puckett Spring [N37.234474°/W88.200454°] is a large gravity spring issuing from the base of a 10-m high limestone bluff. The spring issues from beneath a rock ledge that is 6 m wide and perhaps 1 m high. During low water conditions, it is possible to access a cave system through this entrance. The spring's dual county location is because it was used as a landmark for the border of Livingston and Crittenden counties. From the spring southward, its spring run is also employed as the county line. This spring appears on the USGS maps about 100 m south of the intersection of Claylick Creek Road, Emmaus Church Road and Butler Road.

Van Couvering (1962) collected numerous flow measurements at this spring from 1953 to 1960. He hypothesized that the spring was "*fed by numerous small sinks and by Dry Creek, which enters sink 1 mile* [1.6 km] *to NW.*" Combining Van Couvering's data with flow measurements from Lambert and Brown (1963) and from DOW prior to and for this study yields a base flow of 40 L/s.

Shelbys Cave (3896) [N37.237444°/W88.21143°] also appears on the USGS maps 1 km west-northwest of Puckett Spring. A portion of this cave was mapped by members of the WKSS in 1988 (Bryan and others, 2005). A single flow measurement was made in this cave by DOW for this project on the same day that Puckett Spring was gaged. Results indicated that this cave represents the trunk of the system and it was carrying roughly 65% of the discharge measured at Puckett Spring.

Puckett Spring is located between the Claylick and Moore Hill fault systems, which trend northeast to southwest through the region (Amos and Hays, 1974). The fault systems are roughly parallel and separated by 2.5 km of sinkhole plain-type terrain. Both of these fault systems are very complex and contain numerous secondary faults. Soluble carbonate rocks occur on both sides of each fault zone and the Ste. Genevieve Limestone is mapped between them, coincident with the Puckett Spring basin. However, the interior of each fault zone shows considerable displacement with many areas of limestone juxtaposed with less-soluble sandstone and shale. While the Puckett Spring basin is bound geographically by these fault zones, it is unclear if these zones also represent subsurface hydrologic boundaries. This is because no viable dye injection points could be located within the fault zones to test flow connections. However, several streams cross these fault zones with no signs of infiltration or groundwater discharge, which suggests fault-line boundaries to groundwater flow.

The three tracer tests used to delineate Puckett Spring basin are summarized in Tables 39-41 and illustrated on the map in Figure 19. A generalized representation of the fault zones is included on this map with down-thrown (D) and up-thrown (U) sides marked.

Trace # 12-12: Cox Karst Window is one of several minor cave entrances and karst windows located in the vicinity of the sink points mapped for Cox Spring Branch and Dry Creek. Both of these creeks flow southward and have terminal sink points 500 m and 200 m, respectively, due west of Shelbys Cave. Cox Karst Window is located in an area of cover collapses and high-flow sink points shared by these two creeks.

Table 39. Cox 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 (km)
Cox Karst Window N37.23716°/ W88.217107° Jul 27, 2012	Karst Window # 12-12	SRB-227g (*Natural Flow-* Amount unknown)	**Puckett Spring** N37.234474°/W88.200454° **Shelbys Cave** N37.237444°/W88.21143°	1.6 0.6

Trace # 12-17: Maddux Sinkhole is a relatively small feature, with a deep, narrow slot canyon-type sink point in the bedrock. It is located due south of Pinckneyville Church, just 5 m south of Maddux Loop Road. It is one of many smaller depressions within a large compound sink encompassing the Pinckneyville area.

Table 40. Maddux 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 (km)
Maddux Sinkhole N37.21651°/ W88.246417° Aug 24, 2012	Sinkhole # 12-17	Eosine-227g (*Hauled Water-* 750 L)	**Puckett Spring** N37.234474°/W88.200454° **Shelbys Cave** N37.237444°/W88.21143°	5.1 4.1

Trace # 12-19: Asbridge Sinkhole is a small cover-collapse sinkhole near the intersection of McClure Road and Kitchen Road. Located at the north end of a large pond, it receives occasional recharge from its overflow. The sinkhole is approximately 150 m north of the Claylick Fault System.

Table 41. Asbridge 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 (km)
Asbridge Sinkhole N37.211992°/ W88.228852° Sep 7, 2012	Sinkhole # 12-19	Uranine-170g (*Hauled Water-* 750 L)	**Puckett Spring** N37.234474°/W88.200454°	4.4
			Shelbys Cave N37.237444°/W88.21143°	3.4

Tracer Tests Not Recovered

Of the 43 tracer tests conducted for this study, 38 were recovered for an 88% success rate. Only five dye injections were not recovered. Multiple dye injections were made at two of the failed injection sites that seemed most promising. Due to non-recovery of dye and site characteristics, three of the sites were determined to be inadequate injection points and replications were not attempted. These five sites are summarized below, but are not presented on any maps.

Trace #10-01: Otter Sinkhole [N37.029313°/W87.823942°] is a large sinkhole with numerous cover collapses and is located 10 km south-southeast of Princeton, Kentucky. This sinkhole was hypothesized to either drain southward to Martin Spring (3740) or westward to Harpending Spring (1823). Two separate dye injections with hauled flush water were made and a total of 31 spring and stream sites were monitored.

Trace # 11-05: Cedar Hill Cemetery Sinkhole [N37.112497°/W87.872321°] is a small sinkhole on the edge of Cedar Hill, on the east side of Princeton, Kentucky. This sinkhole was hypothesized to drain southward to either Big Spring (1145) or Trailer Park Spring (3852) [N37.105724°/W87.878939°]. Only one dye injection with hauled flush water was attempted at this site and 10 spring and stream sites were monitored.

Trace # 11-15: Hopson Swallet [N36.975436°/W87.82412°] is a low-flow sink point of an unnamed sinking stream, located in southern Caldwell County. During high flow the inflow capacity of this losing reach is exceeded and the stream flows to its terminal sink, roughly 1 km to the southeast. This high-flow swallet was hypothesized to drain southeastward to Nichols Cave Spring (3805) [N36.950804°/W87.79363°]. Only one dye injection was made at this site and 3 spring and stream sites were monitored.

Trace # 12-20: Highfil Sinkhole [N37.215279°/W88.095341°] is a small sinkhole in a minor karst upland, located about 1 km south of Mexico, Kentucky. The sinkhole was hypothesized to drain southward Conway Springs (3861). Two dye injections with hauled flush water were attempted at this site and 11 spring and stream sites were monitored.

Trace # 12-22: Buchanon Sinkhole [N37.186727°/W88.11354°] is a large sinkhole with a cover collapse that is perched on the north end, some 2-3 m above the bottom of the sinkhole. The cover collapse had been mostly backfilled with debris. The sink was hypothesized to drain either northeastward to Conway Springs (3861) or southwestward to Larping Spring (3812) [N37.165516°/W88.152908°]. The sinkhole could also possibly drain west-southwestward to one of a few minor springs mapped on Caldwell Spring Creek. Only one dye injection with hauled flush water was attempted and 7 springs were monitored.

Geologic Faults and Karst Development

The study area is located in the Kentucky-Illinois Fluorspar District, which is highly faulted. The faulting is most intense in the northwest and decreases towards the southeast. The faults and associated fractures were avenues for the deposition of hydrothermal minerals and igneous intrusions. Faults have also influenced karst formation and groundwater flow within the soluble carbonate rocks present. The conventional wisdom is that faults cutting through soluble rocks will transmit groundwater, whereas faults dividing soluble and insoluble rocks will act as a boundary. This held true in several cases, but not others.

Ample evidence from this study and previous research shows that faults have a profound impact on karst formation and groundwater flow. Numerous caves surveyed in the area (WKSS, 2005) coincide with faults mapped on the various US Geological Survey 7.5-minute Geologic Maps. In addition, four tracer tests conducted for this study confirmed groundwater flow from injection sites to springs that occur along mapped faults. Conversely, several of the faults act as subsurface hydrologic boundaries and impede groundwater dispersion. Evidence for this can be seen at the numerous dye injection points draining away from the periphery of fault zones and the paucity of karst features in the vicinity of many faults.

What remains unclear is an adequate means to predict whether faults will transmit groundwater or function as a hydrologic boundary. Lambert and Brown (1963) note that groundwater yield from fault zones is variable and typically higher or lower than what is indicated by the general availability pattern. Faults inducing groundwater flow through the St. Louis Limestone were noted in the Martin Spring, Sandhole Spring and Displacement Spring basins. In addition, three significant springs – Larping Spring (3812), Cantrell Spring (3831) and Mint Spring (3808) – are mapped on faults in the St. Louis and Ste. Genevieve limestones, but do not have associated tracer data. However, a fault zone cutting through the St. Louis Limestone in the vicinity of the I-69 corridor is nearly devoid of sinkholes. Furthermore, tracer tests on both the north and south sides of this fault zone were shown to drain away from it. The USGS Geologic Quadrangle Maps for this area, and their associated cross sections, illustrate relatively minor areas of less-soluble rock units within this fault zone (Sample, 1965; Rogers, 1963 and Hays, 1964). These less-soluble rocks are possibly sufficient to impede groundwater flow. Additionally, the western extent of this fault zone is submerged in Lake Barkley and may transmit groundwater to unknown subaqueous springs.

A fault with soluble and insoluble rocks juxtaposed was found to act as a hydrologic boundary for the northern portions of Mill Bluff Spring and Conway Springs basins in Fredonia Valley. Similarly, complex fault zones bracketing the Puckett Spring basin also seem to form its subsurface hydrologic boundary. However, another fault dividing soluble and insoluble rocks was found to transmit groundwater to Doan Spring. The Hodge Fault System (Amos and Hays, 1974) has formed a steep ridge that is capped by sandstone with underlying units alternating between shale and sandstone until the Ste. Genevieve Limestone is reached at its base. Runoff enters a swallet formed in alluvium overlying the Renault Limestone on the south side of the fault (down-thrown). The associated cross section shows that at depth the Renault and Ste. Genevieve limestones are in contact across the fault. Minor surface limestone exposure and associated weakness along the fault was apparently ample for karst formation in this locale.

The question about determining the effect of faults on groundwater flow arose during the course of the project and was not part of its original intent. The study was designed to characterize groundwater resources in the region, not specifically to determine hydraulic transmission of faults. Further research with expanded tools will be required to adequately address this issue. This could be accomplished through review of exploratory borehole logs, tracer tests focused on fault zones and incorporation of geophysical techniques.

Karst Flow Deviation from Watershed Divides

Groundwater and surface water systems are conjunctive, and the interconnections can be very direct in karst regions. Surface runoff into stream swallets and sinkholes influences groundwater quantity and quality. Likewise, stream flow is maintained by groundwater contribution from springs during low flow, which influences the quality of surface water. However, the configuration of karst drainage basins may or may not conform to hydrologic boundaries delineated from topographic divides, such as Hydrologic Unit Code (HUC) boundaries. White and Schmidt (1966) employed the term *misbehaved karst* to describe these deviations, such as groundwater paths that flow beneath topographic divides. Ray and others (2006) and Blair and others (2009) refined this definition based on confirmed conduit flow passing beneath a delineated HUC boundary. This assessment will compare verified (traced or cave-surveyed) groundwater flow that passes underneath a 14-digit or lower HUC.

Karst drainage can deviate from the topographic watershed divides on a very wide scale. Most often these deviations are relatively minor and the conduit network does not divert drainage to an entirely different watershed. This includes the 14-digit HUC scale, which generally represents sub-basins within a watershed and can sometimes have ambiguous or arbitrary divisions. However, there are cases where major karst deviation creates a transfer between watersheds or even river basins. These HUCs, at the 11-digit to 6-digit level, represent major rivers and significant watersheds. They are delineated based on surface topography from the mouth of a stream to its headwaters.

Issues arise due to karst deviation when conduits redirect water to a spring outside of a basin drainage area. When this occurs within a 14-digit HUC the impact is generally minor, as the karst system typically just provides an alternate, subsurface route for flowing water within a single watershed. However, if karst drainage deviates from a major watershed divide then water may be diverted to a location that cannot be identified without tracer tests or cave surveys. This can have significant implications for water resource assessment, as well as response to environmental hazards. In the case of water resource assessments, it may lead to areas of unknown contribution and unidentified contaminant sources. In the case of an environmental spill, it may cause initial monitoring and mitigation activities to be focused in the wrong area(s). Specific examples of karst deviation from this study are described below in the context of relevant HUC levels.

Of the 38 successful tracer tests conducted for this project, 23 revealed flow that deviated from the 14-digit HUC boundaries. These deviations represent approximately 229 km^2 of drainage area, or 58% of the total mapped karst basin areas of 395.5 km^2. Springs with confirmed karst deviation are Conway Springs (3861), Mill Bluff Spring (1825), Ruben Ray Spring (3742), Cohorn Spring (3741), Wallace Branch Spring (1855), Displacement Spring (3846), Sandhole Spring (3894), Harpending Spring (1823), Martin Spring (3740) and Seven Springs (3859). When compared with the 12-digit HUCs, only 12 of the tracer tests showed karst drainage deviation. These deviations represent approximately 132 km^2 of drainage area or 33% of the total mapped karst basin areas. Springs with confirmed karst deviation are Conway Springs (3861), Mill Bluff Spring (1825), Ruben Ray Spring (3742), Wallace Branch Spring

(1855), Displacement Spring (3846), Sandhole Spring (3894), Harpending Spring (1823) and Seven Springs (3859). There were no confirmed karst deviations from any of the 11-digit, 10-digit, 8-digit or 6-digit HUC boundaries.

The most notable karst deviation was the dye injection at Skinframe Log Jam Cave (Trace # 11-14). This trace proved that Skinframe Creek-east is diverted northward to Mill Bluff Spring (1825), nearly 7.5 km to the northwest. Although Skinframe Creek-west and Mill Bluff Spring both drain to Livingston Creek, this particular karst deviation is significant. Skinframe Creek-west discharges to Livingston Creek at DOW River Mile Post (RMP) 11.7, whereas the spring run for Mill Bluff Spring meets Livingston Creek at DOW RMP 17.2. This represents nearly 9 km on Livingston Creek between the perceived and actual discharge points for Skinframe Creek-east. This also represents the largest area of karst deviation within a single spring basin in the study area at 68.3 km^2 (65% of the Mill Bluff Spring basin). The area of karst deviation encompasses the entire Skinframe Creek-east and Brewster Creek watersheds, which drain into Skinframe Log Jam Cave and Skinframe Sinks Cave, respectively.

Other spring basins in the study area with noteworthy karst deviation are Harpending Spring, Martin Spring and Cohorn Spring. Harpending Spring has 40.3 km^2 of drainage area that deviates from both the 14-digit and 12-digit HUCs. This represents 97% of the spring's 41.7 km^2 recharge area. Martin Spring has 64 km^2, or 96%, of drainage area that deviates from the 14-digit HUC, although there is no deviation from the 12-digit HUC. Cohorn Spring has 30 km^2, or 81%, of drainage area that deviates from the 14-digit HUC, but does not deviate from the 12-digit HUC. A minority of the study area spring basins – Puckett Spring, Big Spring and Lisanby Spring – do not deviate from any of the HUC boundaries. A summary of karst deviation in springs monitored for water quality is presented in Table 42. The map in Figure 20 illustrates the varying degrees of verified karst drainage deviation using color-coded basin areas. The HUC boundary delineations have been omitted for ease of map interpretation.

Table 42. Karst Deviation of Monitored Springs (*areas of greatest deviation in bold*)

Spring Name	AKGWA	Spring Basin Area (km^2)	Karst Deviation (km^2)		Ratio of Maximum Spring Basin Deviation
			HUC 14	*HUC 12*	
Harpending	1823	41.7	40.3	40.3	**0.97**
Wallace Branch	1855	26.7	5.7	5.7	0.21
Mill Bluff	1825	105.0	68.3	68.3	0.65
Martin	1855	66.5	64.0	0.0	**0.96**
Puckett	1853	40.9	0.0	0.0	0.00
Cohorn	3741	37.0	30.0	0.0	0.81
Conway	3861	27.7	7.4	7.4	0.27
Ruben Ray	3742	11.7	8.5	5.2	0.73
Big	1145	6.5	0.0	0.0	0.00

Unit Base Flow Assessment

Spring base-flow discharges in the Western Pennyrile tend to be smaller than those measured in the central and eastern parts of this region. Base flows measured for 17 springs in the study area ranged from 3.4 to 77 L/s, with a median value of 20 L/s, and are summarized in Table 43. Ray and others (2005) assessed a total of 34 springs in the Mississippian Plateau Region and reported spring base flow range of 10 to 277.5 L/s, with a median value of 59.5 L/s. Ray and others (2006) assessed 25 springs in the Little River Basin (Trigg, Christian and Todd counties) and found a spring base flow range of 1.7 to 170 L/s, with a median value of 53.8 L/s. The DOW groundwater database contains 256 base flow measurements for 140 unique springs in the Mississippian Plateau Region. Those data show a base flow range of 2.8 to 680 L/s and a median value of 68 L/s. This indicates that springs in the study area fall near the middle to low end of the base flow spectrum for the overall region.

Unit Base Flow (UBF), or normalized flow, is the ratio of a spring's base flow to its apparent basin size and is generally expressed as L/s/km^2. Its usefulness to characterize karst basins has been discussed by Quinlan and Ray (1995) and Paylor and Currens (2001). The most applicable base flow measurement to utilize for this ratio is the minimum annual flow, or dry-season base flow (Ray and Blair, 2005). This measurement accounts for groundwater released from seasonal storage within the aquifer, and excludes storm-related runoff. The reference UBF values for comparison come from Ray and others (2006) and White (1977). Ray calculated UBF for 25 springs in the Little River watershed and found a median value of 2.2 L/s/km^2. White reported that UBF of 2 L/s/km^2 is a useful dividing line between low-storage and high-storage karst aquifers in the Appalachians.

Table 43. Base-Flow Discharges for all Springs Gaged in Study Area

Spring Name	AKGWA	Latitude	Longitude	Base Flow (L/s)	County	Quadrangle	Receiving Stream
Harpending	1823	37.03785	-87.934026	77	Caldwell	Princeton W	Eddy Cr
Wallace Branch	1855	37.070627	-87.929466	62	Caldwell	Princeton W	Eddy Cr
Mill Bluff	1825	37.189992	-88.073043	60	Caldwell	Fredonia	Livingston Cr
Martin	3740	36.970278	-87.782825	48	Caldwell	Cobb	Kenady Cr
Puckett	1853	37.234474	-88.200454	40	Livingston	Dycusburg	Claylick Cr
Cohorn	3741	37.142708	-88.108847	37	Lyon	Fredonia	Skinframe Cr
Conway	3861	37.192653	-88.100335	31	Crittenden	Fredonia	Livingston Cr
Ruben Ray	3742	37.184334	-88.08343	28	Caldwell	Fredonia	Livingston Cr
Larping	3812	37.165516	-88.152908	20	Crittenden	Dycusburg	Livingston Cr
No Bottom	3819	37.108885	-88.155212	17	Lyon	Grand Rivers	Spring Cr
Big	1145	37.108072	-87.881517	14	Caldwell	Princeton W	Eddy Cr
Doan	1854	37.2275	-88.17444	7.1	Crittenden	Dycusburg	Claylick Cr
Montalta Cave	3862	37.255016	-88.154673	6	Crittenden	Salem	Clements Cr
Peek	3813	37.155356	-88.144256	5.7	Crittenden	Dycusburg	Livingston Cr
Head Dry Fork	3860	37.197445	-88.099815	5.7	Crittenden	Fredonia	Dry Fork
Iron Post	3806	36.931086	-87.846936	3.7	Trigg	Cobb	Long Pond Br
Nichols Cave	3805	36.950504	-87.798363	3.4	Trigg	Cobb	Kenady Cr

For the nine springs monitored in this study the UBF ranged from 0.6 to 2.4 L/s/km^2, with a median value of 1.1 L/s/km^2. The spring with the lowest UBF is Mill Bluff Spring and the highest is Ruben Ray Spring. Six springs had UBF below and three springs had UBF above White's (1977) partition of 2 L/s/km^2. The springs with UBF above this dividing line have values very close to the reference value of 2.2 L/s/km^2 (Ray and others, 2006). However, five out of the six springs with UBF below reference values have only half or less of the expected UBF.

The five springs with the lowest UBF are Mill Bluff Spring, Martin Spring, Puckett Spring, Cohorn Spring and Conway Springs. Areas of sandstone cap-rock and significant faulting within the mapped karst basins may help generate these apparent UBF deficits. Sandstone cap-rock can act as a shield and impede groundwater infiltration, and many of the faulted areas have been shown to act as hydrologic boundaries. Accordingly those areas may not significantly contribute to groundwater storage during dry-season base flow. These areas were included within the spring basins, however, because they represent the origins of sinking streams traced to these springs. Subtracting those areas from the karst basins makes marginal difference when recalculating UBF (Table 42 – bracketed values) although the median value does increase from 1.1 to 1.9 L/s/km^2. The increased median value is largely due to the exclusion of nearly 50 % of the Conway Springs basin, which raises its UBF from 1.1 to 2.3 L/s/km^2. In the case of Cohorn Spring, its location and morphology make gaging rather difficult. This caused possible low discharge errors, which in turn would have artificially decreased its UBF. The unadjusted UBFs for these springs range from 29-50% of what could be expected based on the UBF reference values. The adjusted UBFs for these springs range from 45-110% of expected UBF, based on reference values. For example, by adjusting the Mill Bluff Spring data, the spring would have an expected base flow of 132 L/s rather than the excessive 210 L/s. Still, 132 remains well above the observed discharge of 60 L/s, so additional factors may help depress base flow. Other possible causes are failure to gage all basin discharge, unknown water withdrawals from the basin during gaging periods, or lower actual groundwater runoff than reference areas.

UBF for monitored springs is summarized in Table 43 and illustrated on the graph in Figure 21. The table and graph both include measurements and calculated values that have been adjusted by subtracting areas that, potentially, do not contribute to groundwater storage during base flow conditions.

Table 44. Unit Base Flow Summary for Monitored Springs ***Denotes adjustment to* [*basin area*] *and* [*UBF*] *for drainage areas contributing little or no groundwater storage during base flow.*

Spring Name	AKGWA	Base Flow (L/s)	Spring Basin Area (km^2)	Unit Base Flow (L/s/km^2)
Harpending	1823	77	41.7* [40.3]	1.8* [1.9]
Wallace Branch	1855	62	26.7	2.3
Mill Bluff	1825	60	105* [66]	0.6* [0.9]
Martin	1855	48	66.5* [39.1]	0.7* [1.2]
Puckett	1853	40	40.9* [32.6]	1.0* [1.2]
Cohorn	3741	37	37* [32.8]	1.0* [1.1]
Conway	3861	31	27.7* [13.7]	1.1* [2.3]
Ruben Ray	3742	28	11.7	2.4
Big	1145	14	6.5	2.2

WATER QUALITY ASSESSMENTS

Introduction

Once the spring basin delineations were completed, water quality monitoring sites were chosen. As previously discussed, priority was given to springs with larger base flows since this typically represents greater drainage areas. This maximized the land area for evaluation. The second tier for site selection was land use; sites were selected to represent the various land uses within the study area. Budgetary constraints allowed for 10 sites that could be assessed adequately to meet the requirements for the integrated approach. Unfortunately, access to one site was lost a few months after monitoring began, and thus only nine sites were assessed to completion. This number of sites was still sufficient to characterize groundwater resources in the study area.

All chemical and biological data assessed were collected by DOW. These water quality data were compared with criteria set forth by the Kentucky Water Quality Regulations (401 KAR 10:031). As previously mentioned some parameters were omitted. Ultimately, data were adequate to draw meaningful conclusions relative to use-support levels for Warm Water Aquatic Habitat (WAH) and Primary Contact Recreation (PCR) at each of the nine springs.

The water quality and use-support levels for each spring are discussed individually. The accompanying 305(b) Checklist is presented for each spring. Relative to WAH, seven of the springs were found to be fully supporting and two springs were determined to be partially supporting. Low dissolved oxygen content was the only water quality problem noted.

Three of the nine springs monitored were found to be fully supporting for PCR, and the other six were found to be partially supporting. However, the monitoring period during August 2013 was excessively wet. According to National Weather Service records (NOAA, 2014), the study area received 15-20 cm of precipitation that month. This represents roughly 250-300% of the normal August precipitation for the area, which is 5-7.5 cm. This caused numerous runoff events and overland flow into sinkholes and sinking streams leading to turbid high flows at the springs. These storm-related increases in spring discharge generally correspond to higher *E. coli* counts. Those particular samples likely reflect short-term contamination of groundwater from nonpoint sources (Ryan and Meiman, 1996). Many of the springs had very low *E. coli* counts when discharge was not influenced by runoff events. In fact, only two springs – Wallace Branch and Big springs – had *E. coli* counts that were consistently over the PCR standards (notably, Big Spring has an urbanized watershed).

The maps in Figure 22 and Figure 23 show the support levels determined for each spring for WAH and PCR, respectively.

Harpending Spring (1823) – Caldwell County/Princeton West 7.5-minute quadrangle

Harpending Spring [N37.03785°/W87.934026°] has a base flow of 77 L/s and drains an area of 41.7 km^2. Land use in this spring basin is predominantly agricultural (72.5%), with a small amount of forested land (22.1%) and minor impervious area (4.6%). The majority (97%) of the karst basin delineated for Harpending Spring deviates from the surface drainage of Dry Creek and diverts flow to Eddy Creek.

Results for chemical samples showed that this spring is fully supporting for WAH. However, during the monitoring period there were 33 detections of four different pesticides at this spring. The most frequently detected pesticide was Atrazine, which is one of the most commonly used herbicides. While none of these detections exceeded the WAH standards, their presence indicates nonpoint source pollution because they are not naturally occurring compounds.

This spring was found to be partially supporting for PCR. Results for *E. coli* samples ranged from 35 to >2419.6 Most Probably Number (MPN), with a geometric mean of 158 MPN. The median value of *E. coli* results was 147 MPN. Table 45 has the simplified checklist assessment form for this spring and Figure 24 shows the entire karst basin overlain on generalized land cover.

Wallace Branch Spring (1855) – Caldwell County/Princeton West 7.5-minute quadrangle

Wallace Branch Spring [N37.070627°/W87.929466°] has a base flow of 62 L/s and drains an area of 26.7 km^2. The predominant land use is agricultural (62.6%), with some forested areas (28.4%) and minor impervious cover (8.7%). A small fraction (21%) of the karst basin deviates from the surface drainage and diverts flow from Scott Branch to Eddy Creek.

Results for chemical samples showed that this spring is fully supporting for WAH. However, during the monitoring period there were 28 detections of five different pesticides at this spring. The most frequently detected pesticide was Atrazine. While none of these detections exceeded the WAH standards, their presence indicates nonpoint source pollution.

This spring was found to be partially supporting for PCR. Results for *E. coli* samples ranged from 308 to >2419.6 MPN, with a geometric mean of 679 MPN and median value of 613 MPN. Table 46 has the simplified checklist assessment form for this spring and Figure 25 shows the entire karst basin overlain on generalized land cover.

Mill Bluff Spring (1825) – Caldwell County/Fredonia 7.5-minute quadrangle

Mill Bluff Spring [N37.189992°/W88.073043°] has a base flow of 60 L/s and a karst basin of 105 km^2. Excluding faulted areas because of their potential for lack of base-flow storage decreases the karst basin to 66 km^2. Agriculture is the dominant land use at 66.4%, followed by forest (28.4%) and a small amount of impervious area (5.4%). A large portion (65%) of the karst basin deviates from watershed divides and diverts flow from Skinframe Creek-east to Livingston Creek.

Results for chemical samples showed that this spring is fully supporting for WAH. However, during the monitoring period there were 32 detections of 10 different pesticides at this spring. The most frequently detected pesticide was Atrazine. While none of these detections exceeded the WAH standards, their presence indicates nonpoint source pollution.

This spring was found to be partially supporting for PCR. Results for *E. coli* samples ranged from 172 to >2419.6 MPN, with a geometric mean of 352 MPN and median value of 461 MPN. Table 47 has the simplified checklist assessment form for this spring and Figure 26 shows the entire karst basin overlain on generalized land cover.

Martin Spring (3740) – Caldwell County/Cobb 7.5-minute quadrangle

Martin Spring [N36.970278°/W87.782825°] has a base flow of 48 L/s and was found to drain an area of 66.5 km^2. When areas of sandstone cap-rock are excluded as potentially lacking base-flow storage, the karst basin is decreased to 39.1 km^2. The majority of the karst basin area is used for agriculture (60.6%), with a moderate amount of forested land (34.3%) and minor impervious area (4.7%). The majority of the karst basin (96%) deviates from the 14-digit HUC. However, the 14-digit HUC boundary is somewhat ambiguous and groundwater is not diverted to a separate watershed. In fact, the karst basin does not deviate from any of the other HUC boundaries.

Results for chemical samples showed that this spring is fully supporting for WAH. However, during the monitoring period there were 40 detections of 12 different pesticides at this spring. The most frequently detected pesticide was Atrazine. While none of these detections exceeded the WAH standards, their presence indicates nonpoint source pollution.

This spring was found to be partially supporting for PCR. Results for *E. coli* samples ranged from 233 to >2419.6 MPN, with a geometric mean of 288 MPN and median value of 261 MPN. Table 48 has the simplified checklist assessment form for this spring and Figure 27 shows the entire karst basin overlain on generalized land cover.

Puckett Spring (1853) – Livingston County/Dycusburg 7.5-minute quadrangle

Puckett Spring [N37.234474°/W88.200454°] has a base flow of 40 L/s and drains an area of 40.9 km^2. Excluding areas of sandstone cap rock as potentially lacking base-flow storage, decreases the karst basin to 32.6 km^2. The predominant land use is agricultural (54.6%), with a moderate amount of forested land (39%) and minor impervious area (5.2%). The karst basin does not deviate from any of the topographic watershed divides.

Results for chemical samples showed that this spring is partially supporting for WAH, due to low dissolved oxygen. Several factors influence dissolved oxygen in water, such as water contact with air, water chemistry, turbulence, sunlight exposure and aquatic life. The exact cause of this impairment is unknown. In addition, during the monitoring period there were 34 detections of 11 different pesticides at this spring. The most frequently detected pesticide was Atrazine. While none of these detections exceeded the WAH standards, their presence indicates nonpoint source pollution.

This spring was found to be partially supporting for PCR. Results for *E. coli* samples ranged from 138 to 1986 MPN, with a geometric mean of 606 MPN and median value of 613 MPN. Table 49 has the simplified checklist assessment form for this spring and Figure 28 shows the entire karst basin overlain on generalized land cover.

Cohorn Spring (3741) – Lyon County/Fredonia 7.5-minute quadrangle

Cohorn Spring [N37.142708°/W88.108847°] has a base flow of 37 L/s and its karst basin is 37 km^2. Excluding faulted areas due to the potential lack of base-flow storage, the karst basin is decreased to 32.8 km^2. The dominant land use is agricultural (59.7%), followed by forested land (33.2%) and a small amount of impervious cover (6.1%). The majority of the karst basin (81%) deviates from the 14-digit HUC. The 14-digit HUC boundaries are somewhat ambiguous and most groundwater is not diverted to a separate watershed. However, a small area (3.4 km^2 or 9%) diverts flow from the Crab Creek drainage northward to Skinframe Creek-west. This karst basin does not deviate from any of the other HUC boundaries.

Results for chemical samples showed that this spring is fully supporting for WAH. However, during the monitoring period there were 21 detections of five different pesticides at this spring. The most frequently detected pesticide was Atrazine. While none of these detections exceeded the WAH standards, their presence indicates nonpoint source pollution.

This spring was found to be fully supporting for PCR. Results for *E. coli* samples ranged from 25 to >2419.6 MPN, with a geometric mean of 93 MPN and median value of 162 MPN. Table 50 has the simplified checklist assessment form for this spring and Figure 29 shows the entire karst basin overlain on generalized land cover.

Conway Springs (3861) – Crittenden County/Fredonia 7.5-minute quadrangle

Conway Springs [N37.192653°/W88.100335°] has a base flow of 31 L/s and drains an area of 27.7 km^2. Agricultural (47.8%) land use and forested land (47.3%) are roughly equivalent in the basin, with very minor impervious areas (4.2%). A moderate portion of the karst basin (27%) deviates from watershed divides and diverts flow from Caldwell Spring Creek to Dry Fork of Livingston Creek.

Results for chemical samples showed that this spring is fully supporting for WAH. However, during the monitoring period there were 10 detections of just one pesticide, Atrazine, at this spring. While Atrazine does not have a WAH standard, its presence indicates nonpoint source pollution.

This spring was found to be fully supporting for PCR. Results for *E. coli* samples ranged from 28 to >2419.6 MPN, with a geometric mean of 112 MPN and median value of 135 MPN. Table 51 has the simplified checklist assessment form for this spring and Figure 30 shows the entire karst basin overlain on generalized land cover.

Ruben Ray Spring (3742) – Caldwell County/Fredonia 7.5-minute quadrangle

Ruben Ray Spring [N37.184334°/W88.08343°] has a base flow of 28 L/s and its karst basin is 11.7 km^2. Land use is predominantly agriculture (75%), with some forested land (18.9%) and a minor amount of impervious area (5.2%). A significant portion of the karst basin (73%) deviates from the watershed divides. Drainage is diverted from portions of the watersheds attributed to Skinframe Creek-west and an unnamed tributary of Livingston Creek northward to this spring.

Results for chemical samples showed that this spring is partially supporting for WAH, due to low dissolved oxygen. Several factors influence dissolved oxygen in water, such as water contact with air, water chemistry, turbulence, sunlight exposure and aquatic life. The exact cause of this impairment is unknown. In addition, during the monitoring period there were 24 detections of six different pesticides at this spring. The most frequently detected pesticide was Atrazine. While none of these detections exceeded the WAH standards, their presence indicates nonpoint source pollution.

This spring was found to be fully supporting for PCR. Results for *E. coli* samples ranged from 15 to >2419.6 MPN, with a geometric mean of 71 MPN and median value of 93 MPN. This spring had the lowest overall values, geometric mean and median values for *E. coli*. Table 52 has the simplified checklist assessment form for this spring and Figure 31 shows the entire karst basin overlain on generalized land cover.

Big Spring (1145) – Caldwell County/Princeton West 7.5-minute quadrangle

Big Spring [N37.108072°/W87.881517°] has a base flow of 14 L/s and its karst basin drains an area of 6.5 km^2 (Ewers, 1990 and Ganter and others, 2005). The dominant land use is urban/residential, or impervious (39%), followed closely by forested land (33%) and agricultural areas (27.9%). Its karst basin does not deviate from any of the topographic watershed divides.

Results for chemical samples showed that this spring is fully supporting for WAH. However, during the monitoring period there were 16 detections of seven different pesticides at this spring. The most frequently detected pesticide was Atrazine. While none of these detections exceeded the WAH standards, their presence indicates nonpoint source pollution.

This spring was found to be partially supporting for PCR. Results for *E. coli* samples ranged from 1553 to >2419.6 MPN, with a geometric mean of 1954 MPN and median value of 2419 MPN. This spring had the highest overall values, geometric mean and median values for *E. coli*. Table 53 has the simplified checklist assessment form for this spring and Figure 32 shows the entire karst basin overlain on generalized land cover.

BENTHIC MACROINVERTEBRATE COMMUNITY EVALUATION

Introduction

Pond and others (2003) outlined a macroinvertebrate bioassessment index (MBI) for the headwater and wade-able streams of Kentucky. This established regional criteria for surface stream assessments and a means to evaluate their ecological health. However, karst spring macroinvertebrate communities are known to differ with regard to taxa, diversity and abundance. Therefore, it is unclear how well these regional surface water criteria will apply to springs.

Macroinvertebrate fauna of eight springs in the study area (Table 54) were evaluated to gather baseline data on their assemblages and to examine potential relationships with spring characteristics such as water chemistry, base flow and drainage area. In Kentucky, karst springs and their associated spring runs are important, yet understudied environments for aquatic macroinvertebrates. While a pilot study was conducted at springs in the Green River Basin (Blair and others, 2012), DOW has not developed sampling methodology or biological indices for springs. Due to this lack of evaluation compared to surface waters, various components of springs and spring runs remain poorly understood (Spitale and others, 2012). Given their importance in watershed hydrology, there is a need to better understand and document their function and components. In addition, studies by Glazier and Gooch (1987), Webb and others (1995) and Cantonati and others (2012) have shown that springs can serve as important sources for unique and rare aquatic taxa.

Table 54. Springs Evaluated for Benthic Macroinvertebrates. (Note: Big Spring excluded due to high potential for tampering of passive samplers)

Spring Name	AKGWA	Land Cover Category			Spring Basin Area (km^2)	Base Flow (L/s)
		% Urban/Res.	% Forest	% Agriculture		
Harpending	1823	4.6%	22.1%	72.5%	41.7	77
Wallace Branch	1855	8.7%	28.4%	62.6%	26.7	62
Mill Bluff	1825	5.4%	27.8%	66.4%	105.0	60
Martin	1855	4.7%	34.3%	60.6%	66.5	48
Puckett	1853	5.2%	39.0%	54.6%	40.9	40
Cohorn	3741	6.1%	33.2%	59.7%	37.0	37
Conway	3861	4.2%	47.3%	47.8%	27.7	31
Ruben Ray	3742	5.2%	18.9%	75.0%	11.7	28

Results

Three Hester-Dendy samplers were disturbed during the study, which resulted in each of those sites having only two viable samplers (Cohorn Spring, Martin Spring and Mill Buff Spring). In addition, one Hester-Dendy replicate at Harpending Spring was removed from analysis due to extreme outlier effects. As previously noted, multi-habitat jab net samples were collected but not evaluated due to limited resources. Therefore, the results and discussion that follow are based solely on aquatic taxa obtained with the passive samplers. A total of 2,137 individuals across 10 orders and 52 taxa were observed in this study (Table 55). Diptera, particularly chironomidae, and oligochaete worms dominated the samples, accounting for the majority of the taxa encountered in the study. Diptera (primarily chironomidae) represented nearly 63% of the individuals collected and oligochaete worms represented 24%. The highest taxa richness values were observed at Puckett Spring and Conway Springs and the lowest values were found at Cohorn Spring and Harpending Spring (Figure 33). Aquatic macroinvertebrate densities varied considerably across sites, with the highest value at Puckett Spring and the lowest value at Martin Spring (Figure 34).

Underscoring the dominance from pollution-tolerant macroinvertebrate groups, the median chironomid + oligochaete richness was 88.4%. This may suggest degraded water quality in surface streams (Pond and others, 2003). In addition, the mean values for % Ephemeroptera and %EPT richness were 1.83 and 12.65, respectively. The %EPT richness across sites was very low and not statistically different between springs (df=7; Kruskal Wallis test statistic=8). Both of these measures are for pollution-sensitive macroinvertebrates and the low counts further suggest water quality degradation, when applied to surface streams. Table 56 shows the summary statistics for benthic macroinvertebrates collected from springs in this study.

Mean taxa richness was not statistically significant between sites. No strong associations were found in the dataset between taxa richness, %EPT or %Clingers when compared to water chemistry measures evaluated. Additionally, taxa richness did not correlate with spring basin area (Figure 35) or base flow (Figure 36). Kruskal Wallis tests for differences in total richness between springs (df = 7; Kruskal Wallis statistic = 8) and Hester-Dendy densities between springs (df = 7; Kruskal Wallis statistic = 11) were not statistically significant. However, it was apparent that higher densities were present in Puckett Spring and Ruben Ray Spring. Kruskal Wallis tests indicated differences in Total Kjeldahl Nitrogen in spring months (test statistic 14; df = 7) and winter (test statistic 16; df = 7) months, but not between sites in the summer and fall.

Statistically significant differences were observed across seasons between spring sites for dissolved oxygen in the spring months (df = 7; Kruskal Wallis statistic = 17) and winter (df = 7; Kruskal Wallis statistic = 14). Statistically significant differences were observed for nitrate across all seasons, and orthophosphate in the spring months (df = 7; Kruskal Wallis statistic = 15). No statistical differences were detected between sites across seasons for ammonia or total phosphorus. In addition, there was no relationship observed between mHBI score and total phosphorus.

As with the previous DOW study, taxa richness at individual spring sites was low, with a median value of 13. Differences were not seen in Hester-Dendy densities or total richness between springs. However, this is not surprising given the similarity of these springs in terms of physiography, land use and base flow. A study of five springs in Switzerland found a mean of 31 taxa per site, dominated by the genus *Gammarus* (von Fumetti and Nagel, 2012). Our observations indicate *Gammarus* to be present, but likely not a strong associate of Hester-Dendy Samplers. A regional study of seven springs in Illinois found 85 taxa using net and hand collecting techniques (Webb and others, 1995). That study found the highest taxa richness in the *Oligochaete* and focused on maximizing taxa richness at each site via intensive collection methods.

CONCLUSIONS

This study focused on groundwater assessments for nonpoint source pollution in the Western Pennyrile Karst Region of Kentucky. The area is primarily underlain by soluble, carbonate rocks of Mississippian age with high potential for karst aquifer development. Additionally, the study area occurs within the Kentucky-Illinois Fluorspar district, which has numerous faults and is rich in hydrothermal mineral deposits. The study area is located in the Lower Cumberland River Basin, near its confluence with the Ohio River. This area is characterized as a karst plateau that is moderately dissected by surface drainage and sinkholes. The dominant land use in the study area is agriculture, primarily row crop production.

Groundwater tracing with fluorescent dyes was conducted as part of this project to expand our knowledge of karst flow paths. Of the 43 tracer tests conducted, 38 were recovered at 29 separate cave streams and springs, which allowed for the delineation of 11 additional karst basins. Combining work from this study with previous research yields a total of 373.7 km^2 of delineated karst basins. Approximately 61% (228.8 km^2) of the delineated karst drainage deviates from topographic watershed boundaries. Karst deviation within individual spring basins ranged from 0 to 68.3 km^2, and 0 to 97% of the total karst basin area.

The base flows of monitored springs range from 14 to 77 L/s, and their basin areas range from 6.5 to 105 km. The ratios of flow measurements to karst basin areas yield a spring UBF range of 0.6 to 2.4 $L/s/km^2$, with a median value of 1.1 $L/s/km^2$. Complex faulting throughout the study area has influenced karst development. Fault zones can be highly transmissive *or* act as hydrologic boundaries and predicting the nature of groundwater interaction with any particular fault is difficult. This adds to previous research, conducted by numerous authors, on groundwater resources in the region.

Nine springs were monitored over the course of one year for numerous water quality indicators including bulk parameters, major inorganic ions, metals, pesticides, residues, nutrients, volatile organic compounds and bacteria. The results of groundwater water quality samples were compared to the Kentucky Water Quality Standards set forth in 401 KAR 10:031. Utilizing these standards required integration of surface water and groundwater assessment approaches. At each monitored spring, chemical samples were collected once per month for 12 consecutive months and five bacteria samples were collected in 30 days.

Relative to the WAH standards, seven of the springs were found to be fully supporting and two were found to be partially supporting. The impairment causing partial support ranking was low dissolved oxygen. The reason for low dissolved oxygen at these two springs is unknown. Three of the springs were found to be fully supporting of PCR, while six were found to be partially supporting.

Groundwater quality sample results indicate definite impacts to groundwater from *E. coli*, low dissolved oxygen and pesticides. Although no impairments were noted due to pesticides, their presence is indicative of nonpoint source pollution because they are not naturally occurring compounds.

The macroinvertebrate community evaluation indicates that spring fauna are predominantly pollution tolerant taxa. Taxonomic identification was predominantly done to the genus level; however, worms were left at the order level. A total of 2,137 individuals from 52 taxa were observed in this study. No strong statistical correlations were found between macroinvertebrate populations and water chemistry, spring basin size or base flow. Genus richness at individual springs ranged from 9 to 23 taxa with a median value of 13. Additional samples collected using multi-habitat jab nets were not evaluated at the time of this report's completion.

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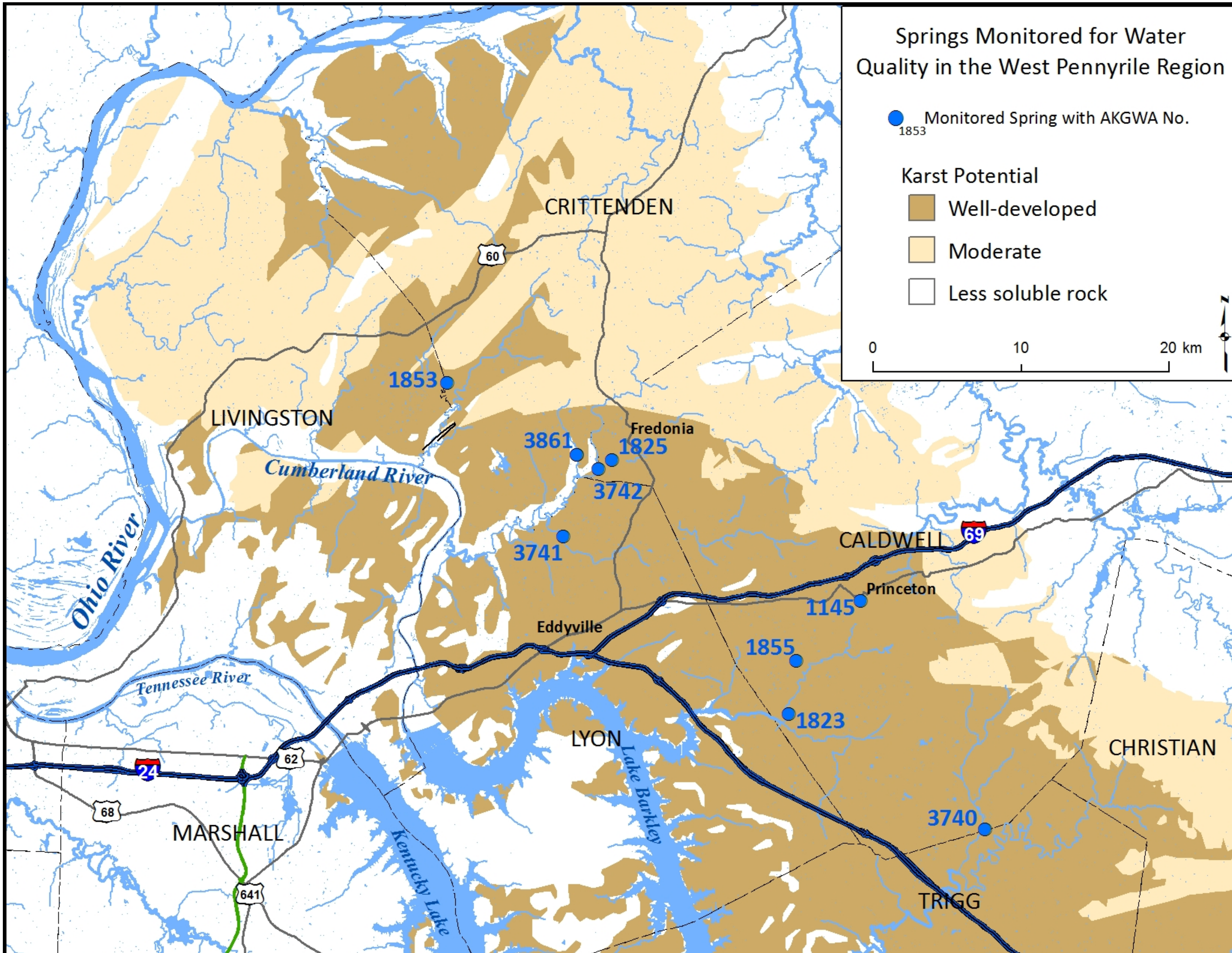

Figure 1. Map of Study Area Springs

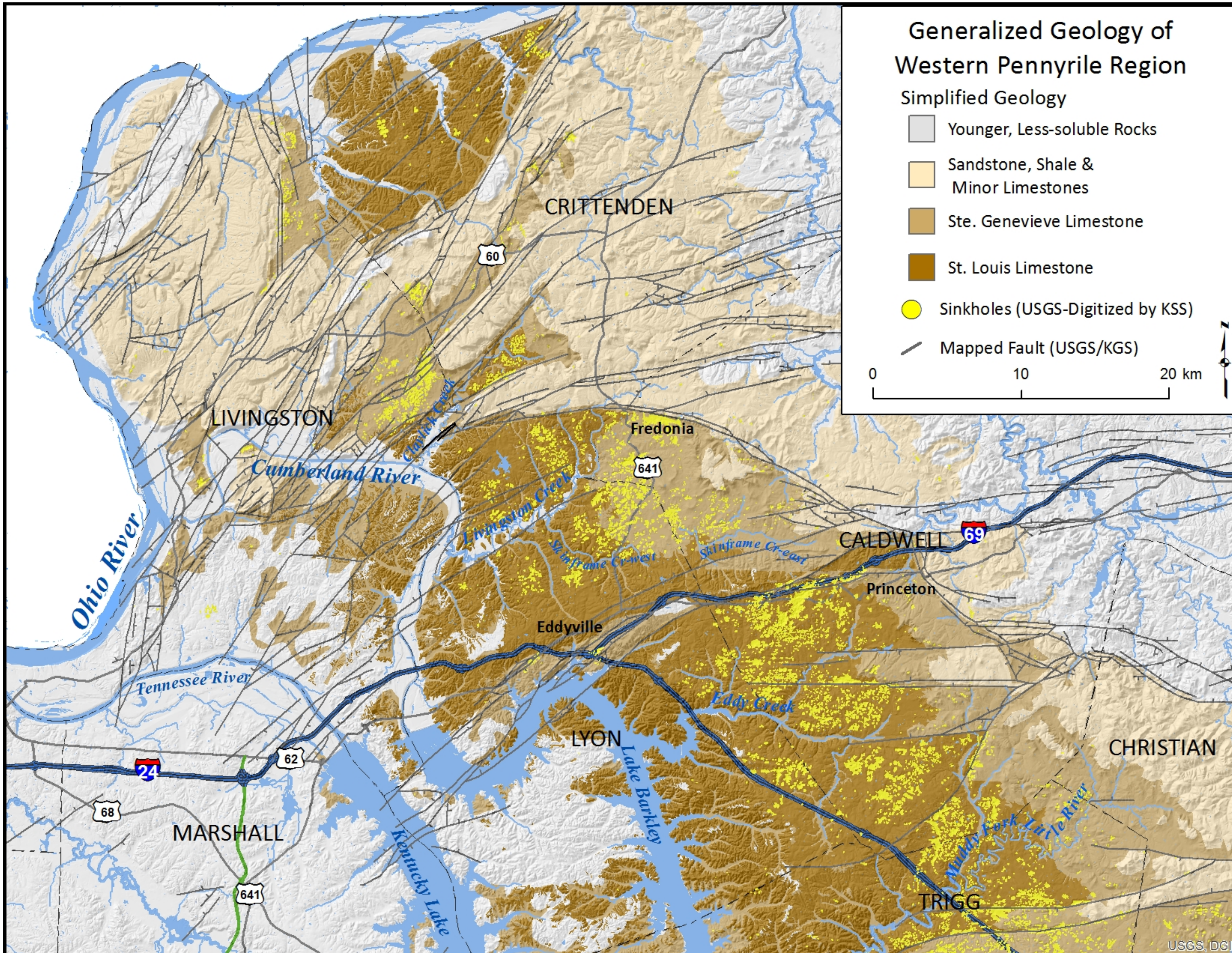

Figure 2. Hydrography and Geology of Lower Cumberland River in Kentucky

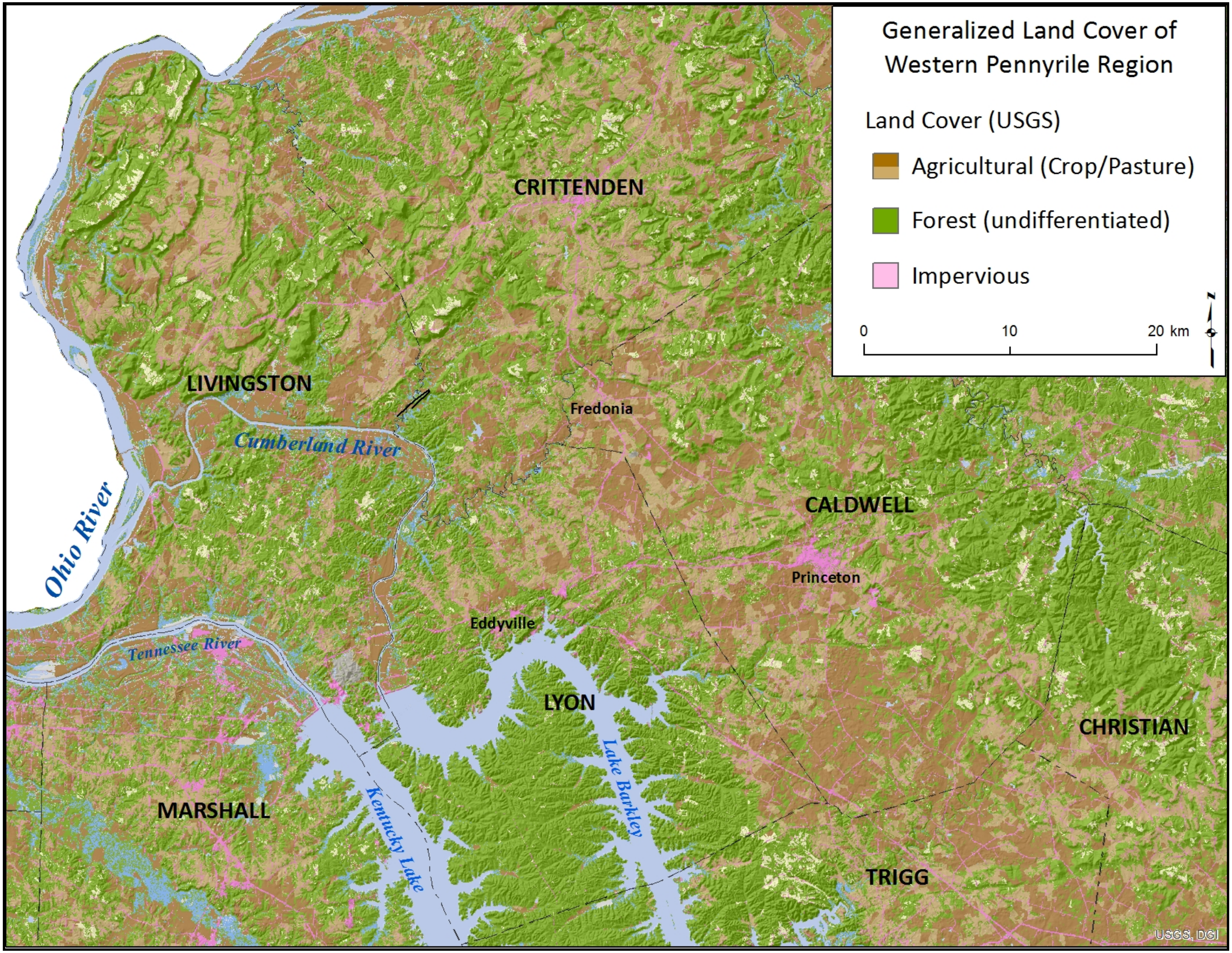

Figure 4. Generalized Land Cover of the West Pennyrile Region

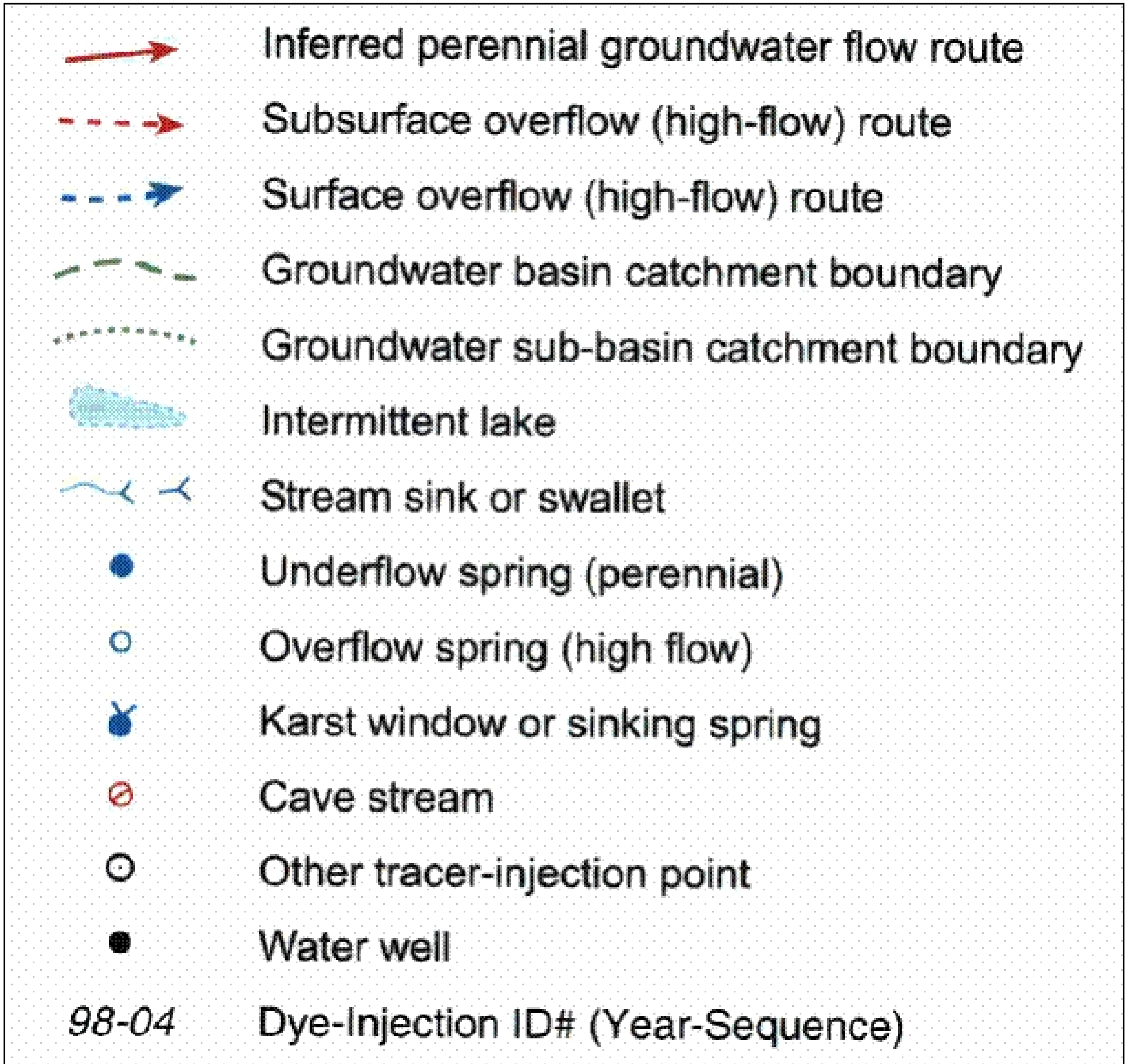

Figure 5. Karst Atlas Map Legend

Figure 6. Activated charcoal packet attached by trot-line clip to “Quinlan Gumdrop” or brick fitted with #10 copper wire. Devices secured to retrieval point with nylon cord.

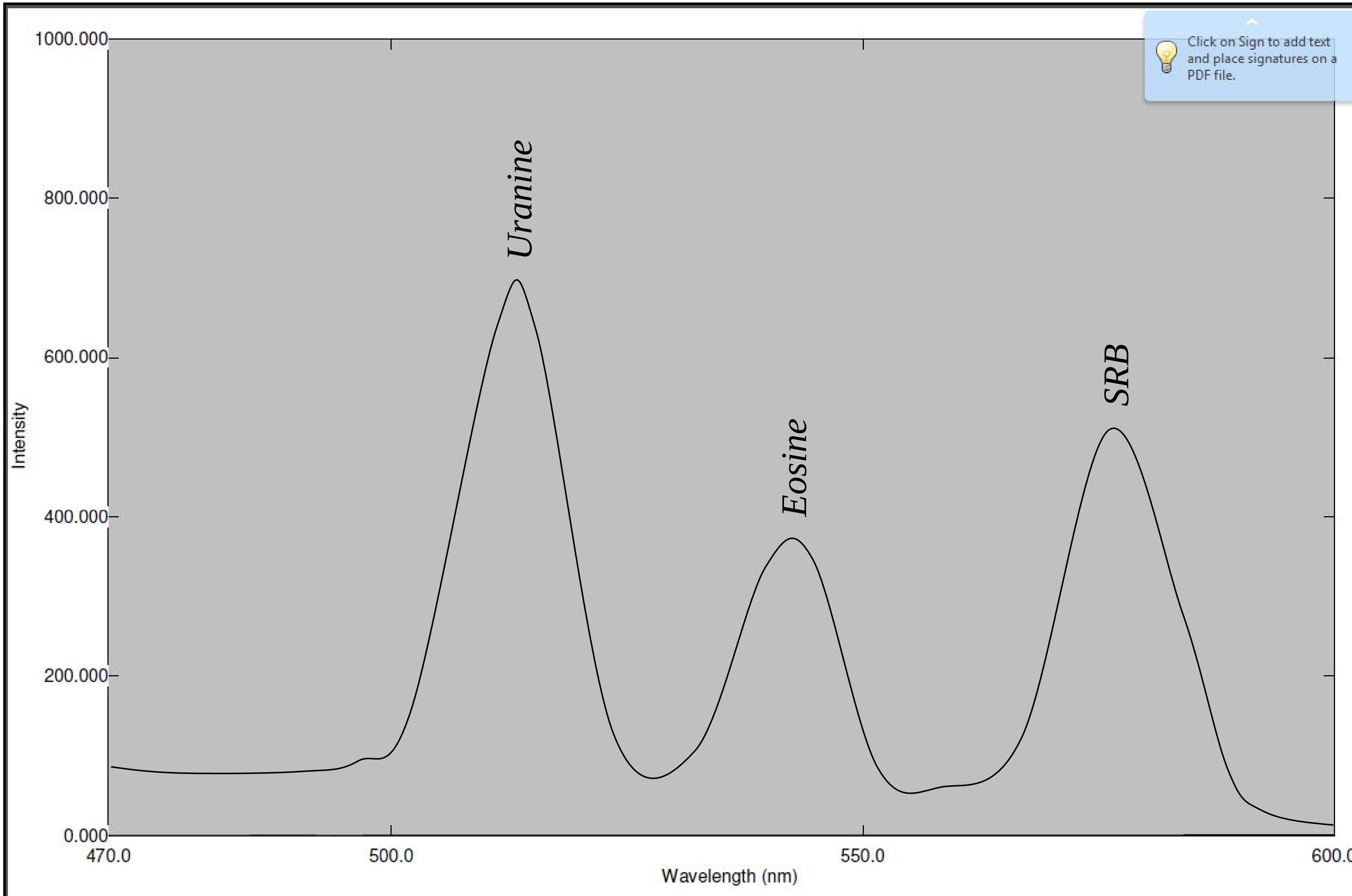

Figure 7. Typical Dye Curves on Spectrofluorophotometer

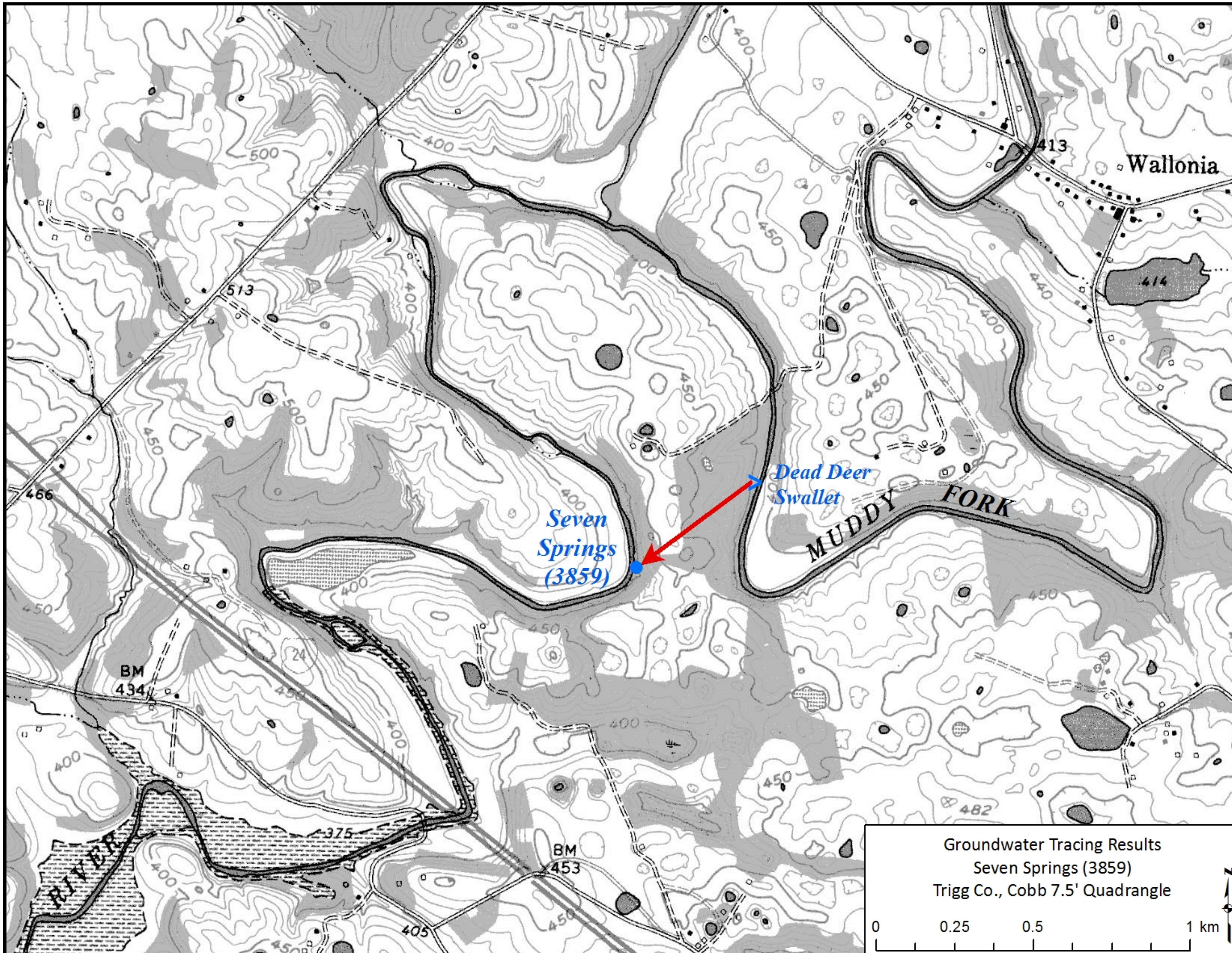

Figure 8. Seven Springs Tracer Map

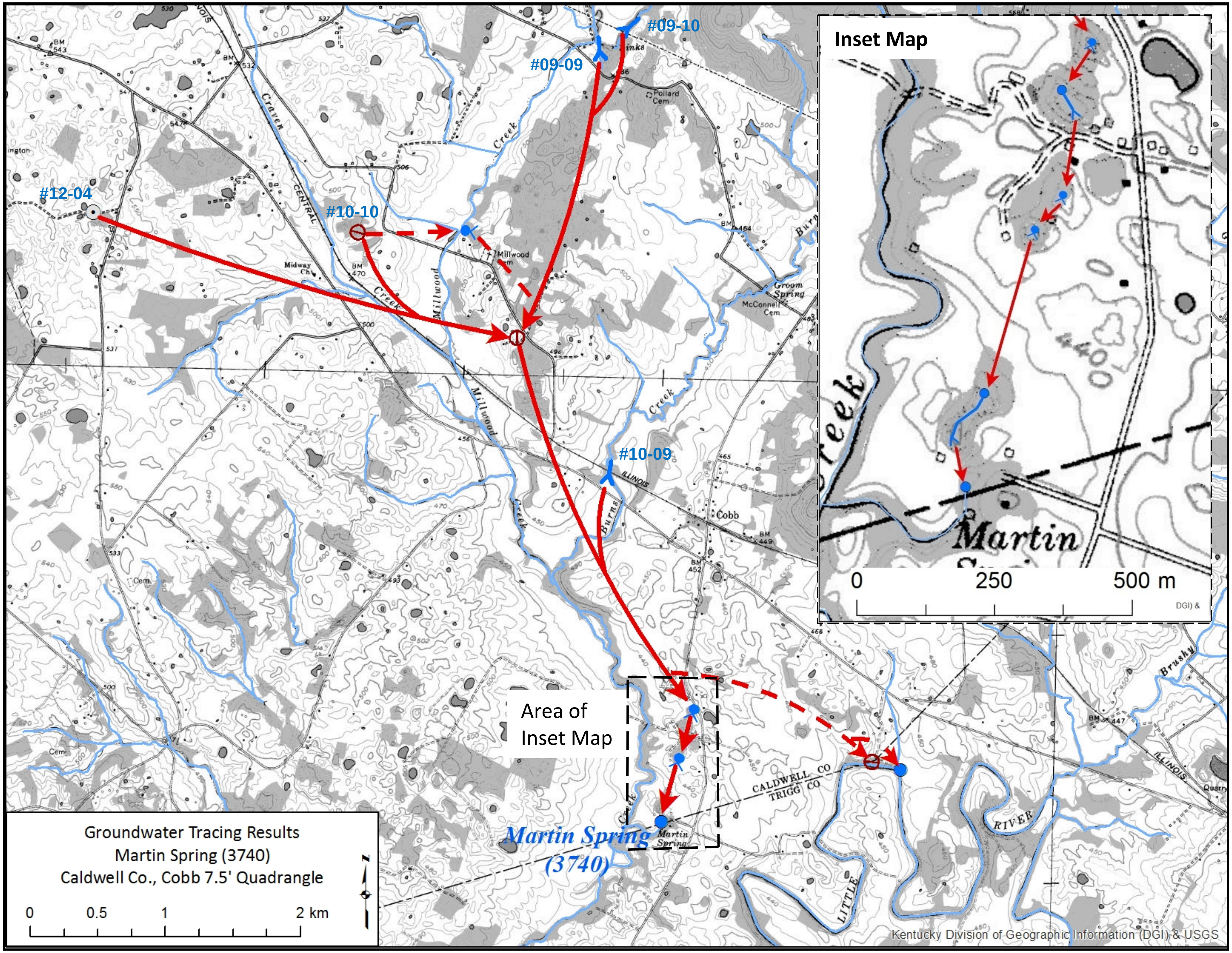

Figure 9. Martin Spring Tracer Map

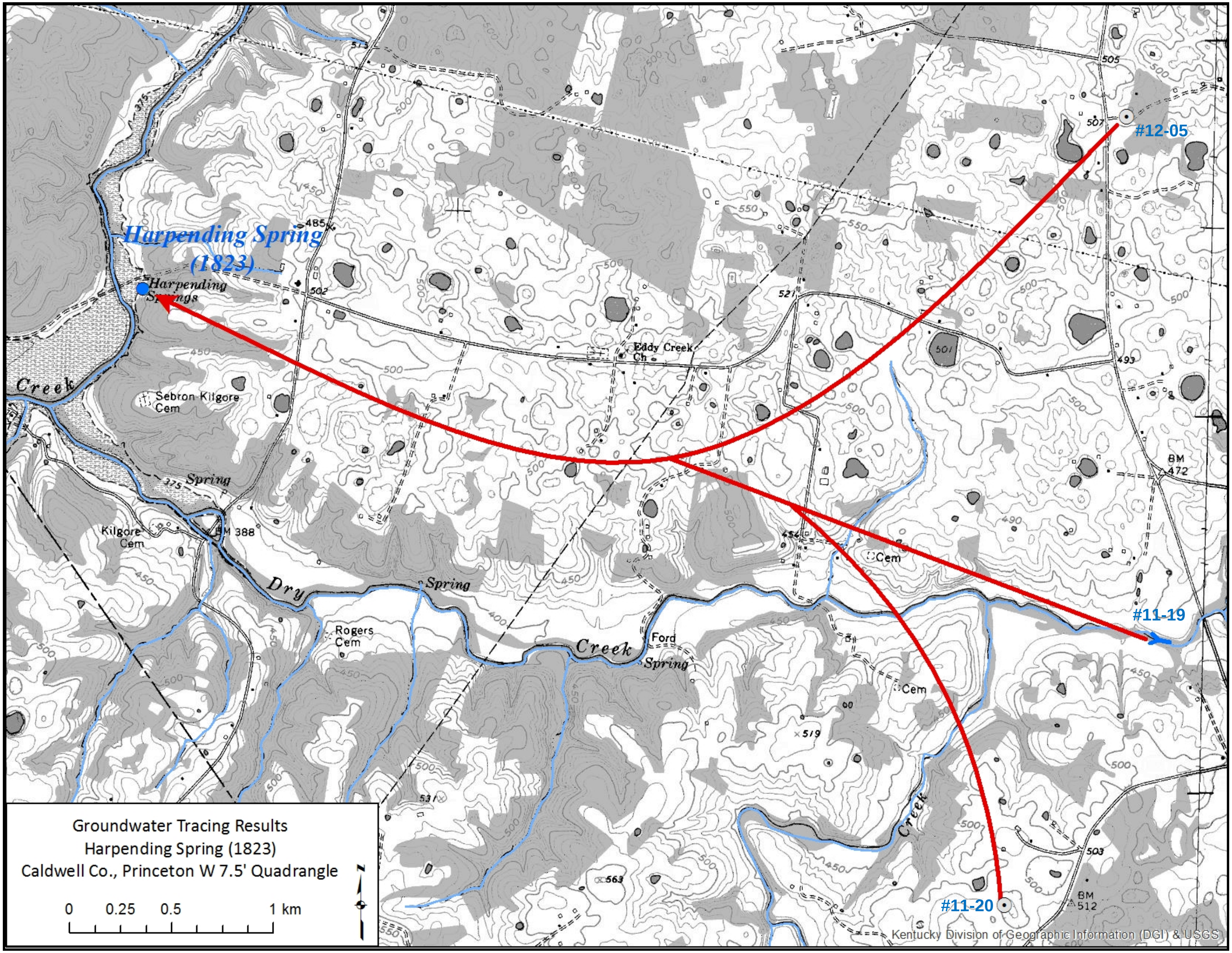

Figure 10. Harpending Spring Tracer Map

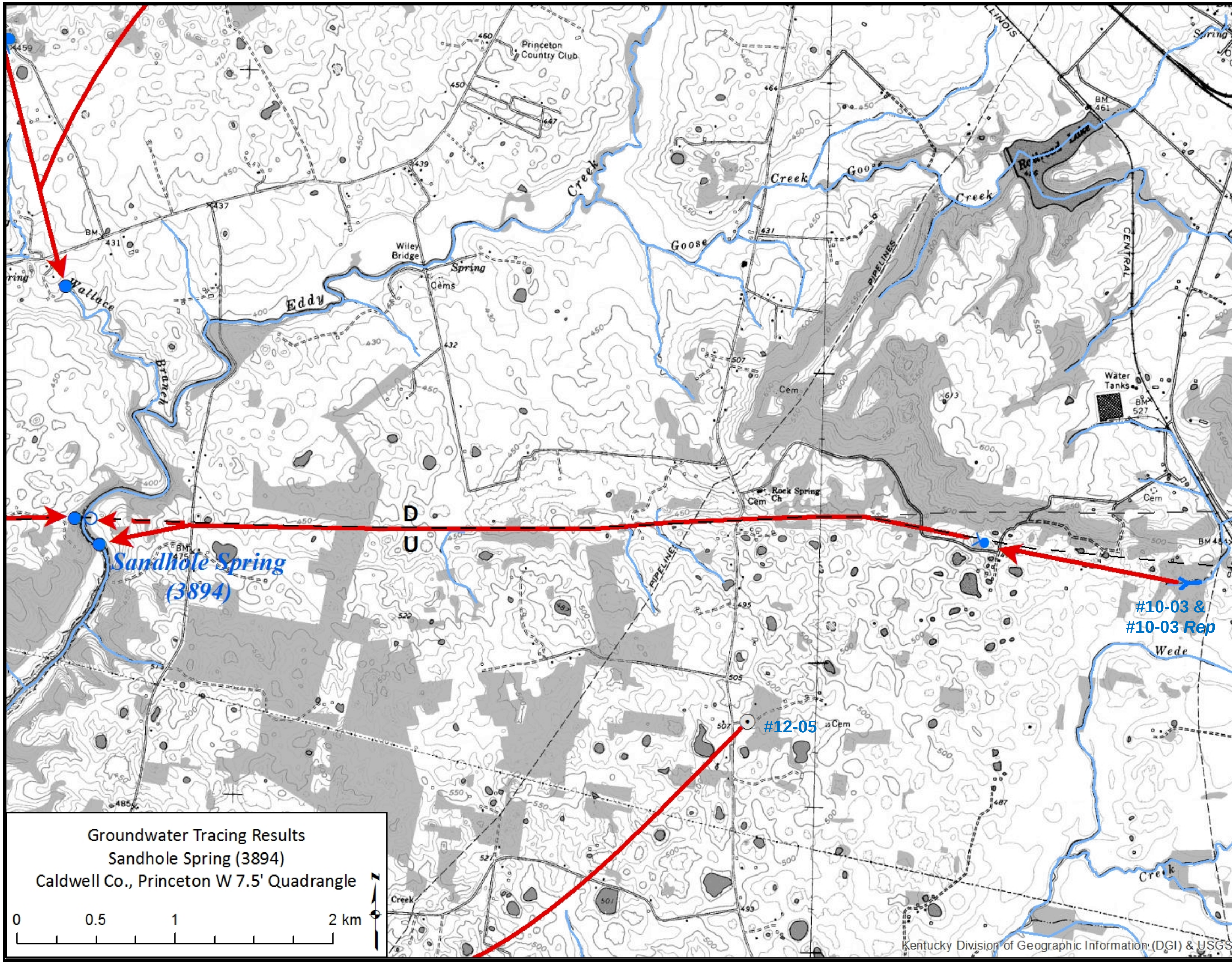

Figure 11. Sandhole Spring Tracer Map

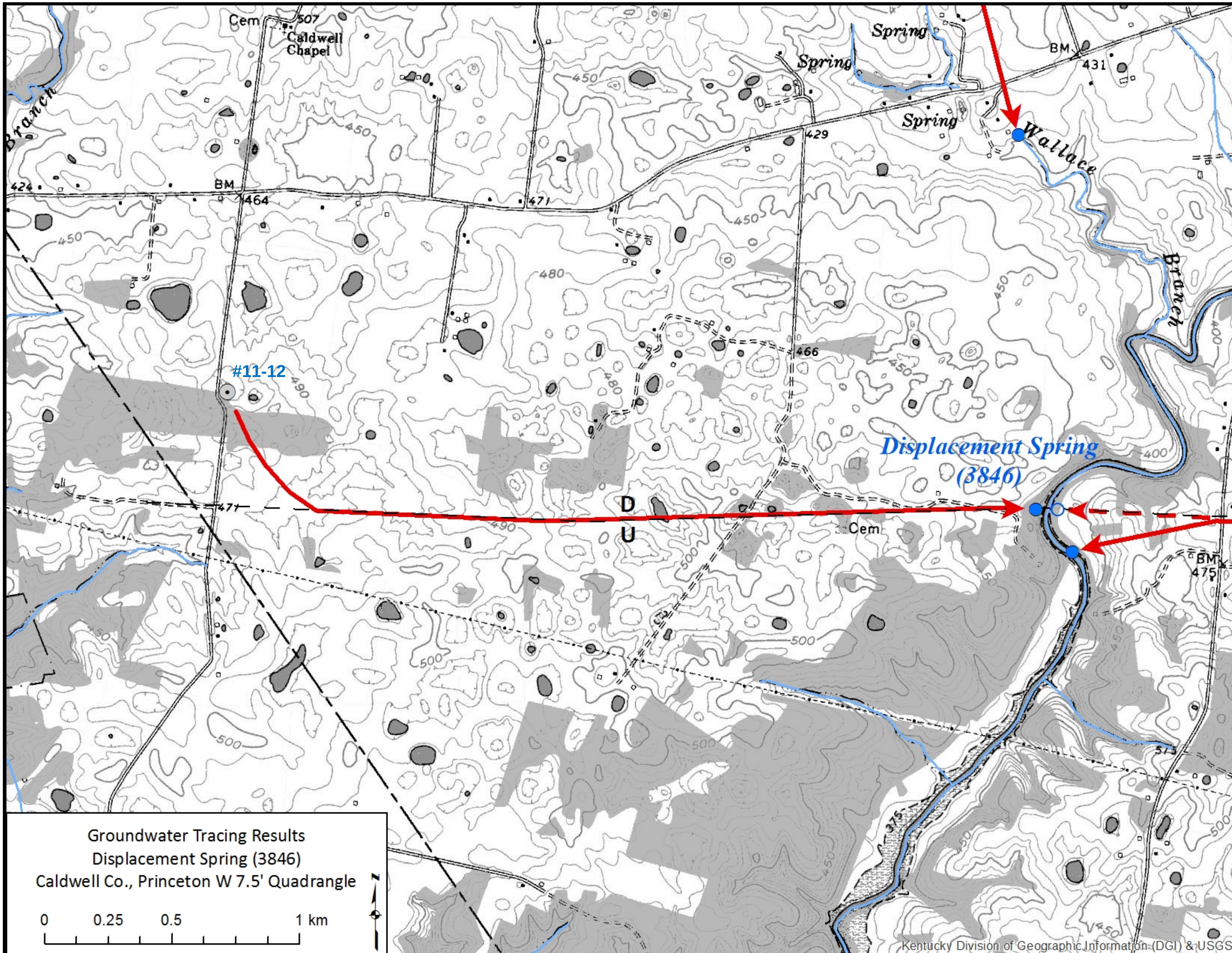

Figure 12. Displacement Spring Tracer Map

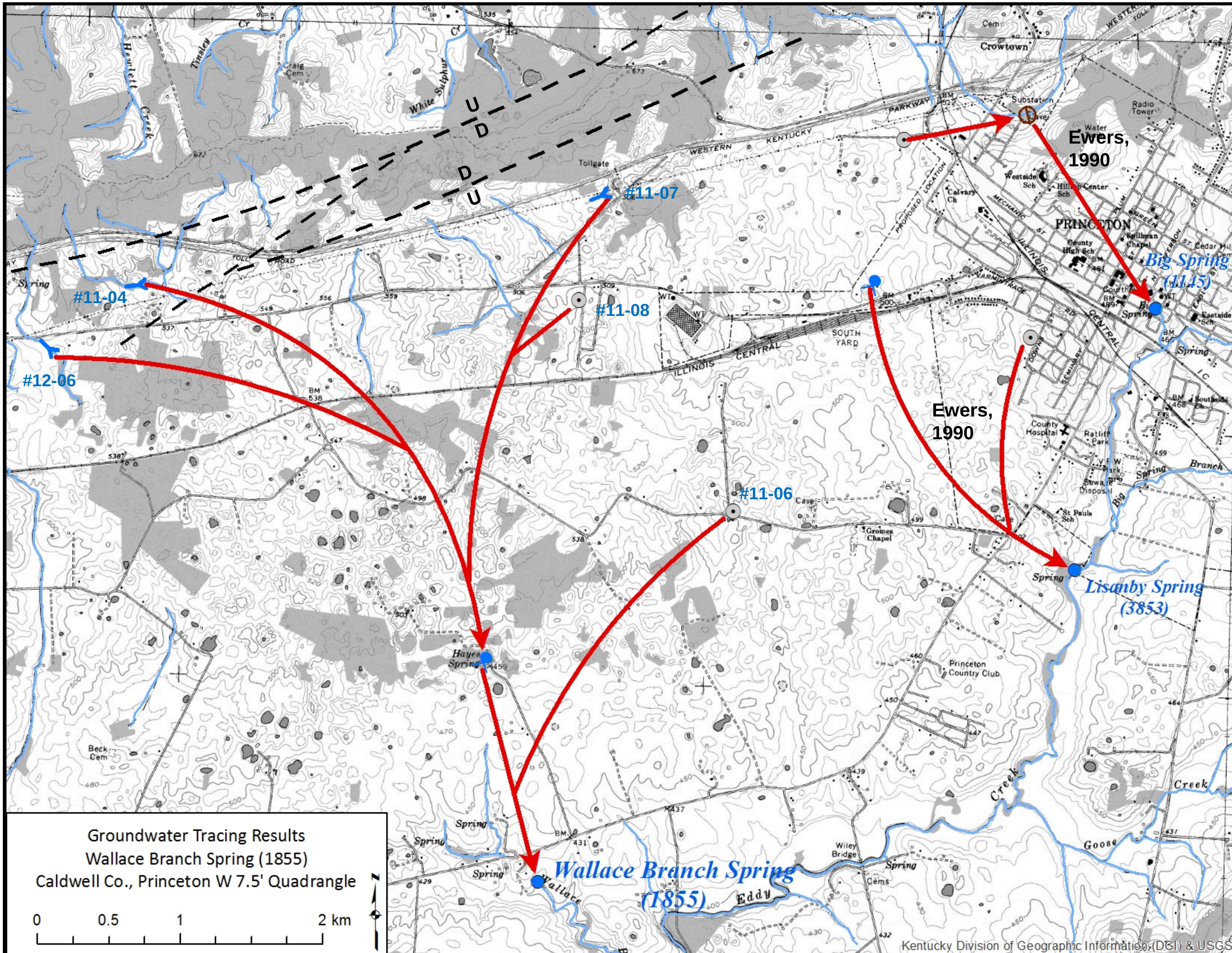

Figure 13. Wallace Branch Spring Tracer Map

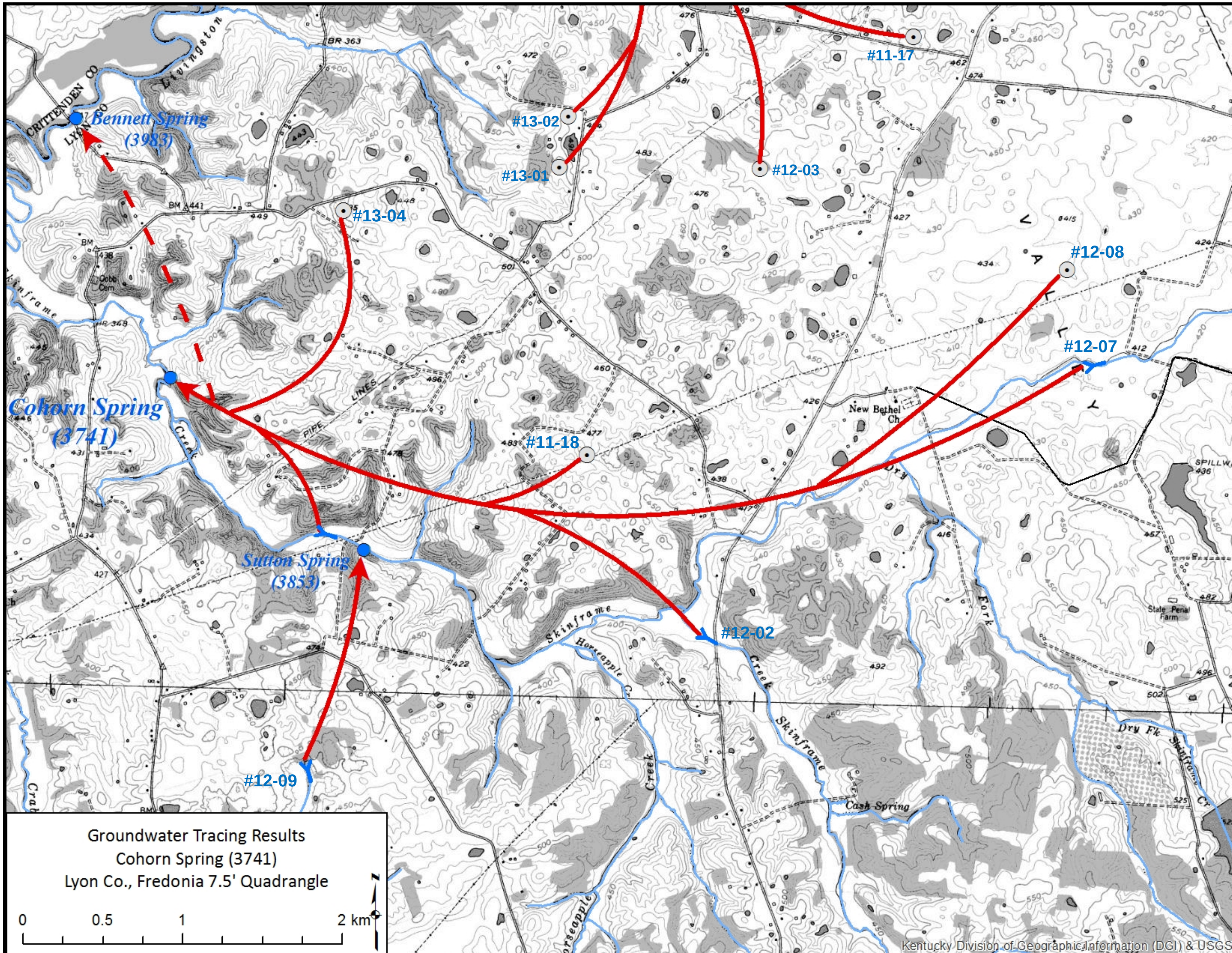

Figure 14. Cohorn Spring Tracer Map

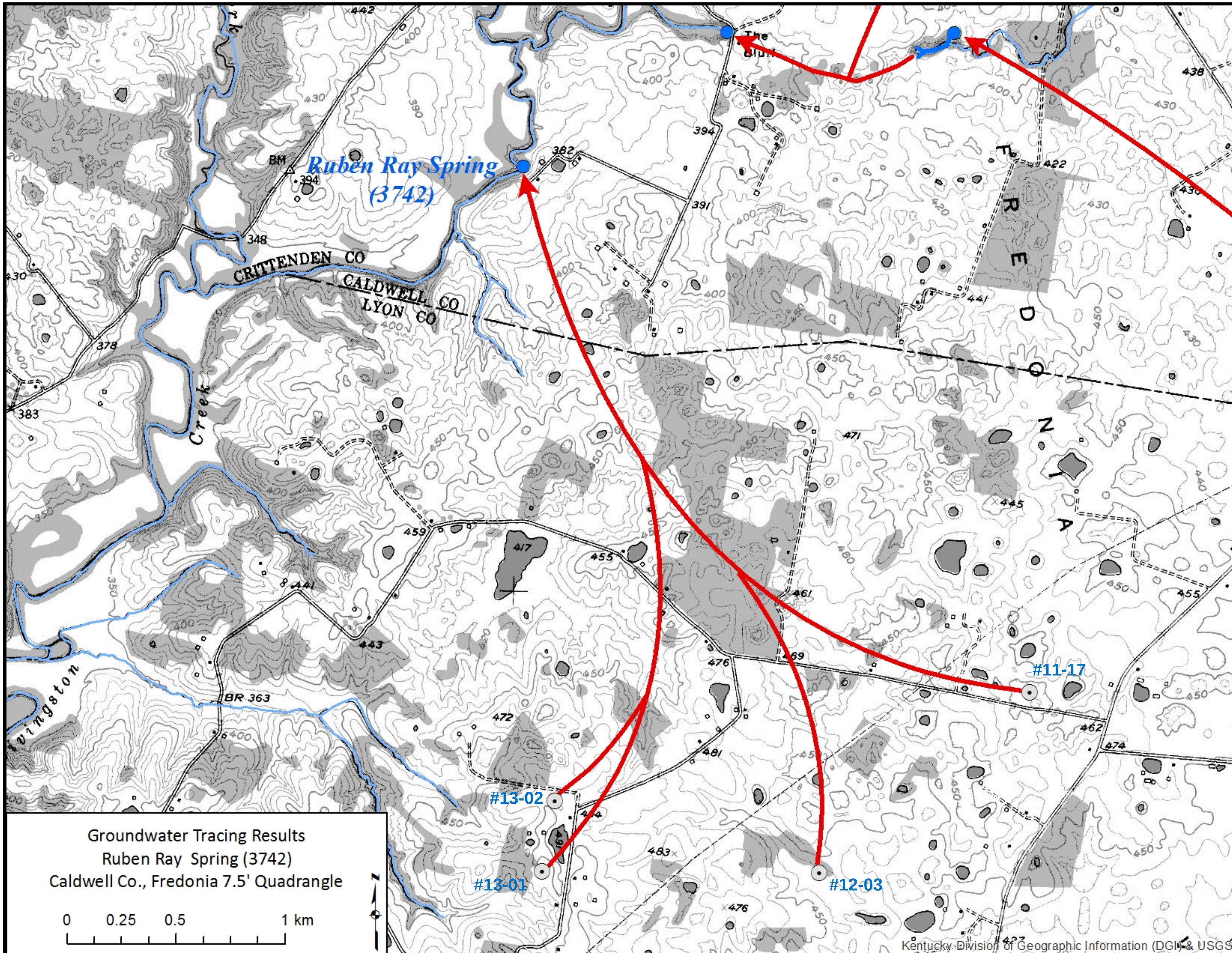

Figure 15. Ruben Ray Spring Tracer Map

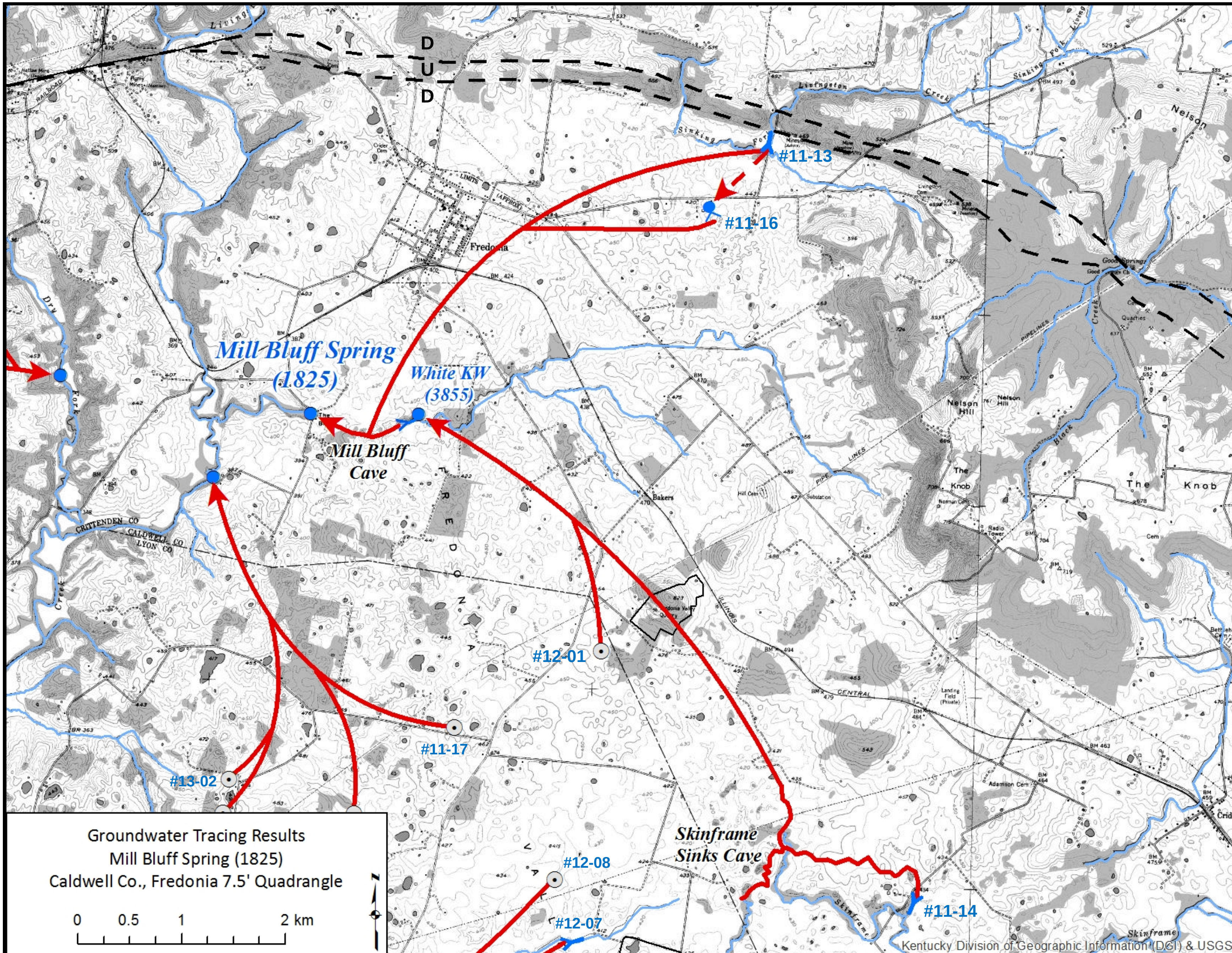

Figure 16. Mill Bluff Spring Tracer Map

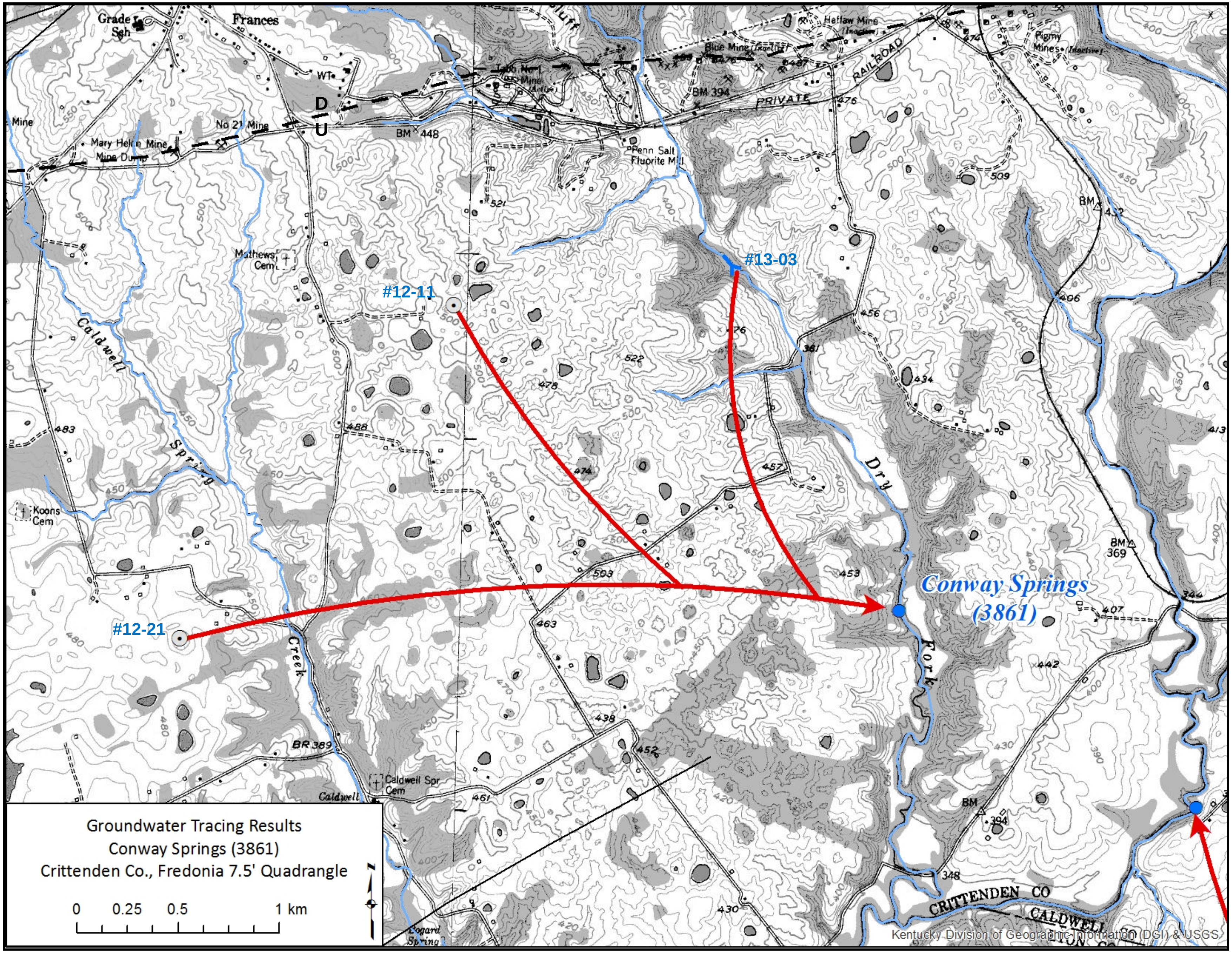

Figure 17. Conway Springs Tracer Map

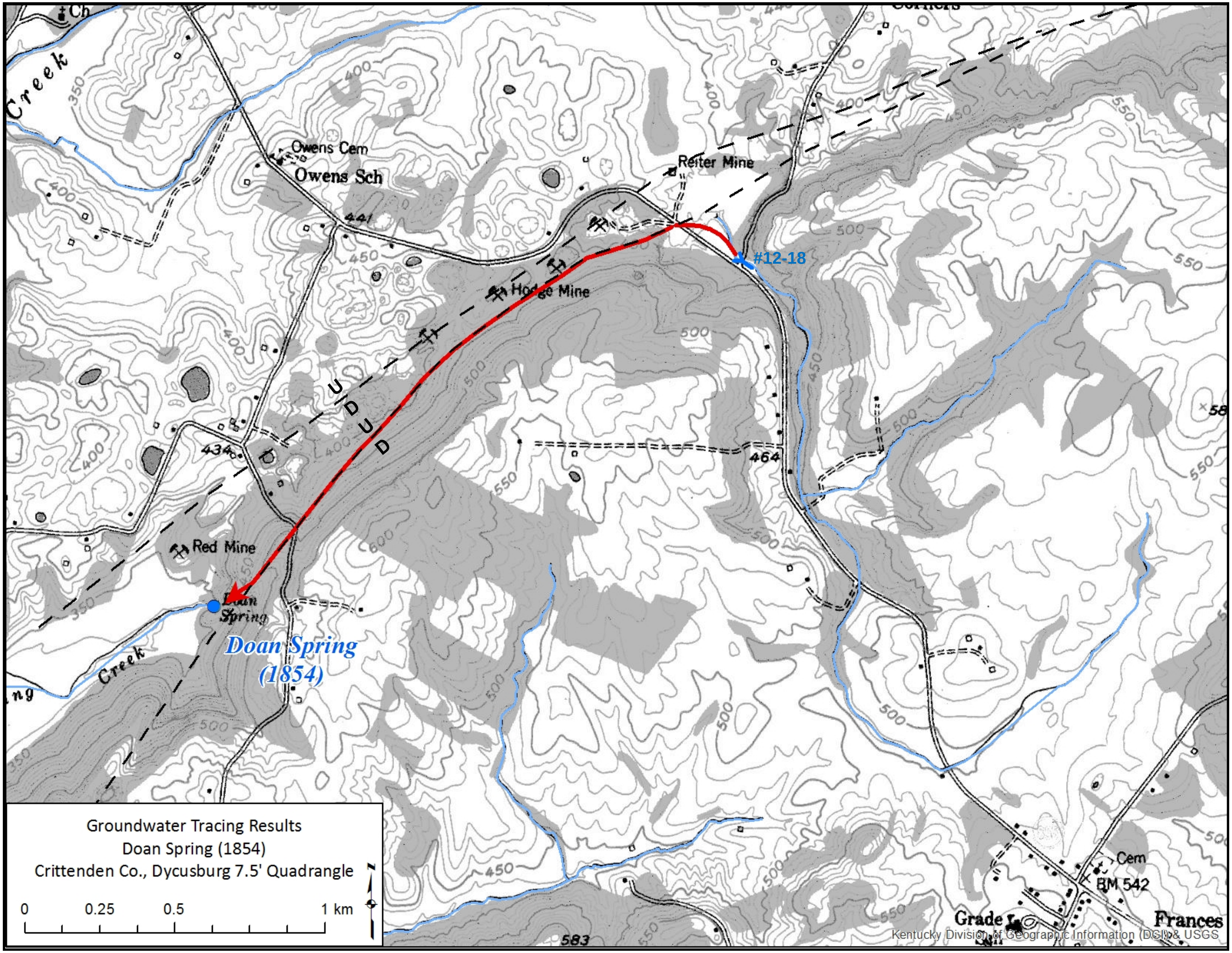

Figure 18. Doan Spring Tracer Map

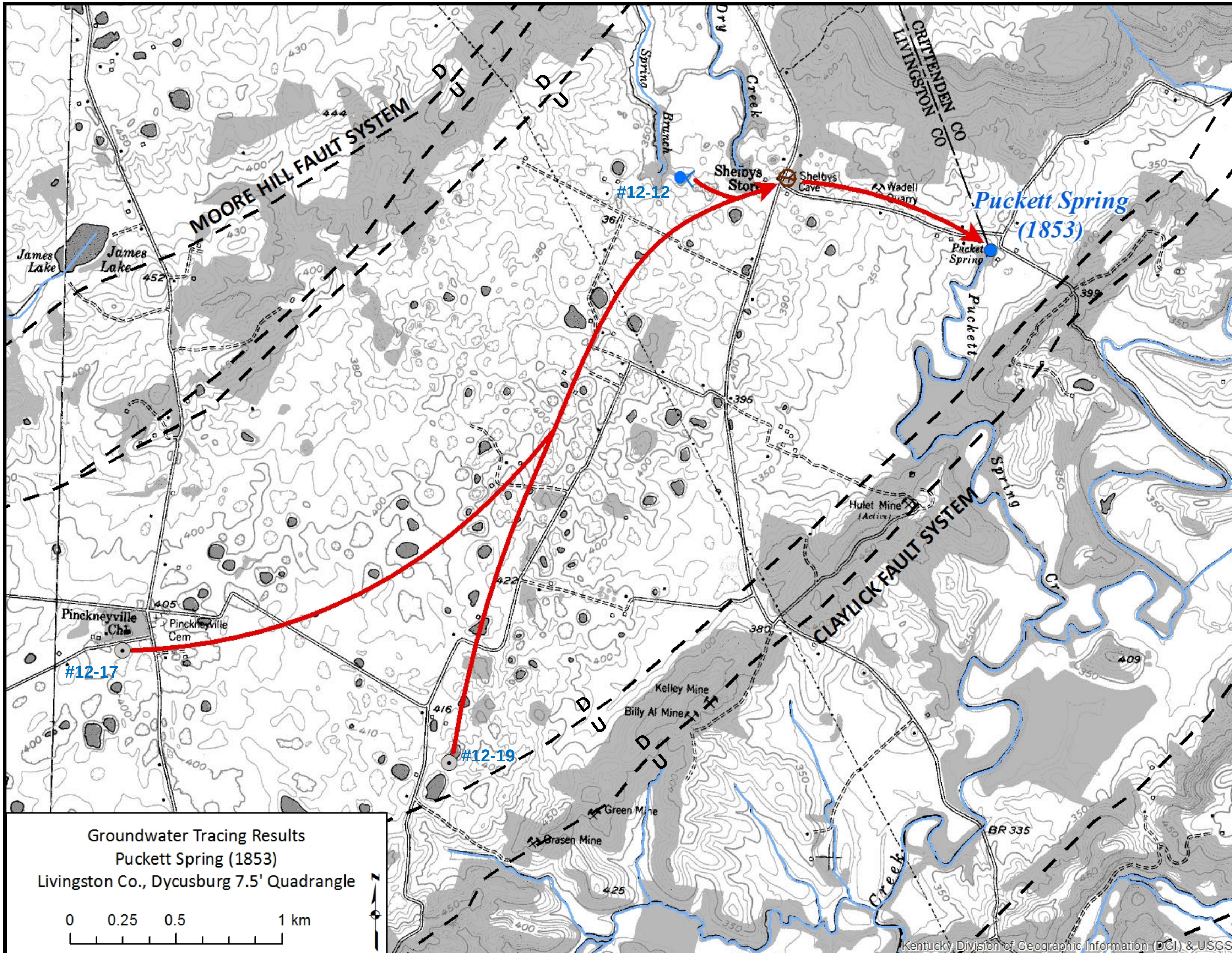

Figure 19. Puckett Spring Tracer Map

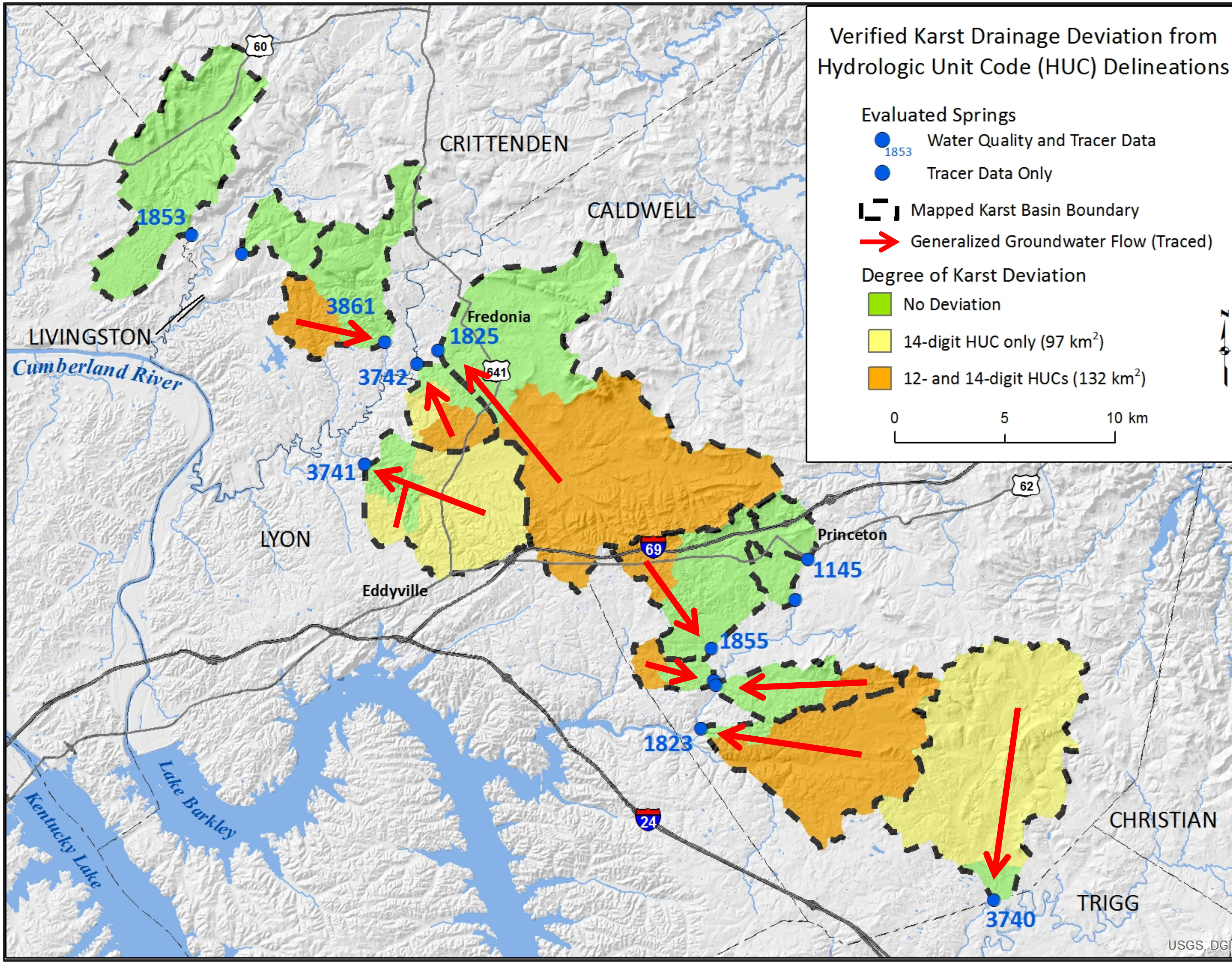

Figure 20. Verified Karst Drainage Deviation from HUC Boundaries

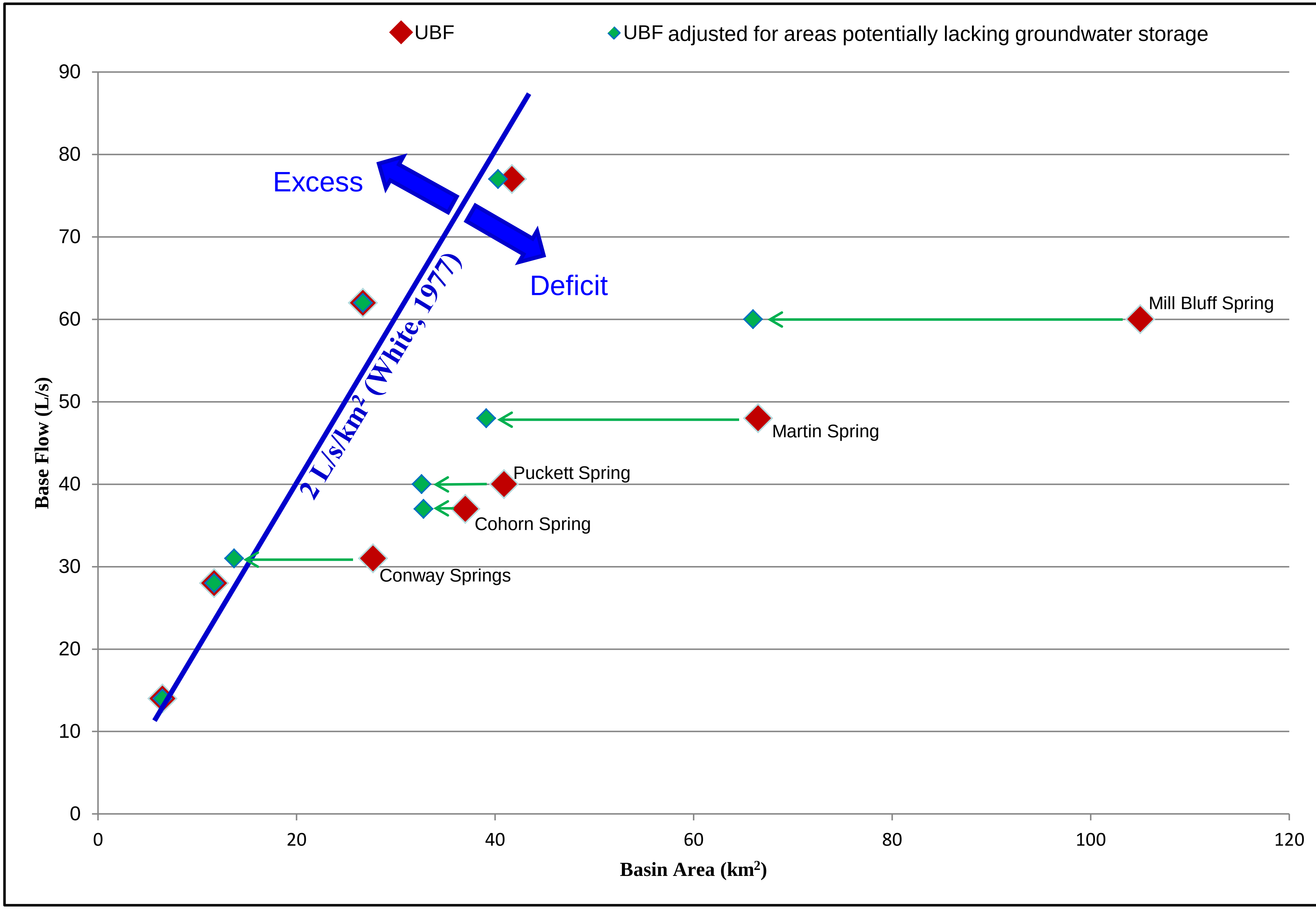

Figure 21. Unit Base Flow for Monitored Springs

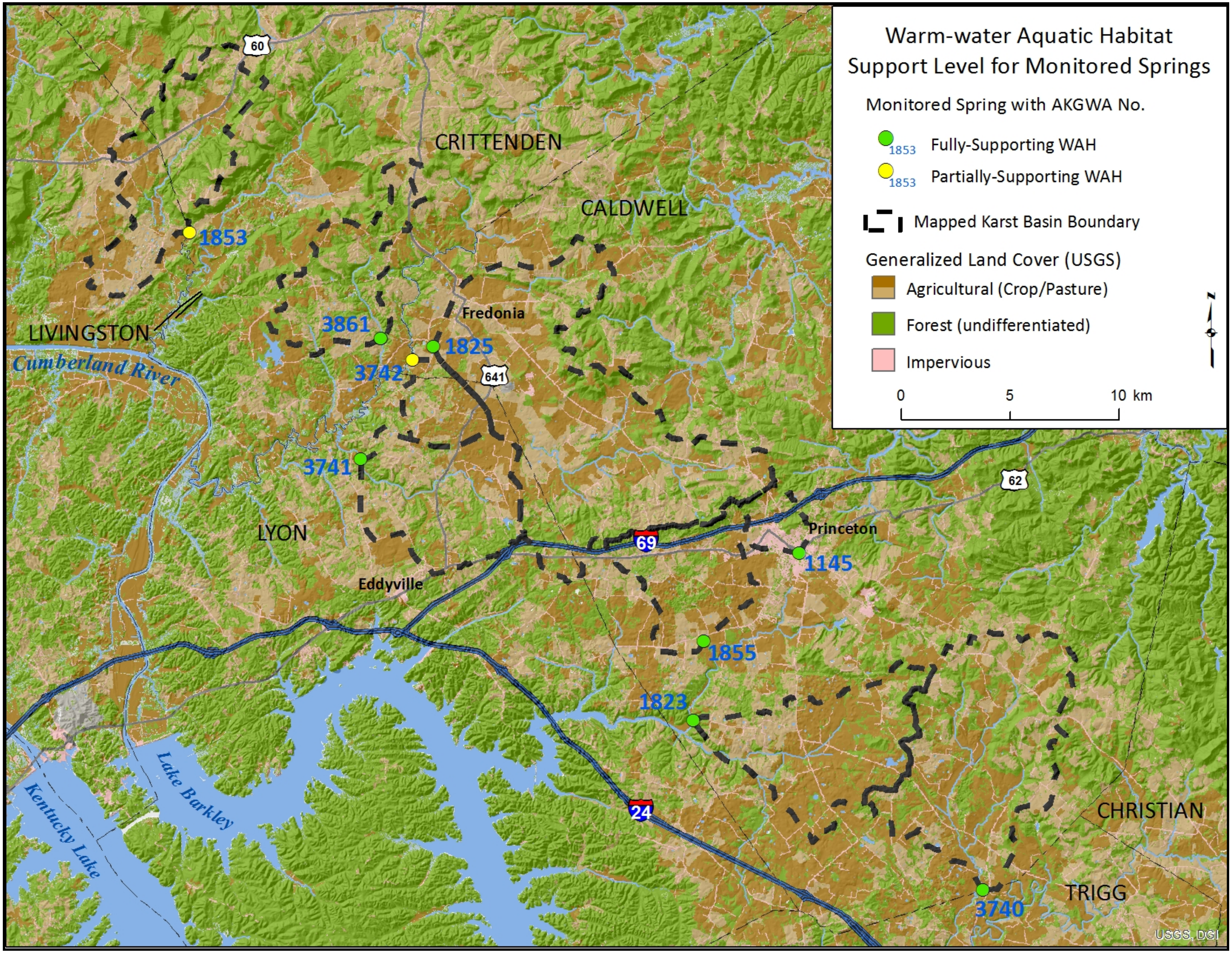

Figure 22. Monitored Springs WAH Support Level

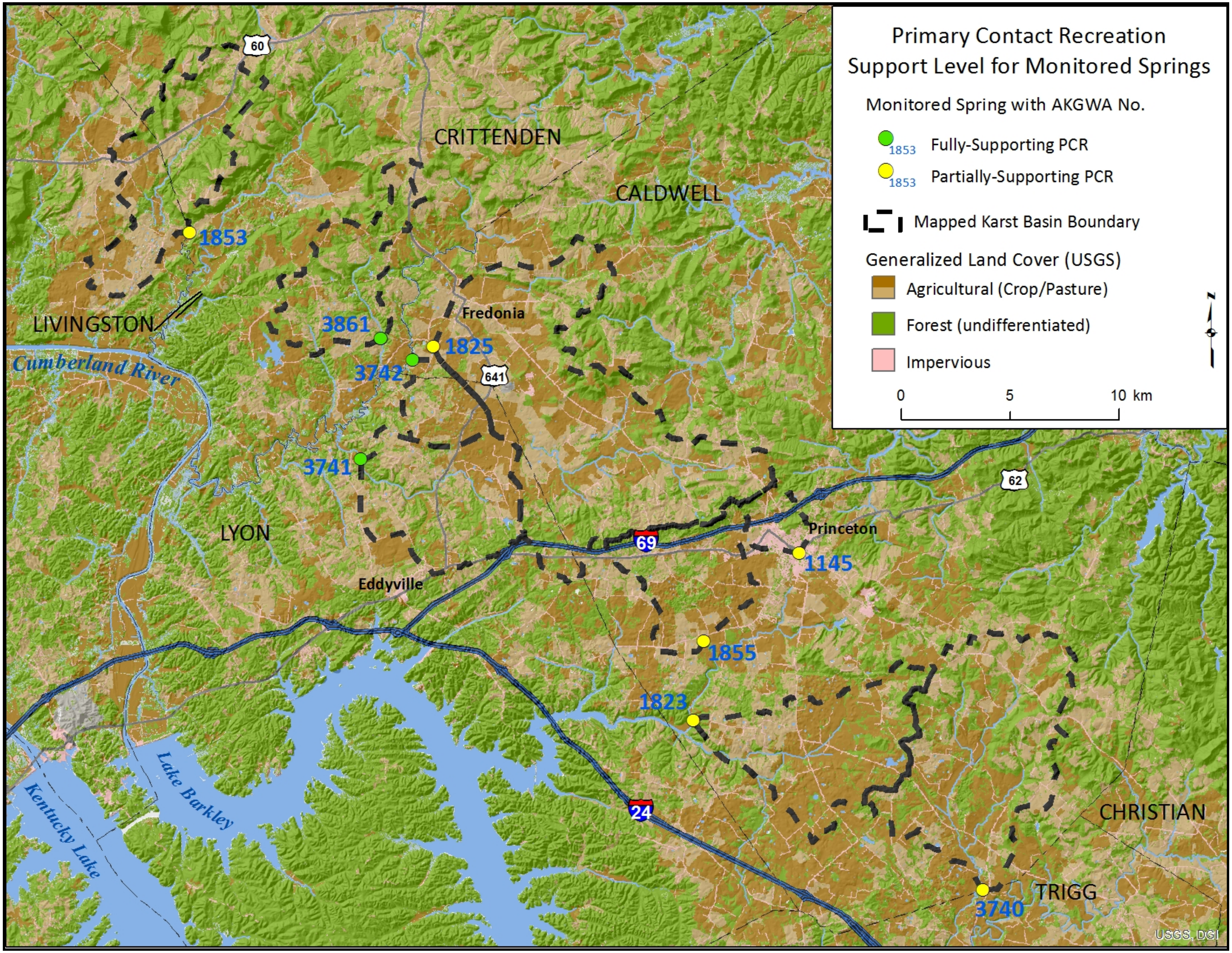

Figure 23. Monitored Springs PCR Support Level

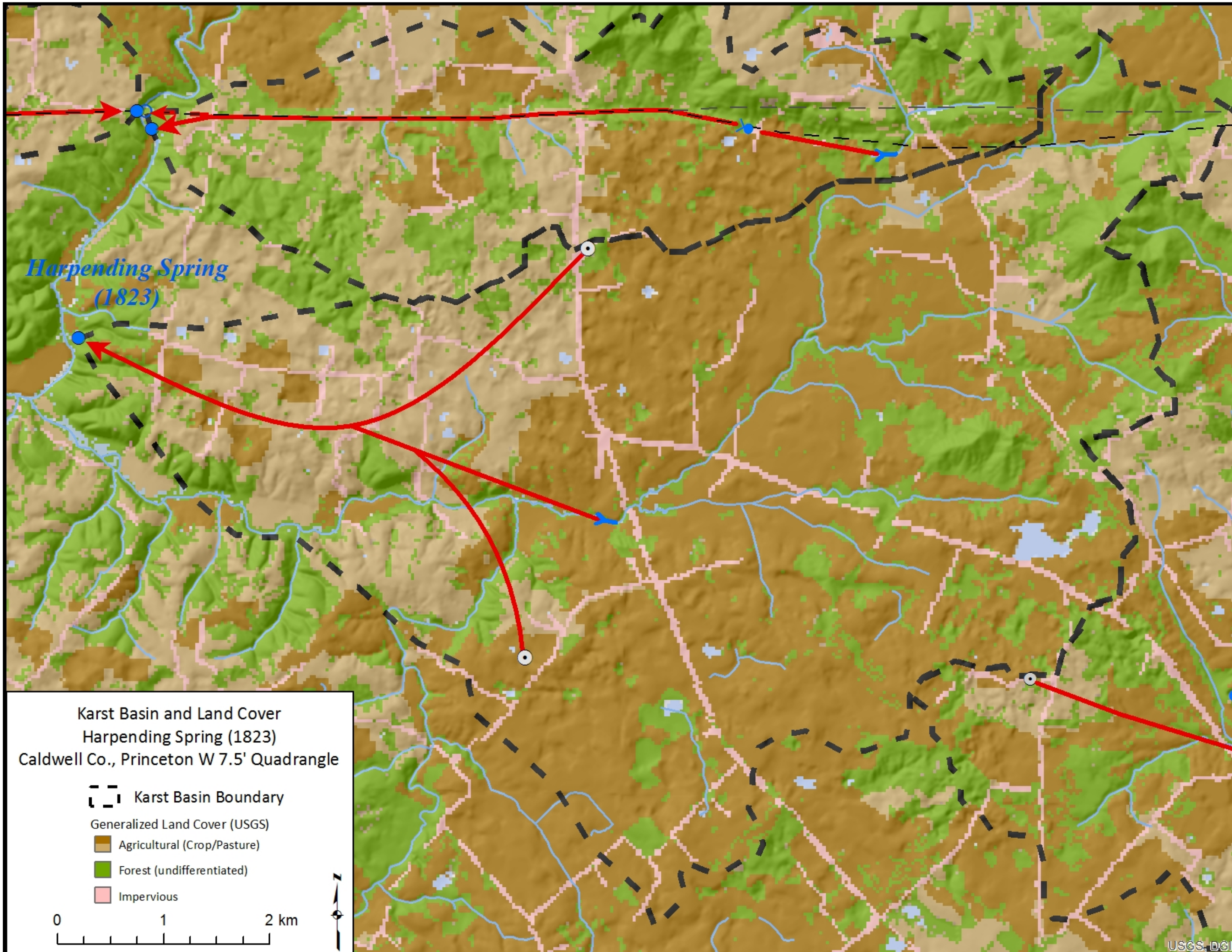

Figure 24. Harpending Spring Karst Basin and Land Cover Map (WAH-Full Support, PCR-Partial Support)

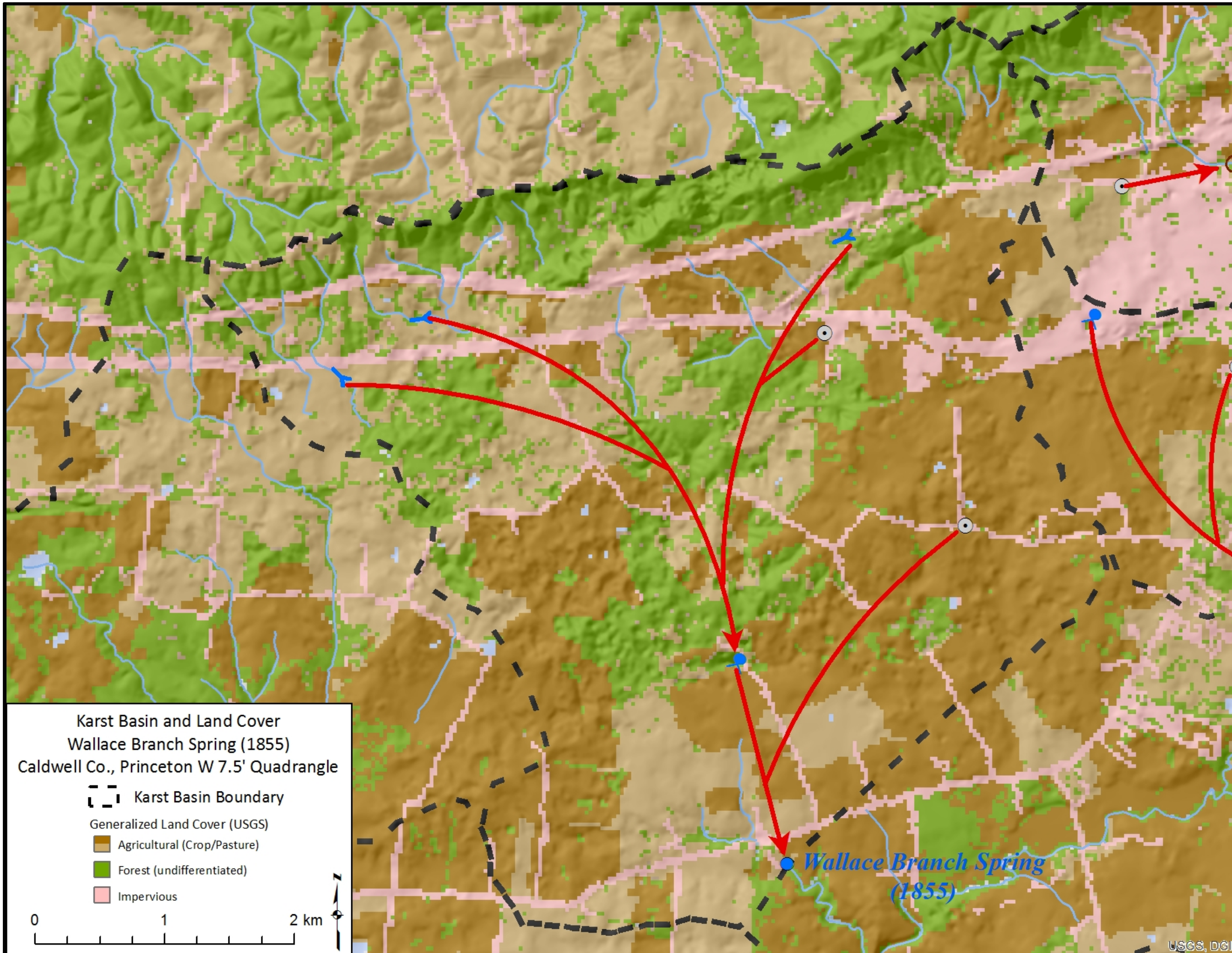

Figure 25. Wallace Branch Spring Karst Basin and Land Cover Map (WAH-Full Support, PCR-Partial Support)

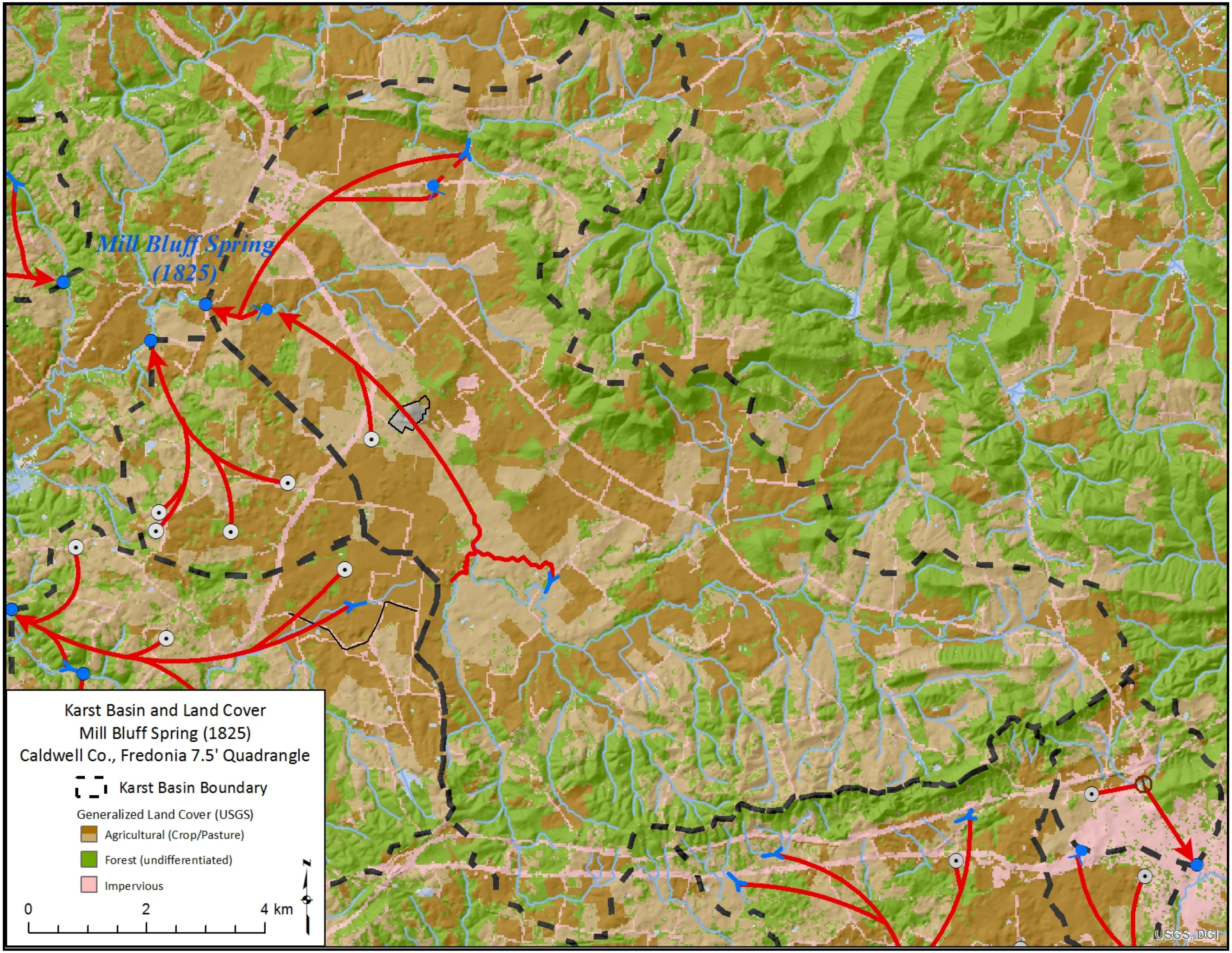

Figure 26. Mill Bluff Spring Karst Basin and Land Cover Map (WAH-Full Support, PCR-Partial Support)

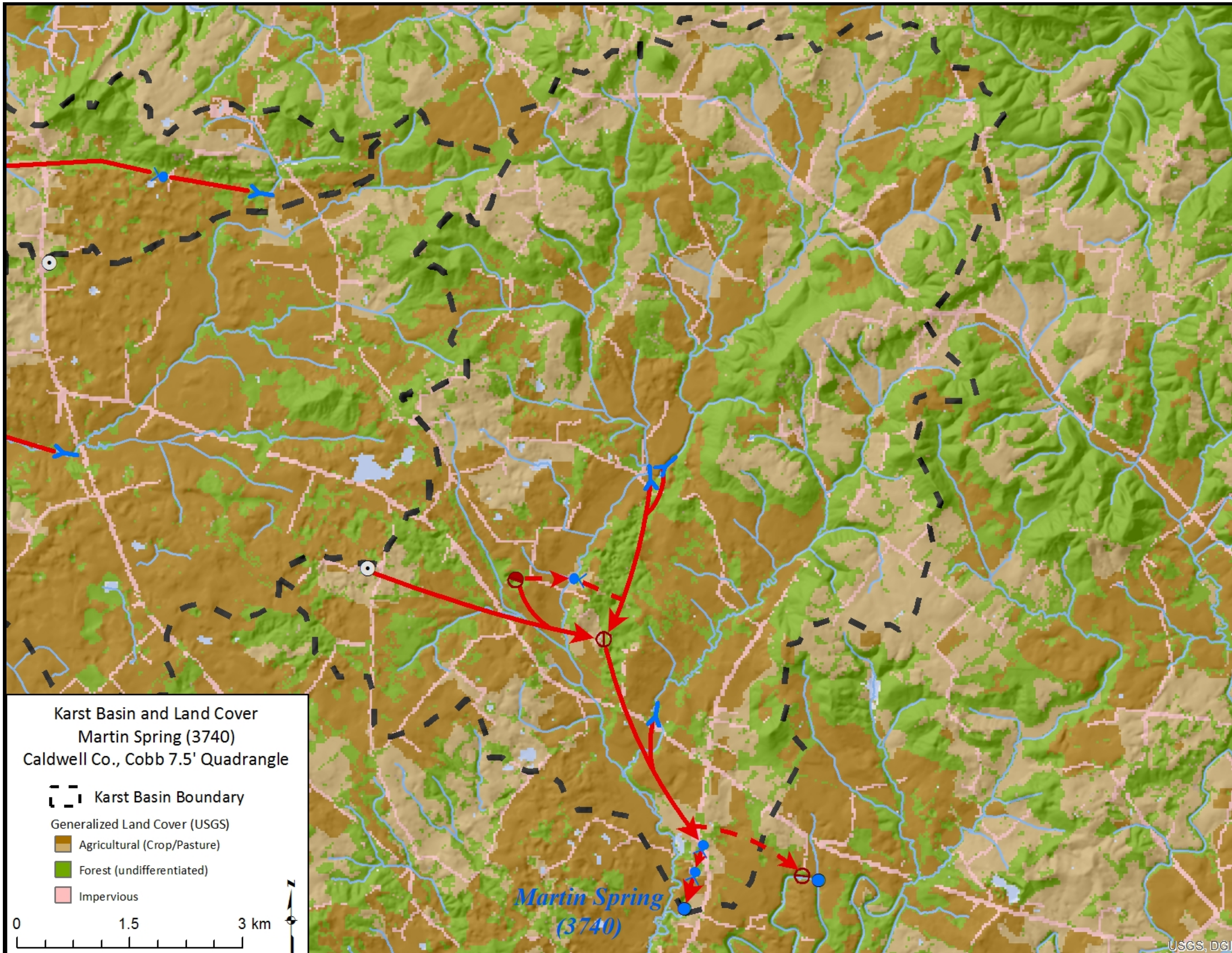

Figure 27. Martin Spring Karst Basin and Land Cover Map (WAH-Full Support, PCR-Partial Support)

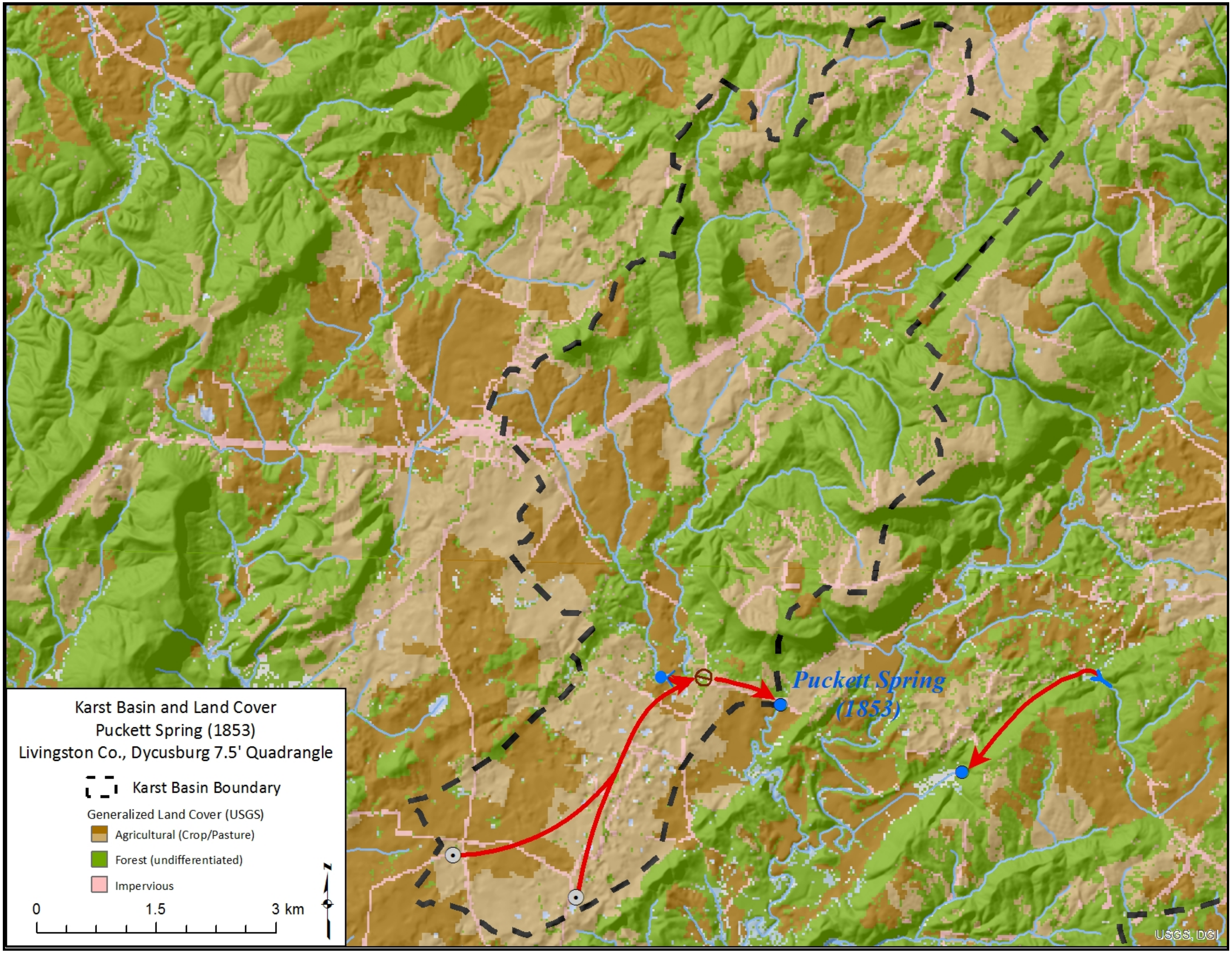

Figure 28. Puckett Spring Karst Basin and Land Cover Map (WAH-Partial Support, PCR-Partial Support)

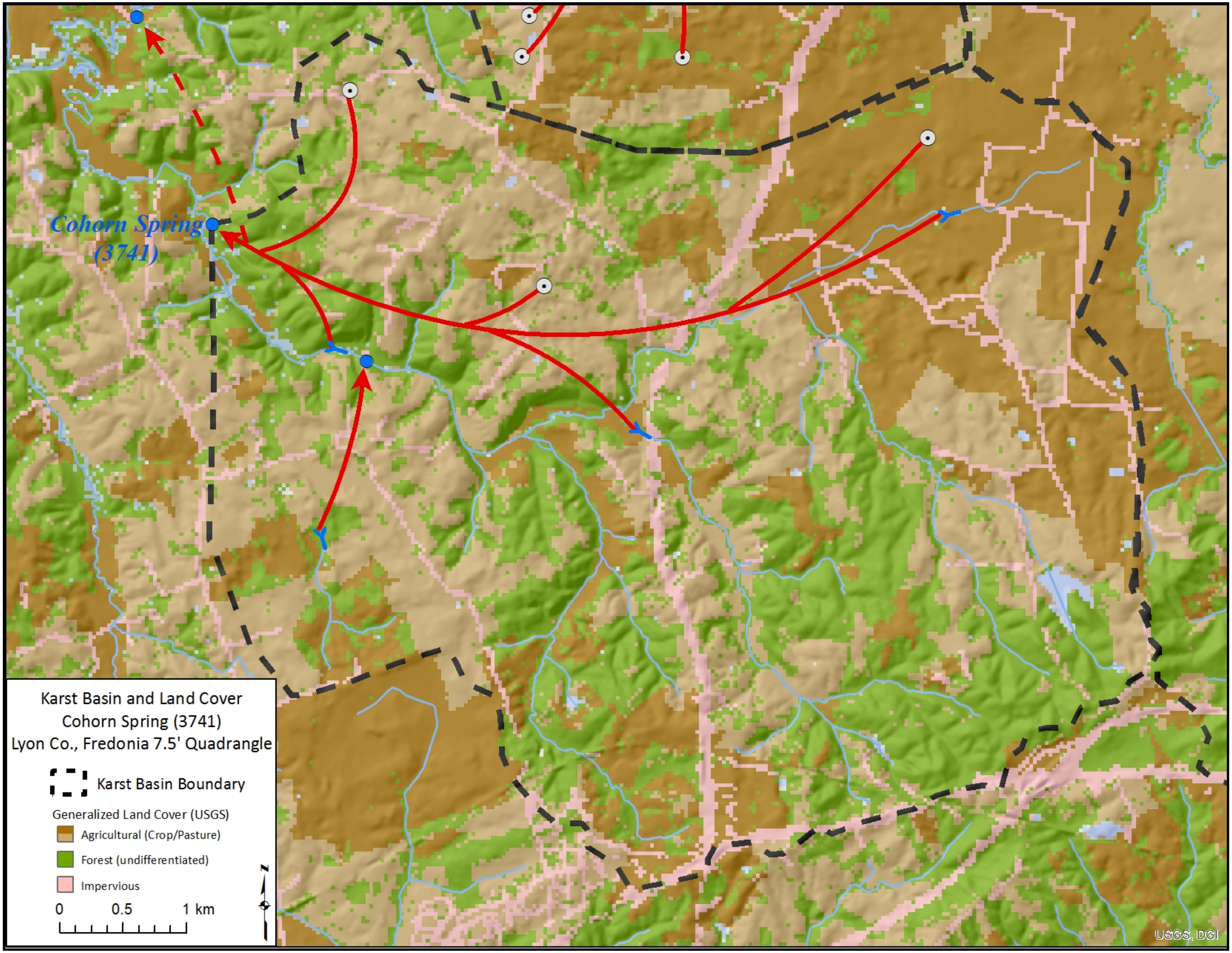

Figure 29. Cohorn Spring Karst Basin and Land Cover Map (WAH-Full Support, PCR-Full Support)

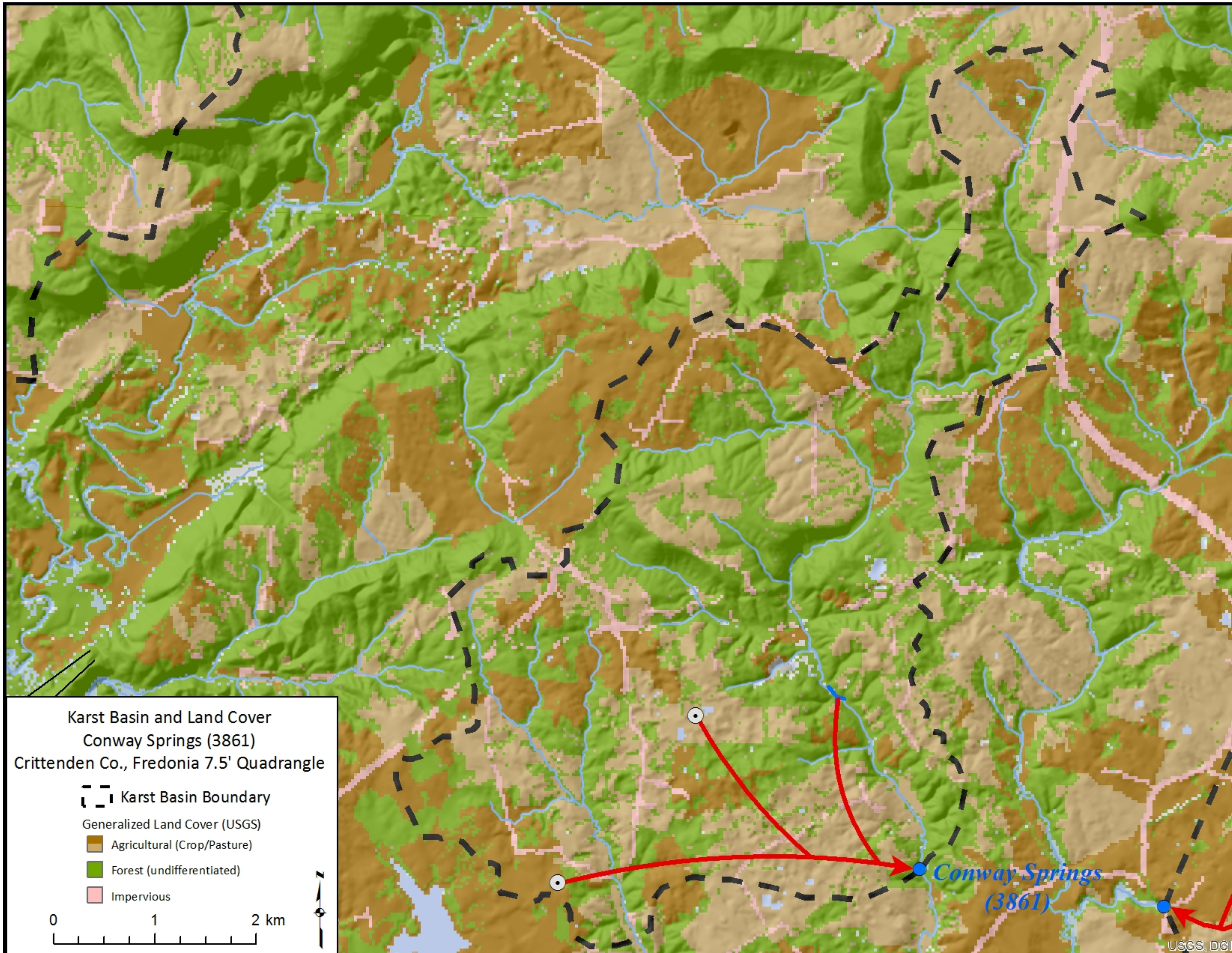

Figure 30. Conway Springs Karst Basin and Land Cover Map (WAH-Full Support, PCR-Full Support)

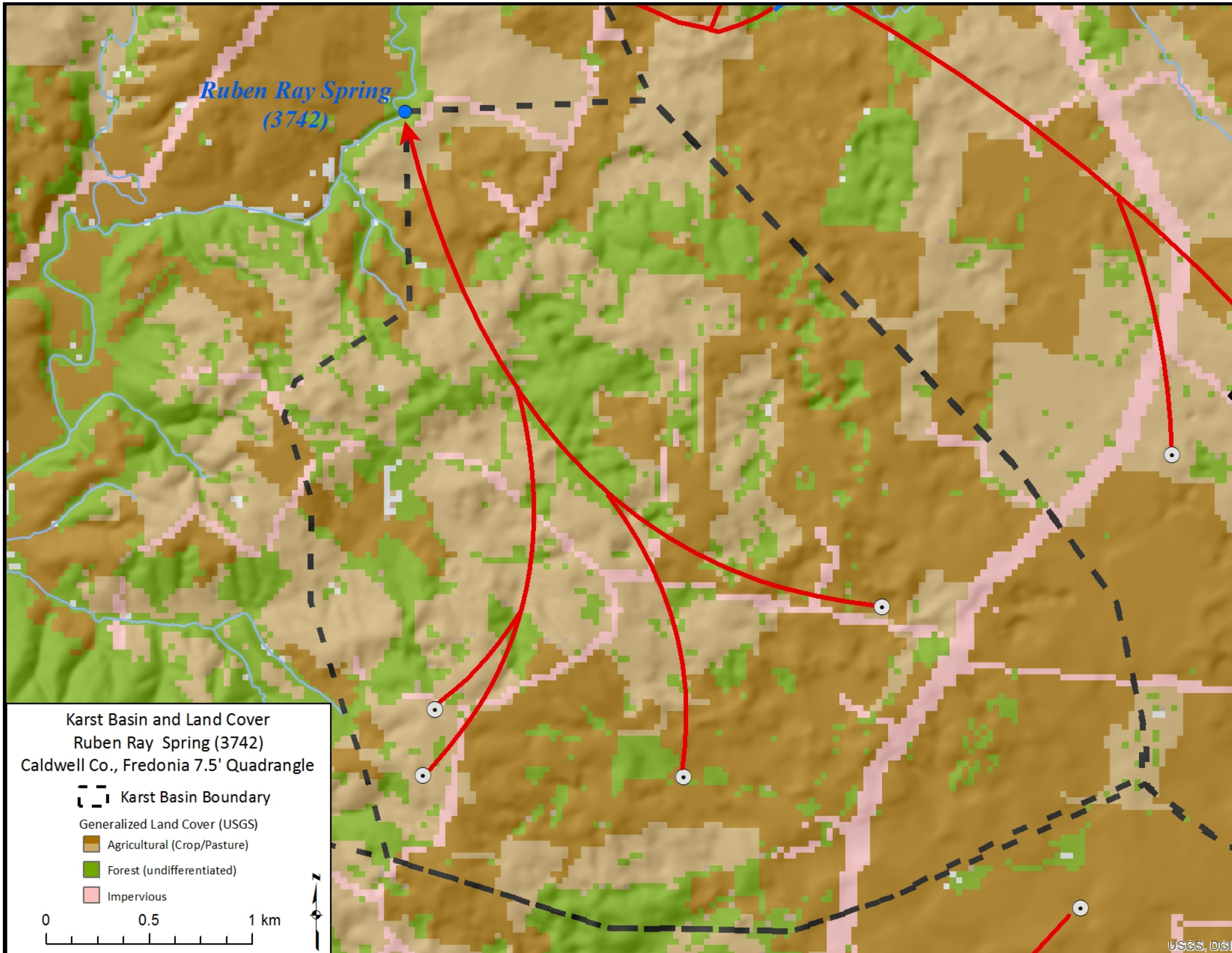

Figure 31. Ruben Ray Spring Karst Basin and Land Cover Map (WAH-Partial Support, PCR-Full Support)

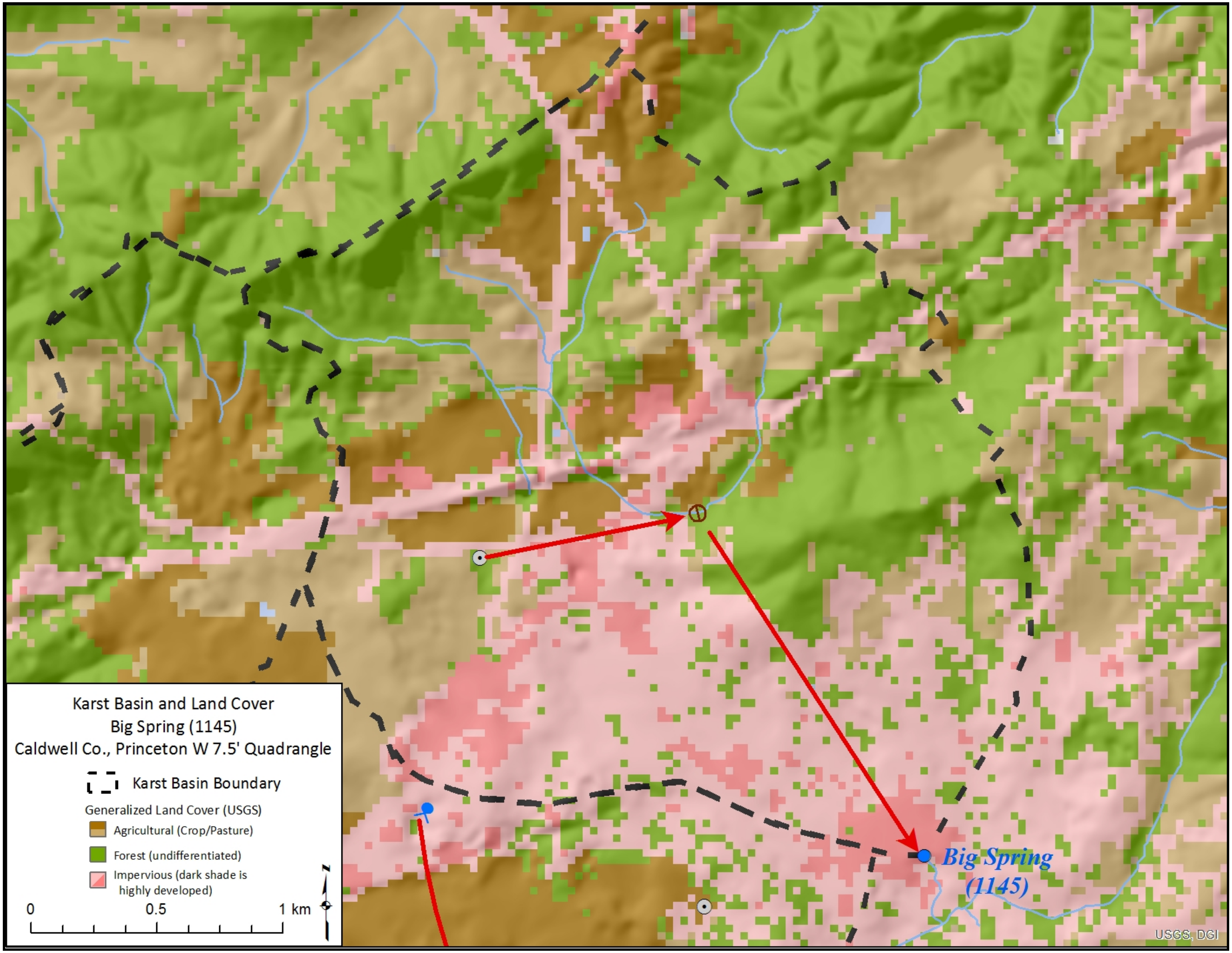

Figure 32. Big Spring Karst Basin and Land Cover Map (WAH-Full Support, PCR-Partial Support)

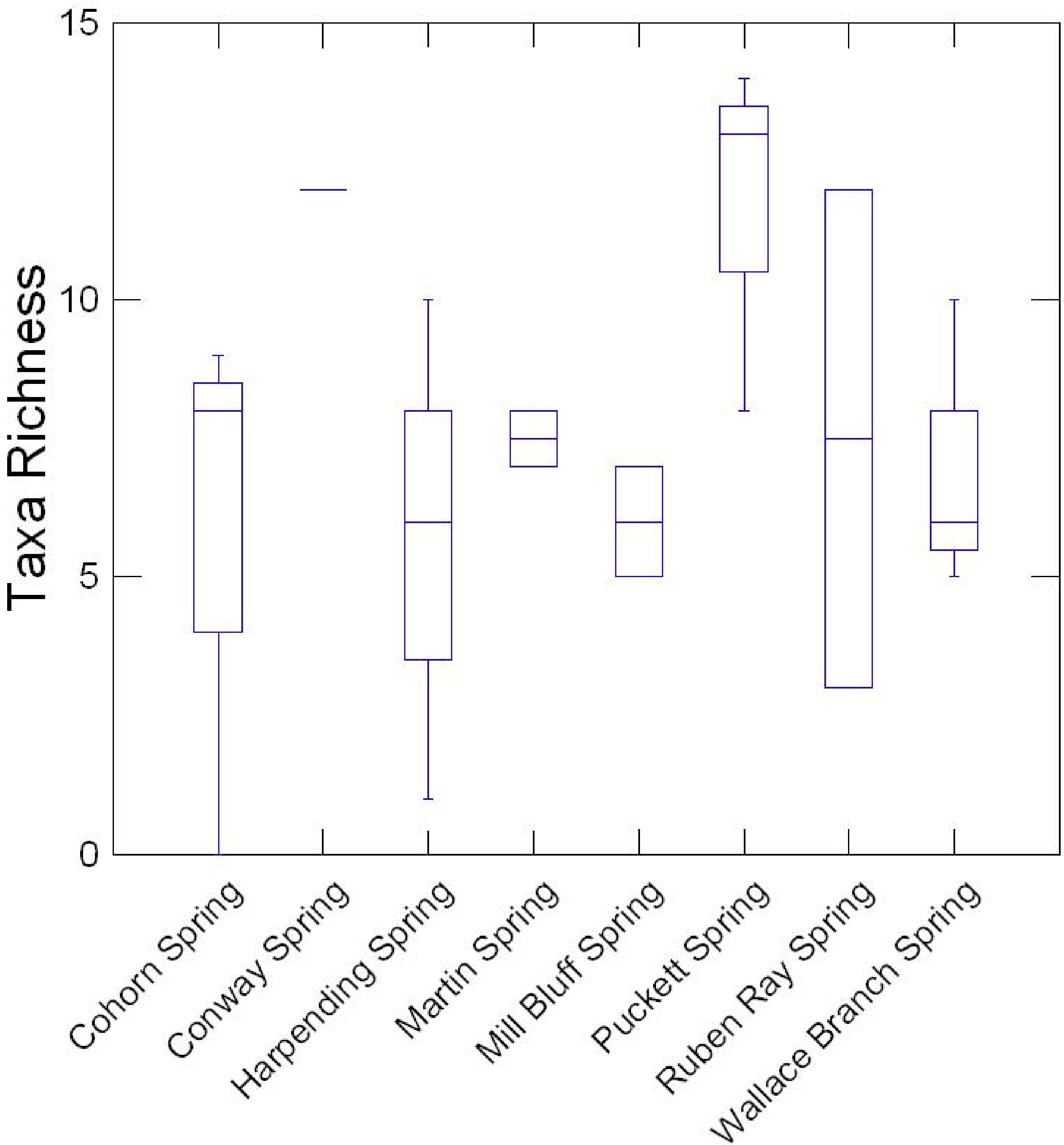

Figure 33. Mean Taxa Richness per Spring

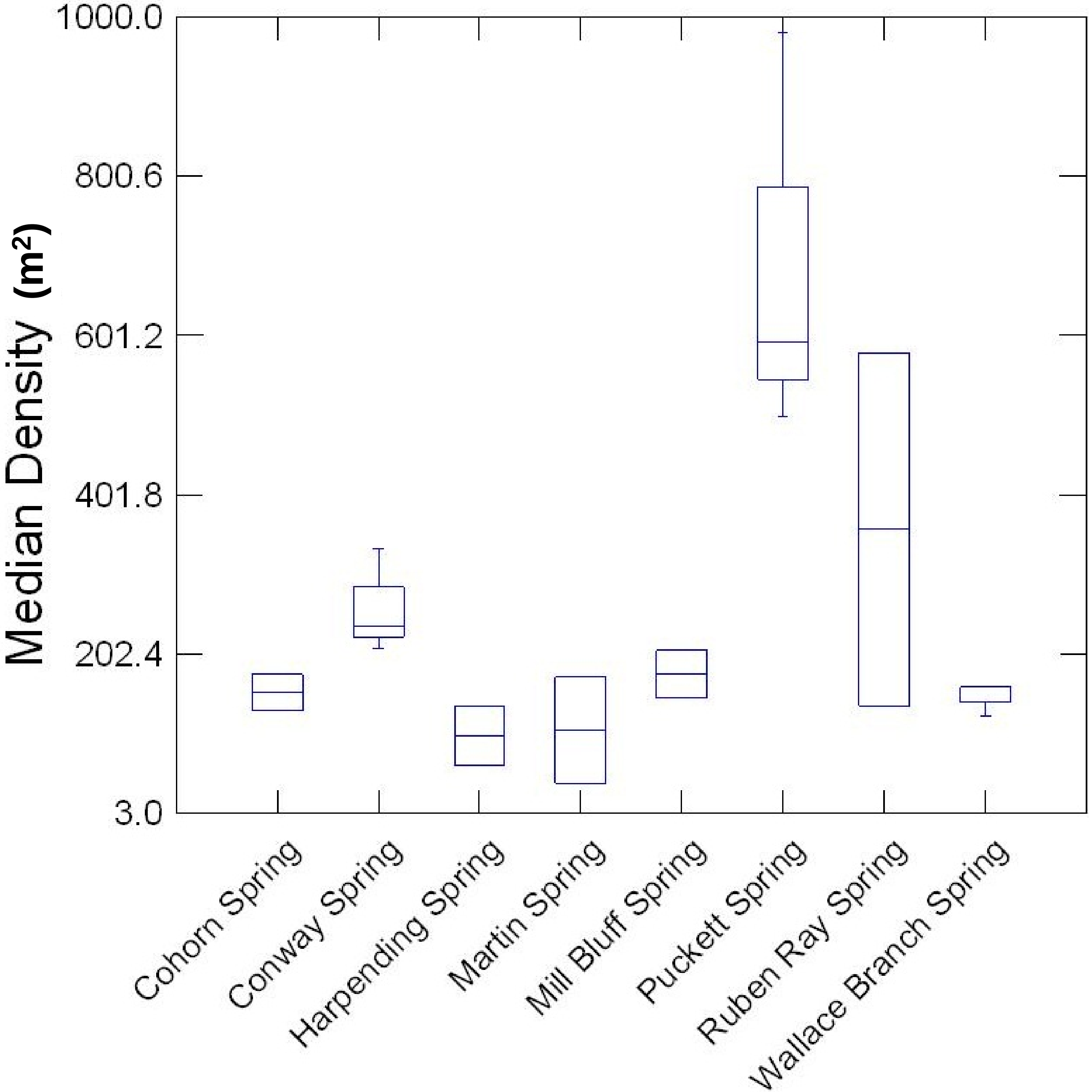

Figure 34. Median Macroinvertebrate Density per Spring (m^2)

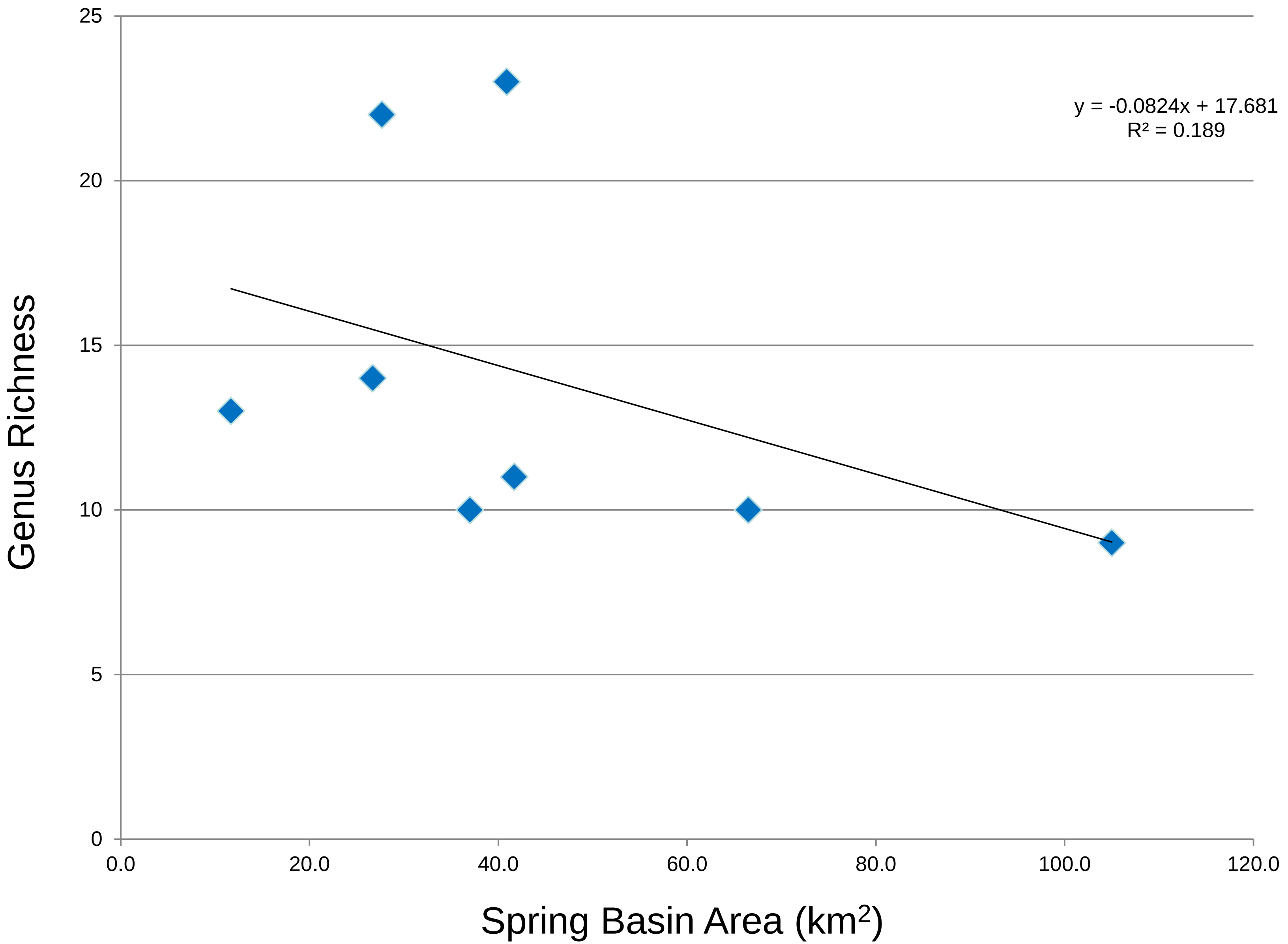

Figure 35. Relationship of Spring Basin Area to Taxa Richness

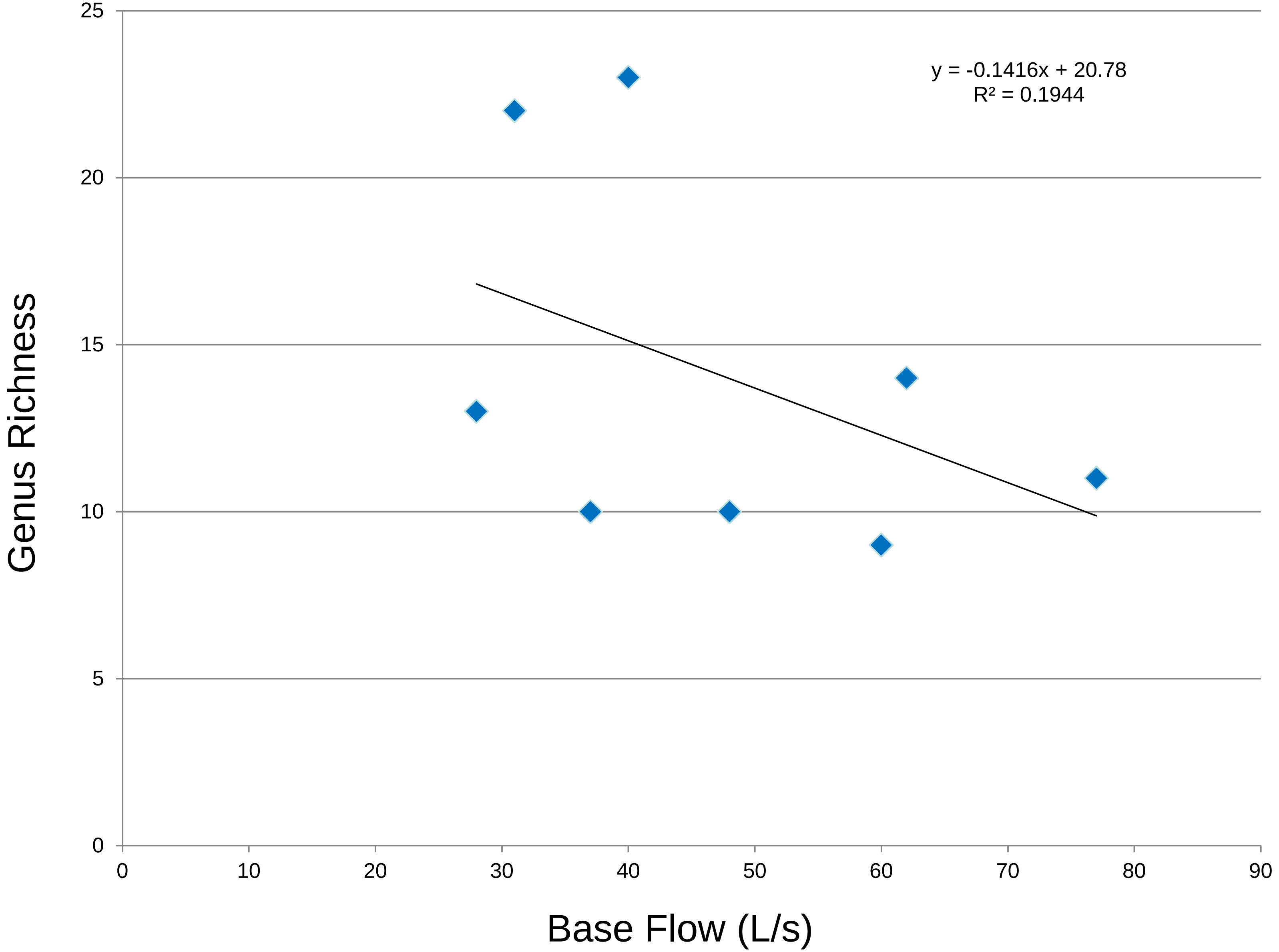

Figure 36. Relationship of Base Flow to Taxa Richness

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ?10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	
Arsenic	7440382	10		340	150	
Beta-Endosulfan	33213659	62	89	0.22	0.056	
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	
Chloropyrifos	2921882			0.083	0.041	
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	
Endrin	72208	0.76	0.81	0.086	0.036	
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	
Iron[6]	7439896			4,000	1,000	
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	
Malathion	121755				0.1	
Mercury	7439976	2	0.051	1.7	0.91	
Methoxychlor	72435	40			0.03	
Mirex	2385855				0.001	
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	
pH		6.5-8.5		6.0 - 9.0		
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	
Selenium	7782492	170	4,200	20	5	
Silver	7440224			e(1.72 (ln Hard*)-6.59)		
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		

Table 4. 401 KAR 10:031 Water Quality Standards – Simplified Checklist

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All non-detect
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	All non-detect
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	All non-detect
Arsenic	7440382	10		340	150	6 detects < Chronic
Beta-Endosulfan	33213659	62	89	0.22	0.056	All non-detect
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	All non-detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All detects < Chronic
Chlorpyrifos	2921882			0.083	0.041	All non-detect
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	7 detects < Chronic
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Diazinon	333415			0.17	0.17	All non-detect
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All non-detect
Dissolved Oxygen				4.0 mg/L	4.0 mg/L	Range: 5.0 - 8.6 mg/L
Endrin	72208	0.76	0.81	0.086	0.036	All non-detect
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All non-detect
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All non-detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All non-detect
Iron[6]	7439896			4,000	1,000	1 detect ≥ Chronic
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	6 detects < Chronic
Malathion	121755				0.1	All non-detect
Mercury	7439976	2	0.051	1.7	0.91	All non-detect
Methoxychlor	72435	40			0.03	All non-detect
Mirex	2385855				0.001	MDL > Standard; All ND
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	11 detects < Chronic
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All non-detect
pH		6.5-8.5		6.0 - 9.0		Range: 6.7 - 6.9
Phthalate esters	N/A				3	3 detects ≤ Chronic
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	MDL > Standard; All ND
Selenium	7782492	170	4,200	20	5	2 detects < Chronic
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All non-detect
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		Range: 12.7 - 16.3 C
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	NO DATA
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	9 detects < Chronic
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	All non-detect
E. Coli (Sec7-Primary Contact)		< 1		Geometric Mean < 130 CFU		Geo-mean = 158.04 CFU

Table 45. Harpending Spring (1823) Water Quality Checklist

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All non-detect
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	All non-detect
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	1 detect; Y < 0.05 mg/L
Arsenic	7440382	10		340	150	9 detects < Chronic
Beta-Endosulfan	33213659	62	89	0.22	0.056	All non-detect
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	All non-detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	12 detects < Chronic
Chlorpyrifos	2921882			0.083	0.041	All non-detect
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	7 detects < Chronic
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Diazinon	333415			0.17	0.17	All non-detect
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All non-detect
Dissolved Oxygen				4.0 mg/L	4.0 mg/L	Range: 6.1 - 10.2 mg/L
Endrin	72208	0.76	0.81	0.086	0.036	All non-detect
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All non-detect
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All non-detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All non-detect
Iron[6]	7439896			4,000	1,000	2 detects>Chronic; 1 detect > Acute
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	6 detects < Chronic
Malathion	121755				0.1	All non-detect
Mercury	7439976	2	0.051	1.7	0.91	All non-detect
Methoxychlor	72435	40			0.03	All non-detect
Mirex	2385855				0.001	MDL > Standard; All ND
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	9 detects < Chronic
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	1 detect < Chronic
pH		6.5-8.5		6.0 - 9.0		Range: 6.85 - 7.4
Phthalate esters	N/A				3	2 detects > Chronic
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	MDL > Standard; All ND
Selenium	7782492	170	4,200	20	5	2 detects < Chronic
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All non-detect
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		Range: 13.1 - 15.8 C
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	NO DATA
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	11 detects < Chronic
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	All non-detect
E. Coli (Sec7-Primary Contact)		< 1		Geometric Mean < 130 MPN		Geo-mean = 679.30 CFU

Table 46. Wallace Branch Spring (1855) Water Quality Checklist

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria μg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		1 detect < Chronic
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	All non-detect
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	2 detects; Y < 0.05 mg/L
Arsenic	7440382	10		340	150	11 detects < Chronic
Beta-Endosulfan	33213659	62	89	0.22	0.056	All non-detect
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	All non-detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	12 detects < Chronic
Chlorpyrifos	2921882			0.083	0.041	All non-detect
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	11 detects < Chronic
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Diazinon	333415			0.17	0.17	All non-detect
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All non-detect
Dissolved Oxygen				4.0 mg/L	4.0 mg/L	Range: 6.8 - 11.3 mg/L
Endrin	72208	0.76	0.81	0.086	0.036	All non-detect
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All non-detect
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All non-detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All non-detect
Iron[6]	7439896			4,000	1,000	1 detect ≥ Chronic
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	12 detects < Chronic
Malathion	121755				0.1	All non-detect
Mercury	7439976	2	0.051	1.7	0.91	All non-detect
Methoxychlor	72435	40			0.03	All non-detect
Mirex	2385855				0.001	MDL > Standard; All ND
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	12 detects < Chronic
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All non-detect
pH		6.5-8.5		6.0 - 9.0		Range: 7.2 - 7.7
Phthalate esters	N/A				3	All non-detect
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	MDL > Standard; All ND
Selenium	7782492	170	4,200	20	5	2 detects < Chronic
Silver	7440224			e(1.72 (ln Hard*)-6.59)		1 detect < Chronic
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		Range: 11.2 - 17.7
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	NO DATA
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	7 detects < Chronic
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	1 detect > Chronic
E. Coli (Sec7-Primary Contact)		< 1		Geometric Mean < 130 CFU		Geo-mean = 351.61 CFU

Table 47. Mill Bluff Spring (1825) Water Quality Checklist

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All non-detect
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	All non-detect
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	2 detects, Y < 0.05 mg/L
Arsenic	7440382	10		340	150	9 detects < Chronic
Beta-Endosulfan	33213659	62	89	0.22	0.056	All non-detect
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	All non-detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	12 detects < Chronic
Chlorpyrifos	2921882			0.083	0.041	All non-detect
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	9 detects < Chronic
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Diazinon	333415			0.17	0.17	1 detect < Chronic
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All non-detect
Dissolved Oxygen				4.0 mg/L	4.0 mg/L	Range: 4.2 - 10.5 mg/L
Endrin	72208	0.76	0.81	0.086	0.036	All non-detect
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All non-detect
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All non-detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All non-detect
Iron[6]	7439896			4,000	1,000	2 detects ≥ Chronic
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	9 detects < Chronic
Malathion	121755				0.1	All non-detect
Mercury	7439976	2	0.051	1.7	0.91	All non-detect
Methoxychlor	72435	40			0.03	All non-detect
Mirex	2385855				0.001	MDL > Standard; All non-detect
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	9 detects < Chronic
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All non-detect
pH		6.5-8.5		6.0 - 9.0		Range: 7.0 - 7.4
Phthalate esters	N/A				3	2 detects > Chronic
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	MDL > Standard; All ND
Selenium	7782492	170	4,200	20	5	3 detects < Chronic
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All non-detect
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		Range: 10.8 - 18.8 C
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	NO DATA
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	10 detects < Chronic
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	All non-detect
E. Coli (Sec7-Primary Contact)		< 1		Geometric Mean < 130 CFU		Geo-mean = 288.15 CFU

Table 48. Martin Spring (3740) Water Quality Checklist

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		1 detect < Acute
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	All non-detect
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	8 detects; Y < 0.05 mg/L
Arsenic	7440382	10		340	150	11 detects < Chronic
Beta-Endosulfan	33213659	62	89	0.22	0.056	All non-detect
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	All non-detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	12 detects < Chronic
Chlorpyrifos	2921882			0.083	0.041	All non-detect
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	1 detect ≥ Chronic
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Diazinon	333415			0.17	0.17	All non-detect
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All non-detect
Dissolved Oxygen				4.0 mg/L	4.0 mg/L	Range: 2.9 - 10.2 mg/L
Endrin	72208	0.76	0.81	0.086	0.036	All non-detect
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All non-detect
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All non-detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All non-detect
Iron[6]	7439896			4,000	1,000	1 detect > Chronic
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	3 detects > Chronic
Malathion	121755				0.1	All non-detect
Mercury	7439976	2	0.051	1.7	0.91	All non-detect
Methoxychlor	72435	40			0.03	All non-detect
Mirex	2385855				0.001	MDL > Standard; All ND
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	11 detects < Chronic
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All non-detect
pH		6.5-8.5		6.0 - 9.0		Range: 6.9 - 7.4
Phthalate esters	N/A				3	3 detects > Chronic
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	MDL > Standard; All ND
Selenium	7782492	170	4,200	20	5	2 detects < Chronic
Silver	7440224			e(1.72 (ln Hard*)-6.59)		1 detect < Acute
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		Range: 10.0 - 18.4 C
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	NO DATA
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	12 detects < Chronic
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	All non-detect
E. Coli (Sec7-Primary Contact)		< 1		Geometric Mean < 130 CFU		Geo-mean = 606.34 CFU

Table 49. Puckett Spring (1853) Water Quality Checklist

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						
Pollutant	**CAS[1] Number**	**Water Quality Criteria µg/L[2]**				**Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired**
		Human Health:		**Warm Water Aquatic Habitat[3]:**		
		DWS[4]	Fish[5]	**Acute**	**Chronic**	
Aldrin	309002	0.000049	0.00005	3		All non-detect
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	All non-detect
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	All non-detect
Arsenic	7440382	10		340	150	6 detects; All < Chronic
Beta-Endosulfan	33213659	62	89	0.22	0.056	All non-detect
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	All non-detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All < Chronic
Chlorpyrifos	2921882			0.083	0.041	All non-detect
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	9 detects; All < Chronic
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Diazinon	333415			0.17	0.17	All non-detect
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All non-detect
Dissolved Oxygen				4.0 mg/L	4.0 mg/L	Range 3.9-9.5 (one<4mg/L)
Endrin	72208	0.76	0.81	0.086	0.036	All non-detect
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All non-detect
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All non-detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All non-detect
Iron[6]	7439896			4,000	1,000	1 detect>Chronic;rest below
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	6 detects; All < Chronic
Malathion	121755				0.1	All non-detect
Mercury	7439976	2	0.051	1.7	0.91	1 detect < Chronic
Methoxychlor	72435	40			0.03	All non-detect
Mirex	2385855				0.001	MDL > Standard; All ND
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	9 detects; All < Chronic
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All non-detect
pH		6.5-8.5		6.0 - 9.0		Range 6.6 - 7.1
Phthalate esters	N/A				3	1 detect > Chronic; rest ND
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	MDL > Standard; All ND
Selenium	7782492	170	4,200	20	5	4 detects; All < Chronic
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All non-detect
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		Range 12.2 - 15.2 C
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	NO DATA
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	9 detects; All < Chronic
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	All non-detect
E. Coli (Sec7-Primary Contact)		< 1		Geometric Mean < 130 CFU		Geo-mean = 92.83 CFU

Table 50. Cohorn Spring (3741) Water Quality Checklist

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	**CAS[1] Number**	**Water Quality Criteria µg/L[2]**				
		Human Health:		**Warm Water Aquatic Habitat[3]:**		
		DWS[4]	Fish[5]	**Acute**	**Chronic**	
Aldrin	309002	0.000049	0.00005	3		All non-detect
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	All non-detect
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	2 detects, Y < 0.05mg/L
Arsenic	7440382	10		340	150	9 detects, All < Chronic
Beta-Endosulfan	33213659	62	89	0.22	0.056	All non-detect
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	1 detect ≥ Chronic
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All detects < Chronic
Chlorpyrifos	2921882			0.083	0.041	All non-detect
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All detects < Chronic
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Diazinon	333415			0.17	0.17	All non-detect
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All non-detect
Dissolved Oxygen				4.0 mg/L	4.0 mg/L	Two readings < 4.0 mg/L
Endrin	72208	0.76	0.81	0.086	0.036	All non-detect
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All non-detect
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All non-detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All non-detect
Iron[6]	7439896			4,000	1,000	2 detects > Chronic
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	7 detects > Chronic
Malathion	121755				0.1	All non-detect
Mercury	7439976	2	0.051	1.7	0.91	1 detect < Chronic
Methoxychlor	72435	40			0.03	All non-detect
Mirex	2385855				0.001	MDL > Standard; All ND
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All detects < Chronic
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All non-detect
pH		6.5-8.5		6.0 - 9.0		Range: 6.75-7.3
Phthalate esters	N/A				3	2 detects > Chronic
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	MDL > Standard; All ND
Selenium	7782492	170	4,200	20	5	1 detect < Chronic
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All non-detect
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		Range: 11.6-15.9 C
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	NO DATA
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All detects < Chronic
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	All non-detect
E. Coli (Sec7-Primary Contact)		< 1		Geometric Mean < 130 CFU		Geo-mean = 112.22 CFU

Table 51. Conway Springs (3861) Water Quality Checklist

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants

Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2] Human Health: DWS[4]	Fish[5]	Warm Water Aquatic Habitat[3]: Acute	Chronic	Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Aldrin	309002	0.000049	0.00005	3		All non-detect
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	All non-detect
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	3 detects; Y < 0.05 mg/L
Arsenic	7440382	10		340	150	9 detects < Chronic
Beta-Endosulfan	33213659	62	89	0.22	0.056	1 detect < Chronic
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	All non-detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	12 detects < Chronic
Chlorpyrifos	2921882			0.083	0.041	All non-detect
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	11 detects < Chronic
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Diazinon	333415			0.17	0.17	All non-detect
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All non-detect
Dissolved Oxygen				4.0 mg/L	4.0 mg/L	Range: 3.5 - 9.2 mg/L
Endrin	72208	0.76	0.81	0.086	0.036	All non-detect
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All non-detect
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All non-detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All non-detect
Iron[6]	7439896			4,000	1,000	2 detects > Chronic
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	8 detects < Chronic
Malathion	121755				0.1	All non-detect
Mercury	7439976	2	0.051	1.7	0.91	All non-detect
Methoxychlor	72435	40			0.03	All non-detect
Mirex	2385855				0.001	MDL > Standard; All ND
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	12 detects < Chronic
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All non-detect
pH		6.5-8.5		6.0 - 9.0		Range: 6.7 - 10.4
Phthalate esters	N/A				3	All non-detect
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	MDL > Standard; 2 detects
Selenium	7782492	170	4,200	20	5	1 detect ≤ Chronic
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All non-detect
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		Range: 13.8 - 15.2 C
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	NO DATA
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	12 detects < Chronic
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	All non-detect
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		2/5 > 240 CFU

Table 52. Ruben Ray Spring (3742) Water Quality Checklist

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	**CAS[1] Number**	**Water Quality Criteria µg/L[2]**				
		Human Health:		**Warm Water Aquatic Habitat[3]:**		
		DWS[4]	Fish[5]	**Acute**	**Chronic**	
Aldrin	309002	0.000049	0.00005	3		1 detect below Acute
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	All non-detect
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	2 detects; both < 0.05 mg/L
Arsenic	7440382	10		340	150	7 detects; all < Chronic
Beta-Endosulfan	33213659	62	89	0.22	0.056	All non-detect
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	All non-detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All data < Acute and Chronic
Chlorpyrifos	2921882			0.083	0.041	All non-detect
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All data < Acute and Chronic
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Diazinon	333415			0.17	0.17	All non-detect
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All non-detect
Dissolved Oxygen				4.0 mg/L	4.0 mg/L	Range 7.0-9.5 mg/L
Endrin	72208	0.76	0.81	0.086	0.036	All non-detect
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All non-detect
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All non-detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All non-detect
Iron[6]	7439896			4,000	1,000	1 detect>Acute; rest<Chronic
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	1 detect>Chronic; rest below
Malathion	121755				0.1	All non-detect
Mercury	7439976	2	0.051	1.7	0.91	All non-detect
Methoxychlor	72435	40			0.03	1 detect>Chronic
Mirex	2385855				0.001	MDL > Standard; All ND
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All data < Acute and Chronic
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All non-detect
pH		6.5-8.5		6.0 - 9.0		Range 7.0-7.3
Phthalate esters	N/A				3	All non-detect
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	MDL > Standard; All ND
Selenium	7782492	170	4,200	20	5	3 detects<Chronic
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All non-detect
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		Range 12.9-17.5 C
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	NO DATA
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All < Chronic
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	All non-detect
E. Coli (Sec7-Primary Contact)		< 1		Geometric Mean < 130 CFU		Geo-mean = 1954.02 CFU

Table 53. Big Spring (1145) Water Quality Checklist

Order	**Taxa**	**Order**	**Taxa**
Amphipoda	*Caecidotea* sp	Ephemeroptera	*Acerpenna* sp
Amphipoda	*Gammarus* sp	Ephemeroptera	*Baetis intercalaris*
Arachnida	Unid. Hydracarina (mite) sp	Ephemeroptera	*Caenis* sp
Clitellata	Unid. Hirudinea sp	Ephemeroptera	*Paraleptophlebia* sp
Coleoptera	Unid. Curculionid sp	Ephemeroptera	*Plauditus* sp
Diptera	*Bezzia/Palpomyia* gp	Ephemeroptera	*Stenacron interpunctatum*
Diptera	*Brillia* sp	Ephemeroptera	*Stenonema femoratum*
Diptera	*Chaetocladius* sp	Mollusca	*Elimia laqueata laqueata*
Diptera	*Chironomus* sp	Mollusca	*Ferrissia* sp
Diptera	*Cricotopus bicinctus* gp	Mollusca	*Micromenetus dilatatus*
Diptera	*Cricotopus/Orthocladius* gp	Mollusca	*Physa* sp
Diptera	*Cricotopus/Orthocladius/Paratricocladius* gp	Mollusca	*Pisidium* sp
Diptera	*Dicrotendipes* sp	Oligochaeta	Unid. Lumbriculid sp
Diptera	*Eukiefferiella* sp	Oligochaeta	Unid. Naidid sp
Diptera	*Chironomus* sp	Oligochaeta	Unid. Oligochaeta
Diptera	*Cricotopus bicinctus* gp	Oligochaeta	Unid. Oligochaeta sp
Diptera	*Cricotopus/Orthocladius* gp	Plecoptera	*Isoperla* sp
Diptera	*Dicrotendipes* sp	Plecoptera	*Perlesta* sp
Diptera	*Hemerodromia* sp	Trichoptera	*Cheumatopsyche* sp
Diptera	*Hydrobaenus* sp	Trichoptera	*Ochrotrichia* sp
Diptera	*Micropsectra* sp		
Diptera	*Orthocladius* sp		
Diptera	*Parakiefferiella* sp		
Diptera	*Paratendipes* sp		
Diptera	*Polypedilum aviceps*		
Diptera	*Polypedilum* sp		
Diptera	*Rheotanytarsus* sp		
Diptera	*Serromyia* sp		
Diptera	*Tanytarsus* sp		
Diptera	*Thienemanniella* sp		
Diptera	*Thienemannimyia* gp		
Diptera	*Tvetenia* sp		

Table 55. Complete List of Taxa Collected for this Study

DOW Site Code	Spring Name	Genus Richness	Genus EPT Richness[1]	% Genus EPT	mHBI[2]	Modified %EPT[3]	%Ephemeroptera[4]	%C + O[5]	% Clingers[6]	% Nutrient Tolerant	ATV[7]
DOW20008004	Harpending	11	1	9.09	5.25	-	0	82.5	43.75	18.75	6.38
DOW20008005	Wallace Branch	14	3	21.43	4.962	3.43	0.571	34.85	77.71	65.14	6.18
DOW20003009	Mill Bluff	9	0	0	4.314	-	0	100	17.98	76.26	6.34
DOW20009008	Martin	10	1	10	4.35	2.2	2.2	97.8	52.74	17.58	6.88
DOW20001027	Puckett	23	8	34.78	6.507	8.92	8.71	90.75	21.82	18.06	6.31
DOW20020039	Cohorn	10	0	0	4.987	-	0	72.5	30	51.67	5.18
DOW20003008	Conway	22	4	18.18	6.499	3.44	2.821	88.4	13.16	21.94	6.47
DOW20003010	Ruben Ray	13	1	7.69	6.843	0.344	0.344	99.31	4.137	84.13	6.64
Mean		**14**	**2.25**	**12.65**	**5.46**	**2.29**	**1.83**	**83.26**	**32.66**	**44.19**	**6.3**
Median		**13**	**1**	**10**	**5.25**	**2.86**	**0.57**	**88.4**	**30**	**44.19**	**6.34**
SD		**7.14**	**7.84**	**7.95**	**2.11**	**2.96**	**43.21**	**33.19**	**25.34**	**26.69**	**0.47**
Variance		**30.29**	**7.36**	**137.4**	**1.02**	**10.22**	**8.9**	**470.23**	**584.23**	**807.38**	**0.25**

Table 56. Summary Statistics for Benthic Macroinvertebrates Collected

[1] EPT = Combined measure for mayflies, stoneflies, and caddisflies; [2] mHBI = modified Hilsenhoff Index. This is a measure of taxa associated with organic enrichment. Increasing mHBI values indicate decreasing water quality; [3] Modified EPT = This calculation excludes the tolerant and common genus *Cheumatopsyche*, a taxa which can create inflation of EPT metrics;

[4] % Ephemeroptera = % mayflies, a highly sensitive indicator group; [5] % C + O = % Chironomidae (midge flies) and Oligochaetes (segmented worms); [6] % Clingers = Clingers are a measure of taxa that 'cling' to substrates. This metric is sensitive to changes in geomorphology and sedimentation issues; [7] Average Tolerance Value

Appendix I. Financial and Administrative Closeout

Workplan Outputs

The Groundwater Section has committed to the following outputs:

- Identification of suitable groundwater monitoring sites in the West Pennyrile Study Area
- Groundwater tracer tests to delineate spring recharge areas
- Collection of samples for one year and delivering these samples to the laboratory for analysis for several parameters, including major inorganic ions, nutrients, pesticides, metals, volatile organic compounds and residues
- Data review and analysis relative to applicable water quality standards
- Production of a report summarizing all relevant groundwater data for priority watersheds
- Delivering copies of the report to the River Basin Teams, local conservation districts, Natural Resource Conservation Service, Agricultural Water Quality Authority, Agricultural Extension offices and interested stakeholders
- Posting the report on the Division of Water's internet site

Budget Summary

- Total project budget is $154,000
- Budget has been expended in personnel costs approximately equivalent to 2.9 person years
- Groundwater Section has managed the project, including:
    - ✓ researching background data
    - ✓ conducting on-site inspections to identify sampling sites
    - ✓ collecting groundwater samples
    - ✓ transporting samples to the laboratory
    - ✓ interpreting sample results
    - ✓ preparing maps and reports
    - ✓ providing reports to interested parties

- Time code used for this project was:

ACT MOAM/MODA

PROJECT NPS0704Z

Project Budget:

The total project budget is $154,000. The budget will be expended in personnel costs reflecting a total equivalent of approximately 2.9 person years. The Groundwater Section personnel will manage the project, research background data, conduct on-site inspections and groundwater sampling, transport samples, interpret sample results, prepare maps and reports, and present the summary information to stakeholders and other interested parties. The Environmental Services Branch (ESB) lab personnel will conduct chemical analysis. A time code will be established to track personnel time spent on the project. Match for this grant will be provided by DOW and ESB personnel costs, including fringe and overhead.

Budget Summary:

Budget Categories	**BMP Implementation**	**Project Management**	**Public Educatio n**	**Monitoring**	**Technical Assistance**	**Other**	**Total**
Personnel	$	$	$	$107,846	$	$	$107,846
Supplies							
Equipment							
Travel							
Contractual							
Operating Costs				$46,154			$46,154
Other							
TOTAL	$	$	$	**$154,000**	**$**	**$**	**$154,000**

Detailed Budget

Budget Categories	Section 319(h)	Non-Federal Match	Total
Personnel	$64,707	$43,139	$107,846
Supplies	$	$	$
Equipment	$	$	$
Travel	$	$	$
Contractual	$	$	$
Operating Costs	$27,693	$18,461	$46,154
Other	$	$	$
TOTAL	$**92,400**	**$61,600**	**$154,000**

Funds Expended

All funds for this project were expended using personnel dollars.

Equipment Summary

No equipment was purchased for this project.

Special Grant Conditions

No special grant conditions were placed on this project by the EPA.

Quality Assurance Project Plan
For

Integrated Surface Water and Groundwater Quality Assessment in Large Springs of the Western Pennyrile Karst Region of Kentucky

NPS 07-04

Prepared By:
Robert J. Blair
robert.blair@ky.gov
Groundwater Section
Watershed Management Branch

Prepared For:
Commonwealth of Kentucky
Energy and Environment Cabinet
Department for Environmental Protection
Division of Water
Watershed Management Branch
200 Fair Oaks Lane
Frankfort, Kentucky 40601
(502)564-3410

Date: August 27, 2012

Revision Date: October 29, 2012

Revision No.: 2

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SECTION A – PROJECT MANAGEMENT

A1. Title and Approval Sheet

Quality Assurance Project Plan: Integrated Surface Water and Groundwater Quality Assessment of Large Springs in the Western Pennyrile of Kentucky

Rob [signature]	8/29/12
Robert J. Blair / QAPP Author & Project Mgr/KDOW	Date
[signature]	8/29/12
David A. Jackson / Supervisor, Groundwater Section	Date
E Paulette Akers [signature]	8/29/12
Paulette Akers / Watershed Branch Manager	Date
Elizabeth Finzer [signature]	10/29/12
Beth Finzer / Branch Quality Assurance Officer	Date
Lisa A. Hicks [signature]	01/08/13
Lisa Hicks /Division Quality Assurance Officer	Date
[signature]	2/19/13
Sandy Gruzesky /Director, Division of Water	Date
[signature]	2/25/13
Larry Taylor /Department Quality Assurance Manager, ~~Division of~~ Department for Environmental Protection	Date
N/A	
Karen Gardner /EPA Grants Manager	Date
N/A	
Danny France / EPA Quality Assurance Officer	Date

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Revision History

Date of Revision	Page(s)/Section(s) Revised	Revision Explanation
Aug 29, 2012	A4-p10; A7-p15-16; B3-p20	General comments/edits addressed
Oct 29, 2012	A3-p8; A6-p13; A7-p16,17; B3-p21; D1-p25	General comments/edits addressed

A2. Table Of Contents

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A3. Distribution List

Division of Water

Lisa Hicks, DOW QA Officer

Watershed Management Branch

E. Paulette Akers, Manager
Beth Finzer, WMB QA Coordinator
Groundwater Section
David Jackson, Supervisor
Robert J. Blair, Geologist-Registered

Division of Water
200 Fair Oaks Lane
Frankfort Kentucky 40601

Environmental Services Branch

Michael Goss, Manager

Environmental Services Branch
100 Sower Blvd., Suite 104
Frankfort, KY 40601

EPA

Karen Gardner, Grants Manager
Danny France, EPA Quality Assurance Officer

A4. Project / Task Organization

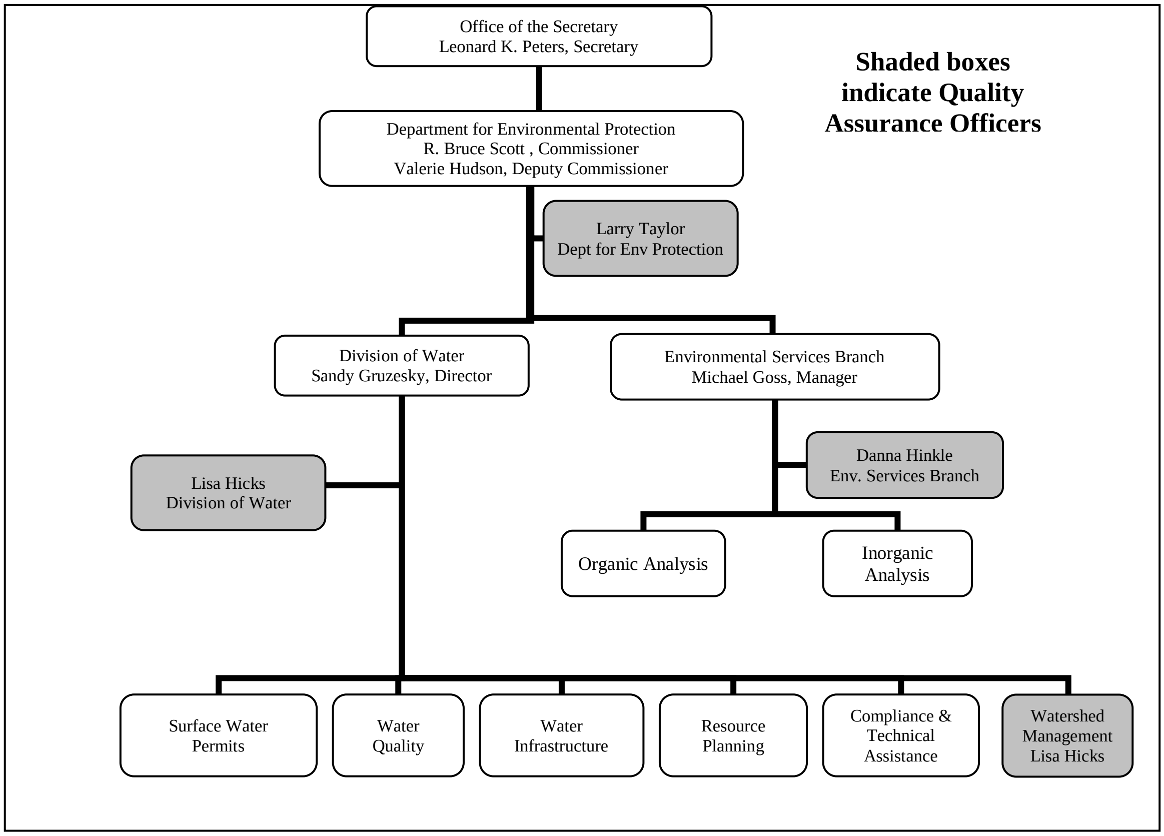

Figure 1. Organizational Chart

Kentucky Division of Water

- Robert J. Blair, PG, Kentucky Division of Water (KDOW) Project Manager and Field Sampling Lead will be the responsible official for this project overseeing overall operations and budget, as well as tasking assistants with work required to complete this project. He will be responsible for assigning field samplers specific tasks and objectives and has overall responsibility for all field activities.

- Lisa Hicks, KDOW QA Manager will be responsible for reviewing and approving the QA Project Plan. She may provide technical input on proposed sampling design, analytical methodologies, and data review.

- Potential KDOW Project Personnel to assist with sample collection.

Sampler Name	Title	Education
Carigan, Deven	Geologist II	B.S. Geography/M.S. Geoscience
Moore, Jessica	Geologist I	B.S. Geology/M.S. Igneous Petrology
Topolski, Rob	Env. Insp. III	B.S. Geology

- Paulette Akers, Watershed Management Branch Manager is responsible for general oversight of branch activities, including SOP development and implementation, insuring SOPs are consistent with the department QMP. She also communicates branch activities and their results/impacts to other branches and upper management.

- David A. Jackson, PG, Groundwater Section Supervisor is responsible for providing direct project oversight and guidance to project manager. He is responsible for tracking overall project status to ensure all activities are being conducted in accordance with NPS grant protocols and completed within designated timeframes and budget constraints. He is also responsible for the final review of the project prior to submittal to the NPS grants coordinator.

Division of Environmental Program Support, Environmental Services Branch

- Michael Goss, Environmental Services Branch (ESB) Manager provides laboratory oversight and final analytical reports for samples received. He also communicates any issues regarding laboratory work load, instrument maintenance and personnel scheduling that could impact sample analyses.

- Amy Stosberg, ESB Sample Custodian receives samples delivered to the lab. She also coordinates sample delivery scheduling and acts as a liaison with KDOW.

- Eric Scott, Acting Supervisor – Sample Prep and Technical Services Sections is responsible for coordinating analysis requests and addressing laboratory issues that may affect sample analysis.

- Shannon Dutta, Metals Section Supervisor is responsible for all metals analyses.

- Todd Adams, Standard Testing Section Supervisor is responsible for general water chemistry analyses.

- Andrea Pergram, Mass Spectroscopy Section Supervisor is responsible for all analyses conducted with the MS/GC.

- Keith Ewing, Pesticides/PCBs Section Supervisor is responsible for analysis of Nitrogen-Phosphorus Pesticides, Organochlorine Pesticides and PCBs.

McCoy & McCoy Laboratories, Inc

- Dave Baumgardner, Regional Manager of Paducah and Madisonville Offices is responsible for assuring that all samples are received and processed within holding times and according to proper procedures. This laboratory will analyze bacteria samples only.

A5. Project Definition / Background

Groundwater and surface water are conjunctive systems, no more directly so than in karst terrane. Surface water assessments (305b report) in the well-developed karst terranes of the Western Pennyrile Karst Region are minimal due to the lack of flowing surface water streams. These karst basins represent large un-assessed areas of contribution to the Tradewater and Cumberland River basins (BMUs 3 & 4). Subsurface streams drain these basins that discharge to surface waters at discrete springs via blue holes and spring runs.

This integrated surface water-groundwater assessment was effectively employed to evaluate large springs in the Green River Basin (NPS 0503), which was considered a pilot study for this approach. This project (NPS 0704) will similarly address the deficiency of significant "stream segments" properly assessed, and provide both the surface water and groundwater programs needed information on spring conditions relative to non-point source impacts.

Ten springs with significant base flow discharge volumes (and therefore draining large groundwater basins) will be monitored in accordance with the standards set forth in 401 KAR 10:031. This strategy will provide sufficient data to conduct an adequate assessment for both surface water and groundwater. Site selection will be focused on well-developed karst basins in the sinkhole plain where discrete springs discharge the drainage of these basins to surface waters. Other important determinants for site selection include: the ease of access to the springs/spring runs, cooperation of the landowners, and access to springs/spring runs. Also considered is whether springs will provide groundwater data in areas with little or no current information, whether the site will support other programs (e.g. surface water assessment (305b) program, TMDL development, wellhead protection), whether the spring basin has been delineated by tracer tests, and whether land use in the spring basin presents nonpoint source pollutant sources of interest and concern.

The ultimate goal of this project is to evaluate these springs using surface water protocols that meet the criteria for assessment and inclusion in the *Integrated Report to Congress* (305b and/or 303d lists).

A6. Project/Task Description

The primary goal of this project is to conduct an assessment of ten large karst springs that represents the drainage of significant areas of the Cumberland River and Tradewater River basins. The objective is to assess nonpoint source pollution impacts in these areas, and to identify which land uses are having nonpoint source pollution impacts on groundwater, and ultimately surface water in these basins. The activities include field reconnaissance of potential sites, spring flow gaging, site selection and water quality sampling, review and distribution of the analytical results, data analysis and final report preparation.

Biological sampling and assessment will be conducted for fish and macro-invertebrates as a complimentary, cooperative effort, as possible, at each of the spring/spring runs in order to have adequate information to conduct a complete assessment of these karst spring basins.

The study area encompasses portions of Christian, Caldwell, Crittenden, Livingston, Lyon and Trigg counties. Specifically, the study will focus on the following USGS 7.5 minute quadrangles: Gracey, Cobb, Lamasco, Princeton East, Princeton West, Crider, Fredonia, Eddyville, Grand Rivers, Dycusburg, Burna, Salem, Lola and Cave in Rock. This region was chosen because it coincides with the outcrop of soluble, carbonate rocks of Mississippian age that are known for well-developed karst drainage. Although numerous springs have been mapped by various government agencies in the study area, no systematic groundwater quality assessments of this nature have occurred.

Table 1 is the list of chemical and bacteria parameters, set forth in 401 KAR 10:031, that will be collected, analyzed and evaluated for this study. Table 2 provides the schedule for sample collection, data management/analysis and assessment/reporting. The QAPP will be completed in June 2012 and water quality monitoring will begin in October 2012. Data analysis and spring assessments will begin in October 2013, upon receiving all sample results.

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants					
Pollutant	**CAS[1] Number**	**Water Quality Criteria µg/L[2]**			
		Human Health:		**Warm Water Aquatic Habitat[3]:**	
		DWS[4]	Fish[5]	**Acute**	**Chronic**
Aldrin	309002	0.000049	0.00005	3	
Alkalinity (as $CaCO_3$)				Reduction >25%	
alpha-Endosulfan	959988	62	89	0.22	0.056
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))
Arsenic	7440382	10		340	150
Beta-Endosulfan	33213659	62	89	0.22	0.056
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)
Chlordane	57749	0.0008	0.00081	2.4	0.0043
Chloride	16887006	250,000		1,200,000	600,000
Chloropyrifos	2921882			0.083	0.041
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)
Chromium (VI)	18540299			16	11
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)
Cyanide, Free	57125	700	220,000	22	5.2
Demeton	8065483				0.1
Dieldrin	60571	0.000052	0.000054	0.24	0.056
Endrin	72208	0.76	0.81	0.086	0.036
gamma-BHC (Lindane)	58899	0.019	0.063	0.95	
Guthion	86500				0.01
Heptachlor	76448	0.000079	0.000079	0.52	0.0038
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038
Iron[6]	7439896			4,000	1,000
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)
Malathion	121755				0.1
Mercury	7439976	2	0.051	1.7	0.91
Methoxychlor	72435	40			0.03
Mirex	2385855				0.001
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)
Parathion	56382			0.065	0.013
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)
pH		6.5-8.5		6.0 - 9.0	
Phthalate esters	N/A				3
Phenol	108952	21,000	1,700,000		
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014
Selenium	7782492	170	4,200	20	5
Silver	7440224			e(1.72 (ln Hard*)-6.59)	
Hydrogen Sulfide, Undissociated	7783064				2
Temperature				See Temp-Month Table	
TDS and TSS	N/A	750,000		No adverse effects on aquatic life	
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)	

Table 1. Parameters required for assessment of springs with applicable standards. (1-Chemical Abstract Society; 2-Values in µg/L unless otherwise noted; 3-metals concentrations as total recoverable; 4-Drinking Water Standards; 5-Fish Consumption Standards)

Additionally, field parameters will be collected using a YSI multiparameter probe at each sampling event. These parameters will include Temperature (in degrees Celcius), Conductivity (µS/cm), pH (Standard Units) and Dissolved Oxygen (mg/L). These units are cleaned, maintained and calibrated according to manufacturer's specifications. These specifications require cleaning on an as-needed basis to keep probes free of debris. This includes rinsing with de-ionized water before and after each use. Maintenance requirements state that the units should not be stored in extreme temperatures (never below 0° C or above 85° C). Calibrations occur at a minimum of every two months, using standard pH 7.0 and 10.0 solutions and standard conductivity 718 µS/cm solution. Dissolved Oxygen is calibrated using percent saturation of a contained atmosphere with 100 % dissolved oxygen saturation. A record of calibration is kept in a note book with each unit that includes the name of personnel performing maintenance, date and lot numbers for each standard solution used.

Upon receipt of each analysis report from the laboratories, results with accompanying letters of explanation will be forwarded to individual spring owners. Following receipt of all analytical results and data analysis, a final report will be prepared to document the geographic and hydrogeologic setting of the study area and assessment results for each spring monitored for the study. This information will also be forwarded to the Kentucky Division of Water, Water Quality Branch for inclusion in the *Integrated Report to Congress*.

Month	10	11	12	1	2	3	4	5	6	7	8	9	10
Develop QAPP/Study Plan									X				
Collect Samples	X	X	X	X	X	X	X	X	X	X	X	X	
Receive Sample Results		X	X	X	X	X	X	X	X	X	X	X	X
Perform QA/QC	X	X	X	X	X	X	X	X	X	X	X	X	
Compare data to WQ standards for 305(b) assessment (analysis and reporting)		X											

Table 2. Planning and implementation calendar

Table 3 provides a list of the springs to be monitored for this study. Figure 2 is a map showing the locations of these springs relative to areas of karst development, major surface drainage and county boundaries. On the map, each spring is labeled with the last four digits of its AKGWA number.

Spring Name	AKGWA	Latitude	Longitude	Base Flow (ft^3/s)	County	Quadrangle	Receiving Stream
Martin Sp	9000-3740	36.96981	-87.782773	1.7	Caldwell	Cobb	Kenady Cr
Harpending Sp	9000-1823	37.03785	-87.934026	1.8	Caldwell	Princeton W	Eddy Cr
Wallace Branch Sp	9000-1855	37.070627	-87.929466	1.5	Caldwell	Princeton W	Eddy Cr
Big Spring	9000-1145	37.108072	-87.881517	0.5*	Caldwell	Princeton W	Big Spring Br
Mill Bluff Sp	9000-1825	37.189992	-88.073043	1.25	Caldwell	Fredonia	Livingston Cr
Ruben Ray Sp	9000-3742	37.184334	-88.08343	1	Caldwell	Fredonia	Livingston Cr
Cohorn Sp	9000-3741	37.142708	-88.108847	1.3	Lyon	Fredonia	Skinframe Cr
Larping Sp	9000-3812	37.165516	-88.152908	0.7*	Crittenden	Dycusburg	Livingston Cr
Puckett Sp	9000-1853	37.234474	-88.200454	1.4	Livingston	Dycusburg	Claylick Cr
Conway Sp	9000-3861	37.192653	-88.100335	1.1*	Crittenden	Fredonia	Livingston Cr

Table 3. Springs to be monitored, with basic information. *Indicates limited data that will be augmented during course of the study.

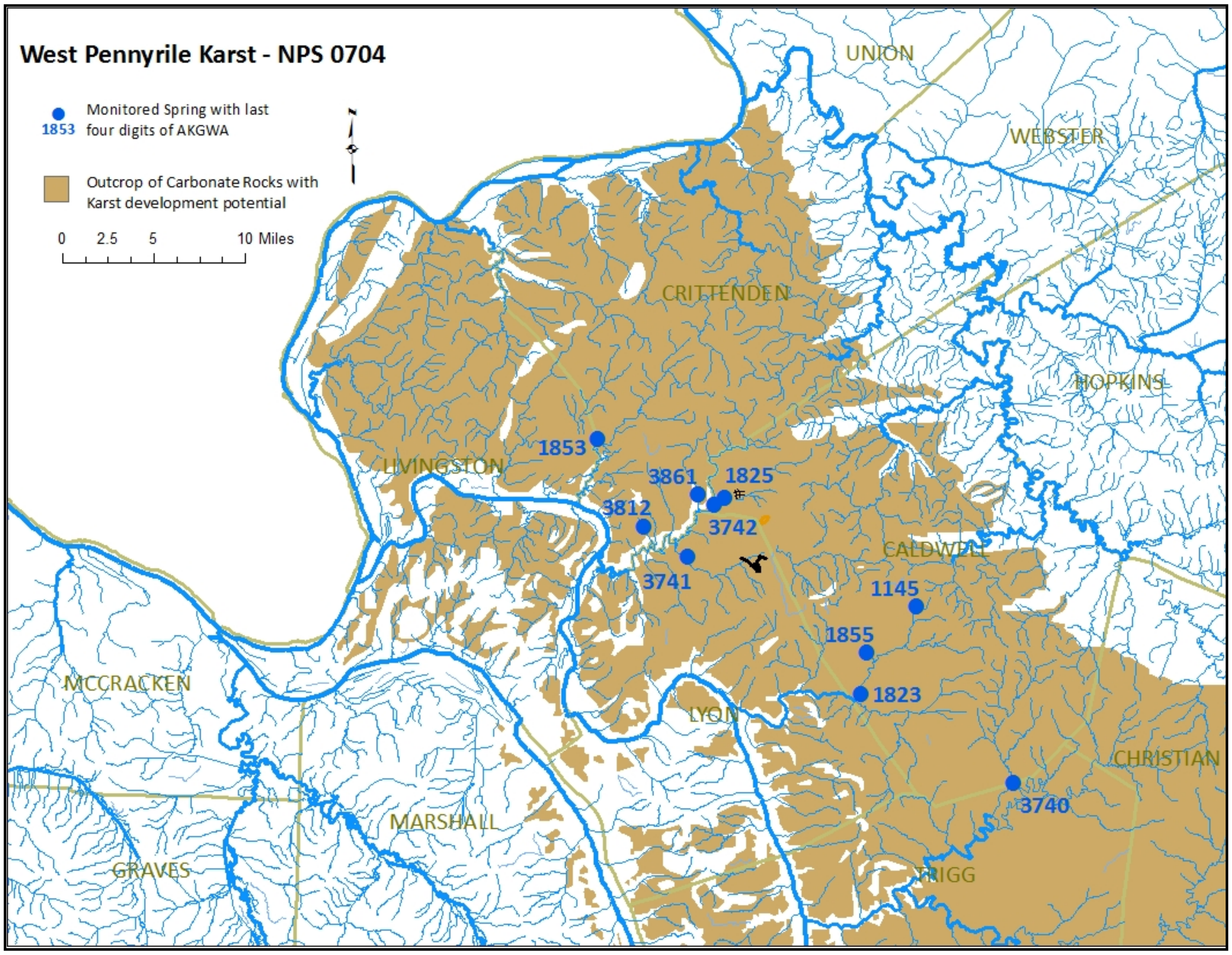

Figure 2. Map showing Springs to be monitored.

A7. Data Quality Objectives (DQOs) and Criteria for Measurement Data

Objectives and Project Decisions

The immediate use of these data will be to assess the Designated Uses of these aquatic resources for 305(b) reporting. This will involve comparing results from these monitored springs to the commonwealth's water quality criteria. Twelve consecutive months of monitored data per spring will be compared to each standard as appropriate, for Warm-water Habitat Assessment. Primary and Secondary Contact Recreation support will be determined using *E. coli* sample results from either 6 consecutive monthly samples or 5 samples within 30 days. The following will provide examples of how these results are compared to those standards to make Designated Use support determinations.

Action Limits / Levels

Those physicochemical data (Table 1) collected at these springs will be analyzed and assessed according to EPA guidance (U.S. EPA 1997). Water quality data are compared to criteria contained in Kentucky Water Quality Regulations (401 KAR 10:031, Sections 4, 6 and 7). The spring fully supports warm-water aquatic habitat (WAH) use when criteria are met in 90 percent or more of the samples collected. Impaired, partial support is indicated if any one criterion for these parameters is not met in 11-25 percent of the samples. A spring is impaired, not supporting, if any one of these criteria are not met in more than 25 percent of the samples.

Aquatic life is considered protected if the acute criteria are not exceeded more than once. Data are also compared to chronic criteria. Observations that equal chronic criteria are not considered as exceeding water quality standards. Toxic criteria are assessed based on 12-monthly samples at each spring. The spring fully supports WAH use if all criteria met or exceeded only once. Impaired, partial support is assessed if any criterion was not met more than once, but in less than 10 percent of samples. The segment is impaired, not supporting if criteria are exceeded in greater than 10 percent of samples.

Escherichia coli, fecal coliform and pH data may be used to indicate the level of support for primary contact recreation (PCR) use (full body contact). Primary contact recreation assessment is based on either six monthly grab samples or five grab samples in 30 days, collected during the recreation season of May – October.

Measurement Performance Criteria / Acceptance Criteria

Precision – Field replicates will be collected for 10 percent of sample sites for all water quality parameters. These field replicates will be processed as an independent sample in the laboratory and will be reported like other field samples.

Precision of chemical analyses will be calculated from two field replicate samples using Relative Percent Difference (RPD) given as:

$$\text{RPD} = \frac{(C_1 - C_2)}{(C_1 + C_2)/2} \times 100$$

where C_1 and C_2 are the values of two replicate samples. The RPD for each analysis will be calculated for each replicate pair.

Precision of *E*. coli analyses will be calculated from two field replicate samples using the Precision Criterion outlined in APHA (2012), section 9020 (9e) *Precision of Quantitative Methods*.

Accuracy – As a measure of bias in a measurement, accuracy will be assessed through the analysis of matrix/matrix spike duplicate samples. The analytical accuracy will be expressed as the percent recovery (R) of an analyte which has been added to the environmental sample at a known concentration before analysis and is given by:

$$R = \frac{S-U}{C_s} \times 100$$

Where S, U and C_s represent measured concentration in spiked aliquot, un-spiked aliquot and actual concentration of spike added, respectively. Kentucky Environmental Services Branch (ESB) laboratory detection limits are noted in DEPS methods manual and QAPP.

Field and Equipment Blanks – No field or equipment blanks will be required for these samples. The laboratory will prepare and analyze method blanks for each set of samples submitted. When analytical results for these blanks exceed $1/10^{th}$ of the values reported in the environmental samples, those data will be flagged as an estimate value due to blank contamination.

Comparability – Equal effort is attempted at each sampling site using consistent field and laboratory methods to collect and analyze data.

Representativeness – Given the environmental and physical conditions necessary to represent ambient groundwater quality conditions, each trip is planned for representativeness of those conditions. Flow conditions sought are those normal for each period throughout the 12 months of monitoring; such that, if a month is represented by high flows those springs will be sampled under those prevailing conditions so long as conditions are safe for the field crew.

Completeness – The study quality objective for completeness is collection and analysis of 90 percent of the list of parameters found in Table 1 from 401 KAR 10:031. This represents the minimum amount of data required to adequately assess these springs relative to 305(b) and/or 303(d) listings.

Sensitivity – All methods employed in this program are approved by EPA and/or Standard Methods. All ESB and McCoy & McCoy laboratory instrumentation and methodology are capable of reporting concentrations of water quality variables that provide the level of discrimination necessary for making assessment decisions for 305(b) purposes. Laboratory methods utilized by ESB and McCoy & McCoy Laboratories are listed in 40 CFR Part 136.

Table 3. Data Quality Indicators (EPA 2002)

DQI	Definition	Example Determination Methodologies	QC Samples
Precision	Reproducibility Measure of agreement among repeated measurements of the same property under identical or near identical conditions. Usually calculated as a range or as the standard deviation.	Use the same analytical instrument to make the same measurement. Split samples in the field, submit to same circumstances of handling, preservation and analysis. Use the same method to make repeated measurements of the same sample within a single laboratory, or use two labs to analyze identical samples with same method.	Field duplicates, laboratory duplicates, matrix spike duplicates, analytical replicates, surrogates
Accuracy	Correctness Measure of overall agreement between measurements to a known value.	Use a different method under the same conditions. Analyze a reference material to which a material of known concentration has been added. Usually expressed as percent recovery or percent bias.	PT samples, matrix spikes, laboratory control samples, equipment blanks
Bias	Systematic or persistent distortion of a measurement process that causes errors in direction	Use reference materials or analyze spiked samples.	Field spikes, matrix spikes
Represent a-tiveness	'the degree to which data accurately and precisely represent an environmental condition' (ANSI/ASQC 1995).	Evaluate whether measurements are made and physical samples collected in a way that the resulting data reflect the environment or condition being studied.	None
Compara-bility	Expresses the measure of confidence that one data set can be compared to another and can be combined for the decision.	Compare the following: sample collection, sample handling, sample preparation, sample analytical procedures, holding times, stability issues, and QA protocols. Describes confidence (expressed qualitatively or quantitatively).	Split samples – with PT samples
Complete-ness	A measure of the amount of valid data needed to be obtained from a measurement system.	Compare number of valid samples completed with those established by the project's DQOs or performance criteria.	All
Sensitivity	Capability of a method to discriminate between measurement responses representing diff. levels of the variable of interest.	Determine the minimum concentration or attribute that can be measured by a method (method detection limit) by an instrument (instrument detection limit) or by a laboratory (quantitation limit.).	lab fortified blanks, method detection limit study, initial calibration standards at quant. limit

A8. Special Training Requirements / Certification

Training needs are identified by reviewing specific tasks of the project and the skills and personnel needed to perform those tasks. The following is required for personnel participating in this project: 1) OSHA 1910.120 HAZWOPER General Site Worker Training Course (40 hr.), 2) OSHA 1910.120 HAZWOPER General Safety Refresher (8 hr.). In addition, sampling personnel are required review appropriate sampling procedures using the Groundwater Section Safe Sampling Procedures, Groundwater Section Standard Operating Procedure GWB 100.3.3 (2009).

A9. Documentation and Records

Field Documentation and Records

Documents and records required for this project include: 1) Spring Inventory forms, 2) Chain of Custody forms, 3) Sampling checklist form, 4) Sample containers forms, 5) Worksite Hazard Assessment forms, 6) Report of Analyses forms for each sample collected, and 7) Miscellaneous reports.

Laboratory Documentation and Records

Standard turnaround time for ESB laboratory data is 4-6 weeks and McCoy & McCoy is generally 1 week. Hardcopy data package content requirements are met by the standardized "Report of Analysis" form, which contains the necessary header information, sample number, the sampling program and the program code, AKGWA number (unique site identifier), the county where the sample was taken, who collected the sample, the date and time the sample was collected, who delivered the samples to the lab and who received the samples for the lab, the date and time of the receipt of samples by the lab, the sample matrix (e.g. water, air), collection method, a sample identification description, and the analytical results, including: CAS Number, Test Code, Constituents, the Quantitative Results, the Units of Reporting, the Limit of Quantification, Limit of Detection, and Flags. The Analysis Report is reviewed by the Director of ESB and signed. Electronic data requirements are met by forwarding information to the Division of Water in an electronic format compatible with the departmental databases and in a format that is suitable for transfer to the Groundwater Data Repository maintained by the Kentucky Geological Survey (KGS).

Data are permanently archived in electronic format. Data are available from both the DOW (including summary information and reports on its website: www.water.ky.gov/gw/) and at the KGS repository mentioned above, which is also available on-line at: www.uky.edu/KGS/water/.

Indirect participants in this study include spring owners. Data from their sites will be forwarded to these owners with cover letters explaining the results along with additional material about groundwater. These data will be used in development of the 305b report. Data will also be forwarded to the Groundwater Data Repository maintained by the Kentucky Geological Survey, where it will be available to researchers and the public. In addition, information from this study will be presented to the TMDL Section of the Division of Water's Water Quality Branch, to the Nonpoint Source and Basin Management Team, to the Agricultural Water Quality Authority, to the Interagency Technical Advisory Committee on Ground Water (ITAC), and to the Watershed Steering Committee, as well as watershed planning teams. The final report will be available on the Division of Water's website.

QA Reports

An initial QA report will be submitted to the Division QAO through the Branch QAO, following the first round of sample collection. A final QA report will be included as an appendix in the final report for the project.

SECTION B. - DATA GENERATION AND ACQUISITION

B1. Sampling Process Design

The DOW maintains monitoring networks with fixed surface water and groundwater sites across Kentucky. Data collected from these sites are used to track long-term trends in water quality, establish baseline chemistry of water resources in the commonwealth and evaluate the impacts from nonpoint source pollution.

Historically, groundwater assessment methods have overlapped, yet been significantly different from those used to evaluate surface water. The methods and protocols utilized to assess surface water are set for by statutes and regulations, which were developed based on requirements of the Clean Water Act. This project will use the same approach to assess groundwater, such that data are comparable and fit into the 305b assessment framework.

Ten large springs in the study area will be sampled for physicochemical parameters for 12 consecutive months and *E. coli* for 6 consecutive months (May – Oct). This will meet the required assessment criteria set forth in 401 KAR 10:031. This is especially important in a karst region where springs represent significant subsurface tributaries to surface streams. While these springs represent large areas of contribution, they do not have accessible segments similar to surface streams.

B2. Sampling Methods

Sample collection procedures, protocols, and methods to be used are those outlined in GWB 100.3.3, Groundwater Section Safe Sampling Protocols (Appendix I). Sampling equipment includes peristaltic pumps, 0.45-micron disposable filters, medical grade silicon tubing used with the peristaltic pumps, and Oakton PC 10 Series meters for collecting field temperature, conductivity, and pH data. Sample collection will not utilize any equipment that comes into contact with sample matrix. Therefore, decontamination will not be required other than for the Oakton PC-10 field meters. The field meters require a single rinse with de-ionized water before and after each use. Sample containers are expendable supplies and are not reused. Sample container types and sizes, preservation methods and holding times are outlined in Appendix II. The parameters listed in Appendix II represent the full suite of analyses typically used by the Groundwater Section and the parameters to be assessed for this study are a subset of those. These parameters are part of the Ambient Groundwater Monitoring Network QAPP.

B3. Sample Handling and Custody Requirements

Samples are collected and handled in accordance with the sample collection procedures, protocols, and methods outlined in the Groundwater Section Safe Sampling Procedures GWB 100.3.3 (Appendix I). Once samples have been collected, they are kept in the sampler's custody or secured under proper preservation conditions until they are delivered to the ESB laboratory for analysis. If regional field office personnel collect the samples, these samples are delivered to main office personnel and whoever receives the samples takes and maintains proper custody. Once delivered to the laboratory, an internal system there directs delivery to the appropriate analysts and tracks the sample and associated paper/electronic processing.

There will be no sample numbering system that is specific to this project. Samples will be identified by the spring's AKGWA number and site name, and collection date and time as described in GWB 100.3.3. One replicate sample will be collected for each sampling event.

Following collection and chemical preservation (when applicable), all samples will be placed in coolers of ice at 4° Celcius for transfer to laboratories. No samples will be shipped by a third party. Examples of applicable labels and chain of custody forms can be found in GWB 100.3.3.

B4. Analytical Methods Requirements

All laboratory analytes (with the exception of *E. coli* which is analyzed by McCoy & McCoy Laboratories) in this program will be completed by ESB laboratory. Please refer to Appendix II for those water quality analytes, along with the EPA method number of analysis and digestion. Results of these analyses have an approximate turnaround time of 4-6 weeks from sample submission.

All methods for chemical analysis of water for the analytes proposed in this study will be followed according to the *Laboratory Operations and Quality Assurance Manual* (2006) of ESB found on the accompanying CD. Quality control for those water quality parameters analyzed at ESB is a hierarchical process and is discussed in *Laboratory Operations and Quality Assurance Manual* (2006) (on CD). The QC checks and balances begin with each analyst on the data they generated and are further checked by section supervisors, branch managers and finally the QAO.

All analytical methods, including digestion when necessary, are EPA-approved or an approved Standard Method per *Standard Methods, 21st Edition, 2005*. For those methods per analysis please refer to Table 4. For necessary analytical equipment please see DEPS' attached *Appendix J Laboratory Instrumentation* (on CD).

E. coli samples analyzed by McCoy & McCoy Laboratory will utilize USEPA Method 1603.

B5. Quality Control Requirements

Information on specific water quality sampling QA/QC protocols can be found in the standard operating procedures for ESB laboratory and the Kentucky Groundwater Section Safe Sampling Protocol (Appendix I). For QA/QC, replicate samples (Section A.7), including acceptance criteria, will be collected for analysis on the frequency and water quality constituents collected for this study. Precision and accuracy requirements for all replicate samples will require the results be within the bounds defined in Section A. 7, *Data Quality Indicators*.

As QC applies to laboratory analyses, please see attached (CD) for laboratory SOPs for QC steps and procedures, including instrumentation blanks and duplicate blanks for a clear presentation of these QC procedures. Initial calibration blank verification, initial calibration verification and laboratory fortified blank are run at the beginning of each analytical sequence per the ESB Laboratory Operations Quality Assurance Manual, 2006 (on accompanying CD).

Project Quality Control Checks

QC Check	Information Provided
Blanks	
field blank	transport, storage and field handling bias
reagent blank	contaminated reagent
method blank	response of a laboratory analytical system
Spikes	
matrix spike	analytical (preparation + analysis) bias
matrix spike replicate	analytical bias and precision
analysis matrix spike	instrument bias
surrogate spike	analytical bias
Calibration Check Samples	
zero check	calibration drift and memory effect
span check	calibration drift and memory effect
mid-range check	calibration drift and memory effect
Replicates, splits, etc.	
field replicates	precision of all steps after acquisition
laboratory splits	interlaboratory precision
laboratory replicates	analytical precision
analysis replicates	instrument precision

B6. Instrument / Equipment Testing, Inspecting and Maintenance Requirements

The field equipment or instruments requiring testing and inspection for this program are hand-held field meters (Oakton© pH/CON 10 Series) used to measure pH, conductivity and temperature. These field meters are cleaned and calibrated in the Watershed Management Branch laboratory, according to the manufacturer's specifications. Field meter performance is considered acceptable if it is clean, free of damage and calibrates properly. The manufacturer performs all required corrective maintenance, other than calibration or electrode replacement. No replacement or spare parts are kept in stock.

Consumable Supplies:

- pH Electrode Cleaning Solution (methanol and HCl) from Cole-Parmer© Instrument Company
- pH 7.00 and 10.00 (+/- 0.01) Buffer Solution (SB 107-500) from Fisher Scientific
- Electrode Storage Solution (SE 40-1) from Fisher Scientific
- Conductivity Standard Solution, 718 μS @ 25˚ C (potassium chloride and water) from Fisher Scientific
- Sample containers and preservatives are consumable supplies; these are identified in Appendix I and Appendix II

Consumables are inspected regularly and replaced as necessary by the Groundwater Section Equipment Manager. Field sampling personnel use hand-held pH/Conductivity/Temperature meters that require calibration. Calibration method, frequency and acceptance criteria conform to the manufacturer's specifications, as set forth in the instruction manual.

B7. Instrument Calibration and Frequency

All field meters are cleaned and calibrated every two months. pH calibration is done with a single point using a pH solution of 7 S.U. Conductivity calibration is performed with a standard solution of 447 µS. Conductivity and pH readings must be within +/- 5% of the value of each standard solution to be accepted (i.e. Conductivity +/- 22.35 µS; pH +/- 0.35 S.U.) Each calibration is documented in a logbook that is kept with its respective meter. Each time a calibration is performed the person enters their initials, the date, the pH solution Lot Number and the Conductivity solution Lot Number.

The ESB Lab Manager determines the number, type and frequency of analytical procedures to be conducted by the ESB lab. The ESB Quality Management Plan and incorporated Standard Operating Procedures dictate the quality control sample collection requirements (type, frequency) and the control sample limits for parameters being analyzed. The ESB Quality Management Plan and incorporated Standard Operating Procedures provide the statistical equations for accuracy, precision, and comparability.

B8. Inspection / Acceptance Requirements for Supplies and Consumables

All supplies used for collecting and preserving samples conform to the supplies requirements found in GWB 100.3.3 (Appendix I). The Supply Manager (identified above in Key Personnel) is responsible for ensuring that all containers meet the requirements of GWB 100.3.3 and the protocols associated with individual parameter laboratory analysis.

B9. Data Acquisition Requirements for Non-direct Measurements

Non-direct measurements include aerial mapping, photos, and land use maps. These resources from KY Raster are maintained by the Division of Geographic Information. These resources are used mainly for planning of sampling before the sampling begins. They are used to determine if sampling areas have domestic wells and the location of water lines before a field visit. Additionally, the resources allow for latitude and longitudes to be taken for each site to allow for the sites to be found during site visits. A field visit, using the latitude and longitudes information and maps formed using the above mentioned data, before sampling begins will allow these resources to be checked to determine if any changes have occurred due to the fact that photos are usually not up-to-date. It is possible that changes could have occurred between the time of the maps and photos were developed, and when the site visit occurred. At this point a change for site selection may have to occur. A new latitude and longitude point will be taken in the field and changes will be noted in the file at the office explaining the reason for the change. If possible photos will be taken to substantiate the change.

B10. Data Management

Tabular electronic data are stored in the DEP Consolidated Groundwater Database, which is managed on a Microsoft Access platform. Sampling site information (e.g. well and spring records, and associated informational forms) will be managed in TEMPO (Tools for Environmental Management and Protection Organizations). Both databases are password-protected and have user-level restricted access.

An electronic image is also created for each record, including spring inventory forms, all COCs and analytical reports. These images of records are maintained in Work Client Manager (WCM), an indexed database platform. The WCM database may be queried by using indexing parameters, such as AKGWA numbers, document type or by using location information. Hardcopies from which the images were scanned are then archived at the Kentucky Geological Survey after acceptable image quality has been verified.

Data for this project are compiled using Microsoft Access queries, which export datasets to Microsoft Excel Spreadsheets.

Electronic data are transmitted to the Groundwater Repository at the Kentucky Geological Survey in accordance with KRS 151:035. Groundwater Monitoring project data are not entered into an EPA or other federal database.

SECTION C – ASSESSMENT AND OVERSIGHT

C1. Assessments and Response Actions

Project Status Tracking:

The Project Manager will track the status of project activities on an ongoing basis to ensure that field and laboratory activities are being completed in accordance with the study plan and the QAPP. Technical staff will report on the status of project activities to the project manager at weekly Groundwater Section staff meetings and/or through written weekly reports. Deviations from the study plan and QA issues identified by technical staff will be reported to the Project Manager in these reports. The Project Manager will implement corrective actions as necessary.

Interim QA Reviews:

The WMB and DOW QAOs will conduct periodic QA reviews to assess compliance with the QAPP and to identify any QA issues that may affect other projects. Interim QA reports furnished by the Project Manager regularly (e.g. quarterly) will be the main source of information for these reviews. Reports will include any QC issues determined using precision criteria, blank samples, sampling methods, or laboratory equipment QC, and any QA issues identified in the process of data verification and validation. The Project Manager will implement corrective actions as necessary with input from QA staff.

Data Quality Assessments:

A data quality assessment will be performed at the completion of all activities under the study plan. This assessment will be done by the Project Manager with input from QA and technical staff. The Project Manager will be responsible for implementing any corrective actions necessary to address QA issues identified in the data quality assessment, including changes to the design of data collection methods, data management, and reporting. The QAPP will be revised as necessary to address issues of data quality and usability.

Management Reviews:

The WMB Manager will review program year summary reports to ensure that all program data are of sufficient quality to support the goals of the overall Watershed monitoring program for Kentucky. The Project Manager will implement corrective actions as necessary in response to management reviews.

C2. Reports to Management

A program year summary report will be prepared by the Project Manager at the completion of the program year and submitted to the Section Supervisor. The timing of this report will vary depending on the lag between field activities through sample analysis and assessment recommendations, but will generally be completed by the end of the year following the year of field activities. The section supervisor will forward this report as appropriate.

SECTION D – DATA VALIDATION AND USABILITY

D1. Data Review, Validation and Verification

All data collected in this project will be subjected to the precision and accuracy acceptance criteria prior to use for 305(b) assessment. Data generated by ESB laboratory will be uploaded from LIMS (laboratory information management system) to the KY Consolidated Groundwater Database. Bacteria data received from McCoy & McCoy laboratory will be entered into a spreadsheet specific to this project, which will note sample dates, site identifiers and results. The data will have gone through a 10 percent check to detect any measurements that may have been reported improperly.

Field replicate sample results are checked against reported values to ensure against contamination or laboratory reporting errors. These findings will result in completeness assurance of critical data.

Sample collection date (verified between bottle label and chain-of-custody), preservation and holding times are checked for any issues by the ESB and McCoy & McCoy sample custodians.

D2. Validation and Verification Methods

Data acceptance will be based on a number of criteria upon receipt of analyses results from the laboratories:

1. Verification from the laboratory that samples were received at proper temperature;
2. Samples were received and analyzed within holding times for each analyte;
3. All *in-situ* physicochemical data collected using Oakton PC-10 will only be accepted provided each sensor was calibrated properly on day of use; and
4. The data flags used by the ESB laboratory are found in Table 4. Use of any flags that calls data validity into question will be cause for exclusion of those data.

Prior to reporting analytical results the ESB laboratory will check and verify them by a second analyst/supervisor conducting recalculation from the raw data to the final results. The project manager will coordinate and follow up with the laboratory performing the analytical work to assure correction of any problem. All data, including field measurements, will be reviewed and verified for completeness, precision, accuracy and comparability as specified in Section A. 7 of this QAPP. Data that cannot be verified may be rejected. The laboratory uses the qualifiers below (Table 4) when reporting analytical results. Any flagged data will be used appropriately depending on the qualifier.

Once data are submitted to be assessed for 305(b) purposes, any missing data points are identified on the spreadsheet used to make decisions against the commonwealth’s water quality standards. This is part of the completeness process; data gaps that are sufficient enough to compromise assessment decisions (see critical data in Section A. 6) result in the spring being placed in Category 3 (insufficient data to make a determination) of the Integrated Report.

Flag	Description
A	Average Value
B	Analyte in Method or Reagent Blank
D	Reanalyzed at a Higher Dilution
E	Exceeded Calibration Range
F	No Field Blank
H	Exceeded prep hold time
I	Internal Standard Limits Exceeded
J	Estimated Value
K	Analyte in Trip or Field Blank
L	Exceeds MCL or Action Limit
M	Matrix Spike Limits Exceeded
N	Presumptive Identification
O	Lab Fortified Blank Limits Exceeded
P	Improper Preservative
Q	QC Limits Exceeded
R	Surrogate Limits Exceeded
S	Insufficient Sample
T	Exceeded Holding Time
U	Analyte Not Detected
V	Calibration Verification Limits Exceeded
X	See Case Narrative
Y	Results < LOQ After Blank Subtraction
Z	Sample Preserved by Freezing

Table 4. ESB Laboratory Flags

D3. Reconciliation with User Requirements and Data Quality Objectives

The section supervisor or their designee will be responsible for reconciling data with the stated data objectives. Data that do not meet the requirements may be rejected from the data set. Reasons for rejection include a lack of QA/QC in the field or in the lab, too large a variance between duplicate samples, not enough samples in a given year, faulty field equipment, a failure to keep up QA on lab equipment, or a change in the sampling protocol. These data may, however, be maintained at DOW in the event that it will fulfill other data gaps or be used as preliminary data.

The main goal of this project is to provide groundwater quality data that meet the criteria for 305b assessment. However, these data may also be used to augment datasets for regional, watershed or site-specific groundwater studies. Data are also made available to the public via the Kentucky Geological Survey's Groundwater Data Repository online database. Data obtained from this project are evaluated to determine that they are adequate to support these various projects, programs and data requests.

REFERENCE

American Public Health Association, 2012, Standard Methods for the Examination of Water and Wastewater, 22nd Edition, Washington, DC.

APPENDIX I. Safe Sampling Procedures: Groundwater Section SOP GWB 100.3.3

WATERSHED MANAGEMENT BRANCH SAFE SAMPLING PROCEDURES

Groundwater Section Standard Operating Procedure GWB 100.3.3

I. Introduction

This Standard Operating Procedure (SOP) establishes the protocol for sampling groundwater to ensure that all groundwater analyses in the Kentucky Department for Environmental Protection's Consolidated Groundwater Database are comparable.

Data in the database may be used for water quality assessments by state government, consultants, city and county governments, and private citizens, and others. Consistent sampling techniques are crucial to making informed decisions based on comparable data.

II. General Safety

The guidelines in this section must be followed to insure the safety of all DOW employees sampling groundwater. Report all accidents to your supervisor, no matter how minor the accident may appear to be.

The groundwater sampler is responsible for making the sampling site as safe as possible. If you are at a site where your safety is in question, leave the site. Assess the site before you start sampling: look for any potential hazards. Use a Site Safety Inspection Form (See **Attachment 1**) to assist in recognizing hazards and what steps should be taken to minimize the hazard

Three acids are used during sampling. Read the MSDs for each of these acids before using them for the first time, and anytime you need a refresher on their properties. MSDs for all chemicals used by samplers are located in a 3-ring binder in the Branch laboratory.

Use the following guidelines and manuals to supplement the information in this SOP:

> Field investigators will not be required to participate in any operation that violates OSHA and EPA safety regulations/guidance. All sampling personnel must have completed the Office of Safety and Health Administration (OSHA) 1910.120 HAZWOPER – GENERAL training course before entering any site with potential or known contamination of any sort.

The safety protocols in this SOP are written in accordance with those defined by the following manual: Field Health and Safety Manual: USEPA, Region IV, 1990: Covers safety involved in all field activities performed in Region 4, and includes regional policy regarding training requirements, medical monitoring, and personal protection.

Any accident must be reported in accordance with Cabinet accident reporting requirements. These requirements are available from your Supervisor or from the Division of Administrative Services.

In addition, protocols from the Division of Water Watershed Management Branch; Department For Environmental Protection Chemical Hygiene Plan will be followed for any Branch laboratory Activities. As a Groundwater Section sampler, you should be aware of the following items from the Plan:

1. Personnel responsible for receiving and storing hazardous chemicals from manufacturers and suppliers will ensure that the containers are marked with the following information:

    a. Identity of the hazardous chemical(s)
    b. Appropriate hazard warnings
    c. Name and address of the chemical manufacturer, importer, or other responsible party

2. Labels on containers or hazardous chemicals will not be removed or in any way defaced.

3. The Chemical Hygiene Officer and the Laboratory Manager shall maintain a master listing of Material Safety Data Sheets (MSDS) for all chemicals in the inventory. A copy of this master listing shall be posted in each laboratory facility.

If any violations to these rules are observed, notify your supervisor and the personnel listed in 3 above.

III. Sampling Preparations

A. General

The Groundwater Section uses several forms and sign-out sheets to keep track of equipment. Learn to use these various forms and sheets and know where they are located. The more complicated forms will have SOPs on methods of completion and use. The type of samples collected, the sample holding times and availability of acceptable labs will dictate the number and types of samples that can be collected in a single trip. Pre-trip planning will maximize efficiency and minimize the need to resample a site.

1. Forms, Checklists, and Sign-Out Sheets

a. Equipment/Supplies Checklist

Use a Groundwater Section Checklist (See **Attachment 2**) to secure the correct sampling supplies and equipment for the sampling run.

c. Equipment Sign-Out Form(s)

Equipment such as peristaltic pumps, field meters, GPS units, cameras, etc. must be accounted for at all times. Therefore, anyone taking equipment to the field must sign for those items they take with them. Small, expensive items are kept in a supply cabinet in the Branch office area. Larger, or less expensive equipment is stored in the Branch storeroom. Equipment sign out sheets are located in each storage area.

2. Other Necessities

a. Trip Blanks

Each time a sample (or set of samples) is collected, a volatile organic compound (VOC) trip blank must accompany the sample(s). These trip blanks are supplied to the Branch by the Environmental Services Branch (ESB) laboratory. Load the VOC trip blanks on the day you sample. These blanks accompany you to each site and are turned in to the ESB lab with the samples taken that day. Generally, each day requires a new trip blank. An exception is when the sampler is out overnight (e.g. does not return to the workplace before starting another round of sampling).

b. Regional Offices Notification

Notify the affected regional office(s) about where you will be working and when. This is mandatory. Often, people see an official vehicle near their home and call the regional office to find out what is going on.

c. Supervisor Notification

Finally, let your supervisor know that you will be in the field sampling.

B. Sampling Equipment

All equipment should be both clean and calibrated, as required, when signed out. If it is not, contact the Equipment and Supply Manager about the problem. All returned equipment will be cleaned of mud, dirt, etc. before being put into its proper place.

1. Equipment required for all sampling:

a. Thermometer

Many analytes have different concentrations depending on the temperature of the water. Meters with internal thermometers do not always agree, so the Branch supplies one with each set of meters. Use this thermometer for reading water temperatures.

b. Meters to measure conductivity and pH.

The Branch employs multi-parameter field meters for temperature, conductivity, and pH of groundwater. Meters are cleaned and calibrated with regular frequency (every 2-3 months). The cleaning and calibration record is kept in a log book stored with each field meter. Refer to the individual meter manual for cleaning and calibration procedures if necessary.

c. Coolers

Coolers are located in the Branch storeroom. Ice may be procured in the DOW Laboratory in Building 150 or purchased in the field. All groundwater samples must be kept at approximately 4ºC. Coolers with ice are used for this sample preservation method until the samples are delivered to the laboratory.

d. Maps

Folders are maintained for each monitoring network run which include: completed inspection/inventory forms, site information forms and individual site maps for each site and a base map for each run. Additionally, the Branch has topographic and geologic maps available for field use. Other maps such as the Kentucky Atlas & Gazetteer can be purchased with Branch funds to assist in site location and navigation.

e. Sharpie™ markers

Sharpies are the best all around writing utensil in the field. Secure both a Fine Point and an Ultra Fine Point Sharpie for labeling the containers.

f. Decontamination supplies

Decontamination supplies consisting of de-ionized water and 10% hydrochloric acid (HCl) are used for cleaning any equipment that cannot be discarded upon use such as buckets, ropes, or field meter probes. All supplies are kept in the Branch storeroom.

2. Equipment required for specialized sampling

a. Peristaltic pump

Peristaltic pumps are used for filtering specified samples for analysis. All laboratories use filtered water to extract dissolved metals, while some labs also use filtered water to extract ortho-phosphate. Other parameters may also require filtered water. The project manager/principal investigator should be contacted for more information. ESB lab personnel are also knowledgeable in which parameters require filtering.

b. Teflon bucket(s) and rope

Some sites are not easily accessible at water's edge. Teflon bucket(s), and rope or string, should be used to safely obtain a sample where getting to the stream edge is not feasible. Remember that these items must be decontaminated between each use.

c. RadAlert meter

The RadAlert meter should be used if radioactivity is suspected at the site to be sampled. It may also be used for site investigations when samplers may encounter unforeseen hazards (i.e. uncontrolled dumps, etc). Refer to the product manual for instructions on the use and care of the RadAlert meter. The manual is kept with the meter.

3. Optional Equipment

Optional equipment (may sometimes be required equipment, depending on circumstances) is any equipment that may make the sampling task easier or faster without sacrificing safety.

a. Backpack

Some sites are remote from vehicular access. Backpacks make sample hauling easier and safer by putting the weight on a strong part of the body while leaving hands free.

b. Bailer(s)

Wells without surface access will require some means to purge the well and then collect a sample. Bailers are long tubes with a stopcock at one end that will allow water into that end of the tube, but will close off the opening at the end of the tube when it is full. (Note: bailers require rope or string)

c. Global Positioning System Unit

The GPS unit gives the correct latitude, longitude, and elevation of a location. Any new spring inventory or well inspection done for DOW should be located using a GPS unit. Read the instructions (housed in the same place as the GPS unit) and Latitude and Longitude Collection: GPS Procedures before attempting to use the unit. Pay special attention to any instructions on use limitations. The unit does not require any calibration that can be done in the field. If the unit does not appear to be working properly (or accurately) inform the equipment manager. Instruction manuals are stored in the cabinet with the units.

d. Cameras

i. Digital Cameras

The Branch has two digital cameras available for use. Instructions for each camera are housed in the same place as the cameras.

ii. Down-hole (or well) Cameras

Use only after proper instruction on the camera's use. An SOP for using the camera is in progress. Until it is finished, however, learn from veteran camera users how it's done. Some of the equipment associated with the camera does not work properly at temperatures below 40° Fahrenheit. Reschedule any trips with the camera if the weather makes operation of the equipment below 40° Fahrenheit likely.

e. Flashlight

f. Brunton Compass

g. Hand level

h. Binoculars

i. Leather or cotton gloves

Gloves of any type protect hands during hard or heavy labor. Sometimes groundwater sites will require hiking through thick brush or crossing fences as well as the use of bailers to collect samples from wells without pumps. Gloves can be a hand-saver at these times. Leather gloves provide better protection, but can get pretty hot during the summer. Cotton gloves breathe better, but provide less protection. Combinations may be the best choice.

j. Key(s)

Some public water supplies and private wells have restricted access. The Branch will have a set of keys to enable samplers to get to the sampling site. Sites that require keys will have a key in the file folder for that site. Most public water suppliers do not like to have too many keys not under their control; only one key may be given to the Branch so do not lose the key. Always check any folder for keys.

C. Sampling Supplies

All supplies are disposable to aid in cross contamination reduction. The Equipment and Supply Manager is responsible for ensuring all sampling containers meet Groundwater Section standards as shown in **Attachment 3** and the Division of Water Watershed Management Branch; Department For Environmental Protection Chemical Hygiene Plan. Project Supervisors are also responsible for ensuring proper containers are used by sampling personnel. All sample containers must be factory cleaned to specifications dependent on the ultimate use of the container (See **Attachment 3** for the complete list of cleaning specs and for the proper container for each type of parameter the laboratory might be analyzing). Note that containers are **NOT** interchangeable because of the cleaning standards required. However, the liter sized amber glass containers may substitute for any other container, except VOC containers or any specialized containers, in an emergency.

Any equipment that uses batteries should be checked for 1) current battery power, if possible, and 2) if extra batteries are available. Changing batteries every time a piece of equipment is used is not feasible or good use of government money. Use batteries as long as possible, but make sure spares are available in the field. If none are to be found, inform the Equipment and Supply Manager, and he will replenish the supply. The digital cameras have time remaining indicators for batteries currently in the camera. TEST batteries in the camera before leaving to ensure you get the pictures you need. Write in the amount of time left on the battery in the camera so the next person will know what to expect. There is a space for time remaining on the equipment sign-out sheet.

1. Supplies required for a typical sampling run

a. Sample containers

i. 1000 (or 950) ml amber glass jars

Used for collection of water for analysis of pesticides, herbicides and caffeine. “Duplicate” samples are also collected in these containers, but duplicates are not collected at every site.

ii. Boston Rounds (HDPL)

Used for the collection of nutrients, bulk (water chemistry, NO_3-N, NO_2-N and major anions) parameters and total and dissolved metals analysis.

iii. 40ml amber glass pre-preserved with HCl

Used for collection of volatile organic compounds (VOCs).

iv. 120ml amber glass

Used for collection of glyphosate.

v. 250ml HDPE wide mouth jar

Used for Alkalinity only-fill completely leaving no head space.

b. Specialized containers

Specialized containers may be obtained from the appropriate laboratory or from your Project Manager or the Equipment and Supply Manager.

i. Bacteria sample containers

ii. Radionuclides sample containers.

c. Preservation Supplies

i. Sulfuric Acid Ampoules

Concentrated (98%) sulfuric acid (in 2ml vials) is used to preserve samples collected for Nutrients ($NH_{3,}$ TKN, TOC, and Total Phosphorus) analysis.

ii. Nitric Acid Ampoules

A 70% concentration of nitric acid (in 2ml ampoules) is used to preserve samples collected for dissolved and total metals analysis.

iii. Hydrochloric Acid

5ml plastic vials of 1:1 concentration hydrochloric acid used to preserve Herbicides/Caffeine and Duplicate samples.

d. Other Supplies

i. Filters and tubing

Some samples must be filtered. The 45-micron filters and medical grade silicon tubing used by the Branch meet all criteria for filtering. Dissolved metals samples and, for some laboratories, ortho-phosphate samples are filtered by Branch personnel.

ii. Latex gloves

Latex gloves shall be worn during every phase of the sampling procedure. This not only protects the sample from contamination, it protects the sampler from any potential contamination present in the sample.

iii. Chains-of-Custody (CoCs)

Fill out CoCs in accordance with GWB 100.2

iv. 3-Ring Binder

A 3-ring binder will keep site material together and clean. It is big enough so that loss of material is minimized, and the sleeves keep things dry. This binder will also hold the CoCs for all the sites to be sampled. Contact your Project Manager for the CoCs you will need.

v. Scissors

Especially useful when working with rope or string for bucket or bailer sampling, but also a good general-purpose tool.

IV. Sampling Procedures

A. Step One – Fill out forms

Fill out a Site Safety Inspection Form (See **Attachment 1**). A completed site form for each site visited will accompany every sampler on the route being sampled. This form will be for an ordinary day at the site. Any changes in the site or weather that could change the safety of the site should be noted directly on the completed form. Return the changed form to the program/project coordinator at the end of the sample run.

Fill out the appropriate program/project CoC for the site in accordance with GWB SOP 100.2 (Chains-of-Custody).

B. Step Two – Label containers

Label all sample containers for the site using a black or blue Sharpie^{TM} – Fine point for container bodies, Ultra fine point for lids and paper labels.

1. Label Boston rounds on side of container;
2. Label 1000ml/950ml amber glass on lid;
3. Label 40ml amber glass using the adhesive labels included in the boxes by the manufacturer;
4. Label 120ml on lid or use the adhesive labels included in the box by the manufacturer;
5. Label 250ml HDPE wide mouth jar on side of container.

Labeling of sample containers will consist of:

1. Eight-digit well/spring number (AKGWA #)
2. Location (site) name, including county
3. Parameters for which an analysis is to be made (abbreviated if necessary)
4. Preservation method(s)
5. Date and time of sampling event: (Use 24-hour clock and note if using Central Time instead of Eastern Time)
6. Initial(s) of sampler

(All this information can be found on the CoC.)

EXAMPLE:

9000-1010
Jack's Spring
Goshen County
Dissolved Metals
Filtered, HNO_3 , Ice
2/2/02 16:45 JRM

C. Step Three – Decontaminate Equipment

Decontamination must be performed prior to each sampling event using equipment that may become contaminated. The Groundwater Section uses, as much as possible, expendable supplies to keep the necessity of decontamination to a minimum. However, Teflon buckets, ropes used in conjunction with the Teflon bucket and field meter probes all must be decontaminated prior to each use. To decontaminate equipment other than field meters, rinse with clean water, rinse with 10% HCl, then rinse twice again with de-ionized water. For field meter decontamination, rinse with de-ionized water only before and after use.

D. Step Four – Collect samples

Always fill containers as full as possible. The ESB laboratory requires at least 250 ml of sample to run analyses (excluding VOCs and Glyphosate). Therefore, fill sample containers at least ¼ full. VOC bottles must be filled completely without air bubbles. Try to get clean samples; don't pick up stirred up material from the last sample (always sample upstream from yourself). Sampling is best done at a point where water is restricted so that it runs more swiftly (when possible). Obviously, turbid water will result in cloudy to muddy samples, but try to ensure any turbidity in the sample is from naturally turbid water, not from something you stirred up.

D. (1) Collecting Bacteria Samples

Bacteria samples are not regularly collected as part of the Ambient Groundwater Monitoring Network. However, bacteria are analyzed for various research projects and groundwater-related complaint investigations. Bacteria samples are collected in 100 mL plastic containers. Only raw water samples shall be collected. If you are sampling a well or spring that has a treatment system, ensure that you can collect samples from a bypass valve or pretreatment (i.e. at the spring mouth or bailed from the wellhead).

When collecting bacteria samples be aware of and follow the directions noted above in Step Four regarding clean samples. For spring samples, open the container and place it in the water upstream of yourself, facing upstream. Fill precisely to the 100 mL mark on the bottle. For well samples, place the container directly beneath the spigot and fill precisely to the 100 mL mark on the bottle. Avoid collecting samples from swivel faucets and frost-proof hydrants.

E. Step Five – Field Measurements

Collect field measurements data: temperature, conductivity, pH, and estimate spring flow in cubic feet per second (cfs). Conductivity and pH meters should be put into water as soon as possible, as they tend to read more accurately if they have time to become acclimated. Record the information from the meters after sampling to ensure the most consistent and accurate readings. Note the measurements directly on the CoC, or use a notebook and put the data on the CoC later. Field meters are cleaned and calibrated in the laboratory on a regular basis and a log book for calibration is kept with each meter. Every meter has a temperature element to it, but these can only be calibrated by the manufacturer. Each meter box contains a separate thermometer that can be used for temperature measurements, if meter readings are suspect. In the event that a meter will not work properly, nor calibrate, note the problem in the comments field on the CoC. Rinse the probe with de-ionized water when measurements are complete. Each meter box also contains electrode storage solution. At your last site of the day, following the final rinse, fill the red cap with electrode storage solution prior to replacing.

F. Step Six – Filter and Preserve

Filter and preserve appropriate samples according to the following: For each container of nutrients, add the contents of one vial of H_2SO_4. For each container used for total metals analysis, add the contents of one vial of HNO_3. For each sample used for dissolved metals, first filter the sample by running the water through a 0.45 micron filter via a two foot length of medical grade silicon tubing. A peristaltic pump is used to induce the water through the filter. After filtration, add the contents of one vial of HNO_3 to the container for preservation of the sample. For each Herbicides/Caffeine sample and each Duplicate sample add the contents of one vial of HCl (1:1). Place all samples on ice in the coolers.

WARNING: Wear latex gloves for hand protection and contamination prevention, and wear eye protection in case of splashing.

Fill in Field Measurements section of the CoC with the necessary information. (Note: The computer program we use can only show data for spring flow in cubic feet per second (cfs), so it is best to learn to estimate stream flow in this mode. However, a flow conversion table is available if you are not accustomed to this mode. Flow estimates are made by estimating the cross-sectional area of the channel and multiplying by the estimated velocity. This requires significant practice and it may help to study various USGS documents relative to flow gaging and estimation.) Clean up area, checking to make sure you have all your equipment, and move on to next site.

V. Sample Delivery and Clean-up

A. Sample Delivery

Complete CoC (e.g. place check mark in box beside each set of parameters you are requesting) and fill in any blanks that were not previously completed. Be aware of holding times especially for bacteriological samples. Deliver samples to the lab early so that they can begin sample preparation before the holding time has expired. Many bacteria analyses require the lab to begin the test within six hours after the sample was taken.

Deliver samples to proper laboratory. At the ESB lab, request that your completed CoCs be sent to Groundwater Section after the lab is finished with them.

B. Clean-up

Put unused supplies back into storage room. If you have partial boxes of containers left, check to see if you can consolidate your boxes with any that are already open. We don't have much space, and any consolidation means one less box to take up space.

Return equipment to the appropriate storage area. If it is dirty, clean it. There is a mild cleaning agent at the sink and there are some outside spigots if it is too big or too dirty for the lab. The cleaner cuts grease (or oil) well, so use it if you get the equipment into an oil spill or something similar.

Note any equipment problems in the remarks section of the sign-out sheet. If supplies are low, inform the Groundwater Section Equipment Custodian.

Return the vehicle the way you found it. Fill the gas tank and clean the vehicle if necessary. Refuel the vehicle at the motor pool or any sanctioned Fleet One Card gas station. The motor pool has an automated carwash that will clean the outside of vehicles. There is also a vacuum available to clean the inside. Put any receipts for gas, oil, or anything else bought for the vehicle into the log book pouch (inside the front cover of the log book). Make sure you enter appropriate information about your purchases in the log book.

Park the vehicle with the other DEP vehicles, complete the log book, and return all keys and log book to appropriate places.

References:

USEPA, Region IV, 2008, Field Branches Quality Management System and Technical Procedures, cited October 2008, http://www.epa.gov/region4/sesd/fbqstp/.

USEPA, Region IV, 1990, Field Health and Safety Manual, 31 p.

KY Division of Water, 2006, Latitude and Longitude Collection: GPS Procedures, KDEP, Frankfort, KY.

KY Division of Water –Watershed Management Branch, 2008, Chemical Hygiene Plan, KDEP, Frankfort, KY.

DeLorme, 1997, Kentucky Atlas & Gazetteer*, Yarmouth, ME.*

KY Division of Water – Watershed Management Branch, 2008, GWB 100.2.1 Completing Chains-of-Custody, KDEP, Frankfort, KY.

ATTACHMENT 1

SITE SAFETY INSPECTION FORM

Personal Protective Equipment (PPE)

Worksite Hazard Assessment

Part A	
Site ID:	NOT/COM #: GPS:
Part B	
Circle Hazard/s Located at the Site being Assessed Sufficient to Require PPE. Comment in Part C.	
HEAD POTENTIAL INJURY/HAZARD 1. Struck By 2. Struck Against 3. Electrical 4. Temperature 5. Other ____	**EYES/FACE** POTENTIAL INJURY/HAZARD 1. Airborne 2. Chemical 3. Flash/Light/UV 4. Other ____
RESPIRATORY POTENTIAL INJURY/HAZARD 1. Oxygen Deficiency 2. Airborne Particles a. Dusts b. Fumes c. Mists 3. Airborne Contaminants a. Gases b. Vapors 4. Combinations 5. Temperature 6. Other ____	**HAND/ARM** POTENTIAL INJURY/HAZARD 1. Cut/Abrasion/Puncture/Crush 2. Electrical 3. Chemical 4. Biological 5. Temperature 6. Body Fluids 7. Cumulative 8. Strain 9. Other ____
FOOT/LEG POTENTIAL INJURY/HAZARD 1. Cut/Abrasion/Puncture/Crush 2. Electrical 3. Chemical 4. Biological 5. Temperature 6. Struck by/Against 7. Strain 8. Other ____	**TORSO/WHOLE BODY** POTENTIAL INJURY/HAZARD 1. Cut/Abrasion/Puncture 2. Electrical 3. Chemical 4. Biological 5. Temperature 6. Struck By/Against 7. Body Fluids 8. Strain 9. Cumulative 10. Slip/Trip/Fall a. Same Level b. Different Level 11. Entrapment 12. Immersion/Submersion/Water 13. Other ____
AUDITORY NOISE LEVEL 1. Ambient Level Above 85 dBa 2. Impact Level Above 85 dBa	
PART C **GO/NO GO** **COMMENTS**	

WORKSITE ASSESSMENT SURVEY GUIDANCE
PERSONAL PROTECTIVE EQUIPMENT (PPE)

I. 29 CFR 1910.135 HEAD PROTECTION 1. HARD HAT 2. HARD HAT 3. HARD HAT/NON-METALLIC 4. HARD HAT W/WINTER LINER OR SWEAT BAND	**29 CFR 1910.133 EYES AND FACE PROTECTION** 1. SAFETY GLASSES W/SIDESHIELDS, GOGGLES, OR FULL FACESHIELD 2. NON-VENTED GOGGLES OR FULL FACESHIELD 3. FILTER OR TINTED LENS
29 CFR 1910.134 RESPIRATORY PROTECTION 1. SCBA OR SUPPLIED AIR RESPIRATOR 2. USE MSDS TO DETERMINE FILTER REQUIREMENT 3. USE MSDS TO DETERMINE FILTER REQUIREMENT 4. USE MSDS/DETERMINE FILTER REQUIREMENT/CONFIRM W/RESPIRATOR PROGRAM ADMINISTRATOR 5. COLD-COVER MOUTH/NOSE, HEAT-SCBA OR SUPPLIED AIR (TEMPERED)	**29 CFR 1910.138 HAND/ARM PROTECTION** 1. GLOVES-CANVAS, LEATHER, MESH, KEVLAR 2. DIELECTRIC GLOVES/SLEEVES 3. APPROPRIATE GLOVES/SLEEVES OR COVERALLS 4. CLOTHING/GLOVES/COVERALLS/BARRIER CREAM/REPELLANT 5. GLOVES/CLOTHING 6. LATEX/NITRILE GLOVES (BBP KIT) 7. GLOVES/RESTRAINTS 8. ADEQUATE TOOLS/ASSISTANCE FROM OTHERS
29 CFR 1910.136 FOOT/LEG PROTECTION 1. APPROVED SAFETY SHOE/PROPER CLOTHING 2. NON-METALLIC SAFETY SHOE/PROPER CLOTHING 3. RESISTANT FOOTWEAR/PROTECTIVE CLOTHING 4. COVERALLS/BARRIER CREAM/REPELLANT 5. COLD-INSULATED FOOTWEAR/CLOTHING HEAT-RESISTANT FOOTWEAR/ADEQUATE CLOTHING 6. SAFETY SHOE/ADEQUATE CLOTHING 7. PROPER TECHNIQUES/ASSISTANCE	**29 CFR 1910. MISCELLEANEOUS STANDARDS - TORSO/WHOLE BODY** 1. ADEQUATE CLOTHING 2. MAINTAIN DISTANCE 3. PROTECTIVE APRON/COVERALLS, SUITABLE FOR MATERIAL 4. PROPER CLOTHING, BARRIER CREAM, REPELLANT 5. COLD-INSULATED JACKET/COAT, HEAT-APPROPRIATE CLOTHING WORK/REST INTERVALS 6. PROTECTIVE CLOTHING/WARNING DEVICES/GUARDS 7. PROTECTIVE APRON, COVERALLS 8. PROPER WORK HABIT/ASSISTANCE/APPROPRIATE TOOLS 9. BODY MECHANICS/PROPER TOOLS/WORKSTATIONS 10. PROPER FOOTWEAR/HARNESS/TETHER/LIFELINE/ ASSISTANCE 11. DO NOT ENTER 12. PERSONAL FLOTATION DEVICE/TETHER/LIFELINE
29 CFR 1910.95 HEARING PROTECTION 1. APPROPRIATE NRR EAR PLUGS OR MUFFS 2. APPROPRIATE MRR EAR PLUGS OR MUFFS	

ATTACHMENT 2

SAMPLING CONTAINERS

Sampling Containers Used by Watershed Management Branch

1. **HDPE Boston Rounds.** High Density Polyethylene container certified to meet or exceed EPA standards for metals, cyanide and fluoride. Used for collecting Total and dissolved metals, Nutrients and Bulk Parameters.

2. **Amber Glass, 40ml Capacity.** Amber borosilicate glass certified to meet or exceed EPA standards for volatiles. Pre-preserved with hydrochloric acid.
   Used for collecting VOC samples.

3. **Amber Glass, 950 - 1000ml Capacity.** Amber glass certified to meet or exceed EPA standards for metals, pesticides, and semi-volatiles.
   Used for collecting pesticides, herbicides, caffeine and duplicates. This is an all-purpose container. If there is a shortage of other containers (except bacteria and VOC containers), this one, and <u>only</u> this one, will substitute for any of the others.

4. **Amber Glass, 120 ml Capacity.** Amber glass certified to meet or exceed EPA standards for metals, pesticides, and semi-volatiles. Used for collecting Glyphosate samples only.

5. **HDPE Wide Mouth Nalgene Jar, 250 ml Capacity.** High Density Polyethylene container certified to meet or exceed EPA standards. Used for collecting Alkalinity samples only – MUST BE FILLED COMPLETELY, NO HEAD SPACE.

Table. Field Equipment/Instrument Calibration, Maintenance, Testing, and Inspection

Analytical Parameter	Field Equipment/ Instrument	Calibration Activity	Maintenance Activity	Testing/ Inspection Activity	Frequency	Acceptance Criteria	Corrective Action

APPENDIX II. Analyte containerization, preservation, holding times and analytical methods