GROUND WATER (DYE) TRACING IN MURFREESBORO FOR PLANNING BEST MANAGEMENT PRACTICES FOR STORMWATER RUNOFF, PREDICTING SINKHOLE FLOODING PROBLEMS, AND TO AID IN CHEMICAL SPILL RESPONSE: RESULTS OF YEAR THREE OF THE INVESTIGATION

Prepared for:

The City of Murfreesboro

Water and Sewer Department

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GROUND WATER (DYE) TRACING IN MURFREESBORO FOR PLANNING BEST MANAGEMENT PRACTICES FOR STORMWATER RUNOFF, PREDICTING SINKHOLE FLOODING PROBLEMS, AND TO AID IN CHEMICAL SPILL RESPONSE: RESULTS OF YEAR 3 OF THE INVESTIGATION

EXECUTIVE SUMMARY

The third year of ground water tracing in Murfreesboro has been a very successful one. A total of 8 ground water (dye) traces were conducted during the investigation in which 7 showed positive results proving a hydrologic connection between the injection points and the monitored springs. No dye traces had ever been conducted to any of the springs involved with this year's study so significant knowledge has been gained on the recharge area (watershed) of 5 springs that all contribute flow to the upper reaches of the West Fork of the Stones River. Most of the springs provide the base flow for the upper West Fork during the summer months. One successful trace was conducted to Three Rivers Spring which is one of two springs that forms the head of Spence Creek which is dry above the springs during the late summer and early fall months. Two successful traces were conducted to Barfield Spring which is upstream from the confluence of Spence Creek and the West Fork. Barfield Spring is one of the largest springs in Murfreesboro's Urban Growth Boundary and is recharged by runoff from nearly all sides of Barfield Knobs. One trace actually went under the south side of the Knobs flowing downdip toward the synclinal trough along which Barfield Spring is located. This demonstrates that topographic divides are not always a reliable method for determining a drainage basin in a karst terrane. Tuma Spring is located upstream from Barfield Spring. The West Fork goes dry in the late summer above this spring. No successful trace was conducted to the spring, but the other traces now strongly suggest that the spring water is largely from Harrison and Fontaine springs located upstream. The water from these two springs sinks into the bed of the West Fork soon after their confluence with the river. A synclinal trough in the area also suggests that some of the flow of Tuma Spring is from runoff from the western side of Marshall Knobs in Barfield Park. It will be necessary to conduct dye tracing in the summer months when the upper West Fork is dry to prove these hypotheses. Two successful traces were conducted to Fontaine Springs and another two successful traces were conducted to Harrison Spring via Crescent Spring. Harrison Spring is the larger of the two springs and is believed to have a much greater recharge area than the information provided by the two dye traces. The upper West Fork of the Stones River is the most pristine portion of the river. In order to keep its pristine nature, careful planning of growth by the City and County will be necessary. More ground water tracing is needed in this area to better help in this planning.

INTRODUCTION AND PURPOSE

The upper West Fork of the Stones River is a relatively pristine waterway. During normal dry summers and early fall, the West Fork is dry upstream of Barfield Park. All of the flow of the river below that point is water that emerges from two large springs. Therefore, the water quality of the upper West Fork is actually that of the two springs when there are no storm water runoff events. Rutherford County is underlain by cavernous rock in which rain waters and contaminants rapidly enter the ground through sinkholes with little or no filtration. Murfreesboro and the County has been experiencing unprecedented growth that has led to increasing amounts of storm water runoff that is often laden with chemicals applied to yards and fluids that leak from cars. In addition, the increased growth has resulted in more trucks carrying hazardous chemicals and gasoline, that if spilled, would quickly disappear into a sinkhole without any prior knowledge as to which spring the chemicals are going to emerge. This would result in killing of aquatic species in our surface streams and endangering our water supplies (Percy Priest Lake). Ground water tracing from sinkholes to springs using non-toxic dyes enables the delineation of surface watersheds that provide water to the subterranean streams that feed springs. Therefore, the primary purpose for conducting the ground water tracing was to determine the surface drainage basins of the springs in the upper West Fork of the Stones River to aid in planning growth and insure water quality protection.

The secondary purpose for the ground water tracing is to aid the city in predicting whether an area with sinkholes that is proposed for development will likely flood during large storm events. The results of this investigation can be used by city personnel to determine the elevation difference between a sinkhole bottom and the spring to which it drains. If the bottom is close to the spring elevation, the water table will simply rises quickly from the bottom of sinkholes during large storms. Thus, constructing drainage wells or digging out clay bottoms of sinkholes will not help alleviate the flooding. If there is approximately 25 feet of difference between a sinkhole bottom and spring, flooding can likely be prevented.

STUDY AREA and HYDROGEOLOGIC SETTING

The study area is located largely within the Murfreesboro Urban Growth Boundary in the upper West Fork of the Stones River. Figures 1 shows the location of the springs involved in the investigation. These include Three Rivers Spring, Barfield Spring, Tuma Spring, Pruitt Spring, Fontaine Spring, Harrison Spring, and Crescent Spring. No traces had ever been conducted to any of these springs prior to this study. During the drier months of late summer and early fall, the West Fork goes dry above Tuma Spring. Harrison Spring flows year round, but upon reaching the West Fork, the water soon sinks into the river bed. The results of the present investigation suggest that the flow of Tuma Spring during dry times is largely the sinking water of Harrison Spring and others further upstream. This has yet to be proven.

Rutherford County is located in the Central Basin physiographic province, which is underlain by limestones of Ordovician age that have been gently upwarped to form the Nashville Dome. The first detailed geologic map of Rutherford County was made by Galloway in 1919. Detailed geology maps now exist for the entire County. Although the overall structure of the Central Basin is a dome, there are numerous small anticlines, synclines, domes, and basins superimposed upon the larger domal structural. Moore et.al, 1969, made a structure contour map for much of the Stones River basin that shows the largest of the synclines. Figure 1, adapted from Moore, et.al, 1969 and Rima, et.al, 1977 and produced by Josh Upham, presents a conceptual of the geologic structure showing other possible synclinal troughs and anticlinal axes based on field observations and the new tracing results. The details of this will be discussed within each of the sub-sections of the dye tracing results within the report. In general, though, ground water flows off the anticlinal axes downdip toward the synclinal troughs. Nearly all of the springs in the study occur near where a synclinal trough intersects the West Fork of the Stones River.

The oldest rocks exposed in Rutherford County are those of the Murfreesboro Limestone Formation, which is approximately 400 feet thick. Above the Murfreesboro

Limestone is the Pierce Formation (Figure 2), a shaly, thin-bedded limestone that confines water beneath it in the Murfreesboro Aquifer and perches w ater above it in the Ridley Limestone. The Ridley Limestone underlies most of the area of investigation, and it is the most karstic (cavernous) limestone in Rutherford County. Proprietary files of the Tennessee Cave Survey show that a majority of the 124 caves discovered and explored in Rutherford County occur in the Ridley Limestone aquifer. Snail Shell Cave near Rockvale is the largest with over nine miles of passage. All of the springs involved in this study are believed to emerge near the contact between the impermeable Pierce Formation and the overlying Ridley Limestone (Three Rivers Spring, Barfield Spring, and Tuma Spring) or the upper Ridley Limestone and the underlying Lower Ridley Confining Unit (Pruitt, Fontaine, Harrison, and Crescent Springs).

The first documented dye tracing in the Rutherford County occurred in the area of Snail Shell Cave as part of the State's proposal for the Superconducting Super Collider (Crawford, 1988). Crawford conducted two traces in the study area as part of his investigation. Since then, approximately 130 ground water traces have been conducted in the County by the author of this report. Five previously funded projects by the Rutherford County Planning Commission, three grants from the City of Murfreesboro, four MTSU Faculty Research Grants, and a grant from the Rutherford County Board of Education have enabled important discoveries to be made regarding ground water flow directions, causes for sinkhole flooding, and potential sources of spring water contamination. This research has resulted in a number of publications (Ogden and Scott, 1997; Ogden et.al., 1998; Ogden et.al., 1999; Ogden and Powell, 1999; Ogden, 2000; Ogden et.al., 2001; Ogden et.al., 2002, Ogden, et.al., 2003, James, et.al, 2004, Ogden, et.al., 2006, and James, et.al, 2006, Ogden et. al., 2012). Josh Upham, of Murfreesboro's Water and Sewer Department, has diligently updated the statewide GIS ground water tracing database he and the author created for TDEC-Ground Water Management Section in 2003. The author has conducted approximately 40 new traces in Rutherford County since 2003.

GROUND WATER TRACING METHODS

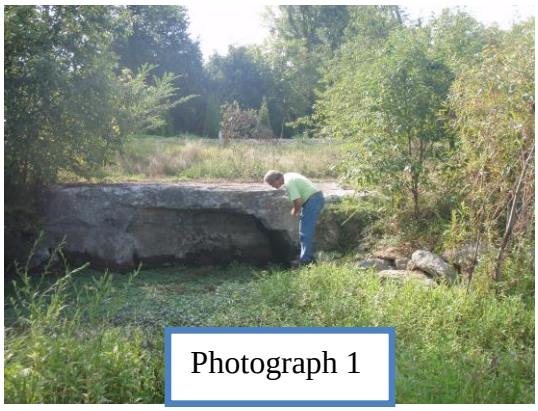
The ground water tracing was performed using three fluorescent dyes: sulphorhodamine B (SRB), eosine, and fluorescein. These tracing agents are non-toxic and routinely approved for use by various divisions of the Tennessee Department of Environment and Conservation. Prior to conducting the traces, the Tennessee Underground Injection Control Program was notified in writing as required for their dye tracing registration program (see Appendix A). Material Safety Data Sheets for the dyes can be found in Appendix B. The injected tracing agents were detected by using activated charcoal packets that absorb and concentrate the dye levels in the water. The charcoal packets, called "traps", were suspended in the waters expected to receive the dyes on a stiff wire connected to a concrete base. Prior to tracing, some of the traps were placed in the spring waters for approximately a week to test for background concentrations. The dyes are common coloring agents and frequently found as "contaminants" in the ground water. Once background levels were determined, new packets were set out immediately prior to injection. After injection of the tracing agents, the packets were changed at approximately seven to ten day intervals and sent to the laboratory for analysis. Crawford Hydrology Lab, located at Western Kentucky University, was used to perform the analyses, which were done by a scanning spectrofluorophotometer.

GROUND WATER TRACING RESULTS

A total of eight traces were conducted for this project of which seven were successful. All of the springs studied, empty into the upper West Fork of the Stones River. No tracing had ever been conducted to any of the springs prior to the present investigation. The following is a discussion of the results by spring basin starting at the most downstream spring and then moving upstream throughout the rest of the report. Appendix C provides the results from the laboratory.

Three Rivers Spring

Figure 3 shows the location of Three Rivers Spring. This spring is located along Spence Creek which follows a synclinal trough (Figure 1). Spence Creek goes dry during summer months above the spring's cave orifice (Photograph 1). Therefore, during drier months, the quality of Spence Creek is a combination of quality of Three Rivers Spring and River Rock Spring which is located not far downstream. Very few sinkholes exist in the suspected drainage basin of Three Rivers Spring which has made tracing to it difficult. There is an overflow spring located about a mile southwest of the spring that is a flowing spring during very wet conditions but a sinkhole that takes water during drier conditions. Three-quarters of a pound of fluorescein was injected into a small pool of water at the bottom of the sinkhole on October 12th, 2012 . It was detected at Three Rivers Spring a few weeks later. It is believed that a significant amount of the discharge of Three Rivers Spring and possibly River Rock Spring is from water lost along the streambed of upper Spence Creek. To confirm this would require a summer dye trace utilizing fire hydrant water to flush dye into a hole in the dry streambed.



Photograph 1

Barfield Spring

Figure 4 shows the location of Barfield Spring. Barfield Spring empties directly into the West Fork from several different small caves at river level (Photograph 2). Structurally, the spring is located close to where a synclinal trough crosses the West Fork (Figure 1). The spring is one of the largest within Murfreesboro's Urban Growth Boundary based on observations during very dry conditions when the upper West Fork was dry

Photograph 2

(Photograph 3). This spring, the smaller Tuma Spring, and Spence Creek join to form all of the flow of the West Fork throughout most of the late summer and early fall. Therefore, the quality of water in the West Fork above Spence Creek during drier months likely matches the quality of Barfield and Tuma springs. Two successful traces were conducted to Barfield Spring. The first trace involved injecting one pound of eosine dye on October 12th, 2012, into a sinking stream that drains a substantial portion of the northern slopes of Barfield Knobs (Photograph 4). The second trace was conducted on November 2nd, when one pound of eosine was injected into a cave pool on the south side of Barfield Knobs (Photograph 5). The second trace was expected to go to Tuma Spring. Instead, the eosine traveled under the Knobs to emerge at Barfield Spring demonstrating that in karst terraines surface divides and ground water divides do not always coincide. Structure is apparently more important than topography in controlling the flow of ground water. The rocks at the cave dip slightly to the north toward the syncline along which Barfield Spring is located. The ground water is simply flowing down the dip toward the trough of the syncline. The failed traced mentioned in the introduction of the results section of this report may actually have gone to Barfield Spring as well. The dashed line on Figure 4 shows where just one half pound of eosine was injected into

Photograph 3

Photograph 4

Photograph 5

a sinkhole on January 9th, 2013 during a storm event. A small amount of eosine was used because it was believed that it would emerge at nearby Tuma Spring, but it did not. Instead, there was a rise in the level of eosine at Barfield Spring. It is felt that all of the eosine from the earlier cave trace would have been flushed out of the Barfield system due to numerous heavy rain events, but this cannot be stated with certainty. The large flow of the spring strongly suggests that a significantly greater recharge area exist for the spring than the information provided by the two traces. It is likely that areas west of Barfield Knobs and other areas south of the Knobs, contribute recharge to the spring. More tracing is necessary to confirm this.

Tuma Spring

Tuma Spring is located upstream from Barfield Spring and forms the head of the West Fork during late summer and early fall months when the river is dry above it (Figure 5; Photograph 6). No successful trace was conducted to the spring. It was hypothesized before the project began that most of the flow from Tuma Spring was from water that sank into the bed of the West Fork during drier months. A successful trace to Harrison Spring located upstream has given credence to this idea. One fluorescein trace to Harrison Spring turned the spring green, and the spring water remained green where it entered the West Fork of the Stones River. The river had a significant amount of water in it at the time due to recent storm events which would have seriously diluted the dye. Even so, the level of fluorescein four days later at Tuma Spring was the highest of the four measurements made throughout the study period. Unfortunately, that high level was still less than ten times above background which is the necessary lab criteria for considering a trace positive. Since the water from Harrison Spring sinks into the bed of the West Fork during dry conditions, it would be easy to prove if this trace was indeed

Photograph 6

positive. There are numerous sinkholes and caves on Marshall Knobs where Barfield Park is located. It is suspected that water sinking in this area during storm events goes under the West Fork to emerge at Barfield Spring. This could only be proven during the late summer when the West Fork is dry above Tuma Spring.

Pruitt Spring

Pruitt Spring is located upstream from Tuma Spring and was monitored for dye during many of the dye traces (Figure 5). No dye was ever found to emerge at the spring. The owner, who has observed the spring for over 50 years, said he has known it to go dry only once. Therefore, it does contribute flow to the West Fork which also likely emerges at Tuma Spring when the upper West Fork sinks into its bed. The discharge of Pruitt Spring was observed to be nearly the same as Fontaine Spring located not far to the south. Two successful traces were conducted to Fontaine Spring. Therefore, the drainage basins of the two springs are likely similar in size.

Fontaine Spring

Fontaine Spring is located about a half mile south of Pruitt Spring (Figure 5). Although not a large spring, it was reported to flow year round. Two successful traces were conducted to the spring. On December 17th, 2012, one-half pound of eosine was injected into a sinkhole at the edge of a new subdivision in an area where new homes were under construction. A small ephemeral stream that flows off of land on the west side of Barfield-Crescent Road sinks on the same property as the dye injection. It certainly goes to Fontaine Spring, as well. On December 20, 2012, one-half pound of fluorescein was injection at the intersection of Barfield-Crescent and Morton roads. It too was detected at Fontaine Spring. Pruitt Spring was monitored during both of the traces in case the two springs were hydrologically connected. No dye was detected at Pruitt Spring. The water from Fontaine Springs flows into the West Fork and sinks into its bed during the dry months of the year.

Harrison Spring

Harrison Spring is a large spring located about a mile southwest of Fontaine Spring (Figure 6; Photograph 7). The water from the spring travels nearly a mile before entering the West Fork of the Stones River. Its flow combines with that of Fontaine and Pruitt springs before the river sinks into its bed. Two successful traces were conducted to the spring. Before each dye injection, charcoal dye detectors were also place at an impressive karst window that can be observed at the intersection of Barfield-Crescent Road and Crescent Lane (Photograph 8). Water in the karst window comes from Crescent Spring. On October 15th, 2012, three-quarters pound of fluorescein was injected into a karst window located on a farm south of Harrison Road (Photograph 9). The next day, the water in the karst window along the highway was bright green, as was the water emerging from Harrison Spring. The water was green when it entered the West Fork, but did not turn the West Fork green in color. The detectors were not sent to the lab since the trace was visual so the lab results shown in Appendix C do not record this trace. The dye detector retrieved at Tuma Spring four days later did show an elevated level of fluorescein, but not high enough to prove that sinking water from the river recharges Tuma Spring. The second trace

Photograph 7

Photograph 8

was conducted January 9th, 2013. One pound of fluorescein was injected into a sinking stream about one-quarter mile east of Fann Road (Photograph 10). The detectors at both the karst window and Harrison Spring were positive for the dye. The large size of Harrison Spring strongly suggests that the recharge area is much greater than demonstrated by the two traces. Since most of the sinking water of the West Fork is that of Harrison Spring, it is likely that the water quality of Tuma Spring reflects that of Harrison Spring during the late summer and early fall. This will not be known until a summer dye trace is conducted to determine if the sinking waters of the West Fork contribute to most of the flow of Tuma Spring. A discharge measurement of Tuma Spring and the upper West Fork before the sink point would be useful in quantifying the percentage of spring water discharge that could be directly correlated to the flow of the river.

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to delineate the surface watersheds that provide recharge to springs within the pristine reaches of the upper West Fork of the Stones River. Springs in this area provide essentially all of the flow of the upper West Fork during late summer and early fall when the river above the springs goes dry. Therefore, protecting the water quality of the springs insures protection of the river during drier months. A total of eight ground water (dye) traces were conducted for this project of which seven were successful. Traces were conducted to five springs in which no previous knowledge existed as to the source of the spring flow.

One successful trace was conducted to Three Rivers Spring which is one of the two springs that form the head of Spence Creek during dry conditions when the creek is above the springs is dry. Barfield Springs, located about a mile upstream of the confluence of Spence Creek and the West Fork, is one of the largest springs in the County. Two dye traces were conducted to this spring enabling delineation of perhaps two-thirds of the spring's ground water basin. Tuma Spring is located upstream of Barfield Spring and forms the head of the upper West Fork during the summer and early fall. No successful traces were conducted to Tuma Spring, but the results of the other traces has led to the conclusion that most of the water emerging from Tuma Spring is that of water that sinks into the bed of the Stones River several miles above the Spring. Tracing provided valuable information on the source of the water for two springs that contribute most of the flow of the sinking river during the dry months. These two springs are Fontaine Spring and Harrison Spring. Two successful traces were conducted to Fontaine Spring and two more traces were conducted to Harrison Spring which is the larger of the springs. Although these two springs are outside of the Urban Growth Boundary, their combined water quality is believe to largely affect the water quality of Tuma Spring that is located within the City. The results of the ground water tracing now provide subterranean drainage information on about 10 square miles of the City and County in which no previous knowledge existed.

RECOMMENDATIONS

The last three years of investigating ground water flow paths in Murfreesboro have provided valuable insight to possible sources of ground water contamination within nearly fifteen different spring drainage basins. Generally, the winter and spring are the best seasons to conduct dye tracing when storm water is entering sinkholes during rain events. The results of this year's investigation show that tracing is necessary during the late summer and early fall when the upper West Fork of the Stones River and upper Spence Creek go dry. This will be the only way to determine the source of Tuma Spring and most of the flow of Three Rivers Spring. The sinking waters of Harrison and

Fontaine spring could be proven to provide the base flow of Tuma Spring. It may also be possible to prove that the western side of the Marshall Knobs in Barfield Park contributes flow to the spring. Therefore, it is recommended that this research be continued for a fourth year with these springs being the focus of the investigation. In addition, at least two traces should be conducted along the dry reaches of Bear Branch during the summer months to determine if it is hydrologically connected to Lufkin Spring and/or Ayers Spring.

ACKNOWLEDGEMENTS

The author would like to thank Josh Upham and Bruce Ross for all their help in the field. Additional appreciation is given to Josh Upham for his help in preparing most of the figures and photographs in the report. Finally, the author would like to thank Eric Hill, an engineer for Rutherford County for assisting us in the field. Eric lives near several of the springs involved with the study and helped us gain access to many of the properties involved with the investigation.

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sources of *e-coli* in springs: Journal of Caves and Karst-selected abstracts of the 2012 NSS convention.

APPENDIX A

Dye Tracing Registration Form submitted to the

Tennessee Department of Environment and Conservation-UIC Program

Tennessee Department of Environment & Conservation
Dye Trace Registration

Owner/Operator of Facility Necessitating Trace:

Name: Murfreesboro Water + Sewer Dept. Attn: Robert Haley

Mailing Address: 220 NW Broad St., P.O. Box 1477

City, State, Zip Code: Murfreesboro, TN 37127

Phone: (615) 848-3200 County Rutherford

Person/Company Performing Trace:

Name: Albert E. Ogden

Mailing Address: 6478 Jones Lane,

City, State, Zip Code: Murfreesboro, TN 37127

Phone: (615) 907-0004

Property Owner at Injection Site:

Name: various owners on private land

Mailing Address:

City, State, Zip Code:

Reason for Trace: to help determine sources of spring water contamination

If State or Federal Agency Oversight, Give Agency: NONE

Dyes to be Used with Approximate Amounts and Respective Injection Locations:

fluorescein, eosine, + sulphrhodamine B
approximately 1 pound of dye will be used during each injection

CN-1112 RDA 2474

(continued on reverse)

Type Receptors or Visual: charcoal

Background Test: yes

Describe Injection Point(s) and Include Photocopy of Topographic Map with Locations Latitude and Longitude:

see attached map.
coordinated on attached page

Anticipated Injection Date: February and March, 2011

Public Water Systems: List Surface Water Intakes, Wells or Springs within 2 Miles of the Injection Point(s):

No public water supply intakes within 2 miles
Everyone in the study area uses public water
so NO wells or springs are utilized for drinking

Is the Area Served by a Public Water System? Yes

Estimate Percentage of Private Well/Spring Use Versus Public Water Use:

No wells or springs are utilized for drinking

Submitted by: Albert E. Ogden

Phone: (615) 907-0004

Date: 1/12/11

Mail or Fax the Completed Form to:

Tennessee Division of Water Supply
Ground Water Management Section
Attn: Scotty Sorrells
6th Floor, L & C Tower
401 Church Street
Nashville, Tennessee 37243-1549
Phone: (615) 532-0191; Fax: (615) 532-0503

There are currently no regulations requiring dye trace registration in Tennessee, unless there is the potential to impact a public water system. This registry is designed to avoid cross contamination and re-performing the same or similar trace. The dye tracing registry allows the Department to make informed responses to water pollution inquiries so that dye traces are not mistakenly identified as pollution to waters of the state.

Riverrock Spring: 86.431, 35.817; **Boiling Spring:** 86° 27'52", 35 °49'34"

Injection Points: 86.451, 35.824 and 86.455, 35.819

Three Rivers Spring: 86.411, 35.813

Injection Points: 86.442, 35.797 and 86° 25'57", 35° 48'20"

Bear Spring: 86.365, 35.876

Injection Points: 86° 21'51", 35° 51'53" and 86° 22'20", 35° 52'28"

APPENDIX B

Summary of Laboratory Results

CRAWFORD HYDROLOGY LAB * HOFFMAN ENVIRONMENTAL RESEARCH INSTITUTE

* Hydrogeologists, Geologists, Environmental Scientists *

* Karst Groundwater Investigations * Fluorescent Dye Analysis

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

LABORATORY REPORT SHEET

FLUORIMETRIC ANALYSIS RESULTS

Murfreesboro - YEAR 3

Analysis requested by:

Albert Ogden

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

CHARCOAL SAMPLES

						FLUORESCEIN			EOSINE			SULPHORHODAMINE B			
						PQL in Eluent: 0.005 ppb			PQL in Eluent: 0.005 ppb			PQL in Eluent: 0.005 ppb			
						PQL in Water: 0.010 ppb			PQL in Water: 0.010 ppb			PQL in Water: 0.010 ppb			
						λ in Eluent: 516.0 nm			λ in Eluent: 540.1 nm			λ in Eluent: 577.0 nm			
						λ in Water: 510.0 nm			λ in Water: 534.4 nm			λ in Water: 582.2 nm			
Lab ID	Event	Date Collected	Feature Name	TIME	Peakfit	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Comments
EH-001-0	01	10/19/12	TUMA SPRING	NA		++	3.076	515.8	ND			ND	0.444	NPI	
EH-001-0	02	11/09/12	TUMA SPRING	NA		++	0.768	516.0	ND			ND	0.244	NPI	
EH-001-0	03	12/20/13	TUMA SPRING	NA		++	0.733	515.8	ND			ND	0.250	NPI	
EL-001-0	04	01/24/13	TUMA SPRING	NA		++	0.520	515.6	ND			ND			
EH-002-0	01	10/19/12	BARFIELD SPRING	NA		+?	1.078	516.8	+++	9.615	540.6	+?	3.267	576.0	
EH-002-0	02	11/08/12	BARFIELD SPRING	NA		ND			++	4.234	541.2	ND	0.109	NPI	
EH-002-0	03	12/07/12	BARFIELD SPRING	NA		ND			+++	11.593	541.2	ND			
EH-002-1	03	12/21/12	BARFIELD SPRING	NA		ND			+++	27.635	541.2	ND			
EH-002-0	04	01/23/13	BARFIELD SPRING	NA		ND			+++	35.040	541.2	ND			
EL-003-0	01	10/19/12	3 RIVERS SPRING	NA		B	0.061	524.8,POR	ND			+?	0.797	573.4	
EH-003-0	02	11/06/12	3 RIVERS SPRING	NA		+++	12.996	516.0	ND			ND			
EH-003-0	03	01/23/13	3 RIVERS SPRING	NA		++	4.537	516.2	ND			ND			
EL-004-0	01	12/21/12	Pruitt Spring	NA		B	0.050	508.8,POR	ND			ND			
EH-005-D	01	12/30/12	Fontaine Spring	NA		+++	200.100	515.8	+++	241.000	540.0	+?	96.200	576.8	DILUTED 1:100
EH-005-0	02	02/04/13	Fontaine Spring	NA		++	0.358	519.2	+++	8.767	541.0	ND	1.711	NPI	Possible SRB shoulder on EO peak
EL-006-D	01	01/24/13	Harrison Spring	NA		+?	177.600	515.8	ND			ND			DILUTED 1:100

Approved by: L.Bledsoe on 02/11/13

Comments: **Results based on assumption that background was non-detect.**

DUP = Field Duplicate
B = Background
ND = No Detection
IB = Initial Background

NS = No Sample Recovered
GS = Grab Sample
NPI = No Peak Identified
POR = Peak Out of Range

Q = Lab Duplicate
+ = Positive
?+ = Questionable Positive, needs two hits in a row to equal +
Peakfit Utilized

ND Below Quantitation Limit
B Background
NS No Sample

\+ Positive
++ Very Positive
+++ Extremely Positive

Created 2/11/2013

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APPENDIX C

Material Safety Data Sheets for the Dyes used for Tracing

Material Safety Data Sheet
(FLUORESCEIN)
15174 URANINE C

CHEMCENTRAL/Dyes & Pigments
13395 Huron River Drive
Romulus, MI 48174

REVISION DATE: 12-6-00
CHEMTREC: 800-424-9300
EMERGENCY: 734-941-4800

SECTION I - IDENTIFICATION

TRADE NAME: ..... 15174 URANINE C
CHEMICAL NAME: ..... Acid Yellow 73 CAS# 6417-85-2
CHEMICAL FAMILY: ..... Xanthene

SECTION II - HAZARDOUS INGREDIENTS

HAZARDOUS INGREDIENT	PERCENT	CAS NUMBER	PEL
NONE as per 29CFR part 1910.1200 or Sara Title III			

HMIS HAZARD RATINGS (if applicable):
HEALTH: 1
FIRE 0
REACTIVITY 0

SECTION III - PHYSICAL DATA

APPEARANCE: ..... Orange powder, no characteristic odor.
BOILING POINT: ..... N/A
MELTING POINT: ..... N/A
FREEZING POINT: ..... N/A
VAPOR PRESSURE: ..... N/A
VAPOR DENSITY (AIR=1): ..... N/A
SPECIFIC GRAVITY: ..... Approximately 1
pH: ..... N/A
SOLUBILITY IN WATER: ..... Moderate
VOLATILITY: ..... N/A

SECTION IV - FIRE AND EXPLOSION DATA

FLASH POINT: ..... N/A
EXTINGUISHING MEDIA: ..... Water fog, CO_2, or Dry chemical.
FIRE FIGHT PROCEDURES: ... Fire fighters should be equipped with self contained breathing apparatus and turnout gear.
UNUSUAL FIRE HAZARD: ..... Adequate ventilation and clean up must be maintained to minimize dust accumulation. May form explosive dust/air mixture.

Material Safety Data Sheet
(FLUORESCEIN)
15174 URANINE C

SECTION V - REACTIVITY DATA

STABILITY: ..... Stable
CONDITIONS TO AVOID: ..... N/A
HAZARDOUS POLYMERIZATION: Does not occur
POLYMERIZATION TO AVOID: N/A
INCOMPATIBILITY: ..... Avoid contact with strong oxidizing agents
DECOMPOSITION: ..... Carbon monoxide,Carbon dioxide,and oxides of Nitrogen and Sulfur.

SECTION VI - HEALTH DATA

THRESHOLD LIMIT VALUE:.. Not Established
OVER EXPOSURE EFFECTS: Contact with eyes may result in severe irritation. Contact with skin may result in irritation. Ingestion may result in gastric disturbances. Inhalation of dust may irritate respiratory tract.

SECTION VII FIRST AID

FIRST AID PROCEDURES: Flush eyes with flowing water at least 15 minutes. If irritation develops, consult a physician. Wash affected skin areas thoroughly with soap and water. If irritation develops, consult a physician. Remove and launder contaminated clothing before reuse.

If swallowed, dilute with water and induce vomiting. Get immediate medical attention. If inhaled, move to fresh air. Aid in breathing, if necessary, and get medical attention.

NEVER GIVE FLUIDS OR INDUCE VOMITING IF PATIENT IS UNCONSCIOUS OR HAS CONVULSIONS.

SECTION VIII EMPLOYEE PROTECTION

RESPIRATORY PROTECTION: NIOSH/OSHA approved dust respirator as necessary.
PROTECTIVE GLOVES: ..... To prevent skin contact.
EYE PROTECTION: ..... Goggles.
ADDITIONAL MEASURES: ..... Eye wash fountains should be easily accessible.
HANDLING AND STORAGE:... Keep away from excessive heat and moisture. Keep containers closed.
VENTILATION: ..... Local exhaust to control dusts.

SECTION IX - SPILL AND DISPOSAL DATA

SPILL: ..... Spills should be contained and placed in suitable containers.
WASTE DISPOSAL: ..... Do not discharge into sewers or waterways. Dispose of in accordance with local regulations.

Material Safety Data Sheet
(FLUORESCEIN)
15174 URANINE C

SECTION X - TRANSPORTATION DATA

PROPER SHIPPING NAME: ..... Ink Material NMFC Item #101720
HAZARD CLASS AND LABEL: MFR LABEL ONLY
UN NUMBER: ..... N/A
REPORTABLE QUANTITY: ..... N/A

SECTION XI - ADDTIONAL INFORMATION

FOOT NOTES: This information is furnished without warranty, representation, or license of any kind, except that it is accurate to the best of CHEMCENTRAL Corporation's knowledge or obtained from sources believed by CHEMCENTRAL Corporation to be accurate.

The CHEMCENTRAL Corporation does not assume any legal responsibility for use or reliance upon same. Customers are encouraged to conduct their own tests. Before using any product, read its label.

MATERIAL SAFETY DATA SHEET

15189 Eosine OJ

(EOSINE)

SECTION I - IDENTIFICATION

MANUFACTURER/DISTRIBUTOR. CHEMCENTRAL/Dyes & Pigments Division
13395 Huron River Drive
Romulus, Michigan 48174
EMERGENCY PHONE NUMBER... (313) 941-4800
EFFECTIVE DATE..... 10/25/1996
REVISED DATE..... 10/25/1996
CHEMICAL NAME..... Acid Red 87 (Color Index name)
TRADE NAME..... 15189 Eosine OJ
CHEMICAL FAMILY..... Xanthene
CHEMICAL FORMULA..... 45380 (Color Index formula)

SECTION II - HAZARDOUS INGREDIENTS

HAZARDOUS COMPONENTS	HAZARDOUS %	TLV (Units)	PROD. CAS #
None as per part 29 CFR 1910.1200. This product supplied is in compliance with TSCA Reporting Requirements, SARA Title III. Not Listed.			

SECTION III - PHYSICAL DATA

BOILING Point(F)..... N/A
FREEZING POINT (F)..... N/A
VOLATILITY/VOL(%)..... N/A
MELTING POINT..... N/A
VAPOR PRESSURE (mm Hg)... N/A
VAPOR DENSITY (Air=1).... N/A
SOLUBILITY IN H20..... Moderate
APPEARANCE/ODOR..... Red powder, no characteristic odor
SPECIFIC GRAVITY (H20=1). Approximately 1
EVAPORATION RATE..... N/A
PH..... N/A

SECTION IV FIRE & EXPLOSION HAZARD DATA

FLASH POINT..... N/A
LOWER FLAME LIMIT..... N/A
HIGHER FLAME LIMIT..... N/A
EXTINGUISH MEDIA..... Water fog, CO_2, or Dry chemical.
FOR FIRE..... Fire fighters should be equipped with self contained breathing apparatus and turnout gear.

MATERIAL SAFETY DATA SHEET

15189 Eosine OJ

JNUSUAL FIRE HAZARD..... Adequate ventilation and clean up must be maintained to minimize dust accumulation. May form explosive dust/air mixture.

SECTION V - HEALTH HAZARD DATA

THRESHOLD LIMIT VALUE.... Ingestion in rats, LD50=4,700 mg/kg

OVER EXPOSURE EFFECTS.... Contact with eyes may result in severe irritation. Contact with skin may result in irritation. Ingestion may result in gastric disturbances. Inhalation of dust may irritate respiratory tract.

FIRST AID PROCEDURES..... Flush eyes with flowing water at least 15 minutes. If irritation develops, consult a physician. Wash affected skin areas thoroughly with soap and water. If irritation develops, consult a physician. Remove and launder contaminated clothing before reuse. If swallowed, dilute with water and induce vomiting. Get immediate medical attention. If inhaled, move to fresh air. Aid in breathing, if necessary, and get medical attention.
NEVER GIVE FLUIDS OR INDUCE VOMITING IF PATIENT IS UNCONSCIOUS OR HAS CONVULSIONS.

SECTION VI - REACTIVITY DATA

CHEMICAL STABILITY..... Stable

CONDITIONS TO AVOID..... N/A

INCOMPATIBLE MATERIALS... Unknown

DECOMPOSITION PRODUCTS... Carbon monoxide,Carbon dioxide,and oxides of Nitrogen.

HAZARDOUS POLYMERIZATION. Does not occur

POLYMERIZATION AVOID..... N/A

SECTION VII - SPILL OR LEAK PROCEDURE

FOR SPILL ..... Spills should be contained and placed in suitable containers.

WASTE DISPOSAL METHOD.... Do not discharge into sewers or waterways. Dispose of in accordance with local regulations.

SECTION VIII - SPECIAL PROTECTION

RESPIRATORY PROTECTION... NIOSH/OSHA approved dust respirator as necessary.

VENTILATION..... Local exhaust to control dusts.

PROTECTIVE GLOVES..... To prevent skin contact.

EYE PROTECTION..... Goggles.

PROTECTIVE EQUIPMENT..... Eye wash fountains should be easily accessible.

MATERIAL SAFETY DATA SHEET

15189 Eosine OJ

HANDLING AND STORAGE..... Keep away from excessive heat and moisture. Keep containers closed.

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SECTION IX - SPECIAL PRECAUTIONS

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HAZARD CLASS..... N/A
DOT SHIPPING NAME..... Ink Material
NMFC Item #101720
REPORTABLE QUANTITY (RQ). N/A
UN NUMBER..... N/A
NA #..... N/A
DOT LABELS REQUIRED..... Mfg. Label Only
SPECIAL SHIPPING INSTRUCTIONS:
MANUFACTURER'S LABEL ONLY
PACKAGING SIZE..... Various

FOOT NOTES
This information is furnished without warranty, representation, or license of any kind, except that it is accurate to the best of CHEMCENTRAL Corporation's knowledge or obtained from sources believed by CHEMCENTRAL Corporation to be accurate. The CHEMCENTRAL Corporation does not assume any legal responsibility for use or reliance upon same. Customers are encouraged to conduct their own tests. Before using any product, read its label.

N/A = Not applicable

REFERENCES

Material Safety Data Sheet
(SULPHORHODAMINE B)
17152 Acid Rhodamine DW

CHEMCENTRAL/Dyes & Pigments
13395 Huron River Drive
Romulus, MI 48174

REVISION DATE: 10/17/01
CHEMTREC: 800-424-9300
EMERGENCY: 734-941-4800

SECTION I - IDENTIFICATION

TRADE NAME: ..... 17152 Acid Rhodamine DW
CHEMICAL NAME: ..... Acid Red 52 (Color Index Name) CAS # 3520-42-1
CHEMICAL FAMILY: ..... Xanthene

SECTION II - HAZARDOUS INGREDIENTS

HAZARDOUS INGREDIENT	PERCENT	CAS NUMBER	PEL
None as per 29CFR part 1910.1200 or Sara Title III			

HMIS HAZARD RATINGS (if applicable):
HEALTH: 2
FIRE 1
REACTIVITY 0

SECTION III - PHYSICAL DATA

APPEARANCE: ..... Black powder, mild odor.
BOILING POINT: ..... N/A
MELTING POINT: ..... N/A
FREEZING POINT: ..... N/A
VAPOR PRESSURE: ..... N/A
VAPOR DENSITY (AIR=1): ..... N/A
SPECIFIC GRAVITY: ..... Approximately 1
pH: ..... N/A
SOLUBILITY IN WATER: ..... Soluble
VOLATILITY: ..... N/A

SECTION IV - FIRE AND EXPLOSION DATA

FLASH POINT: ..... N/A
EXTINGUISHING MEDIA: ..... Water fog, CO_2, or Dry chemical.
FIRE FIGHT PROCEDURES: ... Fire fighters should be equipped with self contained breathing apparatus and turnout gear.
UNUSUAL FIRE HAZARD: ..... Adequate ventilation and clean up must be maintained to minimize dust accumulation. May form explosive dust/air mixture.

Material Safety Data Sheet

17152 Acid Rhodamine DW

SECTION X - TRANSPORTATION DATA

PROPER SHIPPING NAME: ..... INK MATERIAL
HAZARD CLASS AND LABEL: MFR LABEL ONLY
UN NUMBER: ..... N/A
REPORTABLE QUANTITY: ..... N/A

SECTION XI - ADDTIONAL INFORMATION

FOOT NOTES: ..... This information is furnished without warranty, representation, or license of any kind, except that it is accurate to the best of CHEMCENTRAL Corporation's knowledge or obtained from sources believed by CHEMCENTRAL Corporation to be accurate.
The CHEMCENTRAL Corporation does not assume any legal responsibility for use or reliance upon same. Customers are encouraged to conduct their own tests. Before using any product, read its label.
N/A = Not Applicable

APPENDIX D.

Dye Tracing Result Figures

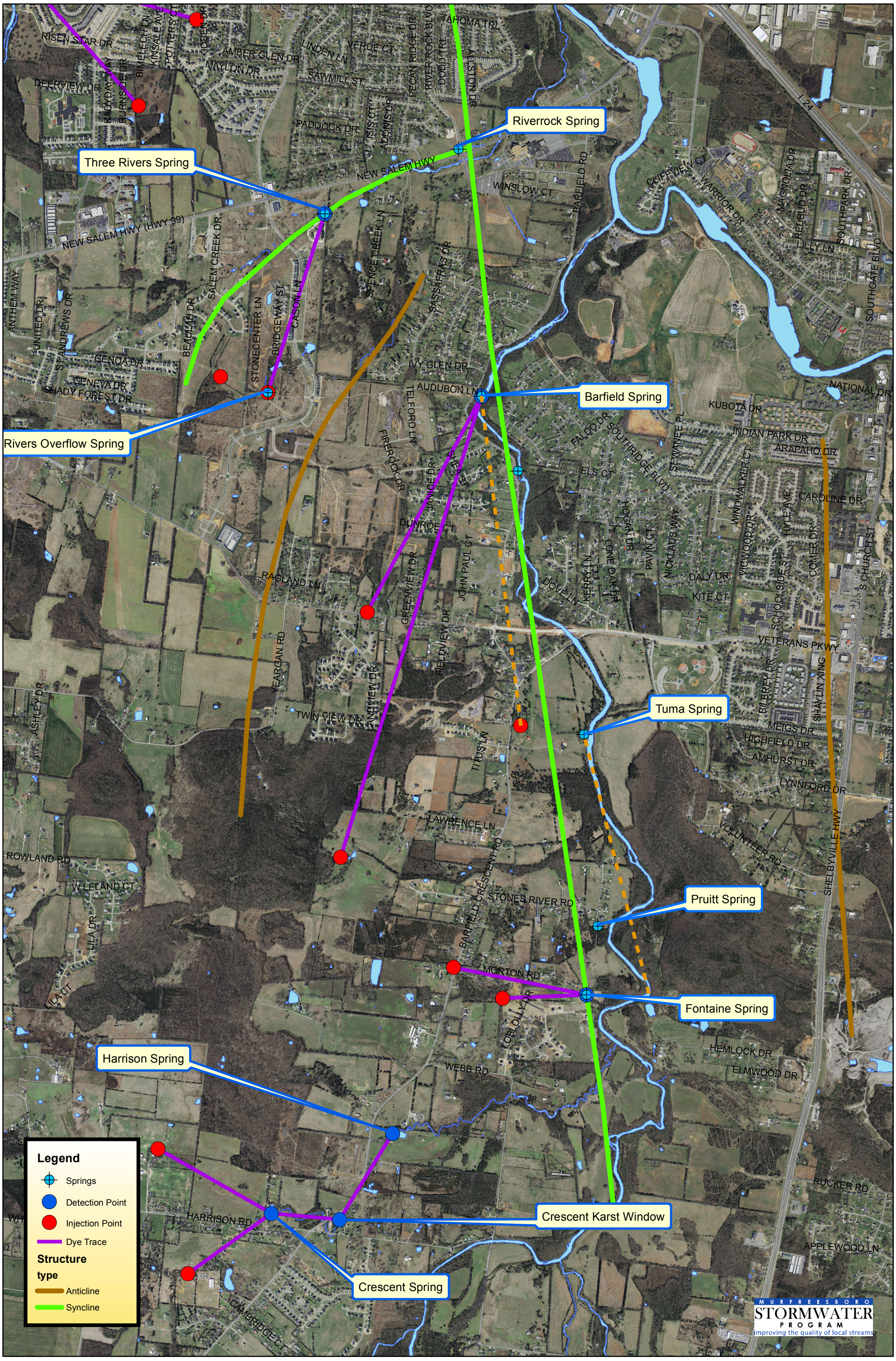

Figure 1. Conceptual geologic structure model of the study area.

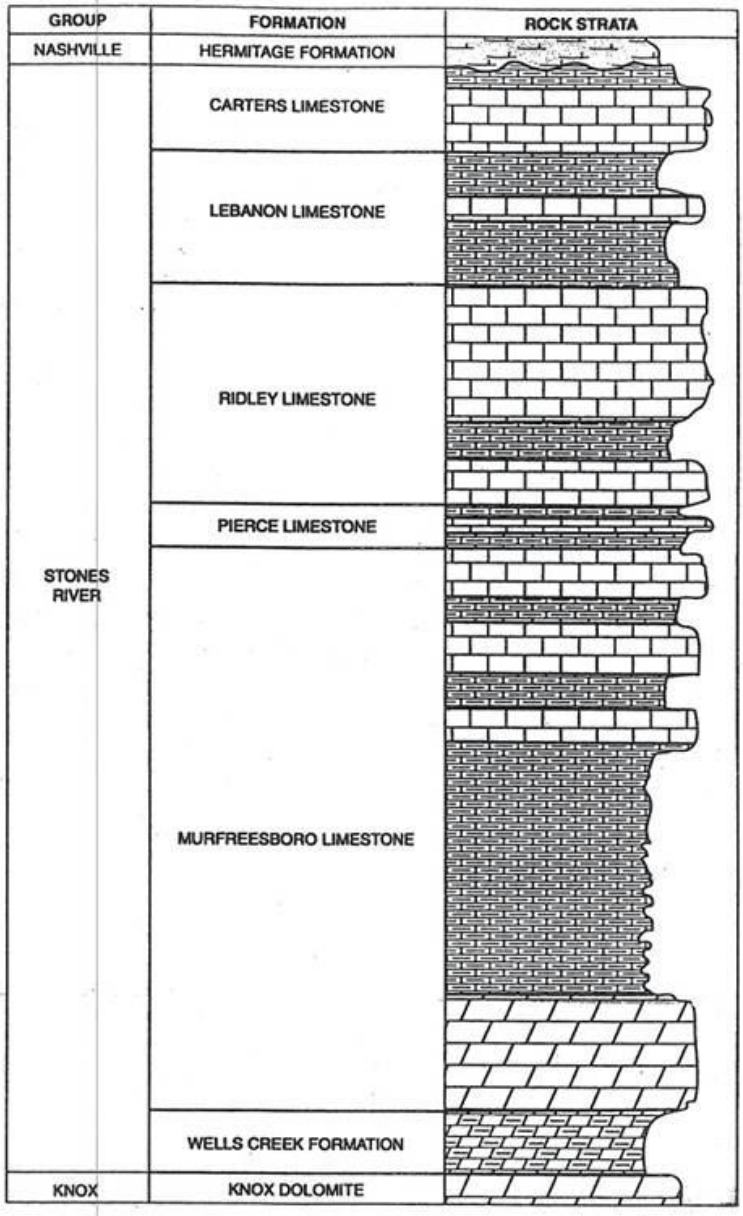

Figure 2. Stratigraphic column of the study area (from Farmer and Hollyday, 1999).

Figure 2. Stratigraphic column of the study area (adapted from Farmer and Hollyday, 1999).

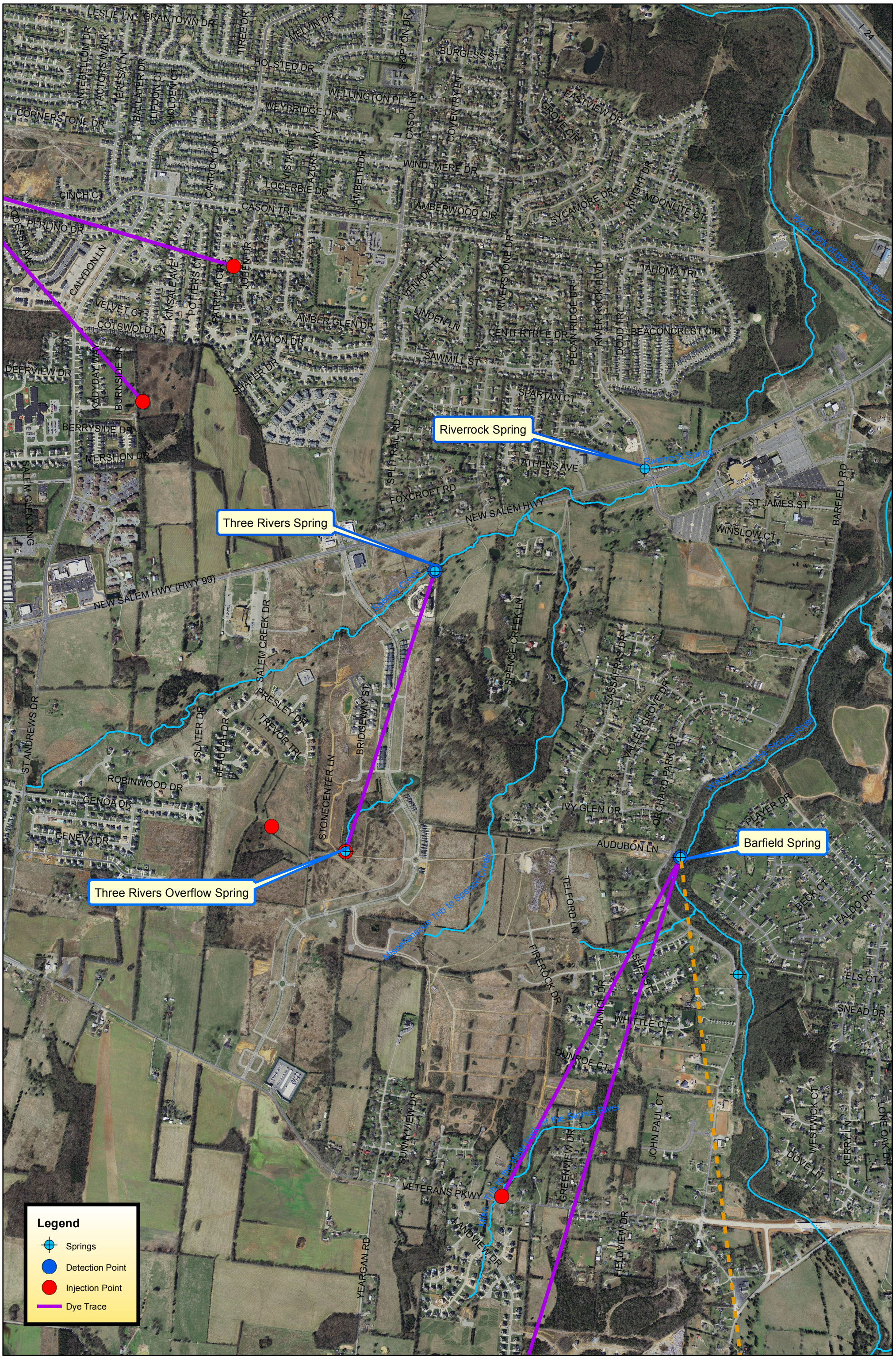

Figure 3. Ground water tracing results for Three Rivers Spring.

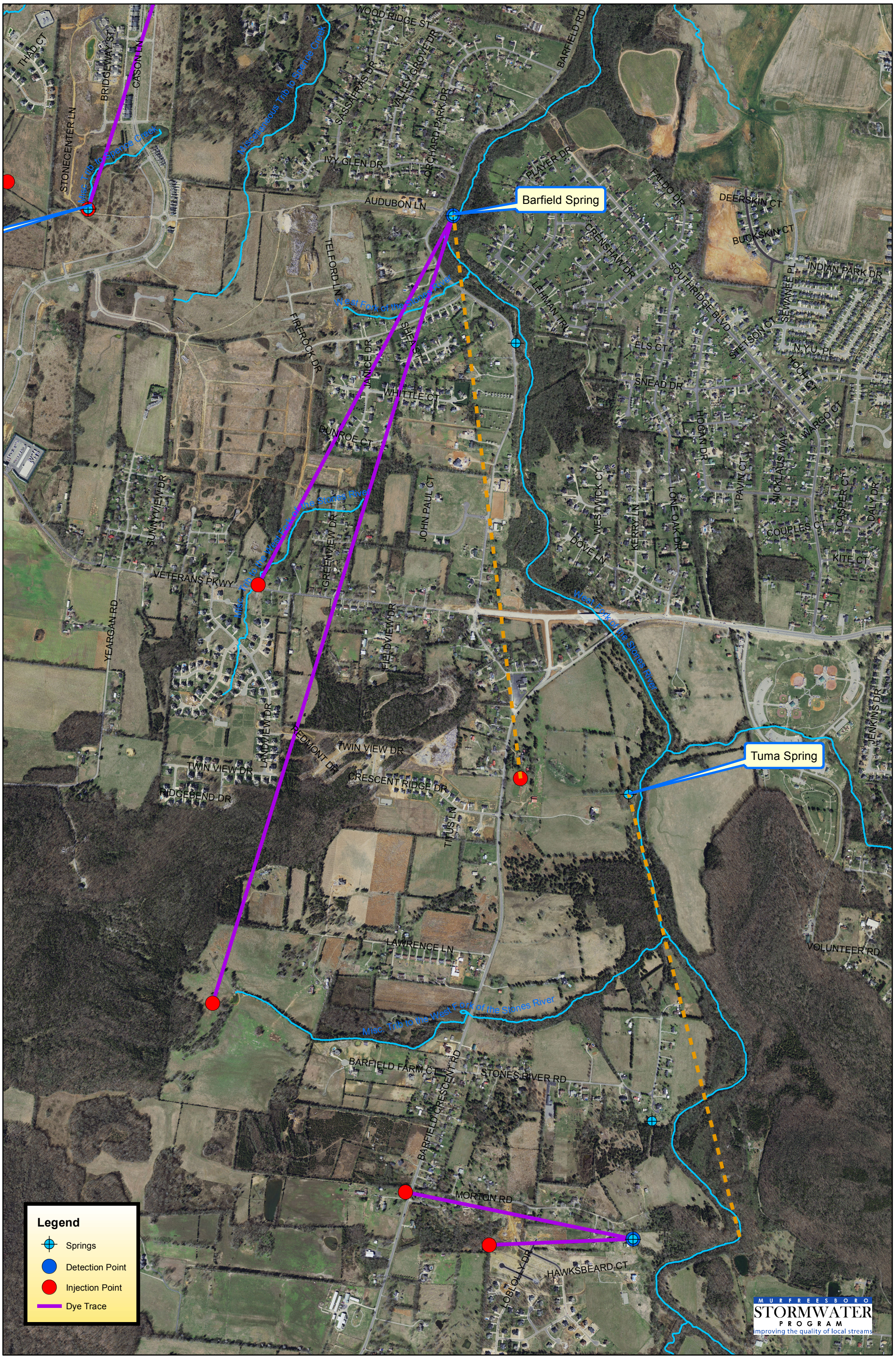

Figure 4. Ground water tracing results for Barfield Spring.

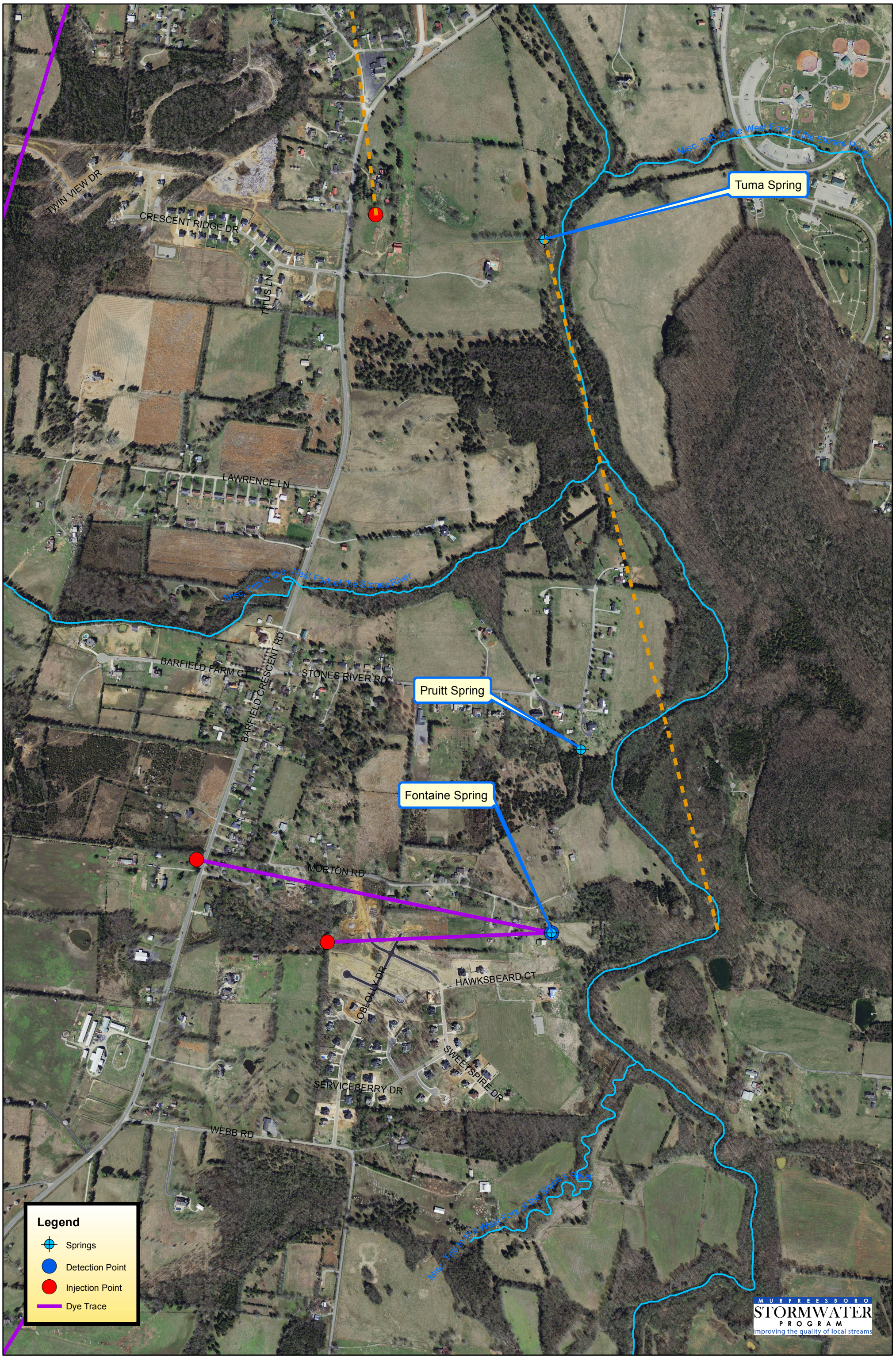

Figure 5. Ground water tracing results for Fontaine Spring.

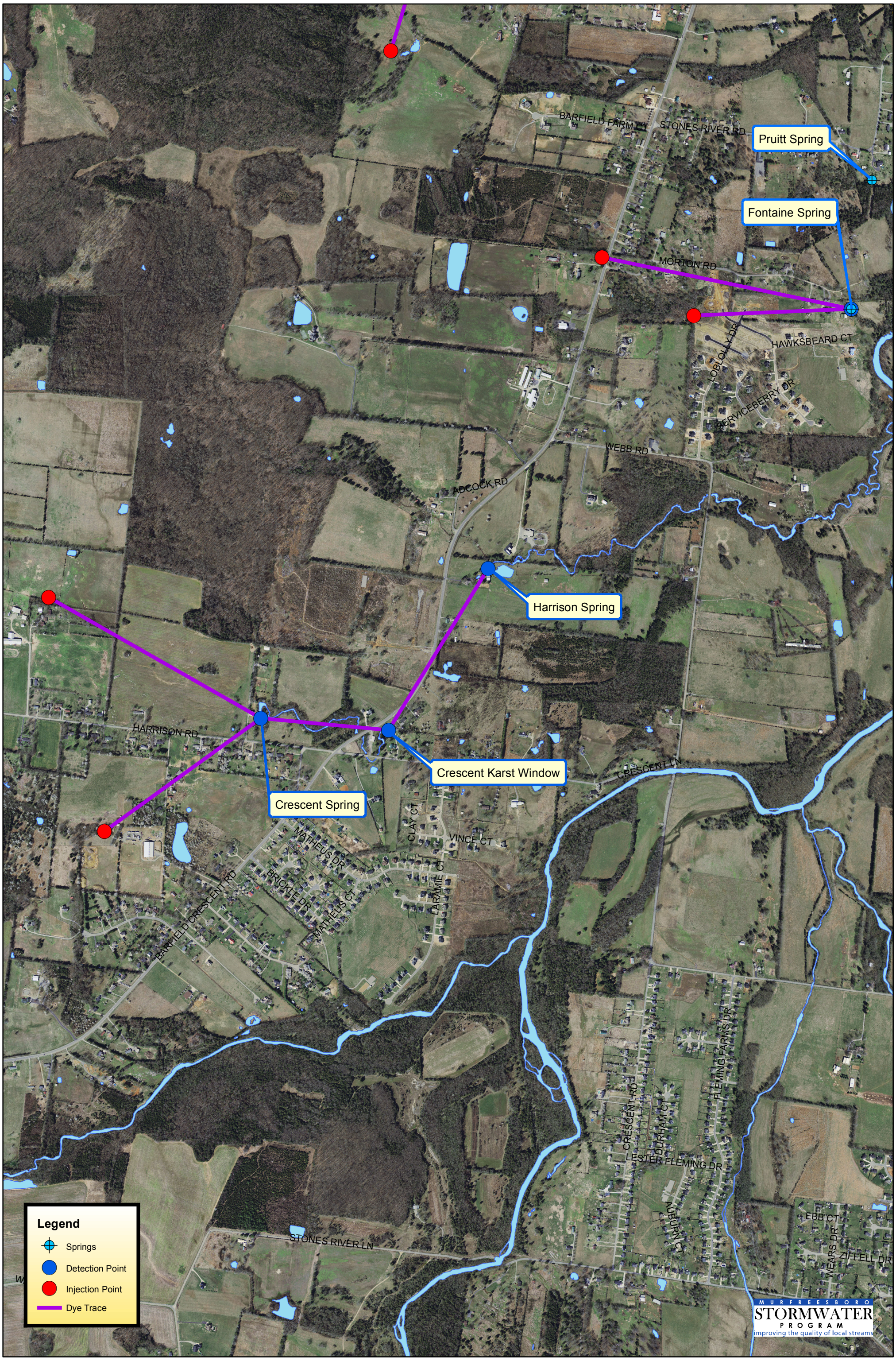

Figure 6. Ground water tracing results for Crescent and Harrison springs.